Journal of Geography and Natural Disasters

Khanduri, J Geogr Nat Disast 2018, 8:2
DOI: 10.4172/2167-0587.1000226

Research Article | Open Access

Landslide Distribution and Damages during 2013 Deluge: A Case Study of Chamoli District, Uttarakhand

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Received date: Feb 09, 2018; **Accepted date:** July 31, 2018; **Published date:** August 08, 2018

Abstract

In June 2013 multiple disaster involving flash flood and landslides struck many parts of Uttarakhand state. This caused massive devastation in the state on 16 and 17 June, 2013. In the present paper, attempt was made to analysis the landslide incidences and damages in Chamoli district. A total of 220 landslides were observed in the area. About 92% of slide occurred on northerly (48 percent) and southerly (43 percent) facing slopes. These may be subject to freeze-thaw and drier cycles. Heavy rainfall and low shear strength of the rocks have played a major role in facilitating these slides. Moreover, flooding, loose sediments, excavation of hill slopes and river side constructions are considerably responsible to carved out the disaster. The purpose of this study was to delineate the contributing factors of mass damages as to suggest disaster management strategies for the region.

Keywords: Heavy rain; Flood; Landslide; Damage; Chamoli; Future strategy; Badrinath; Garhwal Himalaya

Introduction

Landslide is generally understood as being downslope movement of rock mass, debris, soil and earth, with or without water, under the influence of gravity [1,2]. It includes both consolidated and unconsolidated material originating from a variety of geomorphic features due to natural and manmade causes. The definition makes it clear that relief is a precondition for any area to be affected by landslides and it is relief that is the must for identifying any area as being mountainous. Landslides are therefore characteristic feature of hilly or mountainous areas. Whatever the causative factors of landslides, about 90 percent are triggered during monsoon period while the rest take place during winter rains [3,4].

Though causing immense and recurring loss of human lives, infrastructure and property and often looked upon as curse for the hilly areas, landsliding is an important landform building process that promotes soil formation. Most habitations in the hills are situated on stabilized old landslides and over river borne materials terraces. With increasing population pressure and switch over to comfort preferring life style people increasingly prefer to settle down on these materials itself that in many cases is close to the road head and streams. Once instability is introduced in the hill slope it often becomes chronic and slope instability repeatedly take place at the same place.

Moreover construction of road in the hills involves change in slope geometry of the hill slope that induces instability in the mass to the upslope side of the road. Adequate measures are often not resorted to for countering this instability that makes the slopes vulnerable to landslides. Appropriate measures are at the same time not resorted to for ensuring safe and quick disposal of rainwater from the road surface. This often induces landslides in the hill slopes after road construction. Due care is at the same time not taken for the disposal of excavated material and prevalent practice of rolling down the same makes the area prone to landslides.

Uttarkashi, Chamoli, Rudraprayag, Bageshwar and Pithoragarh districts of Uttarakhand Himalaya have experienced worst forms of disaster in recent times. Of these, Chamoli district has a history of repeated natural disasters due to its geological, structural and climatic condition. There are many instances in the recent past when these catastrophes caused heavy losses to human live and property. These include Earthquake of 1803 damage in Badrinath temple [5], landslide blocked the Birahi ganga in 1868 [6], breached of Rishi Ganga artificial lake in 1970 [7], bursting of Patal ganga lake in 1970 [8], flash flood of Birahi in 1970 [9], natural hazards around Gopeshwar in 1991 [10], cloudbursts at Bhimtala and Chamoli in 1995 [11], Alaknanda flood in 1995 and Chamoli earthquake in 1999 [12], cloudbursts and landslides near Badrinath in 2004, debris flows through local nala near Govindghat in 2005 and landslides in 2010 [13].

The Garhwal and Kumaun divisions of Uttarakhand state, experienced abnormally heavy precipitation during June, 2013. It has been observed that the increased amount of rainfall drained the catchments of Alaknanda, Mandakini, Bhagirathi, Pinder and Kali rivers and their tributaries [14,15]. The impact of deluge of June 2013 was extraordinarily violent and it caused heavy loss of human lives, infrastructure and property. It has been observed that the increased amount of rainfall drained the catchments of Alaknanda river and its tributaries. This sudden increase in sediments laden discharge resulted high flood water washed away almost everything falling across its routes. Alaknanda valley in Chamoli district that houses the highly revered holy Hindu shrine of Lord Vishnu at Badrinath, was the most adversely affected.

Besides flash floods, heavy and continuous rains in the area induced slope instability and triggered massive mass movements in the area. Total of 220 landslide incidences together with 30 heavy localized rainfall/cloudbursts induced debris flows have been observed in the area around the study on the aftermath of the disaster. Geomorphic and field observations show the presence of a number of tectonic

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contacts that have rendered the area prone to landslides. The area is also falls in the high seismic Zones V of the Indian Seismic Code [16].

The author carried out field work for preliminary slope stability assessment in the area. This study is largely based upon the observations made during the fieldwork undertaken in the area in year 2013 and 2014.

