

Mapping of Dangerous Glacial Lakes by Using Systematic Extraction Approach in Different Catchments of Upper Indus Basin (UIB) Pakistan

Syed Hammad Ali^{1,*}

Abstract

The glaciers are nature's most valuable fresh water resource for irrigation, industry, and hydroelectric growth, as well as for the present and future needs of millions of people who live downstream. Numerous of the waterways in the HKH region receive a significant percentage of ice melt water from this solid reservoir. 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. Rapid water buildup in these glacial lakes, especially in those near retreating glaciers, can cause their vulnerable embankment "dams" to suddenly fail. Glacial Lake Outburst Floods (GLOF) often result in massive flows of water and debris that have catastrophic downstream repercussions. Understanding of this resource seems an exceptional requirement for future planning for water resources and flood hazards. This paper provides comprehensive information about the glacial lakes in the different catchments of UIB 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. This inventory of glacial lakes is prepared using reliable uniform and single source data with a semi-automatic method using RS/GIS. For the consistency of glacial lakes data, Satellite images obtained at same instant of time used to delineate glacial lakes boundary. The glacial lake boundaries were delineated using an automatic method on Landsat images from the year 2008 $\pm$ 2 years and also considering the data of 2015 + 2 years. The automatic 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. It is challenging to apply the method as it is difficult to obtain good quality images with minimum amount of snow cover, cloud cover, and shadow portion so some of the lakes were manually digitized by validating on high resolution images in Google Earth as well as comparing with previous available inventory data. This inventory includes maximum numbers of lakes surrounding the glaciers.

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INTRODUCTION

Water is life and a vital part of human civilization and humanity cannot survive without securing access to safe drinking water and basic sanitation. Water, to the contrary, also poses a risk to existence. The probability of moisture disasters has increased due to the harsh precipitation, including both respect of frequency and severity.

Societies and economic systems are suffering as a result of the negative repercussions of the disasters, which have claimed many lives. Water-related calamities cause both direct impacts (such as destruction of infrastructure, destruction of crops, and the loss of life and property) and indirect effects (e.g. losses in production and livelihoods, increased investment risk, and human health impacts). Authorities and humanitarian groups should be strongly motivated to focus more on monitoring, avoidance, and treating the underlying determinants of vulnerability as a result of the rising financial impact and toll of catastrophes. According to the United Nations' World Water Development Report 2020, over 3 billion individuals were harmed by droughts and flooding between 2001 and 2018, which resulted in over 166,000 fatalities and nearly US\$700 billion in economic losses. Approximately 74% of all natural disasters between 2001 and 2018 had a water-related component. According to a 2017 UNHCR estimate, it is extremely difficult for the 68.5 million people who have been forced to leave their homes to receive clean water services. 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, by 2050, there will be 2 billion more people who are at risk of flooding due to factors such as growing communities in flood-prone areas, environmental degradation, destruction, loss of ecosystems, and increasing sea levels. According to UNISDR's 2015 report, the total yearly economic damages from weather-related disasters are expected to be between US\$ 250 billion and US\$ 300 billion. Asia is the region most susceptible to water-related catastrophes, such as Glacial Lake Outburst Floods (GLOFs), and then between 1980 and 2006, it was responsible for even more than 45% of all homicides and much more than 90% of all disaster-related casualties. Glacial lake outburst floods (GLOFs), a type of torrential downpour in which water from a lake connected to a glacier is accidentally released, are recognized to have occurred in mountain range regions of Pakistan for as long as statistics have been kept. GLOFs cause a massive discharge of water and silt downstream.

Where erodible debris reservoirs are present, outbursts from glacial and periglacial lakes can result in flood waves and frequently catastrophic debris flows. The effects on infrastructure and human life may be severe and far-reaching. Dangerous lakes emerged specifically behind moraines that had been deposited by prior glacier advances during the 20th century's significant glacier shrinking (predominantly from the Little Ice Age or earlier Holocene cold periods). The glacial lakes dammed by moraines and or ice core of retreating glaciers may breach suddenly due to unstable moraine dams. In contrast to ice blocked lakes, which frequently experience seasonal cycles of overflowing and draining, such moraine-dammed bodies of water exhibit various characteristic [22].

In-depth studies of glacier lake outburst have also been conducted in Central Asia [18, 19] and North America [13, 11, 23], with a focus on western Canada. For instance, the issue has been well acknowledged in Peru ever since Huaráz was completely destroyed by an outburst flood in 1941, killing 4500 people [14]. Large, quickly expanding lakes with a very high potential for damage have developed in glacial forefields in the Himalayas as a result of melting glaciers [5, 30]. Several lakes have experienced outburst floods in the past, which have had an impact on infrastructure and human life [5–7, 12, 31–32].

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

Comprehensive field based research work on glaciers and GLOFs was initiated in the 1980s in the HKH. The first assessment of freshwater lakes in the Koshi River system of Nepal was created by the Water and Energy Commission Secretariat (WECS), Nepal, utilizing a thorough examination of

1:63,360 suitable image from of the 1980s, aerial photos from 1974, and field examinations of a few glacial lakes from 1987. From 1999–2005, ICIMOD generate another glaciers and glacial lakes inventory for five HKH countries covering Bhutan, Nepal, Pakistan, China, and India. The supply chain made use of 1:63,360 scale geographic data for Nepal that were made available among both 1960 and 1982 and 1:50,000 spectrum geomorphologic survey layouts for India that were made publicly available here between 1950s and 1970s by survey, along with Landsat Thematic Mapper (TM), Indian Remote Sensing (IRS), 1D Linear Imaging and Self-scanning Sensor (LISS3), and some specific (SPOT) aerial photographs on topographic maps that were as good as possible. The inventory identify a total of 8,790 glacial lakes, out of which 203 were recognized as of extremely hazardous [3, 10, 15–17, 20–21, 26]. The primary criteria for identifying extremely dangerous or critical bodies of water seem to have been Lake Amount and quick area growth, enhance in water surface elevation, interaction of supra-glacial lakes at various times, location of the lakes in fact related to moraines and the associated glacier, dam condition, glacier circumstance, and physical state of the surroundings [10]. ICIMOD also accomplished a mapping of glacial lakes and an evaluation of GLOF hazard and risk for Nepal in 2009–10. The study identifies 1,466 glacial lakes covering an area of 64.75 km² using Landsat images acquired 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 [9].

