Debris flow hazard of glacial lake in Chitral, Pakistan

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Abstract. Glacial lake outburst floods (GLOF) 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. In Chitral, the most northern district of Pakistan, we have combined field and remote sensing research to study glacial lakes and debris flow initiation zones in periglacial areas. The study of lake dynamics and description of Lake Outburst on downstream settlement is presented. Dir Gol Lake in the north of Arkari valley has been subject to detailed monitoring since 2015. In 2015 the total area of the lake was 127,535m² which has expanded up to 146,539m² area in 2019. Although lake is stable due to the firm support of moraine boulders but due to the adjacent retreating glacier and physical condition of the surrounding area the downstream settlements are endangered by potential debris flow. Based on the analysis of physical and social-economic parameters of the glacier lakes and surrounding area respectively we determined risk index and vulnerability for the downstream settlement. Study shows that most of the glaciers in Hindu Kush region are receding, so the probability of lake development is also increasing in the region. In the future we hope to develop detailed recommendations for risk management, mitigation and adaptation measures of glacier and debris flow hazards in Chitral area.

Key words: *debris flow, lake, GLOF, anticipated debris flow, hazard, outburst*

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Селевая опасность ледникового озера в Читрале, Пакистан

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Аннотация. Паводки, формирующиеся в результате прорыва ледниковых озер, ниже по долине трансформируются в селевые потоки в результате эрозии и вовлечения твердой составляющей, что значительно увеличивает их пиковые расходы и объем и наносит разрушительный ущерб в низовьях реки. В Читрале, самом северном округе Пакистана, мы объединили полевые и дистанционные исследования для изучения ледниковых озер и зон зарождения селевых потоков в перигляциальных районах. В статье представлено изучение динамики озер и описание последствий прорыва озера для населенного пункта ниже по течению. Озеро Дир Гол, расположенное на севере долины Аркари, стало объектом детального мониторинга с 2015 г. В 2015 г. общая площадь озера составила 127 535 м^2, а в 2019 г. она увеличилась до 146 539 м^2. Несмотря на то, что озеро стабильно благодаря тому, что подпружено крупнообломочными моренными отложениями, наличие выше отступающего ледника и физическое состояние окружающей территории объясняют высокий уровень потенциальной селевой опасности для населенных пунктов, расположенных ниже по течению. На основании анализа физических и социально-экономических параметров ледниковых озер и прилегающей территории мы определили индекс риска и уязвимости населенных пунктов ниже по течению. Исследования показывают, что большая часть ледников в горах Гиндукуша отступает, поэтому вероятность формирования озер в этом районе также возрастает. В будущем мы надеемся разработать подробные рекомендации по управлению рисками, смягчению последствий и мерам адаптации к опасностям, связанным с ледниками и селевыми потоками в округе Читрал.

Ключевые слова: *селевой поток, озеро, прорыв ледникового озера, прогнозируемый селевой поток, опасность, прорыв*

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Introduction

Glaciers in high mountain regions benefit human civilization by serving as sources of drinking water, irrigation, and energy generation, but they also pose occasional hazards such as glacial lake outburst floods (GLOFs) and ice avalanches, causing human casualties and economic losses in downstream areas. Debris flows associated with glacier are common mountain hazard, and are driven by climate and weather conditions as well as by glacier dynamics and geological features. In recent decades Hindu Kush-Himalaya (HKH) glaciers have been shrinking and thinning [*Kaser et al., 2006; Zemp et al., 2009; Fujita et al., 2011; Kargel et al., 2011; Scherler et al., 2011*] resulting glacier to retreat. After the termini retreat the vacant area in between the moraine and retreating glacier snout is taken over by proglacial lakes. Such glacier phenomenon and lake formation is currently observed in the majority of glaciated mountain regions of the world including the Himalayas and Karakoram. These glacial lakes often dammed by ice-cored moraines are main sources of devastating outburst floods. These outburst events often transform into more destructive debris flows when the flow path is steep, flow velocity is high and erodible material is available [*Clague et al., 1985; Clague et al., 1992; Huggel et al. 2004; Kaab et al. 2005; Chiarle et al. 2007*], threatening downstream settlements and infrastructure. In comparison with other glacier hazards, GLOFs are widespread and impact several kilometers downstream from the source. Such sudden outburst may lead to widespread damage and result in fatalities. Pakistan has witnessed several GLOF events in the past. A series of studies carried out between 2002 and 2005 in Pakistan identified a total of 5,218 glaciers with an area of 15,041 sq.km, and 2,420 glacial lakes out of which 52 were considered potentially dangerous [*Roohi et al., 2005*]. Gilgit-Baltistan region is said to have witnessed more than 35 GLOF events in the past 200 years [*Watkins, 2007*]. In recent past too, we have witnessed GLOF events. Two GLOF events, one in Brep village in Upper Chitral in 2005 and other in the village of Sonoghur in 2007 displaced 100 families and damaged valuable cultivable land and infrastructures [*Haq, 2007*].

