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# Glacier bursts-triggered debris flow and flash flood in Rishi and Dhauli Ganga valleys: A study on its causes and consequences

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A R T I C L E I N F O

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A B S T R A C T

The territory of the Uttarakhand Himalaya is highly susceptible to meteorological and geophysical hazards. Earthquakes, cloudburst-triggered landslides, debris flows, and flash floods are very common, frequent, intensive, and devastating. Snow avalanches/glacier outbursts are rare, however, they are very dangerous. This article examines the Rishi and Dhauli Ganga tragedy that occurred due to glacier outbursts on February 7, 2021 in the source area of Rishi Ganga, i.e., 'the Nanda Devi glacier' in Chamoli district, Uttarakhand. It describes the major drivers, which triggered debris flows/flash floods in the Rishi and Dhauli Ganga valleys, and illustrates its consequences. The calamity has led to the loss of approximately Rs. 20,000 million and the death of about 205 people. Land degradation, loss of soils and forests, and formation of landslide scars in the affected areas were other consequences. This study suggests several policy measures to reduce the casualties related to natural hazard processes.

## 1. Introduction

The Uttarakhand state in the Northern part of India is located in the Southern part of the Himalaya and is the host of some of the most fragile ecosystems in the world (Kumar et al., 2006). It is highly exposed to potentially disastrous meteorological and geophysical processes. The entire region is geo-morphologically sensitive, tectonically and seismically very active, geographically remote, and faces low development status in economic terms (Sati and Maikhuri, 1992; Sati, 2013). Atmospheric phenomena such as cloudbursts are common hazards and often trigger debris flows, flash floods, landslides, and mass movements. These events occur frequently during the monsoon seasons when heavy rain occurs in the entire Uttarakhand Himalaya (Sati, 2011). Such incidents in the past have led to disastrous consequences in terms of the enormous property losses and human and animal casualties. Glacial Lack Outbursts Floods (GLOF) and snow avalanches/glacier bursts occur less often but also represent a significant risk of triggering natural and human losses due to their great intensity. However, during the recent past, the number of 'glacier bursts' has increased due to changes in climate conditions, and the damages has incresaed due to exposed elements in risk-prone areas such as infrastructural facilities constructed on valley bottoms (Byers et al., 2019; Sati, 2014 a; ICIMOD, 2007; Chalise and Khanal, 2001; ICIMOD, 2007; Bhandari, 1994; Baofeng and Constantine, 2017). Further, high variability and change in climate conditions have increased the frequency and intensity of weather-induced debris flows, flash floods, and landslides in Uttarakhand (2017).

Past studies on terrestrial (endogenous) and atmospheric (exogenous) hazards in the Uttarakhand Himalaya have shown that the atmospheric hazards have become more frequent and intensive. The population has increased multifold in the fragile slopes. Further, the construction of infrastructural facilities along the river valleys and fragile slopes is boosting up. There are a total of 13 macro-river valleys hydropower projects have been constructed or under construction (besides Tehri high dam) along eight river valleys, which are producing about 3000 MW hydro-electricity (Sati, 2014 b; Sati, 2021). Besides, about 200 small-scale hydropower projects are proposed. The hydropower projects are further accentuating the vulnerability of the river valleys. The Rishi Ganga calamity is an example, which reveals that the losses of lives and property were due to the construction of the Rishi Ganga and Tapovan-Vishnu Gad power projects.

This paper examines the major drivers of glacier bursts in the Nanda Devi peak and the impact of its triggered debris flow and flash flood on the affected areas – hydropower projects and the villages situated on the course of Rishi Ganga and Dhauli Ganga, in terms of loss of lives – human and animal, agricultural loss, the collapse of bridges, and the damage to structures of hydropower projects. Land degradation, loss of soils and forest, and the future potential threats due to forming of landslides and land scars along the rivers were

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examined. The paper also suggests how to reduce the impact of disasters in the fragile landscape of the Himalaya.

## 2. The study area

The Rishi Ganga originates from the Nanda Devi glacier at an altitude of 4132 m, latitude 30°23′19″ N, and longitude 79°45′02″ E. In the vicinity, there is the Nanda Ghunti (6309 m) and the Trishul (6415 m) Mountain Peaks of the Himalaya in Chamoli district (Fig. 1). The Rishi Ganga flows to the northwest up to 10 km, and then it flows to the north and northwest up to 6 km, and finally joins the Dhauli Ganga near Raini village with an altitude of 1951 m On the way, many glacial-fed perennial streams join the Rishi Ganga and increase its velocity and volume. The Rishi Ganga catchment is one of the highly fragile and vulnerable among the thirteen rivers' catchments of Uttarakhand. Since the catchment area of the river is close to the fragile terrain of high Himalaya, its valley and slopes are the hotspots to landslides. Similarly, some other rivers –Asi Ganga, Dharma Ganga, Birahi Ganga, Bal Ganga, Byundhar Ganga, and Dhauli Ganga are very vulnerable to hazards because of their locations are in the vicinity of the high Himalaya (see Fig. 2).

