Environmental and Economic Impact of Cloudburst Triggered Debris Flows and Flash Floods in the Himalaya: A Case Study

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Research

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Abstract

This paper examines the environmental and economic impact of cloudburst triggered debris flows and flash floods in the Himalaya. A case study of four villages affected by cloudburst calamity was conducted. Data were gathered by a household-level survey of affected villages and households. The authors visited the affected villages immediately after the cloudburst calamity and interviewed the head of all affected households. A total of 143 households were surveyed. First, the damage of houses, cowsheds, bridges, trees (forests and fruits) dislocation, degradation of total land along the streams and arable land in and around the villages were measured with the help of the head of households (environmental impact). The volume of debris, boulders, pebbles, gravels and mud was measured. Economic valuation of all losses was noted (economic impact). This study finds out that a large area of all villages was severely affected by cloudburst triggered debris flow and flash flood, because, they are located in a severely vulnerable landscape. This study reveals that Nirakot village needs to be rehabilitated entirely and in other villages all households, which are severely affected need to be rehabilitated as soon as possible to escape from the future cloudburst catastrophe.

Introduction

Cloudburst refers to a sudden and heavy rainfall that takes place within a short time and a particular space (Sati 2013). They are very disruptive events that generally take place in the summer and monsoon seasons. Cloudburst triggers debris flows, flash floods, landslides, and mass movements in the mountainous regions (Fig. 1). The nature of lands such as precipitous slope and fragile and undulating terrain further accentuate the velocity of debris flows, flash floods, landslides and mass movements. Worldwide, heavy rainfall events have become more intensive and frequent causing intensive cloudburst events (Houghton et al 1996; Wang et al 2014; Mayowa et al 2015). In the Himalayan region, cloudburst triggered debris flows and flash floods are increasing, causing huge loss of life and property and degradation of landscape (Bohra et al 2006; Allen et al 2016; Balakrishnan 2015; Ruiz-Villanueva et al 2017) because the Himalaya favours location for its generation. The intensity of rainfall is more than 100mm/hr (Das et al 2006).

The Himalaya is the most fragile landscape in the world. It is prone to geo-hydrological hazards such as cloudbursts, avalanches, and glacier bursts, which triggers devastating debris flows and flash floods. It has been observed that the frequency and intensity of cloudbursts in the Himalaya have been increasing. It is linked with the climate change phenomenon and increasing human-induced activities. Changing monsoon patterns and increasing precipitation in the Himalaya are associated with catastrophic cloudbursts that triggered debris flows and flash floods (Devi 2015). In the meantime, they are the least understood weather systems (Das et al 2006) because they occur in remote areas, does not have rain gauges (Thayyen 2013).

The Indian Central Himalayan Region (ICHR), popularly known as Uttarakhand Himalaya is an integral part of the Himalaya (Sati 2019). The entire region is ecologically fragile and vulnerable to natural hazards. Both atmospheric and terrestrial hazards are common and devastating. Cloudburst triggered landslides, mass movements, debris flows, and flash floods are very common phenomena, which take place every year, mainly during the monsoon season. This causes roadblocks, land degradation, forest and cropland loss,
and losses of life and property. The Uttarakhand Himalaya is witnessed to have hundreds of devastating catastrophic events – atmospheric and terrestrial. Kedarnath tragedy, one of the most devastating events in the History of Uttarakhand, which killed more than 10,000 people, was occurred due to cloudburst and glacial lake outburst floods (Upadhyay 2014; Allen et al 2016; Sati 2013). Uttarakhand had received 16 major geo-hydrological and terrestrial hazards within last 50 years (Bhambri et al 2016).

The upper Bhagirathi River basin between Uttarkashi and Gaumukh consists of a highly fragile landscape. It receives heavy rain during the monsoon season. Landslides, mass movements, Debris flows and flash floods are very active in the entire zone. Because of the highly fragile and vulnerable terrain, the Government of India declared a 100 km long belt, which lies between Uttarkashi and Gangotri, as an ‘Eco-Sensitive Zone’ (Sati 2018). Gangotri highland pilgrimage is located on the bank of the Bhagirathi River, where an exodus number of pilgrims visit every year, mainly during the pilgrimage season, which falls in summer and monsoon seasons. Because of landslides, mass movements, debris flows, and flash floods, during the pilgrimage season, roads are often blocked, which leads to human and animal casualties and loss of properties and business avenues. There were many incidences of disasters already taken place during the past decades.

