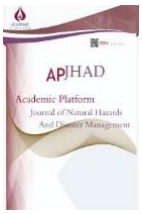

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Cloudbursts Strike over Foothills Himalaya of Uttarakhand, India: A Case Study from Maldeota, Dehradun District

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Abstract

The present study highlights the cloudburst issues that occurred in Raipur region of Maldeota area in Dehradun City. On the night of August 20, 2022, this area of Uttarakhand state capital Dehradun was lashed by high-intensity rainfalls or cloudbursts resulting in the water level of sub-watersheds of the Song river rising enormously, particularly Bandal *Nadi* and Song *Nadi*. Bhaiswar and Sarkhet villages which are situated on the Bandal valley came into the limelight due to loss of human lives and property. 5 people died while 3 people injured and 24 animals lost whereas about 8.25 hectares of agricultural fields were damaged and 12 families were rendered homeless in these incidences. Transport connectivity of the Sarkhet and adjoining areas have been disrupted due to roads being washed away at many places. Geologically, the devastated area is observed to be fragile due to its proximity to the Main Boundary Thrust (MBT) and subsequent Fault as well as its location to the Eastern fringe of the Mussoorie Syncline. It was also noticed that untraditionally ways of habitation patterns and economic opportunities due to increasing tourist inflow in the area are responsible for the enhanced devastating potential of disaster. The purpose of this research is to ascertain the actual causes and impacts of the disaster and the feasibility of rehabilitation land for homeless families. This work mainly concentrates on current risk scenarios that may be reflected in the future and suggestive measures to reduce its impacts within the area.

Key words: Causes, Debris flow, Flash food, Impacts, Lesser Himalaya, Risk mitigation

1. Introduction

In recent decades, extreme weather events like high-intensity rainfalls or cloudbursts have become more frequent worldwide that are attributable to climate change (1- 4). This led to flash floods in many countries causing huge loss of life, property and infrastructure along with geo-environment and economic damage (5-9). Human interference in the form of untraditional ways of habitation patterns and infrastructural developments over fan materials of the local streams and over alluvial terraces or low-laying areas of major streams are mainly responsible for the disaster. However, we always get information about such incidents/disasters from the local inhabitants of the area or media persons. At present, despite having sufficient resources, we are not able to accurately predict high-intensity rainfalls or cloudbursts. We still need to do in-depth research in this area to safeguard against the same in the future.

According to Indian Meteorological Department (IMD), downpour of 100 mm occurs within a shorter duration over an area of 20-30 sq. km, is defined as a cloudburst. Such events are

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unpredictable in nature because they are controlled by distinguished geomorphic and physiographic parameters and generally occur in elevation ranges from 1200 to 2200m in the hilly region (10). Most often, cloudbursts trigger over the higher reaches of Ist and IInd order streams, especially during the monsoon season in the early morning hours cause debris flows through local streams while flash floods through major streams. These observations were confirmed by analysis of 50 cloudburst events in the Upper Alaknanda Basin (11-12).

Uttarakhand, a Central Himalayan state located in the Indian subcontinent, consists of 13 districts, which is well known for its vulnerability to natural hazards such as landslides, earthquakes, floods, avalanches, glacial lake outburst floods and flash floods (13-16). In recent times, with changes in climate due to global warming across the world, the state regularly faces extreme events not only during monsoon, but also in pre-monsoon and post-monsoon periods. Analysis of last 52 years of data of heavy localized precipitation or cloudburst-like events in the state of Uttarakhand from 1970 to 2022 shows that the majority (31%) of such events occurred in the month of August, while 28% were recorded in the month of July and 11% recorded in September month. This was followed by 7%, 9% and 14% incidences that occurred in the months of May, June and October respectively (Figure 1). Mostly, such events were concentrated in Pithoragarh, Chamoli, Uttarkashi and Rudraprayag districts, while slightly fewer than those were observed in Bageshwar, Tehri and Pauri Garhwal districts and very few incidents were reported in Nainital, Almora, U.S. Nagar and Champawat districts (17-19).

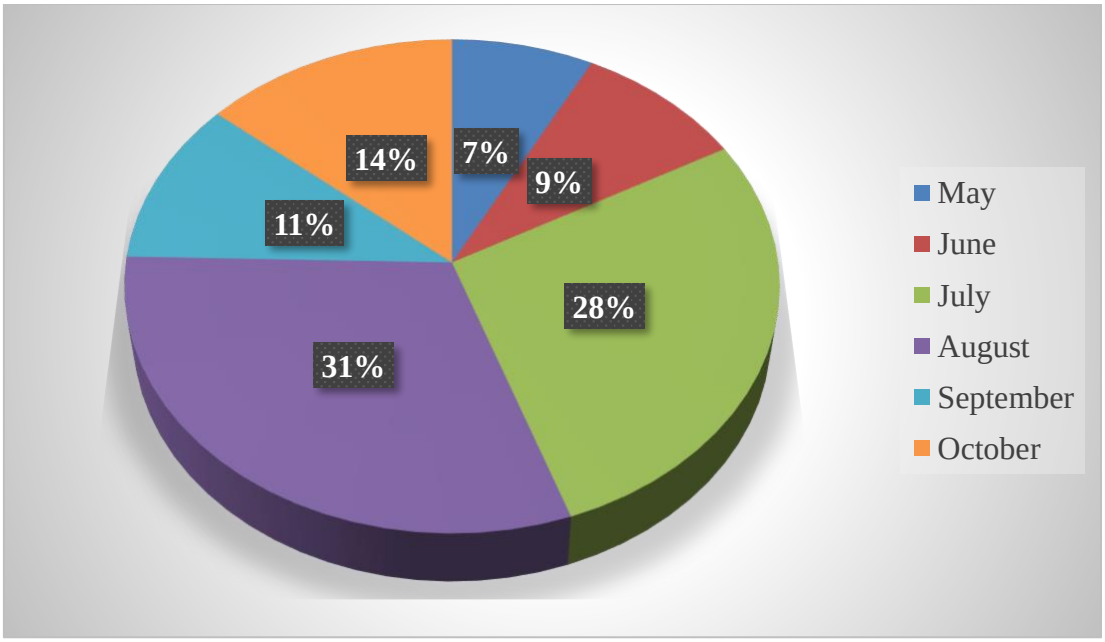

Figure 1. Month-wise percentage of heavy localized precipitation or cloudburst-like events from 1970 to 2022 in the state of Uttarakhand Himalayas (17-19)

