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Formation and Failure of Natural Dams in Uttarakhand Himalaya: An Observation from Lwarkha, Chamba Tahsil of Tehri Garhwal District, India

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INFORMATION

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ABSTRACT

Being within a geo-dynamically active Himalayan belt, the state of Uttarakhand is more susceptible to natural hazards due to inherent geology, high relief, narrow valley, thick overburden, heavy downpour and rapid glacial melting etc. Over the past decades, these natural hazards have resulted in loss of human lives, infrastructures and properties along with other natural resources. The current issue highlights the natural hazards such as rock slides/falls, debris flows, moraines and avalanches which had blocked the streams and impounded the water, left behind the natural dams in the same regions. An attempt has been made to enlist the same in tabular form together with their location, year of occurrences and impacts. Total of 24 incidents have been reported between the year 1857 and 2018 of which alone 50 percent is to be recorded in Chamoli district while 25 percent in Rudraprayag district. Recent incidence of Lwarkha, Chamba Tehsil of Tehri Garhwal district is briefly discussed in this paper. The main aim of this study is to learn lessons from the past incidences and aware the local people from the threats of future natural damming of streams and associated outburst floods.

1. Introduction

Blocking of streams by rock falls/slides, debris flows, moraines and avalanches are common and potential natural hazards in the Himalayan region. Mainly, four conditions are typically important for dam formation: (1) high relief with narrow valley; (2) the deposition thickness of landslide/ debris mass; (3) confluence of tributaries; (4) wide valley, left behind the dam. Losses related to natural dams can occur both during and after the formation of the dam (Nibigiral et al., 2018). Small impounding of water due to blocking of streams by natural hazards are usually not hazardous while larger impounding of water is much more hazardous. Mostly, high magnitude earthquake and persistent rainfall as secondary forces are the initiation mechanism for dam formation (Costa and Schuster, 1987). Some of the natural dams are unnoticed because of their frequently temporary character, following their rapid destruction. Natural dams breach and associated floods can result in initiation of many landslides on the downstream. Significant damage is loss of life, infrastructure, property and geo-environment, from downstream flooding upon catastrophic outburst of the same.

The state of Uttarakhand is located in the southern rim of Central Himalayan landform and it falls between 28° 43"-31° 27" N latitude and 77° 34"-81° 02" E longitude. It is bonded internationally to eastern frontier with Nepal and northern with Tibet while nationally to southern with Uttar Pradesh and western with Himachal Pradesh. The same region is divided into two divisions, one is Kumaun and another is Garhwal and consists of 13 districts. Litho-physiographically the state is lies in five divisions namely Tethyan Himalaya, Greater Himalaya, Lesser Himalaya, Siwaliks and Indo-Gangatic plains. It has a population of 10.1 million and the population density of the state is 189 people per square kilometer having a 2001-2011 decadal growth rate of 19.17 (Census of India, 2011).

