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RESEARCH ARTICLE

Cloudbursts Over Indian Sub-continent of Uttarakhand Himalaya: A Traditional Habitation Input from Bansoli, District-Chamoli, India

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INFORMATION

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ABSTRACT

Although, the cloudburst occurs in the monsoon season but it may also happen in the pre-monsoon showers in Himalayan mountainous region of Uttarakhand sate. Every year, this causes massive loss of life, property, infrastructure, agricultural lands and other facilities. The earlier disasters show that the growing outbreak of rains and its associated flash floods, debris flows and landslides are important reasons for damages and destructions. It is not yet possible to find out, when and in which area the same events will be occurred, particularly in Uttarakhand region. Change in climate due to Global warming is the major concern for these extreme events. However, it's a topic of detailed research to assess impact of climate change on extreme rainfall pattern. Being a geo-dynamically active young Himalayan belt, here the rocks are highly faulted, folded, jointed and fractured resulting in an excessive amount of mass movements and environmental degradations. So, inherent geology, deep regolith cover and high relief difference are more common in the area and the same increases the vulnerability. In addition, human interventions in terms of construction of houses in instable mountainous slopes, over deep regolith and concentration of the streams/rivulets is enlarged the devastating potential of the disaster. It is very important to know the risk of the area to reduce the impact of the disaster. For this, it is important to know the history of previous disastrous events and take a lesson from them and plan ahead. Keeping all these things in mind, all known cloudburst events and their adverse impacts upon inhabitants of the area has been attempted to be compiled in the present study. Additionally, better land use practices also described in the same by an example. This will be help in further research to prevention, mitigation and disaster risk reduction in near future.

1. Introduction

According to Indian Meteorological Department (IMD), cloudburst occurs when high intensity precipitation (>100 mm/h) in a short time span, over a small area and the same area is not exceeding 20–30 km^2 (Das, 2015). It represents cumulonimbus convection in conditions of marked moist thermodynamic instability and deep, rapid dynamic lifting by steep orography (Das et al., 2006). Mostly, it occurs during the monsoon period between late June and early September (Sah and Mazari, 2007) due to strong convection and orography with its steep inclines that lead to flash floods or landslides in the Himalayan region (Dimri et al., 2017).

According to Deoja et al. (1991) the downpour ranges between 200-1000 mm/day, in a shorter duration, 100-250 mm/hour of the rainfall may occur over a limited area is also defined as cloudburst and the size of the droplets may be about 4-6 mm with down pouring rate of 10 m/s (Singh and Sen, 1996). It strikes at random and at a lightning speed, generally lasts for a limited time, and leaves behind a trail of devastation (Anbalagan, 1996).

According Chaudhri and Sing (2012) the micaceous Pinjor sediments are exposed in the Himalayan region that comprise of gneiss, biotite schist and garnet mica schist etc. Fast pace of erosion and weathering process of the same sediments, result in plenty number of freezing nuclei (mainly Illite and keolinite) presence in atmosphere. This rapidly freezes small droplet into ice crystal within 0 °C to -40 °C temperature and cloud become denser and heavy resulting large wide based cumulonimbus cloud formed. These heavy clouds become instable due to adiabatic heating and can be collapsed in the form of a balloon full of water over a small area. Such type of cloud is trapped in a valley, the rate of destruction is become worst (Das, 2015).

Cloudburst is not an uncommon in Uttarakhand Himalaya and it has become quite frequent in recent years. Present days, cloudburst cannot occur only during the monsoon and pre-monsoon but also may occur during the March to May as pre monsoon showers is a regular matter in high altitudinal area of Garhwal and Kumaun Himalaya (Das, 2013). These have often resulted in flash floods, debris flows and landslides result in significant loss of life, property, infrastructure as well as damage to agricultural fields, forest covers, communication systems together with this adversely affects the economy and quality of life of the affected population (Khanduri and Sajwan, 2019). The main objectives of the present study are as given below;

- to assess and review the past cloudburst events and their impacts on inhabitants of the area,
- to find out possible causes of cloudbursts, on the basis of the previous research and field survey,
- to facilitate community awareness with the support of this document,
- to convey the traditional knowledge of settlement to the society and
- to provide possible suggestions for disaster risk reduction in near future within the state.

2. Literature Survey

Nandargi and Dhar (2011) analysis of 137-year period (1871-2007) of extreme one-day rainfall of 475 stations in the Himalayan region indicates that the frequencies of one day extreme rainfall events were smaller before 1950. During the two decades of 1951-1960 and 1991-2000, the Indian region experience good monsoon rainfall. However, there was a sudden decrease in the frequency of extreme rainfall events in the recent period of 2001-2007.

Similarly, Chalise and Khanal (2001) based on 20 years precipitation analysis from 1971-1990 indicates that increasing of extreme events in Nepal. Siddiqui (2002) analyzed of last 71 years climatic data from 1991-2001 that has shown increase in storm precipitation events in Pakistan. It is indicated that change in rainfall pattern in the form of heavy localized precipitation is attributed to climate change in the entire Himalayan belt.

According to Anbalagan (1996) on the night of July 23, 1983, the entire Karmi area was lashed by a sudden cloudburst, resulting in an alarmingly increased water flow in the Karmi stream. The mobilized slope materials blocked the course of streams, creating a landslide dam of about 40m. It was breached within a few hours resulting in heavy loss of human life and cattle.

Joshi and Kumar (2006) analysis of 4 years precipitation data from 1989-1992 in Okhimath region. Apart from the analysis based on the daily rainfall data, some incidents are high rainfall are also reported from different part of Alaknanda river valley catchment. The present data indicates that increasing extreme events in the same region.

Naithani (2001) has investigated the August, 1998 Okhimath tragedy which lies in the upper Mandakini and lower Madhyamaheshwar-Kaliganga catchment in Rudraprayag district of Garhwal Himalaya in Uttarakhand. In this study, an attempt is made to understand the causes of the same events by carrying out geological, structure and geomorphological study.

Joshi and Maikhuri (1997) have reported 3 major cloudbursts occurred in the same night at the 2 hours interval in Gangolgaon, Dewar-Khadora and Olla-Samula. They also reported that on the cloudburst day the area recorded 110mm rain in one day.

Naithani et al. (2002a) reported of 16 July, 2001 cloudburst following landslides and associated damages in Phata-Byung area, Rudraprayag district, Garhwal Himalaya. According to Naithani et al. (2002b) IMD recorded the rainfall data of Ghuttu who situated at 15 kilometers aerial distance from the Gona village. There were incessant rains (55 cm) for 6 hours before this incident. On the other hand, inhabitants of the area said that similar devastating tragedy had also taken place in Bhatgaon village, situated on the opposite side of village Gona, about 80 years back.

According to Rautela and Pande (2005) the tragedy that occurred at Amparav on the fateful night (22/23 September, 2004) has to be seen in the light of the above violations. A massive landslide occurred in the upper reaches of the stream amid abnormally high precipitation (211.83 mm: almost one-tenth of the total rainfall in the year 2004 till that date).

Very heavy rainfall (>200 mm) was recorded in the area around Okhimath in Rudraprayag district in the night of 13th September as also in the morning hours of 14th September 2012 (DMMC, 2012a).

Similarly, DMMC (2012b) reported that localised heavy rains (in Uttarakashi 75 mm while in Bhatwari >80 mm rains) in the early hours of 4th August, 2012 in the catchment of the tributaries of Bhagirathi river, particularly Asi Ganga and Swari Gad, caused the waters of Bhagirathi to rise as much as 4 meters above the danger level at Uttarkashi. Gupta et al. (2013) have studied of August, 2012 cloudburst associated flash floods over Asi Ganga and its impacts in Bhagirathi valley of Uttarkashi district. While Kumar and Jain (2012) monitoring and analysis the same events using Geographic Information Systems (GIS) and Remote sensing techniques.

