FOCUS HUMANITARIAN ASSISTANCE

Risk Assessment of Khordopin Glacier Surge and Glacier Dammed Lake Formation

Pakistan Meteorological Department

July 2017

Risk Assessment of Khordopin Glacier Surge and Glacier Dammed Lake Formation

Technical Report No. 4 (2017)

Pakistan Meteorological Department

July 2017

Helicopter Mission for aerial assessment of Shimshal Lake left to right: Mr. Deedar Karim (AKAH), Mr. Muzafar Uddine (AKRSP), Mr. Zaheer Babar (GB-DMA), Mr. Nawab Ali Khan (Chief Executive Officer, AKAH), Dr. Ghulam Rasul (Director General, PMD), Mr. Adnan Shafiq Rana (PMD), Mr. Sher Wali (AKAH)

Pakistan Meteorological Department (PMD)

Prepared by

Adnan Shafiq Rana

Endorsed by

Dr. Ghulam Rasul

Mr. Muhammad Akram Anjum

Dr. Muhammad Afzaal

Field Investigations Assisted by

Mr. Qamar Munir

Mr. Waqar Ali

Mr. Naveed Hussain

Mr. Farooq Nawaz

Mr. Muhammad Hassan

Mr. Muhammad Babar

Aga Khan Agency for Habitat (AKAH)

Mr. Nawab Ali Khan

Mr. Muzafar Uddine

Mr. Sher Wali

Mr. Deedar Karim

Mr. Waheed Anwar

Abbreviations

DEM	Digital Elevation Model
DGPS	Differential Global Positing System
GLOF	Glacial Lake Outburst Flood
GPR	Ground Penetrating Radar
HKH	Hindukush-Karakoram Himalaya
ICIMOD	International Centre for Integrated Mountain Development
msl	meter above sea level
NDWI	Normalized Difference Water Index
PMD	Pakistan Meteorological Department

Contents

List of Figures and Tables

EXECUTIVE SUMMARY

The early warning of an outburst from glacial lake creating GLOF event is crucial since these GLOF events are increasing in their frequency and magnitude due to impacts of climate change. The monitoring of vulnerable lakes which have a high probability of outburst is need of time. One such lake has recently been developed due to the surging behavior of Khordopin Glacier. The monitoring of this lake is of extreme importance due to its geographical location, proximity to the settlement, frequent changes in Khordopin glacier associated to it and probability of large-scale damage to the downstream community in case of a continuous increase in its size and outburst. The Glacier Monitoring Unit Team of Pakistan Meteorological Department (PMD) visited the area for the assessment of the Khordopin glacier and newly developed lake due to surged dynamical changes in glacier so that the probability and extent of disaster could be ascertained and any remedial measures could be suggested. A helicopter mission was also made on 6th June 2017 and 16th June 2017 with Aga Khan Agency for Habitat (AKAH) to make aerial visualization for vulnerability assessment. The mission of 6th June couldn't succeed due to weather conditions and poor visibility while entering in Shimshal Valley, however, the good aerial assessment was made on 16th June 2017.

The Khordopin glacier has shown an advancing behavior with an average surge of around 18 m per day from April 2017 to May 2017 which reduces to 10 m/day from May to June 2017 as calculated from the satellite imagery of Landsat 8 and Sentinel 2. Its velocity during field measurements was 2 meter per day on 12th June 2017 at approximately 2.3 kilometres upstream the terminus of the glacier. The surge is observed up to the distance of 18 kilometres from the terminus of the glacier, however, different locations on the glacier exhibited different surge behaviors. The area starting from 2 kilometres above the terminus to 6 kilometres above terminus shows comparatively lesser velocities of the surge as compared to the area from 6 kilometres to 9 kilometres. However, the surge behavior of the glacier was slowing down in terms of velocity after 29th May 2017.

The lake size is increasing at a rate of approximately 1390 square meter per day calculated for 31 days. At the time of writing this report, there is an englacial discharge mechanism just after the lake. The englacial discharge of lake is happening for a distance of approximately around two kilometres which afterward come out of the ice to flow on the surface. However, the increase of lake size is showing that the discharge mechanism is reducing day by day as a result of glacier advancement. The location of Lake is also moving since the glacier surge is pushing Lake eastwards from its end. Moreover, the size of englacial discharge is also increasing thus squeezing the englacial discharge. The ice depth was calculated to be 135 to 175 meters just 900 meters below the area where Lake originally started forming. Thus if a chunk of approximately 100 meters deep ice was accelerating at a velocity of 20 meters per day, the probability of blocking the passage is increased. This ultimately increases ice depth due to its accumulation in front of the mountain ridge which will further block the discharge passage and increase the damming wall of the lake that may result in a rapid increase in lake size and vulnerability of outburst with larger implications.

INTRODUCTION

The glaciated area lies within longitudes 70° 57´- 77° 52´ E and latitudes 33° 52´ - 37° 09´ N in Northern Hindukush-Karakoram-Himalaya (HKH) region of Pakistan. The elevation in this region ranges from 366 meters in the south to 8611 meters (height of K-2, second highest peak of the world) towards northeast comprising high mountain ranges. The snow and ice in this area provide an ample amount of water to flow in Indus River and its tributaries which ultimately contributes to large agriculture area in the downstream part for the agrarian based economy of Pakistan. This area also consists of numerous lakes which are formed due to climatic and geomorphologicalchanges, for example, accelerated retreat of glacier due to increase in temperatures, blockage of river channels due to landslide avalanches, Blockage of the river due to glacier surge, debris flows, etc. These lakes sometimes pose a threat to the downstream community due to sudden outburst creating flash floods and results in a devastating effect on socio-economic, environment and natural resources of the region.

Surging behavior is observed in many glaciers of Karakoram mountain ranges (Hewitt & Young 1993; Hewitt 2007; Hewitt 2005; Goudie et al. 1984; Gardelle et al. 2013; Kääb et al. 2015), however, still understanding about them is meager (Quincey et al. 2011). It is widely accepted that the relatively high temperatures, accelerated melting of glaciers due to climate change increaseprobability of glacier hazards, most evident of them is triggering of Glacier Lake Outburst Flood (GLOF) events (Waragai 2012; Hewitt 2014; Ashraf et al. 2015; Rasul et al. 2008). While on the other side the interception of river flow by surging glaciers especially in the Karakoram also triggers GLOF events (Hewitt 1998; Archer & Fowler 2004).

There is often difficulty in assessment of these glacier hazards due to an incomplete understanding of the processes involved and catastrophic nature of related events. The probability of occurrence of Glacier Lake Outburst Floods is difficult to estimate because of rapid changes in the natural dynamics of complex glacial systems. The sudden development of lake due to the interception of a stream or river by a surging glacier often happens in remote areas away from settlements therefore early warning for such mechanisms over a large area is challenging (Round et al. 2017). Likewise, the direct prediction for a GLOF event for the whole Pakistan is a challenging task because of inaccessibility of site for assessment, a large number of lakes around the country etc. But the development of early warning system and forecasting of flash floods and GLOF events have become extremely important due to rapidly increasing GLOF events in Pakistan and economic damages thereof.

The glacier-dammed lakes play very significant role in defining natural landscapes of the valleys in Karakoram mountain ranges. The formation of these lakes and controlled drainage is regular phenomenon and feature in these areas, however, often these became vulnerable when they grow much bigger in size. The vulnerability increases with the increase in the size of these lakes which then ultimately leads to a sudden outburst creating devastation in the downstream communities. The glacier dynamics and changes in glacier regimes are important to understanding while monitoring these lakes especially those which formed as a result of surging behavior of the glaciers.

The valley of Shimshal in Hunza is known for its couple of glaciers which have the capability to block the river passage by exhibiting advancing behavior thus forming glacier dammed vulnerable lakes. The valley of Shimshal is located in the North of Gilgit representing North Karakoram with approximately70 kilometer 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 2003-04. The Shimshal settlement is located at an elevation of 3100 m.a.s.l. and is one of the highest settlement in Gilgit-Baltistan (G-B) with no proper infrastructure. There are four hamlets in Shimshal namely Farmanabad, Aminabad, Center Shimshal, and Khizerabad with a total population of 2000 inhabitants residing in 250 houses approximately. The seasonal pastures are located at 7885m.a.s.l. having highest peak DestaghilSar. The Hispar Valley runs parallel to Shimshal Catchment on its southern side with 62 kilometres long Hisper Glacier.

There are 317 small and large glaciers in Shimshal Catchment. Most of the large glaciers are facing northward advances into the valley and creates a potential threat of blocking main river (which passes through the center of the valley) in the case of their surge behavior (figure-1). The Malungutti Glacier 22 km long, Yazdgil Glacier 30 km long, Pushkin Garden Glacier 18 km long and Khordopin Glacier 37 km long poses a serious threat of blocking East-west running Shimshal Riverdue to their surge. The largest glacier is 40 km Virjerab running in North West direction. The 58 km long Batura Glacier lies in front of the opening of the catchment.