In the last decade, high-intensity rainfall or cloudburst incidences have happened at various places in the state of Uttarakhand wherein killing more than 4000 people and destroying settlements together with huge economic and environmental damage. Losses incurred in these catastrophic events are confirmed by Table 1. This region received unusually high-intensity rainfalls between October 17 and 19, 2021, especially over Nainital, Champawat, Udham Singh Nagar, Pithoragarh, Bageshwar and Almora districts. This led to several landslides and flash floods causing loss of 72 lives (18). This makes it clear that high-intensity rainfall in October is a result of the impact of climate change.

Table 1. Losses incurred in heavy localized precipitation or cloudbursts ensured debris flows and flash floods in Uttarakhand (17-19)

Sl. No.	Year of occurrence	Incidence and human loss
1.	August 3, 2012	35 people died in flash flood caused by cloudburst in Asi Ganga, a tributary of Bhagirathi river in Uttarkashi district
2.	September 13, 2012	Cloudburst ensured debris flows in Okhimath town of Rudraprayag district, killing 69 people
3.	June 16 & 17, 2013	Cloudburst & GLOF ensured flash floods in Mandakini valley, killing 4127 people
4.	July 01, 2016	22 people died due to debris flows generated by cloudburst in Bastari and Naulra of Didihat tehsil in Pithoragarh district
5.	August 14, 2017	Excessive heavy rainfalls or cloudbursts ensured flash floods in the catchment areas of Kali river, especially Simkhola Gad and Malpa Gad respectively at Mangti and Malpa in Dharchula tehsil of Pithoragarh district, killing 27 persons
6.	August 18, 2019	21 people died around the Arakot in the flash flood caused by cloudbursts in Khaneda Gad, a tributary of Pabber river in Mori tehsil of Uttarkashi district
7.	July 20, 2020	11 people died at Tanga Village due to cloudburst ensured debris flows in a Ist order stream in Pithoragarh district
8.	July 18, 2021	Extremely rainfalls or cloudbursts in Mando Gadhera, a tributary of Bhagirathi river, killing 4 people at Mando village in Uttarkashi district,
9.	August 27, 2021	A cloudburst like incidence took place in Jumma Gad, a tributary of Kali river, in which 7 people died at Jumma village in Dharchula tehsil of Pithoragarh district,
10.	August 20, 2022	Cloudburst ensured flash flood and debris flows in Bandal *Nadi* and its sub-watersheds at Sarkhet and Bhaiswar villages of Raipur region in Maldeota area of Dehradun district, resulting in death of 5 people

Earlier, on August 13, 2018, a rock fall/slide triggered on a local stream, a tributary of Bandal *Nadi* that blocked its course for 7 hours creating a lake dimension of 150 m long and 40 m with 3-5m deep at Timli sain *tok* of Lwarkha village in Tehri Garhwal district. Initially, this incidence created panic in downstream settlements, but after 7 hours lake water gushed out through a detached rock mass and drained normally (20).

Except that, on February 7, 2021, 204 people died in the flash flood of Rishiganga and Dhauli Ganga during winter season in Chamoli district of Uttarakhand, which attracted worldwide attention (21). Subsequently, Joshimath town in Chamoli district also faced serious land subsidence in August 2022, due to which some property and infrastructure were seriously affected, while in January 2023, more than 500 houses were severely damaged, which again attracted worldwide attention (22-23). Due to the accelerate subsidence, 81 ground cracks were recorded and the highest number of ground cracks were observed in Manohar Bagh and Singdhar areas along with damage to civil structures in the same localities. The vertical settlements of giant boulders results from removal of fine materials embedded with the same due to the piping of subsurface water flows (24).

Recently on August 20, 2022, high-intensity rainfall or cloudburst-like incidences occurred in the upper catchment of Song river, particularly in the Bandal *Nadi*. Sarkhet and Bhaiswar villages situated over the fan materials of IInd order streams, a tributary of Bandal *Nadi*, were badly affected due to water-saturated debris flows in the same, killing 5 people. Additionally, flash floods through the Bandal *Nadi* caused devastation across the valley, wherein several property and infrastructure were badly damaged and some of those wiped out.

In view of high damage in Bandal valley, this area has been taken up for the present study. The main objectives of the study area include (i) to delineate geological and geomorphological influences in the devastated area; (ii) identifying places where damage to property and infrastructure has occurred; (iii) to demarcate the places where streams have changed their course, (iv) feasibility of rehabilitation land for homeless families of Sarkhet and Bhaiswar villages, (v) to find out the actual causes of damage and distraction, and (vi) assessment of current risk scenario which may be reflected in future and suggested measures to mitigate future impacts.

2. Materials and Methods

2.1. Study Area

Dehradun district is situated in the northwestern corner of Uttarakhand and covers an area of 3088 sq.km at an altitude of 640 m above mean sea level. The district is bounded by Uttarkashi district on the North, Tehri Garhwal and Pauri Garhwal districts on the East, Saharanpur district (UP) in the South and its southern tip touches the border of district Haridwar. Its western border connects to Sirmour district of Himachal Pradesh which is separated by Tons and Yamuna rivers. According to Seismic Zoning Map of India, this area falls in Zone-IV (25).

Delhi, the capital of India is located about 235 km from Dehradun city. Moreover, the famous hill station of tourist destination Mussoorie is situated just 30 km from Dehradun. Dehradun district consists of six Development Blocks as Chakrata, Kalsi, Vikasnagar, Sahaspur, Raipur and Doiwala. The district is well connected to all major cities of North India by rail, road network and airways. The nearest airport is Jolly Grant which is located about 24 km from this City.

