*Quest Journals*
*Journal of Research in Environmental and Earth Sciences*
*Volume 10 ~ Issue 7 (2024) pp: 54-74*
*ISSN(Online) :2348-2532*
www.questjournals.org

**Research Paper**

# Potentially Dangerous Glacial Lakes and Geo-Hazard Assessment in Upper Indus Basin

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***Abstract***
*Glacial lake is a water body formed in/under/besides and/or in front of a glacier due to glacial dynamics. Such high-altitude glacial lakes are hazardous to humanity and infrastructure as they can drain instantaneous and create devastating floods in the downstream. The formation of moraine-dammed glacial lakes and glacial lake outburst flood (GLOF) is major concern in countries such as Bhutan, Tibet (China), India, Nepal and Pakistan. As we know due to the climate change rapid temperature rise, we have been dealing with the rapid snow melt at pace. Due to which the lakes in the Upper Indus show increase in area, volume and decrease in glaciers. Thus the present study was carried out to compute the hazard assessment of potentially dangerous glacial lakes (PDGLs). To envisage the present objective Landsat8, Landsat 4-5TM (Thematic Mapper) datasets were used. Apart from these satellite images ASTER–DEM data sources used for glacial lake mapping and change detection analysis. To examine the change, we use satellite images of different time period of the year2008 and 2018. A total of 547 glacial lakes out of which 93-proglacial lakes, 21-supraglacial lakes and 421unconnected glacial lakes were present in the year 2008 and 560 lakes were found in the year 2018 out of which 97-porglacial lakes, 29-supraglacial lake and 434 are unconnected lake.*
***Keywords:*** *Hazard, Glacial lakes, Landsat, Upper Indus.*

***R**eceived 14 July, 2024; **R**evised 28 July, 2024; **A**ccepted 30 July, 2024 © The author(s) 2024.*
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## I. INTRODUCTION

The Himalayan cryosphere is an indispensable part of the climate system with huge implications on the environmental and socio-economic conditions of the region (Maharjan et al. 2018). The Himalayas have the largest concentration of glaciers outside the polar region. These glaciers are a freshwater reserve; they provide the headwaters for nine major river systems in Asia- a lifeline for almost one-third of humanity. There is clear evidence that Himalayan glaciers have been melting at an unprecedented rate in recent decades; this trend causes major changes in freshwater flow regimes and is likely to have a dramatic impact on drinking water supplies, biodiversity, hydropower, industry, agriculture and others, with far-reaching implications for the people of the region and the earth's environment. One result of glacial retreat has been an increase in the number and size of glacial lakes forming at the new terminal ends behind the exposed end moraines. These in turn give rise to an increase in the potential threat of glacial lake outburst floods occurring. Such disasters often cross boundaries; the water from a lake in one country threatens the lives and properties of people in another. However, in response to climate change and warming, the Himalayan cryosphere is experiencing a remarkable and huge wastage and recession from the last few decades (Bahuguna et al. 2007; Bajracharya et al. 2008; Agrawal and Tayal 2013; Bajracharya et al. 2014; Mir et al. 2018; 2018). It is because, the various components such as the snow, glaciers and permafrost are considered very responsive to ongoing climate change (Oerlemans 1994; Zemp 2008; Bolch et al. 2011). The glacier wastage and recession has consequently, resulted in the formation of different types of glacial lakes and its rapid expansion in the region (Clague and Evans 1994; Bajracharya et al. 2007; Frey et al. 2010; Worni et al. 2012; Mergili et al. 2013; Nie et al. 2013; Wang et al. 2013; Emmer et al. 2015; Ahmed et al. 2021a).

However, it is important to note, that the remote sensing-based observation of glacial lakes are the best method available (Prakash and Maharjan 2018). It is because, the multi-spectral and multi-temporal satellite data offer great potential for continuous monitoring and management of glacial lakes situated in the high mountain areas (Bajracharya and Shrestha 2011) where, the field investigations are very laborious and time-consuming, owing to the tough terrain and hostile environmental conditions in the region.

A glacial lake is defined as a water mass existing in sufficient amount and extending with a free surface in, under, besides, and/or in front of a glacier and originated by glaciers. Such high-altitude glacial lakes are hazardous to humanity and infrastructure as they can drain instantaneous and seasonal climate change during the twentieth century had a significant impact on glaciers and glacial environments. These glacial fluctuations cause the formation and enlargement of glacial lakes in many mountain ranges. Due to increase in the rate of melting of the glaciers, the lakes are increasing in areal extent and water storage capacity. Sudden discharge of large volumes of water and debris from these lakes is termed as glacial lake outburst flood (GLOF). GLOF can cause extensive damage to the natural environment and human property as it can drain extremely rapidly and cause dramatic floods downstream. GLOF can be considered as a geomorphological risk because it is a natural risk which is connected to a geomorphological hazard to devastating floods in the downstream. Glacial lake outburst flood (GLOF), is one of the most serious disasters to occur in the Himalayan region. In this paper, we investigate these changing patterns over the western Himalaya. The region is an important source of snow and ice. Snowfall starts in early November and stops by the end of April, depending on the altitude of the area. Glacial ice is found over the Karakoram mountain range throughout the year. It is therefore important to study the impact of global climate change and warming on the glaciers, snow and ice of this region. In the complex mountainous regions of the western Himalaya, only a limited number of studies were carried out during the period 1901–2003 to analyze the temperature and precipitation trends in the global climate-change scenario.

Thus keeping in view above discussion, the present study has been carried out to generate an updated lake inventory to carry out a hazard assessment of potentially dangerous glacial lakes (PDGLs) in the Upper Indus Basin.

**Classification of Glacial Lakes**

Classification of glacial lakes plays an important role to know the location and to understand the origin and evolution of glacial lakes. Internationally, there has been so far no accepted standard for the classification system of glacial lakes. Some organizations and scholars proposed the different classification systems of glacial lakes according to their own research purposes. In, this study, we classify glacial lakes into three types based on location and their relationship with the mother glaciers.

1. **Supraglacial Lakes**: Supraglacial lakes refer to the water body on the surface of glacier due to different ablation. These lakes usually appear on the surface of ablation zone of debris-covered glaciers. Although these pools are ephemeral, they may reach kilometers in diameter and be several meters deep. Supraglacial lakes (SGLs) form when meltwater ponds in depressions on the surface of a glacier or ice sheet. They range in size from a just a few meters to tens of kilometers in area and they play an important role in an ice sheet's mass balance.

2. **Proglacial Lake**: Lakes that are generally dammed by moraines and are in contact with the glacier or in the vicinity of the glacier. Many proglacial lakes are moraine-dammed, whereas others form in basins created by isostatic depression near the ice margin. The main difference between Supraglacial Lake and Proglacial Lake is their locations: the former is located on the surface of glacier; the latter is located beneath the moraine ridge of the glacier.

3. **Unconnected Glacial Lake**: Lakes that are not directly come in contact or fed by the mother glacier and usually formed in the low lying areas.

This classification system has been also used by various researchers in different parts of the Himalayan region (Gardelle et al. 2011; Salerno et al. 2012; Nie et al. 2013; Wang et al. 2013; Chen et al. 2021).

**STUDY AREA**

The upper Indus Basin is located within the glaciers that have a big potential in water resources and hydropower generation. The main aim of conducting this research is to identify the Potentially Dangerous Glacial Lake in the upper Indus basin. The Upper Indus basin (UIB), which covers a wide range of climatic and topographic settings, provides an ideal venue to explore the relationship between climate and topography. The upper Indus basin is located in the mountain ranges of the Hindu Kush, Karakoram, and Himalaya and on the Tibetan Plateau thus making the area important to study the impact of climate changes. The upper Indus basin is drained by the river Indus which is an international river, with headwater tributaries in China (Tibet), India, Pakistan and Afghanistan. The river originates north of the Great Himalaya on the Tibetan Plateau. The main stem of the river runs through the Ladakh district of Jammu and Kashmir and then enters the northern areas of Pakistan (Gilgit-Baltistan), flowing between the western Himalaya and Karakoram mountains. Upper Indus Basin lying in Jammu and Kashmir and Himachal Pradesh mostly consists of mountain ranges and narrow valleys. The Catchment of this basin falls in range 34°21'4.993"N latitude and 76°46'42.39"E longitude covering an area of 45899.89 km. The Upper Indus Basin (UIB) is home to three of the world's mightiest mountain ranges. The Karakoram and the Himalayan Mountain Ranges are in the north and northeast of Pakistan while the Hindukush Mountain Range guards the north western frontiers of the country.

Barring the Polar Regions, UIB contains the world's °C in winter. Average minimum temperatures range from 18°C in summer to –0.3°C in winter. The coldest month is January and the warmest is June. The average temperature has shown an increasing trend, driven mainly by increases in winter temperatures, and more prominently since the 1980s. Average maximum temperatures have slightly decreased (0.5°C), while minimum temperatures have increased (1.2°C) in the winter. Average minimum temperatures have increased in both seasons. The extreme maximum temperature is increasing most prominently over the upper basin, whereas the trend is decreasing over the lower basin (except for a large area in the southwest). The extreme minimum temperature is decreasing over the central part and in a small area over the northeast and southwest; elsewhere it is on the rise with the highest severity over the north and west.

