IDENTIFICATION OF GLACIAL FLOOD HAZARDS IN KARAKORAM RANGE USING REMOTE SENSING TECHNIQUE AND RISK ANALYSIS

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ABSTRACT

Glacial Lake Outburst Floods (GLOFs) are great hazard for the downstream communities in context of changing climatic conditions in the glaciated region of Pakistan. The remote sensing data of Landsat ETM+ was utilized for the identification of glacial lakes susceptible to posing GLOF hazard in Karakoram Range. Overall, 887 glacial lakes are identified in different river-basins of Karakoram Range, out of which 16 lakes are characterized as potentially dangerous in terms of GLOF. The analysis of community's response to GLOF events of 2008 in the central Karakoram Range indicated gaps in coordination and capacity of the local communities to cope with such natural hazards. A regular monitoring of hot spots and potential GLOF lakes along with capacity-building of local communities and institutions in coping future disaster situation is necessary, especially in the context of changing climatic conditions in Himalayan region.

Keywords: *Glacial lakes, GLOF hazard, Climate change, Remote sensing, Karakoram*

1. INTRODUCTION

The glacial lakes dammed by moraines and or ice core of retreating glaciers may breach suddenly due to unstable moraine 'dams', resulting in discharge of huge amounts of water and debris - known as 'Glacial Lake Outburst Flood'. The frequency of natural hazards like flash floods and GLOFs has increased in the Himalayan region of Pakistan due to increase in global warming in recent decades. They often have catastrophic effects in down country; even a small glacial lake associated with hanging glaciers poses high risk of GLOF event. According to Chaudhry, Mahmood, Rasul and Afzaal (2009), Pakistan experienced 0.76°C rise in temperature during the last 40 years. The frequency and persistence of heat waves in glaciated mountains has risen drastically causing rapid melting and sudden discharge of bulk of water to terminal lakes of glaciers increasing the risk of outburst.

According to Goudie (1981) and Miller (1984), among 339 disastrous incidents identified along Karakoram Highway (KKH) in Hunza valley in 1980, the most destructive ones were related to glacial movement that led to outburst floods of ice-dammed lakes. The importance of this situation has magnified over the past decades due to increase in numbers of glacial lakes that are formed at the glacier terminus. Thirty-five destructive out-burst floods have been recorded for the Karakoram Range during the past two hundred years (Hewitt, 1982). Some of the ice dams may have been the result of glacier surges. There is unambiguous evidence of large reservoirs ponded by 18 glaciers. Kelly (1988) outlines the historical development and disappearance of Virjerab lake in Hunza due to glacial motion. There occurred a series of GLOF events in upper Hunza valley, central Karakoram Range, within short time periods during 2008 that had a devastating effect on the nearby communities (Roohi, Ashraf, Mustafa and Mustafa, 2008). The people residing at considerable distances downstream from the unstable lakes are facing a serious threat to their lives and property. This situation calls for in-depth study on GLOF hazard in the Northern Himalayan region.

This paper describes the situation of glacial lakes and lakes susceptible to creating GLOF hazards in the Karakoram Range of Pakistan. A stepwise approach to assess the risk beginning with an extensive desk study of satellite images for the reconnaissance mapping of the glacial lakes was adopted. Also, community based risk and response analysis was carried out in the selected villages in the Karakoram range in order to provide basis for developing timely response and risk-management strategies for the area.

1.1 Glacial Environment of Karakoram Range

The Karakoram Range in Pakistan is bordered by Hindukush Range in the west, Afghanistan and China in the north, Indian held Kashmir in the east and gigantic Indus River flowing in the south. Overall, about 23 % of the Karakoram Range is found under extensive glacial cover. The range houses about 2,398 glaciers, which possess ice reserves of about 2,387 km^3. The biggest ice reserve is contributed by Shyok River basin (about 37 %) followed by Hunza (34 %) and Shigar river basin (24 %). Some of the largest glaciers outside Polar region are present in the Karakoram range, namely Siachen, Hispar, Biafo, Baltoro and Batura. It is ablation zones of these large glaciers that cause the bulk of glacial ice to melt. A large number of glaciers in the Karakoram Range are stable or even increasing (Hewitt, 2005 and 2007).

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High sliding velocities and isothermal ice produces abundant englacial and sub-glacial meltwater that leave the glacier through sub-glacial tunnels.