Many studies have been carried out on glacier lake outburst floods and cloudburst triggered debris flows and flash floods in the Himalaya (Byers et al 2018; Cook et al 2018; Asthana and Sah 2007; Bhatt 1998; Joshi and Maikhuri 1997; NIDM 2015; IMD 2013; Khanduri et al 2018; Sati 2006, 2007, 2009, 2011, 2014, 2013, 2018, 2019, 2020; Naithani 2011). These studies were conducted in broader perspectives and most of them were conceptualized. However, the present paper looks into the case study of four villages, severely affected and damaged by cloudburst triggered debris flows and flash floods, which occurred on July 18, 2021. It analyses the environmental impact of cloudburst in terms of forest and fruit trees dislocation, land degradation – arable, forests, and barren land, and damage of houses and cowsheds of affected villages. It also evaluates the economic losses of the affected villages due to the cloudburst catastrophe. The study further suggests policy measures to risk reduction and rehabilitation of vulnerable settlements and villages of disaster-prone areas to safe locations.

**Study Area**

The cloudburst hit and affected villages are located in Uttarkashi district of Uttarakhand state, India, close to the famous cultural city named Uttarkashi. A National Highway is connecting Haridwar, the valley pilgrimage, and Gangotri, a highland pilgrimage, passing through Uttarkashi town. It is the most travelled area mainly during the summer season because the pilgrims – national and international – visit the Gangotri highland pilgrimage. The four villages – Nirakot, Mando, Kankrari cluster of villages (Sada and Thalan), and Siror, which were affected by cloudburst triggered debris flows and flash floods and located in the Upper Bhagirathi catchment, are severely prone to geo-hydrological disasters. The slope gradient is high, varies from 15° to 70° depending upon the location of the villages, which further accentuates the landscape vulnerability. Indravati is a perennial stream, a tributary of the Bhagirathi River that meets Bhagirathi from its left bank. All three Gadhers (streams) – Mando, Diya, and Siror are seasonal but violent during the monsoon season. Nirakot (1530 m) village is located in the middle altitude of Hari Maharaj Parvat (2350 m)
in a steep slope, Mando village (1180 m) is located on the left bank of the Bhagirathi River and Mando Gadhera with gentle to a steep slope, Kankrari (1620 m), a cluster of villages, is located on the moderate to the gentle slope on the bank of Diya Gadhera, and Siror village (1280 m) is situated on the left bank of both Bhagirathi and Siror Gadhera with gentle to the steep slope (Figure 2). There are many human settlements located with small arable land. The people of the villages are involved in practising subsistence agriculture and horticulture on the narrow patches of terraced fields. Crop diversity is high depending on the altitudes of the villages. The main crops grow are paddy, wheat, Mandua, Jhangora, Koni, barely, maize, pulses, oilseeds, apple, peach, pear, plum, apricot, walnut, and citrus fruits – orange, lemon, and Malta. These are both rabi (winter) and kharif (summer) crops grow. Since kharif crops grow during July, therefore, all kharif crops have been damaged due to cloudburst calamity. Forest diversity is rich, mainly temperate forests are found, which vary from pine in the middle altitude (1000 m to 1600 m) to mixed-forests (1600 m – 2200 m) and deodar (2200 to 2800 m).