Study area

Present study covers Chamoli district that fall in Lesser and Higher Himalaya and is bounded by Latitude N 29° 15' 00" and 31° 00' 00" and Longitude E 79° 15' 00" and 80° 00' 00" and falls in Survey of India toposheet numbers 53 O, M and N (Figure 1). Apart from Alaknanda, Pinder is the major river draining this area and has confluence with the former at Karanprayag. The geographical area of the district is 7,604 square kilometers. It is the second largest district of Uttarakhand and is also important from strategic point of view as it shares its northern boundary with Tibet (China).

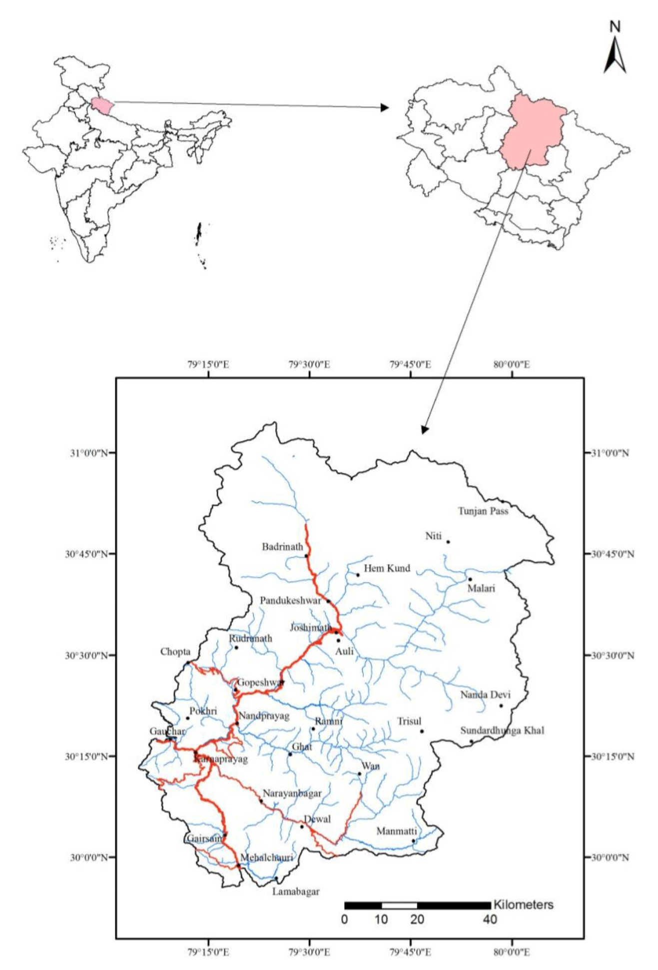

Figure 1: Location map.

District headquarter is situated at Gopeshwar around 10 kilometers west of Chamoli town and being strategically important is well connected by Rishikesh – Badrinath national highway (NH 58). Rishikesh is the nearest rail head while located in close proximity of Dehradun, the capital of Uttarakhand state, Jolly Grant is the airport. Besides, nearest airport is at Gauchar in the area.

Shri Badrinath temple is one of the four Char Dham pilgrimage sites located along the right bank of Alaknanda river at an elevation of 3,133 m above the mean sea level (amsl). The temple is dedicated to Lord Vishnu and is one of the most visited pilgrimage centers of India. Shri Hemkunt Sahib (4632 m amsl) is also one of the most famous pilgrimage site of Sikh community situated in the study area.

Administratively the district is divided into ten tehsils namely, Joshimath, Chamoli, Karnaprayag, Pokhari, Gairsain, Tharali, Narayanbagar, Jilasu, Adibadri and Ghat. The total population of the district is 391,605 out of the male and female populations are 193,991 and 197,614, respectively. The population density is 49 persons per square kilometers and the male, female sex ratio is 1000:1019. The average literacy rate is 82.65% of which male and female literacy rate are 93.40 and 72.32, respectively [17].

Methodology and Tools

Survey of India toposheets no. 53 O, M, N on the scale of 1:50000 have been use to prepare the base map of the area. With the help of Survey of India toposheets and Handset Global Positioning System (GPS), location of landslides along with debris flows, overburden materials and damages were confirmed in the field. Thematic maps of geology, overburden materials and landslide and cloudburst distribution have been prepared using Geographical Information System (GIS) software (Arc View 9.3).

Geomorphology and physiography

The topography of the Chamoli region is highly precipitous, consisting of series of peaks as Nandadevi (7816 m), Kamet (7756 m), Chaukhamba (7138 m), Trishul (7120 m), Dunagiri (7066 m), Nandakot (6861 m), Hathiparvat (6727 m), Neelkanth (6596 m), Mana (5545) etc. The slopes of these peaks are covered with glaciers and separated by the traverse, deep, narrow gorges of Alaknanda, Saraswati, Dhauli Ganga, Birhi Ganga, Rishi Ganga, Kail, Pindar, Nandakini etc. rivers.

Glaciers, horned peaks, cirques, hanging valley etc., sculpture this zone. The morainic materials occupy the valleys areas. The prevalent landforms are lateral moraines, end moraines, U-shaped glacier valleys, V-shaped fluvial valleys, river terraces and Denudational Structural Mountain. This region is prone to landslides due to high relief, presence of overburden and high precipitation.