Although monsoon is the dominant source of precipitation in main Himalaya and Front Ranges, but in some years the monsoon is strong enough to break through the Front Ranges and can deliver substantial precipitation to the central Karakoram region (Mayewski and Jeschke, 1979; Mayewski, Pregent, Jeschke and Ahmad, 1980). The second source of precipitation is depression coming from the west, which provides dominant nourishment to the glacier systems of the Karakoram Range.

2. DATA AND METHODOLOGY

In the present study, remote sensing data of Landsat-7 Enhanced Thematic Mapper Plus of period 2000-2001 provided by ICIMOD, Nepal, was used for spatial data analysis of lakes. The Landsat-7 ETM+ sensor is a nadir-viewing, 7-band plus multi-spectral scanning radiometer that detects spectrally filtered radiation from several portions of the electromagnetic spectrum. The spatial resolution (pixel sizes) of the image data includes 30 m each for the six visible, near-infrared and short-wave infrared bands, 60 m for the thermal infrared band, and 15 m for the panchromatic band. A scene of a Landsat-7 data gives a synoptic view of an area of 183 km by 170 km of Earth's surface. The list of Landsat scenes covering the study area is given in Table-1. The topographic maps of the Survey of Pakistan available at variable scales and National Imagery and Mapping Agency (NIMA) U.S. (on half million scale) were utilized for image georectification, and acquiring topographic attributes and geographic details of the lakes and associated glaciers, infrastructure and settlements, in the target areas.

2.1 Mapping of Glacial Lakes

For mapping of glacial lakes, the Karakoram Range was divided into five draining basins, i.e. clockwise from the west: Gilgit, Hunza, Shigar, Shyok and part of the Indus basin (Figure-1). The spatial database of lakes of each river basin was systematically developed through on-screen digitization of the image data in ILWIS 3.2 software. The attributes used for the lakes in this study are similar to the lake inventories carried out by LIGG/WECS/NEA (1988), Mool, Bajracharya and Joshi (2001) and Roohi, et al. (2005).

In order to describe the lakes and identify their orientation in a basin, the basin and ridge lines were initially marked through visual interpretation of the panchromatic image. In the panchromatic band of Landsat ETM+ image, the lakes are visible in dark patches with distinct curvilinear boundaries. The land features like ridge and basin boundaries, drainage network, etc. become prominent using low range of digital numbers (DN), i.e. 0-150 of this band type. The cascading ice mass of the glaciers can be visualized distinctly in nearly full stretched pan image, exhibiting not only the orientation of the ice-flow pattern, but also of ridge boundaries hidden underneath thick ice mass over high mountains. In the image of May 2001 (Path-148: Row-36) containing limited snow cover, the glacial lakes were identified on the basis of their smooth texture of the overlying frozen surface.

After defining boundaries of the lakes, these were numbered using point identifiers, i.e. which start from the outlet of the major stream/river and proceeds clock-wise round the basin. Reference longitude and latitude were designated for the approximate centre of the glacial lake by creating a digital point map over the digitized glacial lakes. The area of the glacial lake was determined from the generated digital database. The drainage direction of the lake is specified as one of eight cardinal directions (N, NE, E, SE, S, SW, W, and

Table-1: List of Landsat-7 ETM + scenes Covering Study Area

S. No.	Path	Row	Bands	Date
1	148	035	7 plus	21 July 2001
2	148	036	“	18 May 2001
3	149	034	“	30 Sept. 2001
4	149	035	“	30 Sept. 2001
5	150	034	“	07 Oct. 2001
6	150	035	“	07 Oct. 2001
7	151	035	“	09 Sept. 2000

