Glacier lake outburst flood modeling of Khurdopin glacier lake using HEC-RAS and GIS

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Abstract. Advancement of glaciers and dammed the river is common phenomena is glaciated region of worlds, especially Himalaya Hindu Kush (HKH) ranges. Region wise Karakorum is well known to formation of glacier lakes due to glacier damming of river and glacier lake outburst flood, particularly Shimshal valley has been affected by Glacier lake outburst flood (GLOF) in last 2 decades. Khurdopin glacier located in upper reaches of Shimshal village is one of the surging glaciers in Karakorum region. The glacier lakes release large amount of water abruptly under the glacier blocked area at 27th July till 03th August 2017 damages Shimshal road and bridges. This study includes Glacier lake outburst flood (GLOF) simulation modelling using HEC-RAS and GIS couple with field data acquired through aerial survey conduct under Aga Khan Development Network helicopter and field assessment were carried out with geologist and glaciologist expert from Aga Khan Agency for Habitat (AKAH) and Pakistan Meteorological Department (PMD) collectively. The finding of study revealed that Lake Area is 14.8 hectares in 24 November,2017 with 476922 cubic meter volume of water, Satellite data also revealed that glacier advancement since October 2016 to November 2017. Glacier has blocked approximate 2.3 km length of Shimshal River. According to GLOF modeling results, total 3.21 square kilometre area submerge by GLOF. The velocity of flood in Shimshal village is high as compared to Farmanabad. The GLOF time arrival information shows that Shimshal village submerge 3.059 km^2 area while Farmanabad flooded 0.53 km^2 area with in sixty minutes.

Key words: *GLOF, HEC-RAS, PMD, AKAH*

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Моделирование паводка, сформировавшегося в результате прорыва ледникового озера Хурдопин, с использованием программы HEC-RAS и ГИС-технологий

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Аннотация. Продвижение ледников и подпруживание рек – обычное явление в ледниковых регионах мира, особенно оно характерно для горных хребтов Гиндукуша, Каракорума и Гималаев. Регион Каракорума хорошо известен своими ледниковыми озерами, формирующимися вследствие подпруживания рек ледниками, а также их прорывами. В этом свете особенно стоит отметить долину р. Шимшал, в которой прорывы озер за последние 20 лет происходили неоднократно. Ледник Хурдопин, расположенный в верховьях р. Шимшал, является одним из пульсирующих ледников Каракорума. Так, в результате одной из его пульсаций произошло формирование подпрудного озера с последующими его прорывами, наблюдавшимися с 27 июля по 3 августа 2017 г. и сопровождавшимися выбросами больших объемов воды, что в итоге привело к разрушениям Шимшальского шоссе и мостов. Данное исследование включает в себя моделирование прорывного паводка с использованием программы HEC-RAS, ГИС-технологий и полевых данных, полученных в ходе аэрофотосъемки, проведенной с помощью вертолета Агентства развития Ага Хана Хабитат, а также полевую оценку, проведенную совместно со специалистами геологами и гляциологами из Агентства Ага Хана Хабитат и Метеорологического департамента Пакистана (PMD). Результаты исследования показали, что 24 ноября 2017 г. площадь озера составляла 14,8 га с объемом воды 476922 м^3. Данные космосъемки также показали, что продвижение ледника происходило с октября 2016 по ноябрь 2017 гг. Ледник заблокировал р. Шимшал на участке длиной около 2,3 км. Согласно результатам моделирования прорывного паводка, общая площадь территории, подвергшейся воздействию, составил 3,21 км^2. Скорости потока в селении Шимшал были выше, чем в Фарманабаде. Время добегания паводка до селения Шимшал с затоплением 3,059 км^2 территории и до селения Фарманабад с затоплением в 0,53 км^2 территории составило 60 мин.

Ключевые слова: *прорыв ледникового озера, программа HEC-RAS, Метеорологический департамент Пакистана (PMD), Агентство Ага Хана Хабитат (AKAH)*

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Introduction

Advancement of glaciers and dammed the river is common phenomena is glaciated region of worlds, especially Himalayan Karakorum Hindu-Kush (HKH) ranges [*Quincey et al. 2014; Hussain, 2019; Gillani, 2014*]. Region wise Karakorum is well known for formation of glacier lakes due to glacier damming of river and glacier lake outburst flood [*Khan et al., 2011; Ashraf, 2014*]. In extreme cases surging tongues of glaciers blocked rivers, streams and subsequently threatens downstream communities in case accumulated water breaks through the ice or discharges rapidly over the tongue or through Glacier curves [*Ashraf et al., 2012*]. Since these tongues are often located in remote areas far away from the settlements itself adequate warning mechanisms are challenging [*Round et al., 2017*].