The Alaknanda river is the main river in the area which originates from Satopanth-Bhagirat Kharak Group of glaciers. The river initially has a West-East course before meeting Saraswati river at Keshav prayag near Mana village at the north of Badrinath Shrine and further it flows almost North-South. Downstream major tributaries as Khiro Ganga join it below the Badrinath shrine at Benakuli, Bhuindar Ganga meets at Govindghat and Dhauli Ganga meets at Vishnuprayag above Joshimath. Downstream small tributaries as Kalpa Ganga, Garur Ganga, Patal Ganga and Birahi Ganga join the Alaknanda between Joshimath and Chamoli. Nandakini river joins it at Nandprayag. Southeast flowing, Pinder River joins the Alaknanda at Karanprayag.

Alaknanda river occupies an antecedent gorge, which is deep, narrow and sinuous. Towards upstream the narrow gorge becomes highly sinuous and the channel shows meandering. The valley becomes

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wide around Langasu, Nandaprayag and around Karnaprayag before confluence with Pinder River.

During the field investigations, most of the overburden materials have been identified and physically mapped with the help of respective Survey of India toposheets on 1:50,000 Scale (Figure 2). The glacial sediments are observed mostly up to Lambagar in Alaknanda while Bhapkund in Dhauli Ganga. Thick pile of river borne materials terraces are observed to be well developed around Langasu, Karanprayag, Gauchar and Nagrasu in Alaknadna catchment while Deval, Chepron, Tharali (Kedarbagar) and Simli in Pinder catchment. The observations make it clear that most devastation has taken place on these materials along the course of Alaknanda and Pinder rivers.

Flash floods of June 2013 have considerably changed the landscape and geo-environment of the area. Major change in landscape have been introduced in Lambagar, Govindghat, Bhuindar and Pulna in Alaknanda valley while Tharali and Narayanbagar in Pinder valley.

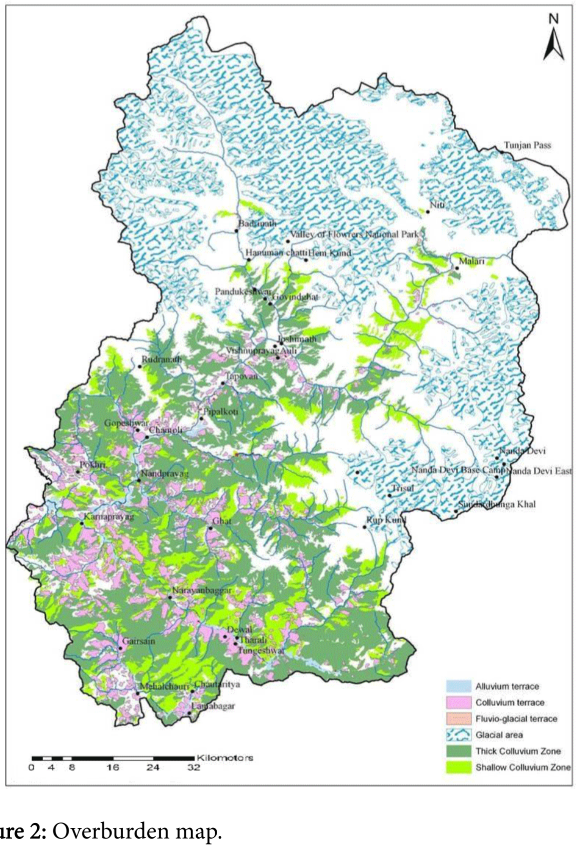

Figure 2: Overburden map.

Geology of the area

Two rock sequences are observed to be exposed in the area around Chamoli district; compressed between North Almora Thrust (NAT) and Main Central Thrust (MCT) constitutes the Lesser Himalayan meta-sedimentary zone, while that exposed to the north of MCT constitutes the Higher Himalayan metamorphic zone (Figure 3).

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 [18-20]. The main rock types observed in the area include kyanite gneiss, staurolite, quartzite, garnet and biotite schists of the Vaikrita Group while the low-grade metamorphism in green schist to amphibolite facies rocks of the Munsiari Formation.

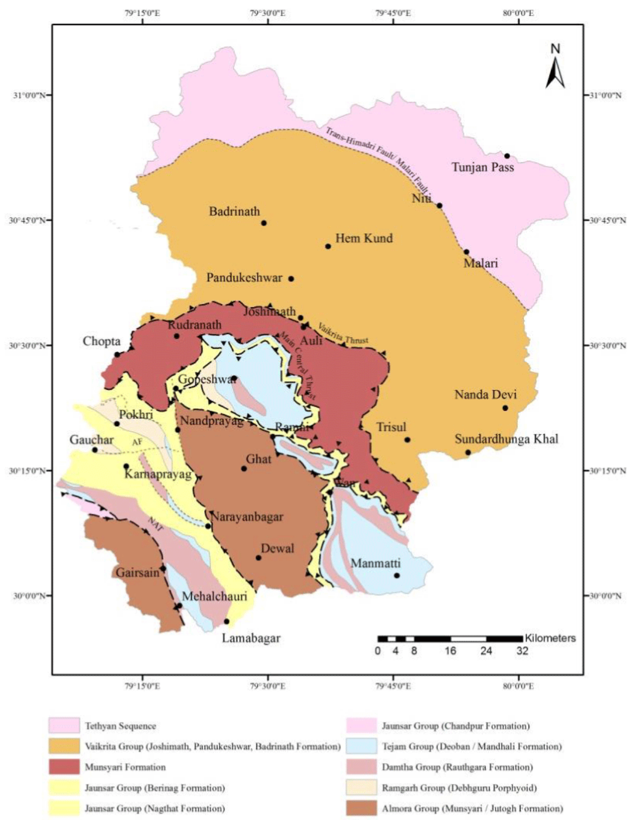

Figure 3: Geological map.

