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HISTORY & PRESENT SITUATION OF GLACIER AND DEVELOPMENT OF ICE-DAMMED LAKE IN HUNZA BASIN: CASE STUDY OF HASSANABAD (SHISHPER) GLACIER

Syed Hammad Ali, Adeel Hassan, Muhammad Tabeen ul Barkaat & Wasim Khan

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By:

Syed Hammad Ali[1], Adeel Hassan, Muhammad Tabeen ul Barkaat & Wasim Khan

Abstract

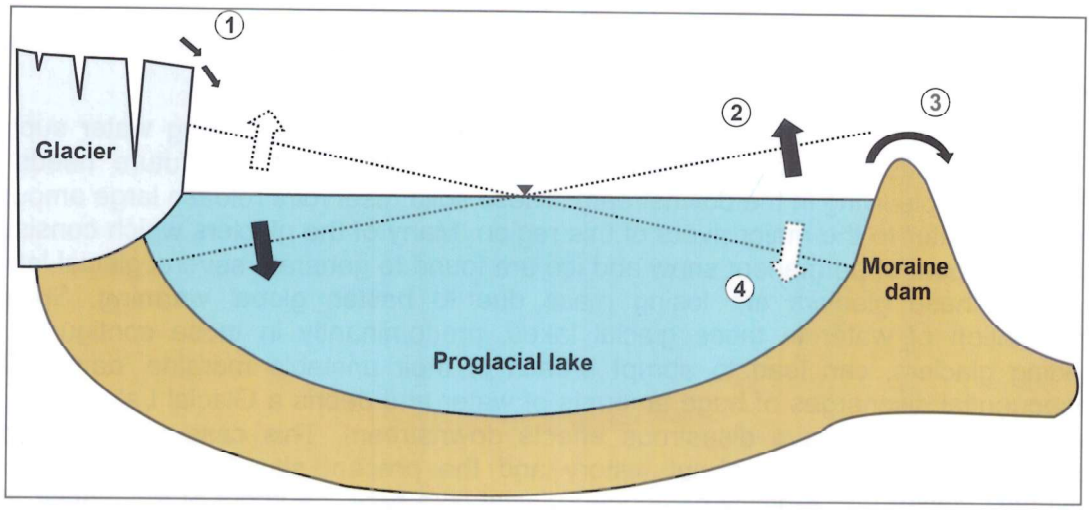
The glaciers are nature's precious resource of fresh water for drinking water supply, agricultural, industrial and hydropower expansions for current and future needs of millions of people living in the downstream. These solid reservoirs release large amounts of ice melt water to the major rivers of this region. Many of the glaciers which consist of massive amount of permanent snow and ice are found to generate several glacial lakes. However, these glaciers are losing mass due to hasten global warming. Speedy accumulation of water in these glacial lakes, predominantly in those contiguous to receding glaciers, can lead to abrupt breach of their unstable moraine 'dams'. The consequential discharges of huge amounts of water and debris a Glacial Lake Outburst Flood (GLOF) often have disastrous effects downstream. This case study provides comprehensive information about history and the present situation of Hassanabad (Shishper) glacier and a newly developed glacial lake near the snout of the glacier also provides baseline data for further investigation of glacial lake, GLOF hazards and risk assessment, and mitigation measures. RS/GIS analysis revealed that the Hassanabad (Shishper) Glacier advanced with a very high surging velocity and caused the formation of lake which starts from November to December and breached during April to June in 2019 and 2020. This year again a lake of ~ 0.050 km^2 size developed in December 2021 and expanded upto ~ 0.142km^2 till February 2022. In the image of 05-05-2022 it is observed that the lake extent reached ~ 0.350km^2 and on 7th of May the lake breached again. It is important to note that the breach occurred when the lake reached almost the same extent as in 2019, 2020 and again in 2022. A lake of 0.16km^2 which reduces to 0.08km^2 till 25th May still present subsequent to the massive release of water from 7th to 9th May 2022 the lake is still prone to blockage and could potentially burst again, during this year as the temperature will rise in coming months. The possibility of greatest risk extends through to September. It is therefore imperative to monitor the lake regularly. This study also provides numerous potential methods for mitigating the impact of GLOF. The most important mitigation measure for reducing GLOF risk is to diminish the volume of water in the lake in order to reduce the peak discharge. Careful evaluation by detailed physical monitoring studies of the lake, nearby glacier, damming materials, and the surrounding conditions are essential in choosing an appropriate method and in starting any mitigation measure. Understanding of these resources seems an exceptional requirement for future planning for reducing the risk and GLOFs hazards.

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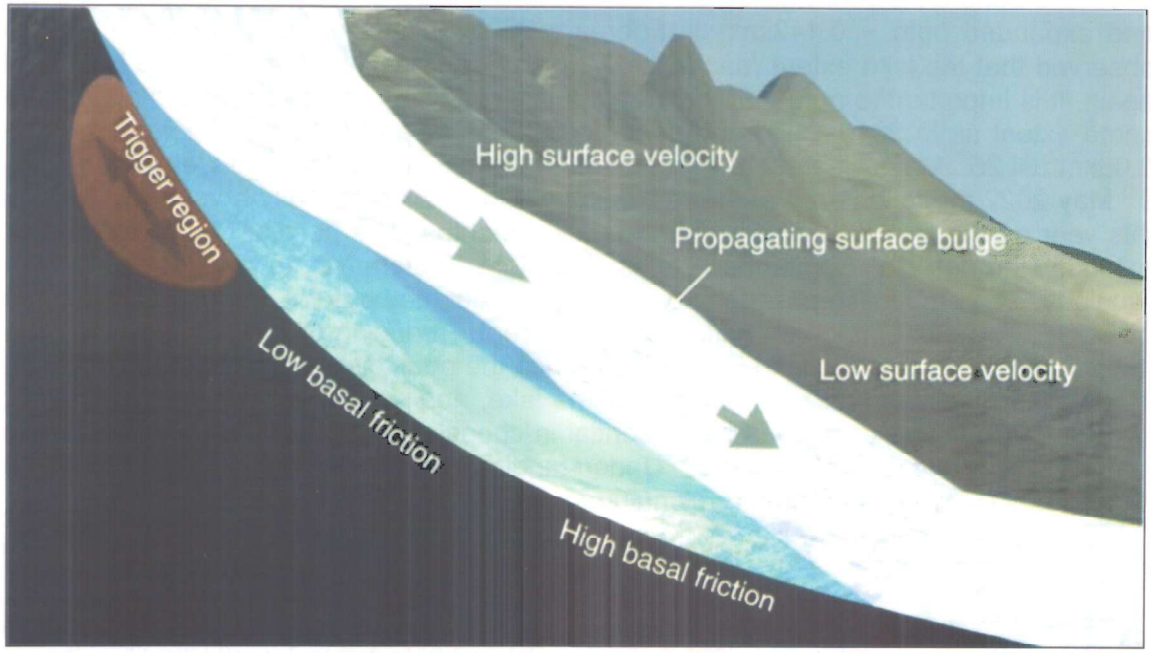
MORAINE DAMS

Moraine dams are among the weak natural dams because of their slope, freeboard and composition. Glacial lake outburst floods occurring due to the failure of moraine dams are significant hazards for the valley downstream the failure, as they possess huge amount of hydraulic energy that can kill thousands and destroy infrastructures and riverine landscape. Following figure show the Moraine dam.