Khurdopin glacier in Shimshal valley is surge type and a recent surge of the glacier measure using high resolution satellite imagery readily available at sub-weekly intervals able to assess changes on the glacier, monitoring of possible threats and make an assessment of probable future developments [*Steiner et al., 2018*]. Glacier lake outburst flood (GLOF) is demonstrated by quick discharge of large volume of water with residues taken from glacier lake and that movement down along with river channel towards downstream settlements in the form of flood upsurge [*Gurung, 2017*]. GLOF happened when lake break due to high pressure of stored water, seepage forces and shear stress factors that surpasses the strength of blocking material [*Worni et al., 2013*]. According to ICIMOD 2005 inventory of glaciers and glacier lakes which described that the trend of increase in temperature in the Himalaya, Karakoram and Hindukush (HKH) regions is higher than global average. The inventory has listed a total of 2420 glacier lakes that have been identified in ten (10) river basins and the maximum number of glacier lakes are identified in Gilgit River basin (614) followed by Indus (574) and Swat (255) and Shingo (238) river basin. In Gilgit River basin, out of 614 glacier lakes 380 lakes have been identified as major lakes which are about 62% of the total lakes. Around 93% of the lake area of the basin is contributed by these major lakes. There were 52 potentially dangerous lakes in HKH mountain regions of Pakistan, among these potentially dangerous lakes 16 lakes were identified in Karakoram ranges [*Zaidi et al., 2013; ICIMOD, 2005*].

Gilgit-Baltistan has witnessed around 35 GLOF events in past 200 years [*Rasul, G. 2014*]. In 1999, two GLOF events occurred in Sosot and Khalti villages in Tehsil Gupis. In 2000, GLOF events occurred in Shimshal valley. From the year 2007 to 2017 (Table 1), six consecutive Glacier floods events took place from the Ghulkin glacier only, which caused the destruction of the Karakoram highway and local property. GLOF event occurred from Khurdopin glacier [*Din, Tariq et al., 2014; Hassan et al., 2020 and Richardson, Quincey, 2009*]. In 2009, one GLOF event was triggered from the Passu glacier. In 2012, a GLOF event from Ghulkin glacier damaged hundreds of trees. Thus, HKH glaciers in general and the Karakorum glacier in particular, have generated more GLOF events in the area since 2007 [*Ashraf et al., 2017*]. It is imperative. Shimshal village was inundated by riverine floods from 27th July till 3 of August 2017. River level rose to double and flooded low lying areas in Shimshal Centre, Aminabad and Farmanabad which as reported damaged Shimshal road, Bridges and low-lying land in Shimshal village (AKAH Geologist) mentioned in Table 1.

Table 1. Historical GLOF events in Gilgit Baltistan

Date of the event	**GLOF Location**	**River**
29 July 1994	Sosot/ Gupis	Gilgit
6 August 1999	Khalti/ Gupis	Gilgit
10 June 2000	Shimshal	Hunza
27 July 2000	Kand/ Hushe	Indus
25 July 2005	Sosot/ Gupis	Gilgit
5 April 2007	Ghulkin	Hunza
6 January 2007	Passu	Hunza
2 April 2008	Ghulkin	Hunza
22 May 2008	Ghulkin	Hunza
24 May 2008	Ghulkin	Hunza
15 June 2008	Ghulkin	Hunza
26 March 2009	Ghulkin	Hunza
8 July2012	Sosot/ Gupis	Gilgit
2010	Shimshal/ Khurdopin	Shimshal Stream
2017	Shimshal/ Khurdopin	Shimshal Stream

A glacier lake is water body formed on the surface, sub surface and near the glacier through glacier melting and retreating processes. When glacier melts, empty spaces were developed and filled by melt water and rapidly increases in volume of water [*Yao et al., 2018*]. Glacier lakes are classified based on their topographic location i.e. In glacier, Sub glacier, moraine dammed lakes and ice dammed lakes. Most glacier lakes in HKH regions formed through glacier retreat and advancement and dammed the rivers, the lake water controlled by unstable frontal lake moraine [*Gardelle, 2011*]. In 2007, IPCC reported that there will be increase in temperature in Himalayan region between 1° to 6°C by 2100 [*Singh et al., 2005*]. This resulted in the high melting of glacier ice and snow cover would reduce between 43-81% leaving behind more glacier lakes in the future [*Banerjee, 2013; Rasul et al., 2011*].

The physical characteristics of glacier lake outburst flood are the rapid release of large volume of debris laden water originates from an upstream glacier lake that flows down along stream or river course in the form of flash flood [*ICIMOD, 2011*]. The breach of the lake is caused primarily by the weakening of the lake capacity and strength to hold water that exerts force on the walls of the lake, leakage forces and stress due to overtopping of water flow. Other factors would be heavy rainfall and instant inflow of large volume of water from upstream water sources that leads to over flow of the water from the lake due to which soil erosion occurs from the dam front. The eroded material weakens the lake strength and ultimately leads to higher outflow of water in the form of flood. The outflowing water applies shear forces on the dam material and eroded debris that spreads downstream as bed load. These debris loaded flood water have a discharge rate of several thousand cubic meters per second. The severity of the flood is the function of the volume of released water, debris/material load and ground features of the basin of the watershed [*Worni et al., 2012*].

