# Mapping and Assessing Glacial Lakes in Pakistan: Risk Insights from NDWI

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**Abstract**

Water is essential for life, but it also brings serious risks, especially through water-related disasters. Over the past two decades, about 74% of natural disasters have been water-related, affecting millions worldwide. Glaciers are vital sources of freshwater for drinking, farming, industry, and hydropower. However, melting glaciers accelerated by climate change are forming unstable glacial lakes that can burst and cause Glacier Lake Outburst Floods (GLOFs), posing serious threats to downstream communities. This study focuses on five major river catchments in northern Pakistan: Hunza, Gilgit, Shyok, Astore, and Chitral. These areas have extensive glaciation and important hydropower infrastructure, making them especially vulnerable to GLOFs. Using satellite images from 2015 to 2020, we applied the Normalized Difference Water Index (NDWI) a technique that highlights water bodies using satellite data to map and monitor glacial lakes. An automated method helped identify around 1,500 glacial lakes, covering a total area of 62.25 km². Out of these, 36 lakes were classified as potentially hazardous. Most lakes (82%) are small, under 0.05 km², and lie at elevations between 3,400 and 5,100 meters, with the highest concentration (43%) between 4,000 and 4,500 meters. The study did not include en-glacial or sub-glacial lakes, as they require ground-based tools/equipment to detect. This research offers valuable baseline data for understanding glacial lake hazards in Pakistan. It emphasizes the need to include GLOF risk in national and regional planning and supports future efforts in hazard modeling and disaster risk reduction strategies.

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

## 1. Introduction

Pakistan's Rivers are vital for agriculture, water supply, and hydropower; rely heavily on meltwater from glaciers in the Hindu Kush, Karakoram, and Himalayas (HKKH). Climate change has accelerated glacier retreat in these ranges, raising concerns about long-term water availability. However, glacier retreat is widely studied, the impacts of glacier advancements such as surges or forward movement remain underexplored. These events can form or expand glacial lakes, increasing the risk of Glacial Lake Outburst Floods (GLOFs), which pose serious threats to downstream communities and infrastructure. Recent GLOF incidents have highlighted the growing frequency and severity of such disasters in northern Pakistan. The growing frequency of hydrological hazards in Pakistan, particularly GLOFs and urban floods, underscores the need for integrated risk assessment methods. Studies utilizing HEC-RAS and AHP-based geospatial techniques provide valuable frameworks for assessing downstream flood vulnerability [16]. Climate-induced changes in land use and land cover significantly alter hydrological regimes and may influence glacial lake dynamics over time [17]. Multi-temporal satellite analyses have shown urban sprawl and vegetation loss, which can exacerbate flood risk in glaciated catchments. Modeling studies in the Upper Indus Basin (UIB) reveal complex interactions between water demand, climate variability, and glacial meltwater inputs, which are critical for managing downstream reservoirs and hydropower infrastructure [21]. Despite increasing occurrence of GLOF events, there is limited understanding of the spatial distribution, characteristics, and hazard potential of glacial lakes associated with surging glaciers. This study aims to fill this research gap by mapping and assessing glacial lakes in high-risk catchments using satellite-based indices. It focuses on identifying potentially hazardous lakes and evaluating their spatial patterns to support early warning systems and risk-informed planning in Pakistan's glaciated regions.

### *1.1. History of GLOFs in Pakistan*

Glacial Lake Outburst Floods (GLOFs) have increasingly impacted northern Pakistan, particularly in high-altitude regions where glacier coverage is extensive. These events pose serious risks to downstream communities and infrastructure, causing destruction of homes, displacement of people, and damage to ecosystems. GLOFs are closely linked to climate change and rising temperatures, which accelerate glacial melt and increase the formation and expansion of glacial lakes. Pakistan has experienced several notable GLOF events throughout its history. One of the earliest recorded incidents occurred in 1929 in the Hunza Valley, where a moraine-dammed lake burst, unleashing a flood that caused widespread destruction. Another significant event took place in 1974 near the Shishper Glacier, also in Hunza, where an ice-dammed lake ruptured, damaging agricultural land and local settlements.

The Upper Indus Basin (UIB), the most heavily glaciated region in Pakistan, contains approximately 7,000 glaciers covering about 15,000 km$^2$. These glaciers play a critical role in sustaining the country's water supply. However, the region is highly vulnerable to glacier-related hazards, including GLOFs. Historically, Pakistan lacked a formal system for recording and categorizing disaster events. This changed in the past two decades with the development of more systematic disaster data collection (Table 1) [14] and classification methods.

Rising temperatures and the rapid melting of snow and ice significantly contribute to the increased frequency of GLOF events. The bursting of even small glacial lakes can trigger devastating floods. Recent GLOFs and debris flows have already impacted major infrastructure projects, including the Golen Gol and Dasu hydropower projects, resulting in severe financial and structural losses (WAPDA, 2018, 2019, 2020). These events highlight the urgent need for improved glacial lake monitoring, risk assessment, and early warning systems to mitigate future disasters in the face of climate-induced glacial instability.

### *1.2. Classification of Glacial Lakes*

In the Hindu Kush Himalaya (HKH) region, glacial lakes are diverse in their formation processes and structural characteristics. To support consistent hazard assessment and monitoring, the International Centre for Integrated Mountain Development (ICIMOD) [2] has proposed a standardized classification system. This system groups glacial lakes into four major classes based on the type of dam that impounds the lake, represented by capital letters, and further divides them into seven sub-classes according to the lake formation process, denoted by lowercase letters.

The four primary dam-type classes are:

**Moraine-dammed lakes (M) –** These are the most common and are formed when meltwater is impounded by unconsolidated glacial debris (moraines).

End moraine-dammed lakes (M(e)): Lake dammed by end (terminal) moraines. Usually touches the walls of the side moraines, but the water is held back by the end moraine (dam), lake usually, but not necessarily, in contact with the glacier, and may have glacier ice at the lake bottom.

Lateral moraine-dammed lakes (M(l)) are lakes that have been dammed by lateral moraines (in the tributary valley, trunk valley, between the lateral moraine and the valley wall, or at the intersection of two moraines). The lake is held back by the outside wall of a lateral moraine, or away from the ancient glacier path.

Other lakes with moraine dams (M(o)): Other moraines block the lake (which contains kettle lakes and thermokarst lakes).

**Ice-dammed lakes (I) –** These occur when a glacier or ice mass obstructs a valley, trapping meltwater upstream.

Supraglacial lakes (I(s)): Supraglacial lakes form within the ice mass distant from the moraine and range in size from 50 to 100 meters. These lakes can form anywhere along the glacier, although their total length is less than half the diameter of the Valley glacier. Supraglacial lakes are distinguished by a tendency to shift, merge, and drain. The confluence of lakes expands the lake area and stores a large volume of water with a high potential energy. The likelihood of a glacier lake to merge and expand determines the hazard level of the GLOF.

Dammed by tributary valley glacier (I(v)): A lake dammed by glacier ice that lacks lateral moraines. These lakes can be found between a glacier's border and the valley wall.

**Bedrock-dammed lakes (B) –** Lakes formed behind exposed bedrock acting as a natural dam.

Cirque lakes (B(c)): Cirque Lake is a small pond occupying a cirque. Cirque lakes occur in practically every glaciated mountain range. Numerous examples of cirque lakes are found in the Cordilleran chains of North America.

Other glacial erosion lakes (B(o)): These are bodies of water that fill depressions created by glacial erosion. These are frequently found on the mid-slope of slopes, but not always in a cirque.

**Other glacial lakes (O)-** Lakes developed in a glaciated valley and fed by glacial, snow, and permafrost melt, but dammed by material that was not directly involved in the glacial process, such as debris flow, alluvial, or landslides.

**Sub-glacial lakes (S):** A subglacial lake is one that exists beneath a glacier, usually an ice cap or ice sheet. Subglacial lakes originate at the interface of ice and underlying bedrock, where gravitational pressure reduces the pressure melting point of ice. Over time, the overlying ice melts at a pace of a few millimeters each year. Meltwater moves from areas with high to low hydraulic pressure beneath the ice and pools, forming a volume of liquid water that can be isolated from the outside world for millions of years.

**En-glacial Lakes (E):** The heat from eruptions would have melted massive amounts of ice to form englacial lakes. These are the bodies of water that form within glaciers like liquid bubbles in a half-frozen ice cube.

This classification framework (illustrated in Figure 1) helps researchers and decision-makers evaluate glacial lake stability, identify potential Glacial Lake Outburst Flood (GLOF) threats, and prioritize lakes for monitoring and risk mitigation in the fragile HKH region.

**Table 1.** Historic GLOFs Events in UIB.

| Year | Month | Glacier | Basin | Causes |
|---|---|---|---|---|
| 1929 | Not Known | Chung Khumdan | Shyok | Rains |
| 1932 | Not Known | Chung Khumdan | Shyok | Rains |
| 1973 | Not Known | Batura | Hunza | |
| 1974 | Not Known | Batura | Hunza | |
| 1977 | Not Known | Balt Bare | Hunza | Rains & Heat Waves |

| | | | | |
|---|---|---|---|---|
| 1978 | Not Known | Brep, Chitral | Chitral | -- |
| 1978 | September | Darkot/Barados | Gilgit | |
| 1992 | August | Yarkhoon | Chitral | Rains and Cloud Burst |
| 1999 | August | Khalti/Gupis | Gilgit | Monsoon Rainfall |
| 2000 | June | Shimshal | Hunza | High Temperature |
| 2000 | July | Kand/Hushey | Indus | Monsoon Rainfall |
| 2003 | July | Yarkhoon | Chitral | Rains & Heat Waves |
| 2005 | July | Brep | Chitral | |
| 2007 | April | Ghulkin | Hunza | Western Disturbance |
| 2007 | August | Terich | Chitral | Rainfall |
| 2007 | July | Sonoghor | Chitral | Rainfall |
| 2008 | January | Passu | Hunza | Western Disturbance |
| 2008 | April | Ghulkin | Hunza | Western Disturbance |
| 2008 | May | Ghulkin | Hunza | Persistent Rainfall |
| 2008 | May | Ghulkin | Hunza | Persistent Rainfall |
| 2008 | June | Ghulkin | Hunza | Heat Wave |
| 2009 | March | Ghulkin | Hunza | South Westerly |
| 2010 | June | Booni | Chitral | Monsoon |
| 2010 | July | Bindo Gol | Chitral | Rainfall |
| 2013 | July | Reshun | Chitral | Rainfall |
| 2015 | July | Khorow | Braldu,Shigar | Rainfall & Subglacial Lake Outburst |
| 2015 | July to August | Ganche | Skardu | Rainfall |
| 2015 | July to August | Bagrot | Gilgit | Rainfall, Glacier melt |
| 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 |
| 2017 | May to June | Khurdopin | Hunza | Surging of Glacier |
| 2019 | July | Dook Pal | Chitral | High Temperature & Snowmelt |
| 2020 | July | Dook Pal | Chitral | High Temperature & Snowmelt |
| 2021 | May | Hassanabd / Shisper | Hunza | High Temperature & Surgingg |
| 2022 | July | Hassanabd / Shisper | Hunza | High Temperature & Surgingg |
| 2022 | July | Laspur valley | KPK | High Temperature |
| 2023 | July | Yarkhoon | Chitral | High Temp. Rainfall, Glacier melt |


**Figure 1.** Illustration of Different types of glacial lakes (Source: ICIMOD).

## 2. Study Areas

### *2.1. Chitral Catchment*

Chitral is located in the Khyber Pakhtunkhwa province of Pakistan, divided into Lower and Upper Chitral districts. Nestled in the Hindukush Mountains in the northwest, it shares borders with Gilgit-Baltistan to the east, Swat valley to the southeast, China and Afghanistan's Wakhan Corridor to the north, and Nuristan and Kunar provinces of Afghanistan to the west. The district is surrounded by Upper Dir to the south. Chitral is renowned for its rugged mountains, lush valleys, vast meadows, and numerous glaciers. The region includes about 35 sub-valleys, with notable ones such as Kalash, Garam Chashma, Shishi Koh, Mastuj, Laspur, Yarkhun, Tor Khow, and Mor Khow. The towering Tirich Mir, at 25,263 feet, is the highest peak in the Hindukush range, located 36 miles northeast of Chitral. The region's peaks exceed 4,000 feet, with over 40 peaks reaching altitudes of 20,000 feet. Chitral itself sits at an elevation of 4,900 feet, covering 14,850 square kilometers, with an elevation range between 1,071 to 7,603 meters above sea level. The area is home to around 1,600 glaciers, spanning 2,300 square kilometers of the catchment (Figure 2).