The climate of Dehradun is more temperate and humid than the surrounding districts. Not only at higher altitudes in this region, but even in Dehradun during winter the temperature drops below the freezing point and reaches 40°C in Summer. Higher mountains are covered with snow during the winter. The total annual rainfall is about 1800 mm, most of which occurs in the months of July- August. Within the limits of the district are the high peaks of the Outer Himalayas as well as the Doon valley, whose climatic conditions are almost similar to those of the plains.

The devastated Bandal *Nadi* comes under Survey of India Toposheet No. 53 J/3 and is located in the North of the Raipur area (Figure 2). This area was devastated by flash floods associated with high-intensity rainfalls or cloudbursts on August 20, 2022. The devastated Bhaiswar village is situated on the right bank of the southwesterly flowing Bandal *Nadi* and is about 10km from Raipur town on Maldeota-Dhanolti motor road. The habitation of this village is placed on fan materials of southerly flowing Musniwala *Nallah* which is a IInd order seasonal stream, a small tributary of Bandal *Nadi* in the area. Another devastated Sarkhet village is also situated on a IInd order seasonal stream and is around 3 km downstream of Bhaiswar village on the right

bank of Bandal *Nadi*. 10 families from Sarkhet village and 2 families from Bhaiswar village, a total of 12 families were rendered homeless due to the destructive debris flows into these streams. Rehabilitation land whose feasibility has been done, is located southwest of Sarkhet village at a distance of about 4 km from the PPCL mine area on the Silla-Kyara motor road.

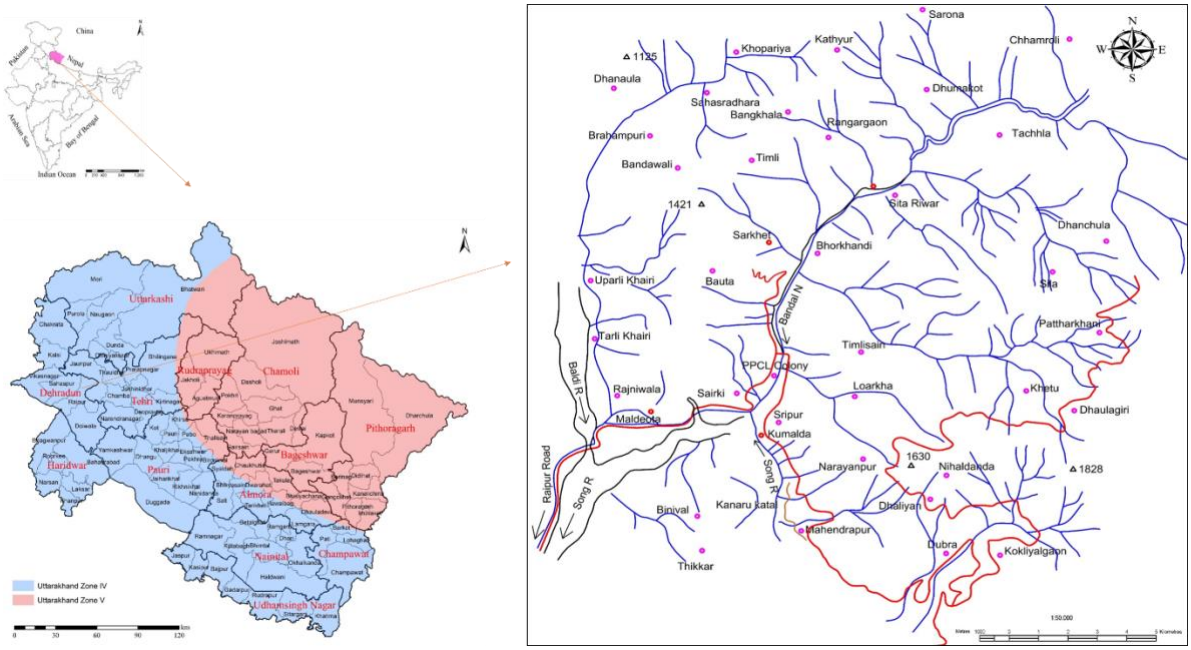

Figure 2. Location map of the study area. On the left side, Uttarakhand map shows earthquake zones (25)

2.2. Data and Approach

A detailed ground investigation has been conducted in the study area to ascertain the actual causes of damage, such as morphometric changes, affected settlements and infrastructures. Feasibility of rehabilitation land has also been verified through on-site inspection. Geological and tectonic inferences are updated based on previous records and ground truth.

I. Survey of India toposheet No. 53 J/3 at a scale of 1:50000 has been utilized for understanding physical factors of the area, such as slope, drainage, elevation and topography and also utilizing for preparing location map of the devastated area.
II. Handheld Global Positioning System (GPS) has been used for precise geolocation of morphometric changes and damage to property and infrastructure.
III. Google Earth Pro satellite image has been utilized to measure distances of locations where changes in stream course have occurred.
IV. ArcMap 10.5 and AutoCAD 15 software were used to prepare thematic maps of the study area.

3. Geological Setting

Geologically, a sequence of sandstone and mudstone of the Siwaliks mountain range of the Outer Himalayas are observed in the devastated area which has juxtaposed along the northeast dipping Main Boundary Thrust (MBT) along with the sequence of phyllite and quartzite of the Lesser Himalayan mountains. This metamorphic succession of the Jaunsar Group comprising the Chandpur and Nagthat formations is overlain by a large unconformity by the sedimentary succession of the Blaini, Krol and Tal formations of the Mussoorie Group. Rocks comprise

quartzite, shale, slate, phyllite, siltstone, dolomitic limestone/limestone, diamictite, conglomerate etc. (26-29). The MBT is disrupted by the presence of the N-S trending Baldi-Song Fault near Raipur area (29).

