Badswat glacial lake outburst flood and debris dammed lake: a case study

W. Anwar[1], D. Karim[1], U. Wahab[1], K. Din[1], D.R. Gurung[2]

[1]Branch of the Aga Khan Agency for Habitat in Pakistan, Gilgit, Pakistan, waheed.anwar@akdn.org

[2]Branch of the Aga Khan Agency for Habitat in the Republic of Tajikistan, Dushanbe, Tajikistan

Abstract. The Glacial Lake Outburst Flood (GLOF) associated with melting of glaciers and sudden breach of moraine is a common threat in the high mountain landscape. Some of these events are associated with inclement weather, when prolonged precipitation along with warmer than usual atmospheric temperature plays a role in triggering the event. The events like the Badswat GLOF from Badswat glacier in the upper reaches of Ghizer district in Gilgit Baltistan gave no pre indication of any development prior to massive GLOF on 17 July 2018. The event was preceded by persistent precipitation for a week. The deluge of debris from the event blocked the Ishkoman river and resulted in impoundment of water creating 1140 meters long and 750 meters wide artificial lake in just a matter of hour. Unlike similar event that occurred from Karumber glacier a few kilometers upstream in the past in the region, debris surge from Badswat GLOF event continued for 12 days at infrequent intervals between event. This subsequently submerged 30 households, a school, and more than 65 acres of productive land. This paper presents the findings of assessment, response of AKAH and the response of the community following the event, which has lot of learnings going ahead.

Key words: *GLOFs, debris dammed lake, climate change, mountain hazard*

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Прорыв ледникового озера Бадсват и сформированного в результате подпрудного озера

В. Анвар[1], Д. Карим[1], У. Вахаб[1], К. Дин[1], Д.Р. Гурунг[2]

[1]Филиал Агентства Ага Хана по Хабитат в Пакистане, Гилгит, Пакистан, waheed.anwar@akdn.org

[2]Филиал Агентства Ага Хана по Хабитат в Республике Таджикистан, Душанбе, Таджикистан

Аннотация. Прорывы ледниковых озер (GLOF), связанные с таянием ледников и внезапными разрушениями моренных перемычек, являются распространенной угрозой в высокогорных ландшафтах. Триггерами некоторых из этих прорывов являются неблагоприятные погодные условия, когда длительное выпадение осадков накладывается на более высокие, по сравнению с нормальными, температуры атмосферного воздуха. Например, такое событие, как масштабный прорыв 17 июля 2018 г. ледникового озера Бадсват, расположенного у ледника Бадсват в высокогорной зоне округа Гхизер в Гилгит-Балтистане, не имело никаких индикаторов, позволявших его спрогнозировать. Этому событию предшествовали продолжительные осадки, выпадавшие в течение недели. Сель, вызванный данным прорывом, подпрудил реку Ишкоман. В результате в ее долине в течение нескольких часов сформировалось подпрудное озеро длиной 1140 м и шириной 750 м. В отличие от прошлого аналогичного события, произошедшего в этом регионе в нескольких километрах выше по течению у ледника Карумбер, сходы селевых потоков с ледника Бадсват происходили в течение 12 дней с нерегулярными интервалами. Это событие имело разрушительные последствия: было затоплено 30 домовладений, школа и более 65 акров плодородных земель. В данной работе представлены результаты проведенной оценки, меры, предпринятые Агентством Ага Хана Хабитат, и реакция местного населения на произошедшее событие, которое преподнесло много уроков.

Ключевые слова: *прорывы ледниковых озер; озеро, подпруженное селевыми отложениями; изменения климата; опасные процессы в горах*