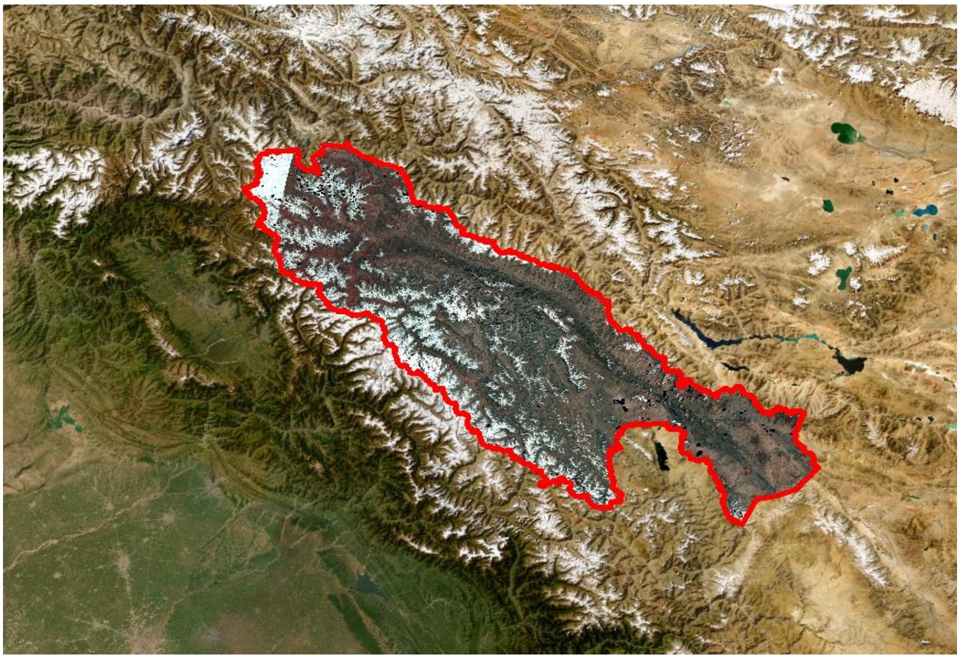
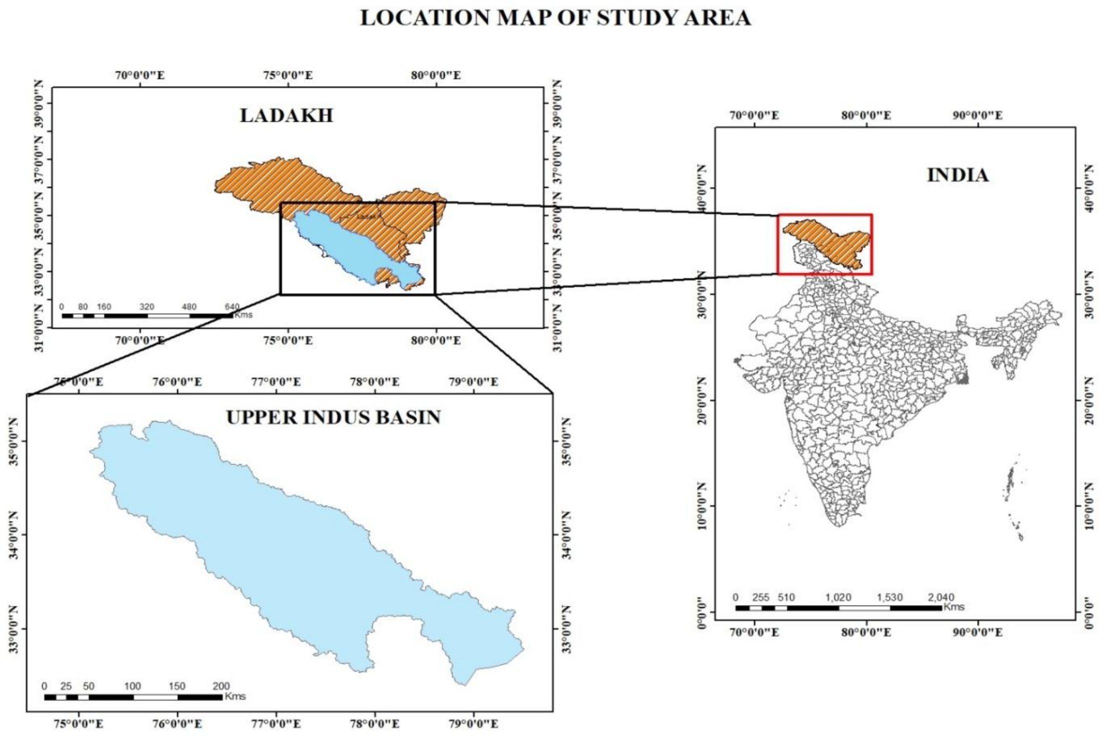


**Fig. No. 1: Location of Study Area**




**Map No. 1: Location Map of study Area**

## II. OBJECTIVES

The main objective of the study is hazard assessment of Potentially Dangerous Glacial Lakes (PDGL) in the Upper Indus Basin, North Western Himalayas and specific objectives are as follows:

- To map the glacial lakes of the time periods 2008 and 2018 using Landsat satellite datasets of Upper Indus basin;
- To characterize the glacial lakes and monitor the lake area and volume changes in 2008 and 2018
- To carry out the hazard assessment of Potentially Dangerous Glacial Lakes (PDGL)

## III. Data Base and Methodology

In the present study, Landsat 4-5 TM and Landsat 8 OLI images with a 30 m spatial resolution were used for the years 2008 and 2018 respectively. The boundary of glacial lakes was demarcated using Arc Map 10.8.1 and Landsat images and Google Earth data. After demarcation of the boundaries, the lakes were categorized as supraglacial, proglacial and unconnected lakes, followed by calculation of area, depth, volume, elevation, slope and length. A detailed flowchart of methodology has been provided in the figure 1.

**Area estimation**

Area of each lake was calculated using "calculate geometry" option in the attribute table of shapefile. The lakes having high area were assigned as rank 1, contributing high risk that would contribute to flood hazard, and lakes having low area were given as rank 3.

**Depth Estimation**

Furthermore, an empirical approach was adopted to compute depth and volume as suggested by Huggel et al. (2002), Cook and Quincey (2015). It is because, as such, there is no realistic method or technique to directly obtain the volume of glacial lakes. The equation for depth calculation is given below as:

**D=0.104A0.42 (Eq. 1)**

Where, D is the mean lake depth in kilometers (km) and A is lake surface area in square kilometers ($Km^2$). The lakes have higher depth values were assigned as rank 1, indicating high potential of glacial lake outburst flood and lakes having low depth were assigned rank 3, indicating low potential of glacial lake outburst flood.

**Volume Estimation**

The equation for volume estimation used in this study is given by Huggel et al. (2002). The equation for volume (m3) is given:

**V= 0.104A1.42 (Eq. 2)**

The lakes have high volume were assigned as rank 1, i.e. high potential of glacial lake outburst flood and lakes having low volume were assigned rank 3, indicating low potential of glacial lake outburst flood.