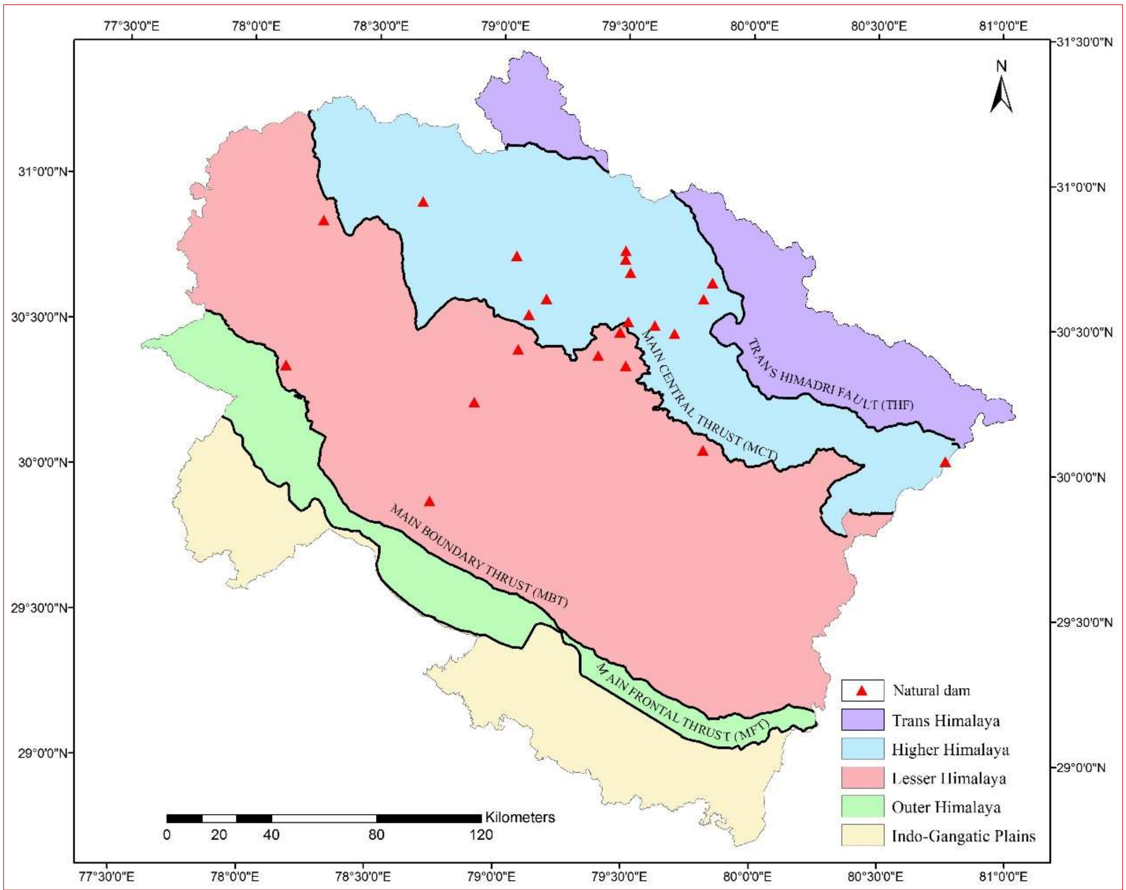

Fig. 1. Geology of the Uttarakahand Himalaya (Heim and Gansser, 1939; Gansser, 1964; Valdiya, 2014)

Geographical area of the state is 53,483 square kilometers; 93% of which is mountainous and 64% is covered by Forest (Khanduri, 2020). Geologically, the same region is the young mountainous terrain and is delimited by various Thrusts/Faults as Trans Himadri Fault (THF), Main Central Thrust (MCT), Main Boundary Thrust (MBT) and Main Frontal Thrust (MFT) from north to south (Fig. 1)

2. Objectives

Among enherent geology, seismicity and environmental factors are crucial which triggers the natural hazards in the forms of debris flows, landslides and glacial lake outburst floods. Apart from this climate also triggers extreme events. Additionally, human interference in close proximity of streams in mountainous regions, the hazards created by dammed lakes will become increasingly serious. Sudden breach of the same caused devastation in downstream. Their consequences in recent times have become severe in terms of loss of human life, property and infrastructure. The objective of this study is to identify the past events and learnt lessons from these natural dams and associated outburst floods. Other important objectives of the study are following:

- To identify the previous natural dams and related devastations.
- To find the natural hazards and vulnerabilities of the region.
- To describe the different types of natural dams as rock falls/slides, debris flows and glacial sediments/marines along with their examples.
- Attempts were made to analyze the same events as district wise distribution, litho-physiographic region wise distribution, materials wise distribution and duration wise distribution.

- To present an observation of recent events along with causes and suggested measures.
- To review the preventive measures along with some examples of natural dams.
- Suggesting the prevention and future developmental planning in the region.
- To aware inhabitants of the region through the same document.

3. Data Set and Methodology

For the present study, basic information and data are mainly collected from primary and secondary sources. With the help of Survey of India toposheets on 1: 50000 scale and ArcView 9.1, geology along with distribution of natural dam's map and district boundaries along with distribution of natural dam's map are prepared. The entire data of formation and failure of natural dams since 1857 and 2018 is analyzed as district wise, litho-physiographic region wise, materials wise and durations wise. Furthermore, preliminary geological investigation of Mon Khala ridge landslide at Lwarkha in Tehri Garhwal district of Uttarakhand Himalaya which occurred on 13 August, 2018 was carried out and observations were taken in the area around affected site. An attempt was also made to suggest recommendations to reduce the risk in the areas.

4. Previous Natural Dams Along with Impacts and Their Analysis

Being within a tectonically fragile mountains together with high relative relief and extremely high precipitation zones, Uttarakhand is well known as a multi-hazard prone state. District wise vulnerability to natural hazards of the same region is given in Table 1. Thus, climate and tectonic stresses in Himalaya trigger extreme events like earthquakes, landslides, cloudbursts, glacial lakes outburst floods and landslide lake outburst floods (Srivastava et. al., 2016).

The same region has been assigned to two seismic zones IV and V according to Earthquake Zonation Map of India (IS 1893:2002). Over the recent past, the state has witnessed earthquakes of 1991 Uttarkashi and 1999 Chamoli (Rautela, et. al., 2019). There are different types of natural dams and associated outburst floods which are given in sections below.

Table 1: District wise vulnerability to natural hazards of Uttarakhand

No	District	Vulnerability to natural hazards				
		Earthquake	Landslide	Flash flood	Flood	Avalanche
1	Almora	H	H	H	L	L
2	Bageshwar	VH	VH	VH	L	VH
3	Champawat	H	H	L	L	L
4	Chamoli	VH	VH	VH	L	VH
5	Dehradun	H	H	M	L	L
6	Haridwar	H	L	L	VH	L
7	Nainital	H	VH	H	VH	L
8	Pithoragarh	VH	VH	VH	L	VH
9	Pauri	H	H	H	L	L
10	Rudraprayag	VH	VH	VH	L	VH
11	Tehri	H	VH	H	L	H
12	Uttarkashi	H	VH	VH	L	VH
13	U.S. Nagar	H	L	L	VH	L

- *VH (very high), H (high), M (medium), L (low)*
- *Earthquake: Zone V- VH (very high), Zone IV- H (high)*

4.1. Rock fall/slide dammed lake and associated outburst floods

Among the more complex and devastating interactions between climate and hydro-morphological processes in mountain environments are landslide lake outburst floods, resulting from mass movements temporarily blocking a drainage system (Villanueva et al., 2017). Landslide dams are extremely dangerous phenomena, especially in tectonically active mountains regions (Costa and Schuster, 1988), as they may trigger devastating dam-break floods that can affect large areas downstream (Fan et al., 2017). The same cause two types of floods: (1) upstream flooding as the impoundment fills, and (2) downstream flooding resulting from failure of the dam (Schuster, 2006). Process of failure of landslide dam can be classified into three types; overtopping, instantaneous slip failure and progressive failure (Awal et al., 2008). Stability of the same largely depends on the dam comprising materials that in turn are strongly related to the types of damming landslides and valley morphometry (Fan et al., 2017).