Asthana and Asthana (2014) have studied cloudburst and flashfloods of June, 2013 in the Kedarnath area of Higher Central Himalaya of Uttarakhand based on geological and geomorpholocial investigations. As per IMD (2013), the rainfall in the State between 15 June and 18 June 2013 was measured at 385.1 mm, against the normal rainfall of 71.3 mm, which was in excess by 440%.

DMMC (2014) based on distribution of various geomorphic and physiographic factors was studied over 22 cloudbursts associated extreme precipitation evens in Rudraprayag district and similar study was carried out by Khanduri (2018a) over 30 cloudbursts events in Chamoli district of Garhwal Himalaya. These studies concluded that most of such events fall in the higher reaches in the catchment of first and second order streams result in fast erosion of agriculture fields following debris/mud flows is largely responsible for the devastation.

Khanduri (2017) reported that slope failure incidences took place at many places in the Pithoragarh district on 01 July, 2016 amid heavy rainfall around 160 mm within 4-5 hours in Didihat region.

Khanduri et al. (2018a) reported that the Pithoragarh flash flood incidences took place at Mangti and Malpa areas on 14 August 2017 amid heavy rainfall at early morning (2:30 am) in the catchment of the tributaries of Kali River, particularly Simkhola Gad and Malpa Gad. However, rainfall data could not be recorded due to the absence of meteorological observatories in devastated areas.

In the previous some years, a few scholars are studied extreme events over the Indian Himalayan region using modeling frameworks. Das et al. (2006) based on Mesoscale Model 5 version 3.6 (MM5) modeling system, simulating 16 July, 2003 Shillagarh cloudburst in Himachal Pradesh. The analysis from the two numerical experiments provides a conceptual model of the cloudburst based on the development of the vertical shear, vertical motion and the moisture distribution.

Rasmussen and Houze (2012) provided a conceptual model demonstrating the dynamics of cloudburst associated heavy rainfall events of 4-6 August, 2010 over the Leh village of Western Himalaya in India. The model highlights that easterly jet help in the convections to organize from the Tibet leading to extreme rainfall events in the same area.

Chevuturi et al. (2015) studied Okhimath cloudburst of 14 August, 2012 using WRF model version 3.4.1 with Advance Research WRF dynamical solver whereas Shrestha et al. (2015) simulated the same event using COSMO framework. Chevuturi et al. (2016) studied disaster of 2013 in Uttarakhand using weather research and forecasting model.

Recently, Dimri et al. (2017) have studied 5 cloudbursts of Leh region over Indian Himalaya based on observational and modeling strategies to arrive comprehensive definition of it. As also, available cloudburst events and associated damages across the southern rim of the Indian Himalayas are provided by them.

3. Materials and Methods

3.1. Study area

Uttarakhand is northwestern Himalayan state of Indian subcontinent and is situated between 28° 43”- 31° 27” N latitude and 77° 34”- 81° 02” E longitude (Fig. 1). Geographical area of the state is 53,483 sq. km; 93% of which is mountainous and 64% is covered by forest. The state is bounded by internationally as China in the North and Nepal in the East while nationally as Himachal in the west and Uttar Pradesh in the South. The Uttaranchal state was carved out to Uttar Pradesh on 9 November, 2000 and is the 27th State of republic of India. In January 2007, the name of the state was officially changed from Uttaranchal to Uttarakhand.

Administratively, the state is divided into two Divisions; one is the Garhwal and another is the Kumaun. There are 13 districts in the state in which 7 (Uttarkashi, Rudraprayag, Chamoli, Tehri, Parui Garhwal, Haridwar, Dehradun) and 6 (Pithoragarh, Bageshwar, Almora, Nainital, Champawat, Udham singh Nagar) numbers are respectively in Garhwal and Kumaun divisions. Dehradun city is the state capital of the state. The total population of state is 10,116,752 of which male and female are 5,154,178 and 4,962,574 respectively. The population density is 189 per square kilometers and sex ratio is 963 females for each 1000 male. The average literacy rate is 79.63 percent of which male literacy rate is 88.33 percent while female is 70.70 percent (Census, 2011).

The state houses a number of sacred shrines and pilgrimage routes. Apart from Chota Kailash-Kailash-Mansarovar and Hemkund Sahib these include Chardham route leading to Badrinath, Kedarnath, Gangotri, and Yamunotri that is the biggest and most cherished Hindu pilgrimage circuit of the country (Rautela, 2018). The area also has a number of picturesque tourist destinations that include Valley of flowers, Joshimath, Auli, Chopta, Gopeshwar, Gwaldam, Harsil, Dodital, Dayra Bugyal, Bedni Bugyal, Lohajang, Mussoorie, Nainital, Tungnath, Bageshwar, Chaukori, and Munsyari. People from across the country and abroad thus visit the area in large numbers.

The state is well connected by road network. National Highway in the region measures about 1,376 kilometers and state highway measures 1,575 kilometers. There are two commercial airports at Joli Grant in Dehradun and another one at Pantnagar in Udham Singh Nagar. Besides, there are three airstrips as Naini Saini, Gauchar and Chinyalisaur in Pithoragarh, Chamoli and Uttarkashi respectively. The Important railway stations of the same region include Dehradun, Kathgodam, Kotdwar, Haridwar and Ramnagar.

Except for a small area falling in the plains the state experiences cold winters with higher reaches experiencing snowfall during winters, appreciably good rainfall during monsoon, and mid summers. The high rainfall occurs between June to September. The summer temperatures, mainly in plains and river valleys often cross the 40 °C. Winters are very cold with average temperatures going below 5 °C.

The Uttarakhand state is source to network of major rivers that include Alaknanda, Bhagirathi, Yamuna, Ramganga and Kali. Alaknanda and Bhagirathi confluence at Devprayag and thereafter the river is known as Ganga. Most of the rivers originating from the Tethyan, Higher and Lesser Himalaya are perennial and their flow direction is in general from north to south. However, the Ramganga East originates from the Namik Glacier and flows towards east.

3.2. Geology and physiography

Geologically, the entire Uttarakhand Himalaya falls in five litho-physiographic regions (Fig. 2). These include Indo-Gangatic Plains, Outer Himalaya, Lesser Himalaya, Higher Himalaya and Tethyan Sediments (Fig. 2). These are separated one and each other by major Thrust/Fault. The Trans Himadri Fault (THF), Main Central Thrust (MCT), Main Boundary Thrust (MBT) and Main Frontal Thrust (MFT) from north to south direction separates the Tethyan sediments from the Central Crystalline rocks, the Central crystalline rocks from the Lesser Himalayan rocks, the Lesser Himalayan rocks from the Siwalik Groups of rocks and the Siwalik Groups of rocks from the Indo-Gangatic Plains, respectively (Auden, 1949; Heim and Gansser, 1939; Valdiya, 1980; Valdiya and Goel, 1983; Valdiya, 1989).

The Tethyan sediments are exposed across Trans Himadri Fault (THF) plane. These sediments are largely un-metamorphosed and occupy synclinal basins of the south of the famous Indus-Tsangpo Suture Zones. The Higher Himalayan Central Crystalline rocks are observed to comprise of Munsiari Formation of low to medium-grade metamorphic rocks in the southern sequence while Vaikrita Group of high-grade metamorphic rocks in the northern sequence that have been intruded by both acidic and basic rocks (Khanduri, 2018b).