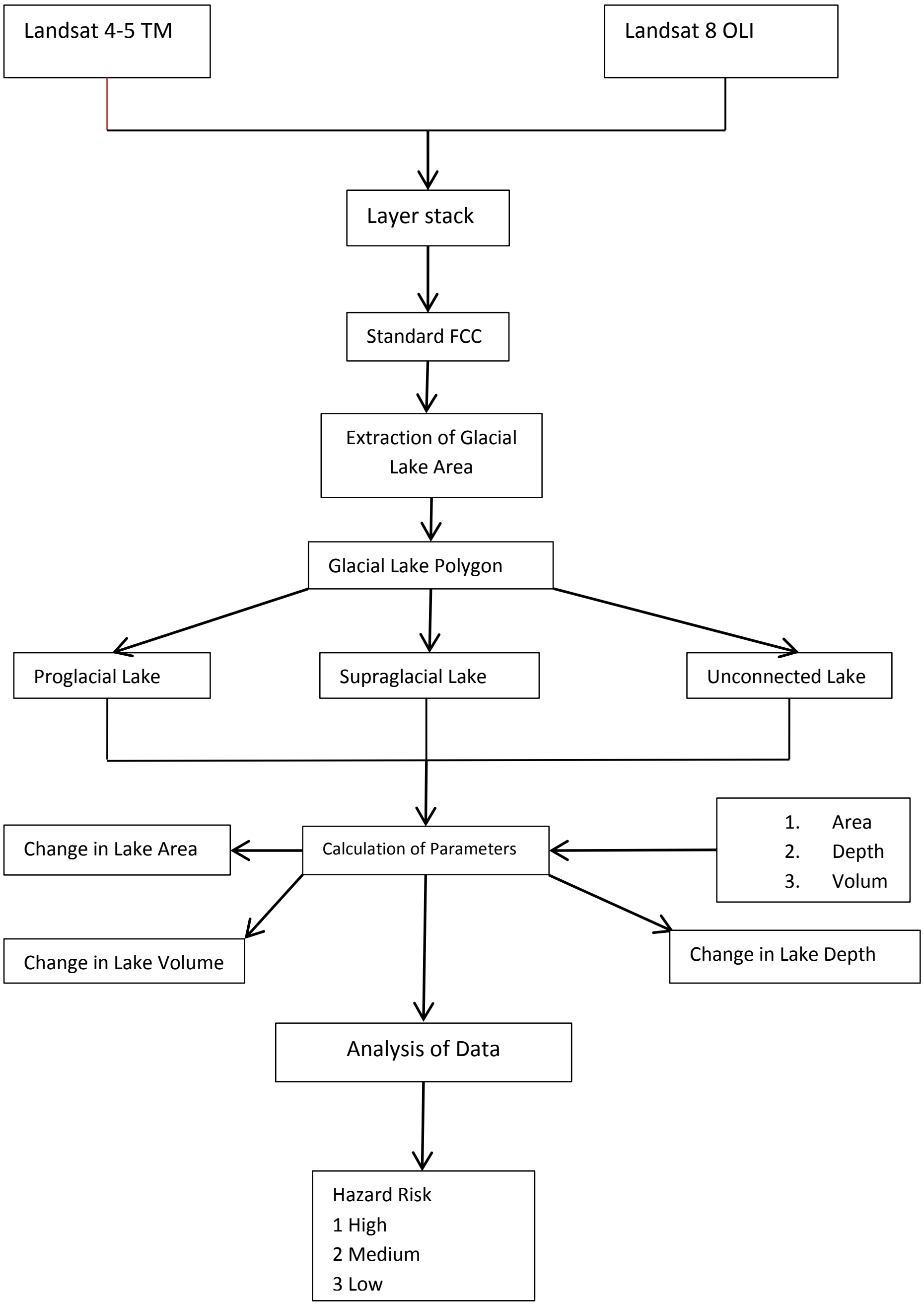



**Figure No. 1: Flow Chart of Methodology**

**Datasets Used**

In our study, we selected Landsat images (including Landsat 5, and 8 images) with a 30 m spatial resolution acquired by Landsat satellites launched by the National Aeronautics and Space Administration (NASA) as the main data sources for glacial lake inventory mapping. In order to understand the Spatiotemporal dynamics particularly of potentially dangerous glacial lakes, the Landsat imagery of 2008 (TM) and 2018 (OLI) with 60 m and 30 m resolution were used. 7 Landsat 5TM scenes for 2008 and 7 Landsat-8 OLI scenes for 2018 covering the area were downloaded from the **NASA USGS** web portal ***www.earthexplorer.usgs.gov***. Landsat data has been extensively utilized for the purpose of mapping and change detection of glacial lakes, due to its free availability, 30 m resolution and wide-area coverage (Li and Sheng 2012; Roy et al. 2014; Bhardwaj et al. 2015; Robson et al. 2015).The snow, mountain shadow and cloud cover associated with the glaciers and glacial lakes in the Himalayan region is a major challenge for mapping (Frey et al. 2012; Romshoo et al. 2020). To overcome this issue, the Landsat data scenes were preferred from the pre- winter season. It is because the glacial lakes in this period show minor changes and almost remain stationary in terms of size. The pre-winter season has little cloud cover and perennial snow coverage (Nie et al. 2013; Wang et al. 2013). Landsat data selected for the delineation of glacial lakes were ideally from the months of September, October and November of 2008 and 2018.Whenever, the shadow, lake ice, and cloud/snow cover obstruct the lake identification, the data scenes were extended to the adjacent month or year to obtain the ideal required imagery.

**Table No. 1: Datasets used in the Study for the year 2008**

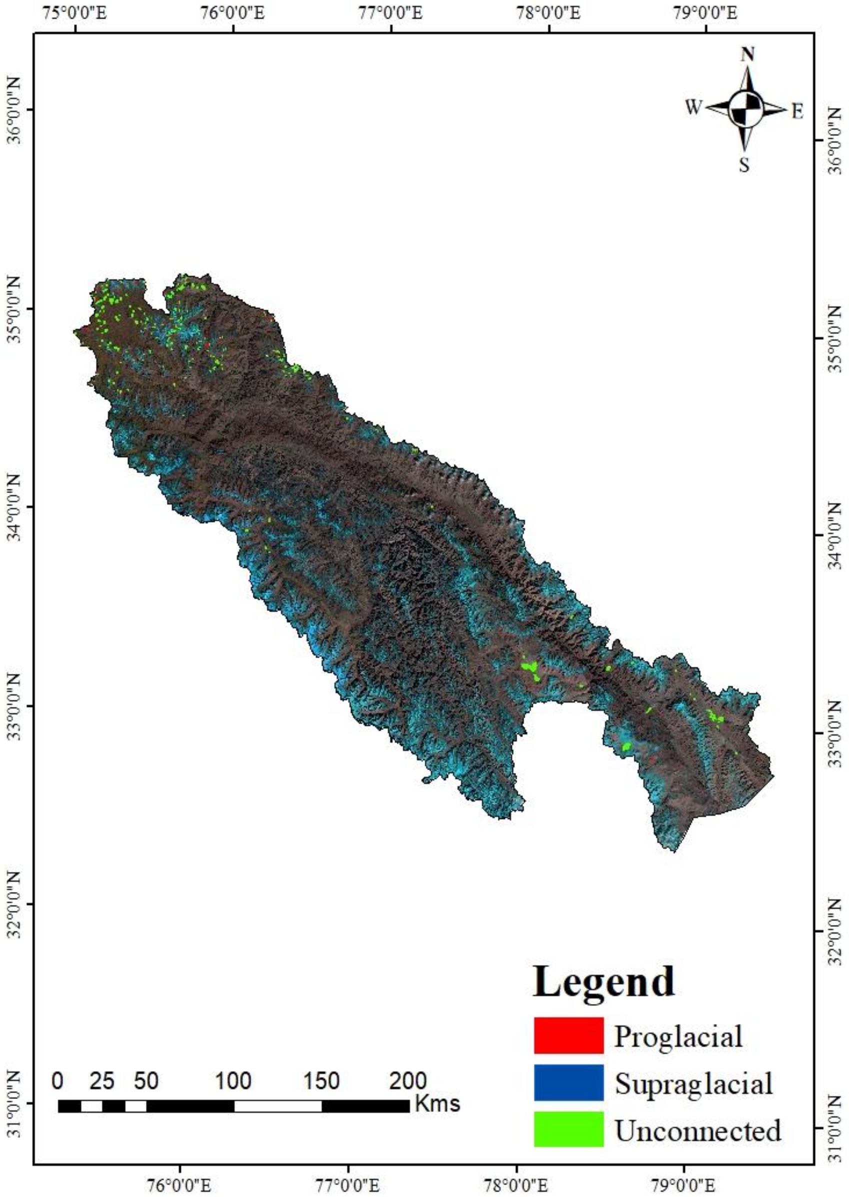
| Year | Satellite data/ sensor | Date | Product ID | Resolution (m) | Path/Row | Downloading site/source |
|---|---|---|---|---|---|---|
| 2008 | Landsat 4-5 TM | 2008-nov-13 | LT51460372008328KHC01 | 30 | 146/037 | USGS NASA https://earthexplorer.usgs.gov/ |
| | | 2008-nov-07 | LT51470362008287KHC01 | | 147/036 | |
| | | 2008-dec-06 | LT51470372008335KHC01 | | 147/037 | |
| | | 2008-nov-11 | LT51480362008278KHC01 | | 148/036 | |
| | | 2008-nov-11 | LT51480372008278KHC01 | | 148/037 | |
| | | 2008-oct-17 | LT51490352008269KHC01 | | 145\035 | |
| | | 2008-oct-11 | LT51490352008269KHC01 | | 149\035 | |

**Table No. 2: Datasets used in the Study for the year 2018**

| Year | Satellite data/ sensor | Date | Product ID | Resolution (m) | Path/Row | Downloading site/source |
|---|---|---|---|---|---|---|
| 2018 | Landsat 7-8 OLI | 2018-oct-10 | LC81460372018355LGN00 | 30 | 146/037 | USGS NASA https://earthexplorer.usgs.gov/ |
| | | 2018-sep-28 | LC81470362018362LGN00 | | 147/036 | |
| | | 2018-oct-14 | LC81470372018362LGN00 | | 14/037 | |
| | | 2018-oct-08 | LC81480362018337LGN00 | | 148/036 | |
| | | 2018-oct-08 | LC81480372018337LGN00 | | 148/037 | |
| | | 2018-oct-15 | LC81490362018328LGN00 | | 148/036 | |
| | | 2018-oct-17 | LC81460382018355LGN00 | | 146/038 | |

# IV. RESULTS AND DISCUSSION (2008)

## 4.1 Distribution of Lakes




**Map No. 2: Showing Distribution of Lakes (2008)**

| Main type | Total Number/(Percentage) (2008) | Total Number/ (Percentage) (2018) |
|---|---|---|
| **Proglacial Lakes** | 93 (17.0%) | 97 (17.3%) |
| **Supraglacial Lakes** | 21 (3.8%) | 29 (5.17%) |
| **UnconnectedGlacial Lakes** | 421 (76%) | 434 (77.5) |
| **Total** | 547 | 560 |

**Table No.3: Distribution of Lakes (2008)**

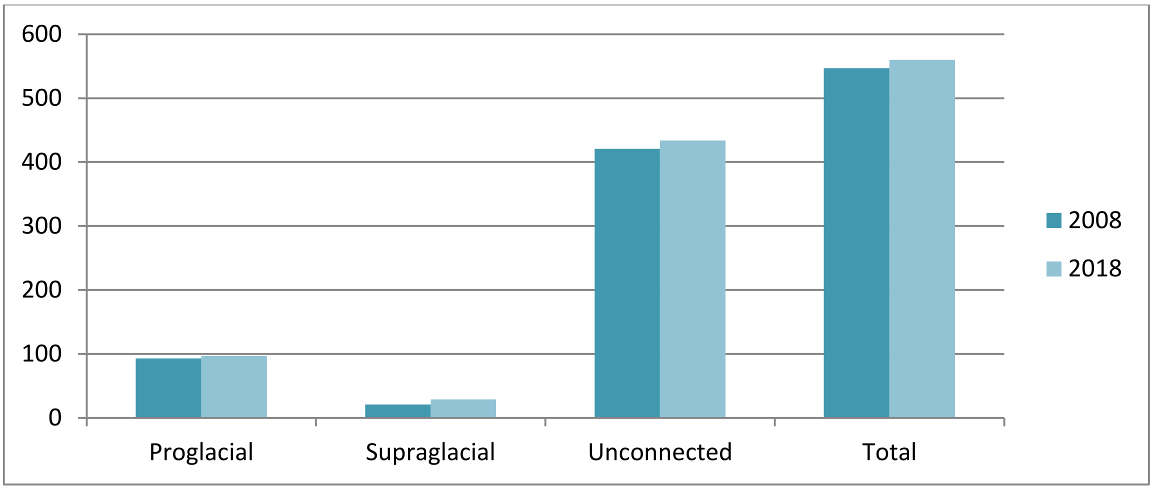



**Fig. No. 3: Graphical Representation of Distribution of lakes (2008)**

Out of these 547 lakes, 93 were Proglacial lakes. Proglacial lakes are formed near the edge of a glacier and are often fed by melting ice. These lakes are usually shallow and have turbid water due to high sedimentation and glacial flour content.