The Garhwal Group rocks of Lesser Himalaya are observed to comprise of low grade metasediments that are intruded by acidic and basic igneous rocks. These consist of thick succession of low grade metasediments made up of quartzite along with penecontemporaneous metabasics and carbonate rocks. The main rock types observed in the area include schistose quartzite, limestone, quartzite, slate, phyllite, granite and metabasics. Gawhwal Group of quartzites is observed to be exposed in the area around Chamoli and Karanprayag in the region.

Rocks exposed in the area around Manmati, Mehalchauri and Pipalkoti, are characterized by massive dolomitic limestone. This rock is observed to show shrinkage features.

Granites exposed in the northwest of Gauchar and north of Pokhri area are observed to be tourmaline and at places chlorite rich. These are the successions of the Debguru Porphyroid and Bahtwari unit. The volcanics are largely observed to be very course grained, non - foliated and generally porphyrytic.

The top of the Vaikrita Group is bounded by a normal Fault and the base of the zone by the Main Central Thrust. Many researchers [21,22] described it as a tectonic contact and named it as Trans-Himadri

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Thrust/ Fault (T-HF). The Tethyan sediments are exposed across this fault plane. These sediments are largely un-metamorphosed and occupy synclinal basins of the south of the famous Indus-Tsangpo Suture Zones. The lithotectonic succession of the study area is given in Table 1.

Tethyan Sedimentary Zone (TSZ)		**Tethyn Sequence**	**Shale, slate and limestone**
		Trans Himadri Fault/Malari Fault	
Higher Himalayan metamorphic zone	Vaikrita Group	Badrinath Formation	Calc-silicate rocks with sub-ordinate biotite-psammitic gneisses and schists, extensive intrusion of dykes and veins of pegmatite
		Pandukeshwar Formation	Massive garnet-kyanite bearing quartzite, schist and psammitic gneiss.
		Joshimath Formation	Coarse-grained kynite sillimanite garnet mica schist and banded sillimenite biotite gneiss, migmatites, biotite schist
		Vaikrita Thrust (VT)	
	Munsiari Formation	Helong/Tungnath	Biotite-garnet schist and garnetiferous gneiss, quartzite
		Main Centre Thrust (MCT)	
Lesser Himalayan meta-sedimentary zone	Jaunsar Group	Berinag / Nagthat Formation	Quartzite with/without penecontemporeneous mafic metavolcanic intruded by epidiorite.
	Tejam Group	Deoban / Mandhali Formation	Limestone, dolomite and phyllite/slate
	Damtha Group	Rautgara Formation	Quartzite with Penecontemporaneous mafic metavolcanic intruded by epidiorite.
	Ramgarh Group	Debguru Porphyroid, Bahtwari unit	Biotite-granite and tourmaline granite, schistose quartzite and chlorite schist
		North Almora Thrusrt (NAT)	
	Jaunsar Group	Chandpur Formation	Pauri phyllite , Bhainswara quartzite
	Almora Group	Dudhatoli Cryastalline	Schistose gneiss, biotite-garnet schist and garnetiferous gneiss

Table 1: Lithotectonic succession in the area around Chamoli district (after Valdiya, 1980).

North Almora Thrust (NAT) separates the northern Lesser Himalayan Garhwal Group from the southern outer Lesser Himalayan Jaunsar and Almora Groups. In this Group, the Pauri phyllite and Bhainswara quartzite are the succession of the Chandpur Formation while schistose gneiss, biotite-garnet schist and garnetiferous gneiss of the Dudhatoli Crystalline. Duhatoli Crysalline rocks are observed to be well exposed in west side of the Gairsain area.

Besides NAT, Alaknanda Fault (AF) is one of the most conspicuous and significant E-W striking Fault in the area [23,24]. It is a major Fault mapped in the Alaknanda valley extending from south of Nandprayag in the east to beyond Chirbatiyakhal in the west. It continuous traces northwestwords, and running almost parallel to NAT.

Damage to habitation and infrastructure

The toe/bank erosion all along the river valleys by enormous discharge triggered landslides at a number of places. Many localities were severely damaged in the Alaknanda and Pinder catchments. This caused massive devastation in the area on 16th and 17th June, 2013. Cumulatively these resulted in immense loss of human lives, livestock, personal property and infrastructure. Total of 242 hectares agricultural lands and 245 hectares crop were lost by these incidences that took toll of 33 human lives while 31 persons injured in the Chamoli district. More than 566 houses fully, 647 houses severally and 2188 houses were partially damaged while around 1119 farm animal were lost [25].