Scenario base flood risk mapping is very important for local government, organizations to developed future flood plan and mitigation measures in flood plain area as well as will helpful for sustainable development like construction of hydropower plants and other critical infrastructures like bridges and houses [*Merz et al., 2007*]. HEC-RAS is an integrated system of software, designed for interactive use in a multi-tasking environment. The system is comprised of a graphical user interface (GUI). Separate analysis components, data storage, management capabilities, graphics and reporting facilities (Brunner, G. W 1995). The HEC-RAS system contains one and two dimensional river analysis components for: (1) Steady flow water surface profile computations: (2) Unsteady flow simulation: (3) movable boundary sediment transport computations: and (4) water quality analysis. A key element is that all four components use a common geometric data representation and common geometric and hydraulic computation routines (Bates, 1996). The objective of this research was to perform GLOF simulation using unsteady flow analysis method in HEC-RAS environment of Khurdopin glacier lake based on 2017 flash flood scenario occurred from newly formed lake through damming of Khurdopin glacier of Shimshal river. GLOF hazard exposure and risk were calculated in Arc GIS environment.

Study area

Khurdopin newly form Glacier Lake (Fig. 1) is located in between Khurdopin and Virjerab glaciers in Shimshal valley situated in the North of Gilgit representing North Karakoram with approximately 70 km length and covering an area of 2763.5 km^2. The valley runs East-West direction parallel to Karakoram main ridge. The Shimshal settlement is located at a distance of 50 kilometres approximately Eastward from main Karakoram Highway and can be reached by passing through narrow gorges via un-metalled road completed in 2003-2004. The Shimshal settlement is located at an elevation of 3100 m a.s.l. and is one of the highest settlement in Gilgit-Baltistan (GB) with no proper infrastructure. There are four hamlets in Shimshal namely Farmanabad, Aminabad, Centre Shimshal, and Khizerabad with a total population of 2000 inhabitants residing in 250 houses approximately.