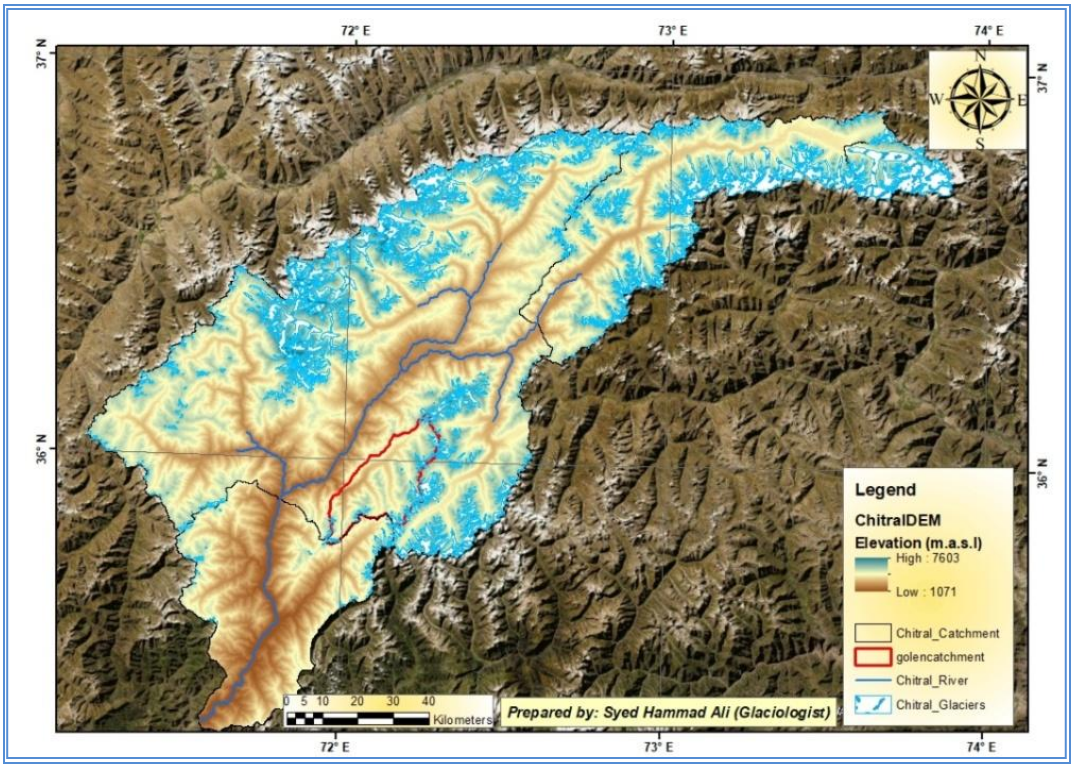


**Figure 2.** Location Map Chitral Catchment

### *2.2. Hunza Catchment*

The Hunza River basin has a drainage area of 13,713 km2 (Figure 3). Geographically, the basin runs from 36.04°N, 74.05°E to 37.07°N, 75.78°E in Pakistan's high-altitude central Karakoram area, with an average catchment elevation of 4,631 m. The elevation ranges from 1,425 and 7,736 meters above sea level. There are 1,384 glaciers in the watershed, covering roughly 2,754 $km^2$ of catchment area, with 2,344 $km^2$ of pure glacier and 410 km2 of debris cover. The elevation of a clean glacier spans from 2,723 to 7,736 meters above sea level, while a debris-covered glacier runs from 2,409 to 5,297 meters above sea level. The entire ice reserves in the Hunza River Basin are 310.61 $km^3$ [2].

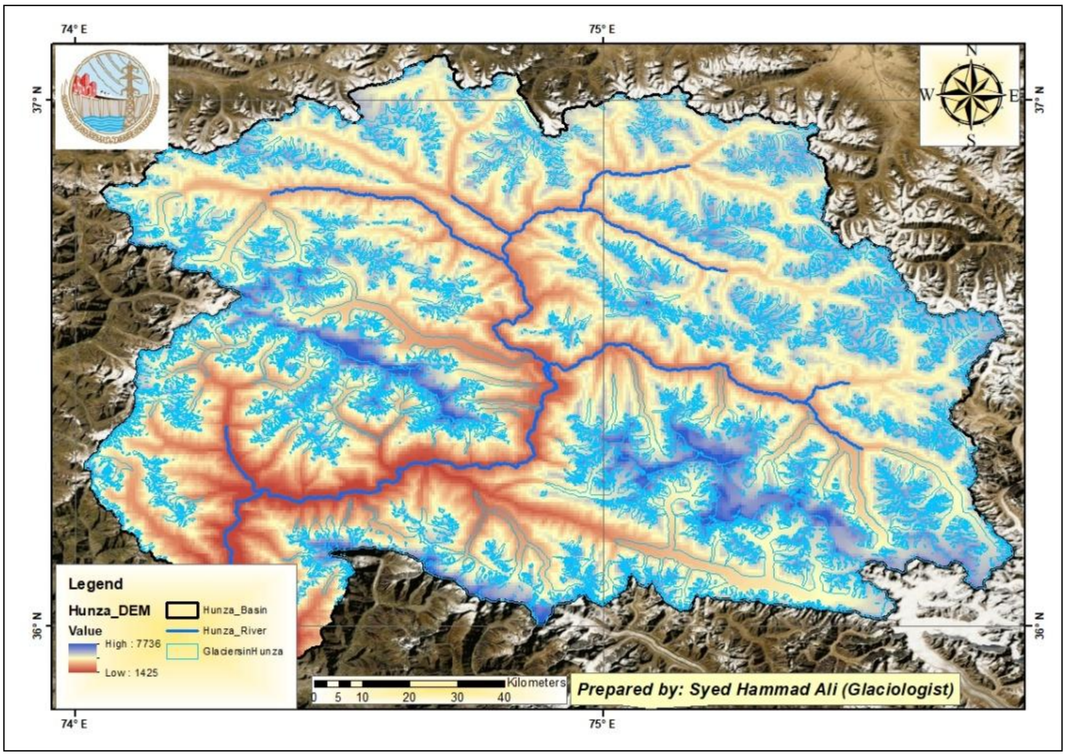


**Figure 3.** Location Map Hunza Catchment

*2.3. Gilgit Catchment*

The Gilgit River basin geographically, extends from 35.80 °N, 72.53 °E to 36.91 °N, 74.70 °E. The elevation ranges from 1,271-7,678 (m.a.s.l.), a sub-catchment of the Upper Indus Basin, located in the Hindu Kush and Karakoram region (Figure 4). Snow and glacier melt water originating from two different ranges, Hindu Kush and Karakoram feeds the Gilgit River basin. The Gilgit River originates in the Hindu Kush region, but the Karakoram glaciers also contribute significantly to its flow at the eastern boundary of the basin. The total numbers of glaciers in basin are approximately 968. Approximately 938 $km^2$ of the watershed area is glaciated, with 857 $km^2$ of pristine glacier and 81 $km^2$. of debris cover. The elevation of a clean glacier spans from 2,840 to 7,678 meters above sea level, while a debris-covered glacier runs from 2,703 to 4,925 meters above sea level. The total ice reserves in the Gilgit River Basin are 71.32 $km^3$ [2].

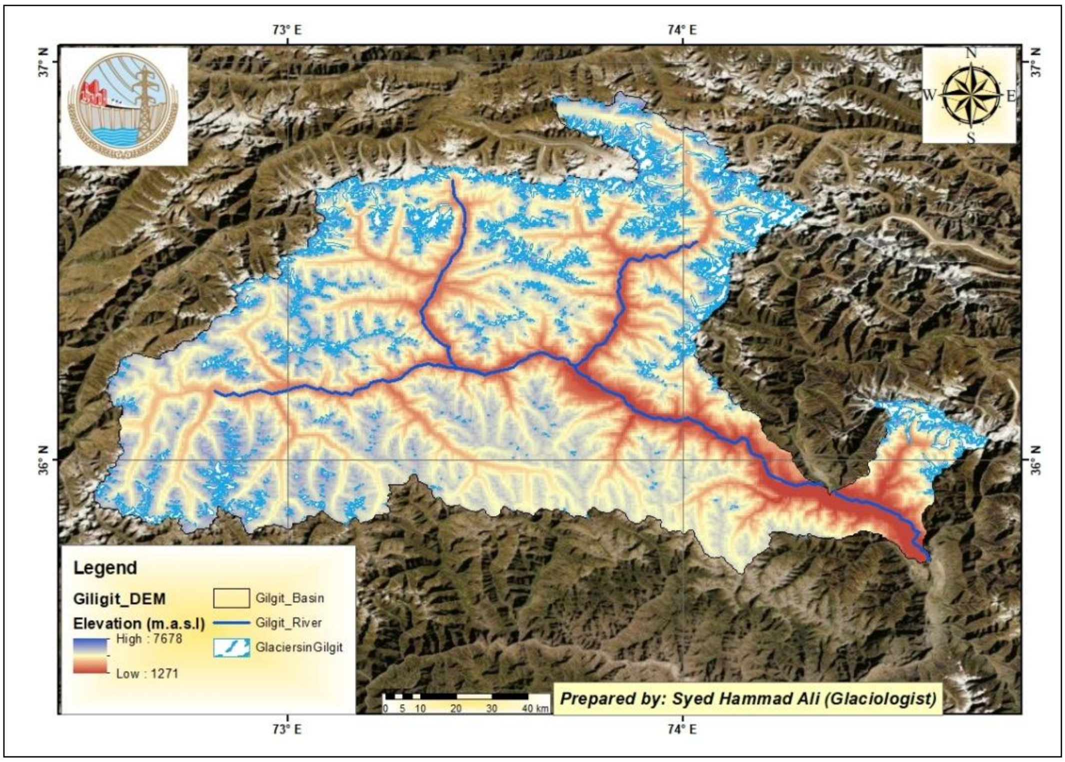


**Figure 4.** Location Map Gilgit Catchment

*2.4. Shyok Catchment*

The Shyok River is a major tributary of the Indus River in northern Pakistan. This river originates in the Rimo Glaciers and a portion of the Siachen Glaciers before flowing through the Kashmir region (Ladakh) and entering northern Pakistan at the Ganche District. The Shyok River is supplied by three major tributaries: the Nubra (in Kashmir), Saltoro, and Hushe Rivers. It has a watershed of 33,429 km2 and reaches into China. The basin extends geographically from 33.60°N, 75.96°E to 35.68°N, 79.59°E in Pakistan's high-altitude central Karakoram region (Figure 5). The elevation ranges from 2,288 m to 7,540 m above sea level. The total number of glaciers in the watershed is around 3,357. Approximately 5,938 km2 of the catchment region is glaciated, with 5,549 km2 of pristine glacier and 372 km2 of debris cover. The elevation of a clean glacier spans from 3,646 to 7,678 meters above sea level, whereas that of a debris-covered glacier ranges from 3,231 to 5,666 meters. The entire ice reserves in the Shyok River Basin are 982 km3 [2].