Benakuli village on the confluence of Alaknanda river and Khiro Ganga, on the national highway (NH 58) were partially damaged along with downstream side to Lambagar market area a number of shops, houses and vehicles by flash floods. In Govindghat area the Alaknanda river left more than 10 meters thick pile of sediments along right bank thus raising its level and burying 2-3 stories of the premises completely in the river debris. At the same locality, around 350 meters downstream of main Gurdwara premises, multistoried parking structure, commercial buildings and part of main approach road to Gurdwara from national highway (NH-58) were completely washed away (Figure 4a).

Bhuindar village was swept away due to excessive rainfall resulting into heavy discharge in Bhuindar Ganga which was located on

Govindghat-Hemkund pedestrian trek. Downstream to this, the part of the Pulna village with about 25-30 houses had been severely damaged (Figure 4b). Besides, leading route to Shri Hemkund Sahib, Holy Shrine of Sikhs was also damaged at a number of places.

Near Pakhi, Jalgwad village was hard hit by flooding of the Alaknanda river. However, certain segments show bulges on the slope and wide cracks and deformation of houses indicating subsidence and creep movements. Besides, Govindmarg Gurdwara and a part of national highway (NH 58) were partially damaged.

Approach bridge to Kalpeshwar temple over Kalpa Ganga, a tributary of Alaknanda river in Urgam valley was swept away while a number of agricultural fields of Deora village were severely damaged.

In Birahi, the terrace had been cut vertically by the Alaknanda river. An eroded terrace with around 5 to 10 meters vertical cut is observed on the left bank of river. In this eroded terrace Garhwal Mandal Vikas Nigam (GMVN) Guest house and other structures were severely damaged. As also, the toe/bank erosion by Alaknanda river triggered landslide at back slope of Kothiyalsain which is located on Chamoli-Gopeshwar road. Crown portion of this destabilized zone adjacent houses/buildings have been creating future risk (Figure 4c).

Flood waters of Alaknanda have damaged around 300 meters long stretch of national highway (NH 58) along with 4 Hotels downstream of the Maithana on its left bank. Around Gauchar, the agricultural terraces had been cut vertically by the river. An eroded terrace with around 10 to 15 meters vertical cut is observed on the left bank of Alaknanda river.

Rishi tok of Manmati and Urabagar tok of Silingi on the Deval-Manmati road area numbers of cultivated terraces were vertically eroded on the left bank of Pinder river.

In Chepron, the terraces along the Tharali-Deval road had been cut vertically by the Pinder river. An eroded terrace with around 5 to 7 meters vertical cut is observed on the right bank of river. A number of houses and a Primary School building on this destabilized terrace had been severely damaged by hydraulic force of Pindar river (Figure 4d). Besides, connecting pedestrian bridge of village Sera was also swept away along with numbers of houses and agricultural fields of Vijaypur village located on the left bank.

In Tharali, a number of buildings and right abutment of connecting Girder Bridge of Tharali-Dewal motor road were severely damaged by flooding of Pinder river. Upstream to this, at Kedarbagar area a number of houses were also completely destroyed and around 0.6 kilometer motor road was swept away on the left bank of river (Figure 4e).

Flooding of Pindar river has resulted in extreme erosion around the market town of Narayanbagar. Due to this, a number of houses, commercial buildings, pedestrian Bridge and old market were completely destroyed while an old landslide had been reactivated on the left bank (Figure 4f).

In Simli, around 3 to 4 houses of Dhunar Basti were completely destroyed on the right bank due to excessive discharge of the Pinder river and numbers of agricultural lands were also washed away on the left bank. Besides, a number of shops were severely damaged on the left bank around the market town of Karanprayag.

Constructed right abutment of Tharali bridge was damaged while Chepron-Sera (Figure 4g) and Narayanbagar old market connecting pedestrian bridges were swept away in flooded water of Pinder river. Besides, pedestrian bridge lead to Kalpeshwar temple in Urgam valley was also washed off by flooding of Kalpa Ganga. Another, Alaknanda river and Khirao Ganga has brought down huge debris material filling the reservoir of Vishnugad hydroelectric project and damaged the barrage along with other appurtenant structures (Figure 4h).

Figure 4: Damage to habitation and infrastructure due to excessive toe/bank erosion by streams/rivers; (a) badly damaged habitation at Govindghat town; (b) severely damaged Pulna village; (c) landslide at back slope of Kothiyalsain; (d) damaged structure at Chepron village; (e) Tharali-Dewal road washed off at Kedarbagar; (f) old reactivated landslide at Narayanbagar town; (g) Chepron to Sera villages connecting pedestrian bridge and (h) aggradations all around the reservoir of barrage.

Flooded water has resulted in damage to transport route at various places. These including Kanchan Ganga, Benakuli, Lambagar, Kamera, Govindghat, Bhapkund, near Uragam, Maithana and Kamera areas in the Alaknanda catchment while Syalsaur, Silingi tok, Lingari Gramsabha, Ganeshpur, Chaunda, near Sumaun, Tejpur, Harmani, Narayanbagar, Bagoli, Amsaur, Paduli in the Pinder catchment. Major damage to national highway (NH 58) has been noticed between Lambagar and Benakuli where about 5 kilometers long stretch got

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completely washed away in the flash flood. The toe/bank erosion all along the river valleys by enormous discharge triggered landslides at a number of places.