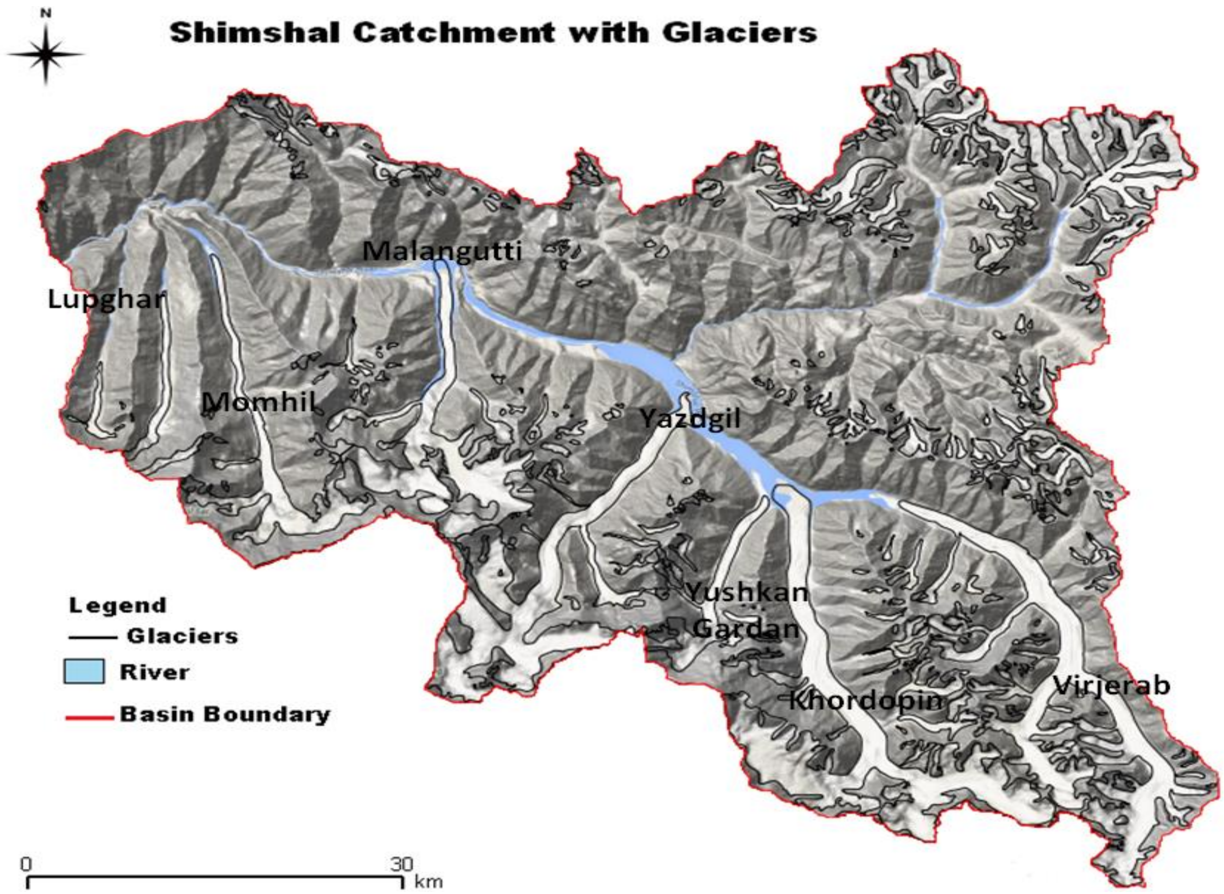

Figure-1 The valley of Shimshal with its glaciers and river

The river flankof the valley is prone to the formation of glacier-dammed lakes at many locations and has been mapped earlier(Iturrizaga 2005). The high probability of glacier-dammed lake formation along different locations along the riverresults in flooding situation in the past history and is still vulnerable for the triggering of flood waves. A brief history of floods that triggers from different locations of Shimshal valley is mentioned in table-2. It is worth mentioning that most of these known historical floods triggered from Khordopin or Yushkin Gardan Glaciers. The fluctuations of these two glaciers are responsible for the formation and outburst of the Glacier Lakes due to the blockage of flow water coming from the melting of Virjerab Glacier.

Overview of glacier floods in the shimshal valley

Year	Date/season	Triggerer/locality	Loss	Source
1884	–	Khurdopin	Considerable damage to lands at Altit and Ganesh	Todd, 1930; Charles, 1985
1893	July	Khurdopin	Damage to lands at Altit	Conway, 1894; Mason, 1929; Todd, 1930
1901	–	Shimshal	Breaking of a dam, bridge at Ganesh destroyed	Todd, 1930
1904	–	Shimshal	Damage to terraces at Shimshal after emptying of two-year old lake (1902)	Todd, 1930
1905	Second August	Khurdopin	Destruction of Chalt Bridge and Gilgit-Chalt road damaged; loss of fields at Pasu and Shimshal	Todd, 1930; Neve, 1913
		Malungutti/Khurdopin	Rise of river level of 30 ft at Bunji	
		Khurdopin	Damage of 7 houses at Shamets and to Hunza-Nager bridge at Ganesh	
1906	11/12 August	Shimshal	Damage to bridges at Askurdas, Tashot and Chamogah	Singh, 1917; Mason, 1929; Todd, 1930
			Rise of river level in Chilas 36 ft, in Chalt 55 ft	
			Fields, houses and bridges destroyed at Pasu, Hussaini, Gulmit and Ganesh	
			3 houses, 35 fields and 3 watermills and orchards destroyed	
			Nomal-Chalt road damaged	
1907	Summer	Khurdopin/Malungutti	Slow drainage in 11 days	Todd, 1930: 175
			Bonfire system (*Puberanj*) to warn the settlements in the Hunza valley	Local informations (Iturrizaga, 2001)
1922	–	Shimshal	Loss of farms	Visser, 1938
1923	–	Shimshal	–	Kreutzmann, 1994
1927	June	Khurdopin ?	Damages to bridges and farms at Shimshal	Mason, 1929; Morris, 1928
1941	–	Shimshal	–	Charles, 1985
1944	–	Shimshal	Damage to terraces at Pasu	Saunders, 1983
1957	–	Shimshal	None	Charles, 1985
1959	21 August	Shimshal	Damage to bridge between Nagar and Baltit	Finsterwalder, 1960; Pillewizer, 1960
	23 August		Fire warning system in use	
1960–1964	–	Shimshal	Loss of farms and terraces at Shimshal in consecutive years	Clark, 1960; Charles, 1985
			Damage to bridges at Shimshal and Pasu	
			Damage to irrigation channel at Nomal	
1976	–	Shimshal	None	Charles, 1985
1978	–	Shimshal	Damage to terrace at Pasu	Goudie et al., 1984
1980	28 June	Khurdopin/Yukshin Gardan ?	None	Charles, 1985, Local informations (Iturrizaga, 2001)
2000	11 June	Khurdopin Yukshin Gardan ?	None	Mock, 2000; Iturrizaga, 2001

Table-1: A Brief History of Floods triggered in Shimshal Valley. Source: (Iturrizaga 2005)

The surge in Khordopin glacier is now again noticed which results in the formation of the glacier dammed lake during the second week of May. According to the local community, the glacier has shown its surging behavior in past as well i.e. during 1960, 1980, 2000 and now in 2017 which is also reported in table-1. Thus, it has a response period of surge cycle after approximately 20 years when the glacier moves its accumulated ice in ablation area resulting in the formation of glacier-dammed lake and subsequent outburst(Quincey & Luckman 2014). Some of the earlier years surge of Khordopin glacier was also documented and the glacier has shown its surge behavior since the 1800s (Visser, 1926; Todd, 1930; Iturrizaga, 2005). The small return period of 20 years approximately in the presence of climate change situation over the globe indicates consistent return period of this glacier since Little Ice Age (Quincey & Luckman 2014). The surge which started in the year 2016 was assessed and its implications in forming lake and threat to nearby settlement are discussed using remote sensing tools and field investigations.