Identification and evaluation of glacial lakes conducted using different methods in few select areas of the HKH [4]. In Indian Himalaya [35], and in Tibet, China [33–34] 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 [2] mapped 1,266 glacial lakes in Uttarakhand, India; ICIMOD 2011 mapped 1,466 glacial lakes in Nepal.

According to a different study [10], the utilization of remotely sensed data (and enduring adjustment of methodology) is a necessary requirement for any evaluations of the potentially significant and pervasive hazard created by the rapid development of new glacial lakes and indeed the continued expansion of existing products. Additionally, historical glacial lake inventories encompassed a broad time span, possibly as a result of the few data sources that were available at the time. This has complicated the investigation of glacial lake change and the estimation of the relative likelihood of GLOF danger and risk. The sources and originating chronology of the information must be as accurate as feasible for a comparative analysis in order to match to the precise date of the data across the region. It is necessary that the mapping be done in a shorter time frame and that a reliable source of information be used.

ZONE OF STUDY

Hunza River Basin

13,713 km² make up the Hunza River basin's drainage pattern (Figure 1). Environmentally, the basin, which has a mean catchment height of 4,631 m, stretches from 36.05°N, 74.04°E to 37.08°N, 75.77°E in Pakistan's high-altitude central Karakoram area. The altitude varies from 2,409 to 7,749 metres above sea level. There are 1,384 total glaciers in the watershed, covering a catchment area of about 2,754 km², of which 2,344 km² are pure glaciers and 410 km² are covered in debris. Clean glacier elevation ranges from 2,723–7,749 m.a.s.l while debris cover glacier elevation ranges from 2409–5297 m.a.s.l. The total ice reserves in Hunza river basin are 310.61 km³. [1]. (Figure 1).

Gilgit River Basin

The Gilgit River basin geographically, extends from 35.80 °N, 72.53 °E to 36.91 °N, 74.70 °E. The elevation ranges from 1250–7650 (m.a.s.l.), a sub-catchment of the Upper Indus Basin, located in the

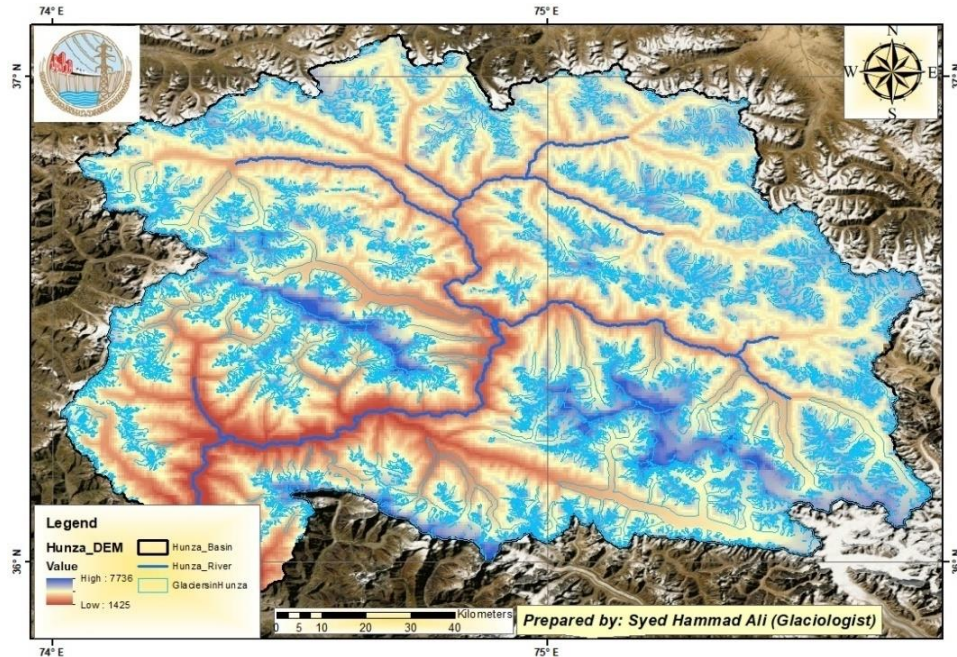


Figure 1. Location map of Hunza river basin.