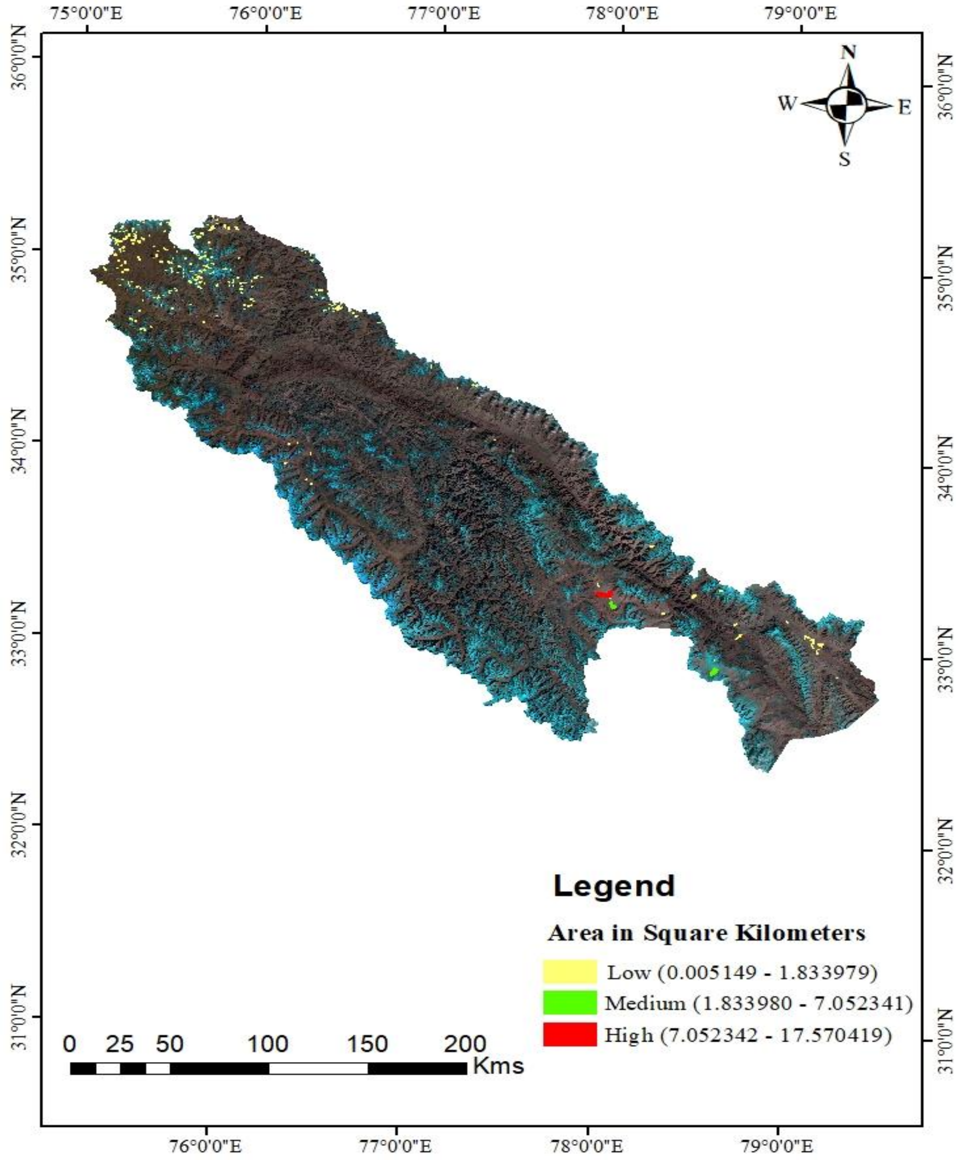
21 of the 547 lakes were Supraglacial lakes. Supraglacial lakes are those that form on top of glaciers or ice sheets. These lakes are usually small and are formed due to melting of the ice on the surface of a glacier. These lakes are relatively rare and can be found only in certain regions where the conditions are suitable for their formation.

The majority of the lakes in the region were unconnected lakes. There were a total of 421 unconnected lakes in the region. Unconnected lakes are those that are not linked to any major river or stream and are often found in low-lying areas. These lakes are usually small and have limited water supply.

In summary, the Table3 indicates that in the year 2008 in the particular region there were fewer proglacial and supraglacial lakes compared to unconnected lakes.

**4.2 Area of Lakes**

Area is an important parameter for assessment of potentially dangerous glacial lakes. The area is calculated using calculated geometry.




**Map No.3: Showing Area of Lakes (Km$^2$)**

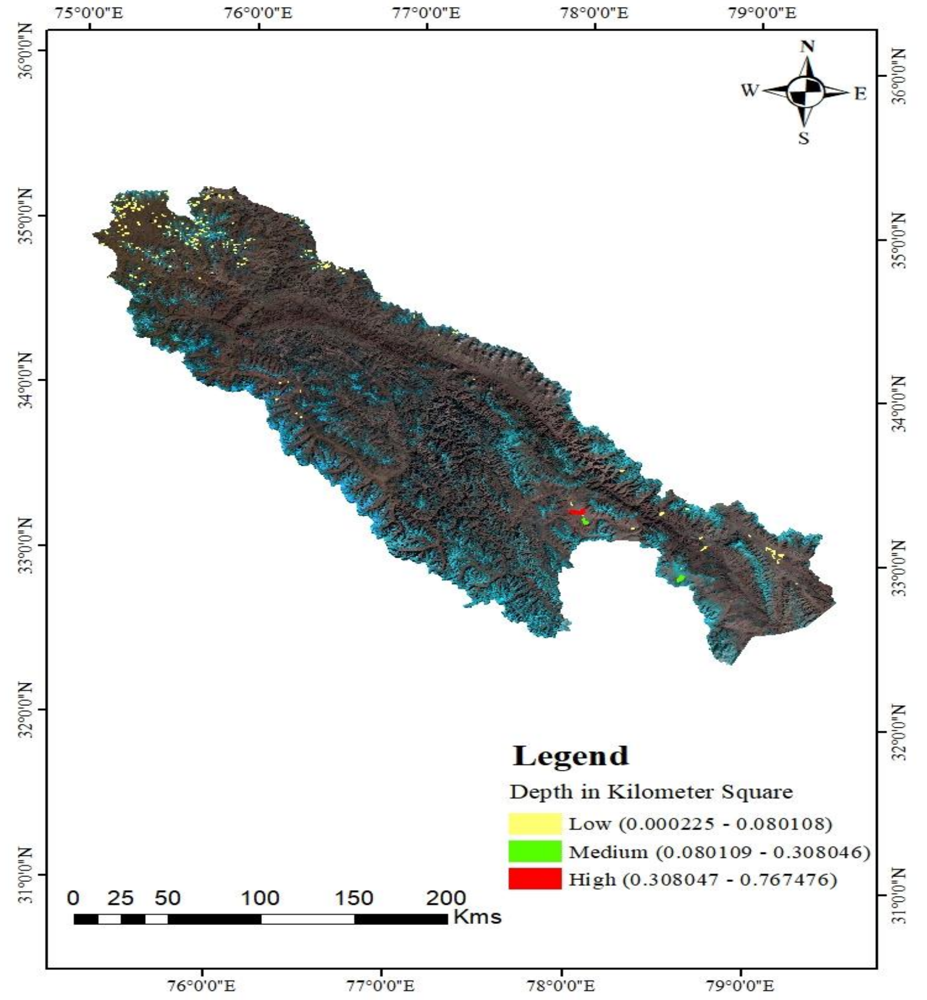
The area of the glaciers in the region ranges from 0.005149 to 17.570 square kilometers. Based on the area of the glacial lakes, these lakes have been classified into three categories: low-risk, medium-risk, and high-risk categories.

Glacial lakes with an area between 0.00514 and 1.8339 square kilometers have been assigned a rank of 1, which means they are categorized as low-risk lakes. These lakes are relatively small and are less likely to pose a significant risk or hazard.

Glacial lakes with an area between 1.8339 and 7.0523 square kilometers have been assigned a rank of 2, which means they are categorized as medium-risk lakes. These lakes are larger in size than the low-risk lakes and are therefore more likely to pose a risk or hazard.

Glacial lakes with an area between 7.0523 and 17.5704 square kilometers have been assigned a rank of 3, which means they are categorized as high-risk lakes. These lakes are the largest in size and are therefore more likely to pose a significant risk or hazard.

### 4.3 Depth of Lakes




**Map No. 4: Showing Depth of Lakes (km$^3$)**

Depth is an essential criterion for identifying potentially hazardous glacial lakes. The depth of a lake determines its capacity to store water, which can directly affect the magnitude and frequency of outburst floods.

