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IDENTIFICATION OF POTENTIALLY HAZARDOUS GLACIAL LAKES IN CHITRAL CATCHMENT USING REMOTE SENSING / GIS FOR FUTURE HAZARD AND RISK ASSESSMENT

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By

Syed Hammad Ali[1], & Adeel Hassan[1]

ABSTRACT

Water is a source of life, but it is also a threat to lives and assets of countries across the Globe. The occurrence and extent of natural disasters are increasing in most regions throughout world with water-related disasters being the most common and frequent. Around 74% of all natural disasters during last two decades were water-related. Water-related disasters pose both direct and indirect impacts. 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 are Glaciers. Many of the glaciers consist of substantial amount of permanent snow and ice which generate several glacial lakes. Formation of glacial lakes is a frequent phenomenon in high mountain areas. This study provides comprehensive information about the glacial lakes in the Chitral catchment and also provides information upon the distribution of glacial lakes and providing baseline data for further investigation of glacial lakes, GLOF hazards and risk assessment, and mitigation measures. The delineation of glacial lake boundaries were carried out by using an automatic method normalized difference water index (NDWI) on Landsat images from the year 2008±2 years and also considering the data of 2015±2 years. This method to delineate the glacial lake boundaries by defining the threshold condition of band ratio images made the process of mapping and monitoring of glacial lakes faster. A total of 301 glacial lakes covering an area of 9.46km^2 were identified within the Chitral catchment. Almost 82% of lakes mapped in the Chitral catchment are having area less than 0.05 km^2. The glacial lakes in the Chitral catchment are distributed at elevations from 3,400 masl to 5,100 masl. The majority of glacial lakes (approximately 43%) are located in elevation zones of 4,000 – 4,500 m.a.s.l. This study focuses the Chitral catchment for the reason that Golen Gol Hydro Power Project is located in this catchment and hit by two consecutive devastating GLOF events in 2019 and 2020 and another expected in 2021. Adequate mitigation measures would need to be developed to reduce the risk of future GLOFs there is a need to combine disaster risk concerns in common and GLOF risk in special into national and regional development plans, policies and programmes, including the infrastructure development. Appropriate actions are need of time in collaboration with all relevant

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players to secure a safe, sustainable Pakistan, and to reduce loss of lives and assets.

Keywords: Glaciers, Glacial Lakes, normalized difference water index, GLOF, remote sensing, hazard potential

INTRODUCTION & BACKGROUND

Water is life and a vital part of human civilization and humanity cannot survive without securing access to safe drinking water and basic sanitation. On the other hand water is also a threat to life. The extreme weather conditions have increased the risks of water-related disasters both in terms of their frequency and severity. Numerous lives have been taken away and societies and economies are suffering from the damaging effects of the disasters. Water-related calamities cause both direct impacts (e.g. smash up the buildings, crops and infrastructure, and loss of life and property) and indirect impacts (e.g. losses in production and livelihoods, increased investment risk, and human health impacts). The increasing economic cost and toll of disasters should be a significant incentive for governments and humanitarian organizations to spotlight more concentration on vigilance, prevention and addressing the root causes of vulnerability. Around 74% of all natural disasters between 2001 and 2018 were water-related and during the past 20 years, the total number of deaths caused only by floods and droughts exceeded 166,000, while floods and droughts affected over three billion people, and caused total economic damage of almost US$700 billion as reported by United Nations in World Water Development Report 2020. UNHCR in 2017 estimated that for the 68.5 million people who have been forced to flee their homes, accessing safe water services is highly problematic. Approximately 700 million people worldwide could be displaced due to intense water scarcity by 2030 as predicted by Global water institute in 2013. According to UNESCO, rising populations in flood prone lands, climate change, deforestation, loss of wetlands and rising sea levels are expected to increase the number of people vulnerable to flood disaster to 2 billion by 2050. Overall, annual economic losses from weather-related disasters are estimated at between US$ 250 billion and US$ 300 billion (UNISDR 2015). Asia is the region most vulnerable to water-related disasters (like Glacial Lake Outburst Floods (GLOFs)), accounting for more than 45% of fatalities and more than 90% of the people affected by disasters between 1980 and 2006.