Methodology

This study is based on the collection of household-level data and the participatory observation method. A qualitative and quantitative approach was applied to conduct and elucidate this study. Immediately after the cloudburst hit and affected the four villages – Nirakot, Mando, Kankrari, and Siror on 18 July 2021 at 8.30 pm, the authors visited these villages between 20 and 30 July 2021. The authors constructed a structured questionnaire, which includes detailed questions on the causes and consequences of cloudburst triggered debris flows and flash floods in these villages. A long list of questions was prepared and questions were asked from the head of 143 households, which were severely affected by cloudburst triggered debris flows and flash floods. The questions were mainly related to the loss of lives – humans and animals, environmental impacts such as forestland degradation, dislocation of trees – pine, mixed-oak, deodar, and fruit trees. The perception of the head of households was obtained. The case study villages have rich agro-climate and agro-biodiversity, where the number of crop races/cultivars is grown. The main crops damaged by debris flows were paddy, Mandua, Jhangora, pulses, maize, and Rajma. Further, among fruit trees apple, peach, plum, apricot, Malta, lemon, orange, and walnut trees were flown. The data on the area under agriculture/horticulture and forests, which was flown due to huge debris flows, were gathered by the household-level survey. Similarly, data on fruit trees, which were washed away, were also gathered by the household-level survey. ‘Nali’ the unit of measuring land was converted into acres and the value of crops and fruit trees, which were damaged, were noticed at the current price. Valuation of damaged houses, cowsheds, and other economic avenues was noted at current prices. A formula was applied to measure circumference = 2πR and Area = π * R². The volume of debris – boulders, pebbles, sands, and soils was measured by measuring the length, width, and depth of debris. Measurement of degraded forest area was carried out. Based on the slope gradient, accessibility, economy, and climate of the villages, we analysed the vulnerability of villages and ranked them very high vulnerability, high vulnerability, and moderate vulnerability. The maps, graphs, and area photographs support the study.

Results
Major Cloudburst Incidences in the Uttarakhand Himalaya

Past incidences of cloudbursts triggered calamities in the Uttarakhand Himalaya show that the state suffered tremendously. We gathered data on the major cloudburst incidences in Uttarakhand in the monsoon seasons of 2020 and 2021 from the state disaster relief force (SDRF), Dehradun. In three months of April, July, and August 2020, 13 major and numerous minor cloudburst incidences were noticed in Uttarakhand (Table 1). These incidences resulted in the death of 22 people and 77 animals, and 19 houses were fully damaged. Similarly, in the May and July months of 2021, 10 major and 24 minor cloudburst incidences were occurred in the Uttarakhand Himalaya, resulted in the death of 27 people and 94 animals, and 56 houses were buried. Besides, it caused a huge loss to property and landscape degradation.
| Date of occurrence | Cloudburst hit area | Casualties |
|--------------------|---------------------|------------|
| April-August 2020  |                     |            |
| April 23, 2020     | Kotdwar (Pauri district) | Low-lying areas were flooded and arable land was washed away |
| April 27, 2020     | Naugaon and Mori (Uttarkashi district) | Five houses were partially damaged and agricultural land flown |
| July 14, 2020      | Dharchula (Pithoragarh) | Landslide on the road connecting India-Tibet boarder |
| July 19, 2020      | Madkot and Tanga (Pithoragarh) | Three people were killed and six injured |
| July 20, 2020      | Bata, Sirtaul, and Munsiyari | Eight houses were buried, three people killed, 10 cattle died, and bridges and farmlands washed away |
| July 28, 2020      | Banagapani (Uttarkashi) | 47 cattle died |
| July 28, 2020      | Ghat (Chamoli district) | Three houses flown, cowsheds collapsed, and three people died |
| August 9, 2020     | Gangi village (Tehri) | 20 cattle were buried |
| August 10, 2020    | Sirwadi (Rudraprayag) | Seven houses were fully damaged |
| August 10, 2020    | Bageshwar | A house was collapsed and a bridge flown |
| August 18, 2020    | Mori village (Uttarkashi) | 12 people died |
| August 19, 2020    | Near Lakhwar Dam (Uttarkashi) | A bridge was collapsed |
| August 24, 2020    | Tali-Ansari (Chamoli) | One person died and one injured |
| May-July 2021 (Total 24 incidences) | | |
| May 3, 2021        | Kumrada, Baldogi, and Kamad (Uttarkashi) | Three people died |
| May 3, 2021        | Narkota (Rudraprayag) | On Three houses damaged and 1-acre arable land was washed away |
| May 3, 2021        | Khankra, Fatehpur Kotli, Gairsari Narkota | One person died |

*Source: SDRF (2021) *Present case study villages
| Date of occurrence | Cloudburst hit area | Casualties |
|--------------------|--------------------|------------|
| May 11, 2021       | Devprayag town     | Sixteen buildings were collapsed |
| May 20, 2021       | Bijnad, Chakrata   | Three people and 24 animals died |
| May 30, 2021       | Bangwari village (Pauri) | Two cows died and 0.5-acre agricultural land washed away, exiting crops damaged and fruit trees dislocated |
| July 18, 2021*     | Nirakot            | One person died, 0.7-acre arable land washed away and three buildings and 5 bridges collapsed. |
| July 18, 2021*     | Mando              | Three people and two animals died, 1.2-acre arable land washed away, and five buildings and two bridges collapsed. |
| July 18, 2021*     | Kankrari           | One person died, 20.6-acre arable land was washed away, 11 buildings were damaged, and 6 bridges collapsed. |
| July 18, 2021*     | Siror              | 0.6-acre arable land flown and one bridge collapsed. |