Surrounded by some of the tallest and highly glaciated mountains, the Chitral District of northern Pakistan lies in the eastern Hindu Kush Range (Fig. 1). The district has an area of 15,000 km^2 and spans within an elevation range from 1000 m to 7700 m above sea level. A common geomorphic feature of the Chitral region is valley facing slopes associated with high-relief Mountains, which merge into broad, relatively flat floodplains. The region is prone to occasional heavy precipitation, snow avalanches and glacial-lake outbursts that cause flooding of the fans, damaging life, property and crops. At least a dozen human casualties are associated with snow avalanches, floods and debris flows in the eastern Hindu Kush every year [*Haq, 2007*]. Roohi et al. [*2005*] reported 187 glacial lakes in the Chitral basin covering an area of 9 km^2 [*cf. Ives et al., 2010*].

The paper presents the debris flow hazard case study from a Dir Gole lake in the Arkari valley. The lake located at latitude 36°10'54.38"N °and longitude 71°47'57.46"E is at an elevation of 4613 m with north-south orientation. It is a moraine dammed lake. The nearest settlement is Safaid Arkari and is situated at a distance of 13 km downstream at 2575 m asl altitude. The geology of the area is composed of Meta sediments which are intruded by granodiorites such as the Tirich Mir Pluton [*Calkins et al., 1981*]. The climate there is temperate type with warm summer and very cold winter. Mean summer temperature ranges from 22°C to 24 °C while winter temperature ranges from -4°C to -6°C.