There are three known report of landslide dams by major rock falls/slides in the Uttarakhand region. Birahi Ganaga, a tributary of Alaknanda River was blocked by rock fall/slide in 1893 which forming Gauna Tal (Fig. 2). The lake formed was 25 kilometers by 2.0 kilometers. Partial breach of this lake in 1894 and ultimate breach of the same in 1970 that caused massive devastation in the Alaknanda valley and rising the water level by 50 meters at Srinagar Garhwal. The flow of the Birahi Ganga was blocked for a long period as 76 years. Similarly, on 18/19th August, 1998 Bhenti and Paundar villages went down in ruin in Okhimath of

Rudraprayag district due to major rock fall/slide. The flow of the Madhyamahewar River was blocked for about 12 hours due to the forming of a natural dam. Later the breached dam caused damages and distructions to downstream. On the other hand, on 18th August, 1998 the massive rock fall was triggered and detached huge rock mass overran the Malpa habitation which was situated just downhill side of the event in the Dharchula tehsil of the Pithoragarh district. This landslide mass was also blocked the flow of the Malpa gad temporary.

Fig. 2. Gohna Lake formation on Birahi Ganga due to rock fall/slide (courtesy: Internet)

4.2. Debris flows dammed lake and associated outburst floods

Debris flows in tributaries rush into and block the main branches of rivers and are considerably destructive and affect a large area, with devastating floods capable of moving large volumes of debris that may greatly threaten the lives and property of populations downstream of the event (Chen et al., 2018; Chen et al., 2019). Three distinctive elements are distinguishable in a debris flow of a flow-type landslide: the source area, the transportation area and the depositional fan. Debris flows are of primary concern due to their long runout and the resulting destructive impacts (Fan et al., 2017). Most of the dams have been caused by relatively high velocity debris flow through the tributary to block streams at confluence in Himalayan region. There are three known reports of debris flow dams formed by debris slides or rock slides. These include Rishi Ganga, a tributary of Dhauli Ganga in Chamoli district; Patal Ganga, a tributary of the Alaknanda river in Chamoli district and Kanoldiya Gad, tributary of Bhagirathi River in Uttarkashi district respectively is to be observed in years 1968, 1970 and 1978. Later these dams breached caused devastation in downstream.

4.3. Glacier/moraine dammed lake and associated outburst floods

Glacial lake outburst floods (GLOFs), resulting from the sudden release of water from lakes impounded by moraine or ice dams, can be a major hazard in high mountain areas (Khanal et al., 2015). Characteristically, glacier dammed lakes can be classified as moraine dammed and glacier dammed lakes - dammed either by active glacier masses or debris-covered icemasses with or without contact with the active part of the glacier (Grabs and Hanisch, 1993). The same evolve into debris flows by erosion and sediment entrainment while propagating down a valley, which highly increases peak discharge and volume and causes destructive damage downstream (Liu et al., 2020). In the summers of 2013, the state of Uttarakhand received abnormally high precipitation that resulted in sudden rise in the level of most rivers and streams (Fig. 3).

Fig. 3. Water level of Alaknanda River at Rudraprayag just upstream of its confluence with Mandakini River before (left) and after June 2013 floods (right)

Table 2: Records of formation and failure of natural dams in Uttarakhand, India between the years 1857 to 2018