Basal Movement of Glaciers

Glaciers move by a combination of (1) deformation of the ice itself and (2) motion at the glacier base. At the bottom of the glacier, ice can slide over bedrock or shear sub-glacial sediments which is called as Basal movement of Glacier as shown in following figure.



Remote Sensing / Geographic Information System (RS/GIS Image)

Remote sensing is the process of detecting and monitoring the physical characteristics of an area by measuring its reflected and emitted radiation at a distance (typically from satellite or aircraft). Special cameras collect remotely sensed images, which help researchers "sense" things about the Earth.

GIS Data. Imagery is a type of data that is useful for many GIS applications and is defined as any type of photograph. Normally photographs used for GIS projects consist of images gathered from a satellite or an aircraft.

GIS technology integrates common database operations, such as query and statistical analysis, with maps. On the other hand, remote sensing is the science of collecting data regarding an object or a phenomenon without any physical contact with the object.

Gabion Protection

A gabion is a cage, cylinder or box filled with rocks, concrete, or sometimes sand and soil for use in civil engineering, road building, military applications and landscaping. Gabions are used to slow the velocity of concentrated runoff or to stabilize slopes with seepage problems and/or non-cohesive soils as shown in the following picture near the bank of river.



Keywords: Glacier, GLOF, Accumulation, Moraine, Hazard & Risk Assessment

Introduction

Pakistan is agriculture based country and is highly reliant on the Indus irrigation system. The major Indus basin divided into three basins the Kabul, Upper Indus, and Panjnad. The upper Indus basin includes the Gilgit, Hunza, Shigar, Shyok, Zanskar, Shingo, Astor, and Uppar Indus sub-basins. The Indus River is the backbone of Pakistan's irrigation and Hydropower generation which draws a major part of its flow from snow and glacier melt. Glaciers are a critical component of the earth system. Pakistan is the most

heavily glaciated area in region contributes significantly to the overall land cover. There are approximately 7000 glaciers in this catchment which covers an area of 15000 km^2. The glaciers are nature's precious resource of fresh water for drinking water supply, agricultural, industrial and hydropower expansions for current and future needs of millions of people living in the downstream. These solid reservoirs release large amounts of ice melt water to many of the major rivers of this region. Many of the glaciers which consist of massive amount of permanent snow and ice are found to generate several glacial lakes. However, these glaciers are losing mass due to hasten global warming. Speedy accumulation of water in these glacial lakes, predominantly in those contiguous to receding glaciers, can lead to abrupt breach of their unstable moraine 'dams'. The consequential discharges of huge amounts of water and debris a Glacial Lake Outburst Flood (GLOF) often have disastrous effects downstream. Understanding of this resource seems an exceptional requirement for future planning for water resources and flood hazards. Pakistan is among the most vulnerable countries to face the impacts of climate change, as the average temperature is increasing per year. As a result of which glacial lakes are increasing in size and volume. A sound understanding of the dynamics and recent variations of the glaciers and glacial lakes are important for evaluating whether changes in their terminus position are driven by factors such as external climate forcing or internal ice dynamics. The climatic changes show the likelihood of glacial advance/retreat, which may be an originator of a period of transformed dam burst floods. Flood risks are dominated by monsoonal storm conditions in summer. However, the larger part of summer high flows on the Indus system are due to snow and ice melting. During certain periods in the past, for example, the 1920s and 1930s, glacier dams and dam burst floods in the Indus system were a major and intermittent risk. There are indications that the return of such problems can be anticipated. Knowledge of glaciers and glacial lake activity is required not only for planning for water resources but also for management of flood hazards such as GLOFs downstream. Unfortunately, understanding of the mountainous headwater of the Indus, and especially of snow and ice conditions is extremely poor.

Glacial Lakes in Pakistan

According to glacier inventory developed by ICIMOD in 2005 with the help of RS/GIS techniques, over this glaciated area, there are about 2500 glacial lakes created due to glacier melt waters and 52 of them were confirmed potentially hazardous for Glacial Lake Outburst Flood (GLOF). The GLOF events are disastrous as huge loads of debris and mud flow downstream smash up the infrastructure, houses and crop-lands resulting in scores of life losses if it happens without any alert signal. For mountain population, GLOF is the greatest hazard which is being reinforced by climate change in terms of occurrence and susceptibility. Booni Gole Glacier located near Chitral in Hindukush mountain range generated outburst flood in July 2010 triggered by monsoon downpour and caused huge 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. Due to steep slope downstream, the carried loads of mud, debris including heavy boulders gain momentum and cause heavy losses to land, settlements and infrastructure. Passu lake outburst had also followed the similar mechanism in the past with the frequency of outburst at an

irregular interval of 2 to 5 years. The scene of its damages is quite visible travelling from Karakoram Highway as Passu village is located along that highway. There is an increasing tendency of formation of new lakes and expansion of existing ones near the glaciers of the Himalayas and Hindukush as confirmed by the temporal comparison of satellite imageries. According to a study conducted by Ashraf et. al. 2012 there are approximately 2,420 glacial lakes are present in GB and KPK region out of which 52 are declared as dangerous as presented in table 2. According to UNDP GLOF-II Project Report a total of 3,044 glacial lakes have developed in Gilgit-Baltistan (GB) and Khyber Pakhtunkhwa (KP). Of these, 33 glacial lakes have been assessed to be prone to hazardous glacial lake outburst flooding (GLOF). Recently UNDP has taken an initiative to study two glacial lakes in Chitral and Gilgit by in-situ observations and remote sensing tools in association with local public and private organizations concerned with glacier monitoring and research. Hopefully, a warning system will be developed to save the lives of the people most likely exposed to that hazard.