The rocks of 'Mussoorie Syncline' are folded into a doubly plunging syncline, with its axis trending in general NW-SE direction in the form of several culminations and depressions are also noticed in the devastated area. Sedimentation pattern is often interpreted as evidence of the progressive rise of the Himalayas and recent onset of tectonism along the MBT (30-31). The greater part of the valley area is occupied by the Dehradun and Bhogpur fans in the South (32), deposited by the rivers flowing from Lesser Himalaya and influenced by the activity of MBT and associated faults. The lithostratigraphic succession of the area is given in Table 2.

Table 2. Lithostratigraphic succession of the devastated region (26-29)

Group	Formations	Lithology	Age
Mussoorie	Tal	Quartzite, phosphoritic pyriterous shale/slate, chert and siltstone	Cambrian
	Krol	Dolomitic limestone/Limestone with interbedded shale	Neoproterozoic
	Balini	Diamictite, conglomerate, Slate and boulder bed	
Jaunsar	Nagthat	Quartzite, shale, phyllite and conglomerate	Paleoproterozoic
	----------Unconformity----------		
	Chandpur	Phyllite, dolomite with basic intrusives	
---------- Main Boundary Thrust(MBT) ----------			
Upper Siwaliks	Boulder conglomerate	Coarse boulders, conglomerates with friable sandstone and clay	Late Pliocene to Early Pleistocene
Older Alluvium	Doon Gravels	Brown silt, clay, sand, pebble and boulders	Middle to late Pleistocene
Newer Alluvium	Channel Alluvium	Grey Sand, silt and clay	Holocene

4. Geomorphology and Physiography

Dehradun is an intermontane longitudinal tectonic synclinal basin bounded by Faults and is delimited by Main Boundary Thrust (MBT) in the North (26, 30, 33-36). The Ganga River demarcates its eastern boundary which flows along NE-SW trending Ganga Tear Fault, while the Yamuna River flowing along N-S oriented Yamuna Tear Fault limits its extension in the west and the southern boundary, demarcated by Himalayan Frontal Thrust (HFT).

Physiographically, the devastated area represents the high rugged mountainous terrain of Lesser Himalayas in the North, with U & V-shaped valleys and high rising steeply sloping hill ranges, while the Piedoment fans and Doon Valley lie in the southern part. Longitudinal ridges, transverse ridges and intermittent deeply dissected valleys are common features of this region. The Doon Valley is a synclinal depression between the Lesser Himalayan terrain in the North and Sub-Himalayas in the South. Aligned parallel to general trends of the Himalayas, it is a veritable intermontane valley, the floor of which is filled with thick detritus shed from overlooking hill slopes.

The southerly flowing Song river forms the main drainage in the region and is joined by its major tributaries Bandal *Nadi*, Song *Nadi* and Baldi River. Bandal *Nadi*, affected by flash floods, originates from the Sidh-Ki-Dhar (2519 m) of Dhanaulti in Mussoorie region. Initially, it flows from NW- SE direction which turns near the Bharmakhal, after that it flows from NE – SW direction and joins the northwest flowing Song *Nadi* at Kumalda village (745 m). Thereafter, the Song river flows in approximately E-W direction and meets the southern flowing Baldi river at Asthal, and ultimately becomes known as the Song river. The overall drainage pattern of the area is dendritic. The Baldi and Bandal sub-watersheds are semi-circular in nature and the area is characterized by high to moderate relief and the drainage system is structurally controlled (37).

4.1. Morphometric Changes

Alluvial terraces were observed at Dhantu Sera, Bhaiswar, Sarkhet, Maldeota, and Kumalda whereas fan material of seasonal streams was also observed, especially at Sarkhet and Bhaiswar villages in Bandal *Nadi* valley during the field visit. On August 20, 2022, high-intensity rainfalls or cloudbursts resulted in high sediment leaden discharge in Bandal *Nadi* along with its all tributaries, causing extensive damage in the areas where these materials resided. Alluvial terraces along the Bandal *Nadi* were also severely eroded resulting in agricultural fields together with property and infrastructure being badly damaged or destroyed. Due to severe bank erosion, Bandal *Nadi* has significantly changed its course at many places and has widened its channel. Details of the places where the stream changed its course are tabulated in Table 3.

Table 3. Details of the places where the stream has changed its course

S. No.	Stream	Location	Change in stream course (in meters)	Change in stream bank (Left/Right)
1.	Bandal *Nadi*	Dhantu Sera	13-18	Left Bank
2.		Between Bhaiswar and Dhantu Sera	20-35	Right Bank
3.		Sarkhet	10-15	Right Bank
4.		Opposite Granny's Den Resort	6-12	Right Bank
5.		Doon Defence College area	18-35	Left Bank
6.		Red Bridge/Laal Pull	10-16	Right bank
7.		At Kumalda	8-18	Left Bank
8.	Song River	Four Banyan Spirits and Nature Resorts	15-55	Right Bank

4.2. Losses and Damages

Raipur region of Maldeota area received extremely heavy rainfall during the late night of August 19, 2022 and early morning of August 20, 2022, due to which the water level of the tributaries of Song River, particularly the waters of Bandal *Nadi* and Song *Nadi* to rise as much as 3-4m above the danger level. This led to erosion of its banks resulting in widespread devastation in the area. Numbers of property and infrastructure were severely damaged at Sarkhet, Bhaiswar, Sairki, Chhamroli and Maldeota areas, while some of these were washed away in flash flood and debris flow incidences.