The Nanda Devi Biosphere Reserve (NDBR) is situated here. It is a protected area where the cutting of trees is prohibited. Despite being located in the NDBR, there are a total of seven hydropower projects constructed within a short distance between Raini village and Nandprayag. Further, there are three hydropower projects proposed in the small catchment of the Rishi Ganga. Because of the fragile geomorphological setting, the environmentalists of the region have filed a petition in the Supreme Court of India, which intends to ban the three proposed hydropower projects in the Rishi Ganga valley.

## 3. Data and methods

The method used in this study was mainly qualitative and based on field observation. Data were collected from primary sources – interviews of people from affected villages, workers who were working in two hydroelectricity power projects, and the officials of the power projects. The details of proposed and constructed river valley projects in Uttarakhand were gathered from the Water Resource Department, Dehradun. Further, the data on the recent past geo-hazards that occurred in Uttarakhand were gathered from the National Institute of Disaster Management (NIDM), Dehradun. In addition, data were collected from the agencies which were involved in constructing power projects and those were investing in the causes and effects of glacier outburst events. A field visit of two hydropower projects – Rishi Ganga and Tapovan-Vishnu Gad and four villages –Raini Chaklata, Raini Chaksubai, Morana, and Jugju was conducted to observe the ground reality and to assess the damage caused by debris flow and flash flood. The volume of the boulders and debris near the two hydropower projects was measured. Cross-sections of soil, deposited by a flash flood at Tapovan, and landslide at Raini village, were drawn. Based on these analyses, vulnerability analysis of four villages was carried out. These villages are the worst affected by the glacial outburst. The possible future of affected villages in terms of accelerating landslides vulnerability was discussed after the field visit. Suggestions are given to minimize the future impact of geo-hydrological hazards in the entire state of Uttarakhand Himalaya.

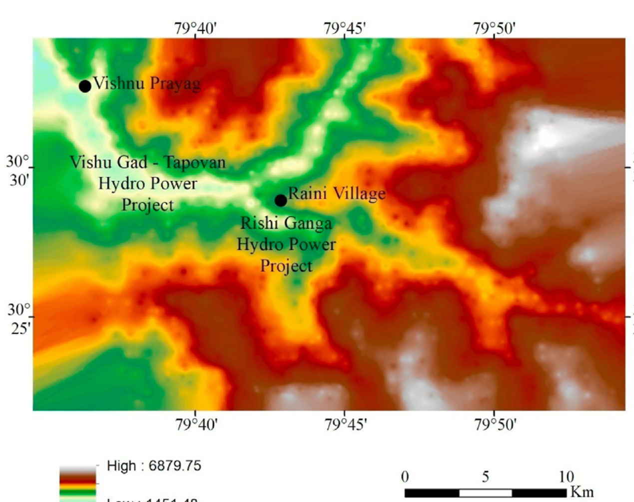


Fig. 1. Elevation map of the glacier outburst and affected areas along the Rishi Ganga and Dhauli Ganga in Chamoli district.

## 4. Results and analysis

### 4.1. Causes of glacier bursts-triggered debris flow and flash flood

On Feb 7, 2021 (Sunday) at 10:30 a.m., a huge glacier bursts-triggered[1] massive debris flow/flash flood occurred in the Rishi Ganga and the Dhauli Ganga valleys. Glacier outbursts/snow avalanches generally occur during the summer because of the increase in temperature and snow melting. Therefore, the glacier outburst in the Nanda Devi mountain peak, which triggered debris flow and flash flood, was unusual because it took place in the first week of February when the upper areas of Rishi Ganga and Dhauli Ganga catchment received heavy snowfall before the glacier outbursts. The scientists, academics, and government authorities worked to find out the actual cause of Nanda Devi glacier outbursts. As the area, where glacier outbursts took place, is remotely located, therefore, the precise reason is not much known. There are different opinions about what triggered the glacier burst (Table 1). The scientists of the Wadia Institute of Himalayan Geology (WIHG) conducted a preliminary study and stated that the glacier outbursts were due to heavy snowfall in the higher reaches of the Rishi Ganga catchment, followed by heavy frost. The snow became hard and got glacier shape. Immediately after, the temperature increased and moisture decreased, which led to the glacier outbursts. In contrast to the scientists of India's Space Centre (ISC), Dehradun said the glacier outburst was due to the sliding of heavy snow after an increase in temperature, which resulted in a massive debris flow/flash flood. The Defense Research and Development Organization (DRDO) conducted a study and noticed that a hanging glacier broke away from the main glacier and fell in the narrow valley, which led to the formation of an artificial lake. Further, the artificial lake outburst and triggered a massive debris flow/flash flood. Another study shows that a huge landslide occurred at 5600 m altitude, which caused to glacier break outflow and triggered debris flow and flash flood. The Indian Space Research Organization (ISRO) Cartosat Satellite found out that cracks were developed in the rocks near the Nanda Devi glacier, which were filled by snow. During 5–7 February 2021, the temperature suddenly increased to an average of 7 °C from the prevailing temperature, which led to the melting of a glacier in these cracks. Due to steep slopes and narrow valleys, the velocity of glacier meltwater increased and triggered debris flow/flash flood.