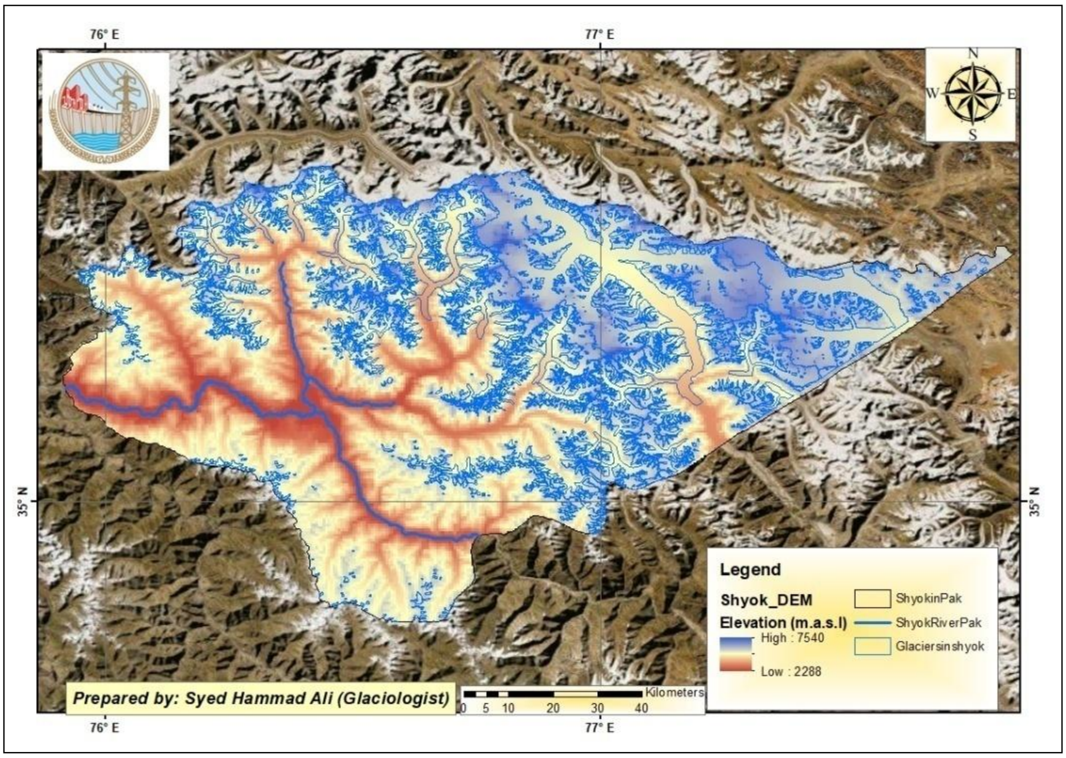


**Figure 5.** Location Map Shyok Catchment

## *2.5. Astor Catchment*

Astor River basin has a drainage area of 3,988 km2. Geographically, the basin extends from 34.80°N, 74.46°E to 35.64°N, 75.24°E in the high-altitude central Karakoram area of Pakistan (Figure 6). The elevation ranges from 1,204 to 7,194 m.a.s.l. The total number of glaciers in the basin is roughly 372. Approximately 240 km2 of watershed area are glaciated, with 209 km2 of pristine glacier and 30 km2 of debris cover. The elevation of a clean glacier spans from 3,367 to 7,194 meters above sea level, whereas a debris-covered glacier runs from 2,991 to 5,031 meters above sea level. The total ice reserves in the Astor River Basin are 16.88 km3 [2].

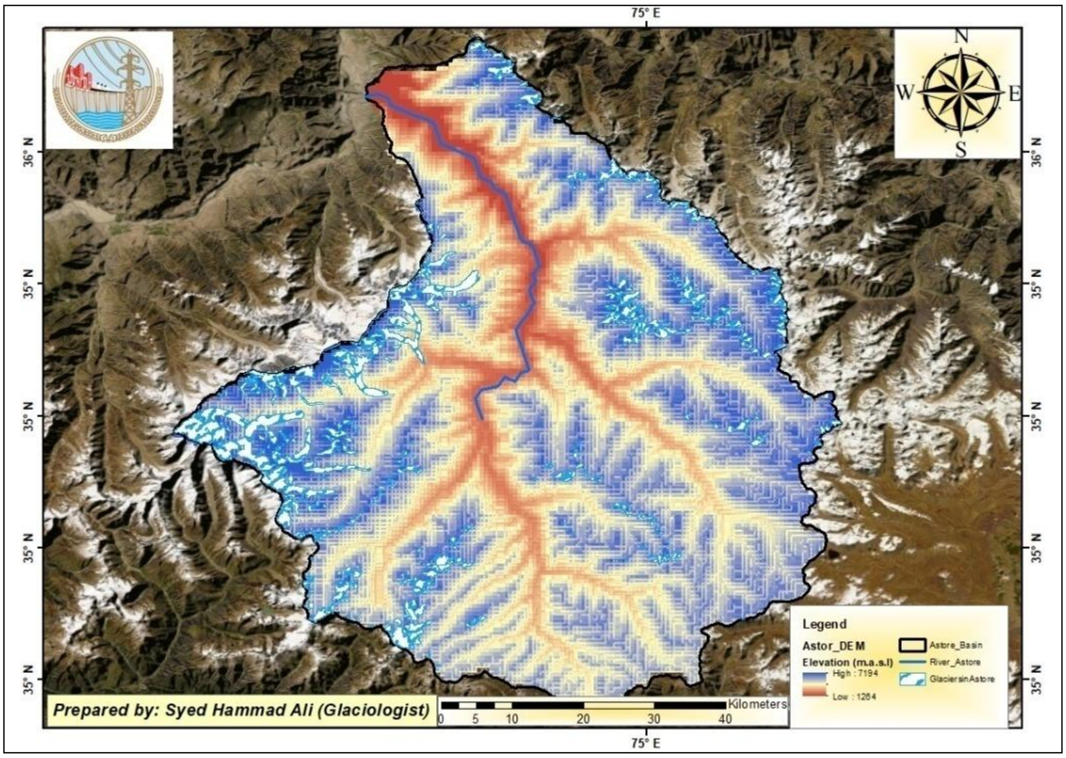


**Figure 6.** Location Map Astor Catchment

## 3. Delineating glacial lakes and detection of dangerous glacial lakes

The first step in assessing the risk posed by glacial lakes in the HKH region is to delineate these water bodies within different catchments. This process involves identifying and mapping the location, size, and characteristics of the glacial lakes, which are prone to sudden outburst floods (GLOFs). Once the lakes are delineated, the next task is to assess which of these lakes pose a potential risk, focusing on factors such as their size, proximity to communities, and the stability of their natural damming structures. Lakes that are large, rapidly expanding, or located in vulnerable areas are prioritized for further investigation. A detailed inventory of these glacial lakes was compiled in 2009/10, utilizing Landsat imagery from 2005/06 as the primary data source [2]. This inventory was based on a previous study from 2001, which relied on topographic maps [10], providing a comprehensive understanding of the lakes' distribution and potential hazards.

### 3.1. Methodology

A range of remote sensing methods have been developed for glacial lake identification, mapping, and inventory preparation [3, 4, 6, 8-10]. This study employs the Normalized Difference Water Index (NDWI) for automated glacial lake detection, supplemented by visual interpretation for accuracy (Figure 7). The NDWI is particularly useful for distinguishing water bodies from other land features by analyzing spectral reflectance differences across various wavelengths. The methodology also incorporates a digital elevation model (DEM) and Google Earth to improve visualization, especially for lakes covered by shadows or snow cover, which might be challenging to detect using NDWI alone [7].

The NDWI is calculated using a specific ratio of two bands, which enhances the spectral signal of water bodies by contrasting the reflectance between visible blue wavelengths and near-infrared wavelengths. In this approach, the visible blue wavelengths are sensitive to the high reflectance of water surfaces, making water bodies stand out. Meanwhile, near-infrared wavelengths show a strong reflectance from terrestrial vegetation and soil, while water bodies reflect very little in this range. This contrast results in positive NDWI values for water features, making them easy to identify. Conversely, land features such as soil and vegetation produce negative or zero NDWI values, which helps to eliminate noise and improve the accuracy of water body detection.

By utilizing NDWI alongside DEMs and satellite imagery, this method ensures effective and efficient mapping of glacial lakes, even in challenging conditions like snow cover and shadows.

The NDWI equation looks like

$$\mathrm{NDWI} = \frac{NIR(or\ Band\ 4) - BLUE\ (or\ Band1)}{NIR(or\ Band\ 4) +\ BLUE\ (or\ Band1)} \quad \text{(a)}$$

To map glacial lakes in Pakistan, NDWI ratio images were generated by performing arithmetic calculations using Band 4 and Band 1 of Landsat images. A threshold value for NDWI, ranging from -0.6 to -0.9, was applied to these ratio images to identify water bodies (glacial lakes) [4]. This automated method provides a quick way to detect glacial lakes and create inventories in various catchments of Pakistan. However, its application is limited, as atmospheric and physical conditions, such as frozen lakes, snow cover, cloud cover, or shadowed areas, can hinder accurate detection. In such cases, manual tracing is used to identify lakes.

NDWI is a proven method for water body extraction, its sensitivity can vary significantly based on regional conditions such as surface reflectance, topography, and seasonal variations in snow and ice cover. Therefore, the chosen thresholds should ideally be calibrated and validated against ground-truth data or high-resolution imagery specific to the glaciated regions of northern Pakistan. Without this validation, there remains uncertainty about the accuracy of lake delineation, particularly in distinguishing between shallow water, shadowed snow, or debris-covered ice. To address challenges posed by atmospheric interference (such as haze, cloud cover, and seasonal snow), the study employed multi-temporal Landsat composites, ensuring that only images with minimal cloud contamination were used. In regions where automatic classification misidentified features such as confusing shadowed terrain or debris fields for water manual corrections were made using visual inspection of false-color composites and topographic cues. For example, lakes adjacent to glacier tongues were cross-verified with Google Earth imagery and corrected manually to refine lake boundaries and eliminate false positives.

To ensure the accuracy of the mapped glacial lakes, the identified lakes were cross-checked by overlaying the Landsat images with previously available inventory datasets [1, 9, 10-13 & 15]. This process helped identify any missing lakes, which were added manually. This combination of automated and manual methods ensures comprehensive and accurate mapping of glacial lakes, overcoming the challenges posed by environmental factors. The process helps in creating a reliable inventory of glacial lakes, crucial for monitoring changes in these water bodies due to climate change and other factors.

In remote sensing, pixels in satellite images typically do not provide homogeneous reflectance, meaning each pixel often represents a mixture of different land features rather than a single object. This is particularly true unless the imaging is perfectly aligned to capture just one specific object. For accurate mapping of an object, such as a glacial lake, multiple pixels are needed to capture its full extent. Generally, at least four pixels are required to define the true boundary of an object on the ground.

In the case of Landsat images, each pixel represents an area of approximately 30 meters by 30 meters. Therefore, the smallest glacial lake that can be effectively mapped using these images must cover at least four pixels, which equates to an area of 0.0036 $km^2$. However, when mapping a glacial lake with only four pixels, the resulting boundary is often smooth, and the actual lake boundary tends to fall slightly within these pixels. As a result, to ensure consistency and accuracy, a threshold value of 0.003 $km^2$ is applied when mapping glacial lakes in the current inventory. This threshold accounts for the minimal size of lakes that can be detected and mapped reliably with Landsat imagery.

To identify critical or potentially hazardous glacial lakes, several key criteria are considered. These include the size of the lake and its rate of growth, as larger lakes with rapid expansion may pose a higher risk of outburst flooding. The position of the lake relative to moraines and associated glaciers is also important, as lakes located near unstable glacial features are more likely to experience dam failures. The characteristics of the surrounding area are crucial; for example, lakes in contact with hanging glaciers, which are prone to collapse, increase the risk of catastrophic events. The condition of the natural dam, including the extent of its crest and the presence of an ice core, is another factor, as ice-dam failure can trigger dangerous floods. Additionally, the physical conditions of the surrounding landscape, such as the potential for rockfalls, avalanches, and the presence of other lakes or moraines in tributary glaciers, are assessed to evaluate the overall hazard potential. These factors together help to characterized as potentially dangerous and require monitoring and risk mitigation efforts [6].