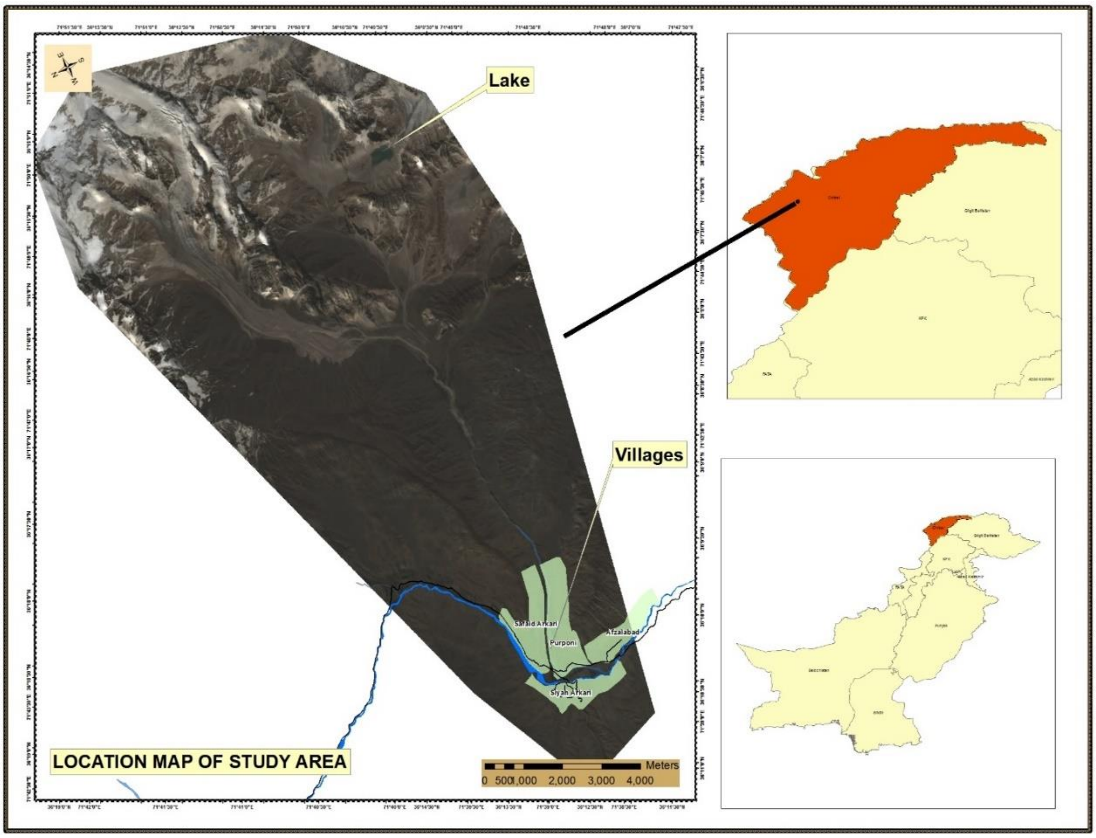

Fig. 8. Location map of the study area

Specific aims of our study are as follows: i) to prepare a comprehensive assessment of GLOF hazard, risk and vulnerability ii) to determine the fluctuation in glacial lake area, volume and iii) to describe the impact of lake burst on the downstream settlement.

Brief Review of the Problem

Geo hazards in the Karakoram have been subject of a few studies in the past [*e.g., Derbyshire and Owen, 1990; Derbyshire et al., 2001*], but the adjacent eastern Hindu Kush remained unexplored due to inaccessibility [*Khan et al., 2012*].

In spite of presence of several glacial lakes in Chitral, assessment of glacial lakes from the point of debris flow risk has not yet been sufficiently researched. The lakes have not been systematically surveyed. It is extremely important to improve our knowledge of glacial-lake formation features, estimate lake volumes and areas, and assess the hazard of outburst floods and debris flows. Up to now, in the region conclusions are drawn mainly on small amounts of direct field data. The outburst trigger mechanism is poorly understood as well as the relations between the lake volume and the debris flow discharge.

Data

Multi-temporal Sentinel 2A images with 10m resolution of the study area were downloaded freely from Sentinels Scientific Data Hub (https://scihub.copernicus.eu/), for 2015 & 2019. Settlement area, road network, drainage network were manually digitized. The digital elevation model (DEM) with 30m spatial resolution was downloaded from Earth Explorer website for generating slope and contour maps. Land cover data of 2015 and 2019 were sourced from Sentinels Scientific Data Hub website and were of 10m spatial resolution. These images have cloud cover less than 20%.

Vector data like road network, settlement area, and drainage network and debris flow path were digitized manually in ArcGIS 10.7. Debris flow path was further verified on field by the Geologists of Aga Khan Agency for Habitat, Pakistan. These data were overlaid on the satellite imageries as base map.

Temperature data were taken from Weather Monitoring Post (WMP) installed by Aga Khan Agency for Habitat at Rabat Mukhi Arkari valley. Physical parameters of the lake and surrounding area, pictures, household data, demographic data and infrastructure data were collected during field survey conducted from 08 to 14 of August of the 2019.

Methods

Lake area change

This study is based on primary data collected from field and secondary data obtained through remote sensing. Mainly, linear stretching and histogram equalization were used to improve image contrast. The enhanced images were taken to ArcGIS 10.7 software for visual interpretation and image classification. The lake area was mapped using supervised classification which was later converted to vector for further calculation. Fig. 2 provides workflow used for this study. Both manual digitization and supervised classification technique were adopted to generate input data. The downloaded images which were in raw format were first imported in ArcGIS and four bands such as B2, B3, B4 and B8 of 10m spatial resolution were layer stacked followed by image enhancement done in ILWIS 3.4 software to enhanced improve visualization.