*Source: SDRF (2021) *Present case study villages

Figure 3 shows economic losses are higher in 2021 than in 2020 due to cloudburst calamities in Uttarakhand. It is because, in 2021, the cloudburst incidences are much more than 2020 even the data of 2021 is only up to July. The figure further shows that animal loss was the highest in both years than houses. It is followed by human loss and then bridges collapsed.

Figure 4 shows district wise major cloudburst events that occurred in the Uttarakhand Himalaya in 2020 and 2021. The highest incidences were noticed in Uttarkashi district (total 09), followed by Pithoragarh, Chamoli, and Rudraprayag districts (three incidences each). Pauri and Tehri districts had two incidences and Bageshwar and Dehradun districts had on each.

**Case Study of Affected Villages**

On July 18 2021, a cloudburst hits the Hari Maharaj Parvat (hilltop) at an altitude of 2350 m at 8:30 pm, which triggered huge debris flows and flash floods. The four villages – Nirakot, Mando, Kankrari (a cluster of three villages including Sada and Thalan), and Siror of Uttarkashi district, located close to Uttarkashi town, were severely affected (Table 2). At the cloudburst hit area, it formed three gullies, which later on merged into three streams, along which these villages are located. The source of debris and flood was one i.e. Hari Maharaj Parvat and it has equally flown in all three directions. Since the cloudburst event occurred at 8:30 pm, the people did not have time to move their household goods, therefore, the damage was enormous. A detailed case study of these villages was conducted and described as follows.

**Nirakot**

Nirakot is located at an elevation of 1530 m on the upper slope (30° 45' 23'' N and 78° 25' 56'' E) of Mando village and two km downwards from the cloudburst hit area i.e. Hari Maharaj Parvat along the Mando
Gadhera (stream). The village is situated on a 30° to 55° slope, surrounded by mixed-oak on the upper slopes and pine on the lower slope. It has a west-facing slope, moderate in the middle and steep in the upper and lower part. The huge debris having 20 cubic m to 2400 cubic m volume and containing boulders, pebbles, gravels, and mud flow, which has devastated settlements, cowsheds, and agricultural lands. Debris shared more than 70%. About 100 mixed oak forests were dislocated by debris flows and about 0.7-acre arable land was destroyed. A total of 22 HHs were affected. Two houses and one cowshed were washed away. About 167 fruits trees were dislocated and about 10 existing crops growing at about 0.7-acre land was destroyed by debris.

Mando

Village Mando is located on the left bank of the Bhagirathi River about 3 km from Uttarkashi town towards Gangotri at the west-facing slope. Situated at an altitude of 1180 m it has 30°44'09'' N and 78°27'16''E coordinates. A stream flows through the village and meets the Bhagirathi River is named Mando Gadhera. The village and its surrounding areas are ecologically fragile and highly vulnerable to geo-hydrological hazards. The distance between the cloudbursts hit the area and the affected area is about 4 km. The large size of boulders, pebbles, and huge debris were flown and deposited in the village, mainly on the bank of the Bhagirathi River. Boulders including debris shared 60-70%. Four km gully erosion occurred with 5x4 m depth and width. The depth and width increase to 6x8 m in its downstream areas. The slope gradient varies from 60°-70° on the upper slope to 30°-55° on the lower slope. Three females and two cows died. About 1.2 acres of arable land completely washed away and similarly, the crops with high biodiversity – paddy, pulses, and green vegetables – were damaged in the given arable land. Five houses, two cowsheds, and 2 bridges washed away. A pipeline was damaged. About 20 fruit trees such as Malta, orange, lemon, and banana were dislocated and flown. About 200 pine and mixed-oak trees were dislocated due to debris flow. This village was also suffered from landslide hazards on 4th July 1984 at 8:00 pm, which has damaged about 0.5 acres of agricultural land and paddy, pulses, and vegetable crops were damaged fully. A house was buried in debris.