No	Year of occurrence	Type of movements/ materials	Impacts	Duration	References
1	1857, Mandakini River, Rudraprayag	Unclear	A massive landslide reportedly blocked the flow of the Mandakini River for three days.	Temporary (3 days)	Rautela and Pande, 2005
2	1868, Alaknanda River, Chamoli	Unclear	Landslide upstream of Chamoli blocked Alaknanda River. Swept through two villages and killed 70 pilgrims.	Unclear	Rautela and Pande, 2005
3	1893 Alaknanda, Chamoli	Rock slide/fall	Floods in the Birehi Ganga River near its confluence with the Alaknanda River triggered landslides, causing major blockage of the river with a 10-13 m afflux. A girder bridge was bypassed and another one was destroyed.	Temporary	Pandey and Mishra 2015
4	October, 1893 Gohna, Birahi Ganga, Chamoli	Rock slide/fall	The Gohna landslide filled the Birahi River bed up to a height of 350 m. The lake formed was 25 km by 2 km. The landslide dam was partial breached in 1894 while ultimate breached in 1970, raising the water level by 50 m at Srinagar. Two days later, the river water level rose by 4 m at Haridwar.	>75 years	Prakesh, 2015
5	1930 Around Badrinath, Alaknanda River, Chamoli	Debris flow	The Alaknanda was blocked in 1930 raising the water level up to 9m and caused flood damaging many houses.	Temporary	Prakesh, 2014
6	14 September, 1951, Eastern Nayar River at Satpuli, Pauri	Debris flow	Nayar floods swept away about 18 buses which were parked in the river-bed at Satpuli. The flood was caused by the bursting of the temporary blockage of the Eastern Nayar in its upper course.	Temporary	Prakesh, 2014
7	1957, Dhauli Ganga, near Bhapkund, Chamoli	Avalanche	An avalanche came down along the Dronagiri rivulet a tributary of Dhauli Ganga in 1957 blocking the river near Bhapkund and forming a 3.0 km long lake which was later filled with debris.	Later filled with debris	Prakesh, 2014
8	May, 1968 Rishi Ganga, near Reni village, Chamoli	Debris slide	The Rishi Ganga in Chamoli district was blocked up to a height of 40m due to a landslide at Reni village. The dam was breached in 1970, causing extensive damage	2 years	NDMA, 2009, Gulia, 2007
9	September, 1969, near Kaliasor market, Rudraprayag	Rock slide/fall	A huge landslide took place, about 3.0 km upstream of the small market place of Kaliasor and blocked nearly three-forths of the width of the river. There was heavy rainfall during the week preceding the landslide with a flood in the river the day it occurred.	Temporary	Gulia, 2007
10	20 July, 1970 Dhak Nala, near Tapovan, Chamoli	Debris flow	The Dhak nala deeply scoured its narrow bed and resulting toe cutting reactivated the prehistoric Kuari pass landslide. A 300m stretch of the Joshimath-Malari road near the Dhak nala slumped by 40 m and the landslide debris temporary blocked the Dhauliganga with a 15 m to 20 m high dam.	Temporary	Gulia, 2007
11	July, 1970, near Helong, Chamoli	Debris slide	The flow in the Karmanasa Nadi reactivated another prehistoric slide which carried away a part of the road and blocked Alaknanda River even as inhabitants of several villages in the vicinity of the Helong nala prayed for their lives throughout the night.	Temporary	Gulia, 2007
12	20, July, 1970, Hanuman Chatti, near Badrinath, Chamoli	Avalanche	About 275 mm rainfall (in few hours) caused landslide that blocked river creating temporary lakes. Alaknanda and Dhauli Ganga raised 30–60 and by 15–20 m, respectively that burst out causing considerable loss of life.	Temporary	NDMA, 2009; Gulia, 2007
13	July, 1970, Patal Ganga, Chamoli	Debris flow	The Patal Ganga, a tributary of the Alaknanda River got choked and a reservoir more than 60m deep was created. The bursting of this choked reservoir resulted in flash floods in the Alaknanda River, triggering many landslides. Belakuchi village was washed away and communications were disrupted due to landslide that occurred on the left bank of the Alaknanda River.	Temporary	Pandey and Mishra, 2015; Thakur, 1996
14	6 August, 1978, Kanoldiya Gad, Uttarkashi	Debris slide	The Kanauldia Gad, a tributary of the Bhagirathi River formed a debris cone across the main river, impounding the river to a height of 30 m. Its breaching caused flash floods, creating havoc. A 1.5 km long, 20 m deep lake was left behind as a result of the partial failure of the landslide dam.	Temporary	Pandey and Mishra 2015; NIDM, 2015
15	August, 1979, Kyunja Gad, Rudraprayag	Debris flow	Flash floods in Kyunja Gad, a tributary of Mandakini, inflicted heavy losses in Kontha, Chandranagar and Ajaypur. 29 persons were killed in this incidence and the course of Mandakini was blocked near Chandrapuri.	Temporary	Prakesh, 2014
16	April, 1979, Bamni Village near Badrinath, Chamoli	Avalanche	Avalanches blocked Alaknanda River and lake was formed, which later breached above Bamni village near Badrinath.	Temporary	Bisht et al., 2002
17	18/19 August, 1998, Okhimath, Rudraprayag	Rock slide/fall	Incessant rainfall in Madhyamaheswar valley, villages Bhenti and Paundar went down in ruin and the flow of the river was blocked for about 12 hours due to the forming of a debris dam. Later the dam breached, leaving behind a 1.2 km long, 50-70 m wide and 25-30 m deep lake in the valley.	Temporary (12 hours)	Sah and Bist, 1998