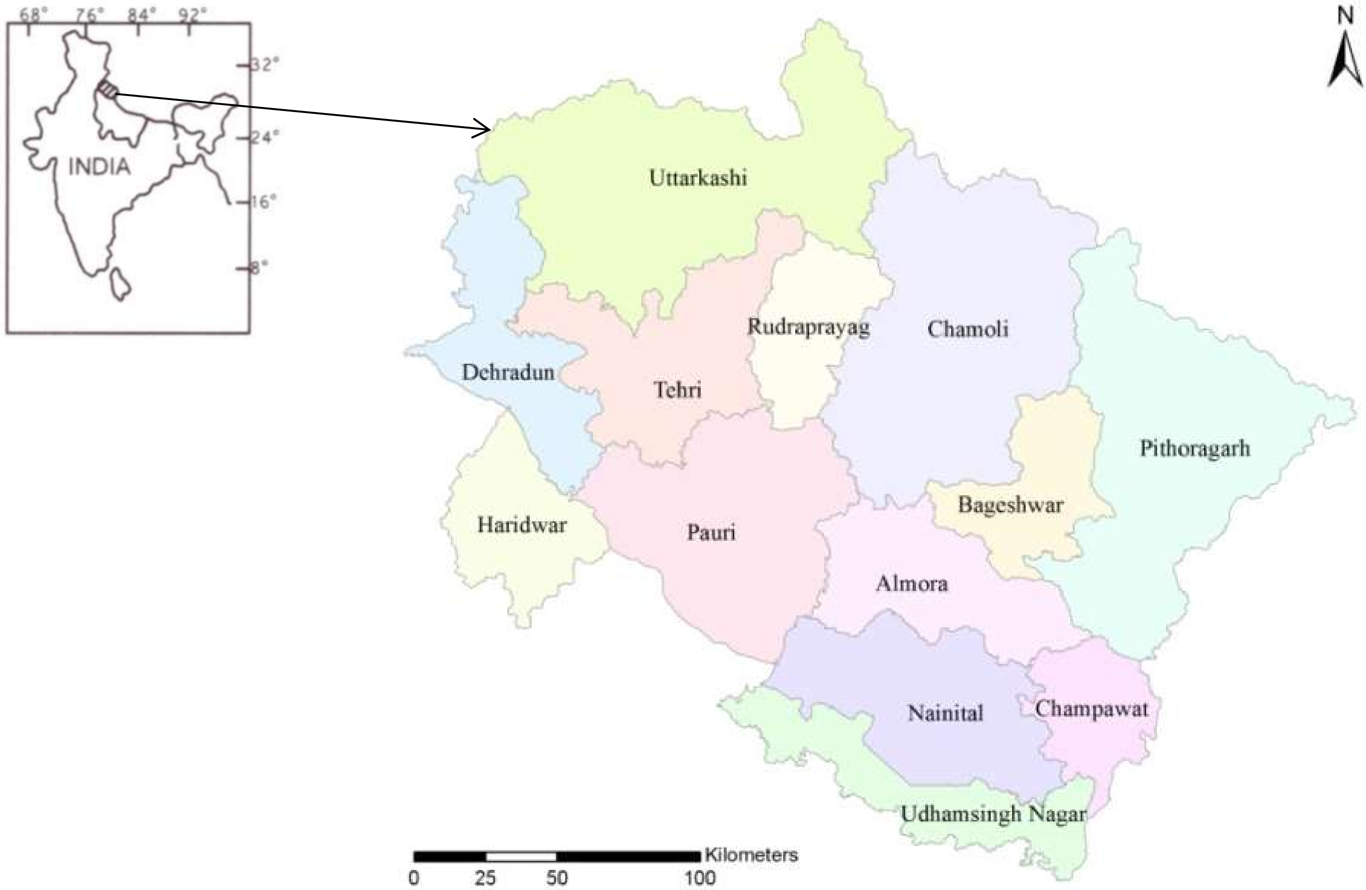

Fig. 1. Map illustrate study area along with district boundary

The exposures of Lesser Himalaya are sedimentary and low-grade metamorphic rocks with basic volcanics and acidic intrusive rocks. The crystalline klippen tectonically occur within the Lesser Himalaya. North Almora Thrust (NAT) separates the northern Lesser Himalayan Garhwal Group from the southern outer Lesser Himalayan Jaunsar and Almora Groups. The Siwalik Groups are divided into Lower, Middle and Upper. While the Indo-Gangatic Plains are composed of alluvial fill deposits. The lithotectonic succession of the study area is given in Table 1.

According to Srivastava et al. (2016) geomorphologically, cross section profile of Himalaya shows marked variations in elevation ranging from ±400m at the mountain front to around 1000m Siwalik hills to ±1200m Lesser Himalaya and >3000m Higher Himalaya. With the elevation of 7,816 meters (25,643 ft) above mean sea level, Nanda Devi is the highest mountain peak in the Uttarakhand Himalaya. Apart from Trishul (7,120 m), Kedarnath (6,940 m), Shivling (6,543 m), Panchchuli (6,903 m), Om Parvat (6,191 m) etc. are also high mountain peaks in the same region. Mostly, northern parts of the state are part of Greater Himalayan ranges, covered by the high Himalayan peaks and glaciers, while the lower foothills were densely forested. There are many of the well-known glaciers occurred in the regions. These include Milam, Bhagirathi Kadak, Khatling, Chorabari, Ralam, Pindari, Namik, Satopanth etc. constantly feed the most of the perennial holy river system.

3.3. Earthquake vulnerability

The area is seismically active and falls in both IV and V zones of Earthquake Zonation Map of India (IS 1893, 2002). Chamoli, Rudraprayag, Bageshwar and Pithoragarh fall in Zone V while Dehradun, Haridwar, Nainital and Udham Singh Nagar fall in Zone IV. Uttarkashi, Tehri, Pauri Garhwal, Almora and Champawat fall in Zone IV and partially in Zone V (Fig. 3).

In the past, the region was devastated by Mw~7.6 Garhwal Earthquake in 1803 (Rajendran et al., 2013) and its being located in the Seismic Gap of 1905 Kangara Mw~7.8 (Middlemiss, 1910) and 1934 Bihar-Nepal Mw~8.2 (Dunn et al., 1939) earthquakes enhances seismic risk in the region (Rautela et al., 2011). On 1th September, 1803 earthquake of >8 Magnitude was highly destructive and caused severe damage in Badrinath temple (Smith, 1843). Similarly, earthquakes of 1979 and 1980 in Dharchula tehsil of Pithoragarh district ravaged several villages along the Kali valley (Khanduri et al., 2018a). Recently, the state has witnessed two major earthquakes of 1991 Uttarkashi and 1999 Chamoli killing 768 and 106 peoples, respectively (DMMC, 2012b). The great earthquake of >8 Magnitude is not coming yet for 200 years. Because of the same enhances the seismic risk in the state.