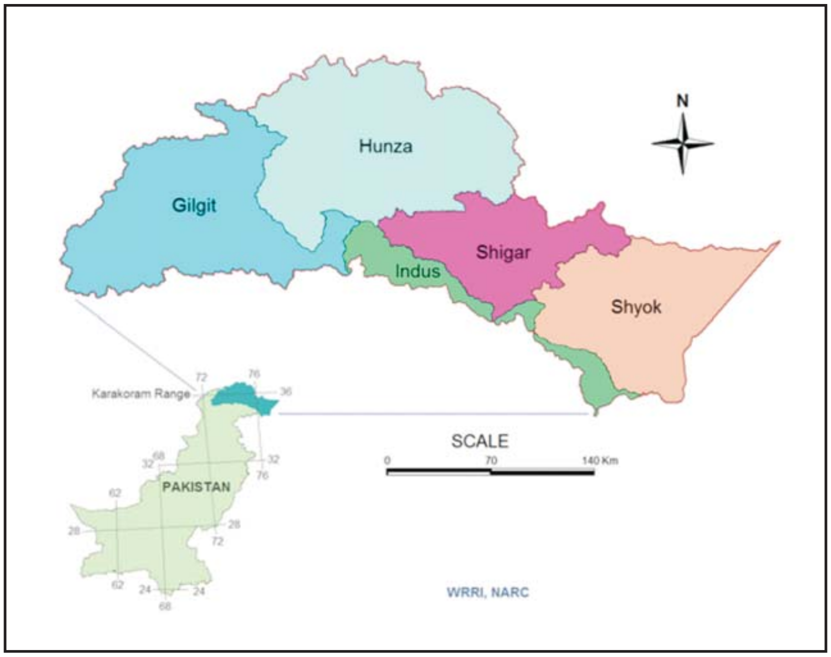

Figure-1: Karakoram Range and its Major River Basins in Pakistan

NW). Glacial lakes are divided into drained lakes and closed lakes according to their drainage condition. The former possess drainage system (Ds), i.e. water from lakes flows into the river; while the latter have closed system (Cs), i.e. water does not flow out from the lakes. For a closed lake, the orientation is specified according to the direction of its longer axis. The lakes were classified into various types according to their formations in the glacial environment. The attribute data of lakes was derived/entered and linked with spatial data in GIS. The glacial lakes with area larger than 0.02 km^2 were characterized as major glacial lakes.

2.2 Criteria for Identification of GLOF Lakes

Although a standard index to define a lake 'potentially dangerous' does not exist, the main factors considered for the study were its physical characteristics and association with its surrounding and nourishing glaciers. The criteria for identifying potentially dangerous glacial lakes are based on factors like processes and records of past events, geo-morphological and geo-technical characteristics. Mool, Bajaracharya and Joshi (2001), and Bajracharya, Mool and Shrestha (2007) identified the following physical conditions of the surrounding area of a lake that may be observed before declaring it to be potentially dangerous.

a. A group of closely spaced supraglacial lakes at glacier tongues merging and forming large lakes;
b. The conditions of the damming material in moraine dammed lakes;
c. The nature of the mother glaciers, i.e. presence of large mother glacier near the lake, debris cover and steep gradient at glacier snout area;
d. Presence of crevasses, ponds at the glacier tongue, collapses of glacier masses at the tongue and ice blocks draining to lake;
e. A moraine dammed lake that had breached and closed subsequently in the past and refilled again with water;
f. Physical conditions of the surrounding area, such as risk of rockfall, mass movements, hanging glacier, snow avalanche site around the lake that can fall into the lake suddenly; and
g. Neo-tectonic and earthquake activities.

The potentially dangerous lakes are generally at the lower parts of the ablation area of the glacier near the End moraine, and the mother glacier should be sufficiently large to create a potentially dangerous lake environment.

The communities' response to GLOF events of 2008 was studied during a survey conducted in selected villages, i.e. Ghulkin, Hussaini and Passu in Hunza valley of Central Karakoram (Questionnaire for the survey is given in Box-1). Ghulkin village is situated in

Box-1: Questionnaire for Community Based Risk and Response Analysis to GLOFs in Hunza Valley, Karakoram Range

1. Personal/Community information
2. What are the main livelihood options in your village?
3. Are these livelihood options seasonal in nature?
4. What is the institutional setup of your village?
5. What are the natural hazards that you have been exposed to in the past?
6. If your village were affected by the last flash floods during 2005, 2007 and 2008, what was the differential impact?
7. What has been the impact of any such event on the livelihood, agriculture, infrastructure, communication network, etc.?
8. Are women and children, elderly and disabled especially affected by such events?
9. Is there a need to train women for disaster preparedness and do they have a significant role to play?
10. How are community leaders, local medical practitioners/priests/teachers involved in any disaster preparedness programme?
11. Was there any loss of life/ other damages, what was the reason behind it?
12. What have been some of the risk reduction measures in the past, either at the community level or the ones initiated by the government?
13. What coping mechanisms do you adopt in the aftermath of an event?
14. How would you rate your access to facilities like healthcare, education, communications, electricity, transportation in connection with disaster preparedness?
15. Before and/or during sudden happening of flood event, what type of warning mechanism is adopted?
16. Who is responsible for rescue activities and selection of suitable sites for shelter?
17. How are the neighbouring villages involved in the rescue work?
18. Are there any redeeming factors of these floods?
19. In which time of the year flooding generally occurred?
20. What is the mechanism adopted for breaching the GLOF lake?
21. Any other comment/note.