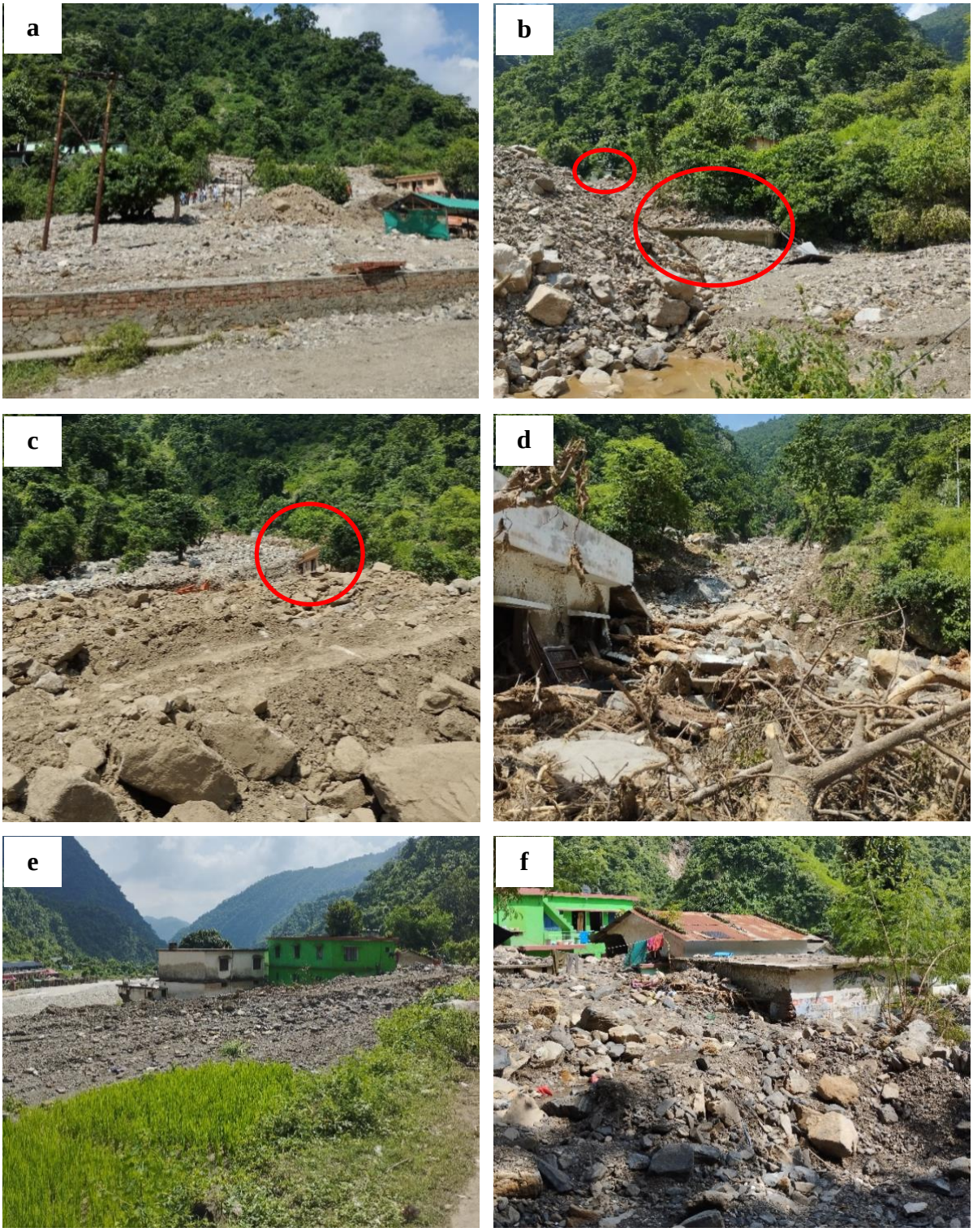

Figure 3. Photographs illustrate the devastated Bhaiswar and Sarkhet villages after heavy rainfall or cloudburst ensured debris flows; (a) accumulated debris in front of Musniwaa *Nallah* at Bhaiswar, (b) houses covered with debris at Bhaiswar, (c) Badly hit a house located at the course of Musniwala *Nallah* at Bhaiswar, (d) severely damaged a house due to change in course of Mushniwala *Nallah* at Bhaiswar, (e) overran agriculture fields and damage to houses in front of the local stream at Sarkhet village, and (f) public and private properties covered with debris of local stream at Sarkhet village

Additionally, about 10-15m outside the left abutment of a motorable RCC bridge leading to Raipur- Thano beyond Sports College near Raipur was destroyed by flood waters of Song River. Due to this, connectivity between the two areas was disrupted. Losses and damages including expected economic loss incurred in the affected region of Dehradun are given in Table 4.

4.3. Debris Flow and Flash Flood Incidences

According to eyewitnesses, high-intensity rainfalls coupled with thunderstorms caused debris flows through seasonal streams and flash floods in Bandal *Nadi*, causing considerable damage and destruction in the area. This is confirmed by the data of the automatic weather station of the Indian Meteorological Department (IMD) established in the Raipur area (38). Incident-wise details of damage incurred at various places along the Bandal *Nadi* and Song river are given in Table 4.

Table 4. Losses and damages including expected economic losses incurred in the affected region of Dehradun (Source: District Disaster Management Authority, Dehradun)

Sl. No.	Details of loss and damage	Expected economic loss (in lakhs)
1.	06 Tents at Four Banyan Resort in Maldeota	6.0
2.	25 houses damaged in Sarkhet	50.0
3.	Panchayat Ghar damaged in Sarkhet	10.0
4.	Primary School damaged in Sarkhet	12.0
5.	Damage to 6 Shops in Sarkhet	10.0
6.	Damage to 3.5 km electric line and about 20 electric poles along with 2 transformers in Maldeota to Sairki, Sarkhet and Saura Saroli	30.0
7.	A Bridge was damaged near Saura Saroli in Raipur area	200.0
8.	A Bridge damaged in Maldeota near Raipur	60.0
9.	Around 10-15 m part of the Bridge was destroyed beyond the sports college Raipur near in Song river	150.0
10.	a). 5 people killed while 3 persons injured along Musniwala *Nallah* due to cloudburst associated debris flows in Bhaiswar village b). damage to 01 house and 01 shops	12.0
11.	10 animals, 4 Calfs and 10 Goats died in Village Chhamroli/Sarkhet	5.20
12.	Around 8.25 ha of agricultural fields were damaged in Villages like Timli Man Singh, Sarkhet, Bhaiswar, Shairki, Chhamroli and Maldeota	200.00
13.	Damage to water lines in villages like Timli Man Sing, Sarkhet and Sairki	485.0

In the early hours (around 0215 hrs) of August 20, 2022, high-intensity rainfalls or cloudbursts-like events occurred in the upper reaches of Musniwala *Nallah*, causing high sediment leaden discharge that generated sufficient momentum to devastate the Bhaiswar village, which is situated in front of its driveway. After water-saturated debris entered the village, bifurcating of *Nallah* into two channels. These materials flow down at high speed along moderate to gentle slopes through these channels resulting in massive damage to property and infrastructure. Many agricultural fields were destroyed while houses and shops were badly hit and some houses were covered with debris in this incidence (Figs. 4a to 4d). As many as 5 people died while 3 people injured in the same incidence.