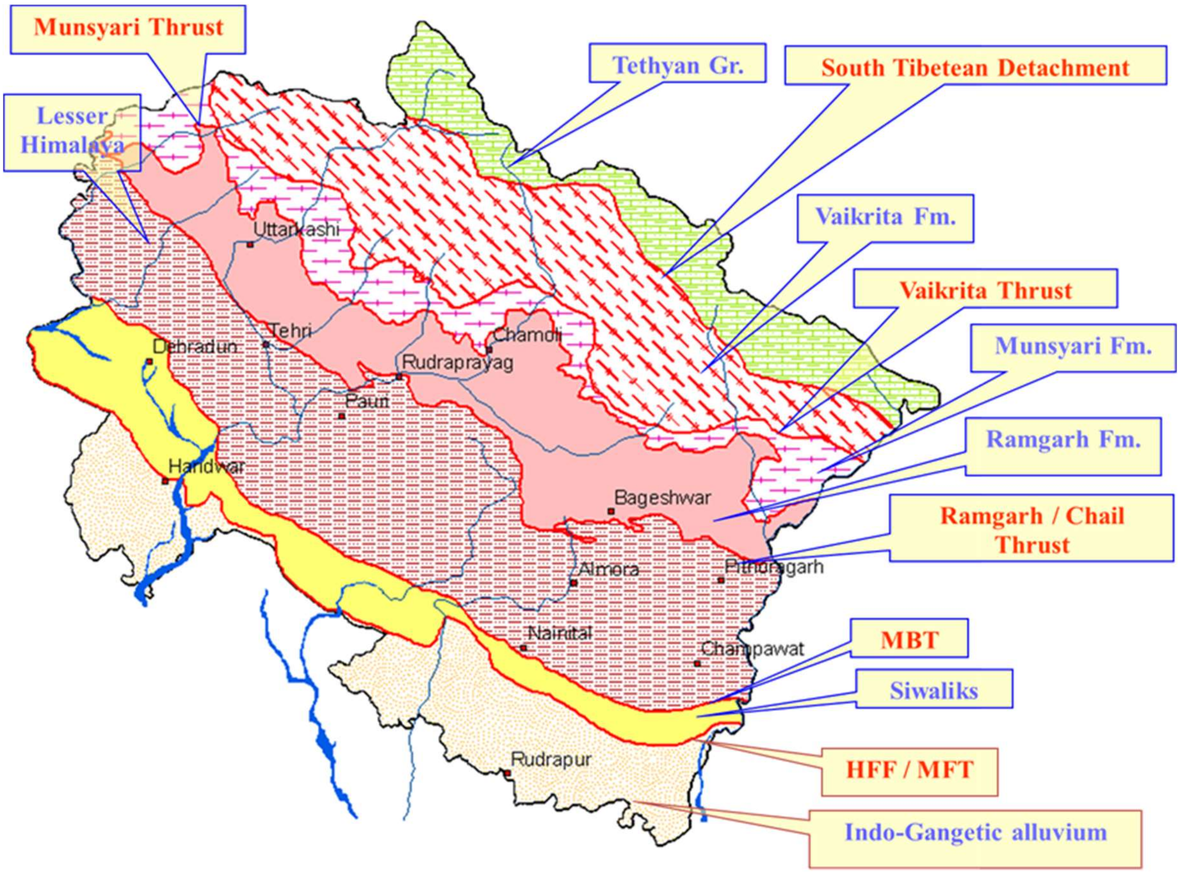

Fig. 2. Map depicting Geology of the area with litho-physiographic regions

3.4. Slope morphometry

Slope plays an important role in governing the stability of mountainous terrain in which steep inclines, vertical scarps, deep regolith covers and mass wasted scree slopes are the result of denudational processes. Slope morphology can probably affect the susceptibility of a slope to landslide in several ways. The shape of a slope influences the direction of and amount of surface runoff or subsurface drainage reaching a site (Dai and Lee, 2002). Concentration of subsurface drainage within a concave slope, resulting in higher pore water pressures in the axial areas than on flanks, is one possible mechanism responsible for triggering landslides (Pierson, 1980).

Steeper terrain with gradients ranging from 40° to 60° is, however, less likely to fail than terrain between 30° and 40°.

This is because the slope forming material of such slope terrain is weathered rock not overlain by colluvium while the moderately steep terrain is often covered by colluvial deposits which is more vulnerable to rainfall induced failure (Dai et al., 1999). Slope map defines slope categories on the basis of frequency of occurrence of particular angles of slope. For the purpose of present study slope map of the area is classified into six categories; 0-10°, 10°-20°, 20°-30°, 30°-40°, 40°-50°, 50°-90° (Fig. 4). Large portion of the study area (26 percent) is observed to be fall in 50°- 90° (very steep slopes) while 22 and 20 percent respectively fall under 40°-50° (steep slopes) and each 30°-40° and 20°-30° (moderately steep slopes). 10°-20° (gentle slopes) and 0-10° (very gentle slopes) in the study area account for 9 and 3 percent of the area, respectively.

Table 1. The lithotectonic succession of the Central Himalayan Uttarakhand Regions

Groups	Lithology
Tethyan Sedimentary Zone (TSZ)	Shale, slate and limestone
	Trans-Himadri Fault (THF)/South Tibetean Detachment (STD)
Higher Himalayan Metamorphic Zone	Granite gneiss, quartzite, migmatites and amphibolites with tourmaline leucogranite
	Vaikrita Thrust (VT)
	Garnetiferous schist, quartzite, crystalline limestone, quartz-mica schist, kyanite-silliminite schist, calc gneiss, porphyroblastic augen gneiss, paragneiss
	Main Central Thrust (MCT)/Munsyari Thrust (MT)
Lesser Himalayan Meta-Sedimentary Zone	Quartzite with/without penecontemporeneous mafic metavolcanic intruded by epidiorite, limestone, dolomite and phyllite/slate
	North Almora Thrust (NAT)/Ramgarh Thrust (RT)/Chail Thrust
	Phyllite, quartzite, biotite schist, quartz mica schist, garnet-mica schist, porphyroblastic augen gneiss, ortho and para-gneiss, granite gneiss, quartzite and basic intrusive
	Main Boundary Thrust (MBT)
Outer Himalayan Siwalik Groups	Sandstone, siltstone, mudstone, shale and boulder conglomerate
	Himalayan Frontal Fault (HFF)/Main Frontal Thrust (MFT)
Indo-Gangatic Plains	Alluvial fill deposits

3.5. Data collection

Survey of India toposheets on the scale of 1:50000 have been use to prepare the base map with litho-physiographic regions of the area. With the help of Survey of India toposheets and Handset Global Positioning System (GPS), some of the affected locations and associated damages were confirmed with the inhabitants of the areas during the field survey. ASTER DEM (Digital elevation model) of 30 meters resolution has been utilized for delineating slope categories.

A thematic map of geology and slope has been prepared using Geographical Information System (GIS) software (Arc View 9.3). Apart from the extreme events and related damages are taken from the various sources as State Emergency Operations Center (SEOC), previous research papers and field survey. Finally, distribution of cloudbursts and losses incurred by the same events since 1970 to 2019 has been taken up and listed in tabular form.

4. Distribution of Cloudbursts

Cloudburst is an unusual phenomenon in the Himalayan terrain and the same frequently occurs during monsoon season particularly between July and September months. Increasing trend of cloudbursts following abnormally localized precipitation events are more common in the region. This is a major cause of concern for the state Government and meteorologists.

Being a geologically fragile mountainous belt, geographically high relief deference and moderate to steep valley slopes, geomorphologically deep regolith covers and meteorological characteristics as adverse climatic conditions and change in rainfall patterns makes the state more prone to a number of disasters. These include earthquake, landslide, flood and avalanches. In the previous some years, increasing trend of abnormally high precipitation, heavy localised precipitation or cloudbursts following landslides, debris flows and flash floods resulting damages and destructions in the same region. This kind of calamities that happened here over the past is easily confirmed by this fact (Table 2).

4.1. Causes and effects of cloudbursts

The Uttarakhand state lies in Central Himalaya and is well known for its vulnerability to a number of hazards. Seismically the same region also lies in zones IV and V. The rocks of the area are highly fragile in nature because of a number of thrusts and faults. Geomorphology and physiographically, high relief difference, steep slopes, thick overburden and streams are common characteristics features in the area. Hydro-meteorological characteristics in the form of abnormally high precipitation are however becoming more frequent because of change in climate. Among these are responsible for the cloudbursts leading to flash floods, debris flows and landslides which cause loss of life and disruption of transport network together with agricultural fields and other facilities.