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Introduction

Climate change has significantly changed the landscape of High Asia region, particularly the areas where glaciers are abundantly found [*Iturrizaga, 2005*]. Gilgit-Baltistan (GB), a region in the northern Pakistan is unique in a way that it is located at lap of three mighty mountain ranges, the Karakorum, Hindukush, and the Himalayas. There are more than 5000 glaciers feeding the Indus from 10 sub-basins through different tributaries ranging from few tens of meters to more than 70 km long [*Rasul, 2011*]. These alpine glaciers are renewable natural freshwater storehouse that benefits hundreds of millions of people downstream [*Shah and Kanth, 2013*]. These glaciers and glacial lakes are source of life support system as well as potential threat in terms of sudden release of accumulated glacier melt, also called glacial lake outburst flood (GLOF). The GLOF, a phenomenon characterized by release of huge volume of water as a result of an outburst of a glacial lake, is one of the catastrophic natural hazards in high mountain landscape [*Ives, 1986*]. According to glacier inventory developed by ICIMOD in 2005 based on RS/GIS studies over this glaciated domain, there are over 2500 glacial lakes formed and 52 of them were identified as potentially dangerous from the point of GLOF. Even the small glacial lake associated with hanging glaciers poses a high potential for breaching resulting in a GLOF [*Ashraf et al., 2012*]. Devastating glacier lake outbursts in the last two centuries are especially well known from the Karakoram- Hindukush Mountains. They are one of the most important types of current geomorphological processes below an altitude of 4500 m. In historical times, about 22 tributary glaciers formed ice-dammed lakes in the upper Indus catchment area, from which 12 dams were responsible for outburst floods [*Hewitt, 1998*].

Owing to global warming glaciers in the area experienced enhanced retreating since the second half of the 20th century [*Das and Meher, 2019*]. This phenomenon has accounted for the formation of many disastrous glacial lakes confined by unstable moraine dams. The loss of significant glaciers in Afghanistan and Pakistan may become more serious progressively unless warming generates greater marine evaporation that augments precipitation [*Schroder et al., 2004*]. The effects of global warming in mountain areas are visibly manifested by shrinking of mountain glaciers and reduced snow cover duration [*Barry, 2002*]. The GLOFs are just not associated with high retreat rate of the glaciers [*Harrison et al., 2018; Khan et al., 2019*] as change in pattern of rainfall also plays key role. Monsoon downpour triggered outburst flood in July 2010 from Booni Gole Glacier located in Hindukush caused extensive erosive damage to agricultural land and human settlements along the flow channel. It used to store water under the terminus of the glacier and produce surge either by accelerated melting of snow/ice or by intense rainfall [*Rasul, 2011*].

This study follows the timeline of how an unforeseen GLOF event unfolded in a remote village of Gilgit-Baltistan region of Pakistan, its subsequent implications and response by the

Aga Khan Agency for Habitat (AKAH) and community to respond to such an unprecedented hazardous episode.

Study Area

Badswat village is in Ghizer District of Gilgit-Baltistan region geographically defined by longitude 36°32'23.70"N and latitude 74°2'8.87"E. The Badswat glacier is located 1.1 kilometers in northeast of the Badswat village. The main glacier trunk with south west to north east orientation has length of 6.8 kilometers and average gradient of 16.12º and is fed by four tributary glaciers. The glacier came got highlighted after it triggered a GLOF in 2015. The intensity and the implications were substantially low as compared to the event occurred in 2018. The stream from the glacier flows into Ishkoman river which eventually joins Gupis river to form Gilgit river.

Weather in the region is cold and moist with warm summers. The annual temperature ranges from -15 °C to 20 °C. The monthly average rainfall is between 4 to 26 mm and high rainfall period is recorded in June and July as per Pakistan Meteorological Department (PMD). High rainfall coupled with high temperature induced snow and glacier melt increasing the stream flow in the Ishkoman and Badswat Rivers.