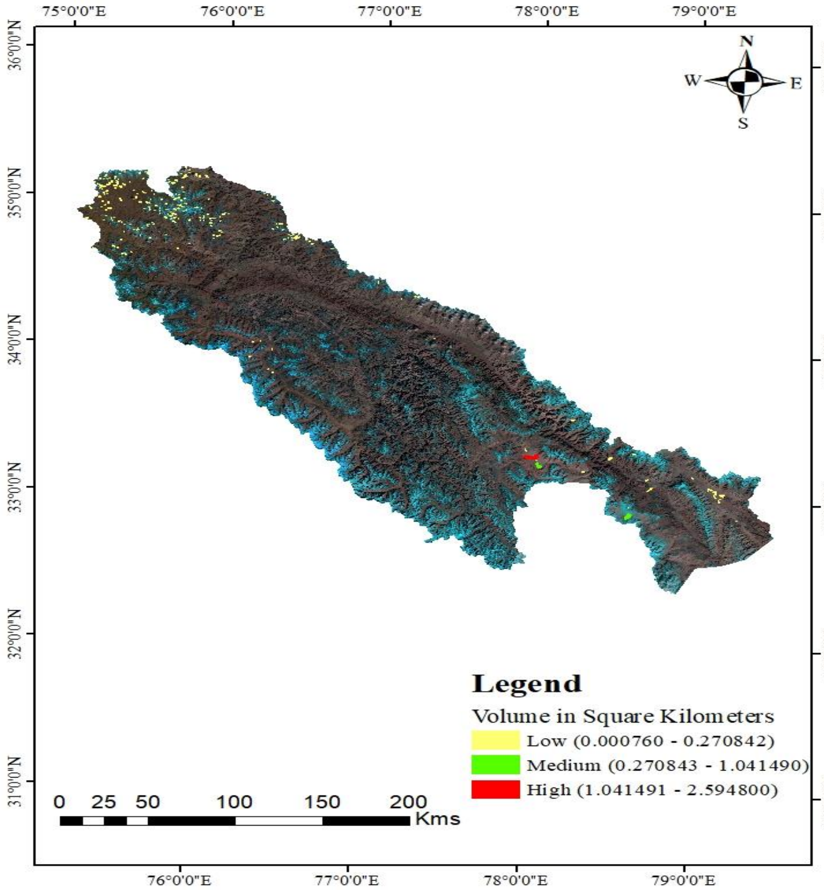
The depth of the glacial lakes in the region ranges from 0.000225 to 0.767476 square kilometers. Based on the depth of the lakes, they have been categorized into three categories: low-risk, medium-risk, and high-risk.

Glacial lakes with a depth of 0.000225 to 0.080108 square kilometers have been assigned a rank of 3 and are considered to be low-risk lakes. These lakes have a relatively shallow depth and thus have limited capacity to store water.

Glacial lakes with a depth of 0.080109 to 0.308046 square kilometers have been assigned a rank of 2 and are considered to be medium-risk lakes. These lakes have a moderate depth and can store a significant amount of water, making them more likely to cause hazards.

Glacial lakes with a depth of 0.308047 to 0.767476 square kilometers have been assigned a rank of 1 and are considered to be high-risk lakes. These lakes have a considerable depth and can store a large amount of water, making them highly susceptible to outburst floods.

### 4.4 Volume of Lakes




**Map No. 5: Showing Volume of Lakes**

The glacial lakes are classified into three categories based on their volume. Volume is an essential parameter for identifying potentially dangerous glacial lakes, as higher volume indicates higher water storage capacity, which increases the risk of outburst floods.

The volume of glacial lakes ranges from 0.000760 to 2.594800 cubic kilometers. Based on the volume, these lakes are categorized into low-risk, medium-risk, and high-risk categories.

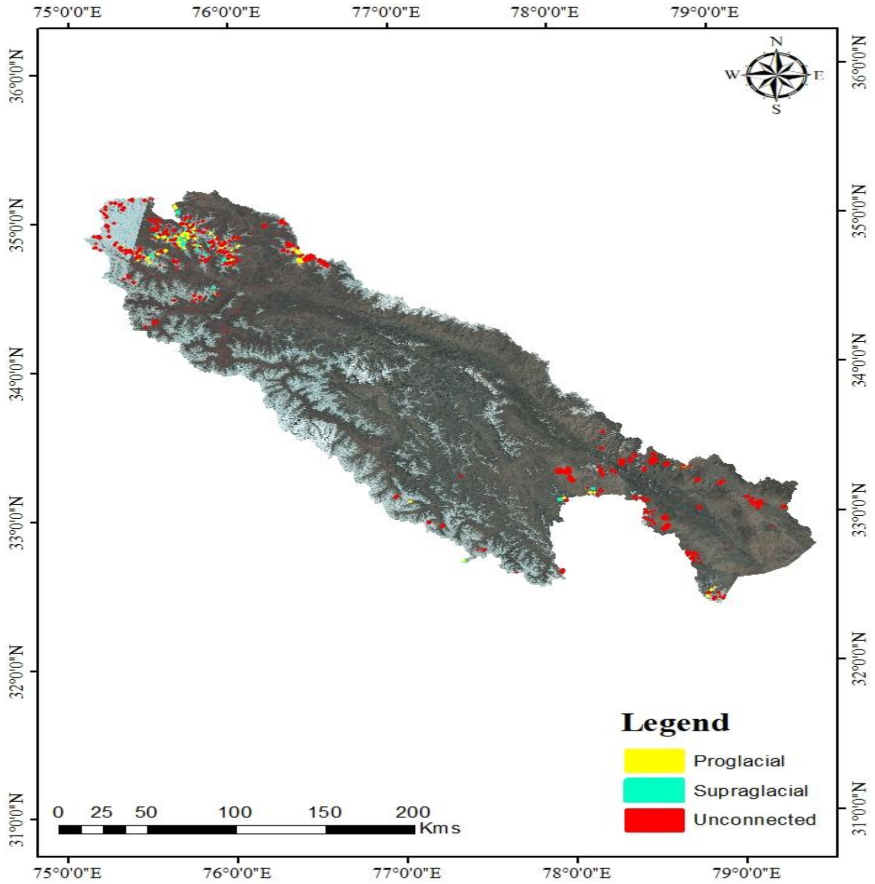
Glacial lakes with a volume of 0.000760 to 0.270842 cubic kilometers are considered low-risk lakes, and they have been assigned a rank of 3. These lakes have a relatively low water storage capacity, and therefore, they are less likely to pose any significant threat.

Glacial lakes with a volume of 0.270843 to 1.041490 cubic kilometers are considered medium-risk lakes and have been assigned a rank of 2. These lakes have a moderate water storage capacity, and they are more likely to pose a risk if the lake levels increase significantly.

Glacial lakes with a volume of 1.041491 to 2.594800 cubic kilometers are considered high-risk lakes and have been assigned a rank of 1. These lakes have a high water storage capacity, and they are more susceptible to outburst floods, which can cause significant damage to the surrounding areas.

# V. RESULTS AND DISCUSSION (2018)

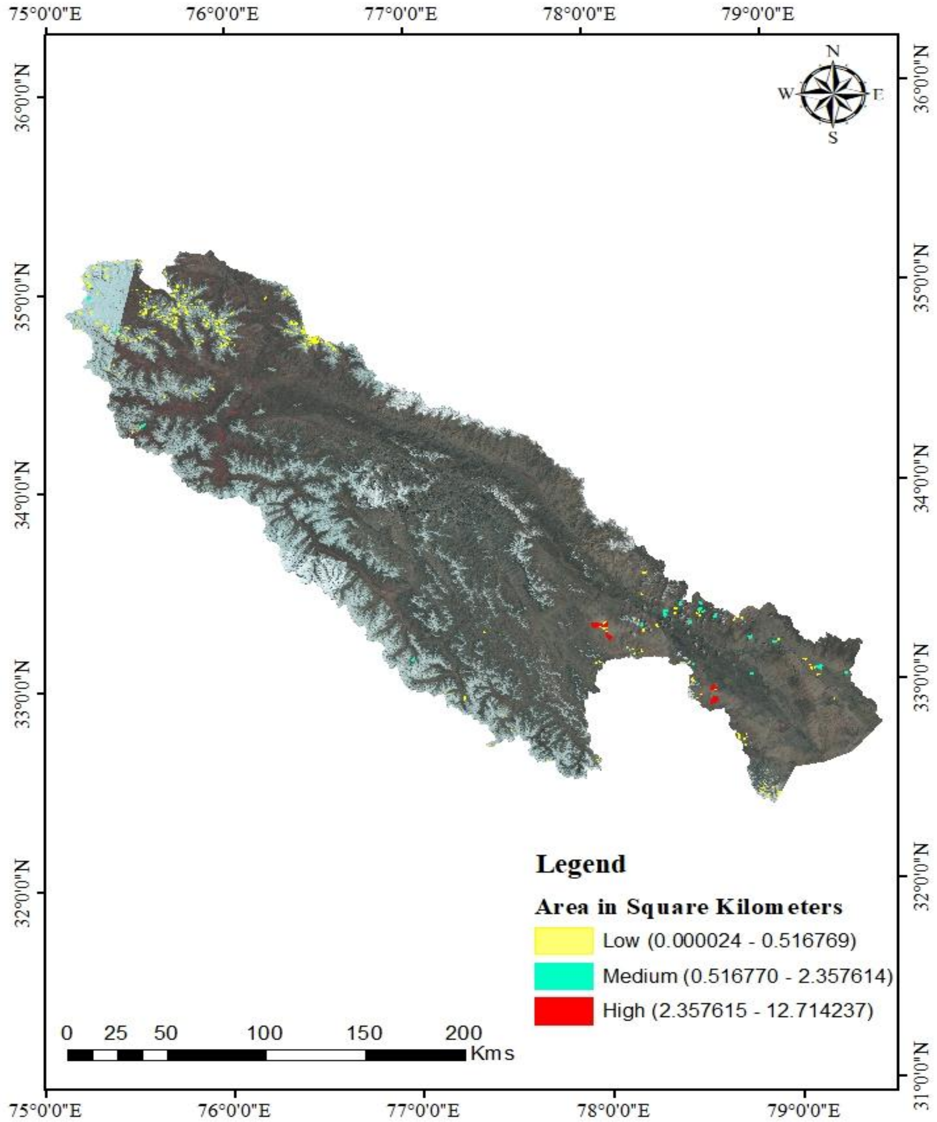
### 5.1 Distribution of Lakes




**Map No. 6: Showing Distribution of Lakes (2018)**

For the year 2018, out of 560 lakes 97 were Proglacial, 29 were Supraglacial and 434 were unconnected lakes.