Table 2: Salient geographical feature of cloudburst hit areas
### Variables

| Variables             | Nirakot                        | Mando                          | Kankrari                        | Sior                            |
|-----------------------|--------------------------------|--------------------------------|---------------------------------|---------------------------------|
| Date of cloudburst    | 18-07-21 (time: 8:30 pm)        | 18-07-21 (time: 8:30 pm)        | 18-07-21 (time: 8:30 pm)        | 18-07-21 (time: 8:30 pm)        |
| District              | Uttarkashi                     | Uttarkashi                     | Uttarkashi                      | Uttarkashi                      |
| Altitude (m)          | 1530                           | 1180                           | 1620                            | 1280                            |
| Latitude              | 30º 45' 23''N                  | 30º44'09''N                    | 30º 38'56''N                    | 30º 44'27''N                    |
| Longitude             | 78º 25' 56''E                  | 78º27'16''E                    | 78º 27' 56''E                   | 78º 29'15''E                    |
| Slope aspect          | West-facing                    | West-facing                    | South-facing                    | North-facing                    |
| Cloudburst hit area   | Hari Maharaj Parvat (2350m)    | Hari Maharaj Parvat (2350m)    | Hari Maharaj Parvat (2350m)    | Hari Maharaj Parvat (2350m)    |
| Distance travel by debris | 2 km                          | 4 km                           | 5 km                            | 3.5 km                          |
| Name of stream        | Mando Gadhera                  | Mando Gadhera                  | Diya Gadhera                    | Siror Gadhera                   |
|                       | (Tributary of Bhagirathi)      | (Tributary of Bhagirathi)      | (Tributary of Indravati River)  | (Tributary of Bhagirathi)      |
| Debris composition and size | Large boulders, pebbles, gravels, and mud; boulders’ volume ranging from 65 cubic m to 2300 cubic m (boulder-mud ratio: 55:45) | Large boulders, pebbles, gravels, and mud; boulders’ volume ranging from 70 cubic m to 2400 cubic m (boulder-mud ratio: 60:40) | Large boulders, pebbles, gravels, and mud; boulders’ volume ranging from 40 cubic m to 2200 cubic m (boulder-mud ratio: 30:70) | Large boulders, pebbles, gravels, and mud; boulders’ volume ranging from 30 cubic m to 2200 cubic m (boulder-water ratio: 70:40) |

**Source:** A case study

### Kankrari

Kankrari is a cluster of three villages – Kankrari, Sada, and Thalan. An average altitude is 1620 m. The coordinates are 30º 38'56"N and 78º 27' 56"E and the slope gradient is 30°-45°. Debris flow travelled 5 km and affected all three villages. Kankrari village is located upstream, heavily damaged, whereas the downstream villages are partially damaged. Diya Gadhera flows through the villages, which is a tributary of the Indravati River, flows into the Bhagirathi River from the left bank before Uttarkashi town. The slope gradient is very high in the upper stream (50°-70°) whereas, in the middle stream, the slope gradient is 30°-45° and lower stream, it is 20°-30°. The depth and width of the gully were 8x7 m in the upper stream, 12x7 m in the middle stream, and 15x5 m in the lower stream with 30% boulders and 70% debris. One person died and six bridges collapsed. About 500 trees were washed away, 20.6 acres of arable land was washed away, 100 HHs affected, 11 houses collapsed about 20.6-acre cropland in which more than 10 crops were grown destroyed, and 300 fruit trees were dislocated. A part of the village is sliding down with houses and agricultural land. The affected people have been shifted to a government school.
Siror

Siror village is located on the left bank of the Bhagirathi River at 1280 m (30°44’27” N and 78°29’15” E). The village was partially affected by cloudburst triggered debris flows and flash floods. Siror Gadhera was inundated with debris. The debris travelled about 3.5 km from the cloudburst hit area. The slope gradient varies from 20° to 30° in the lower slope to 60° in the upper slope. The width and depth of debris along the 5 km varied from 4x4 m on the upper slope to 2x2 m on the middle slope and 6x6 m on the lower slope. The debris was contained by 70% boulders and 30% gravels and pebbles. About 0.3-acres of arable land, 70 trees of deodar, and four walnut trees were dislocated. Paddy and pulses fields were washed away, which had 0.3-acre land. A bridge and pipeline were flown with debris.