For as long as records have been available, high mountain areas of Pakistan are known to have experienced glacial lake outburst floods (GLOFs) a form of flash flood in which water from a lake associated with a glacier is released suddenly, resulting in the outflow of a huge volume of water and sediment downstream. The glacial lakes dammed by moraines and or ice core of retreating glaciers may breach suddenly due to unstable moraine dams. Outbursts from glacial and periglacial lakes can result in flood waves and often catastrophic debris flows where erodible debris reservoirs are present. The impact on human lives and infrastructure can be highly critical and far reaching. During the strong glacier shrinkage of the 20th century, dangerous lakes developed in particular behind

moraines which had been deposited by former glacier advances (predominantly from the Little Ice Age or earlier Holocene cold periods). Such moraine-dammed lakes show different characteristics in comparison to ice dammed lakes, which often have seasonal cycles of filling and emptying (Blown and Church 1985).

Glacier lake outbursts were also studied in detail in North America, mainly in western Canada (Clague and Evans 1992; Mathews and Clague 1993; Clague and Evans 2000) as well as in Central Asia (Popov 1997). In Peru, for example, the problem has been fully recognized since 1941, when an outburst flood destroyed the city of Huaráz killing 4500 people (Lliboutry et al. 1977). In the Himalayas, retreating glaciers have prompted the evolution of large and rapidly growing lakes in glacial forefields with extremely high damage potential (Reynolds 1998; Yamada 1998). In the past decades, several lakes caused outburst floods affecting human lives and infrastructure (Vuichard and Zimmermann 1987; Yongjian and Jingshi 1992; Hanisch et al. 1996). The occurrence of natural hazards like flash floods and GLOFs events has increased in the Himalayan region of Pakistan due to enhancement in global warming in recent decades. They often have disastrous effects in down country; even a small glacial lake linked with hanging glaciers cause high risk of GLOF.

EARLIER RESEARCH WORK

In the HKH, the comprehensive field based research work on glaciers and GLOFs initiated in the 1980s. The Water and Energy Commission Secretariat (WECS), Nepal, prepared the first inventory of glacial lakes of the Koshi Basin in Nepal based on intensive study of 1:63,360 topographic maps from the 1980s, aerial photographs from 1974, and field investigations of selected glacial lakes from 1987 (WECS 1987). During 1999–2005, ICIMOD prepared an inventory of glaciers and glacial lakes of five HKH countries covering Bhutan, Nepal, Pakistan, China, and India. The inventory used analyses of 1:63,360 topographic maps published between 1960 and 1982 for Nepal and 1:50,000 scale topographic survey maps published between the 1950s and the 1970s by survey of India, together with Land Observation Satellite (Landsat) Thematic Mapper (TM) images, Indian remote sensing (IRS), 1D Linear Imaging and Self-scanning Sensor (LISS3), and some selected (SPOT) satellite images on a comparable to topographic maps. The inventory identify a total of 8,790 glacial lakes, of which 203 were recognized as of extremely hazardous (Mool et al. 2001a; Mool et al. 2001b; Mool et al. 2003; Bhagat et al. 2004; Roohi et al. 2005; Sah et al. 2005; Wu et al. 2005; Ives et al. 2010). The main criteria used for defining extremely hazardous or critical lakes were lake size and rapid growth in area, increase in Lake water level, activity of supra-glacial lakes at different times, position of the lakes in relation to moraines and the allied glacier, dam condition, glacier condition, and physical condition of surroundings (Ives et al. 2010). ICIMOD also accomplished a mapping of glacial lakes and an evaluation of GLOF hazard and risk for Nepal in 2009–10. The study mapped 1,466 glacial lakes covering an area of 64.75 km^2 using Landsat images taken in 2005 and 2006. Among them, 21 lakes were recognized as critical

(extremely hazardous) with six lakes defined as high priority requiring extensive field investigation and mapping (ICIMOD 2011).