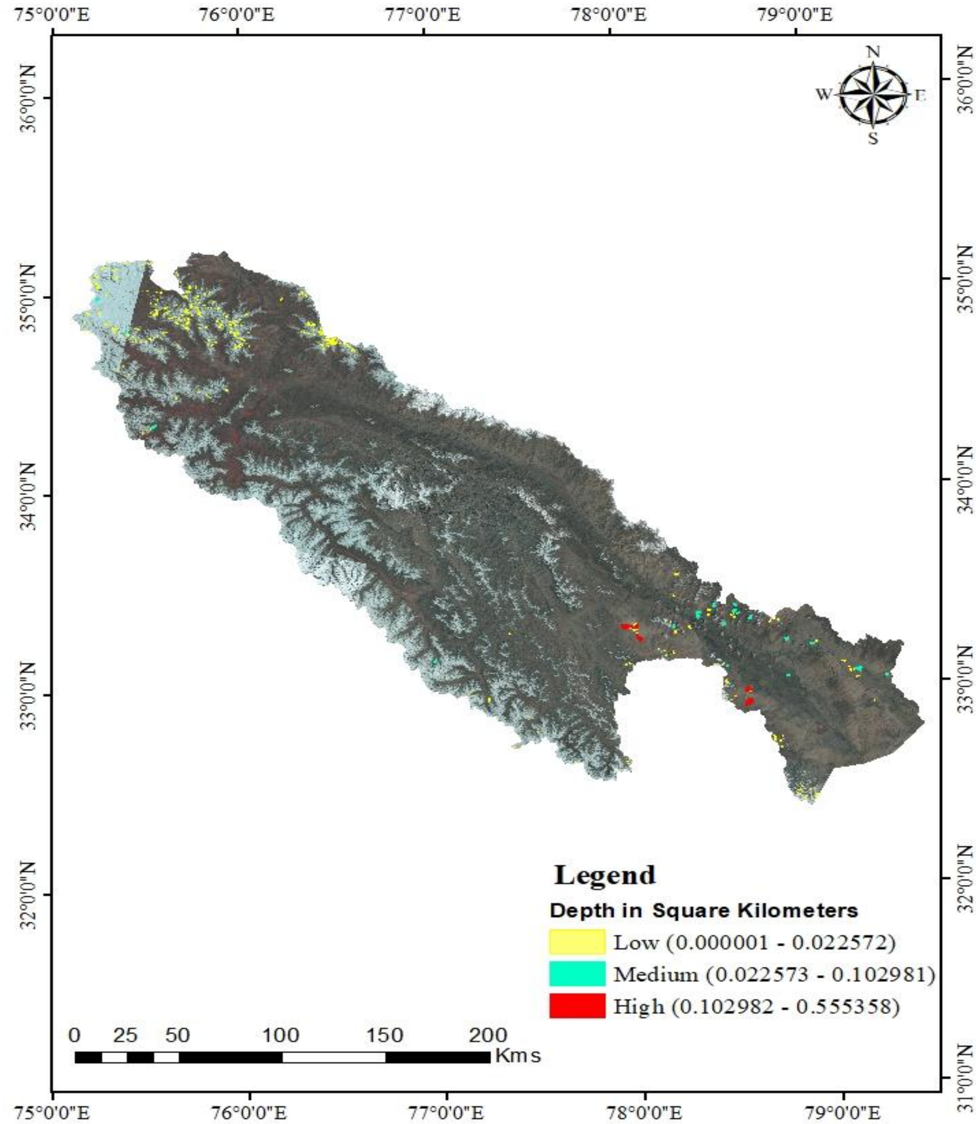
**5.2 Area of Lakes**




**Map No. 7: Showing Area of lakes**

The area of glaciers lies from 0.000024-12.714237 $km^2$.On the basis of area we classify these lakes into 3- categories i.e. low, medium and high risk. The area of glacial lakes lies between 2.357615-12.714237 (High) were assigning as rank 1, rank 2 were assigned to those glacial lakes whose area lies between 0.516770-2.357614 (Medium) and those lakes having areas between 0.000024-0.516769 (low) were assigning as category as rank 3 respectively.

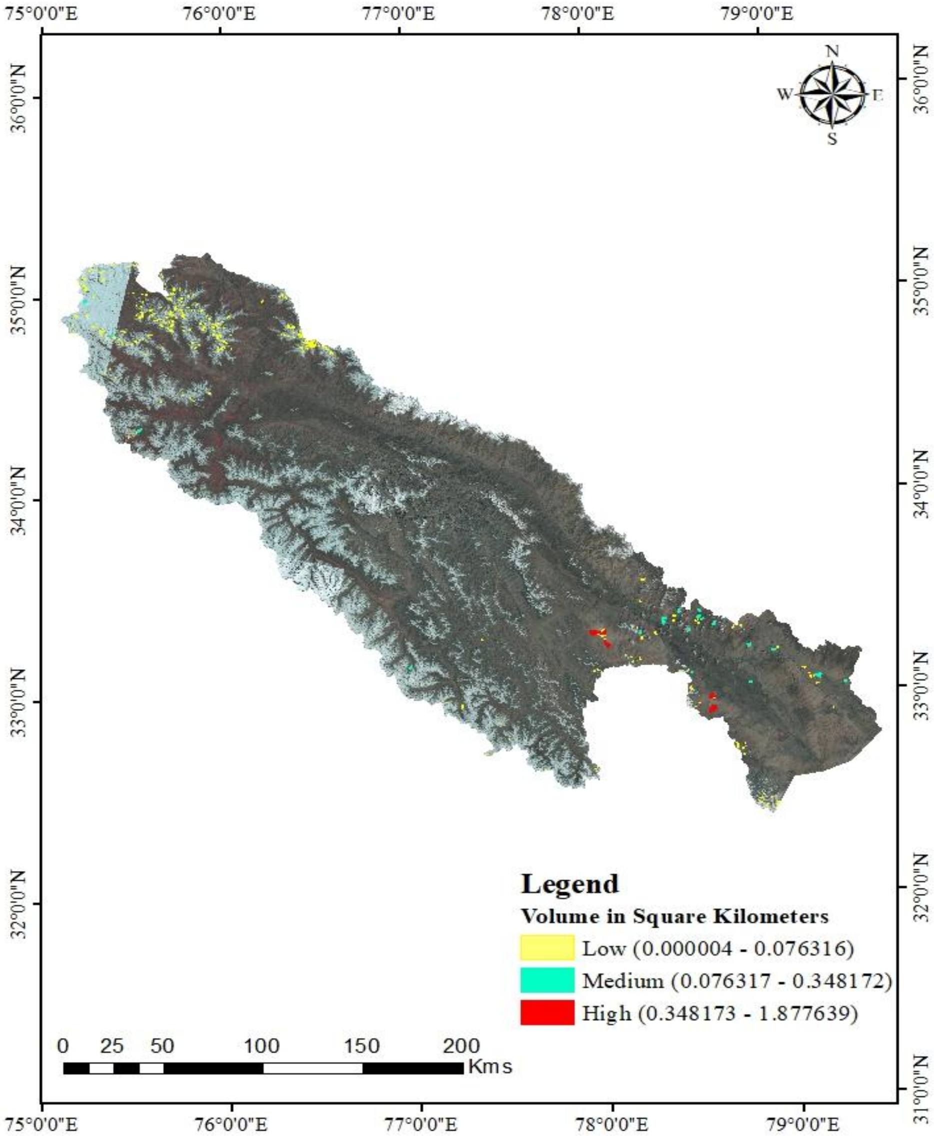
**5.3 Depth of Lakes**




**Map No. 8: Showing Depth of Lakes (km$^2$)**

The depth of glacial lakes varies from 0.0000001- 0.555358 km$^2$. The lakes having depth from 0.0000001-0.022572 km$^2$ considered as low risk and assigning in the rank of 3, from 0.022573-0.102981 km$^2$ are considered as medium risk and assigned as rank 2 and from 0.102982-0.555358 Km$^2$ are high risk which are assigning as rank 3 respectively.

### 5.4 Volume Map




**Map No. 9: Showing Volume of Lakes (km$^3$)**

On the basis of volume all the glacial lakes were classify into three categories just like area map and depth map. The lakes lie between 0.000004-1.877639 Km$^3$ and lakes lying between 0.000004-0.076316 km$^3$ are categorized into low risk and were ranked as rank 3, 0.076317-0.348172 km$^3$ are medium risk which come under the rank 2 and the volume lies between 0.348173-1.877639 km$^3$ are considered as high risk and were assigned in rank 3.