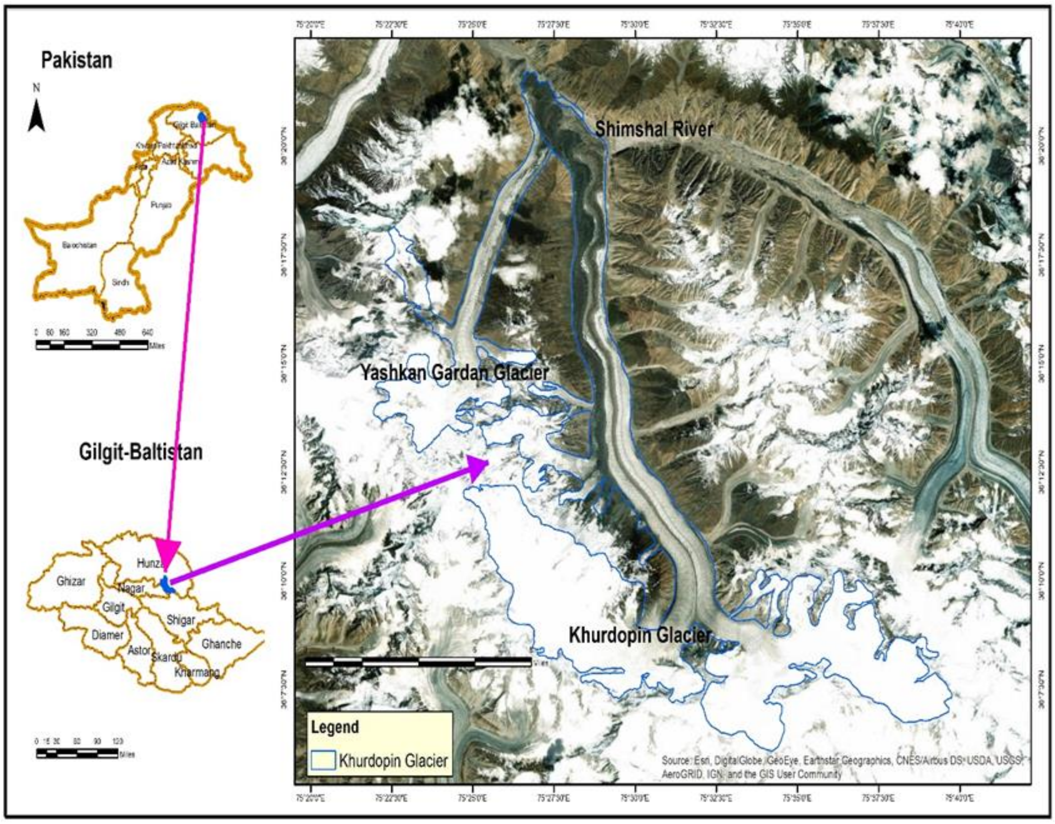

Fig. 1. Location map of study area

Methodology

Three tier methodologies were used to simulate the glacier lake outburst flood (GLOF) for Khurdopin glacier lake of Shimshal valley. The methodology steps include i) pre-processing ii) processing iii) post processing [*Wang et al., 2012*]. Work flow diagram shows the detail of these steps. Pre- processing steps include acquire of high-resolution digital elevation mode (DEM) from FOCUS Pakistan and remove the error from DEM through sink and fill tool. Downloading and pre-processing of sentinel and Landsat satellite images as well as acquired field pictures through aerial survey through AKDN helicopter and filtering of field data acquired in collaboration of FOCUS Geologist, AKCSP engineers and glacier monitoring team (GMT) working under FOCUS Pakistan for monitoring of glacier lake [*Yang et al., 2016; Hussain A. & Hussain A. 2019; Shrestha et al., 2010*]. Processing steps include delineation of new formed glacier lake boundary through normalized difference water index (NDWI) and volume calculation using functional surface tool in Arc GIS environment [*Huggel et al., 2002; Hussain, Bano, 2019*]. Terrain development using RAS Mapper is Geospatial tool (GIS) in HEC-RAS platform, prepared geometrical data in geometric window of HEC_RAS (5.0.0). Geometric data include creation of mesh (2D flow area) for two-dimensional modeling in HEC_RAS and set up of boundary condition (upstream and downstream), insert of unsteady flow data based on 2017 flood event discharge data and calculated outburst discharge data of Khurdopin glacier lake, after discharge data insert GLOF scenario was developed using 2-dimensional unsteady flow routing (full Saint Venant equation or also called as Diffusion wave equation). In unsteady flow analysis window, we have set up program to run, simulation time, and computational setting [*Konan, 2018; Hussain et al., 2018; Zaidi, 2013*]. The results of flood surface i.e. flood depth; velocity and WSE were exported from RAS mapper, which imported in Arc map to calculated flood exposure like land cover flood exposure statistic using overlay of flood surface polygon with land use land cover shape file using intersection tool in arc map. Vulnerable road and bride along Shimshal river were also identify and measured using overlay analysis tools in arc GIS environment [*Khattak, 2016; Azouagh, 2018*].

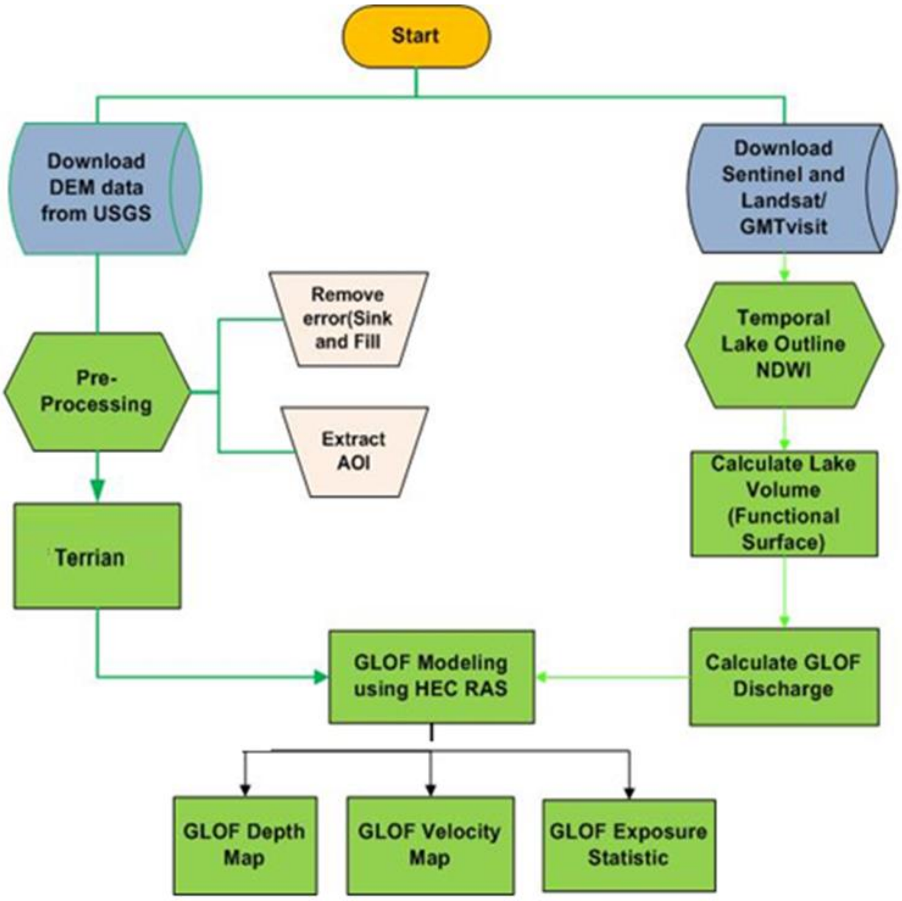

Fig. 2. The work flow diagram of research methodology

Results and discussion

The study was conducted with the aim to produce a glacier lake outburst flood model by the application of HEC-RAS, GIS and Remote Sensing approaches to assess and analyse the impact on downstream settlements in Shimshal valley [*Shrestha, 2010; Zaidi, 2013*]. Temporal satellite images and pictures of Glacier Lake were taken through of AKDN Helicopter of Khurdopin glacier revealed that the lake has been drained through underground water channel of glacier dammed site, which generate riverine flood from 27th July till 3rd August 2017 in Shimshal valley [*Hussain, 2019*].

Fig. 3. Temporal aerial photographs 16 June and 7 August of 2017 from Helicopter

River level rose to double and flooded low lying areas in Shimshal Centre, Aminabad and Farmanabad which as reported damaged Shimshal road, Bridges and low-lying land in Shimshal village (Geologist FOCUS Pakistan).