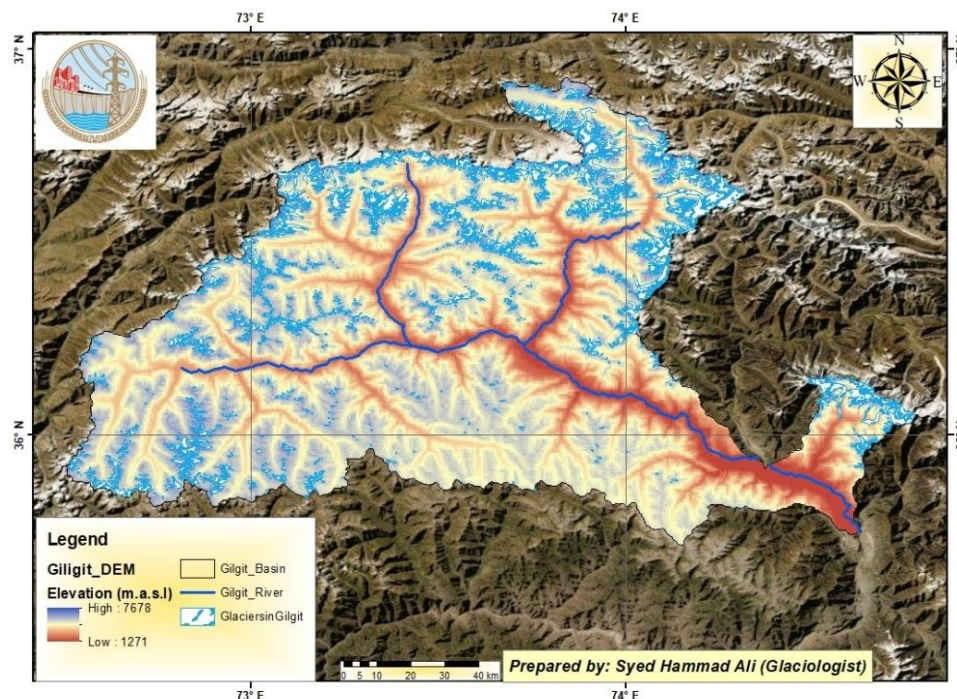


Figure 2. Location map of Gilgit river basin.

Hindu Kush and Karakoram region. Snow and glacier melt water originating from two different ranges, Hindu Kush and Karakoram feeds the Gilgit River basin despite having its source in the Hindu Kush, the Gilgit River receives a large amount of its flow near the eastern end of the basin from the Karakoram glaciers. There are roughly 968 glaciers in the watershed as a whole. Approximately 938 km² of catchment area is glaciated out of which clean glacier area is 857 km² and debris cover area is 81 km². Clean glacier elevation ranges from 2,840–7,730 m.a.s.l while debris cover glacier elevation

ranges from 2,703–4,925 m.a.s.l. The total ice reserves in Gilgit river basin are 71.32 km³ as presented in Figure 2 [1].

Shyok River Basin

Among the principal tributary of the Indus River in northern Pakistan is the Shyok River. This river begins in the Siachen and Rimo Glaciers (partially), travels throughout Kashmir (the Ladakh zone), and afterwards enters northern Pakistan close to the Ganche District. The Shyok River is fed by three principal tributaries, the Nubra (in Kashmir), Saltoro, and Hushe Rivers, and encompasses a watershed of 33,429 km² extends into China (area in China contains 704 glaciers with an area of 203 Km²; CI/DC refer to the remaining 10,709 glaciers with an area of 14,858 Km² (Figure 3). Geographically, the basin extends from 33.60°N, 75.96°E to 35.68°N, 79.59°E located in the high-altitude central Karakoram region, Pakistan. The elevation ranges from 3,231–7,803 m.a.s.l. The total numbers of glaciers in basin are approximately 3,357. Approximately 5,938 km² of catchment area is glaciated out of which clean glacier area is 5,549 km² and debris cover area is 372 km². Clean glacier elevation ranges from 3,646–7,803 m.a.s.l while debris cover glacier elevation ranges from 3,231–5,666 m.a.s.l. The total ice reserves in Shyok river basin are 982 km³ [1].

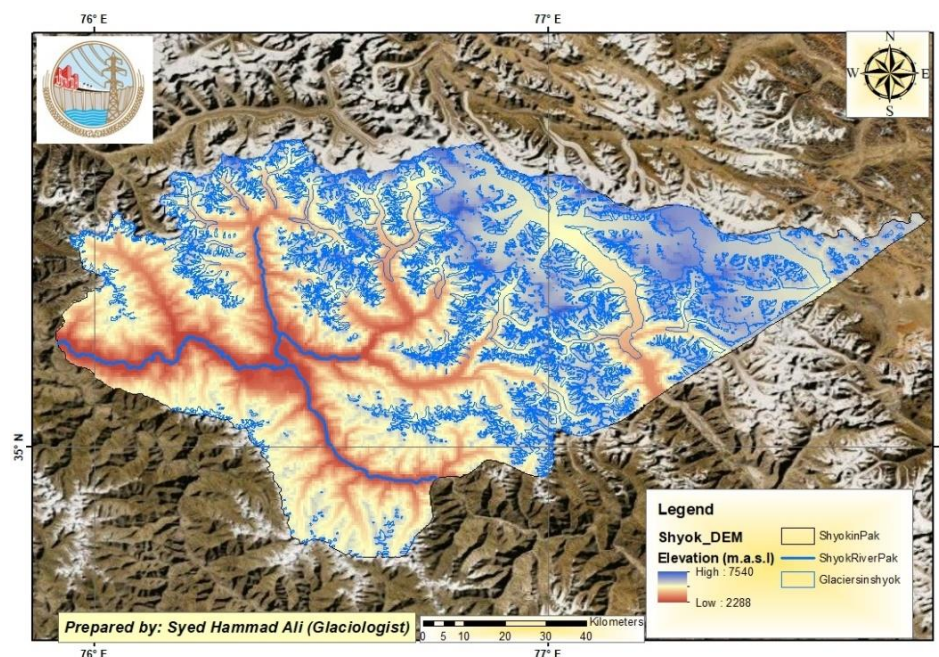


Figure 3. Location map of Shyok river basin.