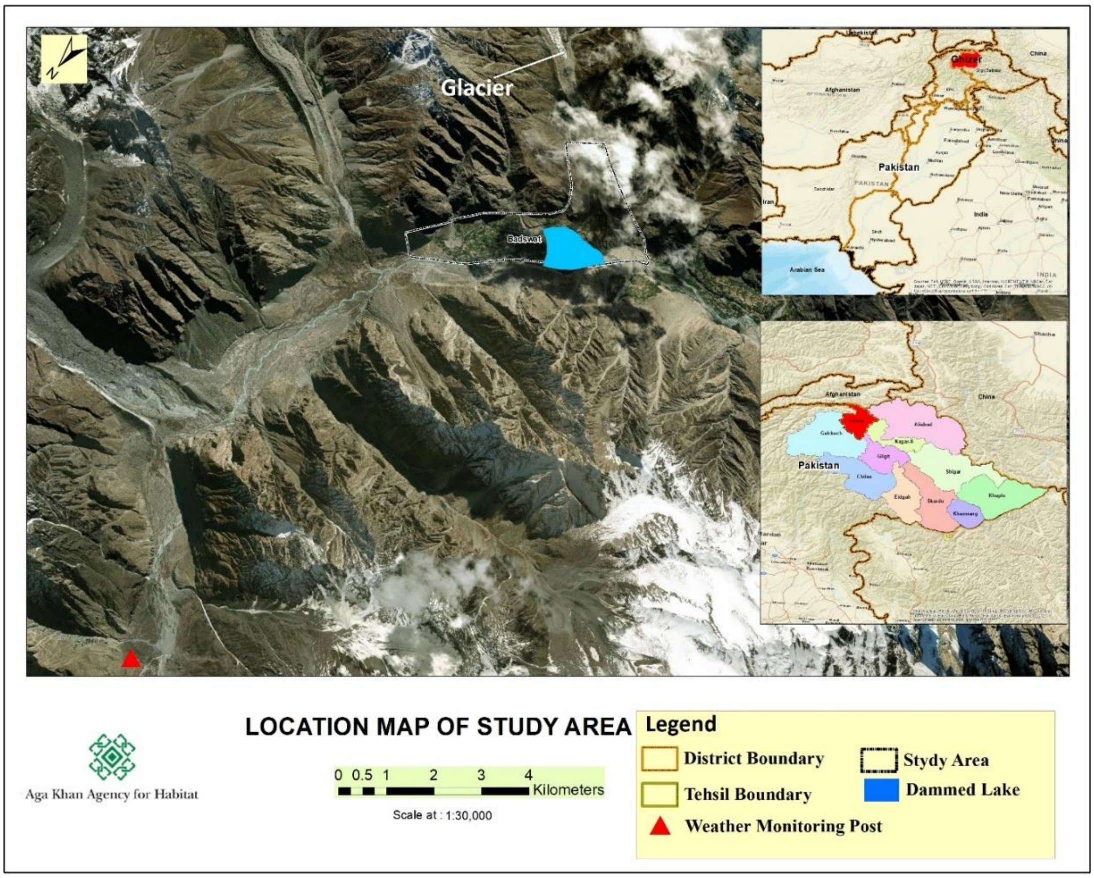

Fig. 7. Location map of Badswat village with district boundaries

Brief Review of the Problem

According to the statistics of global vulnerability index, Pakistan is ranked among 10 countries hard-hit by climate change where large segments of its population are extremely poor and are highly vulnerable to the negative impacts of climate change. The GB region particularly has been bearing the ever-increasing effects of global climate change, it is the hotspot of climate change in true sense. Glaciers and snow are the most sensitive indicators of global warming with immediate response time influencing glacier health and subsequent contribution of melt water to sea level rise [*Rasul, 2011*]. As the glacier retreat a depression is created between retreating snout and moraine dam which is filled up by melt water from glacier and snow. Thus, these lakes are formed on the glacier terminus due to retreating processes of glaciers [*Meyer et al., 1993*]. Supra glacial lake can be seen through satellite imagery and aerial surveys but not englacial lakes or water lodged in subglacial conduits which do not show sign of threat has been source of flooding.

In addition, GB has extreme arid environment and slopes are poorly vegetated, thus intense precipitation on the slopes and gorges results in run off. As the slopes have plenty of exposed debris because of weathering, slope degradation, glacier and eolian processes, there is likely to occur debris flows. The events range in nature and size from mere run offs in the creek, to catastrophic events by flash flooding or sudden release of glacier melt [*Hughes, 1986*]. For instance, debris of Shishkat in Hunza in 1976 [*Goudie et al., 1984*], Debris flow in Gupis 1980 [*Hughes, 1986*]. One thing is common in these events i.e. all of them dammed the river consequently creating a lake. These events have destroyed roads, houses, lands, livestock, thus negative implications were countless as these events affected already economical fragile communities, depriving them from livelihood.