Contributing factors of mass damages

Persistent rainfall, cloudburst, high sediment leaden discharge in streams causes toe erosion and ensuing loss of infrastructure and property together with toll of human lives. A number of landslides, cloudburst associated debris flow and flood events are observed during the field investigations. Besides, rapid unplanned urbanisation in close proximity of river/stream, over loose materials and steep slopes are deduced to be the other causative factor for the slope instability. Main causes of the slope instability are as follows:

- Abnormally fast melting of snow and ice due to heavy rains increase discharge in the river/stream resulting excessive bank/toe erosion.
- High relative relief and seismotectonically active nature of the area
- Decreasing shear strength of rocks due to a number of thrusts/ faults
- Low cohesion and friction of the rocks and soil materials due to dry and freeze-thaw cycles.
- Rapid unplanned urbanization in close proximity of stream, road and steep slope over overburden mass.
- Indiscriminate and unscientific manner slope cutting for infrastructural development.
- Infrastructural developmental and agricultural activities in close vicinity of stream.
- Presence of overburden material over steep slope makes the area more vulnerable.
- Short distances rainfall in the area, particularly in 1200 to 2200 meters high altitude range.
- Persistent rainfall and low shear strength of the rocks have played a major role in facilitating slides.
- Old landslide mass undercut by river and deposited many places along its bed caused the same has changed its course in many areas.

Land slide distribution

In June, 2013 rainfall in the area was relatively higher and large number of landslides are observed to have been triggered at various places, mostly along the streams and roads. A total of 220 landslides are identified through field investigations in Chamoli district (Figure 5). Catchment wise distribution of landslide is given in Figure 6. The observations make it clear that maximum landslide incidences have taken place along the Alaknanda and Pinder rivers.

On the basis of movement and rigidity of material comprising the slide mass, bed rock, debris and earth, these are classified as debris/ bouldery debris slide, rock cum debris slide and rock slide / fall. Total 158 debris slides, 58 rock cum debris slides and 4 rock slides/falls are to be observed in the area. Of these, 72 percent are observed to be debris/ bouldery debris slide. This makes it amply clear that saturation of overburden or debris material by prolonged heavy rainfall is responsible for the initiation of most slides of the study area.

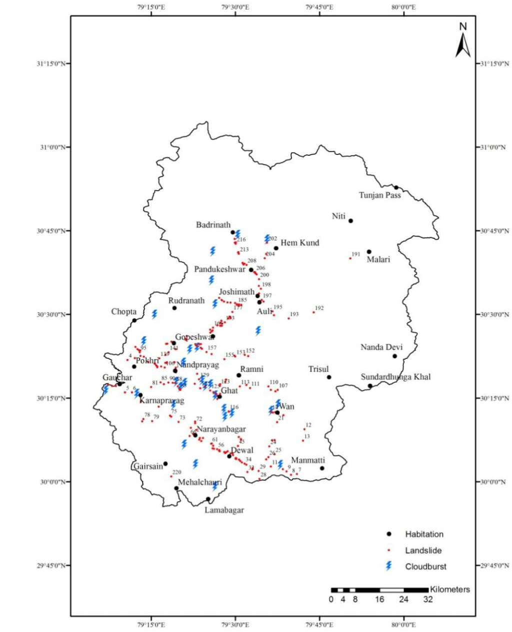

Figure 5: Distribution of landslides and cloudbursts in the area.

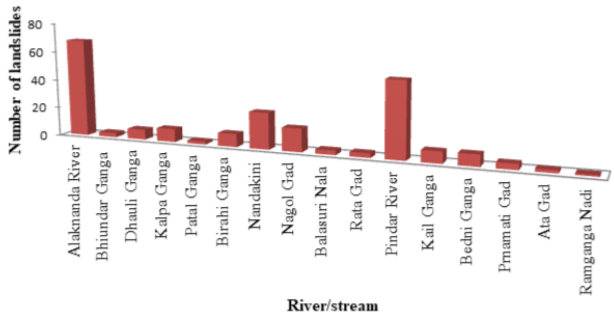

Figure 6: Catchment wise distribution of landslide in the area.

Landslide triggering factors

For the assessment of landslide triggering factors proximity of the landslides to road and river/stream was particularly analysed together with other causative factors that include geological and structural set up of the area. Landslide incidences have been largely (80 percent) caused either by toe cutting for road construction or by toe erosion by streams/rivers. Damages in the mass movement events around Rudraprayag district in 2013 are attributed to this phenomenon [26]. Another, 20% landslides is caused by other factors that include heavy rainfall, gully erosion, lithological and structural condition of the bed rocks, surface and sub-surface water and deforestation.

Correlation of landslides with lithology, land use and aspect

Lithology, landuse and aspect are generally considered to control distribution of landslides and therefore correlations with these parameters are largely taken note of while undertaking landslide

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related studies. Landslides with these different geo-parameters is given in Table 2.

