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Exploring potential glacial lakes using geo-spatial techniques in Eastern Hindu Kush Region, Pakistan

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ABSTRACT

The study aimed to investigate the potential glacial lakes in response to climate change and the associated risk of glacial lake outburst floods (GLOFs). Remote sensing data and GIS techniques were utilized to analyze glacial lakes, employing empirical models to estimate their area, volume, and depth. The Normalized Difference Water Index (NDWI) was applied to detect changes in glacial lakes using Sentinel imagery. The findings revealed a notable increase in both the number and surface area of glacial lakes over the past two decades. Specifically, the number of glacial lakes rose from 101 in 2000 to 162 in 2020, while their combined surface area expanded from 9.72 km^2 to 12.36 km^2 during the same period. Among these lakes, 31 were identified as Potentially Dangerous Glacial Lakes (PDGLs), with 6 located in Chitral, 16 in Swat, and 9 in Upper Dir. Two lakes were classified as high potential glacial lakes, with depths estimated at 41.86 m and 30.43 m. Continued monitoring of these glacial lakes and their susceptibility to GLOFs is crucial in the face of ongoing climate change. Long-term planning and adaptation strategies are necessary to safeguard the well-being and safety of communities residing in these vulnerable regions. By understanding the evolving characteristics of these lakes, researchers and policymakers can better prepare for and mitigate the impacts of GLOFs on downstream communities and infrastructure.

1. Introduction

The melting of glaciers in the Hindu Kush Himalayan region is a significant concern, and urgent action is needed to mitigate the impacts of climate change on these vital freshwater resources. (Rahman and Shaw, 2022). The melting of these glaciers can lead to the formation of glacial lakes, which pose a significant risk of disastrous floods. Such events have occurred in the region before and have caused considerable human life loss and damage to infrastructure (Gul et al., 2020). The melting of glaciers lead to the development of new water bodies and expansion of existing lakes that can pose a great threat to downstream exposed communities in the case of glacier lake outburst floods (GLOFs) (Ashraf et al., 2017a). Glacial lakes are categorized on the basis of their glacier position relative to the glaciers, e.g., pro-glacier, en-glacier, sub-glacier, supra-glacier and moraine-dammed lakes (Zhang et al., 2015). Similarly, these lakes were classified on their dam material: moraine dammed lake, ice-dammed lake and granite dammed lake. The classification scheme of lakes is the distinction of two levels is based on size of lake system and Volume (ICIMOD, 2007). The Hindu Kush range is a source of glacier and snow feeding the river systems (Ageta et al., 2013). The high mountain regions of Asia, such as the Himalaya, Karakoram and Hindukush Mountains, have significant glacier deposits and are key water suppliers for major rivers in Asia (Chen et al., 2021). However, the climate of the region varies, with the southern and eastern parts influenced by monsoons and the northern and western parts influenced by westerlies (Krishnan et al., 2019).

Glaciers are also important climate indicators and can help detect rapid responses to climate change (Christian et al., 2022). Spatio-temporal monitoring of glacier dynamics over time, such as mass balance, snout position, and equilibrium line altitude (ELA), is important to understand the impact of climate change on the health of glaciers (Romshoo et al., 2022). However, access to high mountain Asian glaciers is challenging, and remote sensing techniques are often used for glacier monitoring (Zhang et al., 2022). The Remote sensing products are cost effective and efficient tools of spatial and temporal analysis of glaciers and identification of glacial lakes (Lanfredi et al., 2022). Various studies (Yu et al., 2023; Koch et al., 2023; Yang et al., 2022; Jawak et al., 2023; Sood et al., 2022; Bazilova and Kääb, 2022; Verma and Ramsankaran, 2022; Sogno et al., 2022) have used remote sensing techniques such as ASTER and SRTM DEMs, Landsat Thematic Mapper, and multispectral and landform analysis for glacier delineation and mapping. The band ratio method and normalized difference snow index (NDSI) method have

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also been compared for extracting glacial parameters, with the band ratio method found to be better for glacier boundary extraction.

In 2005, the International Center for Integrated Mountain Development (ICIMOD) published an inventory of glaciers and glacial lakes which reported that the trend of rising temperature in the HKH regions is higher than the global average (Richardson and Reynolds, 2005). The inventory listed a total of 2420 glacial lakes that have been identified in 10 river basins; the maximum number of glacial lakes is identified in the Gilgit River basin (614) followed by the Indus basin (574). In the Gilgit River basin, out of the 614 glacial lakes 380 lakes have been identified as major lakes (Bajracharya et al., 2015).

The Intergovernmental Panel on Climate Change (IPCC) predicted a rise in temperatures between 1 °C and 6 °C in the Himalayan area by 2100 (Campbell and Pradesh, 2005; Sakai et al., 2000). It would lead in the rapid loss of glacier ice and the snow cover will be decreased in the future by 43%–81%, leaving further glacial lakes behind (Paul et al., 2007). Consistent mapping and monitoring of these dynamic resources is pivotal to keeping track of the pattern and trend of changes. The temporal mapping of glacial lakes provides an indicator for monitoring changing climate patterns (Ives et al., 2010). The mountain glaciers as freshwater ecosystems and it are important to understand the impact of climate change on glaciers, and the need to adopt remote sensing techniques for glacier monitoring in high mountain regions. In this regard, this study aims to explore potential glacial lakes and analyze temporal changes in the glacial lake extent in the past two decades (2000–2020) using geo-spatial techniques.