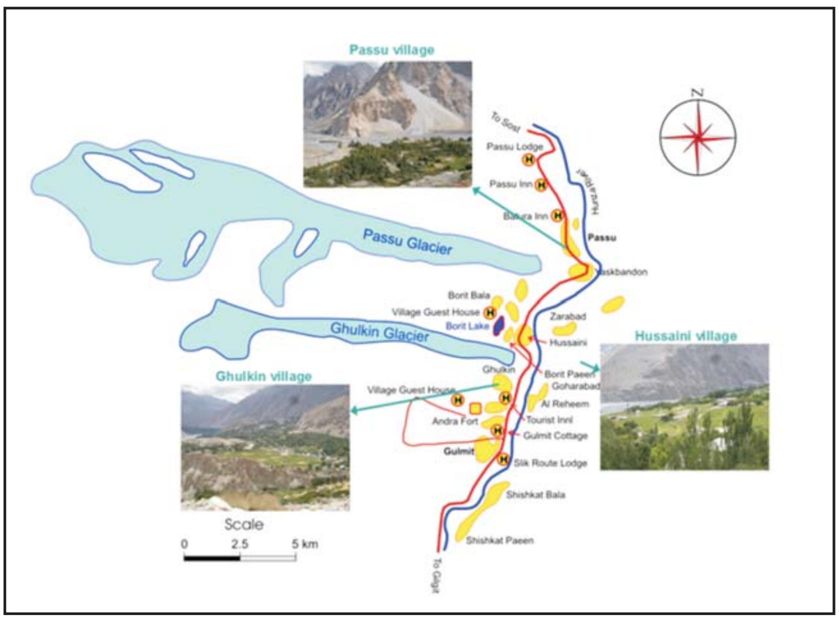

Figure-2: Location of the three Villages Surveyed in Hunza valley of Central Karakoram Range

Table-2: Summary of Glacial Lakes in Major River Basins of Karakoram Range

Basins	Total Lakes	Lakes Area (km^2)	Major Lakes	Potential GLOF Lakes
Gilgit	614	39.2	380	8
Hunza	110	3.2	47	1
Shigar	54	1.1	11	-
Shyok	66	2.7	31	6
Indus part	43	1.6	23	1
Total	887	47.7	492	16

the south of Ghulkin glacier, whereas Hussaini in the north east (Figure-2). Passu village lies in the east of Passu glacier. The village is the setting-off point for climbing expeditions up the Batura, Passu, Kurk and Lupgar groups of peaks, and for trekking trips up the Shimshal Valley and Batura Glacier (www.mountainleaders.com). The Ghulkin, Hussaini and Passu villages have 138, 83 and 117 households and populations of 1133, 621 and 863 persons, respectively (Focus, 2008).

3. RESULTS AND DISCUSSION

The systematic application of remote sensing in GIS environment has revealed about 887 glacial lakes that cover an aggregate area of about 48 sq. km in the Karakoram Range of Pakistan (Table-2 and Figure-3). These lakes can be seen in true color and contrast with the surrounding features using band combinations of 5, 4, 2 and Pan, 7, 6b (Red, Green, Blue) of Landsat ETM+ image. In false color composite (FCC) of 5, 4, 3 (RGB), the lakes in blue color can be differentiated from the black appearance of shadow areas. Majority of the glacial lakes belong to Erosion (39 %) and Valley (17 %) followed by End moraine dammed types (14 %). Most of these lakes lie in the Gilgit basin (Table-3). Supraglacial lakes (formed over glacier surface) are dominant in Hunza, Shigar and Shyok river basins due to prevalent glaciated environment. About 55 % lakes were characterized as major lakes (surface area greater than 0.02 sq. km).