Astor River Basin

Astor River basin with drainage area of 3,988 km². In terms of location, the basin stretches from 34.80°N, 74.46°E to 35.64°N, 75.24°E situated in the high-altitude central Karakoram region, Pakistan. Elevations vary from 2,991 to 8,032 metres above sea level. There are roughly 372 glaciers in the watershed as a whole as presented in Figure 4. Approximately 240 km² of catchment area is glaciated out of which clean glacier area is 209 km² and debris cover area is 30 km². Clean glacier elevation ranges from 3,367–8,032 m.a.s.l while debris cover glacier elevation ranges from 2,991–5,031 m.a.s.l. The total ice reserves in Astor river basin are 16.88 km³ [1].

METHODOLOGY

Different remote sensing techniques had been adopted for glacial lake recognition and plotting or devising inventory (7-8, 10, 12, 17). Figure 5 displays the methods utilised in this investigation. The Normalized Difference Water Index was used for automated glacial lake recognition and harmonized by visual elucidation. 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 unification two different bands presented in following equation to get better water spectral signals by distinct reflectance between different wavelengths and eliminating a large portion of noise components in different wavelengths [11]. Further the Landsat images of TM and ETM+, NDWI was computed as used in equation below by [8] using the near infrared band (Band 4) and Blue band (Band 1).

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

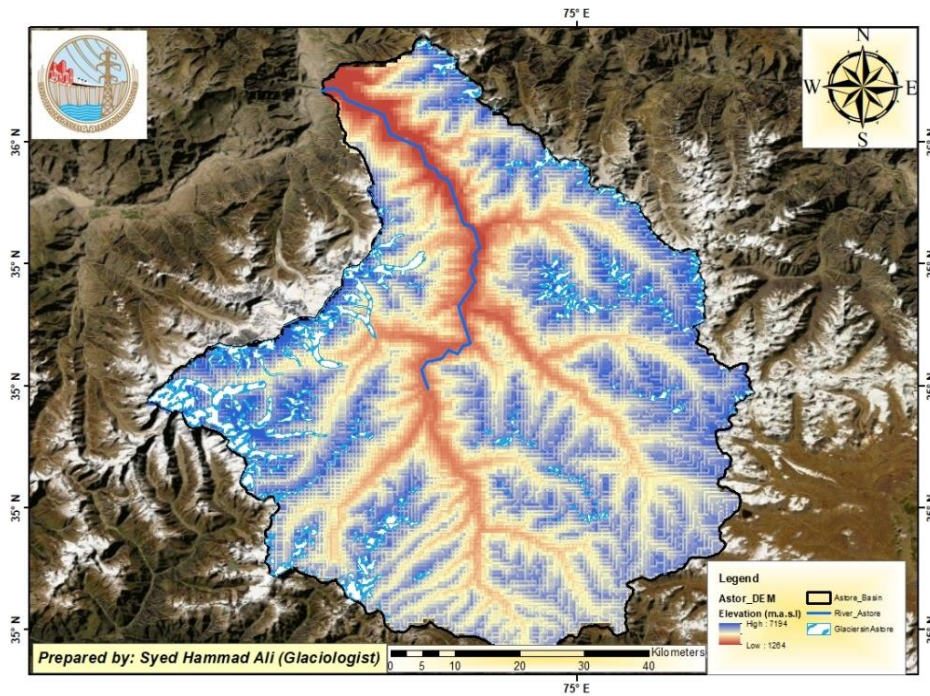


Figure 4. Location map of Astor river basin.

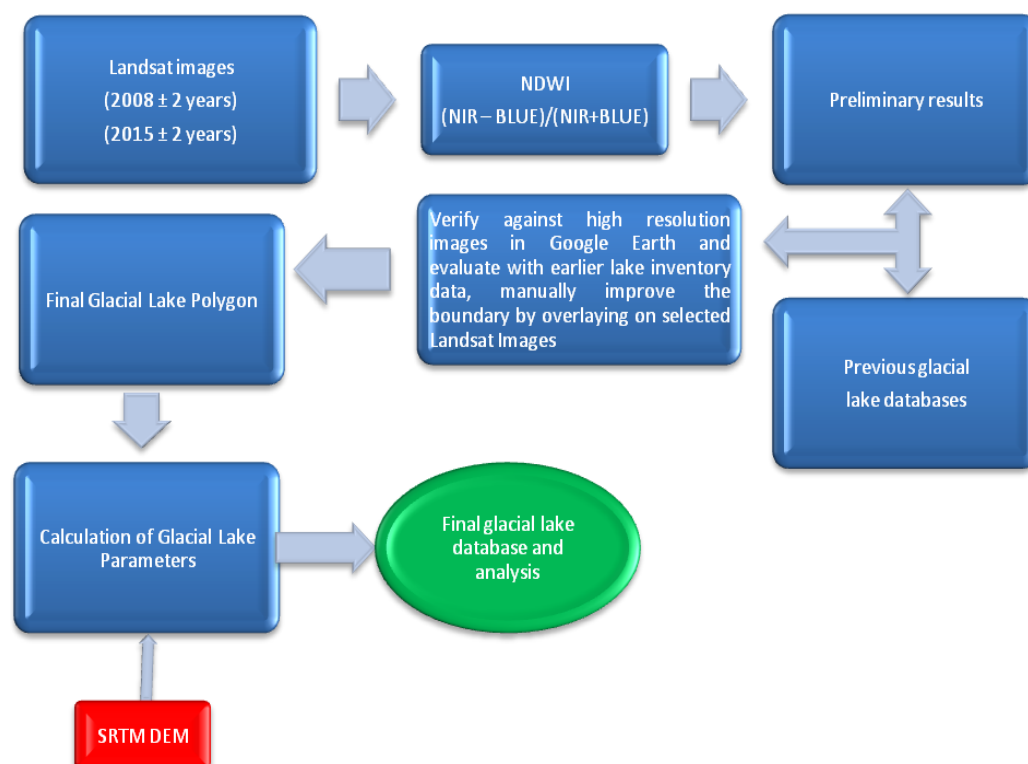


Figure 5. Methodology for glacial lake mapping.