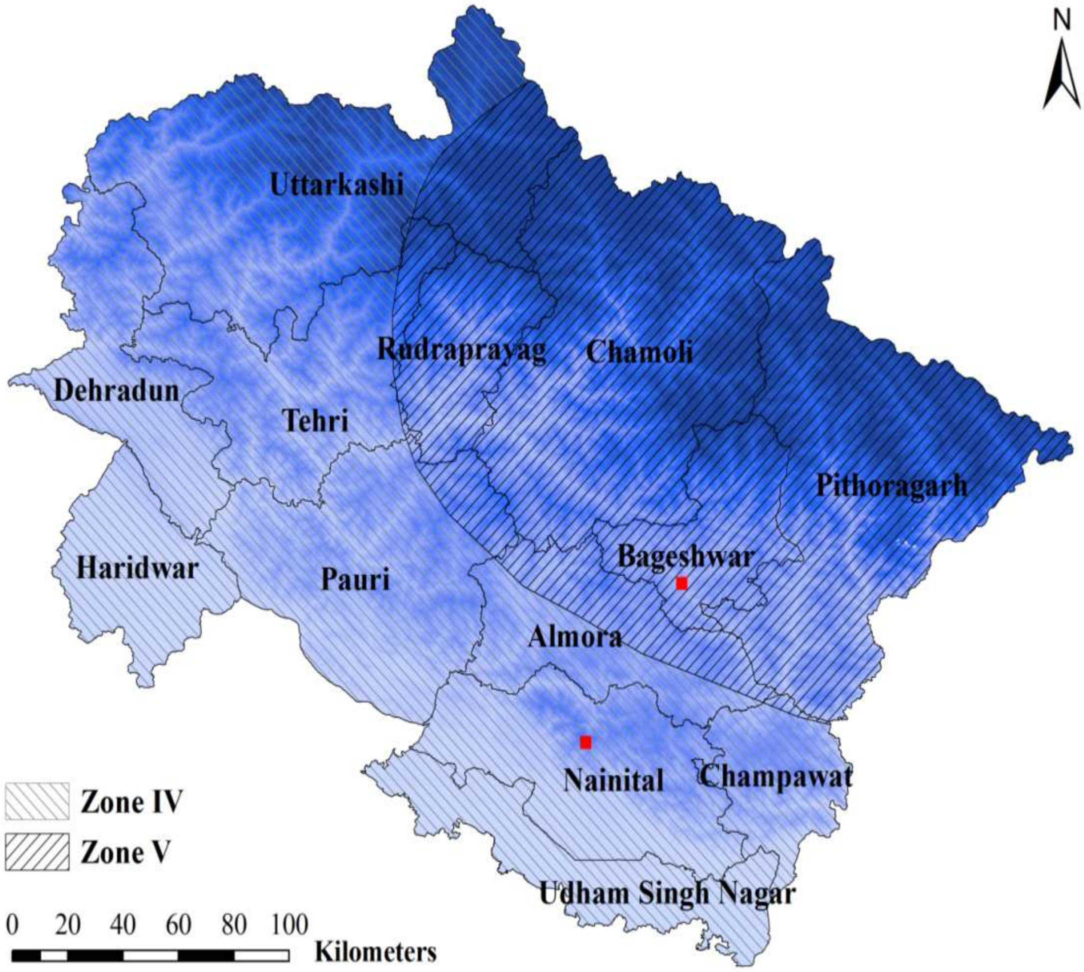

Fig. 3. Map showing Earthquake Zonation of the region (Source: IS, 1893)

Quaternary deposits such as glacial sediments, colluvium and river born materials terraces etc. which has been mostly used for the township and agricultural activity are badly affected by the cloudbursts. On the basis of the previous occurred cloudburst events and associated flash floods, debris flows and landslides, the following basic characteristics of the same can be drawn out.

- Certain peculiar geomorphic features that include cirque, saddle and funnel shaped valleys and high relief difference are considered to provide favorable conditions for cloudbursts occurrence.
- Physiographically, average altitudes between 1400 to 2200 meters above mean sea level are extensively sensitive for the cloudburst events.
- Mostly cloudbursts activities occur between MBT and MCT, particularly in the Uttarakhand region.
- Exposures of schist, garnet schist, biotite gneiss and quartzite are mostly vulnerable for the cloudburst due to their conductive nature of lightning.
- Cloudbursts often occur on the upper reaches of first and second order streams having with high gradient.
- Mostly cloudbursts trigger at late night or early morning during monsoon season from June to September months.
- Cloudbursts generally occur along the more isolated slope generally facing towards west and south direction.
- Cloudbursts are mostly confined by a number of geo-environmental factors such as high relief deference, steep slopes, land use and lithology.
- The cloudbursts following persistent rainfall oversaturates the slope materials and develops pore water pressure resulting into slope instability and mass movements.

- Cloudbursts triggered landslides blocked the course of streams, sudden breach of landslide dam resulting into inundation in downstream.
- Most of the settlements in the hills situated in concentration of streams, over deep regolith covers which are eroded by cloudbursts following flash floods, debris flows and landslides result in enormous damage and destruction in term of losses of human life and property.

4.2. Traditional/better land use practices

Cloudburst is a natural phenomenon over Himalayan orography which is suitable platform for triggering its. There are various distinguished geomorphic and physiographic parameters like mountains with its high inclines, funnel shape valley, hanging valley, saddles, cirque and streams etc. are more prone to cloudbursts.

In most cases, there is a greater chance of damage from the rock falls/slides, debris/mud flows and flash floods caused by the cloudburst events. Therefore, it is very important to keep respectable distance from these places. The same event cannot be stopped but its impact can be reduced by taking some prevention measures in term of safe land use practices.

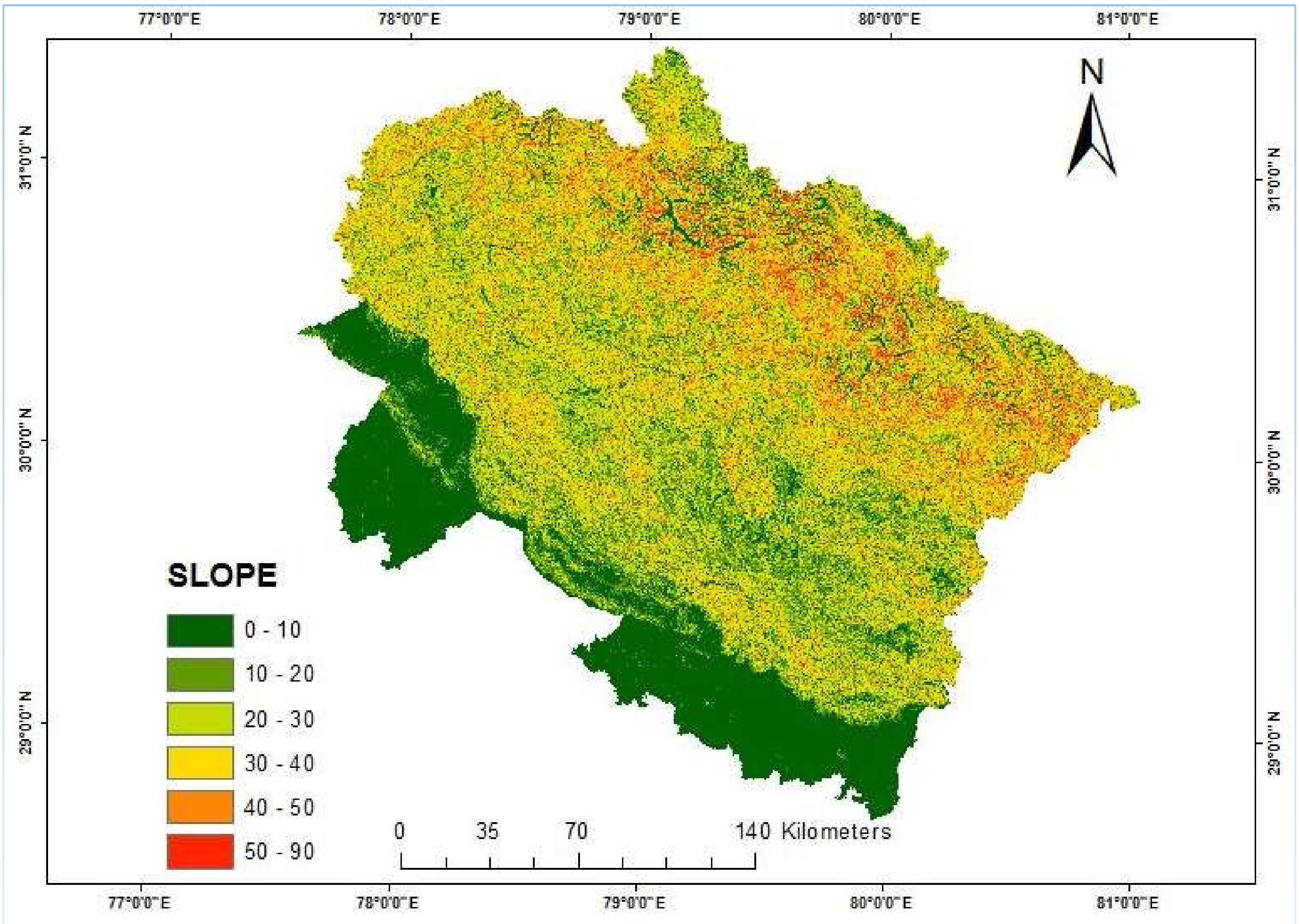

Fig. 4. Map depicting Slope Morphometry of the area

While houses constructing in the hills, it is very important to keep right of seven things in mind which are given below.