3.1 GLOF Lakes in Karakoram Range

Out of the 887 glacial lakes, 492 were identified as major lakes in the Karakoram Range. Among these

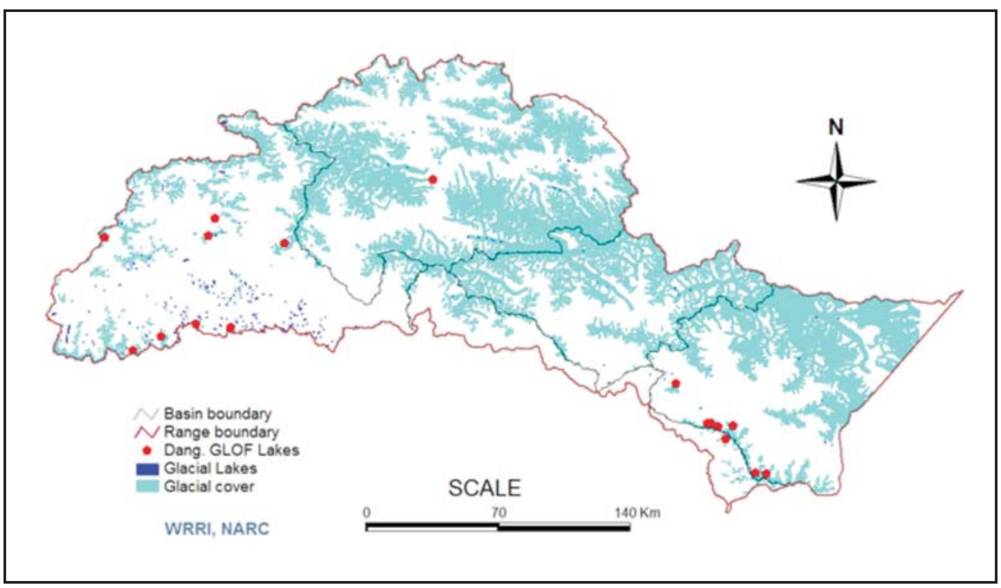

Figure-3: Glacial Environment Indicating Potential GLOF Lakes in Different Karakoram Basins

Table-3: Summary of Different Types of Glacial Lakes in Karakoram Range of Pakistan

Type	Gilgit	Hunza	Shigar	Shyok	Indus	Total
Cirque	53	-	-	2	-	55
End-moraine dammed	100	4	-	12	12	128
Lateral moraine dammed	49	3	1	3	6	62
Erosion	283	20	-	26	13	342
Supraglacial	2	55	30	11	4	102
Valley	125	24	2	8	6	165
Blocked	2	4	21	4	2	33
Total	**614**	**110**	**54**	**66**	**43**	**887**

major lakes, 16 were identified as potentially dangerous GLOF lakes. About 12 of these GLOF lakes belong to End-moraine dammed type, while the rest belong to Valley type. There may be some lakes beneath or within glaciers, but these are usually not visible on images and so cannot be mapped (ICIMOD, 2011). The majority of dangerous lakes are located at elevations between 4,000 and 5,000 metres above sea level, and are either near or in contact with large source glaciers, which make them potentially dangerous (Table-4). The End-moraine dammed lakes are usually in contact or very close to the snout of the glaciers. Some of the source glaciers are hanging in nature, the ice mass of which can fall any time in the lakes causing sudden outburst flooding. The lakes are mostly oriented towards NW, N and NE directions – the aspects that are relatively less exposed to solar radiations.

Among four river basins in the range, Gilgit basin has the maximum of 614 glacial lakes, out of which 380 lakes were characterized as major lakes. Among these, 283 were characterized as Erosion lakes and the largest lake of this type has an area of about 0.21 sq. km. Erosion lakes are usually formed in depressions eroded by the receding glaciers. Here, eight glacial lakes comprising of six End-moraine dammed and two Valley type lakes were identified as potentially dangerous GLOF lakes. Most of these dangerous lakes are associated with large size mountain glaciers of hanging nature, i.e. ice mass of glaciers can fall any time in the lakes creating outburst floods hazard. The settlements, agriculture and grazing land along the streams and Gilgit river are vulnerable to any extreme GLOF incidence in future. Although it is difficult to estimate the probability of occurrence of such flood hazards because of rapid changes in the nature of glacial systems, but effective monitoring of hot spots/glacial lakes and dissemination of early warnings could help in better risk mitigation.