The advancement of glacier toward river has started since October 2016, In July 2017 glacier blocked 0.3 km^2 of river with volume of 6.2 million m^3 furthermore, the movement of glacier drastically increase and blocked the river area 0.7 km^2 till 24 November 2017 with 23.8 million m^3 volume of glacier deposits [*Steiner et al., 2018*]. Fig. 4 show the glacier surge temporal view of Khurdopin glacier blocked the Shimshal river, pink line shows the glacier boundary before surge, yellow and red line shows the glacier surge and blocked area while blue polygon demonstrations the newly formed glacier lake temporal boundaries.

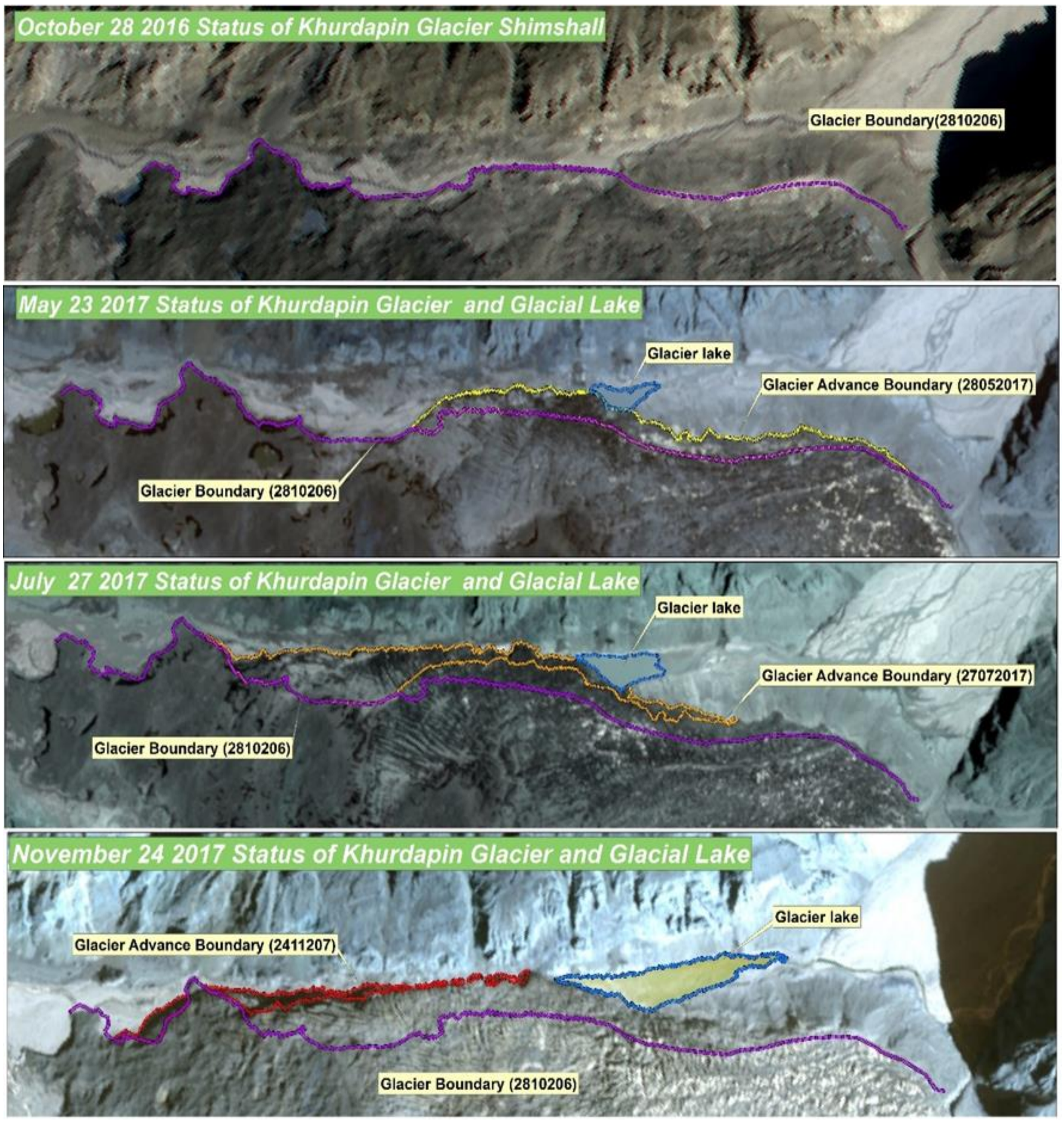

Fig. 4. Temporal view of Glacier blockage and Glacier Lake variation

Table 2. Glacier blocked area and volume statistics from 28 October 2016 to 24 November 2017

Date	**Area, km^2**	**Volume (Glacier deposit), million m^3**
23 May 2017	0.10	0.8
27 July 2017	0.27	6.2
24 November 2017	0.34	16.6

Glacier lake was formed at upper part between Virjerab and Khurdopin glacier. The Khurdopin glacier blocked 963-meter length of Shimshal river from 27 October, 2016 to 23 may, 2017 furthermore it blocked 1036-meter length of river from 24 May- 27 July 2017 and 365-meter length of river blocked by glacier from 27 July – 24 November 2017.