18	17/18 August, 1998 Malpa, Kali River, Pithoragarh	Rock slide/fall	The lake burst in the night of 17 August 1998 released a huge amount of water together with boulders and debris. On 18 August 1998, the inevitable happened and the huge landslide overran the Malpa habitation and took toll of more than 200 people besides blocking the stream yet again. Bursting of the landslide dam this time washed off the dead bodies and severely hampered the pace of the rescue work.	Temporary	Paul et al., 2000
19	30 August, 2001, Khanera, Yamuma valley, about 14km upstream to Barkot, Uttarkashi	Debris slide	The heavy rains resulted in downslope movement of the slope mass, blocking the Yamuna River. The river width of about 30 m was reduced to 4-5 m after the slide. A lake 300 m long, 30- 40 m wide and 5-6 m deep was formed in the adjacent upstream portion.	Temporary	NIDM, 2015
20	2002, Saigari Village, Chamoli	Glacial sediments/ Moraine	Gankhwi River was blocked by sediments and debris. Glacial lake outburst flood occurred in 2002 and 2003 and completely destroyed the Saigari village in Dhauli Ganga valley.	Unclear	Bisht et al., 2011
21	2013, Jagi-Bedula, Madhya-maheswar valley, Rudrapryag	Rock cum debris	Lake formation is observed around Jagi-Bedula slide on the right bank of Madhyamaheswar River. It is however in an initial stage but further downslope movement of debris and rock mass has the potential of posing a serious threat.	Temporary	Khanduri et al., 2018
22	16/17 June, 2013, Chaurabari, Kedarnath, Mandakini valley, Rudraprayag	Glacial sediments/ Moraine	Moraine dammed Chaurabari lake outburst flood caused massive devastation in the Mandakini valley. More than 4000 persons went missing, around 11,091 farm animals were lost and around 19,309 residential houses were damaged in these incidences.	> 75 years	Rautela, 2018; Khanduri et al., 2018
23	2018, Kunwari village, Bura Gad, Bageshwar	Debris cum rock slide	Debris cum rock slide is located just downslope of Kunwari village on the right bank of Baura Gad. Signatures of lake formation are also observed on Baura gad which is attributed to damming of the same by the huge slide debris.	Temporary	Khanduri, 2018
24	14 August, 2018 Lwarkha Timli Sain tok, Tehri	Rock slide/fall	A rock slide/fall located opposite to Timli Sain tok of Lwarkha village. The same has blocked the flow of the nala and created the lake about 150 m long, 40 meters wide and 3 to 5 m deep which was stopped the flow of water for 6 to 7 hours. A number of cultivated lands and a water mill were damaged in the same.	Temporary (7 hours)	State Emergency Operations Center (SEOC)

There is a well-known report of Chaurabari glacier/moraine dammed lake outburst flood (GLOF) which occurred on 16 and 17 June, 2013 caused massive devastation in the Mandakini valley of Rudraprayag district. Large portion of the Kedarnath temple township, particularly to the north has been overrun by debris and boulders in the same events. Downstream side to Kedarnath, Rambara town was washed off together with pedestrian trek. Besides, Gaurikund, Sonprayag, Sitapur, Barasu, Khat, Semi, Gaundar, Jal Talla, Kalimath, Kunj, Taljaman, Banswara, Syalsaur, Chandrapuri, Sauri, Pathalidhar, Ganganagar, Jawaharnagar, Vijaynagar, Agastmuni, Silli (Chaka), Sumari, Tilaknagr, Tilwara are adversely affected (Khanduri, 2018).

The same region has witnessed a number of natural dams formed by various geomorphic processes such as avalanches, glacial sediments/moraines, rock fall/slide, rock cum debris/debris cum rock slides, debris slides and debris flow since 1857 to 2018 as is listed in Table 2. Events of 1857 and 1868 have not been marked on the map because of unclear locations. Out of total 24 natural dams, which were observed in the region of Uttarakhand, about 12, 6, 2, 1, 1, 1, 1 number respectively are recorded in Chamoli, Rudraprayag, Uttarkashi, Tehri, Pauri, Bageshwar and Pithoragarh districts (Fig. 4a).

The data indicate that the maximum (54 percent) of incidences is to be observed in Chamoli district while 21 percent in Rudraprayag district. Only, 9 percent incidence is to be observed in Uttarkashi district and each 4 percent in Tehri, Pauri, Bageshwar and Pithoragarh districts.

Of total natural dams documented from all around the Uttarakhand, about 14 natural dams is to be observed in Higher Himalaya while 10 numbers in Lesser Himalaya (Fig. 4b). The data indicate that majority (58 percent) is to be observed in Higher Himalayan region while 42 percent in the Lesser Himalayan region. Of total, about 6, 5, 4, 3, numbers respectively formed by rock slides/falls, debris flows, debris slides, avalanches and each 2 numbers by rock cum debris/debris cum rocks, glacial sediments/moraines while the remaining 2 numbers incidences details of which could not be conformed (Fig. 4c). Largely (25 percent) natural dams are observed to be formed by rock slides/falls while 21 percent by debris flows. Apart from, relatively less about 17 percent and 13 percent respectively by debris slides and avalanches. Only, each 8 percent damming of streams is to be observed by glacial sediments/moraines and debris cum rock/rock cum debris slide. Out of total, 18 numbers natural dams are to be observed temporary and each 2 numbers are observed >1 year and >75 years while the remaining 2 numbers incidences detailes of which could not be conformed (Fig. 4d). The data indicate that largely (63 percent) of the natural dams is observed to be formed temporary while each 8 percent is observed to be >1 year and >75 years.

5. Case Study of Lwarkha, Chamba Tahsil of Tehri Garhwal district

Mon Khala ridge landslide (30°21’24” N, 78°09’2” E) is a rock slide/fall located opposite to Timli Sain tok of Lwarkha village (Fig. 5). The landslide area is observed to be occupied by well exposed rock on the crown part.