**Potentially Dangerous Glacial Lakes**

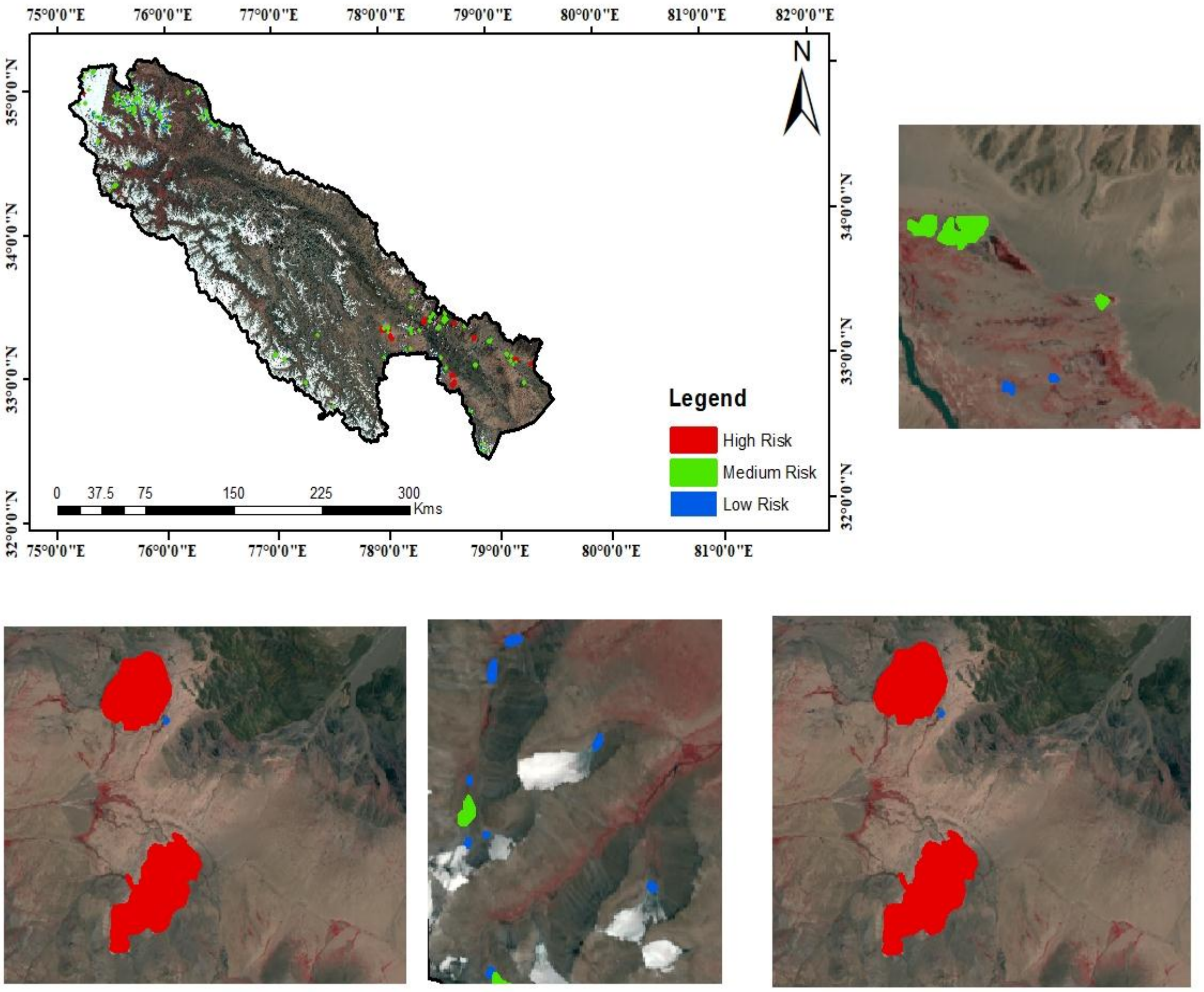



**Fig No. 4: Geo-hazard Assessment of Glacial Lakes**

The analysis of data has helped us to identify 11 glacial lakes that are potentially dangerous due to their high risk of a glacial lake outburst flood. These lakes have a combined area of 38.654 km$^2$, which is a significant amount. The high risk category indicates that the potential for a catastrophic flood due to a glacial lake outburst is very high for these lakes.

Additionally, there are 162 glacial lakes that fall under the medium risk category, with a combined area of 28.011 km$^2$. These lakes still pose a risk for a glacial lake outburst flood, but the chances of such an event occurring are lower than for the high-risk category.

Finally, there are 387 glacial lakes that are categorized as low risk, with a combined area of 8.570 km$^2$. These lakes have the lowest potential for a glacial lake outburst flood.

Overall, this analysis helps to identify which glacial lakes are potentially dangerous and need to be monitored closely to mitigate the risks associated with a potential glacial lake outburst flood.

| S No. | Potential of Lakes | Number | Area (km$^2$) |
|---|---|---|---|
| **1** | High | 11 | 38.654 |
| **2** | Medium | 162 | 28.011 |
| **3** | Low | 387 | 8.570 |