Table 3. Temporal river blockage by Khurdopin Glacier

Date	**River blocked Length. m**
27 Oct 2016- 23 May2017	963
24 May- 27 July 2017	1036
27 July – 24 November 2017	365

Image analysis like delineation of glacier lakes was carried out by using normalized difference water index (NDWI) for calculation of glacier lake area for 24 November 2017. Digital elevation model (DEM) and glacier lake outline boundary of 24 November, 2017 was used to calculate the volume of lake using functional surface tool in Arc GIS environment. Total area of lake is 0.15 km^2 (14.8 hectare) with 476922 m^3 volume of water (Table 4) [*Watson et al., 2018*]. Fig. 5 shows lake area in blue polygon.

Table 4. Lake Area Coverage and Volume

Date	**Area (Sq.km)**	**Shape_Area (Hectare)**	**Volume Lake (Cubic meter)**
24 November 2017	0.15	14.8	476922

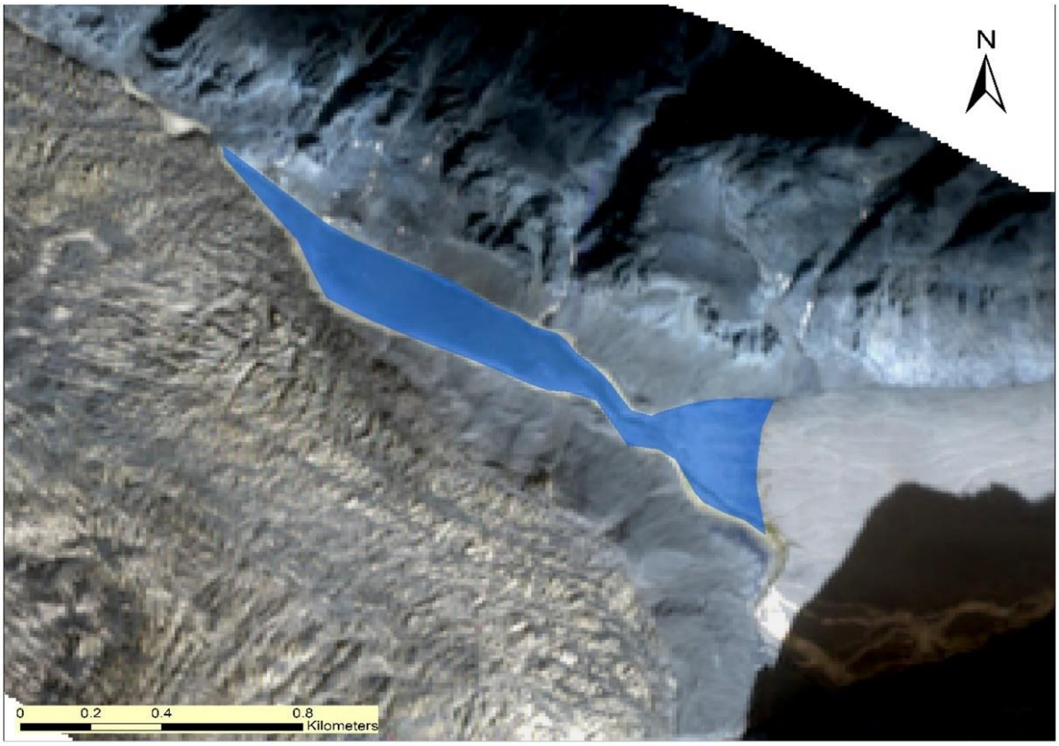

Fig. 5. Glacier lake boundary, 24 November 2017

Glacier lake outburst flood scenario developed based on 2017 flood event combined with GLOF discharge data calculated based on below scenarios occurred from the Khurdopin glacier lake. The projected outburst frontal moraine width is 110 m, depth is 10.23 m with 6.28 m/sec velocity of water. The peak GLOF discharge in case of outburst of lake as per scenarios in Table 5 is 2155.3 meter/sec [*Somos-Valenzuela et al., 2015*].

Table 5. Peak Scenario Discharge Rate

Width (m)	**Depth (m)**	**Velocity (m/sec)**	**GLOF discharge (m/sec)**
110	10.23	6.28	2155.296

Glacier lake outburst flood first hit the Shimshal village affected the 3.21 square kilometre area according to peak scenario. The flood depth area varies with respect to topography below (Fig. 6) show the depth of GLOF 0-15 meter with flooded area is 1.91 while 0.79 sq.km area is submerged in Farmanabad village of Shimshal valley, the detail is shown in below graph depth in meter verse submerge area in sq.km the results show that Shimshal village is more affected than Farmanabad village. The flood depth of simulated show close coordination with real flood occurred in 2017 from Khurdopin glacier lake (Table 6).