We have interviewed 143 heads of households, which were affected by cloudburst calamity from all four case study villages. The people of these villages are living in panic. After devastating cloudburst triggered calamity, the people are suffering psychologically. They wanted to rehabilitate in other safe places. Many of them responded that they are unable to sleep at night because of fear of another calamity. The people are living at risk and vulnerability. When the authors asked them about the recent trends of cloudburst incidences, most of them opined that the frequency and intensity of cloudburst calamities are increasing year to year.

Figure 5 shows four villages – Nirakot, Mando, Kankrari, and Siror, which were severely affected by cloudburst triggered debris flows and flash floods. The volume of debris and boulders can be seen in all the villages. These villages are surrounded by dense temperate forests that vary from pine to mixed-oak and deodar. Kharif crops are growing in the arable land whereas a large cropped land has been washed away.

Environmental Impact

The environmental impact of cloudburst triggered debris flow and flash flood in four villages of Uttarkashi district was analyzed (Table 3). The major variables were the number of forest trees dislocated, total land degradation, land degradation under existing crops, number of fruit trees dislocated, land degradation under arable land, number of buildings were damaged, number of bridges damaged, and boulders’ volume. Forest trees, which dislocated were pine in the middle altitude and mixed-oak and deodar in the higher altitude. A total of 770 forest trees were dislocated from all four villages out of which, 500 were from the Kankrari cluster of villages (highest). The lowest trees dislocated were from Siror village (70). Total land degradation from the cloudburst hit area to the affected areas was huge, however, we have measured the land which was within and surrounding each village. The total land degradation was 52.5 acres with the highest in Kankrari (45 acres) and the lowest in Siror (0.5 acres). The land degradation under existing crops was 22.6 acres in all four villages, varies from 0.1 acres in Siror to 20.6 acres in Kankrari. The total number of fruit trees dislocated was 486. Land degradation under arable land was 22.6 acres. It includes the area under existing crops both agriculture and horticulture. A total of 19 buildings were damaged whereas a total of 14 bridges, connecting villages were damaged.

Table 3: Environmental impact of cloudburst triggered debris flow and flash flood
Economic Impact

The economic impact of cloudburst triggered debris flow and the flash flood was tremendous in the forms of a household affected, loss of human and animal life, building loss, forest loss, existing crop loss, loss of fruits, loss of arable land, and loss of bridges (Table 4). The value of all these variables was calculated in Indian Rupees (INR) at the current prices. The total number of households affected was 143, of which, 100 households belonged to the Kankrari cluster of villages (highest) and three households (lowest) were from Siror village. Four people died due to the calamity – three women from Mando village and 1 man from Kankrari village. Two cows from Mando village died. The total loss from the collapse of the building was 1.7 million INR, with the highest (1.1 million INR) from Kankrari village. A total of 0.77 million INR was lost due to forest loss, and the loss from existing crops was 3.35 million INR, the second-highest in all other losses. Loss from dislocation of fruit trees was noted high, which was about 0.5 million INR. A large portion of arable land was flown which value was 11.3 million INR, the highest loss. About 14 million INR was lost due to the collapse of bridges. As a whole, about 31.62 million INR was lost due to cloudburst calamity. Per household loss by a cloudburst, calamity was noted 0.22 million INR.

Table 4: Economic impact of cloudburst triggered debris flow and flash flood
### Variables

| Variables                     | Nirakot | Mando | Kankrari (including Sada and Thalan) | Sior | Total |
|-------------------------------|---------|-------|-------------------------------------|------|-------|
| Number of affected HHs        | 22      | 18    | 100                                 | 03   | 143   |
| Loss of human life            | Nil     | 3     | 1                                   | Nil  | 04    |
| Loss of animals (cows)        | Nil     | 2     | Nil                                 | Nil  | 02    |
| Building loss (million INR)   | 0.25    | 0.45  | 1.1                                 | Nil  | 1.7   |
| Forest loss (million INR)     | 0.1     | 0.1   | 0.5                                 | 0.07 | 0.77  |
| Crops loss (million INR)      | 0.4     | 0.8   | 1.4                                 | 0.75 | 3.35  |
| Loss of fruits (million INR)  | 0.162   | 0.02  | 0.3                                 | 0.004| 0.5   |
| Loss of arable land (million INR) | 0.35   | 0.6   | 10.3                                | 0.05 | 11.3  |
| Loss of Bridges (million INR) | 5       | 2     | 6                                   | 1    | 14    |
| Total (INR)                   | 6.26    | 3.97  | 19.6                                | 1.87 | 31.62 |