On 17 July 2018 a GLOF from Badswat glacier occurred with no early sign of threat. It was revealed on the following day through satellite images that the actual origin of the event was tributary glacier of the Badswat glacier which fed the glacier approximately 2.3 kilometers up the main trunk from the snout. The debris transported by the GLOF blocked the Ishkoman river which created an artificial lake. Successive GLOF events continued to occur till 29th of July. Each event strengthened the blockade at the nullah. The lake continued to grow inundating houses, school, orchards, agriculture land and road in upstream. The village is connected through one access road which was also damaged disconnecting village for 3 months. As lake started to grow chance of dam outburst was also anticipated, which led to evacuation of people from low lying areas of 3 downstream villages.

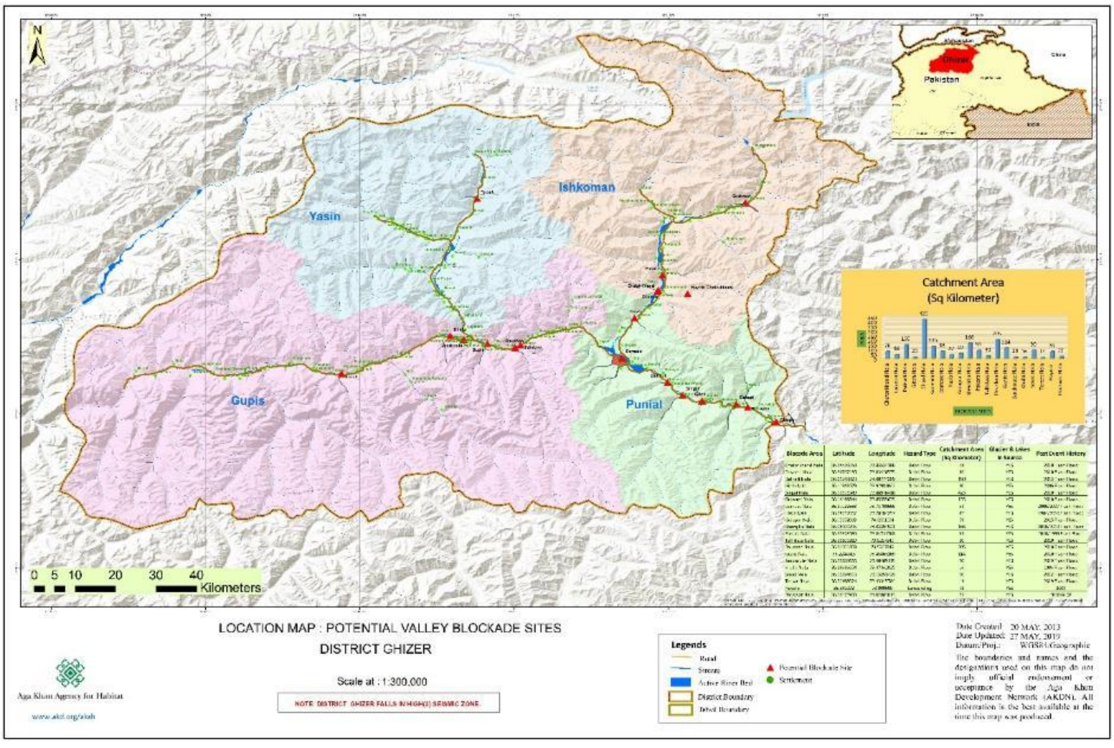

Fig. 2. Map showing the potential blockade sites in Ghizer district of Gilgit Baltistan. Source: AKAH, Pakistan

Method and Data

Post Disaster Assessment

To collect primary data on the scale and genesis of the event, helicopter surveys on 26th and 27th July were carried out by senior geologists, engineers, and disaster first responders. The aerial photographs gave required perspective on origin of the event. A team comprising of geologist and engineers was deployed in the field after 10 days to collect data on blockade nature, properties of debris, growth of lake upstream and assess glacier situation. Since the event did not occur from the main glacier but from a tributary, and access to the location was a big challenge and UAV really came handy. Big part of the assessment involves focus group discussions with elders and notables and interviews of eyewitnesses in the village.