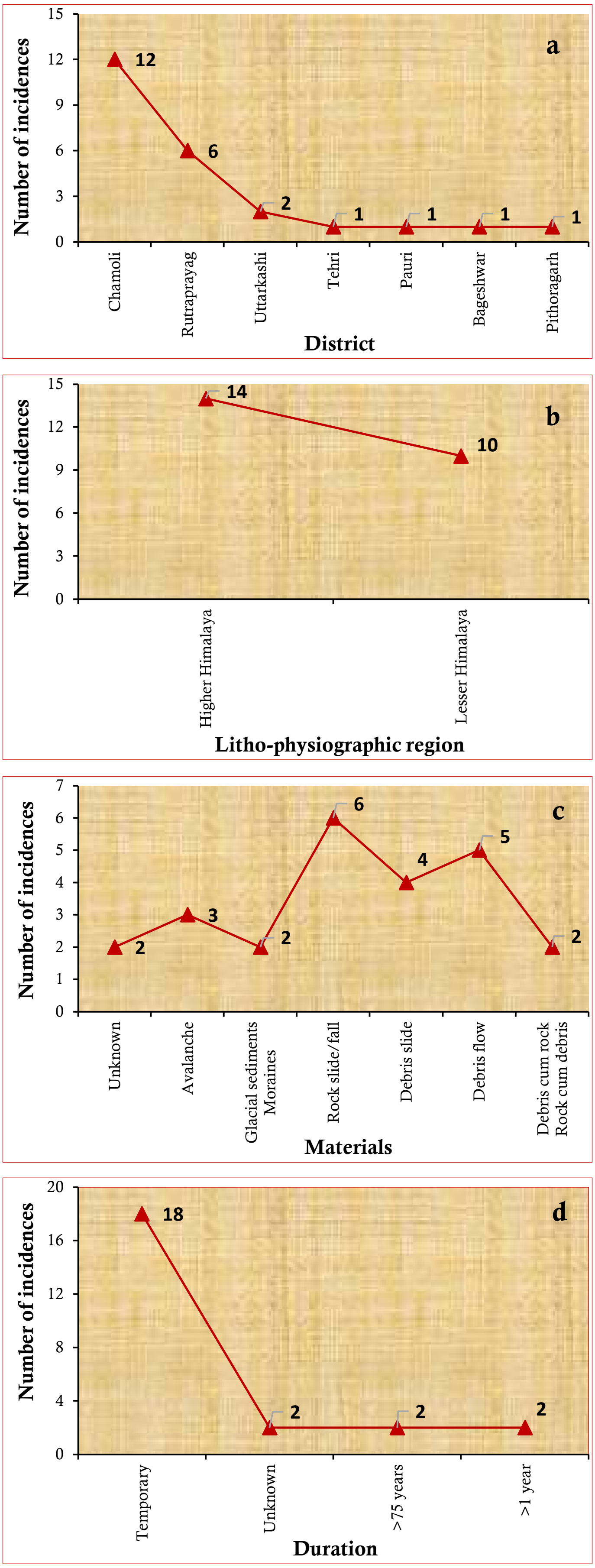

Fig. 4. Distribution of formation and failure of natural dams in Uttarakhand Hiamalaya; (a) district wise, (b) litho-physiographic region wise and (c) materials wise and (d) durations wise

The sliding material was observed to comprise of rock mass debris consisting of rock fragments. The affected area can be approached by road till Sitapur village that is located at a distance of 11 kilometers from Raipur in Dehradun. From Sitapur one has to travel on foot for around 2.5 kilometers to reach Timli Sain tok of Lwarkha. Preliminary geological investigation of Mon Khala ridge landslide was carried out on 14 August, 2018 and observations were taken from Timli Sain tok of Lwarkha village that is on the left bank of the stream (Fig. 6).

5.1. An observation

According to local people Mon Khala ridge landslide initiated in the morning hours of 13 August, 2018 around 10:00 AM. The same took place on the right bank of local stream that is tributary of Song River. Large volume of dislodged rock mass consequently got accumulated over the course of the stream and blocked the flow of water creating a lake about 150 meters long, 40 meters wide and 3 to 5 meters deep. The stream flow was reported to be completely stopped within about 6 to 7 hours. A number of cultivated fields together with a water mill were damaged by the same. The landslide dam posed threat to the downstream settlements that are located in the close proximity of the stream.

The slide was observed to have occurred on the southwestern slope of NW-SE trending Mon Khala ridge. The slide was observed to be located in the forest land and some of trees were observed to have been uprooted by the same. Fractured and jointed quartzites and shales were observed around the slide zone. The inclination of failed slope was observed to be 65° to 70° whereas in the crown portion it was observed to be almost sub-vertical to vertical. The width of the failure slope was about 110 meters along the stream and height of the slide from the stream bed to the crown was about 150 meters. The course of the stream was observed to have shifted around 10 to 15 meters towards the left bank due to landsliding. Downstream side flank of the slide at crown portion was also observed to be active and could also trigger in future.

The rock exposures of Lesser Himalayan quartzites/slates were observed along the footpath section on the left bank of the stream around 50 meters upstream to tok. The rocks were generally observed to trend NW– SE with gentle dips towards NE. The rocks were observed to be traversed by numerous joints. Important joint sets are observed to dip towards SE and SW (50° / 120° and 45° / 250°). Factors contributing to landslide in the area were deduced to include high relief, very steep slope and heavy precipitation together with highly jointed and medium to thinly bedded nature of quartzites and shales observed in the area. A number of seepages on mid slope of the slide and on the upstream side flank area highlight the role of precipitation in the landsliding.