Study Area

Hassanabad is a small village adjacent to Aliabad city, Hunza, Northern Pakistan. Hassanabad (naalah) originates from Shishper and Muchichal glaciers, and runs toward the south, joining with the adjacent Hunza River and finally drains into the Indus River. The Shishper Glacier geographically extends through Latitude 36° 15′ – 36° 30′N to Longitude: 74° 28′ – 74° 39′ E (Fig. 1). The elevation ranges from 2,478 to 7,450 m.a.s.l. It covers an area of approximately 45.712km^2. The study area has an essential role in hydro-power generation for Hunza Valley (Hassanabad power complex: 1200 KW Norwegian unit, 700 KW Chinese unit and 2000 KW Diesel generated power station).

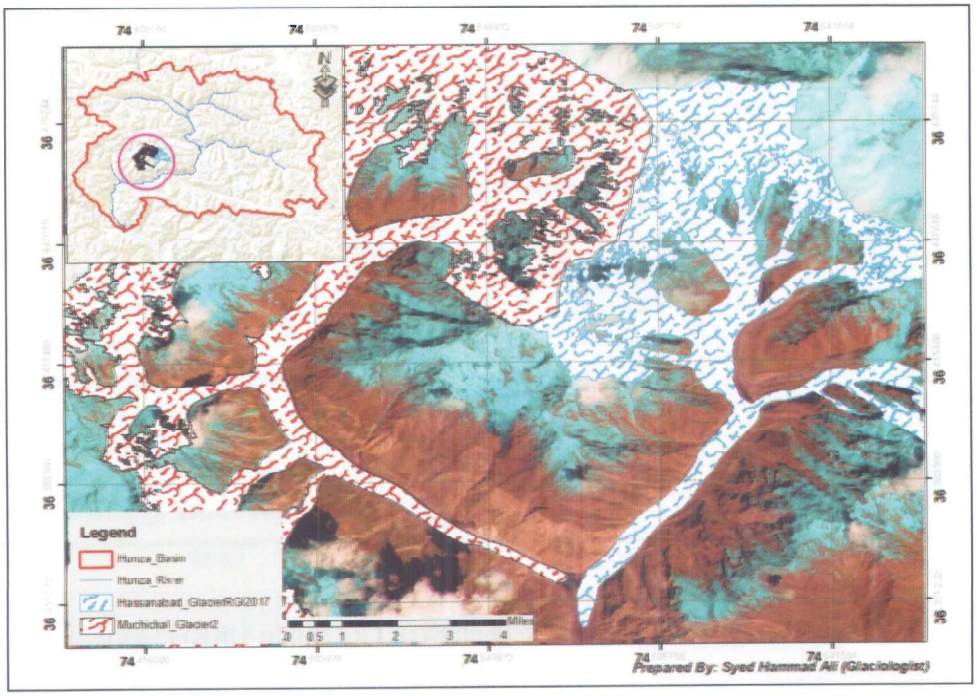


Figure-1: Location map of Shishper Glacier

Triggering Factors of Historical GLOF Events

Climate change is likely to make something worse further some of these natural hazards such as glacial lake outburst floods (GLOFs), which can cause major social and economic damage for large populations living in the Himalayan region. Pakistan has a very long and devastating history of natural disasters. However, in the past there has been no proper mechanism to record and maintain data on disaster events and classify them accordingly. Thirty-five destructive outburst floods have been recorded for the Karakoram Range in the past 200 years. However, during the past one decade systematic mechanism has been adopted to establish relevant data on disaster. Some of the historical data of GLOFs in UIB given in table 1. GLOF is the dynamic process as it involves complex phenomenon to occur. It varies from place to place depending on the geomorphological setting of the area, lake geometry, dam material and other external factors (earthquake, heavy participation). There are three main triggering factors, a) surging glaciers 41%, b) Intense rainfall 8% and c) High Temperatures 3% and also some other factors which are unknown 47% causes the catastrophic recorded historical GLOF events respectively in HKH region as shown in the figure 2 by ICIMOD.

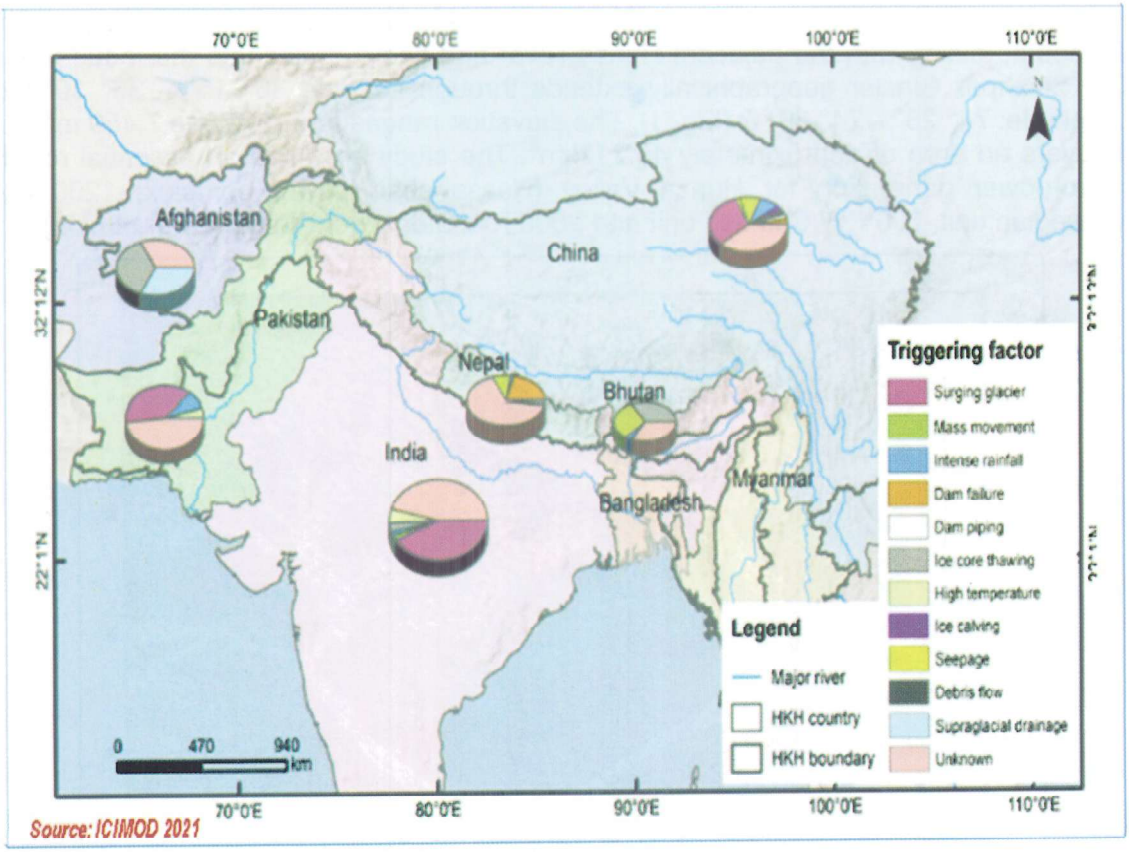


Figure-2: Triggering factors of Historical GLOFs in HKKH Region

Process of Ice Dam Formation, Lake Expansion and GLOF Generation

Throughout a surge cycle, glacier mass is transported from the accumulation zone to the ablation zone, promoting the expansion and thickening of high mass barriers at the terminus that effectively block rivers to form ice-dammed lakes (Figs. 3 a, b). Consequent to lake drainage by a GLOF, there is a close connection between resealing formation of lakes, transfer of ice volume to the terminus zone, and surge variation in crevassing. The transferring ice is the key source of the dam barrier and the barrier elevation can raise the likelihood of forming high volume lakes (Round et al., 2017) and the subsequent creation of a series of resealed lakes (Hewitt and Liu, 2010).