Sl. No.	Head		Number of landslides
1.	Lithology	Vaikrita Group	27
		Munsyari Formation	18
		Damtha Group (Rautgara Formation)	13
		Berinag Foramtion (Jaunsar Group)	46
		Ramgarh Group (Debguru Porphyroid)	16
		Tejam Group (Deoban/Mandhali Formation)	33
		Almora Group (Munsyari Formation)	67
2.	Landuse	Forested land	121
		Agricultural land	49
		Barren land	32
		Habitated area	18
3.	Aspect	North	18
		East	10
		South	17
		West	9
		Northwest	28
		Northeast	60
		Southwest	49
		Southeast	29

Table 2: Landslides with lithology, landuse, slope and aspect in the area.

Almost 58 percent of the total observed landslides are observed to be located in Central Crystalline (Vaikrita Group, Munsyari Formation and Almora Group) and Ramgarh Group of rocks. Large proportion 21 percent of landslides are observed to be in Berinag Formation. Only 6% and 15% fall under Damta Group (Rautgara Formation) and Tejam Group (Deoban/Mandhali Formation) respectively.

Most landslides (55 percent) in the area are observed to be located in area falling in the landuse category identified as being forest land and 22%, 15% and 12% fall under agriculture, barren and habitated lands classes respectively.

The correlation of the landslides of the area with the slope aspect shows that the northerly slope aspects (NW, N and NE) have the maximum (48 percent) whereas the southerly slope aspects (SW, S and SE) relatively less (43 percent) landsides. East and west facing slopes have minimal landslides.

Heavy rainfall and floods have resulted in development of a number of major landslides, in the Alaknanda and Pinder catchments. At many places old slides are observed to be reactivated. These include Kamera, Nandprayag and Lambagar on the national highway (NH 58) while Harmony landslide along Karnaprayag – Gwaldam road, Hapla landslide along Hapla – Pokhri road and Thala band landslide along Pokhri – Rudraprayag road on the important hill routes (Figures 7a-7f).

Figure 7: Old reactivated landslides due to extreme rainfall events and stream erosion; Kamera; (b) Nandprayag; (c) Lambagar; (d) Harmony; (e) Hapla; (f) Thala.

Besides landslides, heavy localized rainfall/cloudbursts through small streams/seasonal streams have caused severe damaged to number of settlements and infrastructure. As many as 30 heavy localized rainfall/cloudburst incidences are to be observed in the area. Kuwarikhal hill (Belakuchi), Bhimtalla and Chamoli, near Gopeshwar, Khankrakhet hill (Gadini), Patidi hill (Musudiyar), Gairsain (Devpuri) were reportedly devastated by such rainfall events in the past [9-11,27-28]. 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/debris flows (Figures 8a-8f).

Results and Discussion

In June 2013, heavy rainfall and floods have resulted in development of a number of landslides; mostly Alaknanda and Pinder rivers and their tributaries. The present study area is occupied by rocks of Tethyan, Centre Crystalline and Garhwal Groups. It mainly consists of gneiss, schist, quartzite, limestone/calc zone, phyllite, shale, slate and marble etc. Vaikrita Thrust, Main Central Thrust, North Almora Thrust, Malari Fault and Alaknanda Fault are traverse through the district and the same has rendered the rocks of the area highly sheared, fractured and jointed.

Figure 8: Heavy localized rainfall/cloudburst induced debris flows through the streams; (a) newly constructed house filled with debris at Siligi tok (Lingari Gramsabha); (b) agricultural land damaged at Bansoli village; (c) severely damaged house just below road at Sunali village; (d) damaged structures at Ghat; (e) partially damaged Tefna village; (f) washed off road section lead to Ghat-Bhenti.

A study conducted in the area around Chamoli district delineated the exact location of 220 landslides. Each landslide was verified in the field and its type and status was determined. Each slide was numbered and mapped at scales of 1:50,000. However, distribution of landslides will be useful for developmental planning in the area.

At many places old slides are observed to be reactivated in the area. These include Kamera, Nandprayag and Lambagar on the national highway (NH 58) while Harmony landslide along Karnaprayag – Gwaldam road, Hapla landslide along Hapla – Pokhri road and Thala band landslide along Pokhri – Rudraprayag road on the important hill routes. These landslides should therefore to be studied separately for their treatment and therefore recommended that detailed geological investigations on 1:5000/2000 scale must be carried out for the same.

Landslides together with bank/toe erosion have caused severe damage to transport route and habitation in the area. Many habitations including Benakuli, Lambagar, Govindghat, Jalgwar, Birahi, Kothiyalsain, Maithana in Alaknanda catchment and Chapron, Vijaypur, Kedarbagar, Narayanbagar, Simli in Pinder catchment are observed to be damaged by slope instability. In Bhiundar ganga valley, Bhiundar village no longer exists while downstream to this the Pulna village is however facing a major threat and is required to be rehabilitated. Some portions of Benakuli, Lambagar, Govindgaht, Maithana in Alaknanda catchment and Chapron, Kedarbagar, Narayanbagar, Simli in Pinder catchment are also required to be relocated. Detailed geological mapping on 1:1000 scale with an objective to demarcate the suitable areas for rehabilitation of the affected habitations.