Temperature and Precipitation Data

To simulate the breach mechanism, the local meteorological data from weather monitoring post (WMP) has been used which is located in Matramdan village located 8 kilometers upstream of the study area (Fig. 1). The WMPs were installed as part of a project led by AKAH, Pakistan principally to forecast the snow avalanches in winters by keeping track of local weather conditons. The weather data that comprised of solid and liquid precipetation, wind speed and direction and maximum minimum temperature, have been used to disseminate early warning against snow avalanches for community to keep them from harm's way. In summer, these data are analysed to monitor riverine and flash floods in the area. The graph below shows (Fig. 3) maximum and minimum temperature and rainfall precceding to the event that occurred on 17th July 2018.

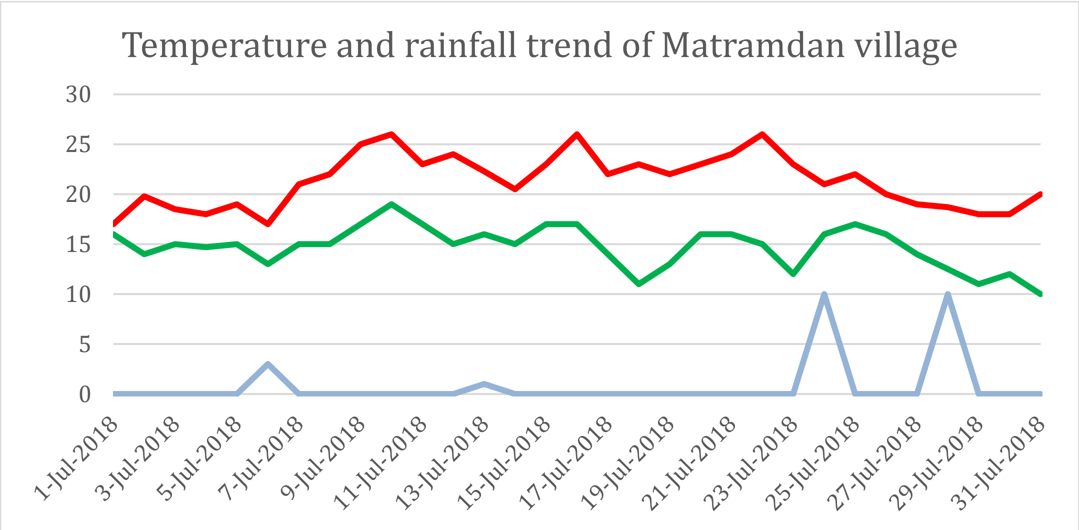

Fig. 3. Graph showing the temperature and rain fall trend WMP data from Matramdan village. Red trendline shows the maximum temperature whereas green line is for minimum temperature and blue line depicts rainfall. Data Source: AKAH Pakistan

Analysis and Results

It was indicated after initial HVRA in 2013 that presence of colossal glaciers with very high sediment load along the lateral moraine in the catchment area could trigger remote geo-hazards such as GLOF, which could not only erode the banks (margins) but also result secondary hazard such as formation of artificial lake by blocking the Ishkoman River. In 2015, it happened exactly what was anticipated causing moderate flood event which choked the river path. As a result, 6 houses and a pedestrian bridge were affected. This event is unmatched with the GLOF of July 2018, which deposited massive debris at the mouth of the nullah which led to creation of a massive lake by blocking Ishkoman river and resulted in impoundment of water creating 1140 meters long and 750 meters wide artificial lake in just a matter of an hour. Apparently 34 houses were submerged, and the effects were far reaching. It has been found out that local climate played a key role in triggering the GLOF, intermittent rainfall and raised temperature preceding the event was primary trigger. From graph shown in Fig. 3 it can be observed that there have been recurrent rainfall days from start of the first week which continued up to the day of the event. During the rainfall days on 7th and 13th July the temperature plummeted from the general trend. Then temperature started to rise from 8th July which indicating clearer weather.

The intermittent rainfall prior to the event followed by increase in temperature may have raised the level of water in crevasses and sub glacier conduit. Rasul et al., 2014 also studied the effects of rainfall and subsequent rise in temperature in increasing in melt water.