*Source: by authors*

### Average Circumference, Area, and Volume of Boulders

We calculated the average circumference, area, and volume of boulders in the case study villages using the formula: circumference = $2\pi R$; Area = $\pi R^2$; Volume = length x width x depth (Table 5). We noticed that the highest average area of boulders was in Mando village which is 28.3 m$^2$ followed by Kankrari 19.6 m$^2$, Nirakot 12.57 m$^2$, and Siror 7.1 m$^2$. In terms of the total volume of debris, it was the highest in Kankrari, followed by Mando, Nirakot, and Siror.

Table 5: Average circumference, area, and volume of boulders

| Variables                        | Nirakot | Mando | Kankrari (including Sada and Thalan) | Sior |
|----------------------------------|---------|-------|-------------------------------------|------|
| Radius (m)                       | 2       | 3     | 2.5                                 | 1.5  |
| Diameter (m)                     | 4       | 6     | 5                                   | 3    |
| Circumference (m)                | 12.57   | 18.8  | 15.7                                | 9.4  |
| Area (m$^2$)                     | 12.57   | 28.3  | 19.6                                | 7.1  |
| Total volume of debris (cubic m) | 36000   | 48000 | 62000                               | 24000|

*Source: by Author*
Figure 6 shows the average diameter of boulders in the cloudburst affected villages. We drew the figure with a scale, 1 cm is equal to 1 m. The average biggest diameter of boulders was found in Mando village (6 m), followed by Kankrari (5 m) and Nirakot (4 m) villages. The average smallest diameter of boulders was found in Siror village (3 m).

**Vulnerability Analysis**

Based on the above analysis and Table 6, vulnerability analysis of the case study villages was carried out. The main variables of vulnerability were slope gradient, accessibility of villages, economic conditions of households, and climatic conditions. Based on these variables, Nirakot village has a high vulnerability, Kankrari has a high, and Siror and Mando have a moderate vulnerability.

**Table 6: Vulnerability analysis of case study villages**

| Variables          | Nirakot  | Mando  | Kankrari (including Sada and Thalan) | Siror  |
|--------------------|----------|--------|-------------------------------------|--------|
| Slope gradient     | 30º-55º  | 30º-55º| 30º-45º                             | 20º-30º|
| Accessibility      | Highly inaccessible | Accessible | Inaccessible                     | Accessible |
| Economic condition | Not favourable | Average | Not favourable                       | Average |
| Climate            | Cold in winter | Conducive | Cold in winter                      | Conducive |
| Vulnerability      | Very high | Moderate | High                                | Moderate |

*Source: by Authors*

**Discussion**

The Himalaya is the loftiest and the youngest mountain system in the world. Because of its geological formation, it is one of the most vulnerable mountains for natural disasters (Vaidya et al. 2019). Among them, earthquake and geo-hydrological disasters are prominent. Because the Himalaya falls in the IV and V earthquake zones, it is severely prone to earthquakes. The formation of the Himalaya is young, therefore, it is an ecologically fragile, geologically sensitive, and tectonically and seismically very active mountain range (Sati 2019). It has two geo-hydrological events – cloudbursts and glacier bursts are catastrophic. The incidences of cloudbursts are much more than glacier bursts. The entire region receives abundant rain during the monsoon period, which leads to catastrophic cloudburst triggered debris flows, flash floods, landslides, and mass wasting. The Uttarakhand Himalaya, which constitutes an integral part of the Himalaya, is most vulnerable to cloudburst events. The districts, which are mountainous and located close to the Greater Himalayan ranges, are worst affected as the history of cloudburst calamity depicts. And among them, Uttarkashi, Rudraprayag, Chamoli, and Pithoragarh districts are prominent.
We observed that the cloudbursts incidences in 2020-21 in the Uttarakhand Himalaya occurred mainly in the remote mountainous districts. The plain district did not receive any cloudbursts incidences during the period. It is a fact that mountain districts of Uttarakhand are highly vulnerable to geo-hydrological disasters mainly cloudbursts triggered incidences. The slope gradient is high, the terrain is fragile, and rural settlements and institutions are situated mainly along the perennial streams, which are violent during the monsoon season. There is a long list of catastrophic cloudbursts, which have devastated the entire rural settlements several times. During the monsoon seasons, heavy rainfall results in a high amount of water in the rivers and streams and they flow over the danger marks. The roads of Uttarakhand traversed along the bank of the rivers, where the local people constructed settlements and economic avenues. These roads lead to the highland and river valleys pilgrimages where the number of tourists and pilgrims visit every year during the monsoon season. The local people provide services to the tourists and pilgrims. There are many instances where the house construction is done on the old debris, which was formed due to deposition of debris of earlier events of debris flows and flash floods. Therefore, the environmental and economic losses due to geo-hydrological incidences are very high. One of the recent examples is the Rishi Ganga tragedy, which was resulted by glacier outburst, and economic loss was due to the construction of hydroelectricity station and its colony along the bank of the Rishi Ganga and Dhauli Ganga were more than 200 people died and billions of INR lost (Sati 2021)