In Hunza River basin, out of 110 glacial lakes, 47 lakes were characterized as major lakes. Majority of these belong to Supraglacial and Valley types. An End-moraine dammed lake (Hunza_gl 6) was identified as potential hazardous. This lake has a surface area of about 0.12 sq. km and is close to a large valley glacier - Passu which has length of about 26 km and average thickness of about 173 meters. The lake had caused heavy flooding in July 2007 and later in April 2008. This resulted in heavy damage to the Karakoram highway, nearby hotels and houses in the Passu village. According to the locals, this lake has breached several times in the past. Although this lake is hazardous for the nearby communities of the Passu village but with the creation of a large land-slide dammed lake at Attabad during February 2010, the villages along Hunza River upto Gilgit and downstream become highly vulnerable of lake outburst flood hazard. Proper monitoring of the lakes' behavior and installation of early warning system can reduce risk of any flood disaster in the downstream areas.

In Shigar River basin, out of 54 glacial lakes, 11 lakes were characterized as major lakes. As most of the northern part of the basin is glaciated, the lakes generally belong to the Supraglacial type. There was no lake identified as potentially hazardous, in this basin.

In Shyok River basin, out of 66 glacial lakes 31 were characterized as major lakes. Six glacial lakes comprising four End-moraine dammed and two Valley type lakes were identified as potentially dangerous GLOF lakes in this basin. The criteria used for characterizing these lakes potentially dangerous are their association with large valley type and mountain

Table-4: Potential GLOF Lakes in Karakoram Range of Pakistan Identified Using 2000 and 2001 Images

Lake Number	Elevation (masl)	Area (ha)	Length (m)	Drainage	Type	Situation
Gil_gl 336	4107	21.4	833	Cs	End Moraine	Near large glacier source
Gil_gl 399	4148	72.9	1569	Cs	End Moraine	In contact of large glacier of hanging nature
Gil_gl 469	4323	26.5	966	Cs	End Moraine	Near large glacier of hanging nature
Gil_gl 505	4375	21.2	690	Cs	End Moraine	Near large glacier of hanging nature
Gil_gl 550	4265	9.6	497	Ds	End Moraine	Near massive glacier
Gil_gl 589	4026	20.4	946	Ds	Valley	In contact of large glacier of hanging nature
Gil_gl 590	4413	19.2	905	Cs	End Moraine	Near several hanging glaciers
Gil_gl 611	3699	28.6	809	Cs	Valley	Near several hanging glaciers
Hunza_gl 6	2546	12.0	453	Ds	End Moraine	Near large glacier
Shyk_gl 45	5022	12.7	802	Cs	End Moraine	In contact of large glacier of hanging nature
Shyk_gl 51	4832	17.1	680	Ds	Valley	In contact of large glacier of hanging nature
Shyk_gl 60	4815	8.0	332	Ds	End Moraine	In contact with large glacier
Shyk_gl 62	4639	9.4	560	Ds	End Moraine	In contact with large glacier
Shyk_gl 64	4656	10.7	705	Cs	Valley	Large glacier source
Shyk_gl 65	4593	21.0	800	Ds	End Moraine	Preceded by a lake and large glacier
Ind_gl 290	4770	13.3	904	Ds	End Moraine	Large glacier source

Note: *Where Cs: Closed system, Ds: Drained system*

type glaciers of hanging nature (criteria c & f under section 2.2) besides End moraines damming and draining characteristics of the lakes. The two End moraine dammed lakes, i.e. Shyk_gl 64 and Shyk_gl 65 lie close to each other and are fed by large source glaciers, draining into a single stream, making the nearest town 'Bara' and further downward 'Shyok River' vulnerable to outburst floods. According to the local sources, the two lakes possess cyclic histories of breaching. Although the lake Shyk_gl 64 was identified being closed due to snow effect in the image, yet it was draining out at the time of survey in the year 2004, which shows misinterpretation of the image due to RS period limitation. It also highlights the importance of synchronization between the image period and time of survey because ground situation may sometime alter rapidly with time. Although maximum potential GLOF lakes lie in remote areas in the southern part of this basin, but in case of any flood event, their effect may reach to communities settled in valleys along main Shyok river. A community-based early warning system needs to be established in order to avoid consequences of any extreme GLOF incident in the basin. In Indus sub-basin part of the Karakoram Range, 43 glacial lakes were identified, among which 23 were characterized as major lakes and only an End-moraine dammed type lake, Ind_gl 290, was characterized as potentially hazardous (Table-4). The low and medium terraces of agriculture land and settlements along the main streams and River Indus in mountain valleys remain vulnerable to glacial flood hazard. The post flooding effects, like bank erosion, debris flows and landsliding may cause high sedimentation, besides other environmental problems.