Lake volume estimation

Although there is no better alternative to field based bathymetric survey in case of lake volume estimation, an empirical equation established by Huggel et al, 2002 is used in this study. This approach has been used by many researchers mainly to overcome lack of field data which is hard to come. The empirical equation expressed volume, V (in m^3) of a glacial lake as a function of the area A (in m^2) as in Eq. 1:

$$V = 0.104A^{1.42}, \tag{1}$$

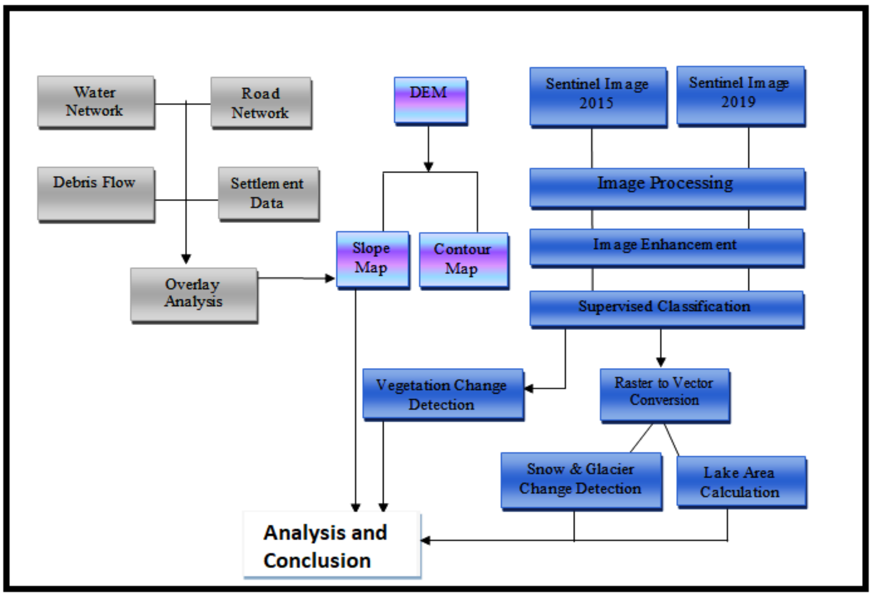

Fig. 9. Work flow diagram

Cause of the GLOF

A team of geologists were fielded for field assessment to understand potential causes that resulted in the GLOF. The team made visual observation of associated glacier features like hanging glaciers, glacial retreat and assessed possibility of ice avalanche, ice calving, rock fall or rock slope failure.

Data analysis

We carried out detailed surface area mapping around the lake, downstream hazard vulnerability risk assessment and bathometry of the lake using Remote Sensing and empirical formula respectively to determine the lake's development processes and assess the prospect of the GLOF from the lake. The surface area and volume of the lake in 2015 and 2019 are given in the Table 1.

Table 5. Calculated lake area and volume, Volume calculation is based on Eq. 1

#	Lake	Area 2019 (m^2)	Area 2015 (m^2)	Difference in Area (m^2)	Volume 2019 (m^3)	Volume 2015 (m^3)	Difference in Volume (m^3)	Status
1	Dir Gole Lake	146,539	127,535	190,004	2,252,614.8	1,849,383.8	403,231	Both Increased

This lake is dammed by a glacial moraine, which is strong enough to sustain the pressure for a longer period of time. But other factors that are reducing the reliability of the dam are the secondary hazards which are in direct contact with the lake, and in case of their reactivation, they can put severe impacts on the dam. There are five potential sites of the snow avalanche activity where debris along with snow may fall directly into the lake producing a strong wave. This strong wave of water will increase the pressure on the dam and ultimately will increase the probability for its outburst. The presence of small lake towards the downstream side of the understudy lake also indicates the presence of hidden channels passing through the dam which may weaken the shear strength of the dam. Almost 5 villages settled along either sides of the Dir Gole are critically studied for the expected flood from Lake. With few exceptions, major areas of all the villages will be affected from this flood.