The high velocities produce variations in crevasse configurations during the active surge phase and increase the density of crevasses (Jiskoot, 2011; Kamb et al., 1985; Thorarinsson, 1969). The extension of the terminus imposes an ice barrier such that small lakes can be impounded without the presence of a well-developed subglacial conduit (Kamb et al., 1985; Meier and Post, 1969) leading to an expansion of the lake volume (Fig. 3c). Ultimately, sub-glacial melt links crevasses and forms an open conduit, allowing lake water to drain as a small volume GLOF in the first instance (Fig. 3d). After the initial active surge phase, the glacier movement continues for several years, which increases the terminus elevation but with a lower rate of glacier movement, at which time crevasses and conduits close (Hewitt and Liu, 2010; Kamb et al., 1985; Liestøl, 1969; Meier and Post, 1969). These latter conditions are constructive for resealing/reforming deeper and larger lakes (Hewitt and Liu, 2010) such that the probability of further and larger GLOFs remains present for coming seasons and years.

The process enhances the storage capacity behind the blockage, thus creating greater reservoir volume in subsequent cases (Fig. 3e). Hewitt and Liu (2010) stated that the outburst floods are linked to summer temperatures which facilitate melting at the glacier surface, which water is transferred to the base enhancing the basal movement of the glacier (Round et al., 2017). However, the causal link between the variation in crevasse configuration, density and depth of penetration with the fluctuation of velocity during both the active and lower phase of surging has not yet been clearly determined. Nonetheless, average glacier surge velocities in the Karakorum are observed to be higher during the summer seasons which support the arguments that the summer temperature can influence the subglacial water flux and thus the surge velocity.

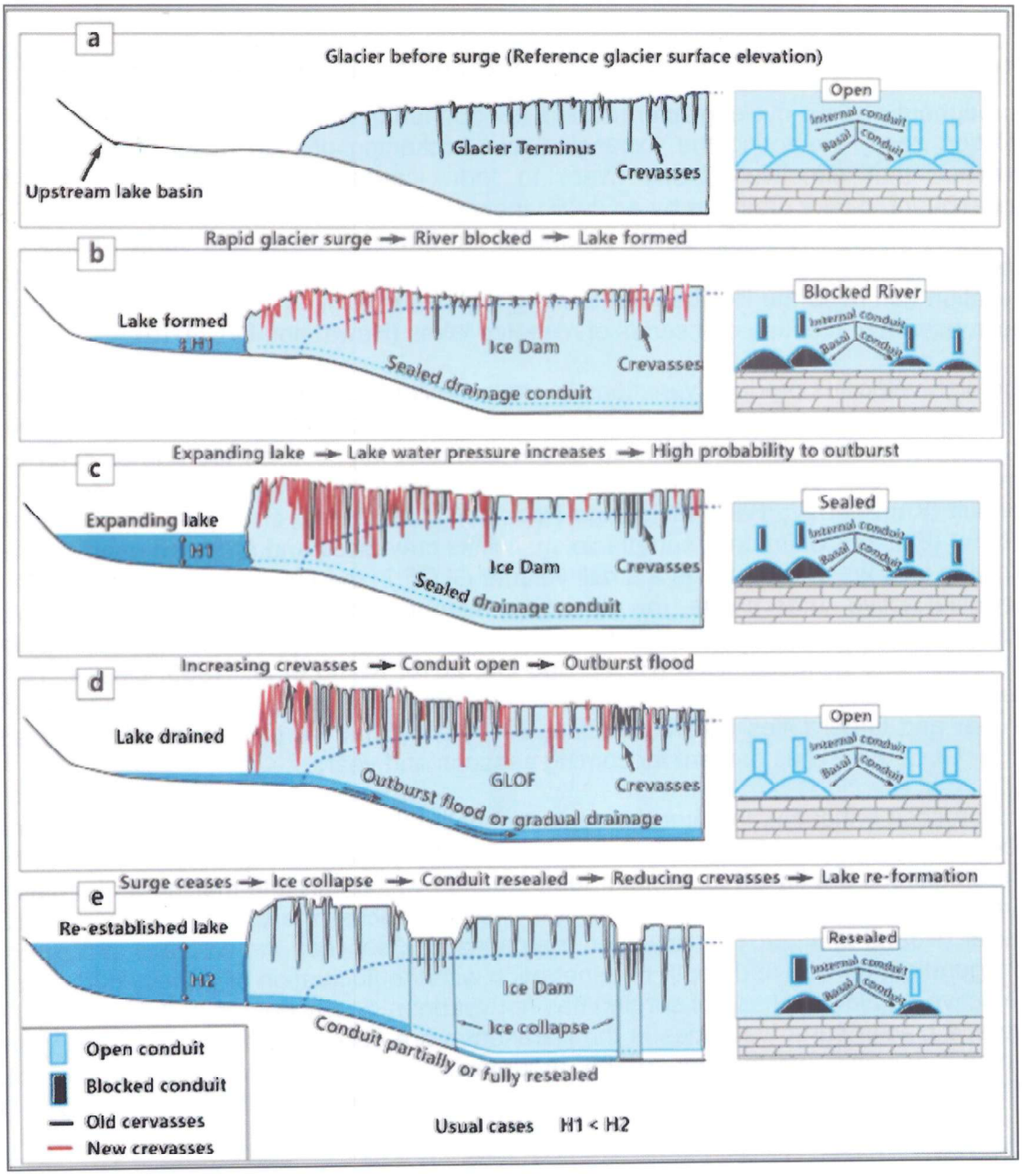


Figure-3: Conceptual model for glacial lake outburst floods *(Source: N.A. Bazai et al. 2021)*

The development of the lakes and subsequent GLOFs reflect the fluctuation of surge velocity during active and lower phase of surge. Based on historical and current data, the summer temperature likely is one control of the variation of surge phases and the flux of water to the lakes and to any open or partially-open conduit. However, the longer-term transfer of ice mass to the terminus is the ultimate control on the formation, draining and resealing lakes (Fig. 3a-e). Overall, the seasonal temperature mainly contributes to the initial hastening.