Our study shows that the environmental and economic loss in the case study villages was huge due to the cloudburst tragedy. Almost every household was affected by this calamity. There were large land degradation, forest and fruit trees dislocation, arable land degradation, human loss, animal loss, the collapse of houses and bridges and of course the future impediment, in terms of large deposition of debris including boulders, pebbles, and gravels in the villages along the streams and gullies is tremendous. The rural people are poor and their livelihood is dependent on subsistence agriculture. Many of them (about 12% of households) are living under the poverty line. Because the existing crops have been lost, they are facing problems of availability of food. Further, the psychological problems are immense. The fear of another calamity is always there in the mind of people as all villages are situated in very high to moderate vulnerable areas. The NH is traversing in the right bank of the Bhagirathi River and the affected villages are situated on the left bank, the connectivity problem is immense. A similar situation arises in the entire rural areas of Uttarakhand.

**Conclusion**

Cloudburst triggered debris flows and flash floods are natural calamities in mountain regions in general and the Himalaya in particular. They will occur and no one can control them. Subsequently, the environmental losses will be there. However, the economic loss due to their occurrences can be minimized. The study reveals that the economic and human losses of the present calamity were mainly due to the location of four villages. All four villages are located on fragile and precipitous slopes, along the streams, which are violent during the monsoon season. Their settlements and arable land lie on both sides of the streams. Further, the slope gradient is very high and the terrain is fragile. This is the case for the entire Himalayan region. The psychological shocks due to disasters have led to large-scale out-migration. We suggest that the villages –
Nirakot and Kankrari need to be fully rehabilitated immediately because they are highly vulnerable and already they were affected by cloudburst calamity. Some settlements of Mando and Siror villages also need to be rehabilitated because their location is in highly vulnerable areas. Mando village was affected twice by cloudburst triggered landslides and debris flow – the present one and in the past July 4, 1984. Suitability analysis of rural areas can be conducted and accordingly, policy for rehabilitation of settlements can be ensured. This will reduce risk and vulnerability, and can minimize economic and human loss. The whole process needs short and long term policies to support the affected families and to rehabilitate them in safe areas. The affected people need immediate compensation (relief package) to restore normalcy in livelihoods and routine work. Early warning system, a rehabilitation centre on the safe side, and plantation of deep-rooted big trees along the stream instead of agriculture or house construction (ecologically-based disaster risk reduction) are the other drivers, which will reduce the risk and vulnerability.

**Declarations**

**Conflict of Interest:** There is no any conflict of interest in the manuscript.

**Author Contribution:** The first author analyzed data, prepared maps and diagrams, and wrote the manuscript. The second author conducted field survey and collected data.

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**Figures**

![Figure 1](image)
Cloudburst triggered hazards in the Himalaya

Figure 2

Location map of cloudburst hit areas and their surroundings
Figure 3

Economic losses due to cloudburst calamities in Uttarakhand in 2020 and 2021
Figure 4

Location map of cloudbursts hit areas in 2020 and 2021
Figure 5

Cloudburst affected villages (a) Nirakot (b) Mando (c) Kankrai (d) Sior
Figure 6

Village wise average diameter of boulders