ASSESSMENT OF RECENT SURGE

The elevation of the snout of Khordopin glacier is 3336m.a.s.l. and it originates from KanjutSar-II peak with an elevation of 6831m.a.s.l. The glacier is also known due to well-known Khordopin pass which joins Khordopin Glacier with 56 km long Biafo Glacier via Snow Lake. The surge of Khordopin glacier started somewhere around November 2016. During September PMD team was there and crossed the glacier just in front of its terminus and right moraine, where water coming from Virjerab glacier flows and now blanketed by Khordopin glacier ice. Moreover, very minimal or no surge is observed after September till November 2016. During September visit the glacier terminus was not in contact with the river that originates from the terminus of Virjerab Glacier as shown in a satellite image of 1st October 2016 in figure 2. Satellite images from Landsat 8 and Sentinel 2 were used to figure out the surge dynamics of the glacier fluctuations. Unfortunately, no cloud-free images could be obtained to find the exact date of surge initiation. The images acquired on 1st October 2016, 17 October 2016, 2 November 2016, 20 December 2016, 11 April 2017, 27April 2017, 13 May 2017,29 May 2017 and 12 June 2017 were assessed to find the velocity of the glacier. The methodology adopted by (Paul 2015) along with visual interpretation of satellite images was used to figure out the velocity of the glacier. The velocity measurements at different locations were made to determine the maximum velocity area. It was noticed that the approximate surge of the glacier was one kilometre from November 2016 to June 2017 at the location from 2 to 6 kilometres from the snout and 1.5 kilometres from 6 to 9 kilometres from the snout shown in figure 3. The glacier movement accelerated during April 2017 to June 2017. The glacier accelerates more at 6 to 9 kilometres above terminus with a speed of more than 20 meters per day for the period from April to June 2017 while around 15 to 18 meters per day from 2 to 6 kilometres above snout. The average velocity remains around 18 meters per day from period April to June 2017. However, there is a reduction of velocity after 29 May 2017 with an average value of 10 meters per day.

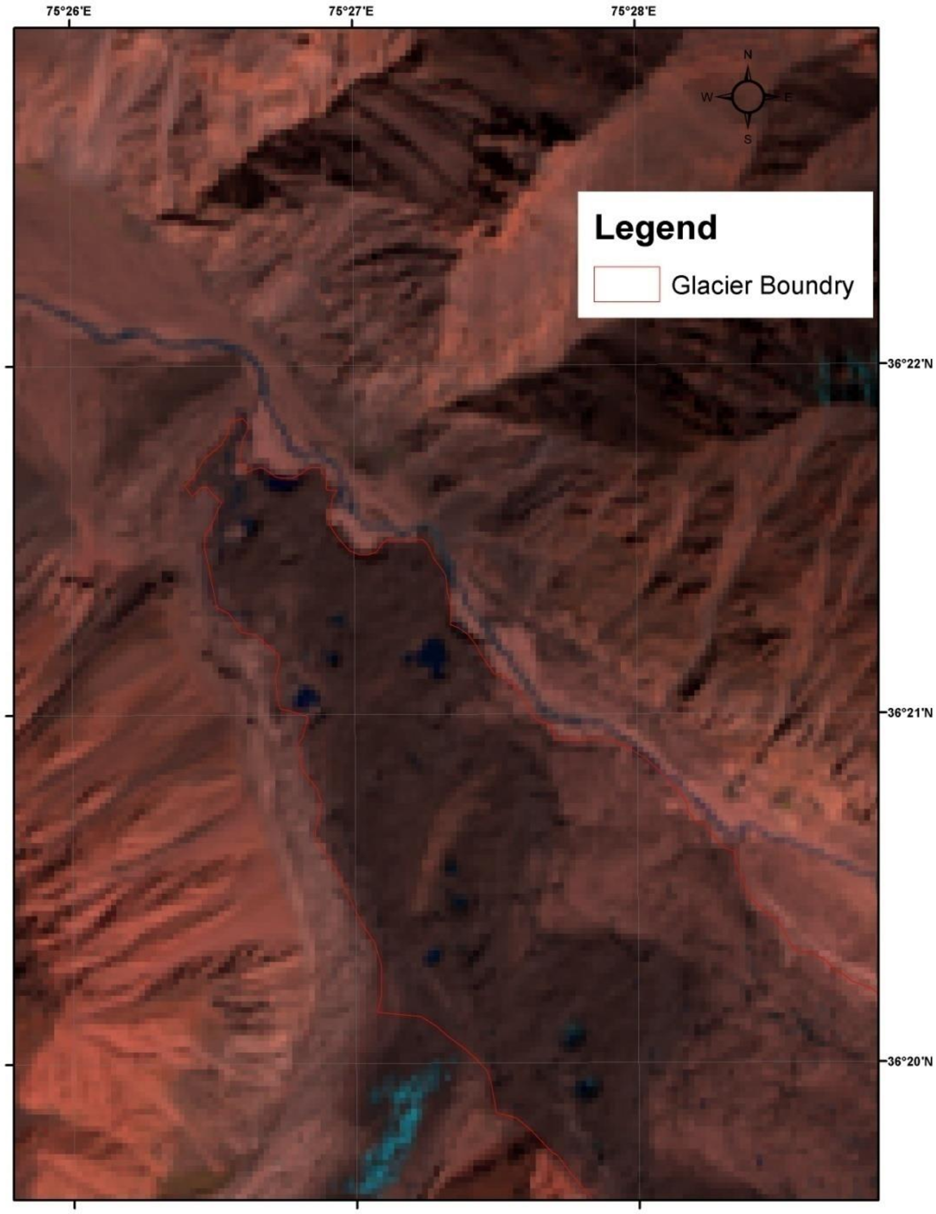

Figure-2: The river flow coming from Virjerab Glacier is visible just along the boundary of the glacier on 1st October 2016.

No movement is noticed in the terminus of the glacier and no or minimal movements were observed upto 2 kilometres from the snout. The glacier velocities increase gradually as we go higher from snout especially when we cross the ridge located on the left side of the glacier when looking downstream of the glacier. The maximum movements were observed in the central line of the glacier which distributes and transfer its acceleration forward and to lateral sides. The velocity and movements were in accordance with the velocities observed earlier during late

1970s surge and year 2000 surge cycle by the glacier (Quincey et al. 2011; Quincey & Luckman 2014).

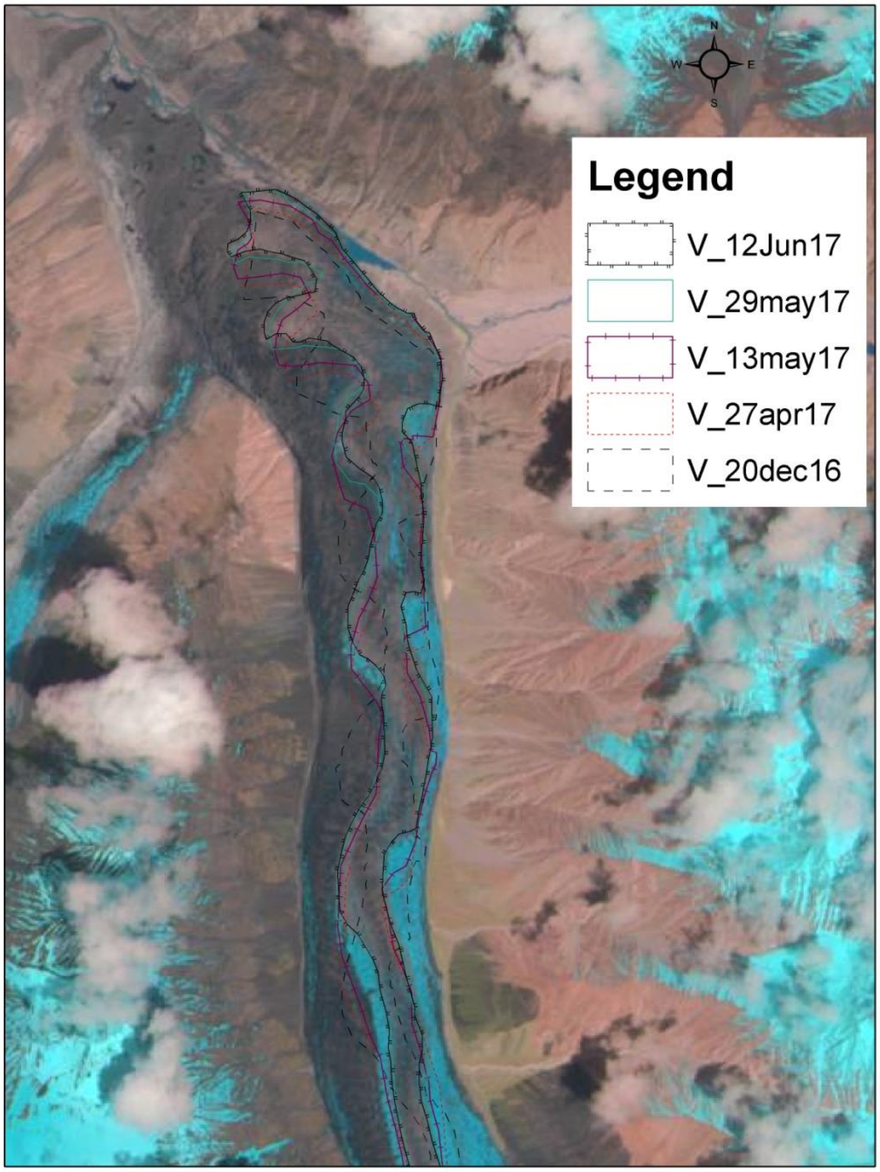

Figure 3: Khordopin Glacier velocities at different times during so far surge cycle