5.2. Recommendations

Timli Sain tok of Lwarkha village is located amid cultivated lands and around 50 meters upslope from the stream bed on the left bank. The landslide therefore does not pose any threat to the tok/village. A number of cultivated fields located just downstream of the lake were however observed to be in a highly vulnerable state. It is therefore recommended that human presence in these fields be avoided, particularly during heavy rainfall and infrastructure development in the area be prohibited. Lake water has made its exit through the debris brought down by the landslide and is getting discharged normally to the main stream. Some detached slabs of quartzite lying on the stream course are however required to be mechanically removed to insure uninterrupted discharge and ruling out possibility of threat of any kind from the lake.

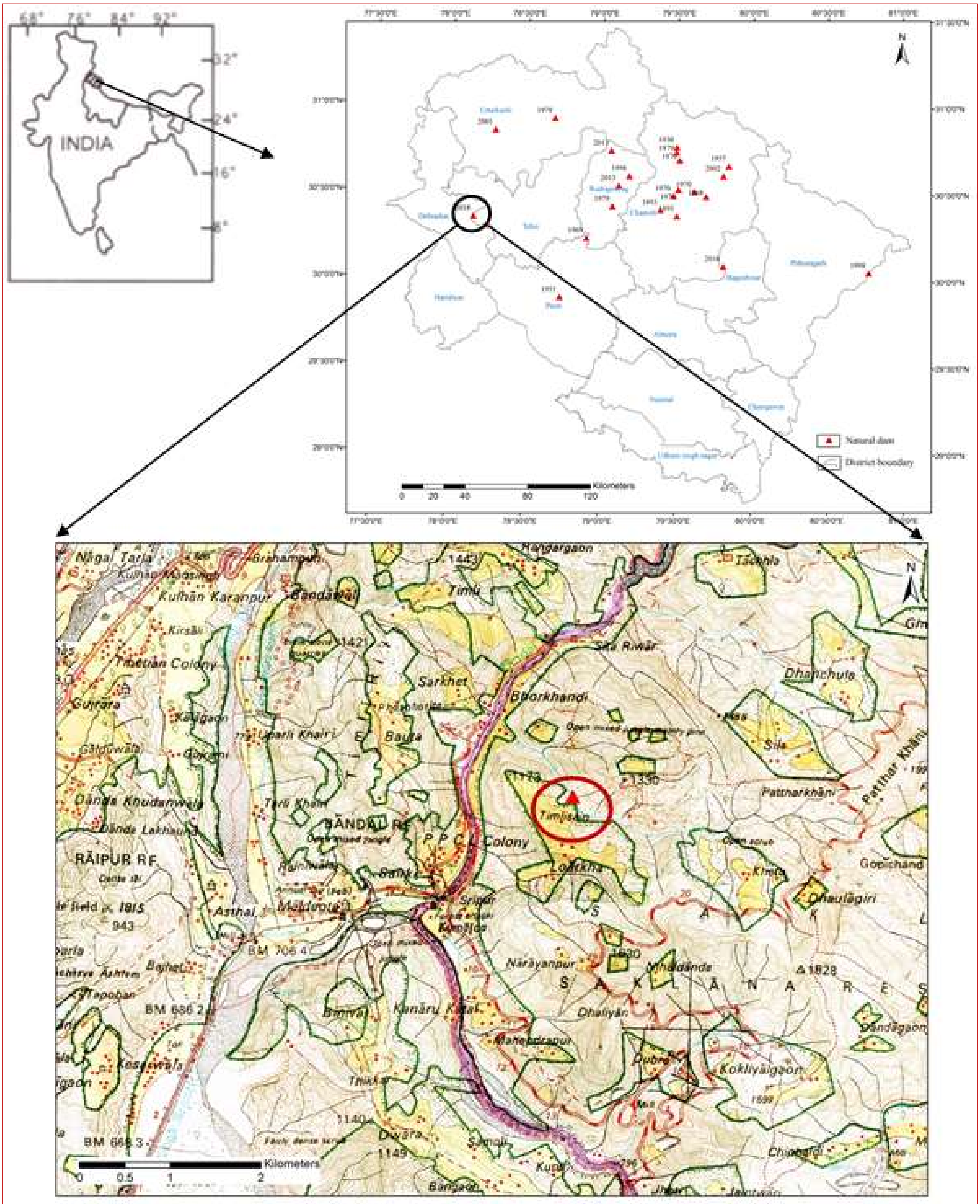

Fig. 5. Location map of the study area on the west hills of Uttarakhand, at Lwarkha in Tehri Garhwal district

Fig. 6. The lake formation by landslide dam (left) and downstream view of landslide (right) at Lwarkha in Chamba tehsil of Tehri district

6. Results and Discussion

The Himalayan state of Uttarakhand is geo-dynamically active and is delimited by major Thrusts/Faults as Trans Himadri Fault (THF), Main Central Thrust (MCT), Main Boundary Thrust (MBT) and Main Frontal Thrust (MFT) from north to south. The same region is seismically active and lies in zone IV and V according to Earthquake Zonation Map of India. Among geo-tectonically, geomorphologically and hydro-meteorological characteristics make the state more prone to a number of natural hazards such as earthquake, landslide, flood, flash flood and avalanche. Formation of natural dams by various natural hazards such as landslides, moraines and avalanches are most frequent and widespread in Higher Himalayan region due to abundance of overburden, high relief and narrow valleys. Mostly, high magnitude earthquake and persistent rainfall as secondary forces are the initiation mechanism for dam formation. Significant damage is loss of life, infrastructure, property and geo-environment from downstream flooding upon catastrophic outburst of the natural dams.