The fractions of NDWI were generated by calculation of Band 4 and Band 1 of the Landsat images and the NDWI threshold value was applied to highlight the water bodies (glacial lakes) in the imagery. NDWI threshold value of -0.6 to -0.9 applied in preparing the inventory of the different catchments of UIB glacial lakes [8]. Though this mapping technique can expedite the detection of glacial lakes easily. If lakes are ice-covered or surrounded with snow or cloud and lie down in a shaded area, they cannot be exposed using this automated technique so, the manual tracing approach has been applied to delineate the lakes.

The identified glacial lakes were re-evaluated by superimposing the Landsat images over the earlier inventory available [3, 10, 15–17, 20–21, 26]. Consequently, the missing lakes were added manually. In addition to that the delineated lakes for validation were placed over with high resolution images in Google Earth environment.

Usually, pixels in the images do not provide the corresponding 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 periphery of the lake to map from the images. Hence, the shortest glacial lake that can be delineated from the images should be covered by 4 pixels, which is 0.0036 km² in the case of Landsat images. The glacial lake periphery mapped from 4 pixels is smooth and the boundary lies some level inside the 4 pixels, so we have considered the lower round up values as 0.003 km² [25, 27–29]. Therefore the glacial lake area of 0.003 km² is the threshold for the lake size that has been applied to generate the current glacial lake inventory.

The lake's dimensions and rate of expansion location in regards to moraines and nearby glaciers, neighbouring features (such as the appearance of floating glaciers in interaction with the lake), the condition of the dam (such as the significant degree of its crest or perhaps the appearance of an ice core), as well as the physical environments (such as the likelihood of rock falls and rockslides, the presence of other lakes as well as moraines) were all taken into consideration when identifying potentially dangerous lakes.

RESULTS

Identified Glacial Lakes in Hunza Basin

In total Hunza catchment has 142 glacial lakes covering an area of 2.976 km². The size of glacial lakes in Hunza ranges from 0.003 to 0.279 km² with an average size of 0.021km² lies between altitudes 2524–5023 m.a.s.l. (Figure 6). There are 30 major lakes in this area which covers an area of 2 km². The distribution of lakes in various elevation zones is given in Table 1. The majority of lakes (about 52%) are within the elevation zone of 3,500–4,000 m.a.s.l about 9%, 21%, 14% and 4% of lakes are within the elevation zones of 2,500–3,000 m.a.s.l, 3,000–3,500 m.a.s.l, 4,000–4,500 m.a.s.l and 4,500–5,100 m.a.s.l respectively as shown in Figure 7. The majority of lakes mapped were Supra-glacial lakes 113 (87%) the number and distribution of various types of glacial lakes in Hunza catchment.

Out of 142 glacial lakes 4 glacial lakes (Figure 6) were identified as critical (potentially hazardous) based on criteria mentioned above. These lakes are found in the elevation range from 2500–3500 m.a.s.l.

Identified Glacial Lakes in Gilgit Basin

Gilgit catchment has 691 glacial lakes covering an area of 38.034 km². The size of glacial lakes in Gilgit ranges from 0.003 to 2.734 km² with an average size of 0.055km² lies between altitudes 2203–5046 m.a.s.l. (Figure 8). There are 347 major lakes in this area which covers an area of 34.208 km². The distribution of lakes in various elevation zones is given in Table 2. The majority of lakes (about 69%) are within the elevation zone of 4,001–4,500 m.a.s.l about 0.6%, 1%, 5% and 24% of lakes are within the elevation zones of 2,000–2,999 m.a.s.l, 3,000–3,500 m.a.s.l, 3,501–4,000 m.a.s.l and 4,501–5,100 m.a.s.l respectively as shown in Figure 9. The majority of lakes mapped were other bedrock dammed lakes 448 (65%). Out of 691 glacial lakes 9 glacial lakes (Figure 8) were identified as critical (potentially hazardous) based on criteria mentioned above. These lakes are found in the elevation range from 2700–4500 m.a.s.l.