Another debris flows through a seasonal stream took place at Sarkhet village following high-intensity rainfalls or cloudbursts in the morning hours (around 0215 hrs). This village is situated on the right bank of Bandal *Nadi* about 2km downstream of the Bhaiswar village. It was observed that the village lies on the cone/fan material of a IInd order stream flows southeasterly direction and partly on the terrace material of the Bandal *Nadi*. A huge amount of water-saturated debris came down through this stream, causing widespread damage in the village. Connectivity of the region was disrupted and many houses were directly hit, while some were left under debris as well as agricultural fields overrun (Figs. 4e & 4f). Apart from this, the Panchayat Ghar along with Primary School also suffered heavy damage in this incidence.

Flash floods occurred through the Bandal *Nadi* following extremely heavy localised rainfall or cloudburst events. Unusually high sediment-laden discharge of the Bandal *Nadi* has eroded the terrace material on its both banks across the valley. Extensive property damages have occurred, particularly on the left bank of Dhantu Sera, east of Bauta on the right bank, at Kumalda on the left bank and just downstream of the confluence of Bandal *Nadi* and Song river on the right bank (Figs. 5a to 5d). The transport sector was also badly hit by flash food incidences, with about 500 m stretch of road between Dhantu Sera and Bhaiswar villages and around 50m-100m stretch of road between Sarkhet and Bhaiswar villages located on the right bank of Bandal *Nadi* were completely damaged (Figs 5e & 5f). Additionally, the road just downstream to the confluence of Bandal *Nadi* and Song river was also blocked, disrupting the connectivity in the devastated area.

5. Results and Discussion

High-intensity rainfalls in short periods or cloudburst events have resulted in the flow of water-saturated bouldery debris through local streams on which fan materials Bhaiswar and Sarkhet villages are located, causing damage to several properties and killing 5 people while 12 families were rendered homeless. Similarly, Bastari village of Pithoragarh district (2016), Okhimath town of Rudraprayag district (2012), Jhakhla and Lah of Pithoragarh district (2009), Gadni and Musudiyar of Chamoli district (1993) were badly affected by cloudbursts ensured debris flows in the past wherein killing 148 people (17).

Geologically, the devastated area has folded belt and tectonically controlled valley, due to which the rocks of the area are highly fragile in nature. High-intensity rainfalls ensured flash flood and debris flow events, leading to rapid erosion of weak rocks and slope materials resulting in aggradation at various places along the Bandal *Nadi*. This caused changes in the course of Bandal *Nadi* at various places, particularly at Dhantu Sera, Bhiaswar, Sarkhet, Kumalda and downstream areas wherein damage to agriculture fields, public transport, electricity, drinking water lines together with public and private properties. Earlier, Sangamchatti washed away and Gangori village was severely eroded in the Asi Ganga flash flood of 2012 (39) while the flash floods of June 2013 in the Mandakini river valley badly affected Kedarnath, Gaurikund, Chandrapuri, Augustmuni and Tilwara towns (17). In these incidences 35 and 4127 people were killed respectively.

From the geomorphological point of view, the habitation pattern of the devastated area is not found suitable, as most of the habitations are located near the stream and confluence areas in Quaternary deposits. Heavily concentrated rainfalls ensured debris flows and flash floods caused damage and destruction in these areas. As we all know that course of the stream keeps changing that surely hit its banks on which alluvium, colluvium and weak rocks exposure are placed. It is therefore recommended that houses should be constructed at a minimum distance

of 20-30m from small streams, whereas in the case of major streams, it should be 50-100m depending on site-specific conditions. In case of rock exposures distance may be less while in case of overburden material distance should be maximum from the stream/river.

Figure 4. Flash flood damages in both the banks of Bandal *Nadi*; (a) Damage to habitation of Dhantu Sera on the left bank, (b) damage to a building located East of Bouta at right bank, (c) Houses damaged at village Kumalda on the left bank, (d) damage to Four Banyans Spirit & Nature Resort downstream of the confluence of Bandal *Nadi* & Song *Nadi*, (e) washed away road on the right bank between Dhantu Sera and Bhaiswar villages, and (f) wiped out road between Sarkhet and Bhiaswar area on the right bank

The devastated area known as Maldeota, is one of the famous picnic spots of Dehradun city, which is visited by a large number of locals and outside people throughout the year. Due to increasing influx of tourists in the area, the hotel and shop facilities have been developed along the river banks. The concentration of economic opportunities near streams is largely responsible for increasing the risk of flash floods in the area. It has to be remembered that the stream is bound to reclaim its channel and both rise and fall of water level are processes which operate in all stream systems, hence any stream channel is vulnerable to encroachment in its regime. Therefore, it is recommended that any kind of construction activities in proximity of streams be prohibited in the area. Provisions of the Uttarakhand Flood Plain Zoning Act, 2012 should be invoked for doing so, in addition to those provided in Disaster Management Act, 2005.