Over the past decades, Birahi Ganaga, a tributary of Alaknanda River was blocked by rock fall/slide in 1893 which forming Gauna Tal. Partial breach of this lake in 1894 and ultimate breach of the same in 1970 that caused massive devastation in the Alaknanda valley. In 1868 water displaced by landslide into Gaundyar Tal caused flash floods in Alaknanda valley. In 1978, Kanoldiya Gad, a tributary of Bhagirathi River was blocked by debris slide and breach of the dam created by the same caused massive devastation in the Bhagirathi valley. Similarly, June 2013 flooding of the Mandakini valley is attributed to the breach of moraine dammed Chorabari lake. It is observed that heavy precipitation was the main triggering factor for outbursts of all-natural dams. Recently, on 13 August, 2018 Mon Khala ridge landslide was triggered and blocked the flow of stream. The stream flow was reported to be completely stopped within about 6 to 7 hours. Increasing trend of human settlements in the close vicinity of streams is deduced to be the major cause of enhanced magnitude of damage and destruction in the region. While constructing houses in the hills, it is very important to keep respectable distance from stream and thick pile of overburden. We must follow the traditional habitation practices for building houses in the hills. Keeping these things in mind, the dangers of floods can be avoided (Rautela, 2018; Khanduri, 2020). In case of overburden, structures should be sited 200-500 meters while in rocks 50-100 meters, particularly in the hilly regions. These however depend on the specific site conditions (Khanduri et al., 2018).

The main causes of dam failure are water waves, piping and overtoppling (Evans, 2006). Because of the same, most of the natural dam's failure shortly after the formation. The potential dam breach has represented a high risk for the human beings, property and infrastructure downstream. In Himalayan regions it is impossible to stop the formation of natural dams and their outbursts. It is thus important to protect population and infrastructures by taking some preventive measures. If, any natural dams form across the streams and impounding of water left behind the dam occur for long duration. For controlling situation, investigations should be done by experienced Engineering Geologist/Geo-technical Engineers. According to their recommendations, preventive measures must be incorporated.

However, mitigative measures can prevent the failure of most landslide dams, or at least can reduce the severity of flooding: (i) diversion of inflow water before it reaches the impounded lake, (ii) temporary drainage from the impoundment by pumps or siphons, (iii) construction of an erosion-resistant spillway, (iv) open-channel spillways across the landslide dam commonly are excavated by bulldozers, (v) drainage tunnel through an abutment, and (vi) drainage conduit through the dam (Schuster, 2006). In a few cases, large-scale blasting has been used to excavate new river channels through landslide dams. This technique was used in 1981 to open a channel through the Zhouqu landslide dam on the Bailong River in Gansu Province, China. Other methods of stabilizing lake levels behind landslide dams and preventing overtopping include pipe and tunnel outlets and diversions. Both a pipe and a tunnel have been used to control discharge from Spirit Lake, Mount St. Helens, Washington and at Thistle, Utah (Costa and Schuster, 1987).

Human interference adjacent to glacial clad mountainous regions, the hazards created by glacier dammed lakes will become increasingly serious. The dangers can be mitigated by two actions: recognition of hazardous areas and surveillance of dangerous lakes in order to provide flood warnings. It is highly recommended that glacial dammed lakes hazards should be carefully evaluated by studying hydrological, glaciological, historical, and other pertinent data before planning highways, pipelines, and other economic improvements in downstream areas (Post and Mayo, 1971). In view of vulnerability to such natural hazards, it is highly recommended that the high-resolution imagery should be utilized for studying and monitoring of the natural dams, particularly in remote areas. Apart from the local people are also advised to inform the respective authority to monitor the situation when such type of dam formation occurs. By doing this, we can evacuate the downstream population to the safer places and minimize the loss of life from potential threats of natural dam's outburst floods.

7. Conclusions

Among geo-tectonically, geomorphologically and hydro-meteorological characteristics make the state more prone to a number of natural hazards. The same region has witnessed a number of natural dams formed by various geomorphic processes such as avalanches, glacial sediments/moraines, rock fall/slide, rock cum debris/debris cum rock slides, debris slides and debris flows. Later these dams breached caused massive losses of life, property, infrastructure and geo-environment to the downstream. In the present study, total of 24 natural dams is to be observed in the state of Uttarakhand region since 1857 to 2018 of which alone 58 percent has been occurred in higher Himalayan region and largely (54 percent) of incidences is to be observed in the Chamoli district. Generally, bottoms of the narrow valley, wide valley which is covered with alluvial fans are mostly witness natural dam's outburst floods. We do not know when and where such natural hazards will happen in the same region. However, their worst impacts can be prevented by avoiding of infrastructure and other developmental initiatives in close proximity to streams, over thick pile of overburden. Apart from, the impacts of natural dam's outburst floods can be mitigated by public awareness, community preparedness, prevention and better planning. In order to reduce the loss of life and property, we must follow the traditional habitation practices for building houses in the hills.

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