- Maintaining respectable distance from the streams (even I[st] order stream/rivulet).
- Should not construct houses on the edge of the high hills.
- Constructions should be in firm ground instead of overburden/deep regolith covers.
- Avoidance of any type of constructional activities bottom of high hills.
- Ridge and spur are suitable locations for habitation practices.
- Landslide prone areas must not be considered for any type of civil constructions.
- While constructing a house, keep respectable distance from the hillside slope.

On the basis of above said things, can be minimized the impact of cloudbursts and associated damages. These said things are not new to us. In the past, these things were also noticed by our ancestors and its strictly adhered to by them. Let me try to explain these facts with an example. The hidden village of Bansoli is located at a distance of 17 kilometers from Karanprayag town and is located on the left bank of Bansoli Gad, a tributary of Pinder river. The area can be approached by Karanprayag-Nainisain link road. The Bansoli village is located about 3 kilometers from the road head. Cloudburst following flash floods of June, 2013 in the catchment of Bansoli Gad is observed to have resulted in excessive erosion and collapse of the banks.

The high sediments leaden discharge through streams eroded the banks along all the valleys and spread the catchment area. Widening of the stream course has caused damage to a number of agricultural fields of the Bansoli village. Fortunately, no damages were occurred in the village because the people of the village took care of seven things which are as follows: (i) Kept a certain distance from the stream, (ii) avoided old landslide zone to build a house (iii) converted the old landslide zone to terraces and used it for farming and planted oak trees in upslope of old landslide zone, (iv) used a paved place and concave ridge spur of the hill to build a house, (v) Kept a certain distance from the steep scarp (vi) used of Irrigation fields away from Habitation area, and (vii) built a house at least 50 m away from the hill side slope (Fig. 5). All this shows that; our ancestors took care of everything before building a house. It is clear that those people were more knowledgeable in site selection, choosing the right place for build a house. We should settle in the hills following them. Keeping these things in mind, the dangers of cloudbursts can be avoided, particularly in the hills.

Table 2. Some known reported cases of cloudbursts and losses incurred by the same events since 1970 to 2019

No	Date, month and year of occurrence	Location	Loss and damage (human, cattle, property etc.)	Reference
1	20 July 1970	Ganai, Chamoli	200 persons killed and damaged to 33 houses	Joshi and Kumar, 2006
2	13-19 July 1971	Dobata Village, Pithoragarh district	Killing 12 people and buried 35 houses	Sajwan and Khanduri, 2018
3	04-05 August 1978	Kanoldiya Gad, Uttarkashi	Several villages were marooned. The Maneri-Bhali HEP suffered heavy damaged. Most of the shops and houses in Joshiara near Uttarkashi were swept away	Prakesh, 2015a
4	17 June 1979	Saikot, Chamoli	Killed 3 people, 70 cattle lost and 20 houses completely damaged	Joshi and Kumar, 2006
5	17 August 1979	Kuntha, Rudraprayag	Killing 39 persons, 39 cattle lost together with 20 houses completely damaged	Joshi and Kumar, 2006
6	17 August 1979	Sirwari, Rudraprayag	13 human loss while 150 cattle lost and 34 houses damaged	Joshi and Kumar, 2006
7	24-25 June 1980	Gyansu Nala, Uttarkashi	24 persons killed and washed away many houses in its vicinity	Prakesh, 2015a
8	31 July 1982	Mandakhal Chennil, Pauri Garhwal	As many as 3 persons killed, 80 animals lost and 8 houses completely damaged	Joshi and Kumar, 2006
9	23 July 1983	Karmi, Kapkot, Bageshwar	Killing 25 people, 20 animals lost and 6 houses completely damaged	Anbalagan, 1996
10	09 July 1990	Nilkanth, Pauri Garhwal	100 persons were killed while 10 houses completely damaged	Joshi and Kumar, 2006
11	16 August 1991	Dewar Khadora & Gangolgoan, Chamoli	26 people lost their life while 63 animals killed and damaged to 38 houses completely	Joshi and Maikhuri, 1997
12	02 September 1992	Khankrakhet hill, Gadni, Chamoli	Killing 14 people. Apart from 31 houses destroyed and 20 ha irrigated lands was washed away	Sati, 2007
13	July 1993	Patidi hill, Musudiyar, Chamoli	Loss of 25 animals. Besides, 14 houses completely damaged and 1.0 ha non-irrigated fields washed off	Sati, 2007
14	13 August 1995	Bhintai, Pauri Garhwal	13 persons killed and 6 houses completely damaged	Joshi and Kumar, 2006
15	17 July 1996	Berinaga, Pithoragarh	18 human lives lost and 85 houses fully damaged	Joshi and Kumar, 2006
16	26 July 1996	Raintoli, Pithoragarh	Losses of 16 villagers	Sajwan and Khanduri, 2018
17	11-19 August 1998	Bhenti-Paundar villages, Okhimath tehsil, Rudraprayag	Killing 103 people while 422 animals lost and 820 houses completely damaged	Naithani, 2001