Whatever the theories and studies about the Nanda Devi glacier outbreak depict, one common conclusion was that the glacier burst triggered a series of cascading processes: the material that was sliding/falling into the narrow valley first formed an artificial lake, which later burst and caused a debris flow/flash flood. Also, there is a general agreement that the volume and velocity of debris flow/flash flood was further accentuated by the two water reservoirs constructed on the banks of Rishi and Dhauli Ganga. A team of scientists of the Govind Ballabh Pant National Institute of Himalayan Environment (GBNPIHE) investigated the causes and consequences of debris-flow and flash floods in the

[1] Because of the remoteness, the exact cause of glacier burst is not known. A detailed description on the causes of this event is given in the preceding paragraph.

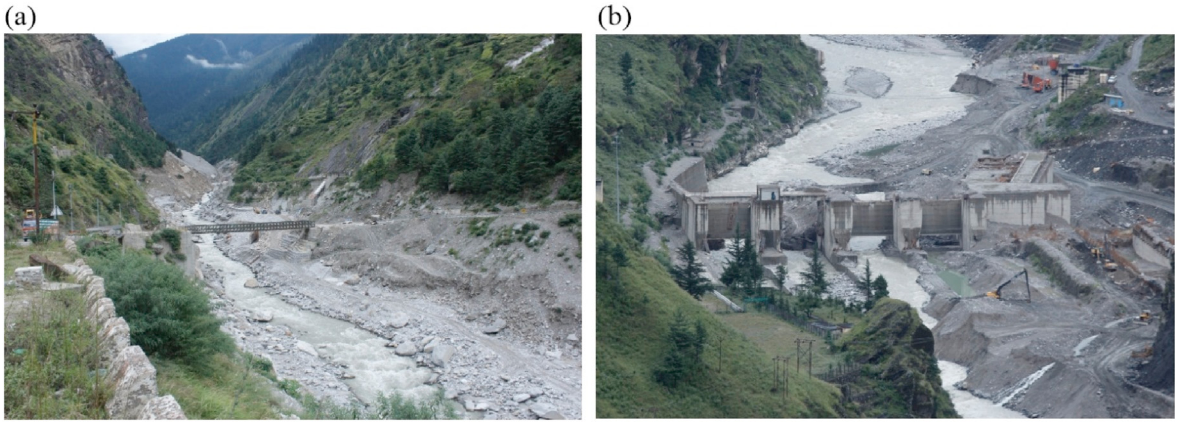

**Fig. 2.** (a) Glacier bursts affected Rishi Ganga hydroelectricity power project (a) Devastated Tapovan-Vishnu Gad hydroelectricity power project along the Dhauli Ganga, Photo by author.

**Table 1**
Scientific speculations about a glacial-burst triggered calamity (The Times of India-State version 8th and February 9, 2021).

| S. No. 1 | Scientific theories | Description | Scientific agencies |
|---|---|---|---|
| 1 | Heavy snowfall | The glacier outbursts were due to heavy snowfall in the higher reaches of the Rishi Ganga catchment followed by heavy frost. The snow became hard and got glacier shape. Immediately after, the temperature increased and moisture decreased, which led to the glacier outbursts. | WIHG, Dehradun |
| 2 | Sliding of heavy snow due to increased temperature | The glacier outburst was due to the sliding of heavy snow after an increase in temperature, which resulted in a massive debris flow/flash flood. | ISC, Dehradun |
| 3 | Breaking of a hanging glacier | A hanging glacier broke away from the main glacier and fell in the narrow valley, which led to the formation of an artificial lake. Further, the artificial lake outburst and triggered a massive debris flow/flash flood. | DRDO, Dehradun |
| 4 | Development of cracks (1) | Cartosat Satellite found out that cracks were developed in the rocks near the Nanda Devi glacier, which were filled by snow. During 5–7 February 2021, the temperature suddenly increased to an average of 7 °C from the prevailing temperature, which led to the melting of a glacier in these cracks. Due to steep slopes and narrow valleys, the velocity of glacier meltwater increased and triggered debris flow/flash flood. | ISRO, Hyderabad |
| 5 | Landslide (2) | A huge landslide occurred at 5600 m altitude, which caused the glacier-bursts outflow and triggered debris flow and flash flood. | ISRO, Hyderabad |

Rishi and Dhauli Ganga valleys. They observed that near Raini village, the Rishi Ganga flows through a narrow valley, which accentuated the velocity of debris. Further, between Raini village and Tapovan, the Dhauli Ganga also flows through a narrow valley. Another perennial stream joins the Dhauli Ganga at Hot Spring Area before Tapovan. The scientists estimate the height of the debris in both narrow valleys of above 100 feet. Our study shows that the boulders of different dimensions flowed because of the high volume and velocity of the river water. Warming of the high reaches in the Rishi Ganga catchment has led to this catastrophe, as the scientists working in this region unanimously opined. The drivers of warming of the catchment have been noticed in the construction of infrastructural facilities including hydroelectricity power projects and quarrying and mining. The author observed that the loss of lives and properties in the Rishi Ganga and the Dhauli Ganga valleys was caused by settlements constructed along the banks of the two rivers. Further, an under-construction tunnel in the Tapovan-Vishnu Gad hydropower project has led to a huge loss of life. The workers of the hydropower projects were stranded in the tunnel and died after a few days.