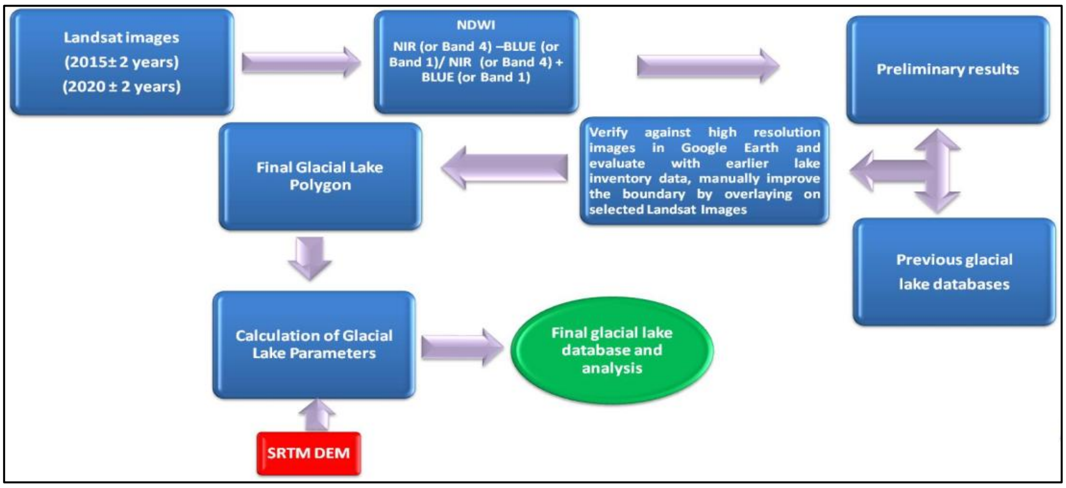


**Figure 7.** Methodology of delineating Glacial Lakes

## 4. Conclusion

### *4.1. Glacial Lakes in Chitral Catchment*

The Chitral catchment in Pakistan contains total of 301 glacial lakes (Figure 8), covering an area of 9.26 km². These lakes vary greatly in size, ranging from as small as 0.003 km² to as large as 2.048 km², with an average size of 0.031 km². The lakes are situated at elevations between 3,400 and 5,100 meters above sea level (m.a.s.l.), with the majority of lakes found between 4,000 and 4,500 m.a.s.l. These high-altitude lakes are located primarily in rugged, mountainous regions.

Out of the total, 65 lakes are classified as major lakes, covering 7.511 km² of the total area. The distribution of these lakes across different elevation zones is varied (Table 3): approximately 43% of the lakes lie in the 4,000 – 4,500 m.a.s.l. range, while 33% are found between 3,500 – 4,000 m.a.s.l., and 23% are located at higher elevations, between 4,500 – 5,100 m.a.s.l respectively as shown in Figure 9.

The majority of the lakes in Chitral are supraglacial lakes, numbering 110 (37% of the total), which are typically formed by the melting of glaciers. The inventory of these lakes includes all bodies of water located in close proximity to glaciers or within glacial landforms, offering a comprehensive understanding of the glacial lake distribution in the region.

**Table 2**. Number and various types of Glacial Lakes in Chitral Catchment.

| 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** | |

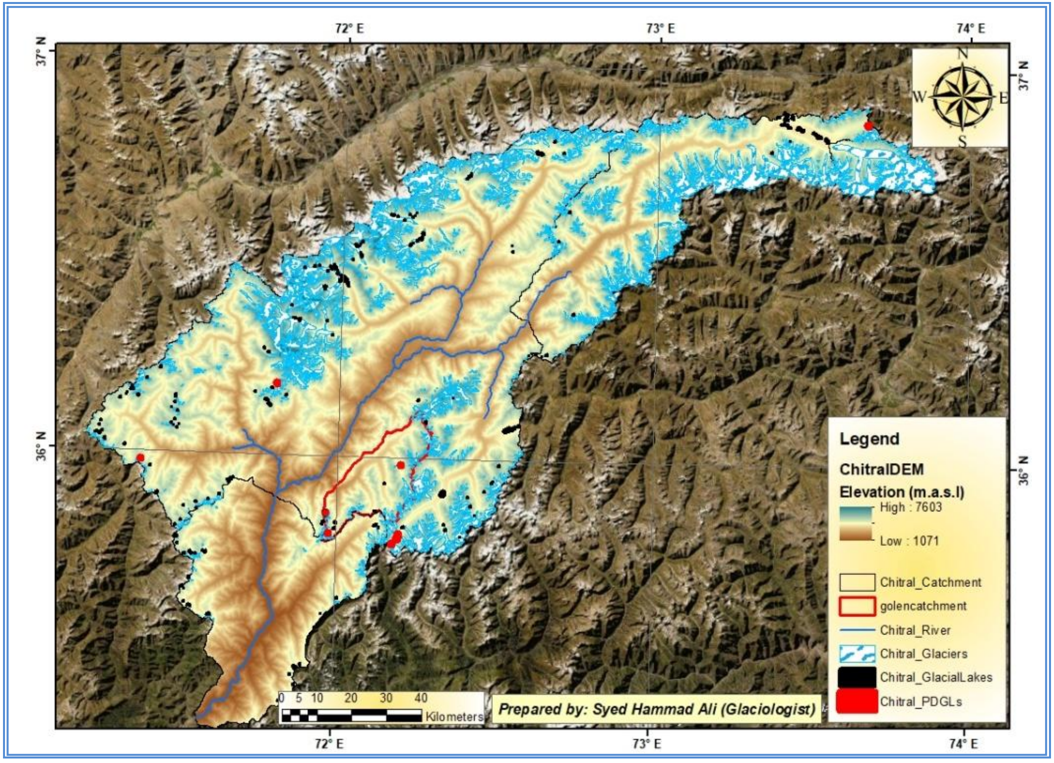


**Figure 8.** Map of Glacial Lakes in Chitral Catchment

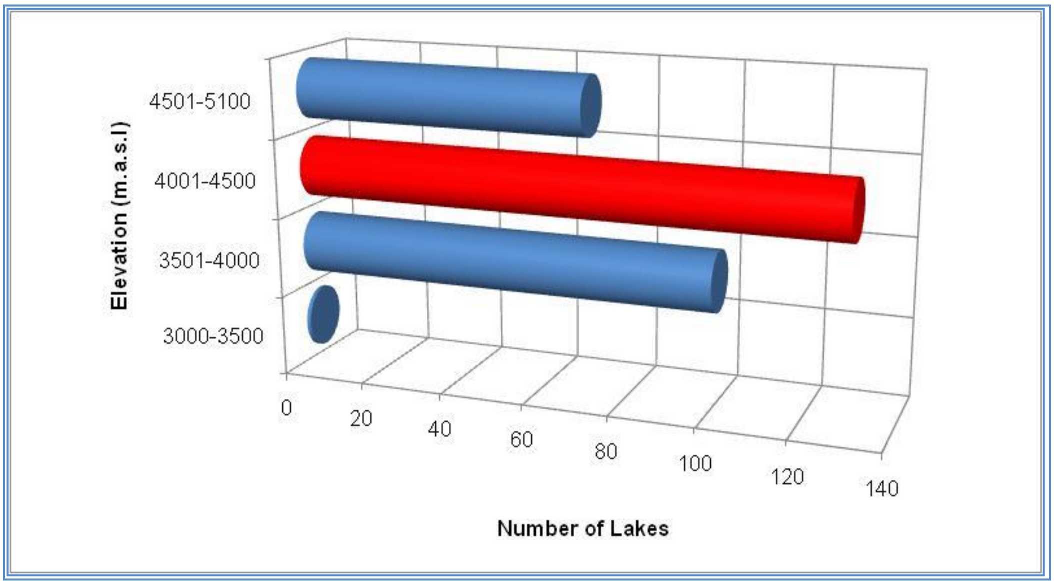


**Figure. 9**. Altitudinal Distribution of Glacial Lakes in Chitral Catchment

**Table 3.** Elevation wise Distribution 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 |

Out of 301 glacial lakes, 8 (Figure 8) were recognized as critical (possibly hazardous) using the criteria mentioned above. These lakes are situated at elevations ranging from 3700 to 4600 metres above sea level. Table 4 summarizes the details about these lakes.

**Table 4.** Potentially Hazardous Glacial Lakes in Chitral Catchment.

| Sr. No. | Latitude | Longitude | Elevation | Type | Area ($km^2$) |
|---|---|---|---|---|---|
| 1 | 36.182 | 71.799 | 4573 | M(e ) | 0.083 |
| 2 | 35.799 | 72.193 | 4134 | B(o) | 0.606 |
| 3 | 35.782 | 72.176 | 4187 | B(o) | 0.107 |
| 4 | 35.98 | 71.373 | 4605 | B(o) | 0.06 |
| 5 | 35.805 | 71.975 | 4183 | M(o) | 0.011 |
| 6 | 36.868 | 73.673 | 4361 | M(e ) | 0.174 |
| 7 | 35.982 | 72.199 | 3737 | M(e ) | 0.031 |
| 8 | 35.855 | 71.966 | 4511 | I(s) | 0.03 |

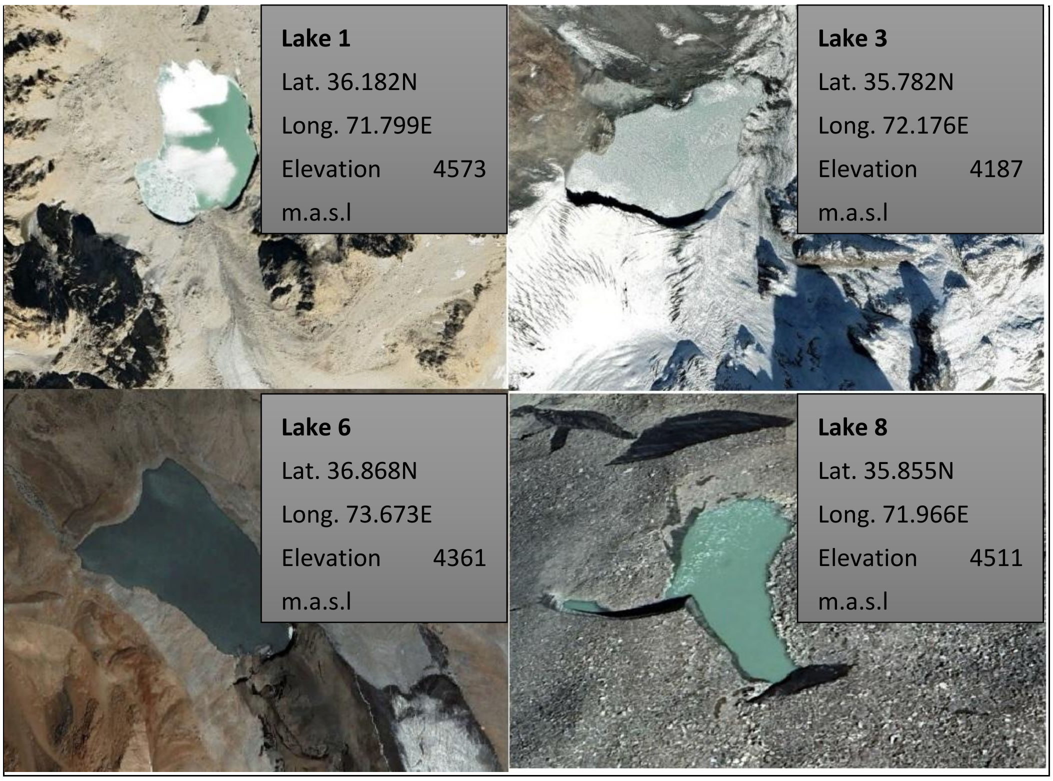


**Figure 4.** Google Earth Images of Potentially Hazardous Glacial Lakes in Chitral Catchment

### *4.2. Glacial Lakes in Hunza Catchment*

In total Hunza catchment has 142 glacial lakes (Figure 10) covering an area of 2.976 $km^2$. The size of glacial lakes in Hunza ranges from 0.003 to 0.279 $km^2$ with an average size of 0.021$km^2$ lies between altitudes 2524 – 5023 m.a.s.l.. There are 30 major lakes in this area which covers an area of 2 $km^2$. Table 2 shows how lakes are distributed throughout various elevation zones. Figure 11 shows that the majority of lakes (approximately 52%)

are within the elevation zone of 3,500 - 4,000 m.a.s.l., whereas 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. The bulk of the lakes identified were supraglacial lakes (114, 80%). Table 5 summarizes the quantity and distribution of several types of glacial lakes in the Hunza basin. This inventory contains all lakes that surround glaciers or are part of landforms.