Glacier velocities increase in late spring, mass is transferred towards the terminus in summer, and ice barriers form across the river bed during active surges. A small lake first form as the ice mass increases in height and partially closes the subglacial conduit (Liestøl, 1969; Meier and Post, 1969). A GLOF may occur due to 'chance' connectivity of sub-glacial conduits, but is probably more related to a deepening lake increasing the pressure within sealed or partially sealed conduits leading to localized ice-mass collapse and/or thermal erosion of conduits. Note that larger and deeper lakes form later in a surge cycle as lower movement of ice, ice height and mass increases in the near-terminus zone.

Following a GLOF, flood conduits opened by thermal erosion during the flood collapse or close by ice creep. Resealed lakes usually form during winter, when river and any conduit flow are close to freezing so thermal erosion of ice is small (Figs. 3d) (Hewitt and Liu, 2010). In this model lake volume qualitatively is proportional to the ice barrier height and inversely to the presence of crevasses; valley geometry at the terminus zone is an additional specific local control (Hewitt and Liu, 2010).

Surge History of Shishper Glacier

Previous studies have indicated that there are many surge-type glaciers in the Karakoram (e.g., Hewitt, 2007; Kotlyakov, 1997;). However, logistical and political constraints mean that to date there have been only limited studies of many of these glaciers. Over the last few decades the Karakoram Glaciers has exposed to irregular behavior and lack of stability.

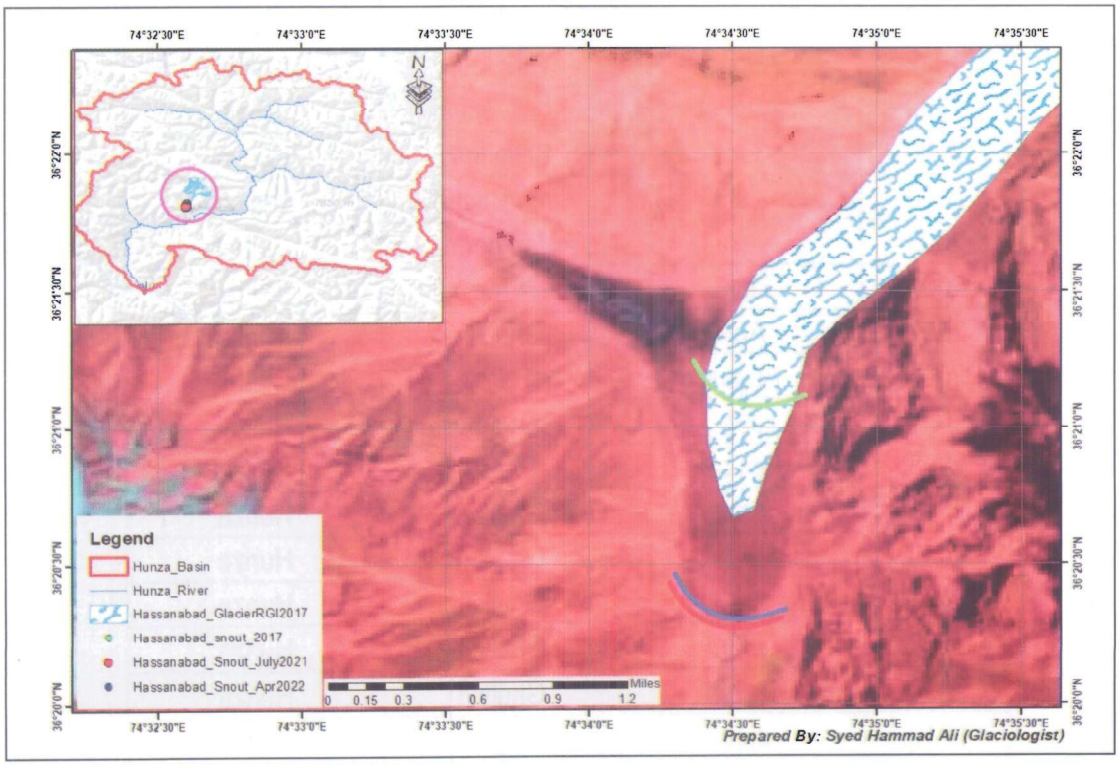


Figure-4: Movement of Snout of Shishper (Hassanabad) Glacier

The Shishper Glacier is noted, historically (1892–93), for claims that it had the longest and fastest terminus advance (9.3 km). Shishper Glacier advanced 9.7 km within 2.5 months in 1904–1905. Shishper and Muchichal retreated and had separated into distinct glaciers by 1954 due to 7km retreat. Muchichal, both tributaries met again before 1972, although the main terminus retreated ~4 km from 1979–2013. Small surges of Shishper Glacier occurred between 1972–76 and 1993–2002 (Bhambri, et. al 2020).

Shishper Glacier has again shown an anomalous behavior in the month of July 2018. During its active surge phase, the glacier's snout advanced around 1.5 km, GMRC Team conducted physical snout movement survey in 2017, 2021 and again recently in 2022 and observe the similar movement (Fig. 4). Different researcher reported this surge movement was the highest recorded in the Karakoram, with a flow rate of 18 m per day and reached up to 48 m per day (Bhambri, et. al 2020).

Year	Month	Glacier	Basin
1929	Not Known	Chung Khumdan	Shyok
1932	Not Known	Chung Khumdan	Shyok
1973	Not Known	Batura	Hunza
1974	Not Known	Batura	Hunza
1977	Not Known	Balt Bare	Hunza
1978	Not Known	Brep, Chitral	Chitral
1978	September	Darkot/Barados	Gilgit
1992	August	Yarkhoon	Chitral
1999	August	Khalti/Gupis	Gilgit
2000	June	Shimshal	Hunza
2000	July	Kand/Hushey	Indus
2003	July	Yarkhoon	Chitral
2005	July	Brep	Chitral
2007	April	Ghulkin	Hunza
2007	August	Terich	Chitral
2007	July	Sonoghor	Chitral
2008	January	Passu	Hunza
2008	April	Ghulkin	Hunza
2008	May	Ghulkin	Hunza
2008	May	Ghulkin	Hunza
2008	June	Ghulkin	Hunza
2009	March	Ghulkin	Hunza
2010	June	Booni	Chitral
2010	July	Bindo Gol	Chitral