Lake Formation Process, Rate of Growth, Chronology

Fig. 4. Repeat photograph of lower Badswat village: top (pre event, March 2016) and bottom (post event, July 2018). Photo credit: AKAH, Pakistan

At 6:45 pm local time a GLOF event occurred on 17th July 2018 from the Badswat glacier and resultant debris was of such massive volume that it blocked the Ishkoman River. It instantly swept 4 houses down the valley and blocked the river forming a lake in upstream. After almost an hour at 7:55 pm overflow of river started but not for long, as second wave of debris flow came and strengthened the blockade followed by third wave of debris flow at 12 pm. The blockage remained for almost 2 hrs. and 15min and overtopped the barrier. As a result, 30 households in upstream of the blockage in Badswat Payeen were submerged under the lake along with 1 government school, 1 Religious Education Centre (REC) and 500 kanals of cultivable land and 235 kanals of orchards with both fruit and non-fruit trees. While on the downstream of the blockage 11 houses were buried under the debris. Moreover, 3 houses were damaged due to erosion and collapse of the banks along the Badswat stream by the GLOF. The 3.2 kilometers section of the road and 1 bridge connecting Badswat was also swept by the flood and as a result the whole valley remained disconnected from rest of the district for three months.

Fig. 5. Repeat photograph of Badswat village left taken in March 2016 and right taken in July 2018. (Photo credit: AKAH Pakistan)

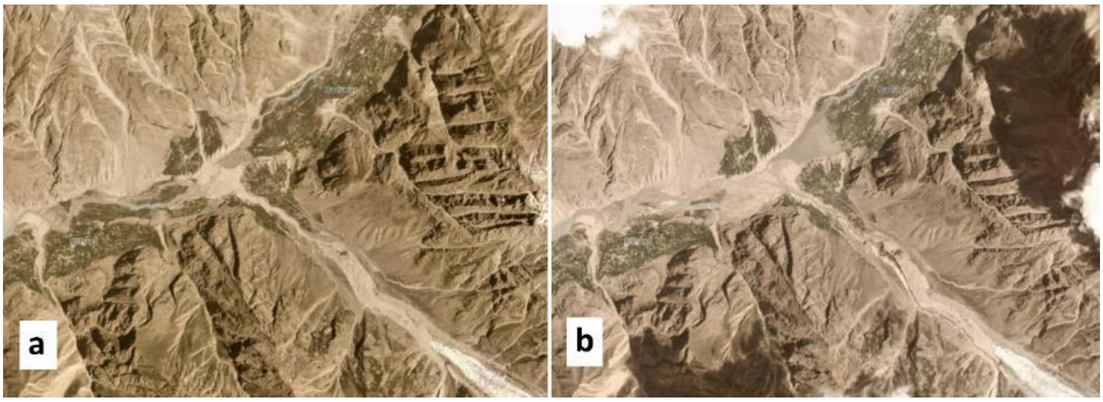

Fig. 6. (a) satellite image of village taken on 13 July 2018; (b) image of 20 July 2018 after the event, lake can be seen. (Source: Planet Lab)

Situational analysis

The blockage has a length of 500m and a width of 1500m out of which around 1000m of debris is spread downstream and around 500m upstream.

The weather was quite hot for several days and in the morning of 18th July rainfall was recorded as displayed in Fig. 3. Sunny conditions for almost a week increased the rate of melting of the glacier and the rain on glacier further amplified melting. The higher discharge of water stored at snout ultimately increased the hydrostatic pressure which is one of the reasons for trigger of the GLOF. When the internal conduit was filled with water, hydro-static pressure it built up releasing the water in the form of flood after glacier break. When flood hit the main trunk of Badswat glacier it teared through the ice mass and eroding it and the lateral marines. The debris surges from the GLOF arrived at the partially blocked Karumbar River and completely blocked resulting in an artificial lake. The flood persisted for around 12 days with surging, chocking, and blocking the river, heightened the barrier.

Causes of GLOF

In times when intensive weather elements persist for long, they trigger massive outbursts even from glacier that does not have pre-existing lakes.