The Uttarakhand is known as the 'Urja' (power) state as it has more than 30,000 MW hydroelectricity power generation capacities projects. The Tehri high dam itself has about 5000 MW capacities (Sati, 2014 c). The hydropower projects are increasing in the entire state and are causing disasters. It has been noticed that every river (big and small) has a hydropower project. Recently, 32 new power projects are planned and under construction. Some of them are being constructed in the high Himalaya where the landscape is highly fragile. Keeping the high fragility of land in mind, the Supreme Court of India has banned 13 hydropower projects, including three proposed hydropower projects in the Rishi Ganga valley.

### 4.2. Consequences of glacier-triggered debris flow and flash flood

#### 4.2.1. Impact on hydropower projects

The glacier burst-triggered debris flow and flash flood devastated the valleys of the Rishi and the Dhauli Ganga and partially affected the Alaknanda River valley between Vishnuprayag and Karnprayag. This flow contained a mix of ice, water, and sediments, which were composed of particles of sizes up to boulders. It damaged the 13.2 MW National Thermal Power Corporation (NTPC)'s hydropower project, which was located on the left bank of the Rishi Ganga below the Raini village. Because of the narrow valley and the additional water of the Dhauli Ganga and other perennial streams betweens the Rainy village and Tapovan, the volume and velocity of the debris/flood were increased. This has resulted in full devastation of a 520 MW under construction hydropower project at Tapovan-Vishnu Gad (left bank of the Dhauli Ganga). Along with this, a hydropower project – Vishnu Gad-Pipalkoti, which is constructed on the Alaknanda River, was partially damaged. Raini, the last village of the Niti Valley, is situated on the right bank of the Rishi Ganga. The upper parts of the adjacent slopes are uninhabited.

Therefore, people could only detect the debris flow/flash flood when it reached near the NTCP's project area on the bank of the Rishi Ganga at about 10:30 a.m. It was so sudden that the workers of the project could not escape the debris. The villagers of the Raini and other villages, which are located on both slopes of the river, alerted the workers of NTPC's project at Tapovan through telephone. However, the workers had already gone into the tunnel for routine work where they could not receive telephone signals. The distance from Rainy village to Tapovan is about 7 km. The bridge connecting Tapovan with Rainy village collapsed due to debris flow and the tunnel was inundated with debris. Most of the workers working on the projects were from the other states of India and they were not familiar with mountain hazards. The downstream villages had sufficient time to get evacuated. The entire Ganga valley up to Uttar Pradesh sounded emergency alert. The local people who were passing through the upper part of the river valleys informed that the NTPCs reservoir, which was constructed on the Dhauli Ganga, was inundated first and then debris flew flowed inside the tunnel, which was under construction on the left bank of the river. The workers of the hydropower project were working inside the tunnel. The tunnel was 250 m long and it was under construction at the Tapovan-Vishnu Gad project at 1802 m altitude; 30°29′38″ N and 79°37′39″ E. The Rishi Ganga was flowing above 100 feet from its normal level. A total of 72 people died and 133 people were missing (A total of 205 people), the report came from the district administration. A total of 35 people were rescued on the day when the calamity took place. Among the missing people, they were either stranded in the tunnel or flown with the debris and have been reported dead. Few dead bodies were found in the reservoir of the Srinagar hydropower project, which is about 160 km from Tapovan. Vishnuprayag, where the Dhauli Ganga joins the Alaknanda River, was inundated, resulting in the damage to the settlements constructed on the bank of both rivers. Pipalkoti hydropower project was also damaged partially. Half of the Raini village area, world-famous for the Chipko-Movement of the 1970s, situated on the upslope of the Rishi Ganga and close to the Dhauli Ganga, was washed away due to the Rishi Ganga debris flow/flash flood. This area falls in the Niti Valley, which is close to the Tibet border. A bridge of 100 m, constructed on the Rishi Ganga and connecting Joshimath to Malari also flew flowed with debris. Similarly, four important hanging bridges, the only means of transportation of four villages - Lata, Raini, Fakti, and Suraithola have washed away. The National Disaster Response Force (NDRF) officials estimated that there was a huge loss of property amounting to 20,000 million Rupees took place due to this calamity. Army, Indian Tibet Border Police (ITBP), Border Road Organization (BRO), NDRF, and State Disaster Response Force (SDRF), three helicopters, and two super herculean planes were deployed for the post-disaster rescue operation immediately after the news spread in the state and the entire country. Both the central government and the state government ordered these forces to work for the post-disaster rescue operation. The Uttarakhand state Chief Minister rushed to Tapovan on the same day and observed damage due to the calamity. The gates of the water reservoir of the Srinagar hydropower project were immediately opened to release the water so that the debris coming from the Rishi Ganga can be accommodated in the reservoir. Further, the gates of the Tehri high dam reservoir were closed to reduce the volume of debris flow and flash flood after Devprayag. The downstream areas, situated on the river bank were evacuated immediately after the news spread. Two villages – Devali Bagar and Alkapuri, which are situated on the bank of the Alaknanda River close to Nandprayag town, were evacuated. About 1000 people were sent to the safe areas. The entire Ganga valley received acute panic. The local people of downstream areas were afraid of the calamity as they compared this situation with the Kedarnath calamity of 2013, where more than 10,000 people were flowed (Kotal et al., 2014; Rautela, 2013; Chopra, 2014). Development works, including railway construction, were interrupted. The temples, situated on the bank of rivers at Nandprayag, Karnprayag, Rudraprayag, and Devprayag were closed and the low-lying regions of Rishikesh and Haridwar were cleared. Many villages were evacuated as floodwaters damaged homes. The NTPC power plants at Tapovan and Rishi Ganga have completely washed away (Table 2). This event could have devastated more however, it was morning time and sunny day, thus, the rescue operation was successful, which could save the lives of the people.