**Table 5.** Number and Various Types of Glacial Lakes in Hunza Catchment.

| Types of Lake | Symbol | Nos. | % age |
|---|---|---|---|
| Other moraine-dammed lake | M(o) | 6 | 4 |
| End-moraine-dammed lake | M(e) | 1 | 1 |
| Lateral moraine-dammed lake | M(l) | 13 | 9 |
| Supra-glacial lake | I(s) | 114 | 80 |
| Other bedrock dammed lake | B(o) | 4 | 3 |
| Cirque lake | B(c) | 0 | 0 |
| Other glacial lake | O | 4 | 3 |
| Total | | **142** | |

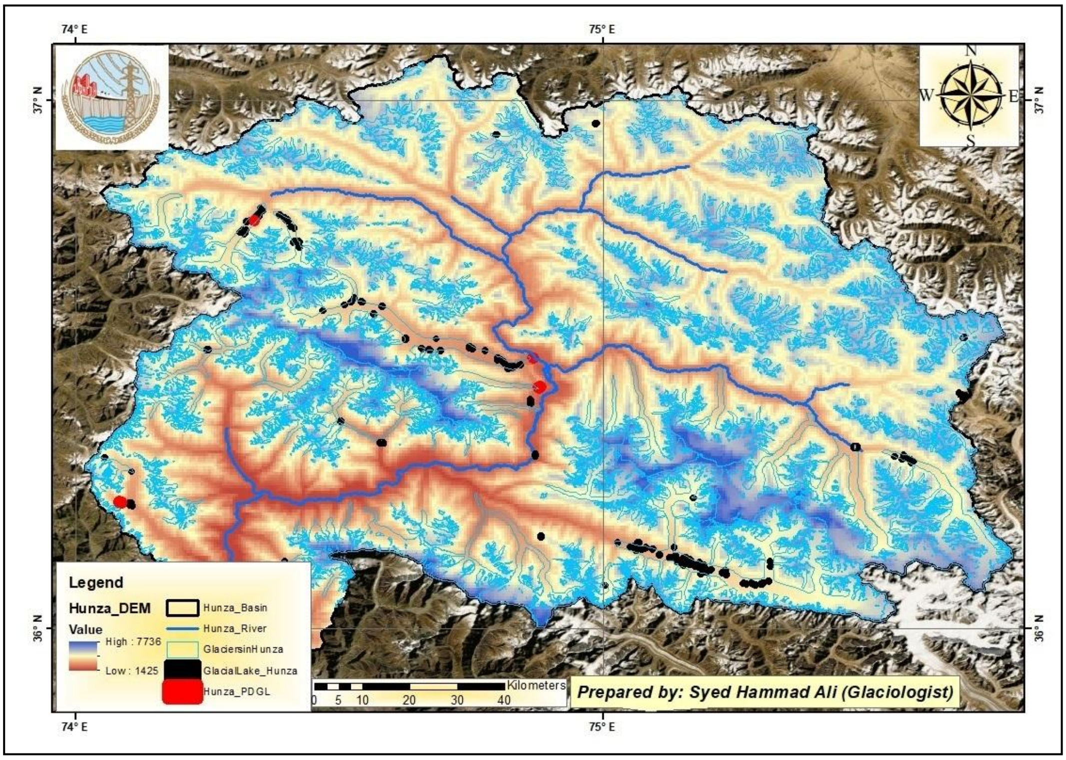


**Figure 10.** Map of Glacial Lakes in Hunza Catchment

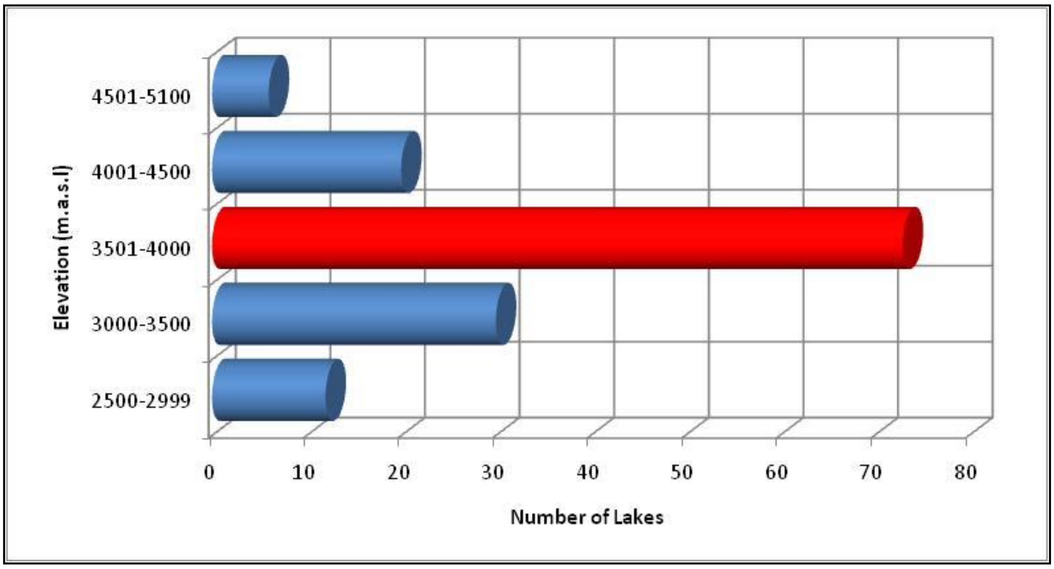


**Figure 11.** Altitudinal Distribution of Glacial Lakes in Hunza Catchment

**Table 6.** Elevation wise Distribution of Glacial Lakes 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 |

Out of 142 glacial lakes 4 glacial lakes (Figure 10) were identified as critical (potentially hazardous) based on criteria mentioned above. These lakes are found in the elevation range from 2500 – 3500m.a.s.l. The details of these lakes are summarized in Table 7.

**Table 7.** Potentially Hazardous Glacial Lakes in Hunza Catchment

| Lake No. | Latitude | Longitude | Elevation | Type | Area (km²) |
|---|---|---|---|---|---|
| 1 | 36.458 | 74.879 | 2543 | M(e ) | 0.145 |
| 2 | 36.513 | 74.867 | 2524 | B(o) | 0.039 |
| 3 | 36.774 | 74.338 | 3757 | I(s) | 0.02 |
| 4 | 36.239 | 74.083 | 3462 | I(s) | 0.022 |

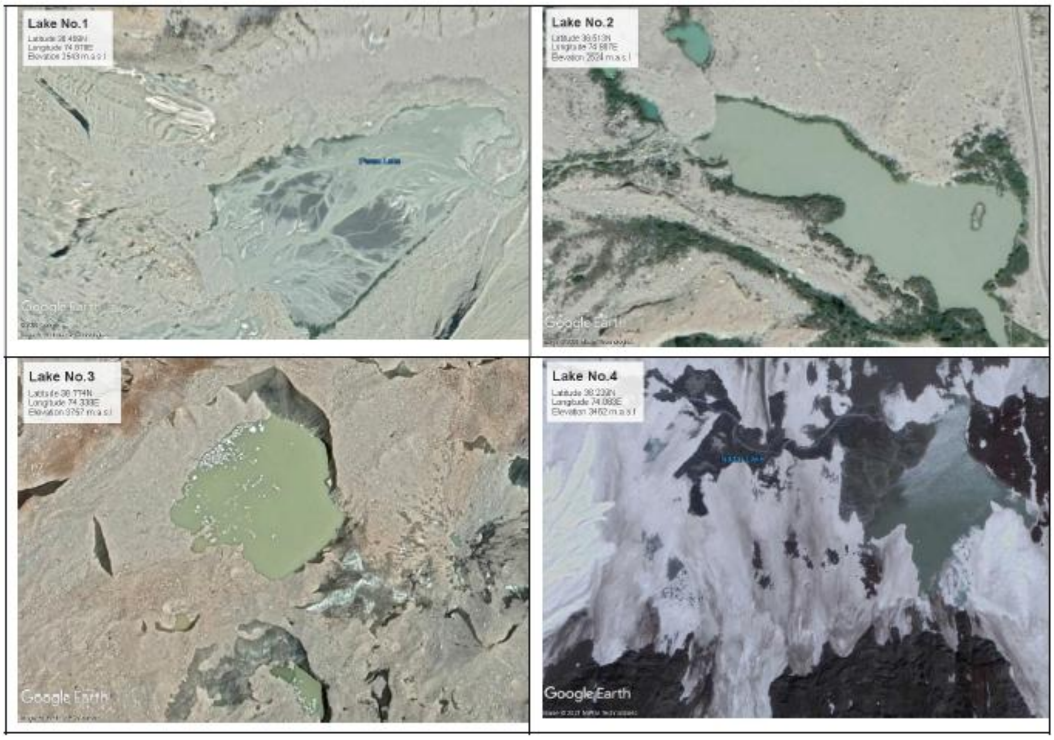


**Figure 12.** Google Earth Images of Potentially Hazardous Glacial Lakes in Hunza Catchment

### *4.3. Glacial Lakes in Gilgit Catchment*

The Gilgit catchment contains around 691 glacial lakes (Figure 13), spanning an area of 38.034 km2. The size of glacial lakes in Gilgit ranges from 0.003 to 2.734 km2, with an average of 0.055 km2 located between altitudes of 2203 and 5046 m.a.s.l. This area contains 347 large lakes and occupies 34.208 square kilometers.

Table 5 shows how lakes are distributed throughout various elevation zones. The majority of lakes (approximately 69%) are within the elevation zone of 4,001 - 4,500 m.a.s.l, whereas 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 14.

The bulk of lakes mapped were Other bedrock dammed lakes 448 (65%). Table 8 summarizes the quantity and distribution of several types of glacial lakes in the Gilgit basin. This inventory contains all lakes that surround glaciers or are part of landforms.

**Table 8.** Number and Various Types of Glacial Lakes in Gilgit Catchment

| Types of Lake | Symbol | Nos. | % age |
|---|---|---|---|
| Other moraine-dammed lake | M(o) | 138 | 19.97 |
| End-moraine-dammed lake | M(e) | 26 | 3.76 |
| Lateral moraine-dammed lake | M(l) | 03 | 0.43 |
| Supra-glacial lake | I(s) | 23 | 3.32 |
| Other bedrock dammed lake | B(o) | 448 | 64.83 |
| Cirque lake | B(c) | 33 | 4.77 |
| Other glacial lake | O | 20 | 2.89 |
| Total | | **691** | |

Out of 691 glacial lakes 9 glacial lakes (Figure 13) were identified as critical (potentially hazardous) based on criteria mentioned above. These lakes are found in the elevation range from 2700 – 4500m.a.s.l. The details of these lakes are summarized in Table 6.