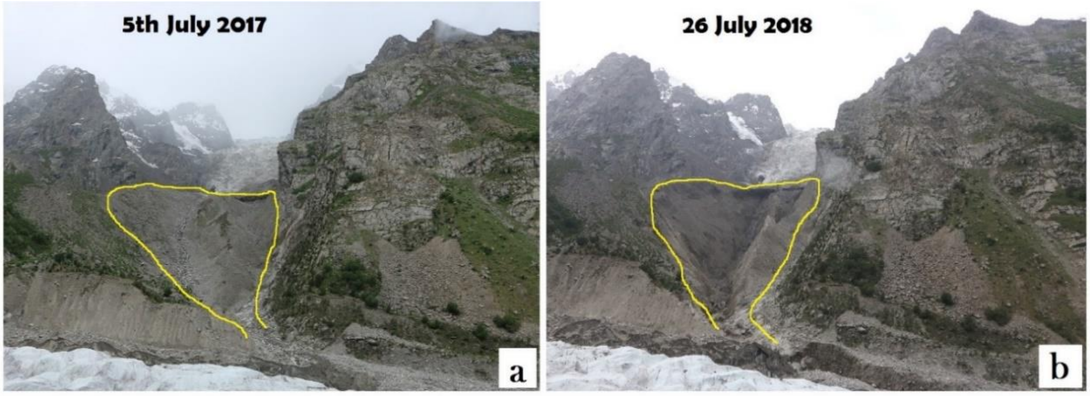

Fig. 7. (a) Photograph of tributary glacier in July 2017, (b) taken in July 2018. Sediment erosion can clearly be seen after the GLOF marked by yellow lines. Photo credit AKAH, Pakistan

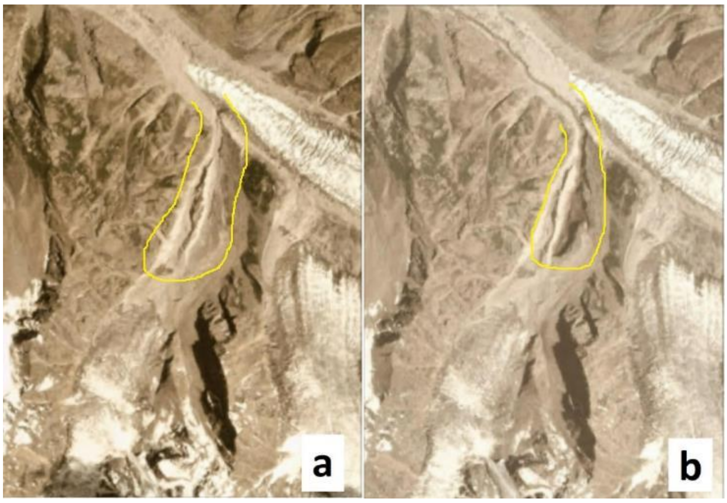

Fig. 8. (a) satellite image of GLOF trigger location in 13 July 2018; (b) image of 20 July 2018 after the GLOF had occurred. (Source: PlanetLabs)

Badswat glacier, being very unstable showed its notorious behavior previously. This glacier is being fed by more than four tributary glaciers in its catchment. Glacial melt from each tributary is then dispensed into main trunk of Badswat glacier. One of the inlets (tributary glacier) on south eastern ridge, which is sun facing had responded more abruptly to the weather elements lately than any other glacier in this valley. Features show us that, a GLOF has occurred initially from this tributary, a sudden outbreak of large volume of water has cut the left lateral moraine and ice of the main trunk of Badswat glacier creating a gully (Fig. 9b).