Mapping and assessment of glacial lakes using different methods had also been carried out in a few select areas of the HKH (Gardelle et al. 2011), in Indian Himalaya (Worni et al. 2012), and in Tibet, China (Wang et al. 2011; Wang et al. 2012; Nie et al. 2013; Che et al. 2014). Zhang et al. (2015) mapped the glacial lakes in the Third Pole region covering the Pamir-Hindu Kush Himalaya and the Tibetan Plateau. It used the manual digitization method using Landsat images and mapped the lakes within the buffer zone of 10 km of the glacier's boundary available in the Randolph Glacier Inventory (RGI v3.2). The number of lakes mapped Amu Darya, 594, Indus, 1,607, Ganges, 364, and Brahmaputra, 2,247, based on Landsat image 2010 were much fewer compared to other published papers (Bambari et al. 2015 mapped 1,266 glacial lakes in Uttarakhand, India; ICIMOD 2011 mapped 1,466 glacial lakes in Nepal).

Ives et al. (2010) stated that "given the vast extent and unusually tough accessibility of the HKH region, use of remote sensing (and persistent modification of methodology) is an essential requisite for any assessment of the potentially large scale and prevalent hazard created by the speedy formation of new glacial lakes and the continuous growth of existing ones". Also, glacial lake inventories prepared in the past covered a wide time range maybe due to limited data sources available at the time. This has caused complexity in glacial lakes change analysis and estimating relative possibility of GLOF hazard and risk. A comparative evaluation requires that the source and source date of the data be as narrow as possible so that it could correspond to the specific date of the data throughout the region. It have need of the mapping be carried out in a narrower time base and the consistent source of data be used.

STUDY AREA

Chitral catchment lies between an elevation ranges from 1,071 to 7,603 meters above sea level. The total area of Chitral catchment is 14,850 square kilometers and this area is situated between 35 & 37 N latitude and 71 & 74 E longitude (Figure 1). Chitral is the most heavily glaciated area in the Pakistan and glaciers in region contribute significantly to the overall land cover. There are approximately 1600 glaciers in this catchment which covers an area of 2,300 km^2. Chitral is divided into districts of lower and upper Chitral in the KPK province of Pakistan.

It is located among Hindukush Mountains in the northwest of Pakistan. Chitral is bordered in the east with Gilgit-Baltistan, south-east Swat valley, north and north-east by China and the Wakhan corridor of Afghanistan, and in the west by the Nuristan and Kunar provinces of Afghanistan. In the south of Chitral is situated the Upper Dir district of Khyber Pakhtunkha province. It is also called the palace of fairies. The highest peak in this range of the Hindukush is Tirich Mir, which lies at a height of 25,263 feet, just 36 miles away in the north-east of Chitral town. No peak in the region is less than 4,000 feet and over 40 peaks have an altitude of 20,000 feet.