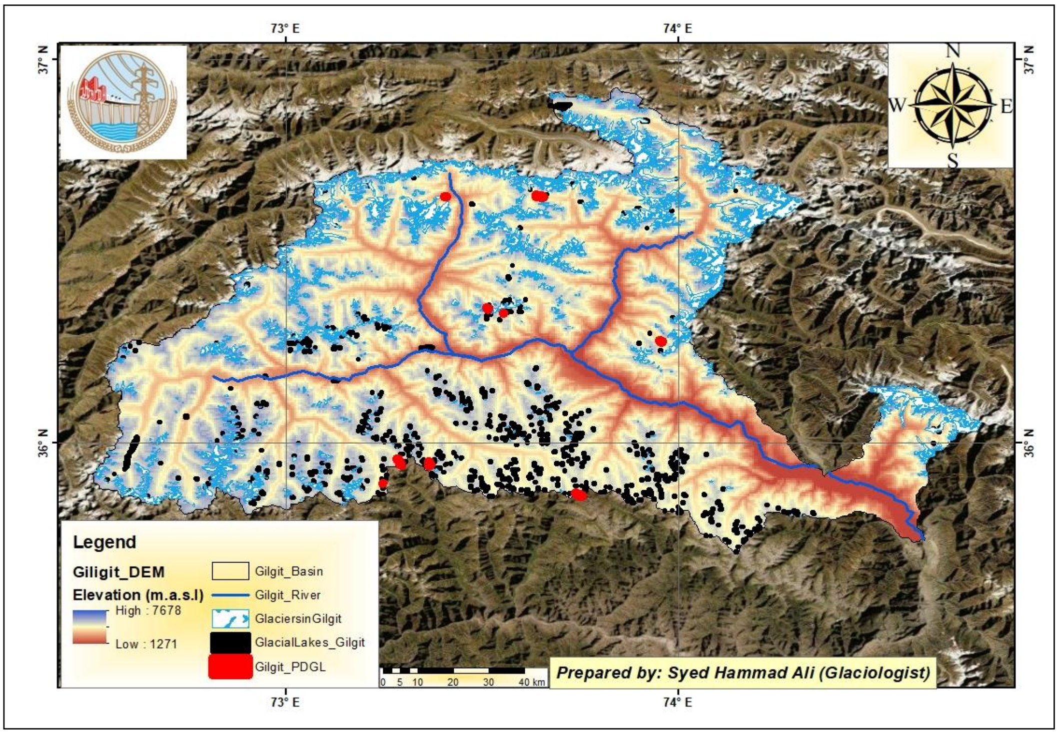


**Figure 13.** Map of Glacial Lakes in Gilgit Catchment

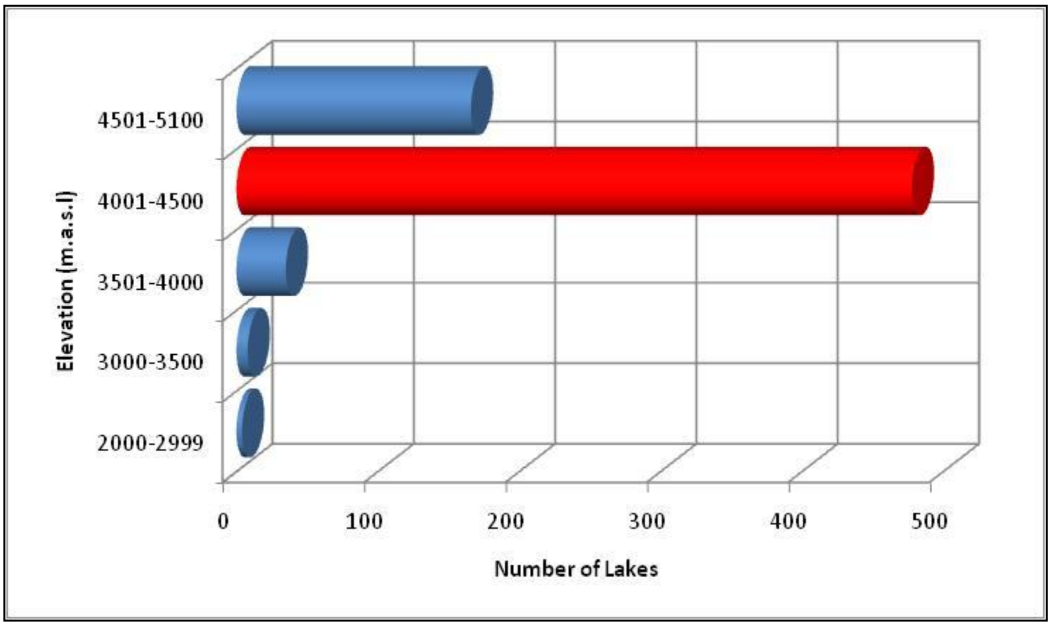


**Figure 14.** Altitudinal Distribution of Glacial Lakes in Gilgit Catchment

**Table 9.** Elevation wise Distribution of Glacial Lakes 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 |

**Table 10.** Potentially Hazardous Glacial Lakes in Gilgit Catchment

| Lake No. | Latitude | Longitude | Elevation | Type | Area ($km^2$) |
|---|---|---|---|---|---|
| 1 | 36.265 | 73.955 | 3706 | O | 0.323 |
| 2 | 36.351 | 73.513 | 4420 | M(o) | 0.208 |
| 3 | 35.865 | 73.745 | 4136 | M(e ) | 0.892 |
| 4 | 35.946 | 73.365 | 4162 | E(c ) | 0.697 |
| 5 | 36.645 | 73.646 | 3810 | M(o) | 1.134 |
| 6 | 36.643 | 73.406 | 2724 | M(e ) | 0.149 |
| 7 | 35.95 | 73.288 | 4223 | E(o) | 0.677 |
| 8 | 35.895 | 73.246 | 4350 | M(o) | 0.047 |
| 9 | 36.339 | 73.554 | 4417 | E(o) | 0.059 |

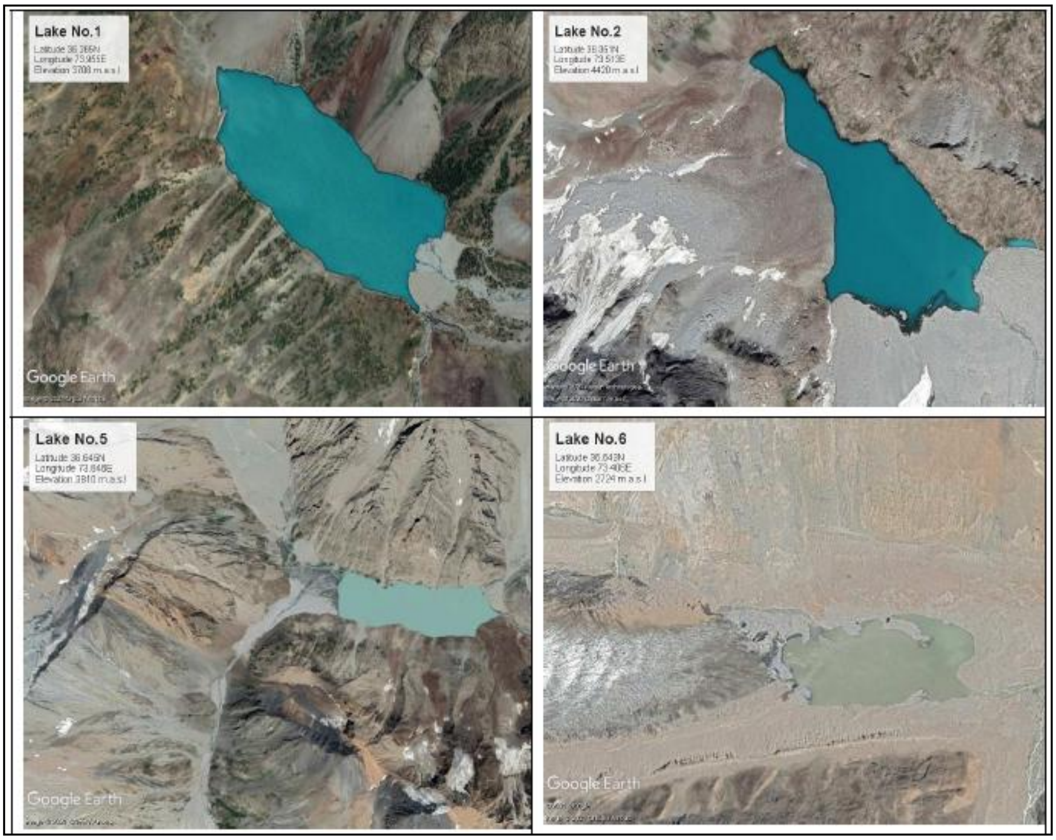


**Figure 15.** Google Earth Images of Potentially Hazardous Glacial Lakes in Gilgit Catchment

*4.4. Glacial Lakes in Shyok Catchment*

The Shyok catchment contains a total of 201 glacial lakes, spanning an area of 6.368 $km^2$. These lakes vary in size, ranging from 0.003 $km^2$ to 0.568 $km^2$, with an average size of 0.029 $km^2$. They are situated at elevations between 3,329 and 5,216 meters above sea level (Figure 17). Among these, 65 lakes are classified as major lakes, collectively covering an area of 4.993 $km^2$.

Table 8 shows how lakes are distributed throughout various elevation zones. The majority of lakes (approximately 71%) are within the elevation zone of 4,501 - 5,100 m.a.s.l, whereas 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 17.

The bulk of lakes mapped were supraglacial lakes (92, 43%). Table 11 summarizes the quantity and distribution of several types of glacial lakes in the Shyok basin. This list contains all lakes near the glacier or in the landforms.

**Table 11.** Numbers and Various Types of Glacial Lakes in Shyok Catchment

| Types of Lake | Symbol | Nos. | % age |
|---|---|---|---|
| Other moraine-dammed lake | M(o) | 60 | 27.77 |
| End-moraine-dammed lake | M(e) | 11 | 5.09 |
| Lateral moraine-dammed lake | M(l) | 18 | 8.33 |
| Supra-glacial lake | I(s) | 92 | 42.59 |
| Other bedrock dammed lake | B(o) | 23 | 10.64 |
| Cirque lake | B(c) | 03 | 1.388 |
| Other glacial lake | O | 01 | 0.46 |
| Dammed by tributary glacier lakes | I(v) | 08 | 3.70 |
| Total | | **216** | |

Out of 216 glacial lakes, six (Figure 16) were recognized as critical (potentially hazardous) using the criteria listed above. These lakes are found at elevations ranging from 4100 to 4800 meters above sea level. The specifics of these lakes are presented in Table 13.

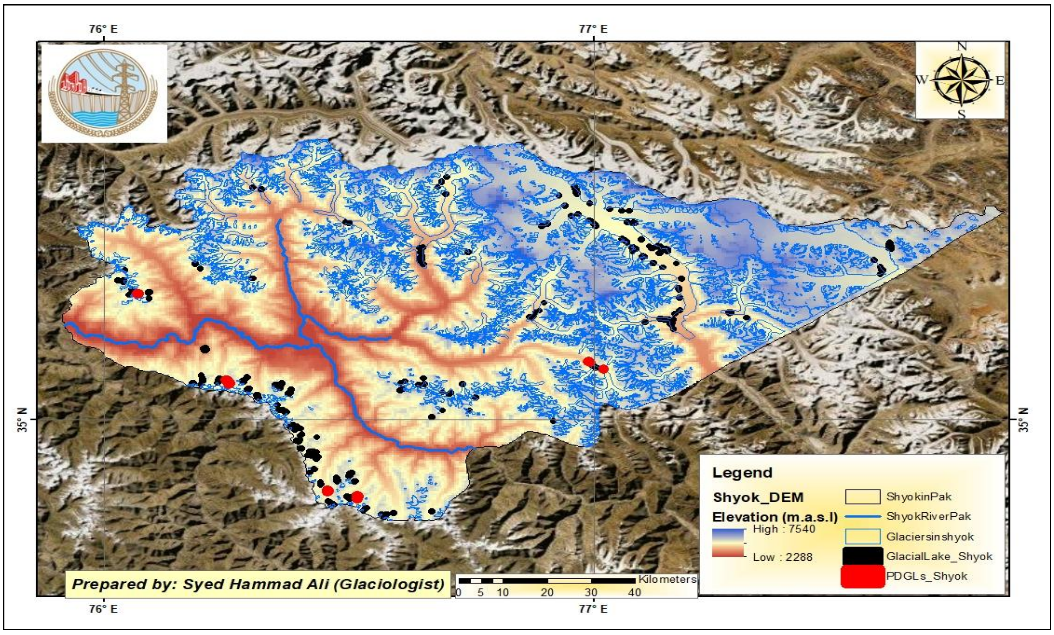


**Figure 16.** Map of Glacial Lakes in Shyok Catchment

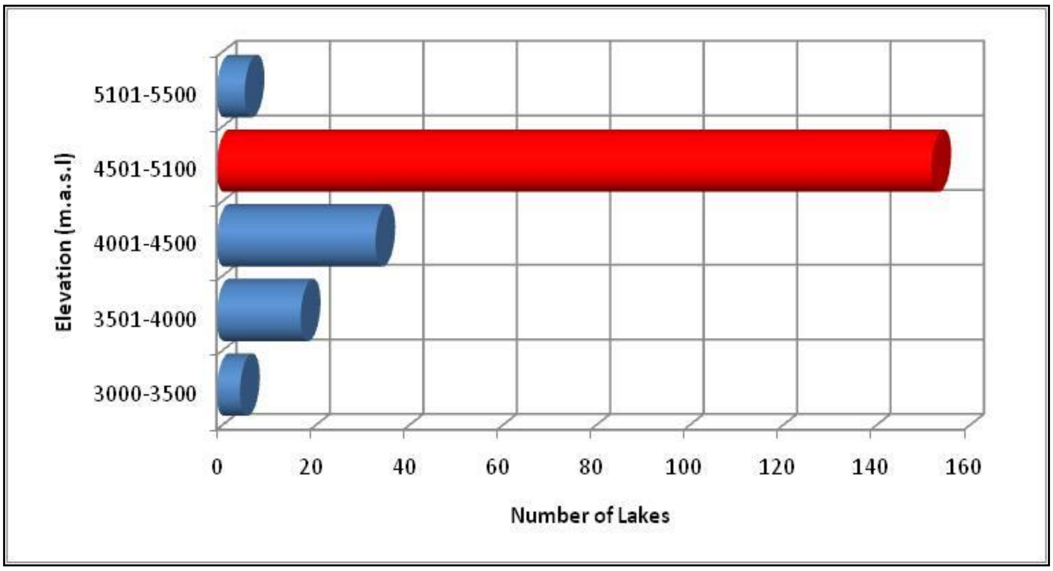


**Figure 17.** Altitudinal Distribution of Glacial Lakes in Shyok Catchment

**Table 12.** Elevation wise Distribution of Glacial Lakes 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 |

**Table 13.** Potentially Hazardous Glacial Lakes in Shyok Catchment

| Lake No. | Latitude | Longitude | Elevation | Type | Area (km²) |
|---|---|---|---|---|---|
| 1 | 35.141 | 76.99 | 4164 | I(s) | 0.044 |
| 2 | 35.092 | 76.252 | 4533 | M(o) | 0.311 |
| 3 | 35.123 | 77.02 | 4443 | I(s) | 0.02 |
| 4 | 35.306 | 76.068 | 4808 | E(o) | 0.043 |
| 5 | 34.813 | 76.517 | 4765 | M(o) | 0.252 |
| 6 | 34.828 | 76.456 | 4642 | E(o) | 0.171 |