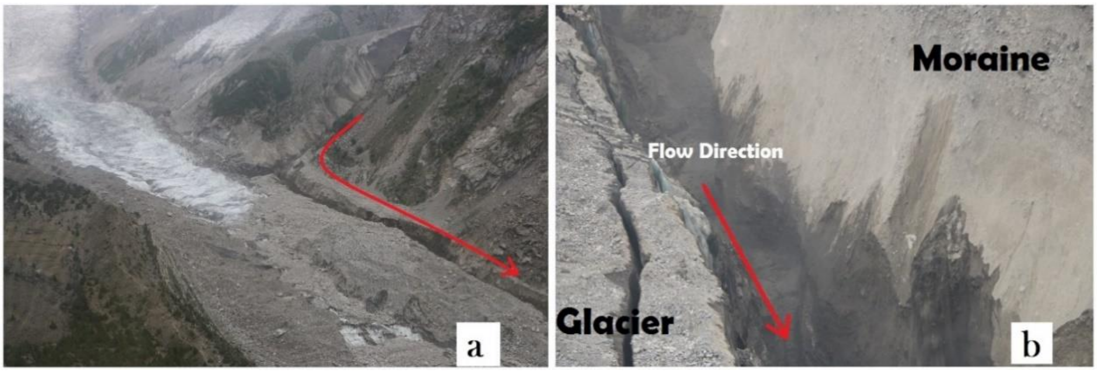

Fig. 9. (a) The main glacier trunk of Badswat and newly formed gully by GLOF from Tributary glacier (b) aerial photo shows direction of flow of GLOF and adjacent ice and Debris banks. Photo Credit AKAH Pakistan

This sudden outbreak of glacier melt took shape of a GLOF when it reached the mouth of Badswat nullah and blocked the Ishkoman River that runs perpendicular to it. This event is however not nascent as similar event has occurred in the same month three years ago, what is surprising is the magnitude and the continuity of debris flows followed by the GLOF of 17 July's. The series of debris flows continued for twelve days with infrequent intervals between each event. These series of debris flow episodes are most probably due to temporary blocking and subsequent outburst events. Temporary blockage was due to collapse of steep moraine wall that was destabilized due to undercutting by the flood. When blocking debris and ice could not retain the pressure of impounded water it burst, which could be observed for next twelve days.

AKAH's Response

Construction of Shelters

The AKAH relief operation started very next day of the event, the event was sudden and intense, the community had no option other then run for their life leaving everything behind. The lake started to form just after the GLOF had occurred and immediately engulfed most of the houses in the impact zone. Although community of Badswat supported the affected people by providing accommodation, however 8 families were shifted to makeshift tents which were provisioned from nearby AKAH emergency stockpile. The technical team was deployed to assess the glacier and find land to construct shelters for the families whose houses were submerged. The target was to shift each of the family into winterized shelters before the brutal winters. It took roughly about three months to complete 50 shelters for the families who were affected and for those whose houses were in high risk zone.

Fig. 10. Shelters under construction. Photographs credit: AKAH Pakistan

Restoration of the Drinking and Agriculture Water

Soon after the GLOF event AKAH deployed its Disaster Assessment Response Team (DART). The team highlighted the problems community faced following the event. Since most of the dwellers rely solely on agriculture as a source of livelihood. The only irrigation channel which supplied the irrigation water to roughly 264 Kanals of arable land was damaged severely. Another team was also sent to look for the options to restore the irrigation channel or find some other ways to provide irrigation water to the community. The team immediately installed 3 inches pipeline to provide essential water supply for drinking and irrigation purposes.

Conclusion

This work documents the event of Badswat glacier outburst and subsequent events which unfolded making bad situation even worst. It is an attempt to correlate the effect of local weather on glaciers which apparently show no sign of threat. The supra glacial lakes can be assessed and monitored in situ or remotely but englacial lakes are hard to identify. Only way to gauge the complexity of such glacial lake is to have keen eye for the events like Badswat.

The Badswat GLOF is just a tip of an iceberg, as the Ishkoman valley houses more than dozens of glaciers larger than the Badswat glacier which need just a little push to trigger GLOF. Ongoing climate change and unprecedented weather conditions could prove the last nail in the coffin. It is to understand that primary hazard as in case of Badswat GLOF can activate secondary hazards by blocking and creating artificial lake, which abruptly increases the exposure of community to disaster provided with incapability to cope with the hazard. Thus, a development of inventory of glaciers in the region and detail assessment of glaciers which have shown unusual behavior both land based and airborne is need of the time, so that effective disaster management/planning could be done way ahead of the disaster.

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