At the site of lake formation, the velocity of the glacier was around 7 meter per day from 29th April to 13th May which reduces gradually afterward and upto 12th June the velocity was around 3 meter per day. It is worth mentioning here that during field investigations on 11th and 12th June 2017, the difference of Differential Global Positioning System (DGPS) reading between the two days shows the velocity of 2 m/day at 2.3 kilometres location above the terminus as shown in figure-4 (b) along the profile track. However, the location of measurement was north and south-west across the glacier (Figure-4 (a)). Previously the river flows on the same location before glacier surge. The velocity of glacier movement is relatively less here. We couldn't take transects cross the glaciers and at the snout due to wide crevasses formed on the glacier (figure-5 (a) and (b)) in response to its surging behavior. Despite small area profiled, the velocity calculated from the available measured readings from DGPS and the velocities calculated using satellite images at the location are similar.

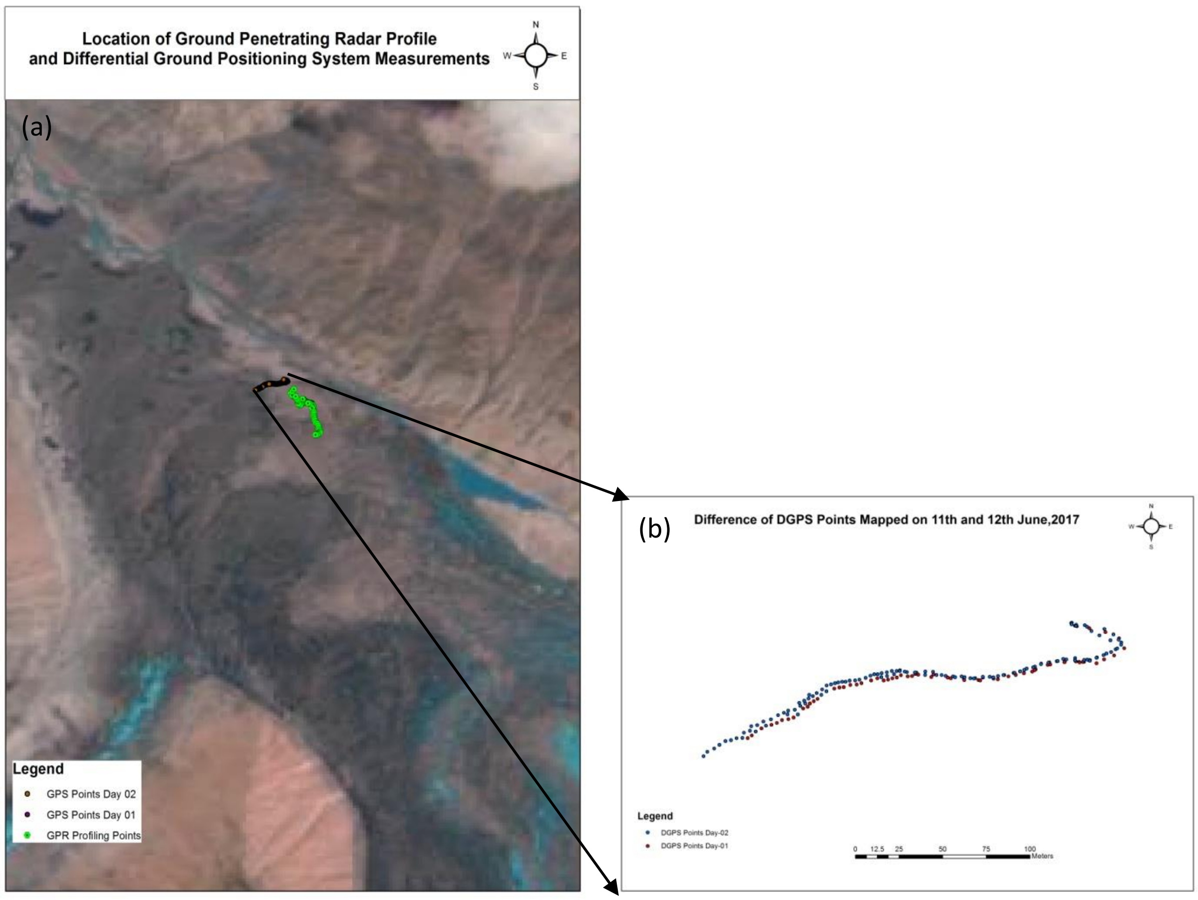

Figure-4: (a) The location of GPR profiling to find the depth of ice and DGPS measurements for detecting the velocity of the glacier. Green points show the GPR profile location and brown points the DGPS measurements. The high crevassed zone was present at the location around it and team couldn't move for the longer area. (b) The difference of measurement made during two days i.e. 11th and 12th June 2017. A difference of average 2 meters is noted between the two readings.

The glacier has a surge history and local community informs during field investigations that previously it surged on 2000, 1980, and 1960. The community also informs about the flood episodes during these years few of which were also reported as mentioned in table-1. The previous surge analysis shows that the velocities during those surges remain above 5 km per annum (Quincey & Luckman 2014). The formation of Lake during these surges are also evident which was ultimately outburst creating flood wave. The lake formed during the surge of 2000 is shown in figure-6.This Lake was drained due to an outburst causing low-level flood with fortunately no damage. Local community informs that the lake was drained in a controlled way.

Figure 5 (a): Aerial view from a helicopter showing the dense crevasses (b) portion of the highly crevassed zone which couldn't allow the team to cross.

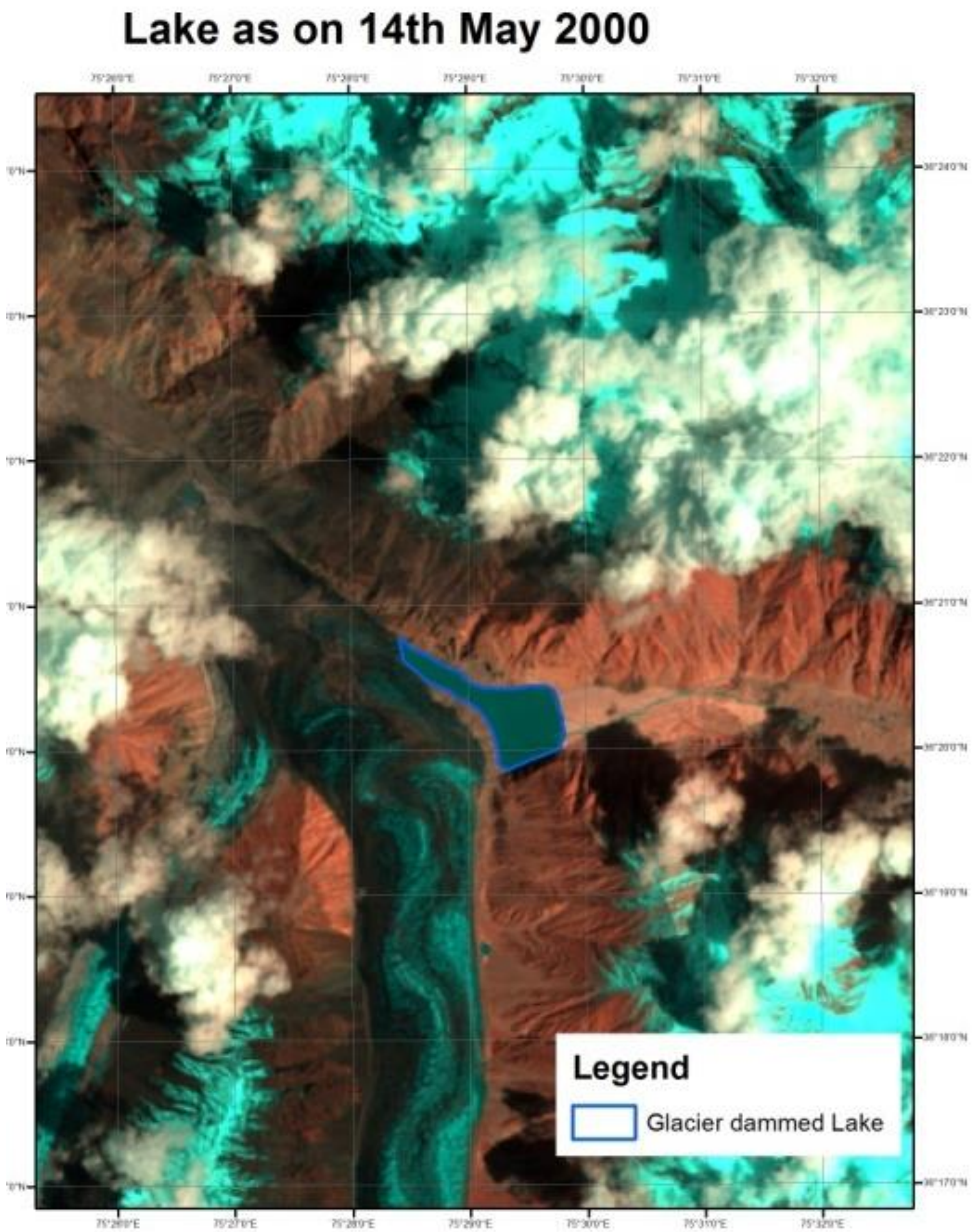

Figure6: Lake situation on 14th May 2000 during surge of Khordopin Glacier in the year 2000