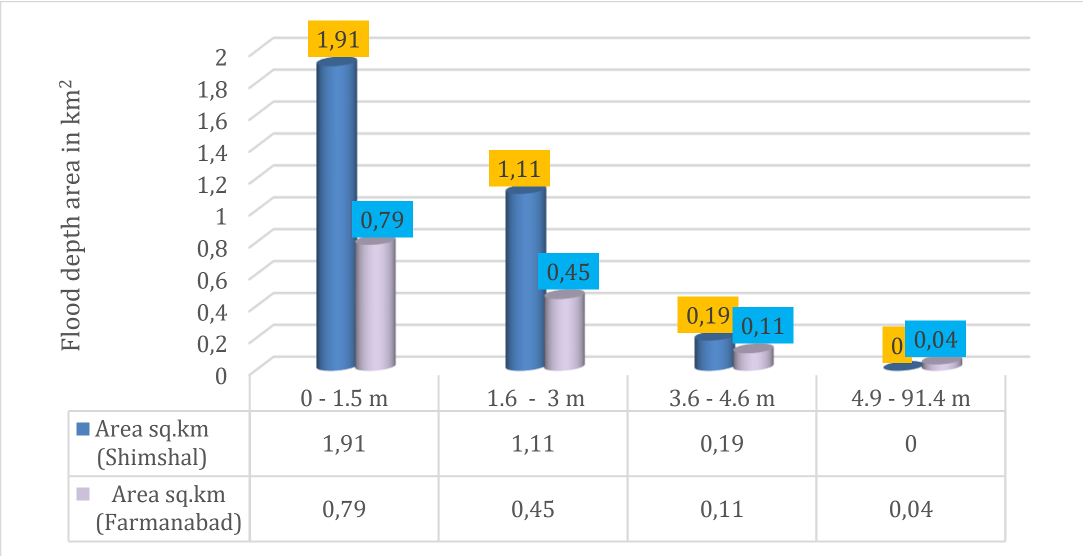

Fig. 6. GLOF depth in meter in Shimshal and Farmanabad village

Table 6. Comparison of Simulated and Real GLOF in specific location

GLOF (Simulated and Real)	**Shimshal**	**Farmanabad**	**Floodplain area**
Simulated GLOF depth in meter	1.5	3.2	4.7
Real GLOF depth in meter	1.7	3.4	4.8

GLOF depth map (Fig. 7) shows the flood depth surface of Shimshal and Farmanabad village and inundation area of agriculture, barren land and other infrastructures.

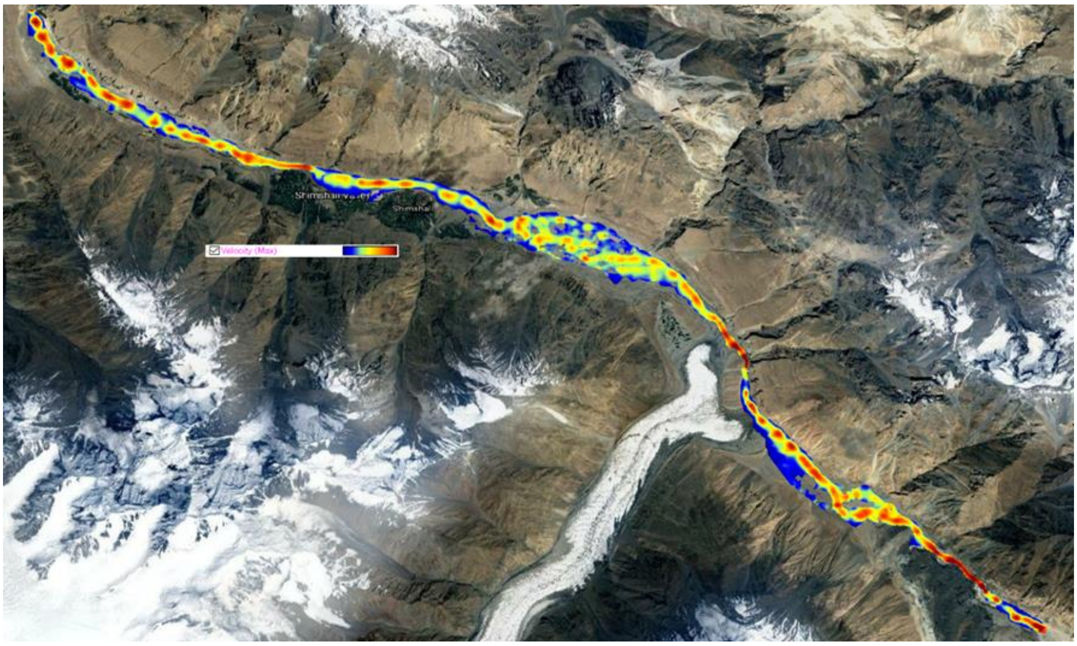

Fig. 7. GLOF depth map of 3 August

Velocity of GLOF is very critical parameter, which depicted about severity of damages, erosion. It is also useful for development of flood protective measure in flood plan area to reduce the flood intensity [*Kreibich et al., 2009*]. The velocity of flood in Shimshal village is high as compared to Farmanabad due more steepness in flood plan of Shimshal with respect to Farmanabad (Fig. 8).