2013	July	Reshun	Chitral
2015	July	Khorow	Braldu,Shigar
2015	July to August	Ganche	Skardu
2015	July to August	Bagrot	Gilgit
2015	July to August	Chitral Gol	Chitral
2015	July to August	Reshun	Chitral
2015	July to August	Bindo Gol	Chitral
2015	July to August	Garam Chashma	Chitral
2015	July to August	Kalash Valley	Chitral
2015	July to August	Kosht	Chitral
2015	July to August	Mastuj	Chitral
2015	July to August	Booni	Chitral
2019	July	Dook Pal	Chitral
2019	July	Shishper	Hunza
2020	July	Dook Pal	Chitral
2022	May	Shishper	Hunza

Table-1: History o G s in B

Basins	um er o lakes			ake Area km²	argest lake km²
	otal	Major	Dangerous		
Swat	255	1 3	2	155	0 1
Chitral	1	0	1	9 3	1
Gilgit	1	3 0		39 1	2 2
Hunza	110		1	3 22	0 29
Shigar	5	11		1 09	0 2
Shyok		31		2	0 2
Indus	5	32	15	2 0	1 35
Shingo	233	139	5	11 59	1 3
Astor	12		9	5 53	0 5
Jhelum	19	95	5	11 9	1 0
Total	2 20	1322	52	122 35	

Table-2: Major & Potentially Dangerous Glacial Lakes in GB & KP
(Source: Ashraf A., et al. 2012)

Current Situation of Lake Observations & Conclusion

Landsat satellite images of the month of May to December 2018 & March 2019 and Sentinal 2 images from November 2021 to May 2022 were acquired to analyze the development of lake. Remote Sensing and GIS analysis revealed that the Hassanabad (Shishper) Glacier advanced with a very high surging velocity and caused the formation

of lake starts from November to December 2018 to block the flow of Muchichal glacier. During its active surge phase, the glacier's snout advanced around 1.5 km. This surge movement was the highest recorded in the Karakoram, with a flow rate of 18 m/day and reached up to 48 m/day. The surge speed was highest in May and June 2018.

The Remote Sharing (RS)/Graphic Information System (GIS) image depicting a lake of ~ 0.026 km^2 formed in November 2018 which expended upto ~ 0.057 km^2 in January 2019. On 20 June 2019, the lake reached its maximum area of 0.340 km^2. On the following day, the first breach occurred, resulting in a GLOF that partly damaged the Karakoram Highway and caused minor infrastructure downstream. The lake continued to discharge as subglacial flow till September 2019. In another image derived from Sentinel-2 data, the lake's extent had reached at 0.340km^2 three days before the breach again 2nd time in 2020. In the image of 05-05-2022 (Fig. 5) it is observed that the lake extent reached ~ 0.350km^2 and on 7th of May the lake breached again. It is important to note that the breach occurred when the lake reached almost the same extent as in 2019, 2020 and again in 2022.

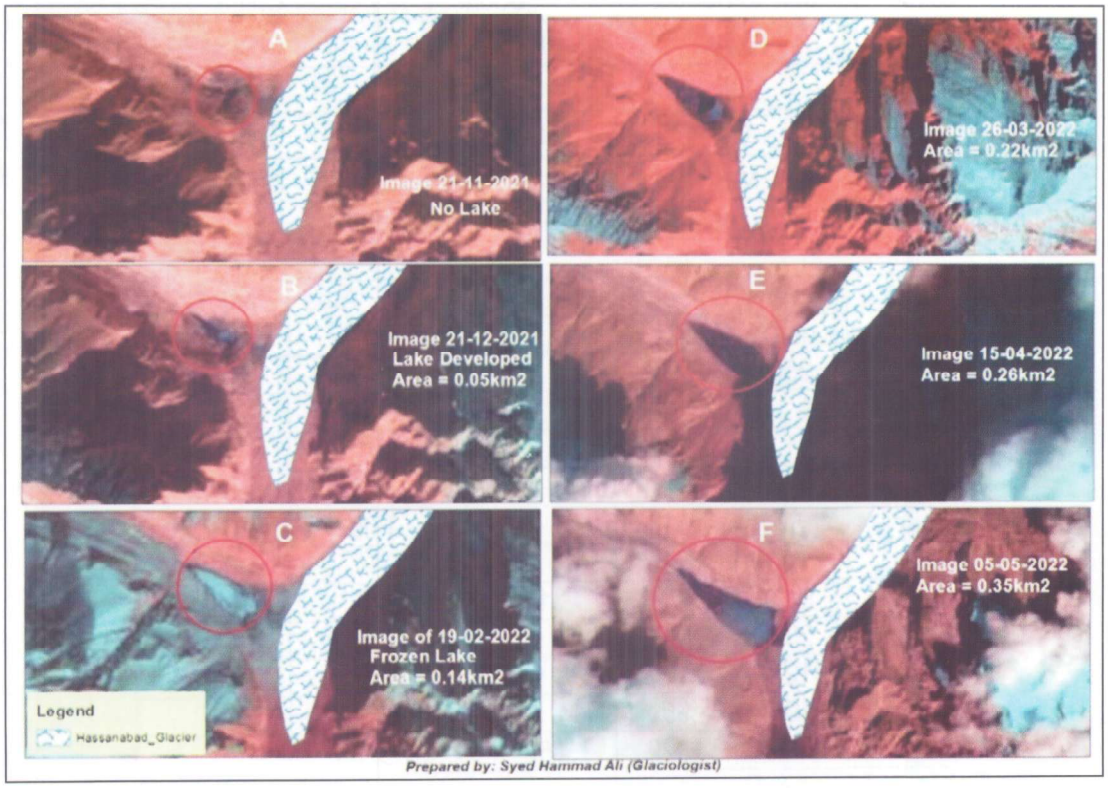


Figure-5: Development of Shishper Glacial Lake from November 2021 to May 2022

The latest early summer outburst was likely triggered by an abnormal temperature rise, which caused momentous glacier melt and accordingly enlarged the lake. The meteorological station installed in the UIB recorded a significant temperature rise since mid of March as presented in the figure 6.