Glacier recession and changes in lake area and volume

Remote sensing-based assessment of the surrounding glacier in the study area indicates that the glaciers have retreated by 410 m from 2015 to 2019. As a result of glacier retreat and substantial ice melting the glacial lake has grown in area from 127,535 m^2 to 146,539 m^2 and volume from 1,849,383.8 m^3 to 2,252,614.8 m^3 (Table 1). It is clear that the lake has drastically expanded from 2015 to 2019. The expansion of lake area in the southern and south western part is more due to the recession of glacier and breakage and falling of crevasses into the lake respectively. Towards the north the lake has shrunk due to the firm support of moraine materials and backward movement of lake area toward the southern part.

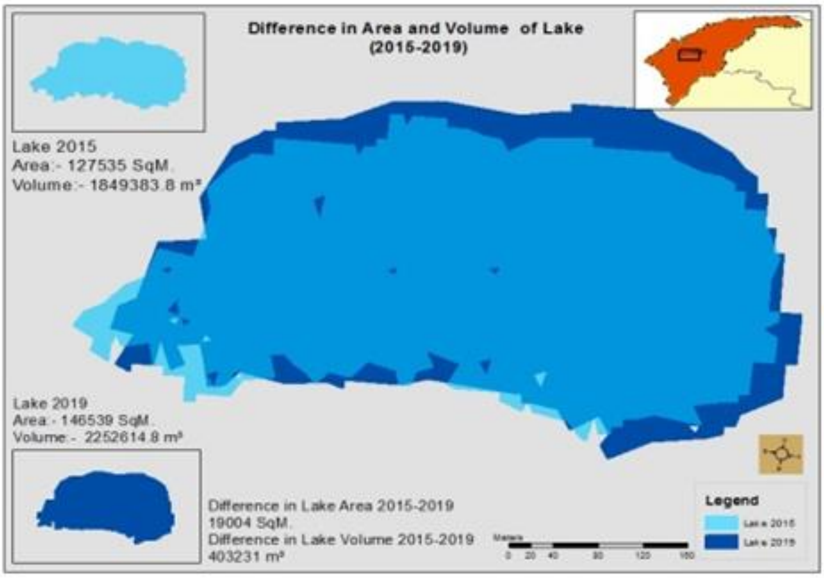

Fig. 3. Difference in lake area and volume (2015 and 2019)

Fig. 4. Snow and glacier distribution (2015-2019)

Fig. 5. Picture of receding glacier snout

Elements Exposed to a Potential GLOF

Using slope map, debris flow path for potential debris flow is generated and used to map out elements exposed to the event. This was cross checked using contour map with 10 m contour interval. It was further verified by demarcating anticipated debris flow path during field visit.

The initial 6 km stretch of the downstream areas for about Dir Gol Lake is almost uninhabited. However, many people from downstream communities commute and install temporary huts in the pasture land from June to August for grazing their sheep and goats. The temporary movement of community towards the pastureland makes them more vulnerable to potential GLOF as the site is very near to debris flow tract. In addition, high temperature in July and August accelerate the melting of glacier, which further add more water to the lake and increase the probability of Lake Outburst.

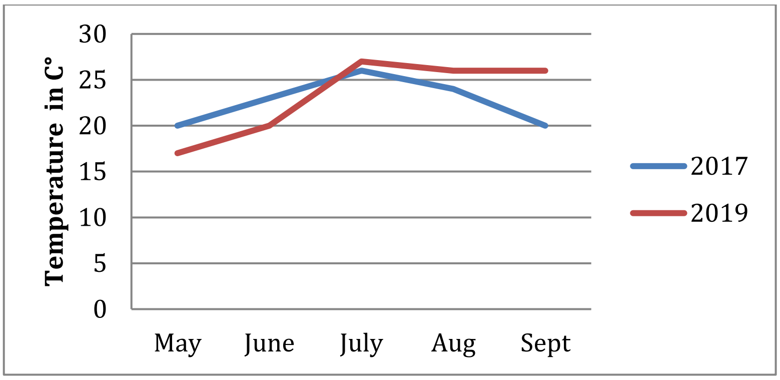

Fig. 6. Mean monthly temperature, Rabat Mukhi WMP

A potential GLOF can have downstream impacts at three different levels: households, vegetation area, and infrastructures.