3.2 Community-based Risk and Response Analysis

In order to provide basis for developing future strategies for timely response and risk-management in the area, a field survey was conducted in Ghulkin, Hussaini and Passu villages in Hunza valley of the Central Karakoram Range during August 2008. The information was mainly collected from about 32 households of the three villages through interaction with notables and elders of both genders. Population distribution in these villages is moderately uneven due to physical conditions of the area. According to most of the respondents, landslides, flash floods and glacier surges are the main natural hazards in this area. A few added earthquake and river erosion. Some of these hazards, like floods, river erosion and landslides are interlinked, i.e. the intensity of flash floods may increase the process of river erosion and, in some cases cause, landsliding. Though rainfall is not a major hazard in the area, but it triggers mass movement and hazard of landslide. The Karakoram Highway is often blocked due to such events during the rainy season.

According to the respondents in Ghulkin and Hussaini, flash floods mostly occurred between spring and summer seasons but for the first time in January 2008. According to the locals, Ghulkin glacier had flooded at least four times in six months during 2008, causing huge damages to infrastructure and property besides loss of human lives. Two big lakes were formed inside the Ghulkin glacier, most likely due to rapid melting of huge glacial ice mass mixed with rock debris. The water level in one of the glacial lake called 'Sheri Baig' on Ghulkin glacier was rising dangerously (Figure-4), posing a great danger to life and property of the villagers downstream. The extent of Sheri Baig lake depression after the occurrence of GLOF event is shown in Figure-5. The depression formed from outburst of the Supraglacial lake was measured as 221 m in length; 12 m in width; and 7 m in depth.

Most of the communities of these villages are poor and belong to low-income category. The main sources of income are farming, animal rearing, home-making, business, and public service. In Hussaini village, floods had damaged the main irrigation channels that disturbed the livelihood of local community. As flood events had occurred mostly near the agricultural land and at a distance from the main village settlements that is why the loss of human lives was less. Reduced tourism and trade affect the livelihood and economy of the communities. The damage to main highway and bridge costs millions of rupees to repair. Due to floods, there was loss of crop, like wheat, potatoes, apricot, apple and popular trees. The livelihood insecurity due to agricultural losses is among the major concerns. The village people, especially the elderly, women and children are under great mental stress because of the shadowing disastrous effects. According to most of the respondents, the response of villagers to such events is on self-help basis. There exists no formal administrative setup in the villages. During the flood event of April 2008 at Passu, the nearby villagers helped people in evacuating their houses close to the glacier and shifting to safer places to avoid further damages. There exist gaps in coordination and capacity of the local communities of the area to cope with natural hazards like GLOFs.

4. CONCLUSIONS AND RECOMMENDATIONS

- The results of the study helped identify a total of about 887 glacial lakes in the Karakoram Range of Pakistan, out of which 16 were characterized as potentially dangerous GLOF lakes. Majority of these dangerous lakes belong to End-moraine dammed type.
- The less glaciated Gilgit river basin contains the highest numbers of glacial lakes and potential

Courtesy: *Asghar Khan*

Figure-4: Expansion of a Supraglacial Lake on Ghulkin Glacier on May 11, 2008

Figure-5: The Extent of Depression Developed over Ghulkin Glacier after Breaching of Supraglacial Lake. ***A Surveyor is Shown in a Circle (Surveyed on August 16, 2008)***

GLOF lakes as compared to highly glaciated Hunza, Shigar and Shyok river basins.

- Most of the dangerous lakes in the Karakoram Range are associated with large valley and mountain type glaciers of hanging nature.
- The local communities are now more vulnerable to frequent glacial hazards probably due to global climate change in the recent decades. Capacity-building of the remote mountain communities of Gilgit, Hunza, Shigar and Shyok, need to be done for their disaster preparedness and survival as well as for issuance early warnings.
- Strategies for flood risk mitigation need to be developed at policy level with the involvement of district management and local communities so that these could be adopted and implemented effectively.
- In the face of increasing efforts of global warming in this region, regular monitoring of GLOF lakes behavior, using high-resolution RS data supported with frequent ground surveys and comprehensive GLOF risk assessment, is imperative to save lives and property of the downstream communities.

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