#### 4.2.2. Impact on villages situated on the banks of two rivers

The impact of the glacier burst was immense on two villages – Raini Chaklata and Raini Chaksubai, situated on the left and right banks of the Rishi Ganga (Fig. 3). The first village has 32 households, dependent on agriculture and livestock farming. During debris flow, one person died and about 0.5 acres of arable land with existing crop (Ramdana) was damaged. In Raini Chaksubai village, two-person died and about 4 acres of land were washed away. The other two villages which were partially affected were Morana and Jugju. In these two villages, two people died and 1 acre of land was washed away along with the existing crop. People of these four villages have started out-migrating to safer areas because, after post-disaster, landslides along the river bank have become very active. Some families already out-migrated. Houses, temples, bridges, shops, and domestic animals were transported out and forest land degradation was highly noticed.

### 4.3. Measurement of volume of debris and boulders

The volume of debris and boulders was measured at the Rishi Ganga hydropower projects (Table 3), which was first hit by glaciers triggered debris flow and flash flood. The radius of boulders was 2.5 m, the diameter was 5 m, the circumference was 15.7 m and the area was 19.6 $m^2$. The total volume of debris was 62,000 $m^3$.

### 4.4. Cross sections of soils and landslide

The flash flood deposited huge debris on the base of the Tapovan-Vishnu Gad hydropower reservoir. A cross-section of soil, deposited by flash floods at the Tapovan-Vishnu Gad hydropower project, was drawn. Four soil types were found at the dam site ranging from topsoil, muddy siltstone, rubble soil, and silty clay (Fig. 4). Further, the debris contains different sizes of boulders. The length of this section was >1 km and the height was >100 m, causing a complete blockage.

**Table 2**
Description of affected areas and impact of debris flow/flash flood.

| Name of location | Altitude (m) | Latitude (N) | Longitude (E) | Time of event | Losses and damage | Reason for the damage |
|---|---|---|---|---|---|---|
| Rishi Ganga | 1984 | 30°29′08″ | 79°41′39″ | 10:30 a.m. | Entirely damaged with human casualties (Total 100 died) | Sudden outbursts people could not escape |
| Tapovan | 1796 | 30°29′37″ | 79°37′44″ | 10:45 a.m. | Entirely damaged with human casualties (total 105 people died). | The workers already entered the tunnel. The telephone signal could not work. |
| Vishnu Prayag | 1449 | 30°33′44″ | 79°34′33″ | 11:30 a.m. | Temple area washed away | Because of the high level of debris |
| Pipalkoti | 1121 | 30°25′59″ | 79°25′25″ | 12:15 p.m. | Partially affected | Because of the high level of debris |
| Srinagar | 569 | 30°14′24″ | 78°49′53″ | 5:00 p.m. | Huge sediments deposited | Because of the high level of debris |

*Source*: GPS and field survey by the author.

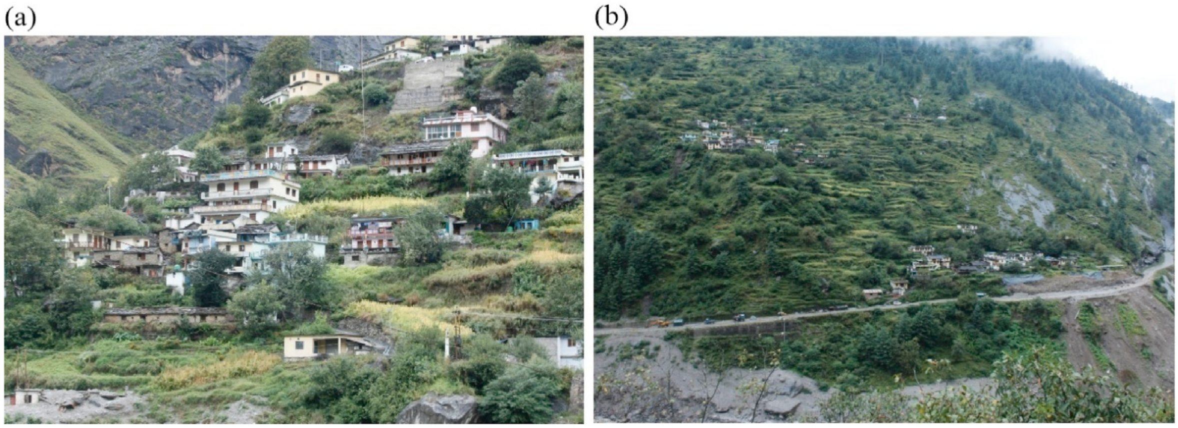


**Fig. 3.** (a) Raini village, situated on the left bank of the Rishi Ganga (b) Raini village, situated on the right bank of the Rishi Ganga have now become vulnerable to landslides; Photo by Author.