Heavy localized rainfall/cloudburst is the natural phenomenon occurs during monsoon season over the regions dominated by orography like Himalaya. It can only be identified on the basis of inundation occurred mostly along the Ist and IInd order drainages in hilly terrain during monsoonal rainfall. Heavy localized rainfall/cloudbursts and associated debris flows have caused severe damage to settlement and infrastructure. Many villages including Ghat, Khunana, Thirpak, Tefna, Sunali, Kamera in the Alaknanda valley and Kanol, Silingi tok of Lingari Gramsabha and Bansoli in the Pinder valley are adversely affected. It is therefore recommended that constructions should be away from natural water courses/seasonal streams. The proposed construction site should be developed in a manner that does not enhance chances of debris flow/mud flow.

Constructions of any kind should therefore necessarily be banned in the proximity of the areas as Lambagar, Govindghat, Pulna, Birahi, Maithana, Chepron and Kedarbagar where a number of structures were washed off by high leaden discharge of rivers/streams. In these areas appropriately designed bank stabilization measures should be put for protection of further bank erosion and safety of rest habitations.

The national highway (NH 58) between Benakuli to Lambagar and state highway at Kedarbagar are observed to be washed off by high sediment leaden discharge of stream/river. It is recommended that national highway and state highway in the same be realignment. Reconstruction of the damaged national highway (NH 58) by appropriately designed retaining structures particularly in Govindghat, Maithana and Kamera areas while state highway in Tharali, Harmani and Narayanbagar.

Chapron-Sera in Pinder catchment and Kalpeswar temple in Kalpa Ganga catchment areas foot bridges were washed off due to flooding. In these areas further foot suspension bridges need to be reconstructed with proper anchored abutments. Considering high flood level, the span and height of the bridge should also be increased while designing the bridge.

The disaster has resulted in massive damage to Vishnugad hydroelectric project that is run of river scheme on the Alaknanda river. Removing of huge sediments from reservoir and damaged components should be repaired for long term safety of the barrage. In June, 2013 disaster, Vishnugad hydroelectric project had also been reduced the pace of flood in downstream side and therefore recommended that run off river schemes should be required particularly in higher reaches where has habitation free zone. This would reduce the velocity of stream water and protect the downstream habitation from pace of flood. Relevant provisions of appropriate codes should also be followed during construction stage.

Persistent rainfall, cloudburst, breach of temporary ponds generated by streams/rivers during high leaden discharge resulted in devastation of June, 2013. Landslide, debris flow and flood are among induced by heavy rainfall. These can be well predicted by real time rainfall data and therefore the monitoring of the rainfall in the area can be used to forecast. This would generate valuable data from predicting and minimizing landslides risk in the area. As a precautionary measure wide network of weather observatory should be installed in entire district.

The area falls in Zone V and is highly vulnerable to earthquake. Besides initiating mass movement big earthquake can cause wide spreads damages in the area. Earthquake of 1803 was highly destructive and caused severe damage in Badrinath temple. Another, 1999 Chamoli earthquake severe damage to the structures was mostly confined between the Alaknanda valley in Chamoli and Rudraprayag districts. As the area falls in high seismic zone, it is necessary to consider adequate seismic coefficient in the design of the structures.

Mountainous terrain of Chamoli district is highly sensitive because of high relative relief, structural discontinuities and predominance of Quaternary deposits. Unplanned hill cutting for infrastructural development makes the area more prone to landsides. It is therefore recommended that special attention be taken during any type of constructions in the hills. It is therefore also required that mapping of Quaternary deposits be undertaken and people be educated on the importance of site selection before making a final decision to settle down at a particular place.

Conclusions

The disaster of June 2013 can be attributed to widespread and heavy rainfall resulting into high floods and landslides in the area. Many localities were severely damaged in the catchments of Alaknanda and Pinder rivers. Total of 220 landslide incidences have been observed in the area on the aftermath of the disaster. Geological investigations carried out in the area suggests that maximum (80 percent) landslide incidences have been caused either by toe cutting for infrastructural development or toe/bank erosion by streams.

The entire Chamoli region is observed to be traversed by a number of thrusts and faults that cause the rocks exposed in the area are observed to be jointed, fractured and sheared, particularly in the close vicinity of thrust/fault zones. Due to this, in the past the area has been devastated by a number of landslides. Geomorphic and field observations show the presence of a number of tectonic contacts that have rendered the area prone to landslides. The area also falls in Zone V and has been devastated by 1803 and 1999 earthquakes. Besides causing immense loss of human live, property and infrastructure it has the most potential of triggering landslides. Additionally, unscientific and indiscriminate way of hill cutting, river side construction and construction on seasonal stream are deduced to have aggravated the devastation in the area.

However, major portion of the road network in the area is observed to be aligned in close proximity of the streams. It is therefore inferred that the solution to the menace of landslides lies in better alignment of the road network and keeping the same away from course of the streams. Mass awareness, implementation of suggested measures, relocation of habitations and infrastructure from high risk area are suggested as possible mitigations.

Acknowledgements

I acknowledge guidance and support from the Executive Director, Disaster Mitigation and Management Centre, Department of Disaster Management, Government of Uttarakhand. Dr. Krishna Singh Sajwan, Geologist and Mr. Ashish Rawat, GIS Operator along with colleagues at Disaster Mitigation and Management Centre and State Emergency Operations Centre are thanked for cooperation and support. The co-operation received from the District Administration, Chamoli district is also gratefully acknowledged.

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