18	17 August 1998	Malpa, Pithoragarh	Killed 221 people including 60 kailash Mansarovar pilgrims. Among the dead was Odissi Dancer Protima Bedi	Paul et al., 2000
19	July 2000	Pujargaon village, Uttarkashi	Damaged to few meters of road and some agriculture fields	Prakesh, 2015a
20	16 July 2001	Phata-Byung, Ukhimath tehsil, Rudraprayag	Killing 27 persons while 64 animals lost and damage to 22 houses completely	Naithani et al., 2002a
21	31 August 2001	Gona, Tehri	7 persons killed while 12 injured together with 7 cattle lost and 28 houses completely damaged	Naithani et al., 2002b
22	12 July 2002	Khetgoan, Pithoragarh	Killing 4 people while 1 person missing and 20 animals lost together with damage to 7 houses completely	SEOC
23	10 August 2002	Marwari and Agunda, Bhudakedar (Thati Kathur) in Balganga valley, Tehri	28 persons killed while 99 cattle were lost. Additionally, 151 houses together with a micro hydro power plant were damaged	Sah et al., 2003
24	19-20 August 2002	Bhatwari and Dunda, Uttarkashi	Killing 5 people while 26 animals lost	SEOC
25	29 August 2003	Sarnol, Uttarkashi	207 animals were lost	SEOC
26	23 September 2004	Aamparav, Nainital	Killing 3 persons while 7 residential and commercial structures were totally destroyed in the incident. Total of 8.9 hac agricultural fields were damaged	Rautela and Pandey, 2005
27	24 September 2004	Near Badrinath	A stretch of 200 Rishikesh-Badrinath road (NH 58) was completely damaged	NIDM, 2015
28	29-30 June 2005	Govindghat, Tuphani nala, Chamoli	11 people lost their life. More than 200 vehicles, 20 shops, Hotels, human settlements have been washed away	Asthana and Asthana, 2014
29	21 June 2005	Teela, Thalisain, Pauri Garhwal	Killing 30 animals and 6 houses completely damaged	SEOC
30	21 July 2005	Jhuni, Kapkot tehsil, Bageshwar	Killed 1 person while 3 cattle lost and 6 houses destroyed	SEOC
31	21 July 2005	Vijaynagar, Agastmuni, Rudraprayag	4 human live lost and 14 houses were destroyed	DMMC, 2014
32	18 August 2005	Semla tok of Rathi village, Dharchula tehil, Pithoragarh	8 persons were killed while 129 animals lost	SEOC
33	27 August 2005	Atholi village, Bhatwari tehsil, Uttarkashi	15 animals lost and 3 cow sheds destroyed	SEOC
34	11 August 2006	Chamoli tehsil, Chamoli	18 mud houses partially damaged	SEOC
35	26 July 2006	Ladoli, Devali, Gholtir and Gursyal, Rudraprayag	19 animals killed while 6 shops and 8 houses partially damaged	SEOC
36	September 2007	Baram, Pithoragarh	As many as 5 persons were killed and 9 others were feared dead	Sajwan and Khanduri, 2018
37	18 August 2009	Jhakhla and Lah, Pithoragarh	Wiped out 2 villages namely Jhakhla and Lah, claiming 43 lives	Sarkar and Kanungo, 2010
38	18 September 2010	Sumgarh Village, Kapkot tehsil, Bageshwar	18 children of classes I and II of a private primary school, Saraswati Shishu Mandir were buried alive under rock debris	Prakesh, 2015b
39	3 August 2012	Pandrasu ridge, Uttarkashi	35 human lives lost while 436 livestock's and injured 20 people. An estimated 61.787 hac of agricultural land was lost	Gupta et al., 2013
40	13 September 2012	Okhimath, Rudraprayag	69 human lives lost and serious injuries 15 persons. More than 70 residential houses were reported to be destroyed	DMMC, 2012a
41	16-17 June 2013	Rudraprayag, Chamoli, Uttarkashi, Bageshwar, Pithoragarh, Uttarakhand	106 people killed while 4021 persons missing. 11,91 farm animals were lost and more than 19,309 residential houses damaged	NIDM, 2014; Khanduri, et al., 2018b
42	28 May 2016	Kemra and Siliara, Kothiara, Tehri	100 animals were lost and 120 houses completely damaged	Dimri, et al., 2017
43	01 July 2016	Didihat, Bastari and Naulra villages, Didihat and Thal Tehsils of Pithoragarh district	In Bastari and Naulra villages respectively 19 and 3 persons were killed. Total 16 buildings were destroyed or damaged and 174 cattle were lost in Bastari village while 3 houses and around 70 animals in Naulra village	Khanduri, 2017

44	26 May 2017	Tatalgaon and Bijrani near Chaukhutia	Life of loss of 8 domestic animals and one house	Chauhan and Mehrotra, 2018
45	14 August 2017	Mangti and Malpa, Dharachula tehsil, Pithoragarh	As many as 9 persons were died while 18 persons went missing and 51 animals were lost	Khanduri et al., 2018a
46	17 July 2018	Yamnotri, Uttarkashi	The foot bridge connecting to the shrine was washed away. Kali Kamli Dharamshala was also severely damaged together with the hot water bath Kunds were filled with debris	SEOC
47	19 July 2018	Malari village of Niti Ghati in Joshimath tehsil, Chamoli	As many as 2 persons dead and 5 persons trapped in debris. Around 150 meters long Joshimath-Malari road stretch is washed away	SEOC
48	8-9 August, 2019	Padmalla- Faldiya, Dewal block, Chamoli	Killing a woman and a kid. About 12 houses, two dozen cow sheds, 6-foot bridges, 10 water mills, water supply lines and agricultural lands were also damaged	SEOC
49	18 August 2019	Mori tehsil of Uttarkashi district	21 persons killed and 74 animals lost. 2 motor bridges are damaged along with 2 pedestrian bridges.	Khanduri and Sajwan, 2019
50	6-7 September 2019	Govindghat, Joshimath tehsil, Chamoli	Several vehicles were buried under debris while about 30 meters stretch of Rishikesh-Badrinath road (NH 58) completely damaged	SEOC

5. Results and Discussion

Cloudburst is a frightening phenomenon in the Himalayan mountainous region where it is limited by the distinguished geomorphic and physiographic parameters. These include mountains with its high relief difference, funnel shape valley, hanging valley, saddles and cirque etc. Additionally, dense forest cover especially oak trees with average altitudes between 1600 to 2200 meters above mean sea level are extensively sensitive for the same events.

Cloudburst generally occurs along the more isolated slope generally facing towards west and south direction and in general occurs during the late hours of the day (Asthana and Asthana, 2014). It can only be identified on the basis of inundation occurred mostly along the first and second order drainages in hilly terrain during monsoonal rainfall and associated debris flows have caused severe damage to settlement and infrastructure (Khanduri, 2018a).

However, these heavy downpour crosses the Higher Himalayan major tectonic barrier MCT and trapped in higher inclines and saddles, where these are suddenly stagnant. The Higher Himalayan rocks are much fragile in nature and are found highly deformed, degraded and dissected by structural discontinuities, which are considered to be geo-dynamically active.

Geomorphologically, the surface slopes of the area consist mostly of glacio-fluvial, alluvium and colluvium which are mostly unconsolidated and loose in nature. These result in significant damage and destruction in the downstream. Kedarnath, Pandrasu hills, Okhimath, Phata, Bhenti, and Malpa etc. are the evidences for cloudburst events in the Higher Himalayan zone.

Mostly, cloudburst activities occur between MCT and MBT which is located parallel to the Himalayan tendency (Pal et al., 1998). Bastari-Naulra, Devpuri, Vijaynagar and Gholtir etc. are the evidences for the cloudburst events in the same zone.

Heavy localized rainfall and cloudbursts had been common in the region often resulted in flash floods, debris flows and landslides. Sometime, the same events trigger big landslides which can block the course of the streams and left behind the dam impounding of huge water in the form of the lake. Sudden dam break of the same during monsoon season resulting inundation in downstream that caused again massive loss of life and property together with development of a number of landslides. There are different types of damages by cloudburst events, which are given in sections below.

5.1. Flash floods

Flash floods are considered to be one the worst kind of hazard. It's usually occurs after the high intensity of rainfall in a certain area or a small basin with particular a geological setting like relief, slope, and a shape factor, drainage density of a watershed (Ali et al., 2017). Global climate change leads to the more extreme precipitation and more flash flood disasters, which is a serious threat to the mountain inhabitants (Li et al., 2018).

Over the past, the Mandakini, Alaknanda, Bhagirathi, Tons and Kali rivers and their tributaries have witnessed many instances of damming of stream courses by extremely heavy rainfall following landslides. Later, breaching of these have often resulted in flash floods in the downstream areas. These include Dahuli ganga (1970), Birahi ganga (1970), Patal Ganga (1970), Alaknanda (1970, 2013) in Chamoli district; Kunjya Gad (1979), Madhyamaheswar ganga (1998), Mandakini river (1979, 1998, 2013) in Rudraprayag district; Kanoldiya Gad (1978), Asi ganga (2012), Bhagirathi river (1978, 2012, 2013) and Khaneda Gad, a tributary of Pabber river (2019) in Uttarakashi district; Gori ganga (2010), Kali river (1998, 2013) in Pithoragarh district and Karmi Gad (1983), a tributary of the Sarju river in Bageshwar district are the evidences of the same events.

Fig. 5. View of damaged agricultural fields of Bansoli village on the left bank of the Bansoli Gad (left) and irrigated fields on the left bank of Bansoli Gad in the upper catchment (right)

Localized heavy rains (80 mm) in the early hours of 4 August, 2012 in the catchment of the tributaries of Bhagirathi river, particularly Asi Ganga and Swari Gad, caused the waters of Bhagirathi to rise as much as 4 meters above the danger level at Uttarkashi. This caused widespread devastation in the district and even the district headquarter was not spared by the fury of nature (DMMC, 2012b).