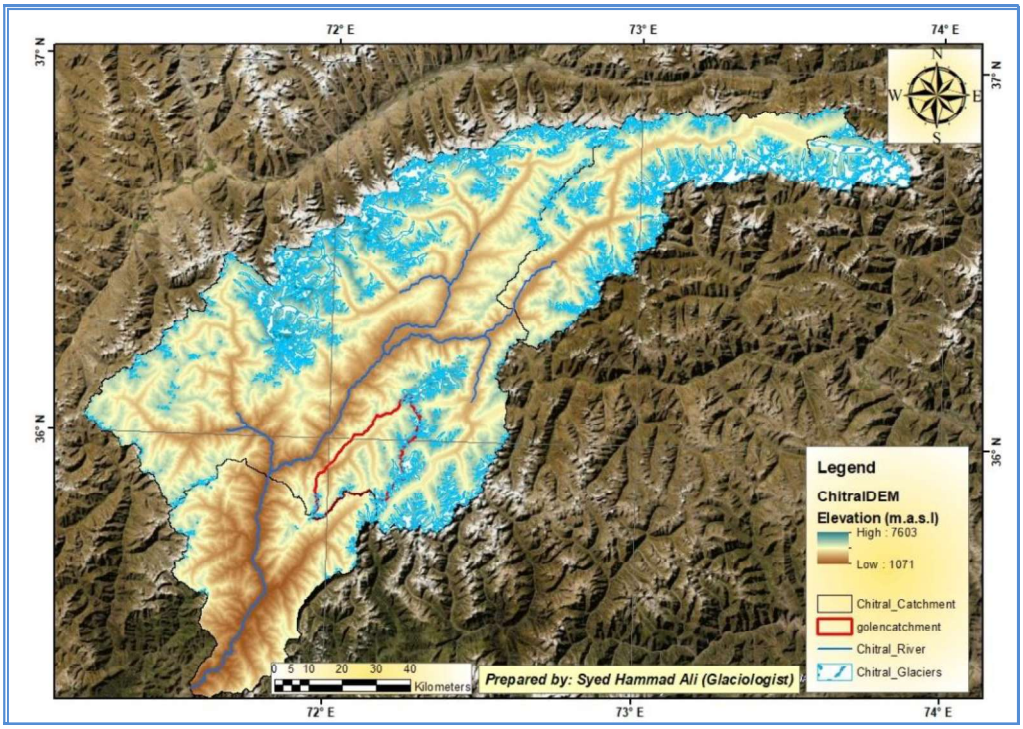


Figure-1. Location Map of Chitral Catchment

It is located among Hindukush Mountains in the northwest of Pakistan. Chitral is bordered in the east with Gilgit-Baltistan, south-east Swat valley, north and north-east by China and the Wakhan corridor of Afghanistan, and in the west by the Nuristan and Kunar provinces of Afghanistan. In the south of Chitral is situated the Upper Dir district of Khyber Pakhtunkha province. It is also called the palace of fairies. The highest peak in this range of the Hindukush is Tirich Mir, which lies at a height of 25,263 feet, just 36 miles away in the north-east of Chitral town. No peak in the region is less than 4,000 feet and over 40 peaks have an altitude of 20,000 feet.

HISTORY OF GLOFS IN CHITRAL

Chitral have 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. However, during the past one decade systematic mechanism has been adopted to establish relevant data on disaster. Some of the historical data given in table-1 below: (UNDP 2016). The bursting of the small glacial lake, continuous rise in temperature which accelerates the excessive snowmelt, may collectively causes the GLOF event (WAPDA 2018).

Year	Month	Glacier	Basin	Causes
1978	Not Known	Brep, Chitral	Chitral	--
1992	August	Yarkhoon	Chitral	Rains and Cloud Burst
2003	July	Yarkhoon	Chitral	Rains & Heat Waves
2005	July	Brep	Chitral	
2007	August	Terich	Chitral	Rainfall
2007	July	Sonoghor	Chitral	Rainfall
2010	June	Booni	Chitral	Monsoon
2010	July	Bindo Gol	Chitral	Rainfall
2013	July	Reshun	Chitral	Rainfall
2015	July to August	Chitral Gol	Chitral	Rainfall, Glacier melt
2015	July to August	Reshun	Chitral	Rainfall, Glacier melt
2015	July to August	Bindo Gol	Chitral	Rainfall, Glacier melt
2015	July to August	Garam Chashma	Chitral	Rainfall, Glacier melt
2015	July to August	Kalash Valley	Chitral	Rainfall, Glacier melt
2015	July to August	Kosht	Chitral	Rainfall, Glacier melt
2015	July to August	Mastuj	Chitral	Rainfall
2015	July to August	Booni	Chitral	Rainfall

Table-1. History of GLOFs in Chitral Catchment

RECENT GLOF IN CHITRAL CATCHMENT

The Diversion Weir, Flushing Section and Lateral Intake of Golen Gol HPP have been severely affected by a glacial lake outburst Flood (GLOF) happened on 7th July 2019 and buried the weir and sediment flushing structures. On 13th July 2020, the plant was again hit by a GLOF from the same glacial lake originating from Dook

Pal Glacier on an elevation of 4500 m.a.s.l. about 10 km upstream of the headwork's of Golen Gol HPP at an elevation of around 2000 m.a.s.l. Both GLOF events appear to be caused by persistent higher temperatures for several days in Chitral and resulted into a sudden formation of a supra-glacial. This glacial lake was increased with the rise in temperature and the sudden outburst happened from the lake in the late afternoon of 7th July 2019 releasing huge amount of water along with debris from the lake as well as from the vicinity along the drainage path. From the pictures, videos from various sources and the site visit it is obvious that the debris flow consisted of rockfall, debris and boulders with a diameter of up to 2-3 meters. The 2020 event was smaller in magnitude and smaller diameters and material was mobilized along the way of the path. The 2019 event caused devastating erosion and depositions. At the headworks about 7 - 11 meters of depositions occurred and buried the weir and blocked the intake. Erosion channels have a magnitude between 30-50 meters width and 12 – 20 meters depth, which occurred along the drainage nullah that starts at the end of Dook Pal glacier and ends at its confluence point with Roghail Gol. Since then the Golen Gol HPP was not able to run under full capacity and major reinstatement works are required to bring the plant back to the as-built condition.