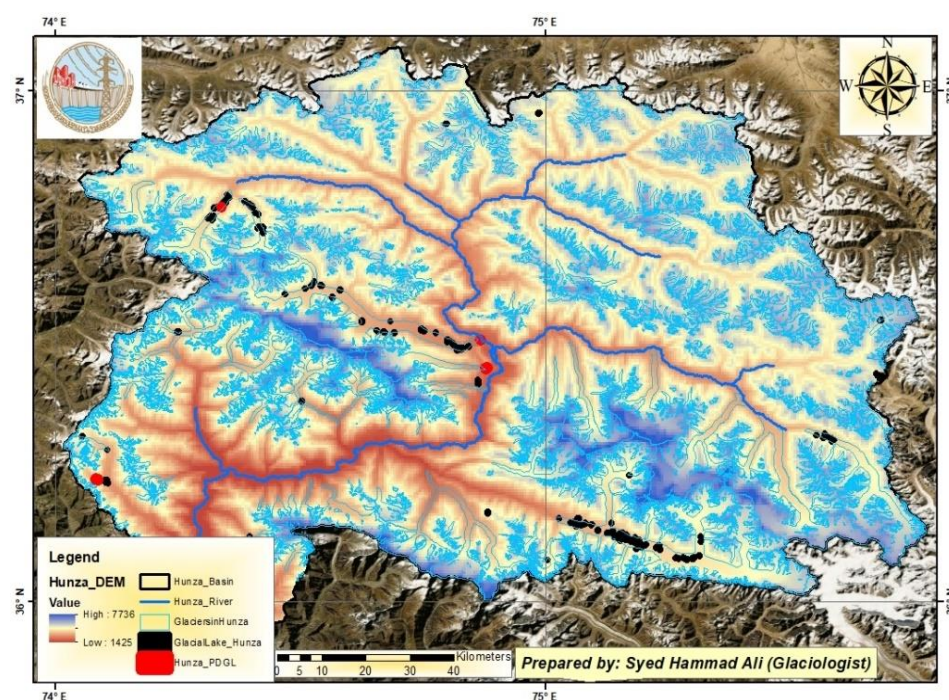


Figure 6. Map of glacial lakes in Hunza catchment.

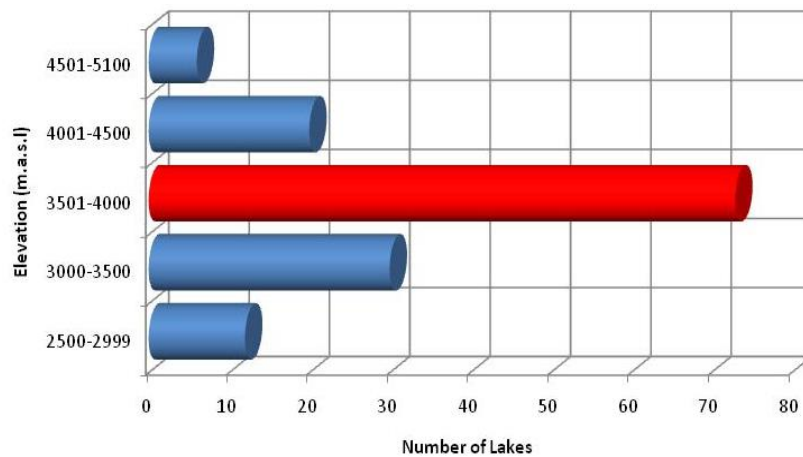


Figure 7. Altitudinal distribution of glacial lakes in Hunza catchment.

Table 1. Distribution of glacial lakes in elevation zones in Hunza catchment.

Elevation Zones	Number of Lakes	% age
2500–2999	12	8.51
3000–3500	31	21.27
3501–4000	73	51.77
4001–4500	20	14.18
4501–5100	06	4.25

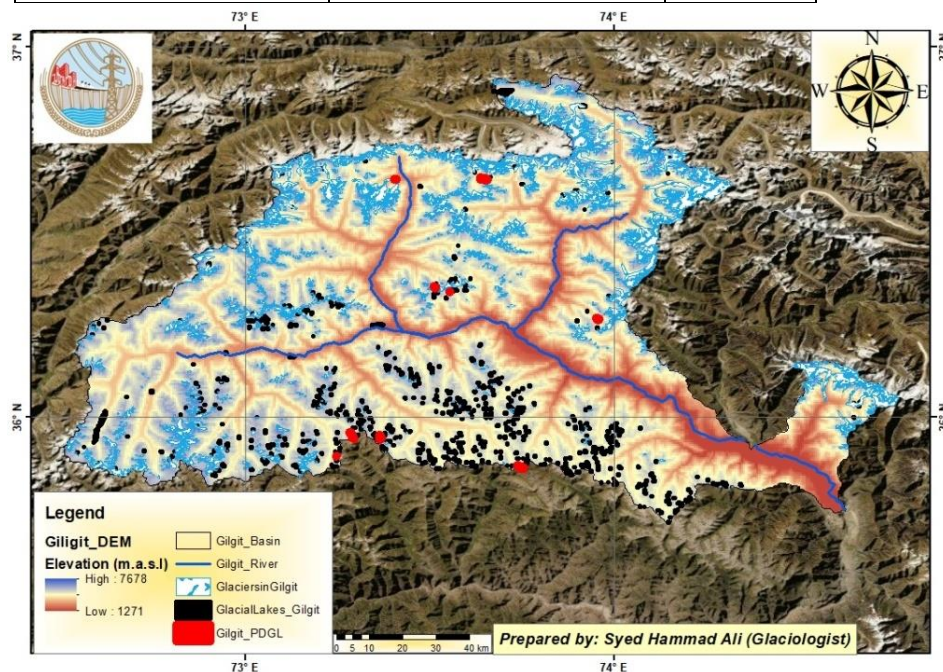


Figure 8. Map of glacial lakes in Gilgit catchment.