**Table 3**
Average circumference, area, and volume of boulders.

| Variables | The situation at the Rishi Ganga hydropower project |
|---|---|
| Radius (m) | 2.5 |
| Diameter (m) | 5 |
| Circumference (m) | 15.7 |
| Area ($m^2$) | 19.6 |
| Total volume of debris ($m^3$) | 62000 |

*Source*: by Author.

A huge landslide was formed by the flash flood in the Rishi Ganga through bottom erosion below the Raini village. Its length and breadth were both >120 m (Fig. 5). As a result of landslide scars, a large part of the Raini village has already been cut off and the rest part of the village has been evacuated.

### 4.5. Susceptibility analysis of affected villages

Based on the observation after the field visit of the affected villages, the susceptibility of the affected villages was analyzed. The variable analyzed were altitude, slope gradient, accessibility from the road, and distance from the river. It has been noticed that vulnerability to future landslides is very high in Raini Chaklata and Morana villages and high in Raini Chasubai and Jugju villages (Table 4).

The affected Rishi Ganga and the Dhauli Ganga hydropower projects and four villages located along the Rishi Ganga and Dhauli Ganga river banks are shown in Fig. 6.

## 5. Discussion

The high Himalayan regions, above 4000 m, have numerous glaciers. They are mainly situated in the six districts – Uttarkashi, Tehri, Rudraprayag, Chamoli, Bageshwar, and Pithoragarh. The major glaciers are Yamunotri, Gangotri, Bandarpoonch, Dronagiri, Satopanth, Chaurabari, Khatling, Milam, Namik, Ralam, Sundardhunga, Pindari, and Shilasamundar. The Ganga River is the lifeline of India. It originates from the Gaumukh glacier. All its tributaries are also glacial-fed and perennial. However, in the upper part of the Ganga catchment, glaciers tend to be unstable cryospheric features that represent a devastating risk to the ecosystem/landscape of Uttarakhand. The geologists of the region observe that earthquakes of even small intensity will be a potential threat to these glaciers. In the Chamoli district, the maximum temperature has increased at the rate of 0.032 °C per year between 1980 and 2018 (ICIMOD, 2021). Further, the temperature data of the mountainous mainland of Uttarakhand were noticed highly variable during the past decades from 15°51′ the highest in 2012 to 13°59' the lowest in 2013 (SMD, 2015). The river valleys are facing acute warming and, as a result, meteorological events are very frequent and intensive. The glacial-fed lakes are increasing due to snow-melting. There were a total of five glacial-fed lakes increased from 2012 to 2020 as per a report of the WIHG. The report further stated that 39 glacial-fed lakes existed in 1976 in Uttarakhand, which increased to 88 in 1990, 129 in 1999, and 217 in 2011. In mountain regions of the world, about 2315 new glacial-fed lakes existed recently, as a report published by UNEP stated (Down to Earth, 2013).

The scientists of WIHG stated that in the recent past, black carbon has been brought to the Himalaya through Western Disturbances that rise