Reservoir Area and Flushing Section before GLOF

Source: WAPDA



Reservoir Area and Flushing Section after GLOF

Source: WAPDA



Figure-2: The extent of the 2019 GLOF
Source: WAPDA

METHODOLOGY

A number of remote sensing methods had been developed for glacial lake identification and mapping or preparing of inventory (Kääb 2000; Mool et al. 2001a; Huggel et al. 2002; Huggel et al. 2006; Ives et al. 2010). The methodology used in this study is presented in figure 3.

The Normalized Difference Water Index (NDWI) was used for automated glacial lake detection and matched by visual interpretation. A digital elevation model and Google Earth were used for better visualization, especially for lakes in shadow and snow-covered areas. The NDWI is a ratio joining two different bands presented in following equation that improve water spectral signals by contrasting the reflectance between different wavelengths and removing a large portion of noise components in different wavelengths (Ji et al. 2009). For the Landsat images of ETM+, NDWI was calculated using the near infrared band (Band 4) and Blue band (Band 1) as used in Huggel et al. (2002).

$$\mathrm{NDWI} = \frac{NIR(or\ Band\ 4) - Blue\ (or\ Band1)}{NIR(or\ Band\ 4) + \ Blue\ (or\ Band1)}$$

First, the ratio images of NDWI were created by arithmetic calculation of Band 4 and Band-1 of the Landsat images and the NDWI threshold value was applied to map the water bodies (glacial lakes) in the ratio images.

The NDWI threshold value of -0.6 to -0.9 adopted by Huggel et al. (2002) has been used in preparing the inventory of the Chitral glacial lakes. Although this automatic mapping method can expedite the detection of glacial lakes easily, this method could not be applied to the whole Chitral catchment due to some atmospheric and physical processes of Earth. For example, if lakes are frozen or covered with snow or cloud and lie in a shadow area, they cannot be detected using this automatic method. In such cases, the manual tracing method has been applied to map the lakes.

The identified glacial lakes were reevaluated by overlying the Landsat images over the earlier inventory datasets which ever available (Mool et al. 2001a; Mool et al. 2001b; Mool et al. 2003; Bhagat et al. 2004; Roohi et al. 2005; Sah et al. 2005; Wu et al. 2005). Thus, the missing lakes were added manually. Further the mapped lakes were superimposed with high resolution images in Google Earth environment for validation.

Usually, pixels in the images do not give the homogenous reflectance and symbolize only one object in a ground except the imaging is absolutely allied in a single object. So, at least 4 pixels are required to signify the accurate boundary of the object (lake) to map from the images. Hence, the smallest glacial lake that can be mapped from the images should be covered by 4 pixels, which is 0.0036 km^2 in the case of Landsat images. The glacial lake boundary mapped from 4 pixels is smooth and the boundary lies some level inside the 4 pixels, so we have consider the lower round up values as 0.003 km^2. Hence the glacial lake area of 0.003 km^2

is the threshold for the lake size that has been applied for mapping in the current glacial lake inventory.