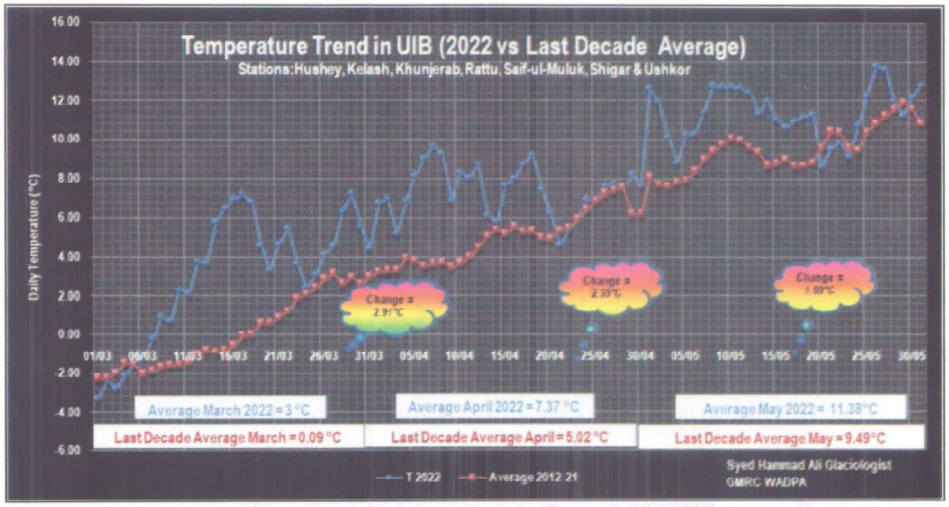


Figure-6: Temperature Trends in UIB

A lake of 0.16km^2 which reduces to 0.08km^2 till 25th May still present as observed in the satellite images (Figure-7) subsequent to the massive release of water from 7th to 9th May 2022 the lake is still prone to blockage and could potentially burst again, during this year as the temperature will rise in coming months. According to the recent post disaster visit of GMRC-WAPDA team on 8th June 2022 the lake is completely drain out. As mentioned earlier that the latter conditions are constructive for resealing/reforming deeper and larger lakes such that the probability of further and larger GLOFs remains present for coming seasons and years. The possibility of greatest risk for Shishper Lake extends through to September. It is therefore imperative to monitor the lake regularly.

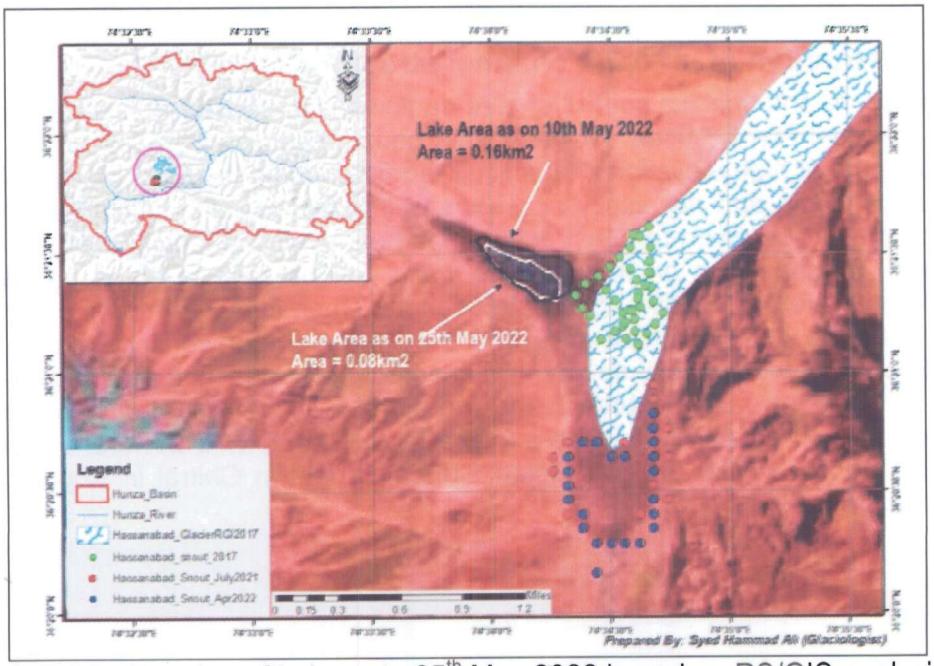


Figure-7: Situation of Lake upto 25th May 2022 based on RS/GIS analysis

Followings are the some glacial lake outburst flood mitigation measures. By adapting one or combination of these measures the GLOF hazards may be reduced.

Plummeting the volume of Lake Water

Possible peak surge discharge from a GLOF could be reduced by plummeting the volume of water in the lake. In general any one or combination of the following methods may be applied for plummeting the volume of water in the lake:

- Controlled breaching,
- Construction of an open channel structure,
- Pumping or siphoning out the water from the lake, and
- Making a tunnel through the moraine barrier or under an ice dam.

a) Controlled breaching

Controlled breaching is carried out by blasting, excavation, or even by dropping bombs from an aircraft. One of the successful examples has been that reported for Bogatyr Lake in Alatau, Kazakhastan (Nurkadilov et al. 1986). An outflow channel was excavated using explosives and 7 million cubic meters of water was successfully released in a period of two days. These methods, however, can give strong, uncontrolled regressive erosion of the moraine wall causing a fast lowering of the lake level. A case was reported from Peru of the sudden discharge of 6–10 million cubic meters of water after two years of careful cutting of a trench in the moraine wall (Lliboutry et al. (1977a, b, c)).

b) Construction of an open channel structure

For more secure and specific control of lake outflows, stiff structures made out of stone, concrete, or steel can be used. However, the construction and repairs of the required mitigation works at high elevations, in difficult terrain conditions and in glacial lake areas far from road points and not easily accessed, will cause logistic difficulties. Therefore, first choice should be given to construction materials available locally such as boulders and stones. The boulders on the moraine walls can be held in place by wire mesh ('gabion') and/or held down by appropriate anchors. Open cuts in a moraine dam can be dig out during the dry season when a lake's water level is lower than during the wet season. Such a method is risky as any displacement wave arising from an ice avalanche can split through the cut and breach the moraine. This method should be attempted where there is no risk of avalanches into the lake. GMRC-WAPDA team successfully drains out Dookpal glacial Lake at Golen Gol catchment in Chitral in August 2022 by using this approach (Fig 8).