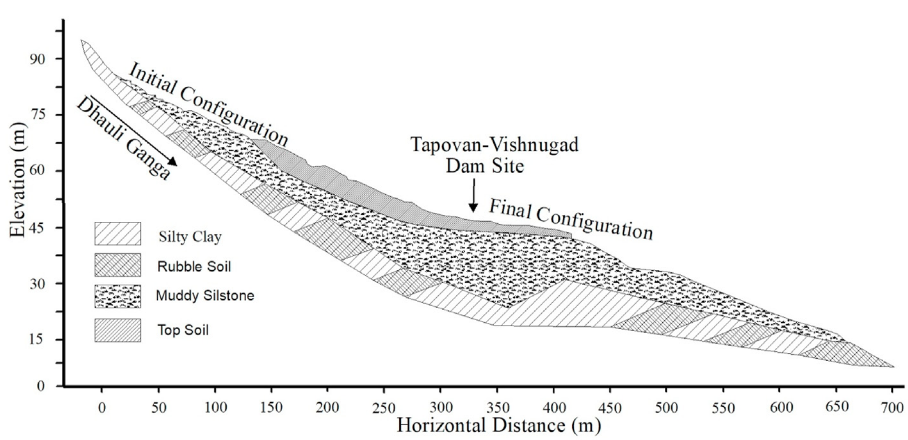


**Fig. 4.** Cross-section of soil deposited by debris flow at Tapovan-Vishnu Gad.

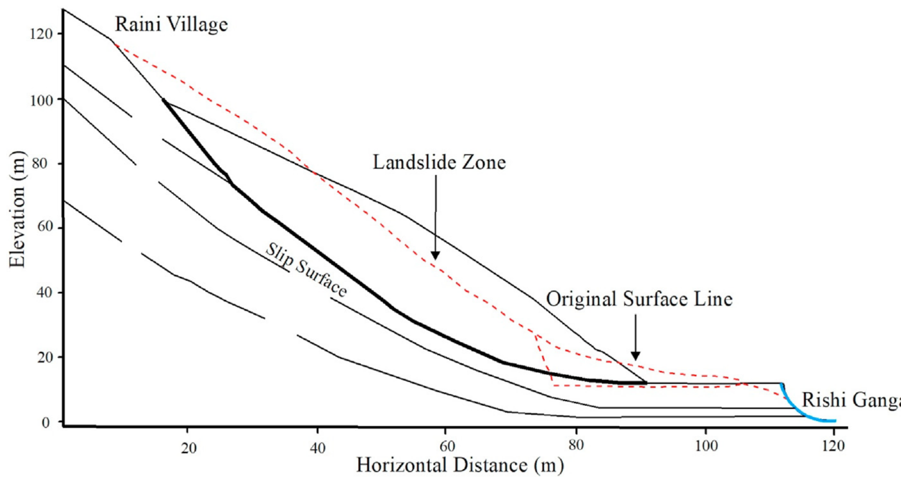


**Fig. 5.** Cross-section of a landslide below Raini village.

**Table 4**
Susceptibility analysis of the affected villages.

| Variables | Raini Chaklata | Raini Chaksubai | Jugju | Morana |
|---|---|---|---|---|
| Altitude | 2010 | 2008 | 2020 | 2150 |
| Slope gradient | High | High | High | High |
| Accessibility from road | On the road | 1 km | 2 km | 3 km |
| Distance from river | 500 m | 1000 m | 800 m | 2 km |
| Susceptibility to landslide | Very high | High | High | Very high |

*Source*: by Author.

from Europe, which is damaging Himalayan Glaciers. They estimated that the carbon aerosols range from 0.01 to 4.62 μg per cubic meter. During the last two decades, Uttarakhand has already received catastrophic hydro-meteorological hazards in the form of snow avalanches, cloudbursts, and flash floods (Table 5). In several cases, snow avalanches and glacier bursts had less adverse impacts than cloudbursts-triggered flash floods and debris flow. The Kedarnath cloudburst was the most devastating calamity among the calamities that occurred during the last two decades in Uttarakhand.

Fig. 7 shows major rivers and district headquarters. Further, it shows major hydrological hazards which occurred between 2008 and 2021. There were a total of 14 major and several minor hydrological incidences including Rishi Ganga occurred within a short period. It further shows that these hydrological hazards were occurred mainly in the upstream river basins, in the higher reaches of Uttarkashi, Tehri, Rudraprayag, Chamoli, Bageshwar and Pithoragarh districts. The terrain of these districts is undulating and precipitous and highly vulnerable to hydrological hazards.

The Himalayan region is prone to natural hazards – landslides, mass movement, debris flows, flash floods, avalanches and glacial bursts. Every year these events occur, causing huge losses of people and property. The events of snow avalanches and glacial bursts have been rarely observed in the Uttarakhand Himalaya during the past, especially during the winter, when the upper regions above 2000 m received heavy snowfall. The Rishi and Dhauli Ganga calamity were unique, unusual, and catastrophic. Glacial bursts triggered landslides that occurred on the day when the entire region received heavy snowfall. The paper mentioned four scientific theories on the origin of glacial-burst triggered debris flow and flash floods. However, all theories presented one common conclusion, that is, the sudden warming of the region has led to glacial burst triggered debris flow and flash flood.

The human casualties and loss of economy due to Rishi and Dhauli Ganga calamity were enormous. The reason for the huge losses was mainly man-induced. The two hydropower projects, which were under construction, have accelerated the magnitude of the disaster. Shugar et al. (2021) also observed that hydropower infrastructure and unstable


**Fig. 6.** The affected hydropower projects and villages after calamity (Google Earth, 2021).

**Table 5**
The major meteorological hazards in Uttarakhand.

| Name and year of hazard | Trigger of hazard | Damage of hazard |
|---|---|---|
| Kedar Kharak Uttarkashi (2013) | Snow avalanches | No damage because it took place in an uninhabited area |
| Chamoli (2010) | Snow avalanches | No damage because it took place in an uninhabited area |
| Kalindi Badrinath Trek (2008) | Snow avalanches | No damage because it took place in an uninhabited area |
| Gaumukh glacier (2008) | Snow avalanches | No damage because it took place in an uninhabited area |
| Ghat (2019) | Cloudburst | 13 people died and two houses were washed away |
| Deval (2019) | Cloudburst | 2 people died and a cowshed and a house was washed away |
| Rudraprayag (2012) | Cloudburst | Land degradation, agricultural land washed away, settlements damaged |
| Kapkot (2010) | Cloudburst | Land degradation, agricultural land washed away, settlements damaged |
| Munsiyari (2009) | Cloudburst | Land degradation, agricultural land washed away, settlements damaged |
| Pithoragarh (2008) | Cloudburst | Land degradation, agricultural land washed away, settlements damaged |
| Kedarnath (2013) | Debris flow/ Flash flood | Kedarnath town and downstream settlements were washed away. More than 10,000 people flowed with debris and many animals died |
| Asi Ganga (2012) | Debris flow/ Flash flood | Land degradation, agricultural land washed away, settlements damaged |
| Bageshwar (2010) | Debris flow/ Flash flood | Land degradation, agricultural land washed away, settlements damaged |

*Source*: State Disaster Management Department, Dehradun.

territory accentuated the disaster tragically. The workers died while working inside the tunnel. The catastrophe was so sudden that the information could not reach the construction sites of hydropower projects. Since the workers' colony was constructed close to the river banks, the workers did not get any chance to escape. The debris flow was huge because of the high volume and narrow valley. The volume of deposited debris was huge on both sides of the two hydropower project. Further, the size of boulders, flowed with debris and deposited, was huge. The four villages, which were partially affected, are located on the fragile slopes close to the river banks. Now their future susceptibility is very high.