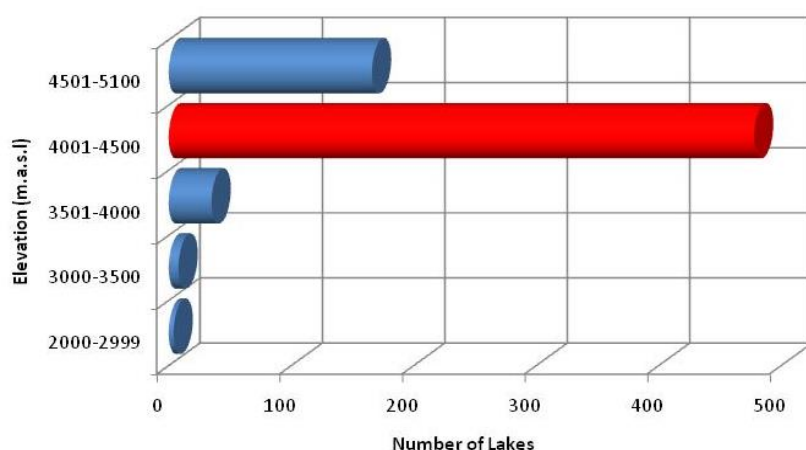


Figure 9. Altitudinal distribution of glacial lakes in Gilgit catchment.

Table 2. Distribution of glacial lakes in elevation zones in Gilgit catchment.

Elevation Zones	Number of Lakes	% age
2500–2999	04	0.57
3000–3500	08	1.15
3501–4000	35	5.06
4001–4500	478	69.17
4501–5100	166	24.02

Identified Glacial Lakes in Shyok Basin

In Shyok catchment there are 216 glacial lakes covering an area of 6.368 km². The size of glacial lakes in Shyok ranges from 0.003 to 0.568 km² with an average size of 0.029 km² lies between altitudes 3329–5216 m.a.s.l. (Figure 10). There are 65 major lakes in this area which covers an area of 4.993 km². The distribution of lakes in various elevation zones is given in Table 3. The majority of lakes (about 71%) are within the elevation zone of 4,501–5,100 m.a.s.l. about 2%, 8%, 15% and 3% of lakes are within the elevation zones of 3,000–3,500 m.a.s.l, 3,501–4,000 m.a.s.l, 4001–4500 m.a.s.l, and 5,101–5,500 m.a.s.l respectively as shown in Figure 11. The majority of lakes mapped were Supraglacial lakes 92 (43%). Out of 216 glacial lakes 6 glacial lakes (Figure 10) were identified as critical (potentially hazardous) based on criteria mentioned above. These lakes are found in the elevation range from 4100–4800 m.a.s.l.

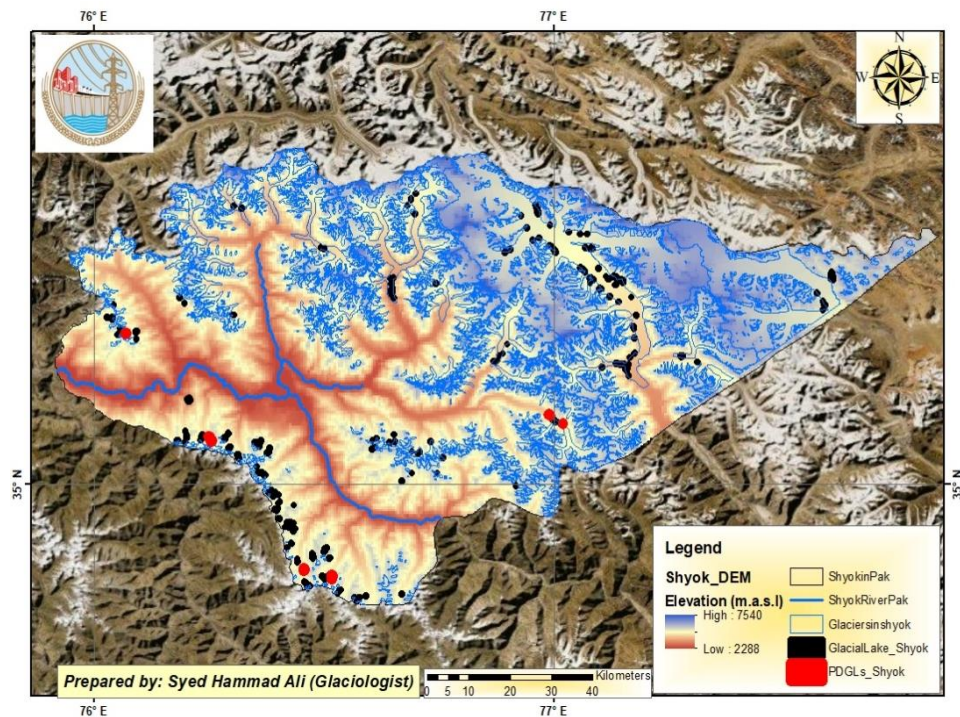


Figure 10. Map of glacial lakes in Shyok catchment.

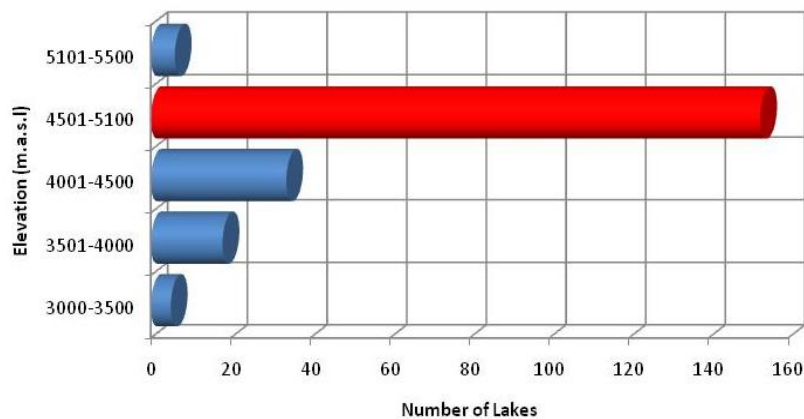


Figure 11. Altitudinal distribution of glacial lakes in Shyok catchment

Table 3. Distribution of glacial lakes in elevation zones in Shyok catchment.