In the year 2013, Uttarakhand experienced unusually high rainfall between 16 and 17 June that resulted in a number of landslides, cloudburst and flash flood events particularly in Rudraprayag, Chamoli, Uttarkashi, Bageshwar and Pithorgarh districts of the state (NIDM, 2014). In terms of human lives lost (5000 persons) Kedarnath tragedy of June, 2013 is thus the biggest tragedy since the creation of the state.

In the years 2013 and 2014, Bhuindar and Pulna (Bhuindar Ganga/Laxman Ganga), Bansoli (Darimyagad), Ghat, Sunali and Tefna while Gwar (Chuphla Gad), Siligi tok (Lingari Gramsabha) and Urgam valley (Kalpa Ganga) are observed to be devastated by heavy localized rainfall/cloudbursts and associated flash floods (Khanduri, 2018a).

Localized heavy rainfall was observed in the areas around Mangti and Malpa in Pithoragarh district in the night of 13 August as also in early hours of 14 August 2017, resulted in flash floods and toe erosion in the Simkhola and Malpa gads respectively, which eventually turned into a disaster (Khanduri et al., 2018a).

Similarly, on 17 July, 2018 around 2:30 am the cloudburst occurred at the Saptrishi Kund the origin of the Yamuna river. This event devastated the Yamnotri shrine as well as the swollen Yamuna river engulfed 5 shops at Janaki Chatti in Uttrakashi district. Similarly, on 18th August, 2019 Mori tehsil was hard hit by flash flood caused by cloudburst following excessive rainfall in the catchment of Khaneda Gad, a tributary of Pabbar River (Khanduri and Sajwan, 2019).

5.2. Debris flows

Debris flows travel long distances and may transport large amounts of debris in a short time span (Zimmermann and Haeberli, 1992). The common conditions for debris flow activity are steep slopes, loose materials and wet conditions (Lewin and Warburton, 1994). It is observed that the debris flows were the main cause of devastation in some of the previous cloudburst incidences in the region. Gadni, Musudiyar, Okhimath, Jhakhla-Lah, Bastari and Naulra are the evidences of the same.

In terms of human lives lost (69 persons) Okhimath tragedy of September, 2012 is thus the first biggest tragedy since the creation of the state. In the same event's heavy rainfall induced landslides and debris flows reportedly devastated Giriyagaon, Salami, Mangoli, Chunni, Premnagar, Brahmankholi and Jua Kimana villages around Okhimath. More than 70 residential houses were reported to be destroyed in these incidences that caused heavy loss of other infrastructure and facilities (DMMC, 2012a).

In the year 2013 Panjan and Bajira are observed to be devastated by cloudburst events while Taljaman, Senagarhsari, Sounda, Dhaunda, Udu, Barangali, Kimana and Khaduli are adversely affected (Khanduri et al., 2018b). Similarly, debris flow along the small nala due to cloudburst, dated 26 May, 2017, caused life of loss of 8 domestic animals and one house in Tatalgaon and Bijrani near Chaukhutia (Chauhan and Mehrotra, 2018).

The landslide, triggered by cloudburst on 18 August, 2009 resulted in massive debris flow along a stream channel. The same incidences wiped out 2 villages namely Jhakhla and Lah, claiming 43 lives (Sarkar and Kanungo, 2010).

Khanduri (2019) reported heavy rainfall amounting to 388 mm within 6 hours in the evening of 6 July, 2015 in Nainital town resulted heavy discharge along the drainages and a debris flow got initiated from around Cement House that is on the upslope of Everest and India hotels on the Mall Road. Water along with debris entered in the habitated area and also accumulated on the Mall road, it resulted vehicular traffic in the Mall road was disrupted.

5.3. Rock falls/slides

Landslides are one of the most devastating and recurring natural disasters and have affected several mountainous regions across the globe. As reflected in the global landslide dataset, most of the landslides in the Indian Himalayan region are rainfall triggered. In the context of the Indian Himalayas, during the same period, 580 landslides occurred with 477 triggered by rainfall, thereby contributing 14.52% of the global landslides (Pradhan et al., 2020).

On 17 August, 1998 a massive landslide following heavy rain and a cloudburst at Malpa area killed 221 people including 60 kailash Mansarovar pilgrims in Kali valley of the Kumaon Division, Uttarakhand (Paul et al., 2000). On the other hand, in the Madhyamaheswar valley of Okhimath area of Rudraprayag district heavy precipitation during the period of 9 to 12 and 17 to 19 August, 1998 caused landslides and rock falls that took a toll of, 103 people and wiped out 47 villages of the area (Naithani, 2001).

Additionally, between 17 and 18 September, 1880 heavy rainfall (838 mm) was recorded in Nainital city that triggered Sher-ka-Danda landslide and killing 151 people including 43 Europeans. Besides, old temple of goddess Naina Devi overran by the water saturated landslide debris (DMMC, 2011). Nandargi and Dhar (2011) reported that the heavy rain spell of 17-18 September, 1880 was associated with the passage of a recurving monsoon depression from the Bay of Bengal. The center of this rainstorm was at Nagina (Uttaranchal) which recorded 820mm of rainfall on 18 September, 1880.

The landslides killed about 220 peoples in the entire rainy season of 2010, while 65 lives were lost, 6 persons went missing, 21 people were injured, 84 livestock died, 534 houses were fully damaged and 2138 houses were partially damaged due to heavy precipitation within 4 days from 18 to 21 September, 2010 (Sati et al., 2011).

6. Conclusions

Cloudburst is an unusual phenomenon, when and in which area it will happen, it has not been possible to predict, particularly in the Uttarakhand mountainous region. High intensity rainfall of more than 100 mm/hour within a limited geographical area of a few square kilometers is defined as cloudburst. Abnormally high precipitation and cloudbursts had been common in the region often resulted in flash floods, debris flows and landslides. These inflicted massive losses of life, property, and infrastructure together with economic loss and environmental degradation.

Geologically, the Central Himalayan terrain of Uttarakhand falls in five litho-physiographic regions which are separated one and each other by major Thrust/Fault like THF, MCT, MBT and MFT. These major tectonic discontinuities make the rocks of the region highly fragile. The area is also seismically active and falls in both IV and V zones. In the past, the state has witnessed two major earthquakes of 1991 Uttarkashi and 1999 Chamoli.

Certain peculiar geomorphic features that include cirque, saddle and funnel shaped valleys and high relief difference together with land use as dense forest cover; especially that of oak (banj) and rhododendron (burans), and average altitude exceeding 1,400 meters are considered to provide favorable conditions for its occurrence. The cloudburst rarely triggers in the Higher Himalayan zone while the same are frequently occur in the Lesser Himalayan zone.

There is a considerable difference in the magnitude of the rainfall within a very short distance in the Himalayan mountainous region due to adverse topography. Because of limited amount of weather observatory, it is difficult to estimate how much rainfall must have occurred in that particular place.

Despite lack of well distributed network of meteorological observatories in the hills, large number of abnormally localized precipitation events, particularly those associated with human life loss and related devastation, are often dubbed as being cloudburst; particularly so by the media. Therefore, there is bound to remain controversy as to whether or not a particular event was cloudburst.

Mostly, the settlements are situated over overburden deposits such as glacial sediments, colluvium and river born materials in concentration of streams in the hills. Continuous downpour through the streams also increases sedimentation in them together with fast pace of erosion and destabilizing high inclines slopes in the form of debris and rock slides in fragile Himalayan region. Among these are responsible for damages and distractions in the same region.

In view of frequent occurrence to cloudbursts in the area, it is highly recommended that better land use practices must be adopted for future developmental initiatives so as to reduce the human and other losses as well as it is absolutely necessary to make people of the area aware from time to time. Apart from this, it is necessary to install an early warning system for the safety of the people who are already living in risk zones.

Last but not least, we have to give more emphasis to traditional practices of habitation so that the cloudburst associated damages in the future can be reduced. At the same time, we have to make people living in the hilly region aware of traditional practices. So that construction work in the future can be aligned with the geo-environment and the probability of damage is negligible.

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Conflicts of Interest
The author declares no conflict of interest.

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