This part of the Himalaya has received several geo-hydrological events. Between 2008 and 2021, there were 14 major geo-hydrological events occurred, which caused huge losses of life and property. The Himalaya is the most fragile landscape of the world. The high frequency and intensity of natural hazards have increased fragility. The increasing warming pattern across the Himalaya is another concern during the recent period. Qi et al., (2021) observed that the impact of climate warming will lead to severe catastrophes in the Himalaya in the coming future. Further, due to the large-scale construction of the infrastructural facilities and exploitation of natural resources, the degradation of the Himalayan landscape is the main concern. The conservation and restoration of the Himalayan ecology are therefore inevitable, which can be carried out by the strong formulation and implementation of policies. Monitoring the slope stability of the Himalaya and beyond, to achieve regional sustainability, is an urgent need.

## 6. Conclusions

This study reveals that the Uttarakhand Himalaya has suffered a lot from hydro-meteorological hazards/disasters from time to time. However, the frequency and intensity of snow avalanches were low. Meanwhile, the present Rishi Ganga calamity was unusual. Snow avalanches/glacier outbursts are natural and common phenomena and as such, they cannot be entirely controlled. Yet the losses caused by them can be reduced by using of natural resources sustainably and reducing the construction of infrastructural facilities, including the construction of hydropower projects. We need to map the highly susceptible and vulnerable areas of the river valleys. The villages which are situated on the river banks need to be rehabilitated in safe areas. The proposed hydropower projects need to be properly studied and reevaluated in terms of Environmental Impact Analysis (EIA) and Social Impact Analysis (SIA).

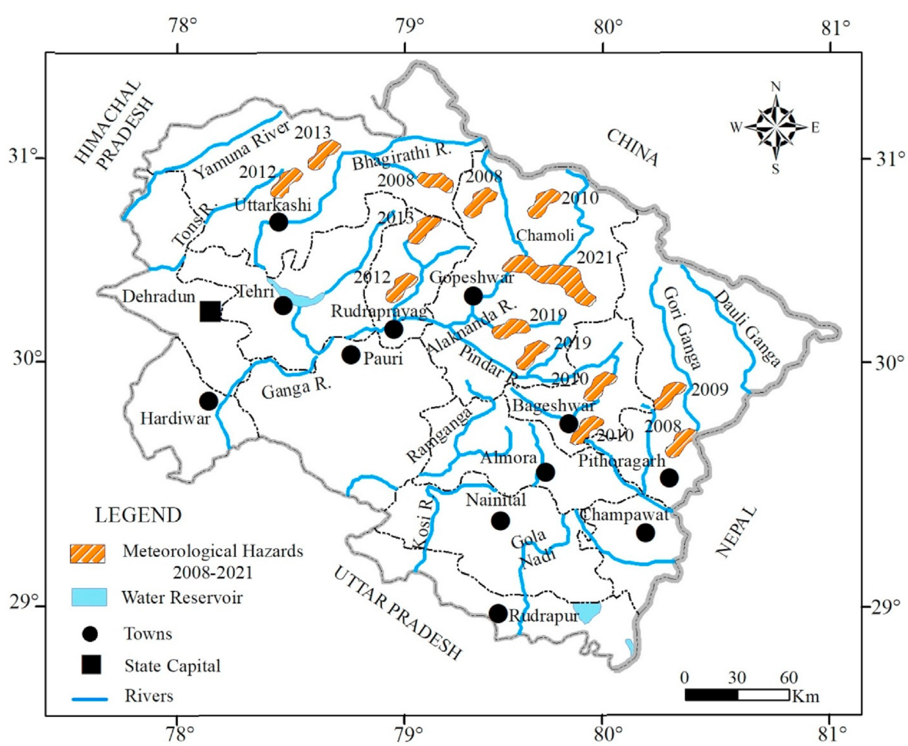


**Fig. 7.** Major hydrological hazards occurred in the Uttarakhand Himalaya between 2008 and 2021.

Mapping and monitoring of glaciers which are potential threats to the downstream areas may be done immediately. The big hydropower projects are not suitable along the fragile river valleys. Therefore, only a few micro-hydropower projects can be constructed in the safe areas, mainly downstream, and where human settlements are very sparse. Early snow-avalanches warning systems can be set up with the use of new technology. The stakeholders – the government machinery, climate scientists, geologists, geographers, and the local people should have to collaborate in mitigating these natural disasters. WhatsApp groups can be created in each river valleys from upstream to downstream areas to disseminate information on any calamity immediately. A nature-based solution such as large-scale afforestation, is the need of the hours to minimize the impact of disasters in the fragile landscape of the Himalaya.

## Declaration of competing interest

There is no conflict of interest in this paper.

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