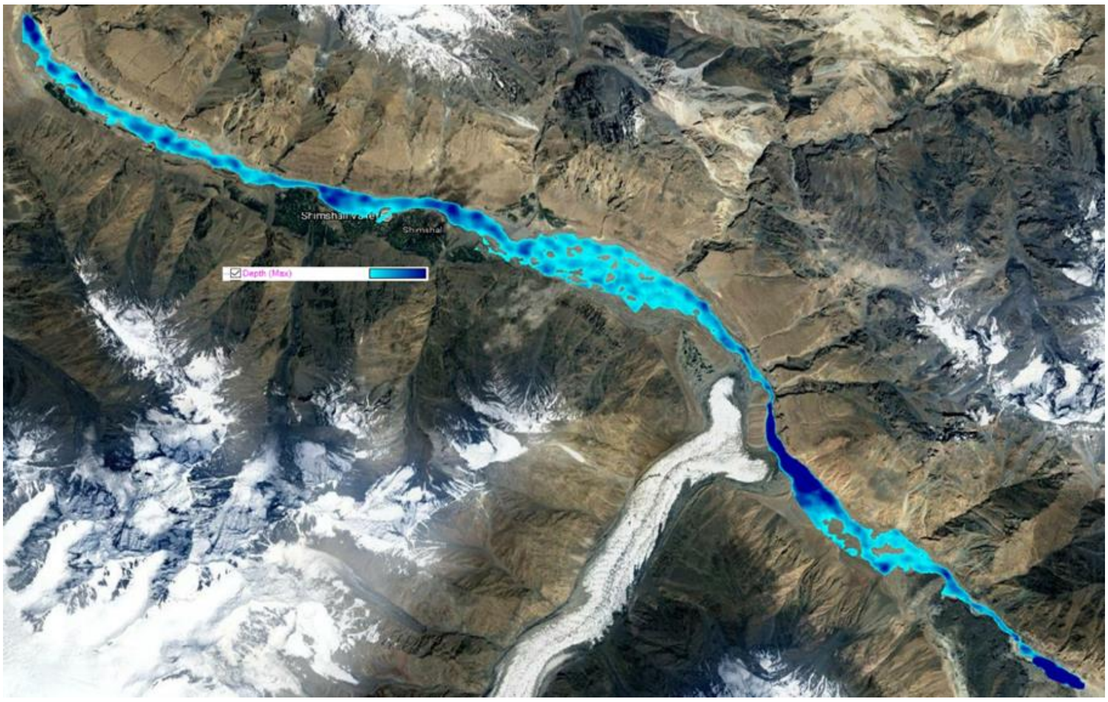

Fig. 8. GLOF velocity map of 3 August

Time arrival information of flood has been used for early warning for evacuation from flood hazardous area. The Fig. 9 show that GLOF hit first Shimshal village and submerge 3.059 km^2 area while Farmanabad flooded 0.53 km^2 area with in sixty minutes. The more area flooded in Shimshal village is due large flood plain are as compare to Farmanabad (Fig. 10) [*Akbari et al., 2010*].

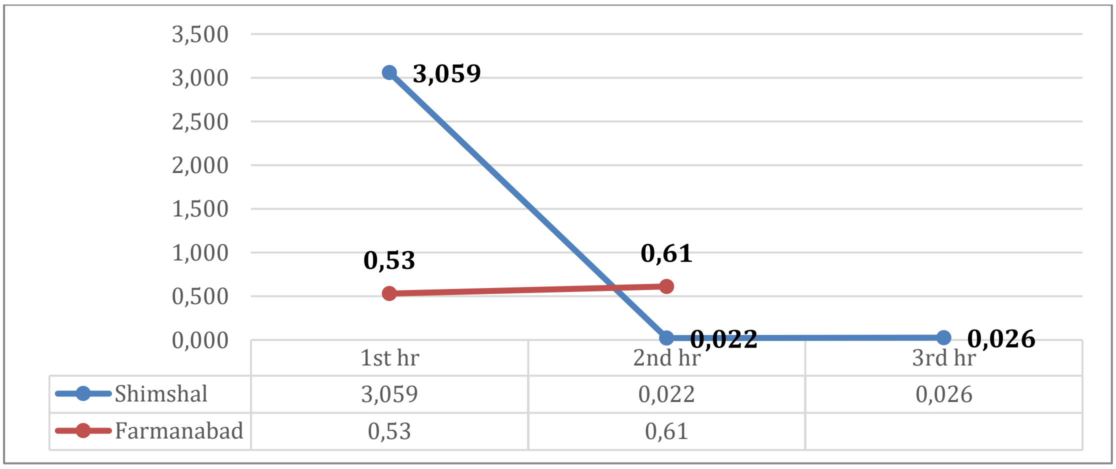

Fig. 9. GLOF time arrival information in hours (Shimshal and Farmanabad)

Fig. 10. GLOF time arrival map of 3 August

Conclusion

The finding of the present study concluded that the spatio-temporal investigation of satellite images shows the significant changes in newly formed Glacier Lake extent as result of Khurdopin glacier dammed the Shimshal River. The analysis revealed that Lake Area is 14.8 hectares in 24 November,2017 with 476922 cubic meter volume of water. Satellite data also revealed that glacier advancement since October 2016 to November 2017. Glacier has blocked approximate 2.303 km length of Shimshal River. The size of lake will be increase in summer season due more melting of snow and glacier as well as rainfall also contributes to raise the volume of lake and create more chance of outburst event. According to GLOF modeling results, total 3.21 square kilometre area submerge by glacial lake outburst flood (GLOF) according to peak scenario. The velocity of flood in Shimshal village is high as compared to Farmanabad due more steepness in flood plan of Shimshal with respect to Farmanabad. The GLOF time arrival information show that Shimshal village submerge 3.059 km^2 area while Farmanabad flooded 0.53 km^2 area with in sixty minutes. The GLOF maps can be used as a basic tool for risk reduction measures i.e. identification of mitigation sites and village/town planning in future.

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