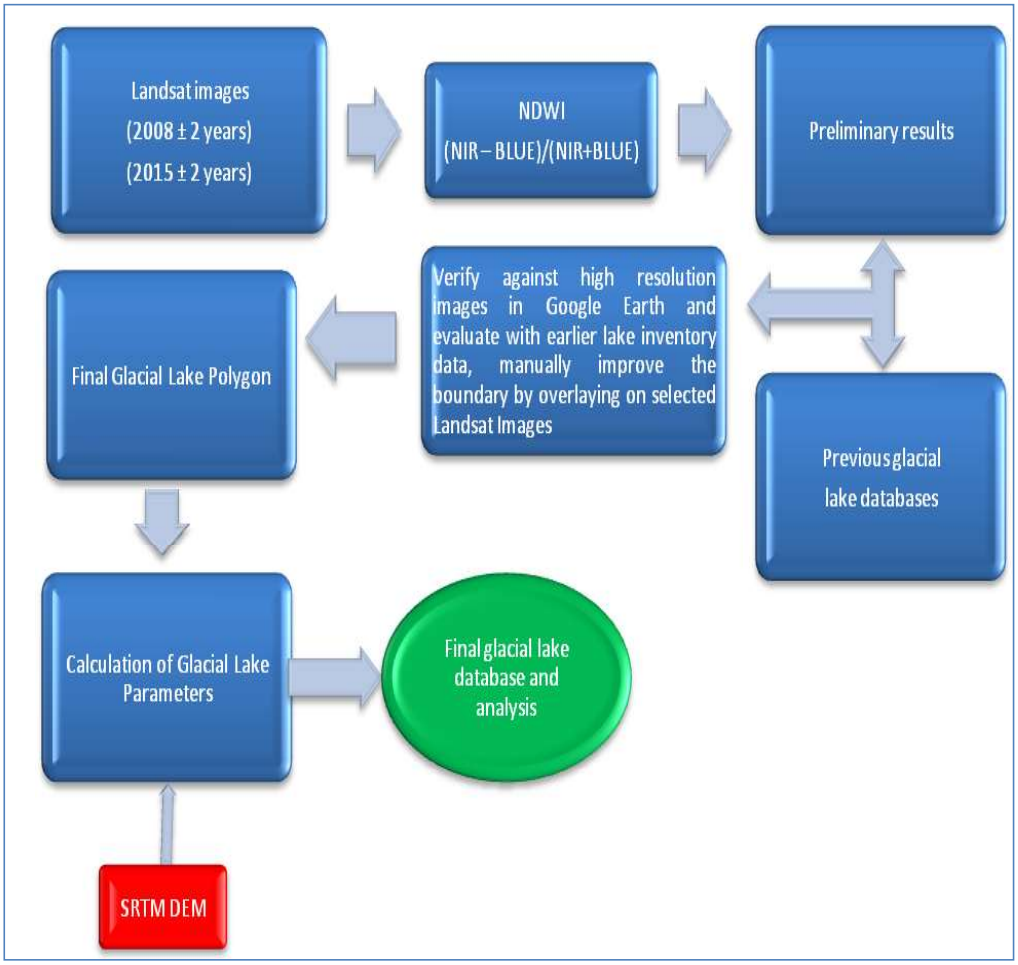


Figure-3. Methodology for Glacial lake Mapping

CONCLUSIONS

In total Chitral catchment has 301 glacial lakes covering an area of 9.26 km^2 (Figure 5). The size of glacial lakes in Chitral ranges from 0.003 to 2.048 km^2 with an average size of 0.031km^2 lies between altitudes 3400 – 5100 m.a.s.l. There are 65 major lakes in this area which covers an area of 7.511 km^2. The distribution of lakes in various elevation zones is given in Table 3. The majority of lakes (about 43%) are within the elevation zone of 4,000 – 4,500 m.a.s.l only one glacial lake is mapped at an elevation between 3,000 – 3500 m.a.s.l about 33% and 23% of lakes are within the elevation zones of 3,500 – 4,000 m.a.s.l and 4,500 – 5,100 m.a.s.l, respectively as shown in Figure-4. The majority of lakes mapped were Supraglacial lakes 110 (37%) the number and distribution of various types of glacial lakes in

Chitral catchment are summarized below in table 2. This inventory includes all lakes in surrounding of glacier or in the landforms.

Types of Lake	Symbol	Nos.	% age
Other moraine-dammed lake	M(o)	66	22
End-moraine-dammed lake	M(e)	16	5
Lateral moraine-dammed lake	M(l)	14	5
Supra-glacial lake	I(s)	110	37
Other bedrock dammed lake	B(o)	61	20
Cirque lake	B(c)	4	1
Other glacial lake	O	30	10
Total		**301**	