The rehabilitation land is surrounded by a small stream in its North proximity which flows western direction in the area. Thickly bedded dolomitic limestone with intercalation of thin shale bands is observed in the proposed area, where the thickness of overburden including weathered rock is <1 m. The bedding planes were observed to dip in Northeasterly direction at angles varying from 40° to 50°. The joint sets were observed to dip at steep angles towards SE and SW (85°/ 170° and 60°/220°). Geologically, the proposed land was found to be feasible for rehabilitation purposes with proper due care of domestic waste-water as well as rainwater management.

6. Conclusions

High-intensity rainfalls ensured flash floods and debris flows caused considerable damage and destruction in the area. These caused death of 5 people and rendered 12 families homeless along with there was also damage to property and infrastructure. Bandal *Nadi* has changed its course and shifted towards the right and left banks by approximately 6 to 35 meters while Song river changed its course up to 50 meters due to flash floods. In this order, rehabilitation of those homeless families has been done as per Uttarakhand Rehabilitation Policy 2021. Besides, taking note of high damage in the devastated area, the author has made the following recommendations for managing the risk: (1) regulations of any kind of construction activities in proximity to stream/river, (2) prohibited construction in areas that were already affected in the flash flood and debris flow events, (3) reconstruction of the damaged stretch of road away from the river bed or elevated road from present high flood level, (4) avoiding excavation of river materials from river bed and *Nadi*/River training, especially where settlement poses risks, (5) implement structural measures in key zones, and (6) conducting disaster risk awareness campaigns among local residents and sharing indigenous knowledge about traditional habitation patterns with them.

As we all know that in recent times the incidents of cloudbursts have increased across the world due to climate change. The unpredictable nature of cloudburst is a cause of concern for planners and researchers. To address this issue, World Meteorological Organization (WMO) has developed the flash flood guidance system with global coverage (FFGS) which covers over 40% of the global population in more than 72 countries (40). This system aims to reduce the impacts of flash floods by enhancing early warning capabilities at regional and national levels. In this order, commissioning South Asia Flash Flood Guidance System for South Asian countries (India, Nepal, Bangladesh and Sri Lanka) on October 23, 2020 wherein India Meteorological Department is recognized as its regional Centre by WMO. In this context, preparations are being made to establish an early warning systems in the state of Uttarakhand as well. There is an urgent need for provision of early warning systems even at the local level, especially in areas identified with high risk of flash floods associated with high-intensity rains.

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Conflict of Interest

The author declares that he has no conflict of interest in this work.

Author Contributions

SK contributed to the design and implementation of the research, to the analysis of the results and to the writing of the manuscript.

References

[1] Furtak, K., & Wolinska, A. (2023). The impact of extreme events as a consequence of climate change on the Soil moisture and on the quality of the soil environment and agriculture- A review. Catena, 231, 1-15.

[2] Sati, V.P., & Kumar, S. (2022). Environmental and economic impact of cloudburst-triggered debris flows and flash floods in Uttarakhand Himalaya: a case study. Geoenvironmental Disasters, 9(5), 1-11.

[3] Vijaykumar, P., Abhilash, S., Sreenath, A.V., Athira, U.N., Mohanakumar K., Mapes, B.E., Chakrapani, B., Sahai, A.K., Niyas, T.N., & Sreejith, O.P. (2021). Kerala floods in consecutive years - Its association with mesoscale cloudburst and structural changes in monsoon clouds over the west coast of India. Weather and Climate Extremes, 33, 1-14.

[4] Wang, X.J., Zhang, J.Y., Shahid, S., Guan, E.H., Wu, Y.X., Gao, J., & He, R.M. (2014). Adaptation to climate change impacts on water demand. Mitig. Adapt. Strat. G. L. https://doi.org/10.1007/s11027-014-9571-6.

[5] Li, Z., Gao, S., Chen, M., Gourley, J. J., Liu, C., Prein, A. F. & Hong, Y. (2022). The conterminous United States are projected to become more prone to flash floods in a high-end emissions scenario. Communications earth and environment, 86(3), 1-9.

[6] Yang, Q., Liu, T., Zhai, J. & Wang, X. (2021). Numerical Investigation of a Flash flood process that occurred in Zhongdu river, Sichuan, China. Frontiers in Earth Science, 9, 1-11.

[7] Ceribasi, G., & Ceyhunlu, A. I. (2021). Generation of 1D and 2D flood maps of Sakarya river passing through Geyve district of Sakarya city in Turkey. Natural Hazards, 105, 631-642.

[8] Abdelkareem, M., & Mansour, A. M. (2023). Risk assessment and management of vulnerable areas to flash flood hazards in arid regions using remote sensing and GIS-based knowledge-driven techniques. Natural Hazards, 117(3), 2269-2295.

[9] Umut, E. R. O. L., Kizmaz, Y., Özden, A., & Ceyhunlu, A. I. (2022). Evaluation of the Transportation Infrastructure Vulnerability in Kaynarca, Sakarya Basin from a Flood Spread Risk Perspective. Academic Platform Journal of Natural Hazards and Disaster Management, 3(1), 20-31.

[10] Asthana, A.K.L., & Asthana, H. (2014). Geomorphic Control of Cloud Bursts and Flash floods in Himalaya with Special Reference to Kedarnath Area of Uttarakhand, India. International Journal of Advancement in Earth and Environmental Sciences, 2(1), 16- 24.

[11] Khanduri, S. (2018). Landslide Distribution and Damages during 2013 Deluge: A Case Study of Chamoli District, Uttarakhand. Journal of Geography and Natural Disaster, 8(2), 1-10.

[12] Khanduri, S., Sajwan, K.S., Rawat, A., Dhyani, C., & Kapoor S. (2018). Disaster in Rudraprayag District of Uttarakhand Himalaya: A Special Emphasis on Geomorphic Changes and Slope Instability. Journal of Geography and Natural Disaster, 8(1), 1-9.

[13] Dikshit, A., Sarkar, R., Pradhan, B., Segoni, S., & Alamri, A. M. (2020). Rainfall induced landslides studies in Indian Himalayan region: A Critical review, Applied Sciences, 10, 2466, 1-24.