Table 6. Impact of GLOF

Houses	131 households with 858 populations
Infrastructure	four schools, office building, two Jamat Khanas, trails, roads, embankment structures, bridges, irrigation channels, water mills, shops, welfare center, Aga Khan Health Center, heliport, dispensary, food store and transmission lines.
Vegetation	Forest, grazing land and crop land.

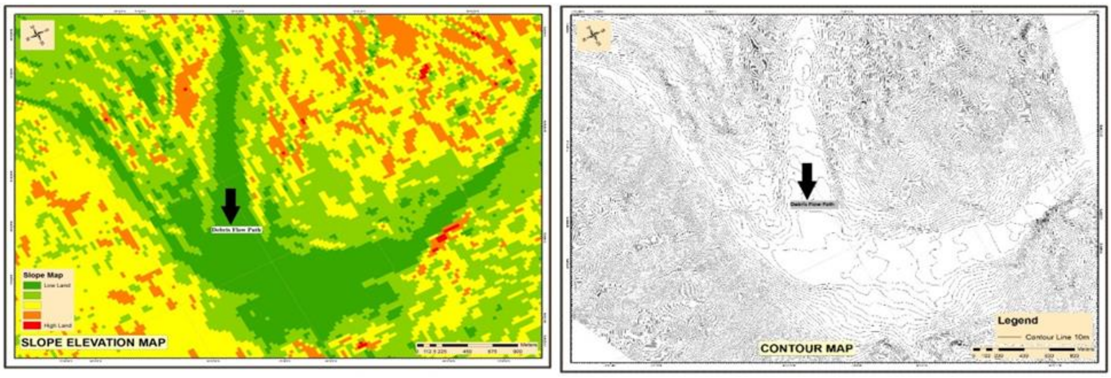

Fig. 7. Slope elevation map and contour map of study area

It was observed that the debris flow may block Arkari River and create artificial lake which will create secondary hazards in the form of bank erosion for some of the houses and infrastructures at Safaid Arkari village along the river bank. If this debris dam remains for some days, the stored water will damage the settlements lying in the lower reaches of the valley up to Ruji more severely than the anticipated GLOF.

Assessment of vegetation and stream width

The changes in vegetation cover can be identified clearly. The green part shows vegetation, including forest covered area, crop land and shrub land while the other shows barren land and buildup area. As both the images were of same month, so by visual interpretation it is obvious that vegetation has decreased and the debris path has increased width wise from 2015 to 2019 in the perennial stream. Therefore, it can be interpreted that in case of out bursting it will erode and affect more area than the perennial stream covered. This was substantiated through field observation where sediment deposition has raised the water level and transformed the gorge into shallow stream due to which bank erosion has occurred at both sides, and widened the stream width and decreased vegetation cover along the sides.