Table-2. Numbers and Various Types of Glacial Lakes in Chitral Catchment

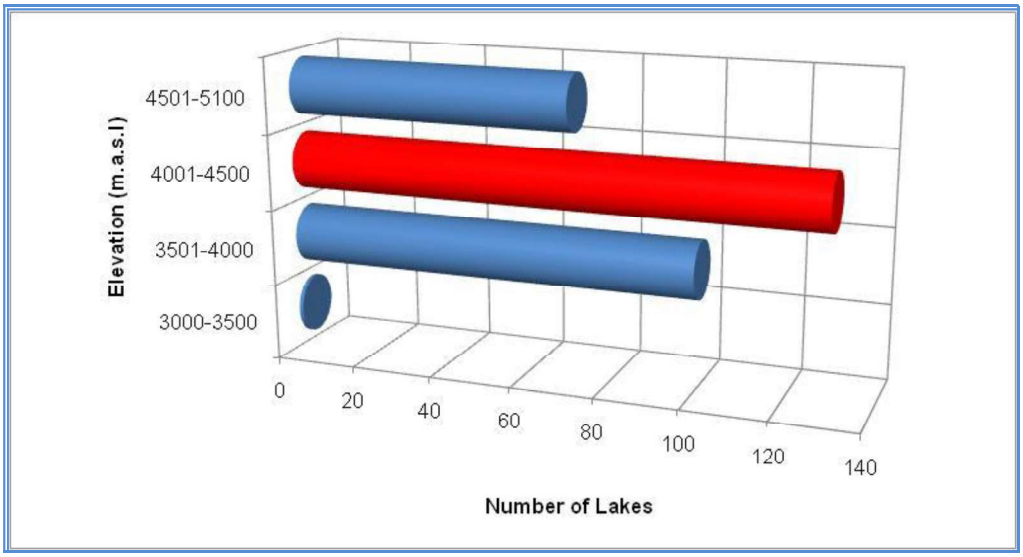


Figure-4. Altitudinal Distribution of Glacial Lakes in Chitral Catch

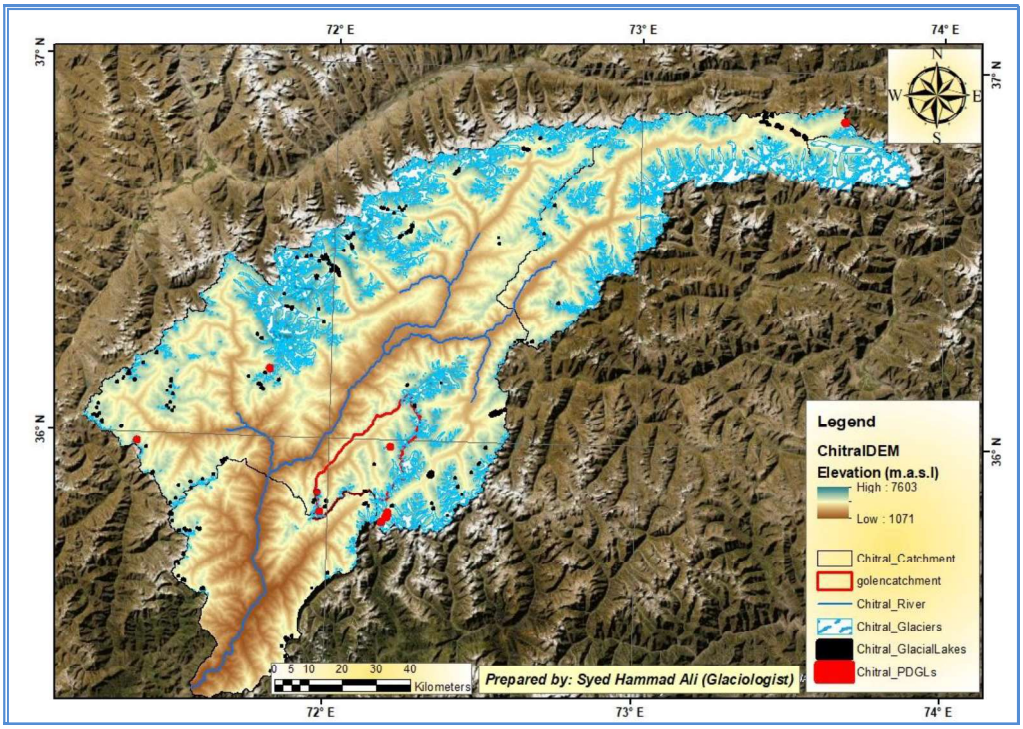


Figure-5. Map of Glacial Lakes in Chitral Catchment

Elevation Zones	Number of Lakes	% age
3000-3500	01	0.33
3501-4000	100	33
4001-4500	130	43
4501-5100	70	23