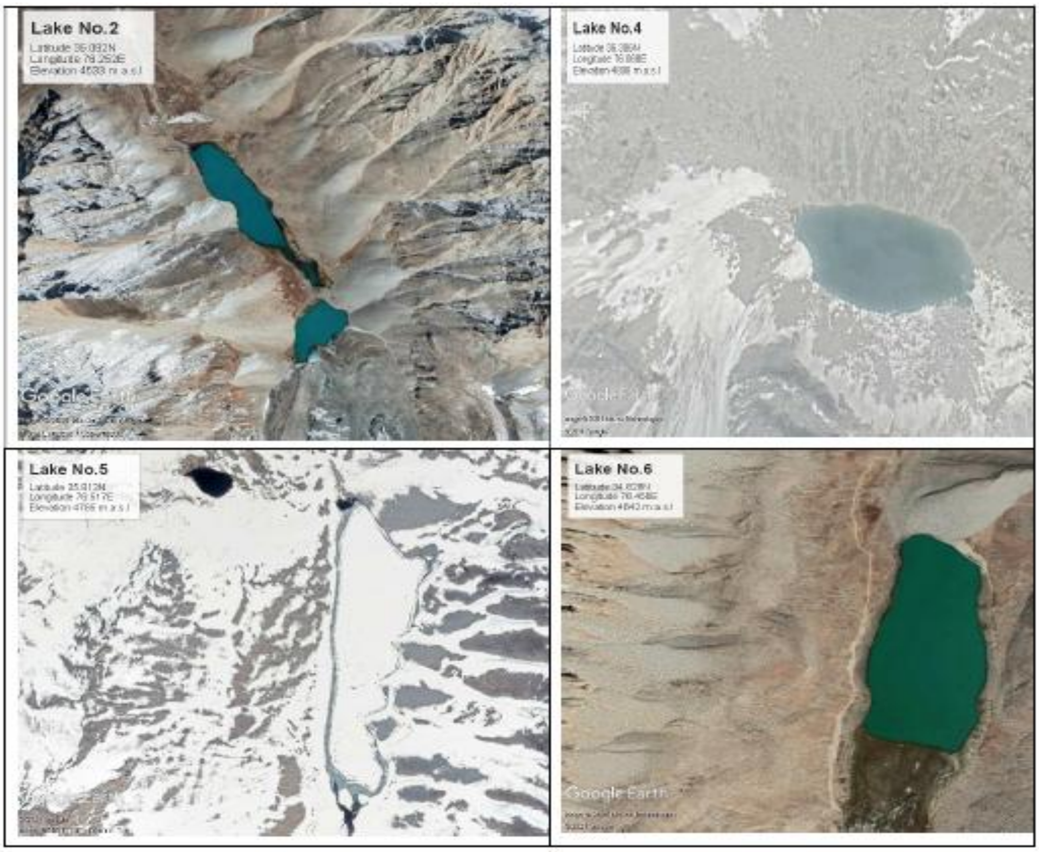


**Figure 18**. Google Earth Images of Potentially Hazardous Glacial Lakes in Shyok Catchment

### *4.5. Glacial Lakes in Astor Catchment*

Astore catchment has 124 glacial lakes (Figure 19) in total covering an area of 5.414 km². The size of glacial lakes in Gilgit ranges from 0.004 to 0.499 km² with an average size of 0.043km² lies between altitudes 3083 – 4752 m.a.s.l. 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 10. 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 20.

The majority of lakes mapped were other bedrock dammed lakes 48 (39%) the number and distribution of various types of glacial lakes in Gilgit catchment are summarized below in table 14. This inventory includes all lakes in surrounding of glacier or in the landforms.

Out of 124 glacial lakes 9 glacial lakes (Figure 16) 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. The details of these lakes are summarized in Table 12.

**Table 14.** Numbers and Various Types of Glacial Lakes in Astore Catchment

| Types of Lake | Symbol | Nos. | % age |
|---|---|---|---|
| Other moraine-dammed lake | M(o) | 37 | 29.84 |
| End-moraine-dammed lake | M(e) | 13 | 10.48 |
| Lateral moraine-dammed lake | M(l) | 01 | 0.81 |
| Supra-glacial lake | I(s) | 02 | 1.61 |
| Other bedrock dammed lake | B(o) | 48 | 38.71 |
| Cirque lake | B(c) | 21 | 16.94 |
| Other glacial lake | O | 2 | 1.61 |
| Total | | **124** | |

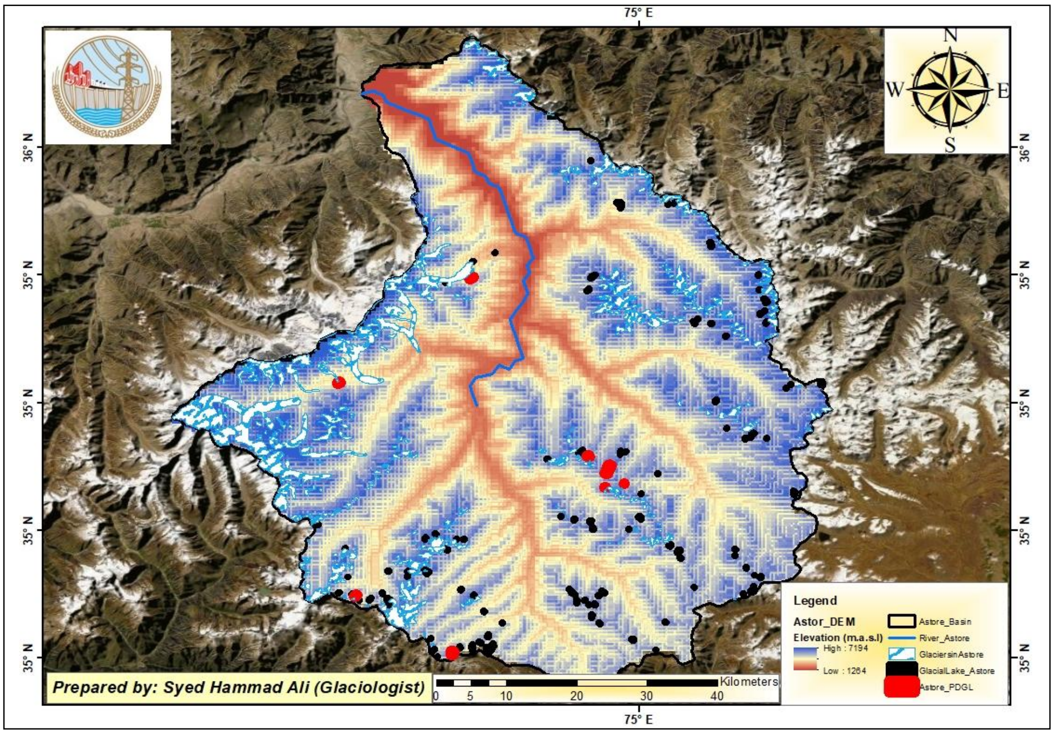


**Figure 19.** Map of Glacial Lakes in Astore Catchment

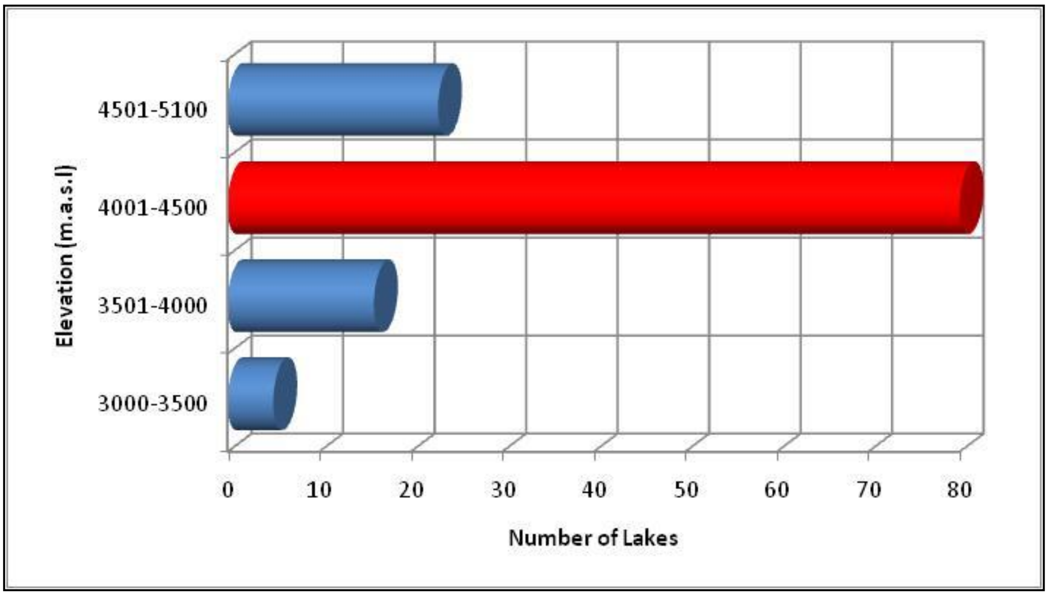


**Figure 20.** Altitudinal Distribution of Glacial Lakes in Astore Catchment

**Table 15.** Elevation wise Distribution of Glacial Lakes in Astore 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 |

**Table 16**. Potentially Hazardous Glacial Lakes in Astore Catchment

| Lake No. | Latitude | Longitude | Elevation | Type | Area (km²) |
|---|---|---|---|---|---|
| 1 | 35.082 | 74.961 | 4312 | E(c ) | 0.284 |
| 2 | 35.075 | 74.958 | 4412 | M(c ) | 0.094 |
| 3 | 35.097 | 74935 | 4185 | E(c ) | 0.087 |
| 4 | 35.33 | 74.785 | 3478 | E(o) | 0.188 |
| 5 | 35.193 | 74.616 | 3594 | M(e ) | 0.079 |
| 6 | 34.914 | 74.638 | 4017 | E(c ) | 0.074 |
| 7 | 35.056 | 74.956 | 4039 | M(o) | 0.032 |
| 8 | 35.061 | 74.981 | 4122 | M(o) | 0.02 |
| 9 | 34.84 | 74.761 | 3973 | E(c ) | 0.234 |