**Table No. 5: Potentially Dangerous Glacial Lakes of study area**

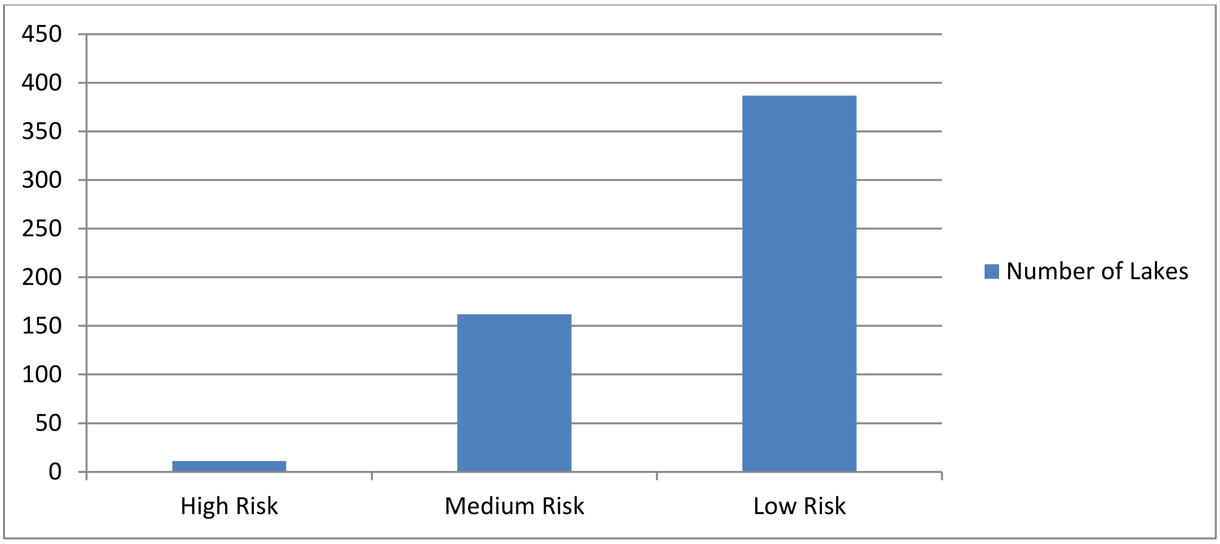



**Fig. No. 6: Graphical Representation of Potentially Dangerous Glacial Lakes**

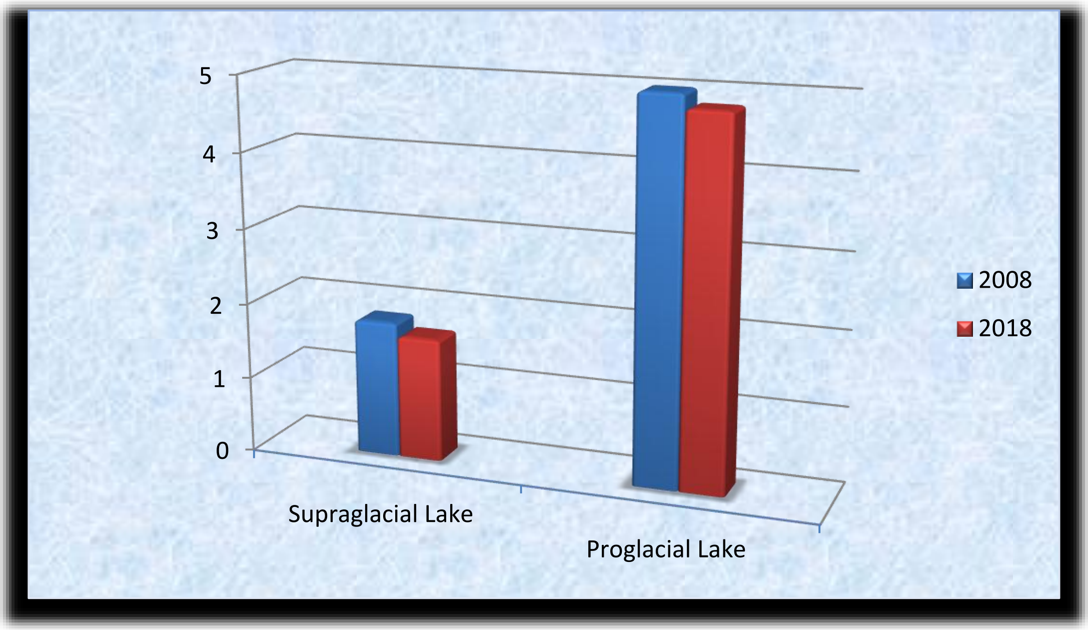



**Fig No. 7: Area and Area Change of Supraglacial Lake, Proglacial Lake & Unconnected Lake (in $Km^2$)**

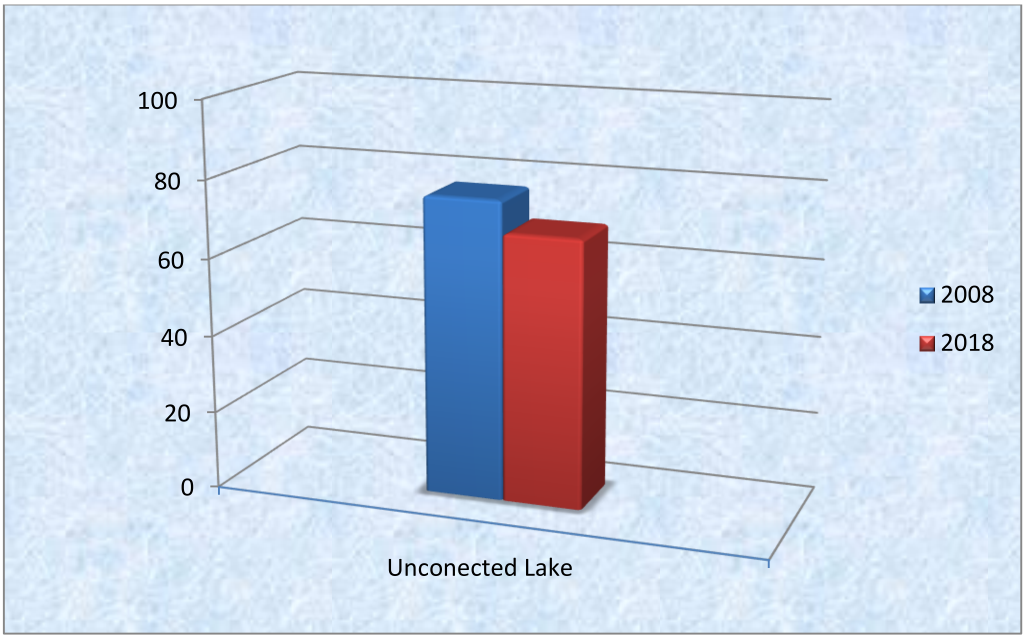



**Fig. No. 8: Area and Area Change of Unconnected Lakes (in $Km^{2}$)**

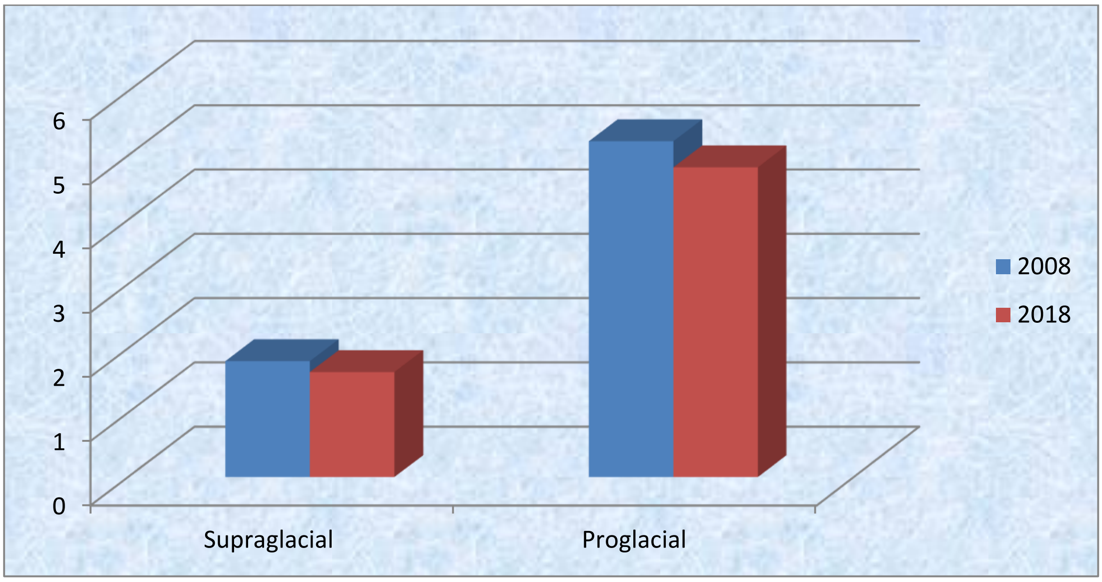



**Fig No. 9: Volume and Volume Change of Supraglacial and Proglacial Lakes (in $Km^{3}$)**

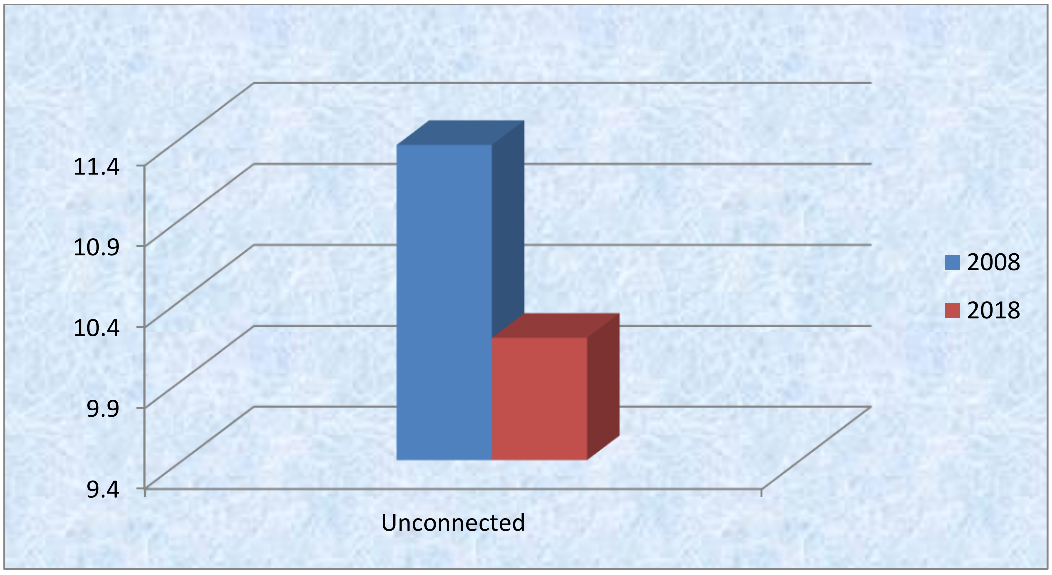



**Fig No. 10: Volume and Volume Change of Unconnected Lakes (in Km$^3$)**

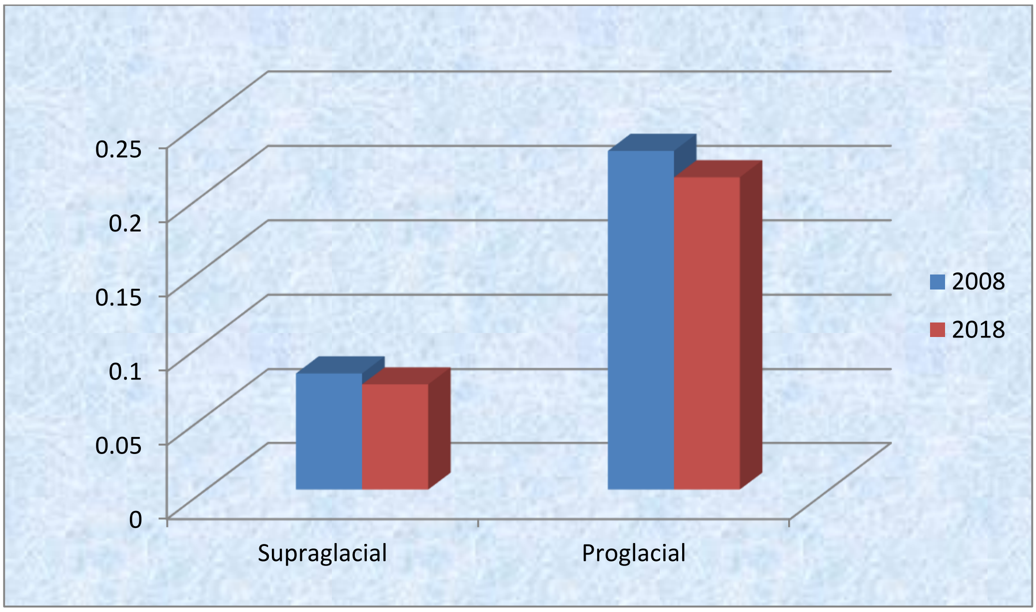



**Fig No. 11: Depth and Depth change of Supraglacial and Proglacial Lakes (in Km$^2$)**

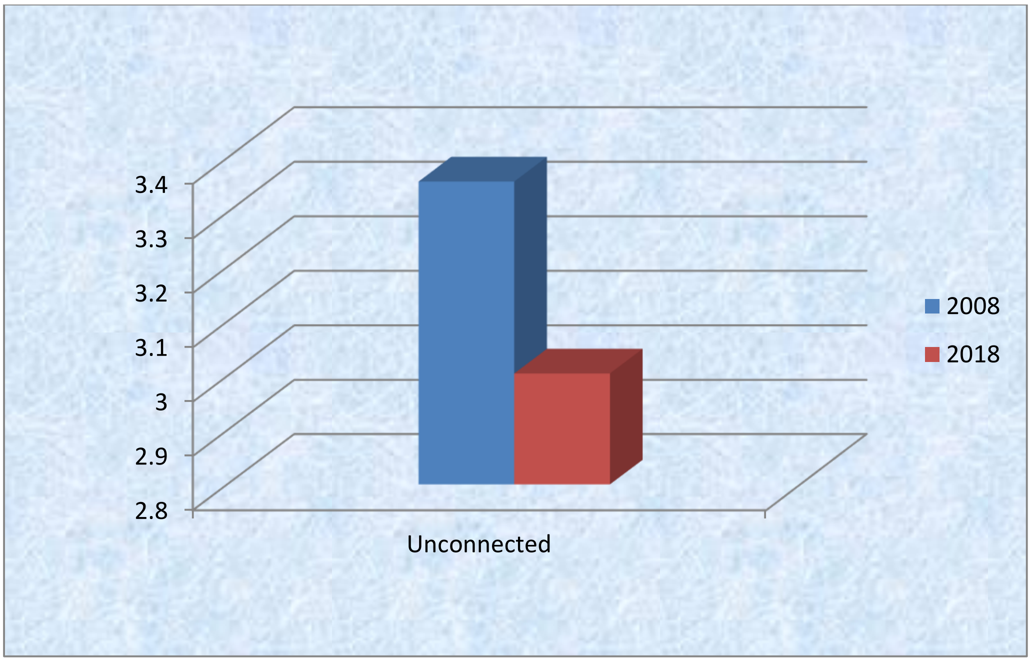



**Fig No. 12: Depth and Depth change of Unconnected Lakes (in Km$^2$)**

## VI. Conclusion

In our study we focused on mapping glacial lakes in the Upper Indus Basin and identifying potentially dangerous glacial lakes based on their area, depth, and volume. We used Landsat imagery to map glacial lakes from 2008 and 2018 and found that there were 547 glacial lakes in 2008 and 560 glacial lakes in 2018. We classified these lakes into low-risk, medium-risk, and high-risk categories based on their area, depth, and volume. Our analysis identified 11 potentially dangerous glacial lakes in the region, with a combined area of 38.654 km$^2$. We also found that there were 162 glacial lakes in the medium-risk category and 387 glacial lakes in the low-risk category.

Overall, our findings demonstrate the importance of studying and monitoring glacial lakes in the context of climate change and natural disaster management.

We hope that our study will contribute to the understanding of the impact of climate change on glacial lakes and the management of natural disasters in the future.

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