Table-3. Distribution of Glacial Lakes in Elevation Zones in Chitral Catchment

Out of 301 glacial lakes 8-glacial lakes (Figure 6) were identified as critical (potentially hazardous) based on criteria related to such factors as the size and rate of growth of the lake; position in relation to moraines and associated glaciers; characteristics of the surrounding area (for example the presence of hanging glaciers in contact with the lake); condition of the dam (extent of crest, presence of an ice core,); and physical condition of the surroundings (potential for rock falls and avalanches, presence of other lakes and moraines in tributary glaciers) (Ives et al., 2010). These lakes are found in the elevation range from 3700 – 4600 m.a.s.l.

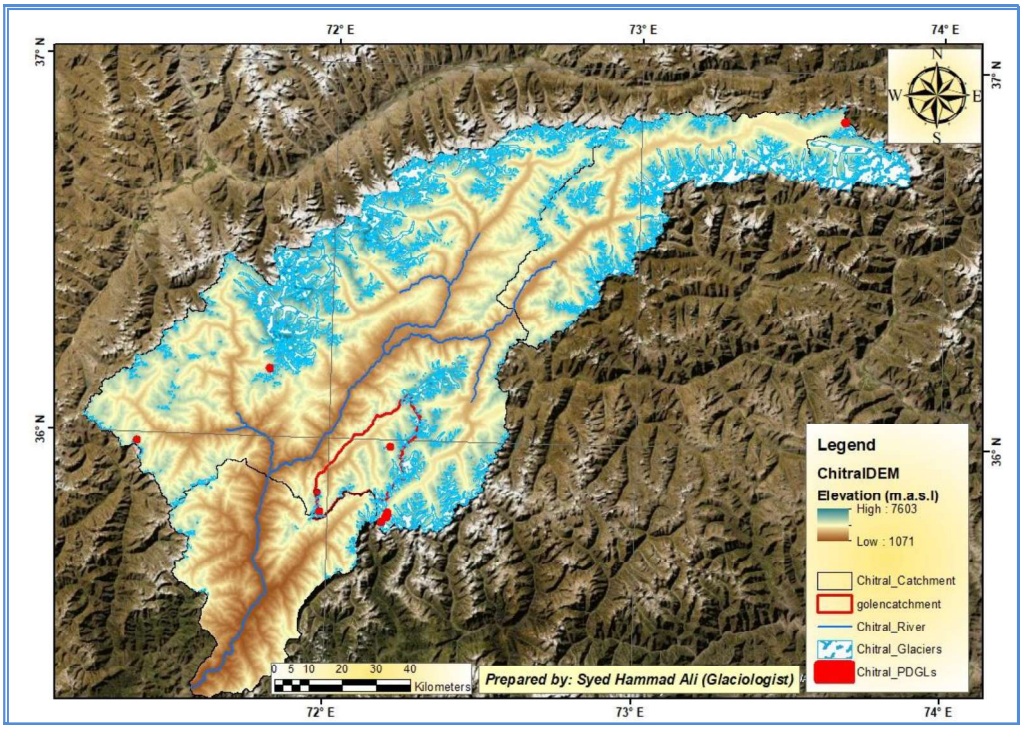


Figure-6. Map of Potentially Hazardous Glacial Lakes in Chitral Catchment

RECOMMENDATIONS

Followings are some recommendations needed for further understanding of the dynamics of glacial lakes and the risks linked with outburst floods.

- Additional work in developing time series data on glacial lakes also in other catchments.
- Physical monitoring of these lakes
- Numerical simulation of outburst flood
- And downstream vulnerability assessment

There is a need to combine disaster risk concerns in common and GLOF risk in special into national and regional development plans, policies and programmes, including the infrastructure development;

- To set up a National GLOF Risk Management coalition to make a intensive effort, mobilize resources and design suitable response measures;
- To build up a unified database and information distribution system;
- To develop proper mechanisms for installation of early-warning systems;
- And to establish a GLOF Risk Reduction Fund for research, awareness creation, and the design and execution of mitigation and adaptation measures.

These efforts need to be integrated into the wider activities related to national development, disaster risk reduction and climate adaptation. We must take necessary actions now, together with all relevant players, to secure a safe, sustainable Pakistan, and to reduce loss of lives and assets.

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