ASSESSMENT OF KHORDOPIN GLACIER ICE DEPTH NEAR TERMINUS

The depth of ice near the terminus of Khordopin glacier was calculated using Ground Penetrating Radar (GPR) and assessed using different techniques during field investigations. A set of small frequency antennas were used to figure out the depth of the glaciated ice upslope of the terminus of Khordopin Glacier near the lake formation. The antennas with frequencies of 16 Mega Hertz, 20 Mega Hertz, and 40 Mega Hertz were used so that deeper penetration into the glaciated surface could be achieved to assess the depth of ice. At the location of GPR profiling, as shown in figure-4(a), depth of ice was calculated to be 135 to 175 meters deep as shown in figure-7. Previously there was no glacier at this site and river flows from the same location which has been intercepted and overlaid by glaciated ice.

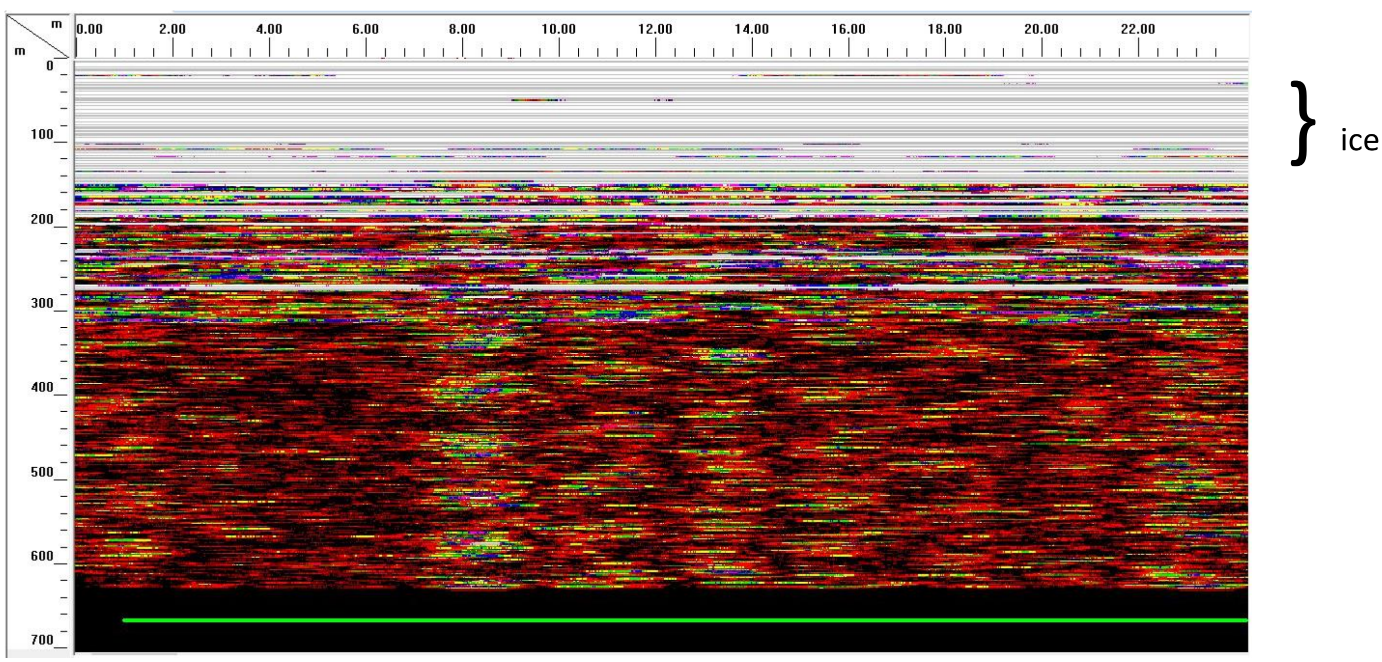

Figure-7: A profile of GPR showing the depth of ice

It is notable that the ground surface at the location where the lake formed is lower than the surface where the glacier advances. This ground surface is 15 to 20 meters higher which increase gradually over the one-kilometer area as shown from the elevation contours in figure 9. The advancement of the glacier at that location further elevates the surface which results in lake formation. The damned wall of the lake toward its drainage end is high enough which provides ample capacity for lake water to accumulate as shown in figure 15.

Figure 8-Profiling using GPR and DGPS on the glacier surface

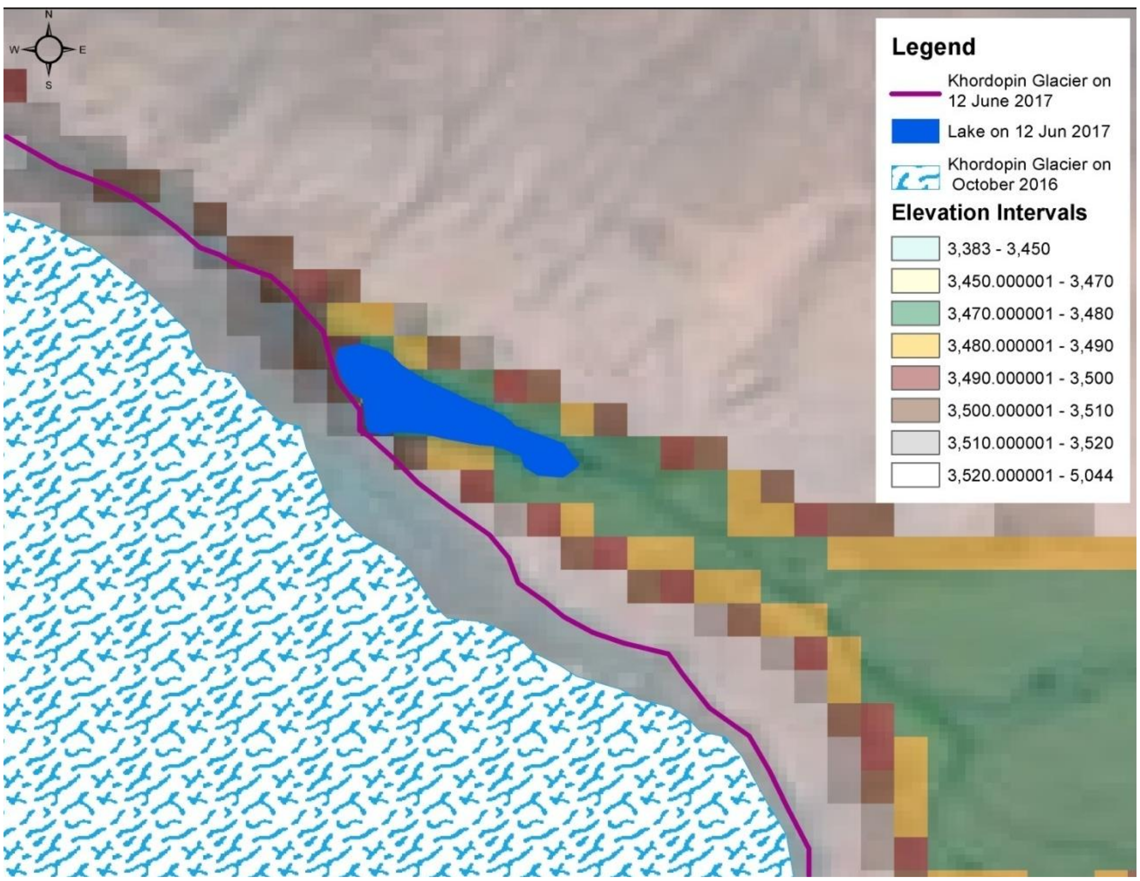

Figure-9: The ground at Lake location site and behind is lower than the area in front of Lake

The elevation of the area where DGPS measurements and GPR profile was taken was 3612 meters, but the elevation of the base where previously River flows according to Digital Elevation Model (DEM) was around 3520. The freely available Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) DEM at 30 meter resolution was used for extracting the elevation values of the site. If we take into account the averaging at 30 meters resolution of DEM even then the depth of the glacier ice is figured out to be around 90 meters which are near to the depth calculated by GPR. A large-scale profile using GPR couldn't be made due to the highly crevassed area (figure-5 (a) and (b)) so unable to move easily with long rods of small frequency antennas. Thus profiling crosses the glacier and along the glacier was not assessable.