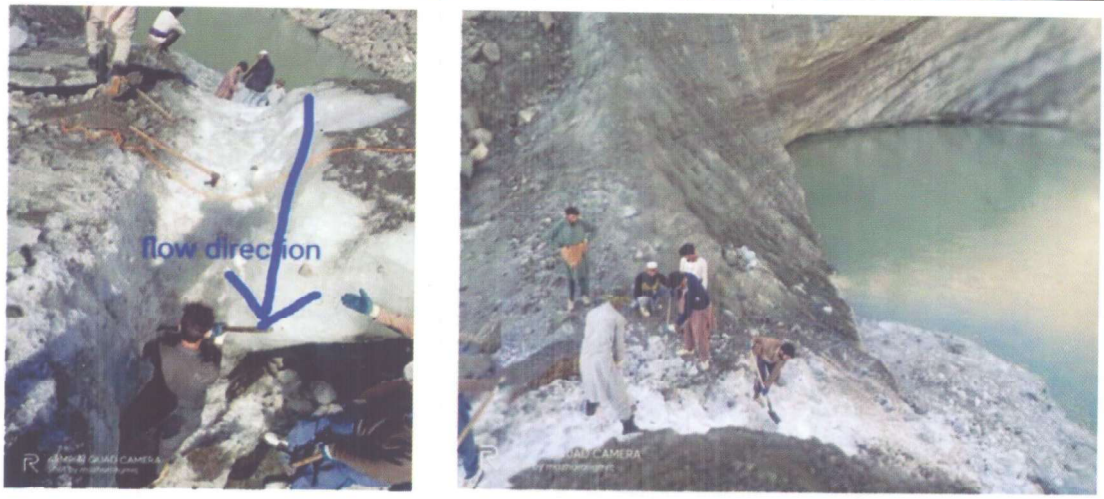


Figure-8: GMRC-WAPDA team constructing the Open Channel for reducing the Lake Water Level

c) Pumping or siphoning out the water from the lake

Another feasible method is pumping or siphoning out of water from the lake but very costly because of the large amount of electricity needed for the powerful pumps which will be done at the Spirit Lake Peru after the eruption of Mount St Helens in Washington State in the USA (Lliboutry et al. (1977a, b, c)). The pumping facility consisted of 20 pumps with a total capacity of 5 m^3/s and the cost of the pumping plant, operation, and maintenance for about 30 months was approximately US $11 million (Sager and Chambers 1986). In the Hindu-Kush Himalayan region, there is neither hydroelectric power distribution at high altitudes nor a simple means of transporting fuel to high elevations. Many of the lakes are higher than the maximum flying altitude for helicopters. The use of a turbine, propelled by the water force at the outside of the moraine dam, will lower the energy costs. The problem of coupling the turbine and the pumps has to be solved. Siphons with manageable component size are attractive in that they are readily transportable, relatively easy to install, and can be very effective for smaller size lakes. One successful example of pumping out of the water from the Dook Pal glacial lake by GMRC-WAPDA team in June 2021 using this approach. Pumped out 5.184 million litre water and reduce 14 feet lake level (Fig 9).



Figure-9: Setup of Pumps and Pipes at the Dookpal Lake in June 2021 GMRC-WAPDA

d) Making a tunnel through the moraine dam

Tunneling through moraines or debris barriers, although risky and difficult because of the type of material blocking the lake, has been carried out in several countries one example is Lake Parón from the Jatunraju glacier lake indicating a decrease in the water level of about 40 m (Fig 10). In Peru, reported problems related to tunneling through a moraine dam which had been severely affected by an earthquake Lliboutry et al. (1977a, b, c). Tunneling can only be carried out through competent rock beneath or beside a moraine dam. The costs of such a method are very high. Unfortunately, not all moraine dams are suitable for tunneling. The construction of tunnels would pose difficulties in the Himalayas due to the high cost of transporting construction materials and equipment to high elevations.



Figure-10: (a) A bedrock dam of Lake No. 513 partly covered by moraine material, and the debris-free bedrock indicates the original water level before being lowered 20 m; (b) the outlet of a tunnel dug through the bedrock dam of Lake No. 513; (c) an overview of Lake Parón from the Jatunraju glacier damming the lake (note the light belt around the lake indicating a decrease in the water level of about 40 m); and (d) the outlet of the tunnel below Lake Parón. (Source: Emmer et al. 2018)

Preventative Measures around the Lake Area

Any existing and potential source of a larger snow and ice avalanche, slide, or rockfall around the lake area which has a direct impact on the lake and dam has to be studied in detail. Preventative measures against the instabilities of the moraine dam and the surrounding area, such as removing masses of loose rocks to ensure there will be no avalanches into the lake; will reduce to some extent the danger of GLOF.

Protecting Infrastructure against the Destructive Forces of the Surge

The sudden hydrostatic and dynamic forces created by a quick moving shock wave can be difficult to hold by traditionally designed river structures such as diversion weirs, intakes, bridges, settlements on the river banks, and so on. Followings are some recommendation:

- Necessary to build bridges with proper flow capacities and spans at elevations higher than those expected under GLOF events. One example is the reconstruction of domed bridges was on the Nepal-China highway well above the 1981 GLOF levels
- Road has been moved to higher levels and has gabion protection at the base of the embankments
- Settlements should not be built at or near low river terraces but at heights well above the riverbed in an area with GLOF potential
- Slopes with potential or old landslides and slope of loose rock debris at the base of a steep incline or cliff on the banks of the river near settlements should be stabilized
- Appropriate warning devices for GLOF events are developed in such areas

Recommendations for Monitoring and Early Warning Systems

A programme of monitoring GLOFs throughout the country should be implemented using a multi-stage approach, multi-temporal data sets, and multi-disciplinary professionals. Focus should first be on the known potentially dangerous lakes and the river systems on which infrastructure is developed. Monitoring, mitigation, and early warning system programmes could involve several phases as follow.

- Comprehensive inventory and development of a eminence digital database of the glaciers and glacial lakes using dependable medium- to large-scale topographic maps
- Updating of the inventory of glaciers and glacial lakes and identification of potentially dangerous lakes using remote-sensing data such as the LANDSAT, Sentinel, IRS1C/D, LISS3, SPOT XS, SPOT PAN (stereo), and IRS1C/D PAN (stereo) images
- Semi-detailed to detailed study of the glacial lakes, identification of potentially dangerous lakes and the possible mechanism of a GLOF using aerial photos
- Annual examination of medium to high resolution satellite images, e.g. LANDSAT, Sentinel, IRS1D, SPOT, and so on to assess changes in the different parameters of potentially dangerous lakes and the surrounding terrain
- Brief over-flight reconnaissance with small format cameras to view the lakes of concern more closely and to assess their potential for bursting in the near future
- Field reconnaissance to establish clearly the potential for bursting and to evaluate the need for preventative action
- Detailed studies of the potentially dangerous lakes by multi-disciplinary professionals
- Implementation of appropriate mitigation measures in the highly potentially dangerous lakes.

- Regular monitoring of the site during and after the appropriate mitigation measures have been carried out
- Development of a telecommunication and radio broadcasting system integrated with on-site installed hydro-meteorological, geophysical, and other necessary instruments at lakes of concern and downstream as early warning mechanisms for minimizing the impact of a GLOF
- Interaction/cooperation among all of the related government departments / institutions / agencies / broadcasting media, and others for detailed studies, mitigation activities, and preparedness for possible disasters arising from GLOF events

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