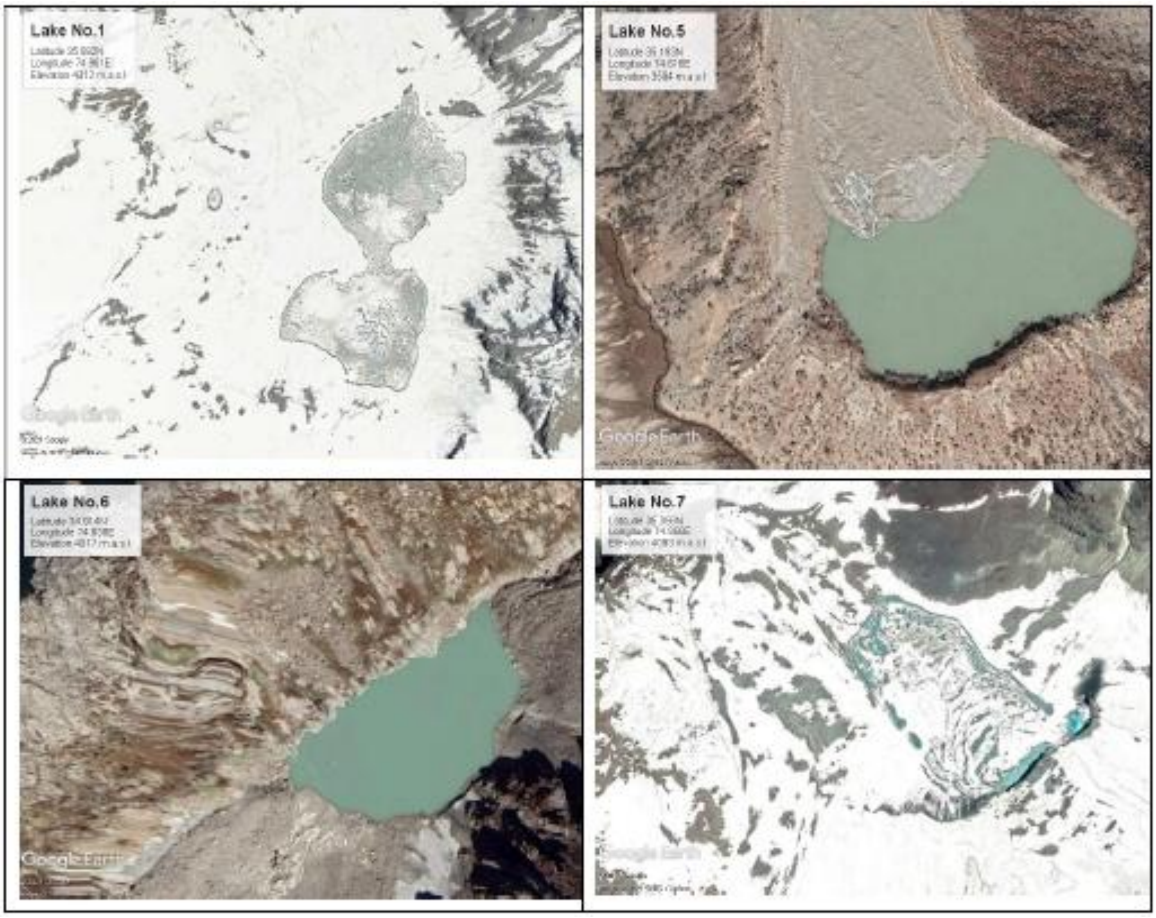


**Figure 21.** Google Earth Images of Potentially Hazardous Glacial Lakes in Astore Catchment

## 5. Recommendations

This study offers important contributions to the understanding of glacial lake dynamics and associated risks in the context of climate change. By utilizing the Normalized Difference Water Index (NDWI) to map glacial lakes across key catchments in northern Pakistan, it provides a valuable local dataset that can support disaster risk reduction planning. However, when critically analyzed alongside existing literature, several limitations and gaps emerge. The current study reliance solely on NDWI, without combining other spectral indices or conducting robust sensitivity analyses. To address the limitations of the NDWI-based methodology, future studies should adopt a multi-index approach, combining NDWI with indices like MNDWI or NDSI to improve accuracy in distinguishing water from snow, ice, and shadows. Threshold values should be locally calibrated using field observations and high-resolution imagery for validation. Incorporating time-series analysis can help track lake evolution and reduce misclassification of temporary features. Additionally, integrating ground-based data, LiDAR, or radar techniques can help detect en-glacial and sub-glacial lakes. Enhanced cloud-masking algorithms and seasonal image selection can further mitigate atmospheric and temporal inconsistencies in satellite-derived lake mapping. Recent advances in hydrological modeling and machine learning offer opportunities to enhance glacial lake monitoring and inflow forecasting integrating deep learning with satellite indices like NDWI could improve predictive accuracy for GLOF events [19-20]. To better understand the dynamics of glacial lakes and the associated risks of Glacier Lake Outburst Floods (GLOFs), several key recommendations are essential for future research and risk mitigation:

- **Develop Time-Series Data:** Ongoing work should focus on creating comprehensive time-series data on glacial lakes, including data from other catchments. This will provide valuable insights into lake expansion, the formation of new lakes, and the overall dynamics of glacial systems.
- **Physical Monitoring:** Regular field monitoring of these lakes is critical to track changes in size, lake behavior, and stability, particularly for lakes at risk of outburst floods.
- **Numerical Simulations:** Conducting numerical simulations of outburst floods will help predict potential flood scenarios and improve preparedness for future events.
- **Downstream Vulnerability Assessment:** It is crucial to assess the vulnerability of downstream communities to GLOFs. This includes evaluating infrastructure and identifying at-risk populations to inform disaster preparedness.
- Additionally, it is vital to incorporate disaster risk management, particularly GLOF risks, into national development plans, policies, and infrastructure projects. Key actions include:
- **Establish a National GLOF Risk Management Coalition:** A dedicated body should be set up to focus on GLOF risks, mobilize resources, and design appropriate response measures.
- **Create a Unified Database:** A centralized system for storing and distributing information about glacial lakes and GLOF risks will improve data accessibility and decision-making.
- **Implement Early-Warning Systems:** Effective early-warning systems need to be developed and installed to provide timely alerts for at-risk communities.
- **Establish a GLOF Risk Reduction Fund:** This fund would support research, raise awareness, and finance mitigation and adaptation measures.

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**Conflicts of Interest:** The authors declare no conflicts of interest.

## References

1. Bhagat, R.M., Kalia, V., Sood, C., Mool, P. K. & Bajracharya, S. (2004). Inventory of glaciers and glacial lakes and the identification of potential glacial lake outburst floods (GLOFs) affected by global warming in the mountains of the Himalayan region: Himachal Pradesh Himalaya, India. Unpublished project report, with database on CD-ROM, prepared for APN and ICIMOD, Kathmandu, by Himachal Pradesh Agricultural University, Palampur, India.
2. Bajracharya, SR.; Maharjan, SB.; Shrestha F.; Khattak, GA.; Wanqin, G.; Shiyin,L.; Junfeng, W. & Xiaojun, Y. (2010). The status of glaciers in the Hindu Kush-Himalayas. ICIMOD. unpub. 543
3. Huggel, C., Kääb, A. & Salzmann, N. (2006). Evaluation of QuickBird and Ikonos Imagery for Assessment of High- Mountain Hazards. EARSeL eProceedings 5, 1/2006: 51-62.
4. Huggel, C., Kääb, A., Haeberli, W., Teysseire, P. & Paul, F. (2002). Remote sensing based assessment of hazards from glacier lake outbursts: a case study in the Swiss Alps, Can. Geotech. J. 39: 316-330.
5. ICIMOD. (2011). Glacial Lakes and Glacial Lakes Outburst Floods in Nepal. Kathmandu: ICIMOD.
6. Ives, J. D., Shrestha, R. B. & Mool, P. K., (2010). Formation of Glacial Lakes in the Hindu-Kush Himalayas and GLOF Risk Assessment. Kathmandu: ICIMOD.
7. Ji, L., Zhang, L. & Wylie, B. (2009). Analysis of dynamic thresholds for the Normalized Difference Water Index. Photogram. Eng. Remote Sens. 75, 1307–1317.

8. Kääb, A. (2000). Photogrammetry for early recognition of high mountain hazards: new techniques and applications. Physics and Chemistry of the Earth 25: 765–770.
9. Mool, P. K. & Bajracharya, S. R. (2003). Inventory of Glaciers, Glacial Lakes and the Identification of Potential Glacial Lake Outburst Floods (GLOFs) Affected by Global Warming in the Mountains of Himalayan Region: Tista Basin, Sikkim Himalaya, India. Kathmandu: ICIMOD, 134pp.
10. Mool, P. K., Wangda, D., Bajracharya, S. R., Kunzang, K., Gurung, D. R. & Joshi, S. P. (2001b). Inventory of Glaciers, Glacial Lakes, and Glacial Lake Outburst Floods: Monitoring and early warning systems in the Hindu Kush-Himalayan Region – Bhutan. Kathmandu: ICIMOD. ISBN 92 9115 345 1, 227pp.
11. Mool, P. K., Bajracharya, S. R. & Joshi, S. P. (2001a). Inventory of Glaciers, Glacial Lakes, and Glacial Lake Outburst Floods: Monitoring and early warning systems in the Hindu Kush-Himalayan Regions – Nepal. Kathmandu: ICIMOD. ISBN 92 9115 331 1, 363pp.
12. Roohi, R., Ashraf, R., Naz, R., Hussain, S. A. & Chaudhary, M. H. (2005). Inventory of glaciers and glacial lakes outburst floods (GLOFs) affected by global warming in the mountains of Himalayan region, Indus Basin, Pakistan Himalaya. Report prepared for ICIMOD, Kathmandu, Nepal.
13. Sah, M., Philip, G., Mool, P. K., Bajracharya, S. & Shrestha, B. (2005). Inventory of glaciers and glacial lakes and the identification of potential glacial lake outburst floods (GLOFs) affected by global warming in the mountains of Himalayan region: Uttaranchal Himalaya, India. Unpublished project report, with database on CD-ROM, prepared for APN and ICIMOD, Kathmandu.
14. UNDP (2016). Feasibility Report for scaling-up of Glacial Lake Outburst Flood (GLOF) risk reduction in Northen Pakistan 24 – 25.
15. Wu, L., Che, T., Jin, R., Li, X., Gong, T., Xie, Y., Mool, P.K., Bajracharya, S., Shrestha, B. & Joshi, S. (2005). Inventory of glaciers, glacial lakes and the identification of potential glacial lake outburst floods (GLOFs) affected by global warming in the mountains of Himalayan region: Pumqu, Rongxer, Poiqu, Zangbuqin, Jilongcangbu, Majiacangbu, Daoliqu, and Jiazhagangge basins, Tibet Autonomous Region, People's Republic of China. Unpublished project report, with database on CD-ROM, prepared for APN and ICIMOD, Kathmandu.Author, F.: Article title. Journal 2(5), 99–110 (2016)
16. Ahmad, I., Waseem, M., Ashraf, A., Leta, M. K., Ahmad, S., & Wahab, H. (2023a). Hydrological risk assessment for Mangla Dam: Compound effects of instant flow and precipitation peaks under climate change, using HEC-RAS and HEC-GeoRAS. SN Applied Sciences, 5(12). https://doi.org/10.1007/s42452-023-05579-2
17. Ahmad, I., Waseem, M., Hussain, S., & Leta, M. K. (2024). Climate change induced spatiotemporal variations of land use land cover by using multitemporal satellite imagery analysis. Journal of Water and Climate Change, 00(0), 1–23. https://doi.org/10.2166/wcc.2024.675
18. Waseem, M., Ahmad, S., Ahmad, I., Wahab, H., & Leta, M. K. (2023). Urban flood risk assessment using AHP and geospatial techniques in Swat Pakistan. SN Applied Sciences, 5(8), 215. https://doi.org/10.1007/s42452-023-05445-1
19. Herbert, Z. C., Asghar, Z., & Oroza, C. A. (2021). Long-term reservoir inflow forecasts: Enhanced water supply and inflow volume accuracy using deep learning. Journal of Hydrology, 601, 126676. https://doi.org/10.1016/j.jhydrol.2021.126676
20. Muqeet, M., Saeed, M., Shahid, M., Ali, M. A., Irfan, M., & Khan, S. (2023). Enhanced cellulose nanofiber mechanical stability through ionic crosslinking and interpretation of adsorption data using machine learning. International Journal of Biological Macromolecules, 237, 124180. https://doi.org/10.1016/j.ijbiomac.2023.124180
21. Ahmad, S., Khan, A. R., Ali, I., Basharat, M., & Janjua, S. (2025). Assessing water demand and supply in the Upper Indus Basin using integrated hydrological modeling under varied socioeconomic scenarios. Applied Water Science. https://doi.org/10.1007/s13201-024-02310-3