LAKE FORMATION AND ATTRIBUTES

The latest available satellite image acquired on 12th June 2017 shows that the area of glacier lake, formed due to the glacier surge reached to 60515 square meters (Figure-.11 and 12). The lake was mapped simply by calculating Normalized Difference Water Index (NDWI). The glacier lake starts forming in the second week of May 2017 just after the advancement of the glacier blocked the river flow coming from Virjerab glacier melt. No lake was found in the image of 6th May 2017 (figure-10). The size of the lake during different dates was estimated by mapping the lake from available images. Only three cloud-free images were acquired which were used for lake size estimation. The mapping shows that lake increased at a rate of 1390 square meters per day (figure-11 and 12) starting estimating from 13th May 2017 to 12th June 2017.The size of this Khordopin-Virjerab lake increases gradually and it took 31 days for the lake to attain the area of 60515 square meters on the latest available image of 12th June 2017. Unfortunately, PMD team couldn't cross the glacier to reach the lake site due to the unfolding of the glacier ice and available dense crevasses. However, special thanks to two local community people namely Mr. Rehamat Ullah Baig (Ex-Chairman, Shimshal Natural Trust and summiteer of K-2 in 2014) and his brother Mr. Qurban Ullah Baig managed to reached at the lake site and share their experiences and on-site pictures which helped a lot in analysing the features of the lake.

There is a shift in the location of the lake due to the movement of the glacier. The lake which formed somewhere after the second week of May 2017, shifts towards eastern side as shown in figure 13. The eastward shift is attributed to the movement of the glacier which pushed and squeezes the lake from its western side. But the melt water from Virjerab is continuously adding to increase the size of the lake. This drift of glacier will surely effect the englacial drainage from the lake and there is a high probability of complete blockage of englacial flow which accelerates the process of increasing water level in the lake.

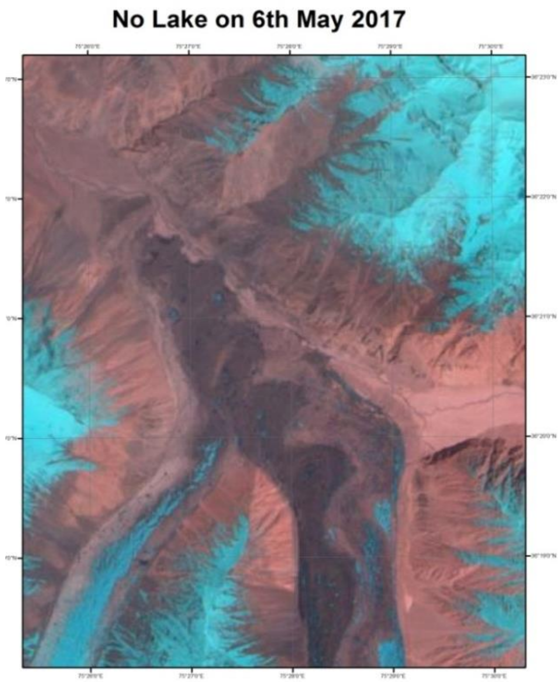

Figure 10: No lake was formed by 6th May 2017 as shown in above image

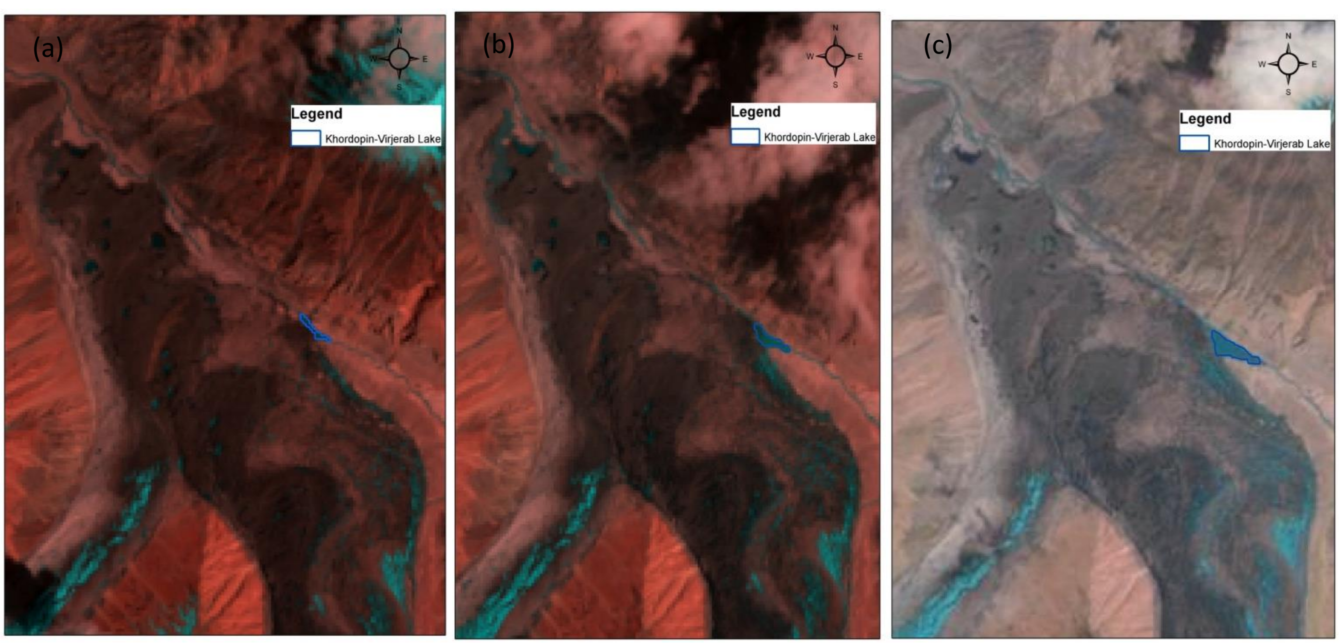

Figure 11: Lake size changes during different days (a) 13th May 2017 (b) 29th May 2017 (c) 12th June 2017.

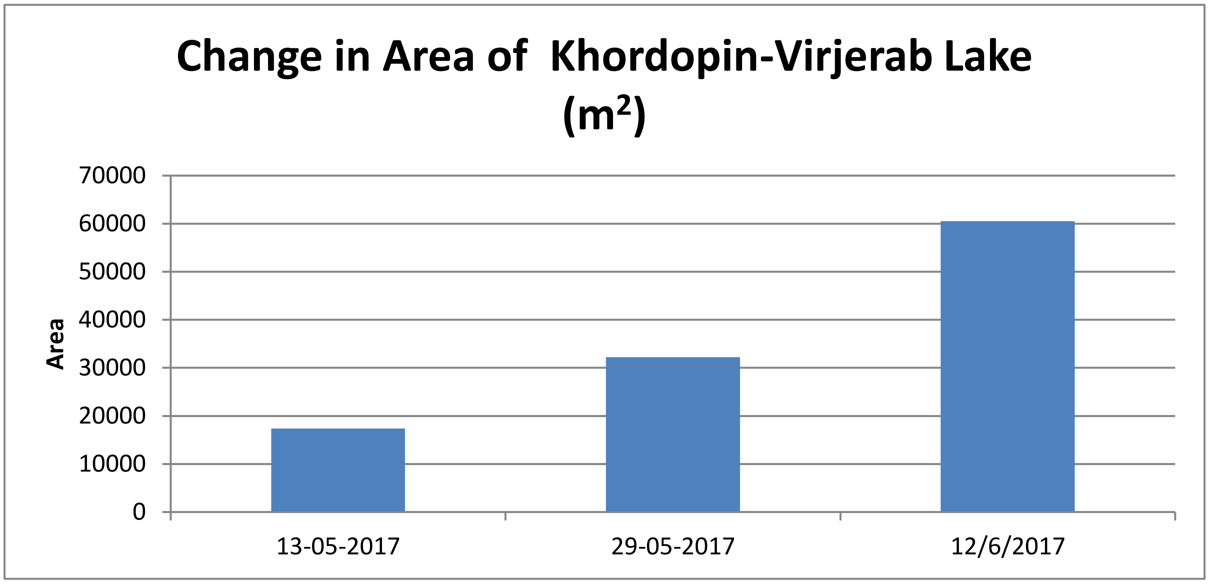

Figure 12: Changes in Lake area.