[14] Kansal, M.L., & Singh, S. (2022). Flood Management Issues in hilly region of Uttarakhand (India) under changing climate conditions. Water, 14, 1879, 1-24.

[15] Mandal, P., Prathigadapa, R., Srinivas, D., Saha, S., & Saha G. (2023). Evidence of structural segmentation of the Uttarakhand Himalaya and its implications for earthquake hazard. Scientific reports, 13, 2079, 1- 15.

[16] Siddique, T., Haris, P. M., & Pradhan, S. P. (2022). Unraveling the geological and meteorological interplay during the 2021 Chamoli disaster, India. Natural Hazards Research, 2, 75–83.

[17] Khanduri, S. (2020). Cloudbursts over Indian Sub-continent of Uttarakhand Himalaya: A Traditional Habitation Input from Bansoli, District- Chamoli, India. International Journal of Earth Sciences Knowledge and Applications, 2(2), 48-63.

[18] Khanduri, S. (2022). Disastrous events of 2021 in Uttarakhand Province of India: Causes, Consequences and Suggestions for Disaster Risk Reduction (DRR). International Journal of Earth Sciences Knowledge and Applications, 4(2), 178-188.

[19] Khanduri, S. (2022). Rain-induced Slope instability: Case study of Monsoon 2020 affected Villages in Pithoragarh District of Uttarakhand, India. International Journal of Earth Sciences Knowledge and Applications, 4(1), 1-18.

[20] Khanduri, S. (2021). Formation and failure of natural dams in Uttarakhand Himalaya: An observation from Lwarkha, Chamba Tehsil of Tehri Garhwal district, India. International Journal of Earth Sciences Knowledge and Applications, 3(1), 12-22.

[21] Khanduri, S. (2021). Flash flood struck Dhauliganga valley on February 7, 2021: A Case study of Chamoli district of Uttarakhand Himalaya in India. Academic Platform Journal of Natural Hazards and Disaster Management, 2(1), 1-15.

[22] Khanduri, S., Saklani, R. D., & Chetry, B. M. (2023). Increasing risk of silent disaster in Uttarakhand Himalaya: An example from Higher Himalaya. Journal of Disaster and Risk, 6(3), 870-889.

[23] Sundriyal, Y., Kumar, V., Chauhan, N., Kaushik, S., Ranjan, R., & Punia, M.K. (2023). Brief communication: The northwest Himalaya towns slipping towards potential disaster. Natural Hazards and Earth System Science, 23, 1425–1431.

[24] Bahuguna, H., Kaistha, M. K., Singh, B., Das, S., Ahmad, T., & Rana, H. (2023). Preliminary Report on the Recent Event of Ground Subsidence at Joshimath, District Chamoli, Uttarakhand. Geological Survey of India, Government of India, 52.

[25] Indian Standard (IS):1893, Part 1 (2002). Criteria for earthquake resistant design of structures, Bureau of Indian Standards, New Delhi.

[26] Auden, J.B. (1934). The geology of the Krol belt. Rec. Geol. Surv. India, 67, 357-454.

[27] Singh, A. K., Parkash B., Mohindra R., Thomas J. V., & Singvi, A. K. (2001). Quaternary alluvial fan sedimentation in the Dehradun Valley Piggyback Basin, NW-Himalaya, Basin Research, 13(4), 449-471.

[28] Valdiya, K. S. (1980). Geology of the Kumaun Lesser Himalaya. Wadia Institute of Himalayan Geology, Dehra Dun, India. 249.

[29] Thakur, V.C., Pandey, A.K., & Suresh, N. (2007). Late Quaternary–Holocene evolution of dun structure and the Himalayan Frontal fault zone of the Garhwal sub-Himalaya, NW India. Journal of Asian Earth Sciences, 29(2), 305-319.

[30] Gansser, A. (1964). Geology of the Himalayas. Interscience Publications. Wiley, London, New York, 298.

[31] Parkash, B., Sharma, R., & Roy, A. K. (1980). The Siwalik Group (Molasse) sedimentation shed by collision of continental plates. Sedimentary Geology, 25, 127-159.

[32] Singh, A. K., Parkash B., Mohindra R., Thomas J. V., & Singhvi, A. K. (2001). Quaternary alluvial fan sedimentation in the Dehradun Valley Piggyback Basin, NW-Himalaya. Basin Research, 13(4), 449-471.

[33] Nossin, J. J. (1971). Outline of the geomorphology of the Doon valley, northern U.P., India. Z. Geomorph. N.F. Suppl. Bd. 12. Berlin. Stuttgart, 18-50.

[34] Nakata, T. (1972). Geomorphic history and crustal movement of the foothills of the Himalaya. Scientific report, Tohoku University Japan, 7th Series (Geography), 22, 39-177.

[35] Rupke, N.A. (1975). Deposition of fine-grained sediments in the abyssal environment of the Algero-Balearic Basin, Western Mediterranean Sea.Sedimentology 22, 95–109.

[36] Philip, G. (1995). Active tectonics in Doon valley. Journal of Himalayan Geology, 6, 55-61.

[37] Pankaj, A. & Kumar, P. (2009). GIS-based Morphometric analysis of five major sub-waters of Song River, Dehradun District, Uttarakhand with Special reference to landslide incidences. J. Indian Soc. Remote Sens., 37, 157-166.

[38] Sain, K., Mehta, M., Kumar, V., Gupta, V. & Chauhan, P. (2023). A climate surdprise-Slope instability triggered by heavy rain in Maldevta region, Dehradun, Uttarakhand, on 20 August, 2022. Journal of Geological Society of India, 99, 317-320.

[39] Gupta V., Dobhal, D. P. & Vaideswaran, S. C. (2013). August 2012 cloudburst and subsequent flash flood in the Asi Ganga, a tributary of the Bhagirathi River, Garhwal Himalaya, India. Current Science, 105(2), 249-253.

[40] htpp://wmo.int/activities/flash-flood-guidance-system-global-coverage-ffgs