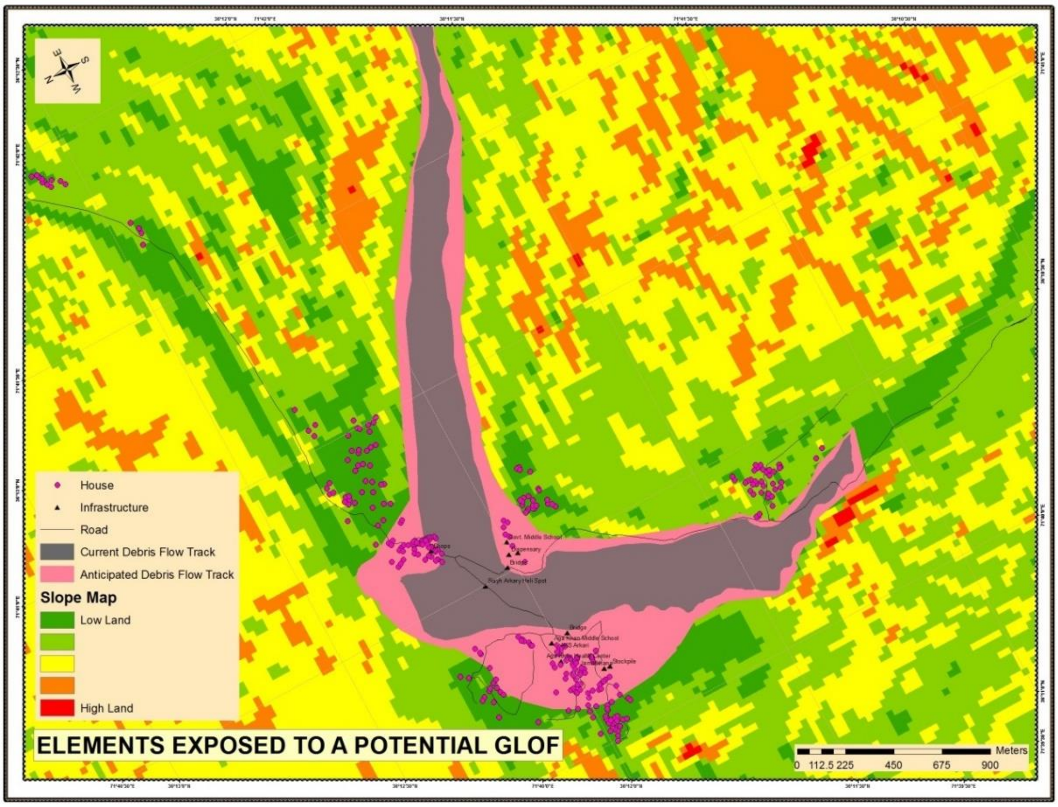

Fig. 8. Elements exposed to potential GLOF

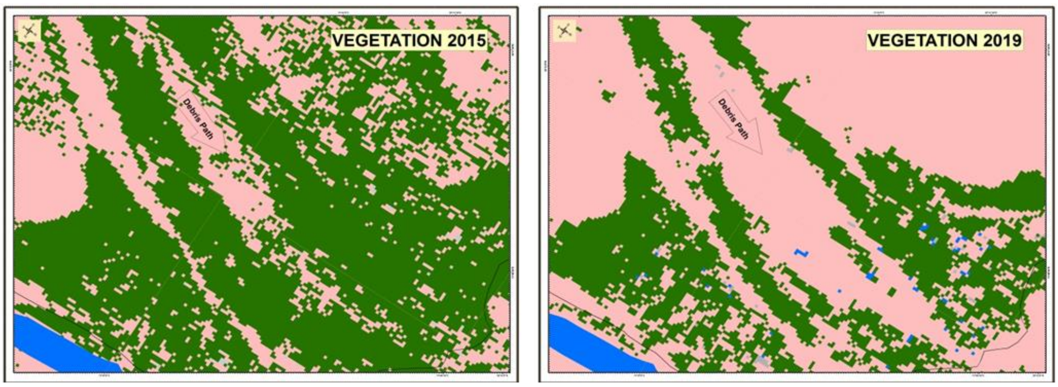

Fig. 9. Decrease in vegetation and increase in debris flow path in the study area between 2015 and 2019

Conclusion

In this study assessment of GLOF hazard and impact of Lake Outburst on the downstream settlement is presented. Although outburst debris flows have been rare in the region, but recession of glacier, expansion of lake and prominent seepage water in the terminal moraine dam means that surge waves can overtop the dam triggering an outburst. Study indicates that the lake can become unstable as surge waves as a result of ice and rock avalanches striking their surface could cause overtopping of end moraine. The study clearly shows that people living downstream of the glacial lakes are at risk from GLOFs. Their lives and property, including infrastructure and crop land are vulnerable. To reduce the impact of GLOFs, we can also increase the preparedness of the community which is settled on the areas laying low along the valley through which water from out bursting lake will flow. Proper planning of land use should be placed in which should focus on using the areas or zones of higher vulnerability for the purposes other than human settlements, i.e., for agriculture or for farming. Enhancement of the coping and adaptive capacity of local governments and communities, reducing of water volume in the lake and establishment of appropriate early warning systems are recommended.

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