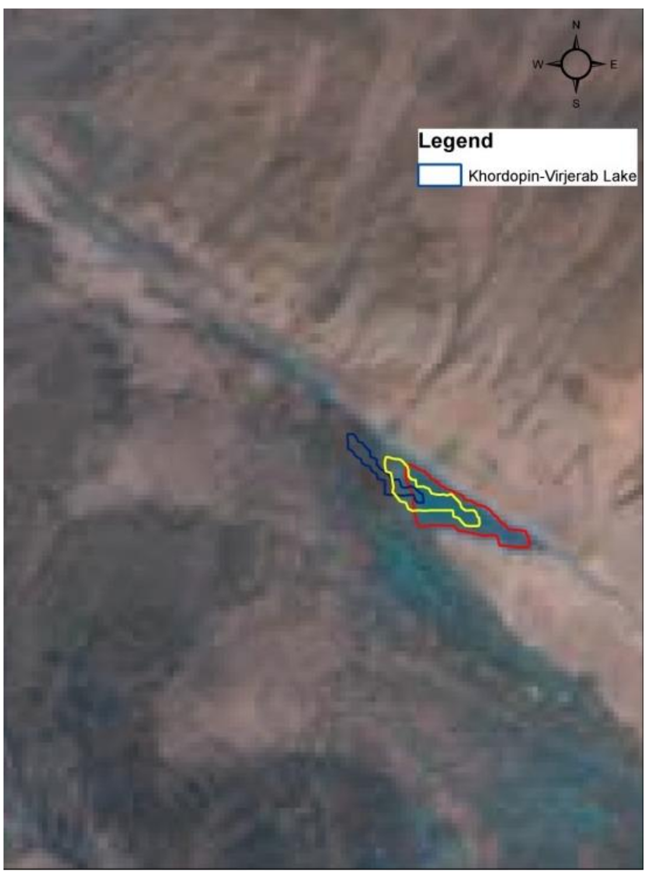

Figure 13: Eastward Shift of glacier lake due to a surge of Khordopin Glacier.

The lake water is draining from subglacial flow for approximately 2kilometersas shown in figure-14 and 15. Thereafter the drainage water comes out from the glacier and flows as surface flow. The length of this sub-glacial flow was 536 meters on 29th May 2017 which increased to 2 kilometres on 12th June 2017. This length increases due to advance of the glacier and blocking surface flow. Fortunately, water finds its way from englacial conduit system and drainage continues which result in a slow increase of lake size. It couldn't be figured out where exactly the subglacial flow is present as shown in figure 15. However, it seems that this drainage channel will collapse if glacier surge continues and the lake is expected to increase in size during this summers. The depth of ice at this location is approximately half of the depth calculated from GPR profile location. So if the subglacial basal flow from the western end of the lake blocks completely then the probability of increasing lake size up to 600,000 square meters or more is expected. This can be calculated from the elevation contours as shown in figure-17 which will then be the very alarming situation. In case of blockage of sub-glacial drainage the drainage from lake start over topping over the glaciated ice in the western end of lake. This will erode the ice and increase the vulnerability of outburst.

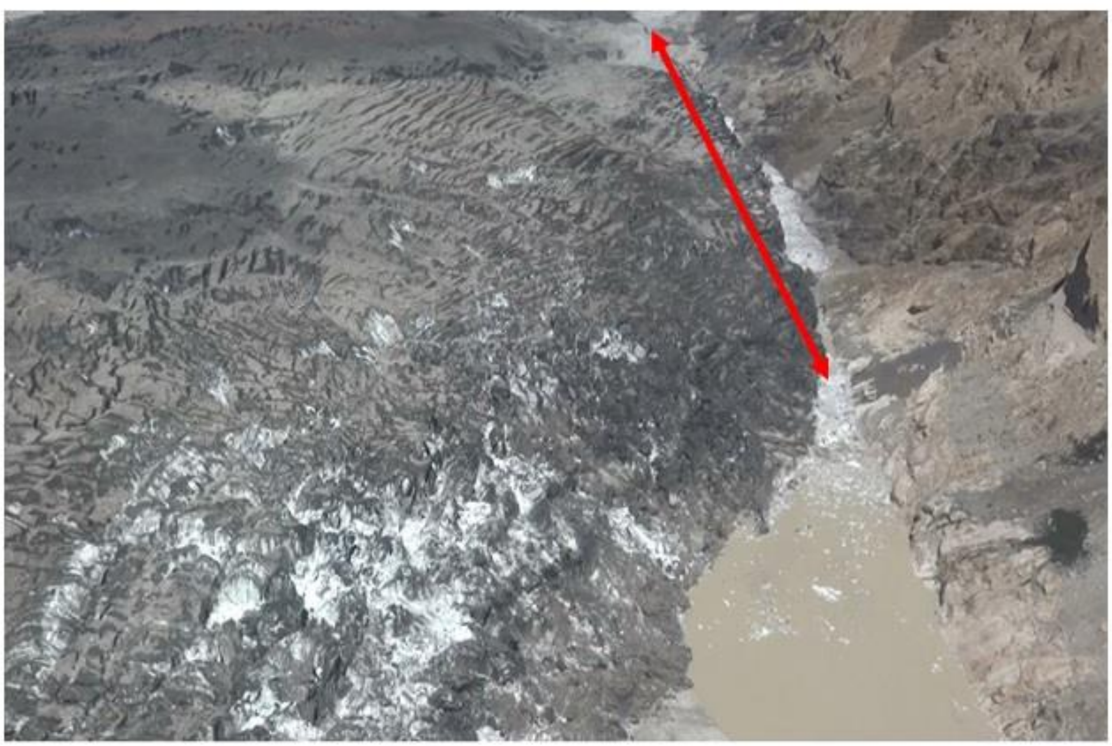

Figure 14 Image showing englacial discharge for two kilometres

Figure 15:Subglacial Drainage of Khordopin-Virjerab Lake (Courtesy Mr. Rehmat Ullah Baig).

The depth of the lake estimated with the help of pictures taken by local people (figure-16 (a)) and Google Maps (Figure-16 (b)). It was estimated that on 11th June 2017 that the estimated depth of the lake was approximately 4 meters. This rough estimate of depth was calculated by pointing water level point and finding elevation at that point using Google Maps and DEM. Thereafter the depth was estimated by the difference of this elevation of the water level of Lake i.e. 3475 masl with the lowest elevation point in the lake.

Similarly, the projected increase of lake size can be estimated from the available DEM as shown in figure 17. If the depth of the lake increases by an interval of ten meters, the projected size of the lake area will increase creating a hazardous situation. The area of the lake will increase muchfolds with even few meters increase in lake depth. The area and depth of the lake will increase due to the blockage of sub-glacial flow as well. The blocked western side of the lake provides enough room for the lake to increase in depth and size. If the subglacial drainage is blocked due to glacier surge or due to debris or sediments coming from Virjerab glacier, the wall of ice dam that blocked the river flow(figure-15) will still be responsible for the increase in lake size. The situation will become worse if the damming wall raises resulting from glacier surge.

Figure 16(a) Google map image before the formation of the lake. The mark is indicating the level of water in the lake estimated using figure (b), (b) Taken from a helicopter the lake on 16th July 2017 showing the level of water in the lake.