Elevation Zones	Number of Lakes	% age
3000–3500	05	2.31
3501–4000	18	8.33
4001–4500	34	15.74
4501–5100	153	70.83
5101–5500	6	2.77

Identified Glacial Lakes in Astor Basin

In total Astor catchment has 124 glacial lakes covering an area of 5.414 km². The size of glacial lakes in Astor ranges from 0.004 to 0.499 km² with an average size of 0.043 km² lies between altitudes 3083–4752 m.a.s.l. (Figure 12). There are 61 major lakes in this area which covers an area of 4.646 km². The distribution of lakes in various elevation zones is given in Table 4. The majority of lakes (about 65%) are within the elevation zone of 4,001–4,500 m.a.s.l about 4%, 13%, and 18% of

lakes are within the elevation zones of 3,000–3,500 m.a.s.l, 3,501–4,000 m.a.s.l and 4,501–5,100 m.a.s.l respectively as shown in Figure 13.

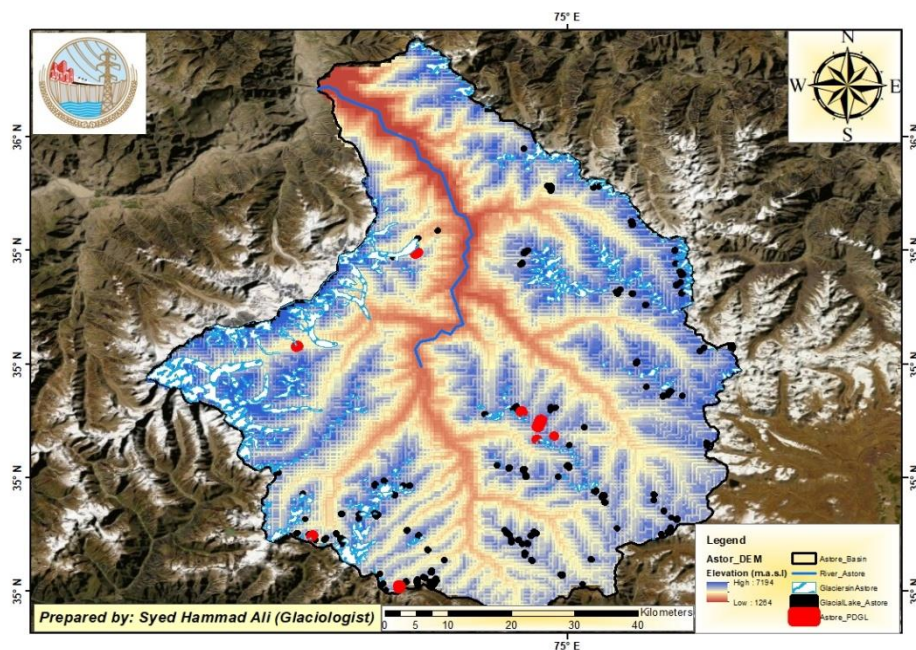


Figure 12. Map of glacial lakes in Astor catchment.

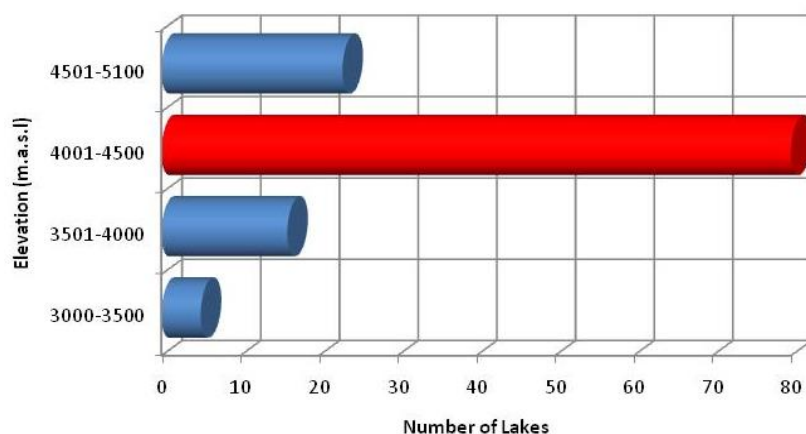


Figure 13. Altitudinal distribution of glacial lakes in Astor catchment.

Table 4. Distribution of glacial lakes in elevation zones in Astor catchment.

Elevation Zones	Number of Lakes	% age
3000–3500	05	4.03
3501–4000	16	12.90
4001–4500	80	64.52
4501–5100	23	18.55

The majority of lakes mapped were other bedrock dammed lakes 48 (39%). This inventory includes all lakes in surrounding of glacier or in the landforms. Out of 124 glacial lakes 9 glacial lakes (Figure 12) were identified as critical (potentially hazardous) based on criteria mentioned above. These lakes are found in the elevation range from 3400–4500m.a.s.l.

CONCLUSION

Followings are the 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 potentially dangerous lakes
- Numerical simulation of outburst flood and downstream vulnerability assessment

Considerations about catastrophe risk, in general, and GLOF risk, specifically, must be incorporated into national and regional development strategies, regulations, and initiatives, encompassing 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;

The formation of a GLOF Risk Reduction Fund for research, raising awareness, and the planning and implementation of mitigation and adaptation measures. The development of suitable mechanisms for the installation of early-warning systems.

These initiatives must be included into larger initiatives involving national development, disaster risk reduction, and adaptive capacity.

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