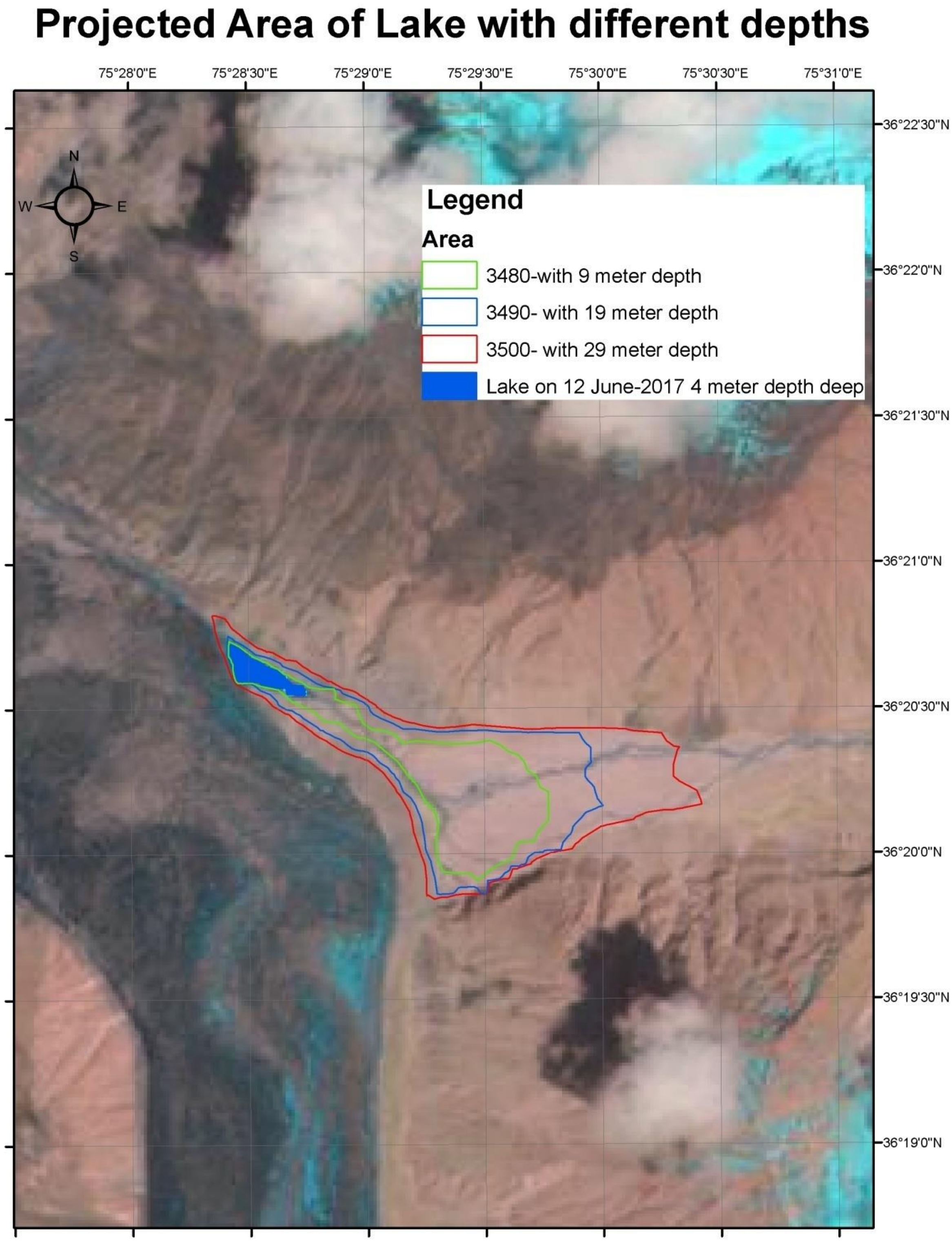

Figure-17: Projected increase in lake area with an increase in depth of the lake.

CONCLUSIONS

The Khordopin Glaciers started surging slowly during winter of 2016-17. The surge rate rapidly increases in early summers of 2017. The analysis of Khordopin advance and resultant lake formation concludes the following:

1. The recurrence of surge has been estimated approximately after every 20 years since record available. Thus the response period of Khordopin glacier is around 20 years since little ice age.
2. These surges often created glacier dammed lake by blocking melt water coming from Virjerab glacier and linked with flood events as a result of glacier-dammed lake outburst. Flood waves sometimes resulted disaster downstream as literature and local elders narrated.
3. The recent surge could result in increase of lake size which has the potential of outburst and high probability of damaging downstream infrastructure/ community. In the case of any small event of debris flow from Virjerab glacier or any movement of some boulders in melt water from Virjerab will choke the sub-glacial flow of newly formed Khordopin-Virjerab glacial lake. Resultantly, the lake size will increase; since there is still enough space for water to accumulate behind damming ice wall.
4. There is almost 2 kilometres long damming ice wall towards the outflow from the lake which can resist its outburst especially during winters. But during summers the probability of enhanced melting at or near the snout will create an alarming situation.
5. The depth of the ice below the lake formed is approximately 135 to 175 meters deep and the glacier is still surging which can increase this ice depth.
6. The lake area on 12th June 2017 was estimated to be 60515 square meter which is increasing at rate of 1390 square meter per day. So lake size is expected to increase in summers unless or otherwise lake drained in a controlled way.
7. The surge dynamics of the year 2016-17 by the Khordopin glacier is similar to previous surges of 2000 and 1980 or before. Previously both surges started during winters and show advancing behavior till coming summers. Moreover, the advance is associated with lake formation as well. This spatial relationship of forming lake as a result of Khordopin glacier surge and its outburst has a temporal period of 20 years. The terminus of the glacier remains stable during this surge and previous surges also reported no change in terminus.

8. Regular monitoring of lake and glacier surge is necessary to predict any disastrous situation on the lake.

ACKNOWLEDGEMENTS

The field work was carried out with the funding assistance provided by International Centre for Integrated Mountain Development for Shimshal Valley.

References

Archer, D.R. & Fowler, H.J., 2004. Spatial and temporal variations in precipitation in the Upper Indus Basin, global teleconnections and hydrological implications. *Hydrology and Earth System Sciences*, 8(1), pp.47–61.

Ashraf, A., Naz, R. & Iqbal, M.B., 2015. Heterogeneous expansion of end-moraine dammed lakes in the Hindukush-Karakoram-Himalaya ranges of Pakistan during 2001???2013. *Journal of Mountain Science*, 12(5), pp.1113–1124.

Gardelle, J. et al., 2013. Region-wide glacier mass balances over the Pamir-Karakoram-Himalaya during 1999–2011. *Cryosphere*, 7(4), pp.1263–1286.

Goudie, A.S., Brunsden D., Collins D.N., Derbyshire E., Ferguson R.I., Hashmet Z., Jones D.K.C., Perrot F.A., Said M., Waters R.S., Whalley W.B., 1984. The geomorphology of the HUnza Valley, Karakoram Mountains, Pakistan. In Miller K.J., editor. The International Karakoram Project. Cambridge, United Kingdom: Cambridge University Press, pp. 268-354.

Hewitt, K., 2014. Glaciers of the Karakoram Himalaya. , (1), pp.327–351. Available at: http://link.springer.com/10.1007/978-94-007-6311-1.

Hewitt, K., 1998. Glaciers receive a surge of attention in the karakoram himalaya. *Eos, Transactions American Geophysical Union*, 79(8), pp.104–104.

Hewitt, K., 2005. The Karakoram Anomaly? Glacier Expansion and the “Elevation Effect,” Karakoram Himalaya. *Mountain Research and Development*, 25(4), pp.332–340.

Hewitt, K., 2007. Tributary glacier surges: An exceptional concentration at Panmah Glacier, Karakoram Himalaya. *Journal of Glaciology*, 53(181), pp.181–188.

Hewitt, K. & Young, G.J., 1993. The Snow and Ice Hydrology Project: a Pakistan-Canada research and training programme. *Proceedings of the Kathmaodu Symposium*, 218(218), pp.49–58. Available at: http://itia.ntua.gr/hsj/redbooks/218/hysj_218_01_0000.pdf#page=63.

Iturrizaga, L., 2005. New observations on present and prehistorical glacier-dammed lakes in the Shimshal valley (Karakoram Mountains). *Journal of Asian Earth Sciences*, 25(4), pp.545–555.

Kääb, A. et al., 2015. Brief Communication: Contending estimates of 2003-2008 glacier mass balance over the Pamir-Karakoram-Himalaya. *Cryosphere*, 9(2), pp.557–564.

Paul, F., 2015. Revealing glacier flow and surge dynamics from animated satellite image sequences: Examples from the Karakoram. *Cryosphere*, 9(6), pp.2201–2214.

Quincey, D.J. et al., 2011. Karakoram glacier surge dynamics. *Geophysical Research Letters*, 38(18), pp.2–7.

Quincey, D.J. & Luckman, A., 2014. Brief communication: On the magnitude and frequency of Khurdopin glacier surge events. *Cryosphere*, 8(2), pp.571–574.

Rasul, G., Dahe, Q. & Chaudhry, Q.Z., 2008. Global Warmin and Melting Glaciers along Southern Slopes of HKH Ranges. *Pakistan Journal of Meteorology*, 5(9), pp.63–76.

Round, V. et al., 2017. Surge dynamics and lake outbursts of Kyagar Glacier , Karakoram. , pp.723–739.

Todd, H.J.,, 1930. The Correspondence: Gilgit and Hunza River Floods. Himalayan Journal, 2, pp. 173-175.

Visser, Ph. C., 1926. Explorations in the Karakoram. Geography Journal, 68, pp. 457-468.

Waragai, T., 2012. Relationship between recent fluctuations of glacier snouts and outburst floods of glacier-dammed lakes in north western Karakoram Mountains, Pakistan. *Quaternary International*, 279–280(2012), p.528. Available at: http://dx.doi.org/10.1016/j.quaint.2012.08.1841.

.