2. Study area

The Eastern Hindu Kush is a mountain range located in the north-western region of Pakistan. This region is known for its high peaks, glaciers, and alpine lakes, many of which are fed by melting glaciers. Geographically, Eastern Hindu Kush extends between 34°34′11″ to 36°54′30″ North Latitude and 71°11′56″ to 73°52′5″ East Longitude (Fig. 1). Eastern Hindu Kush is comprised of the districts of Chitral, Upper Dir, Lower Dir and Swat. The presence of snow-covered mountains and glaciers in valleys with elevations reaching 4000 m above sea level is an essential aspect of the region's ecosystem. The melting of these glaciers and snow cover in the region is likely to have significant impacts on the availability of freshwater resources. Changes in temperature and precipitation patterns can affect the timing and amount of water runoff from melting glaciers, potentially leading to water shortages and natural hazards like flooding and landslides (Mahmood, 2019).

Climatically, the study area has cool-to-warm summer with 16 °C minimum and 32 °C maximum temperature. Temperature falls below freezing point from December to February. Snowfall is the characteristic feature of winter season. Variation in rainfall ranges in December was minimum rainfall 823–2149 mm in March was maximum rainfall. In general, snowfall starts in November and descends southwards as the temperature falls in December. Snow melting starts in March and goes onward depending upon the elevation (Mahmood and Rahman, 2019).

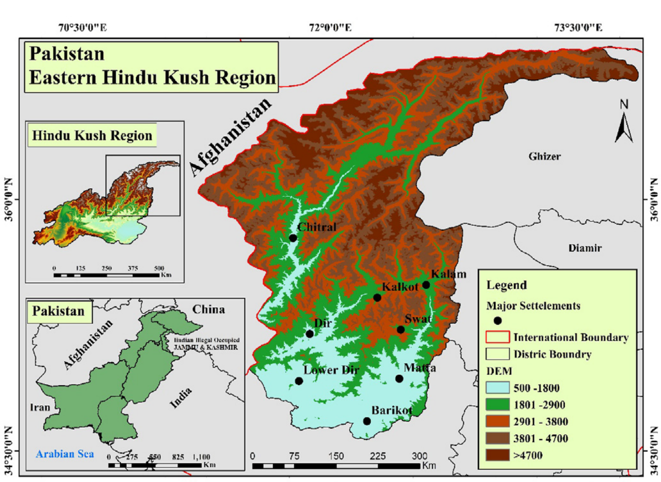

Figure: 1. Location of study area.

3. Materials and methods

3.1. Data acquisition

Advanced Land Observing Satellite Phased Array Type L-Band Synthetic Aperture Radar (ALOS PALSAR) digital elevation model (DEM) having 12.5 m spatial resolution. Cloud free Landsat 5 Thematic Mapper image for the years 2000 and 2010 having 30 m spatial resolution were downloaded from United States Geological Survey (USGS) open source geo-database. Similarly, Sentinel II images for the year 2020 having 10 m spatial resolution were downloaded from the Copernicus Open Access Hub open source geo-database (Table 1). All images were downloaded for August because of the fact that it is peak summer with heavy melting of glaciers that increase lake volume. Meteorological data were acquired from Regional Meteorological Center Lahore (1991–2020). The data were processed in Geographic Information System (GIS) and then Lake Inventory was developed (Fig. 2) (see Table 2).

3.2. Lake assessment

The temporal variation and glacier lakes changes were analyzed using Landsat 5 and Sentinel II satellite images for the classification and change detection using Normalized Difference Water Index (NDWI) and the Modified Normalized Difference Water Index (MNDWI) given in Equations (1) and (2) as suggested by (Bajracharya et al., 2007).

$$NDWI = \frac{GREEN - NIR}{GREEN + NIR} \quad \text{Eq. 1}$$

$$MNDWI = \frac{GREEN - SWIR}{GREEN + SWIR} \quad \text{Eq. 2}$$

The MNDWI was introduced by Han-Qiu in 2005 as a modification of the NDWI. While NDWI uses the near infrared (NIR) band, MNDWI replaces it with the shortwave infrared (SWIR) band. This substitution helps to suppress information from built-up and other background features, allowing for more accurate extraction of water body information in the target area. MNDWI leverages the higher reflectance in the green and NIR bands to express water features effectively.

To delineate water bodies accurately, the threshold value for MNDWI, like NDWI, is typically set to zero. However, manual editing is often performed to enhance the precision and accuracy of water body

Table 1
Properties of Landsat and Sentinel II images.

Name of the Identifier	Year	Bands		Wavelength (μm)	Resolution (m)
		GREEN	NIR		
Landsat 4–5 Thematic Mapper (TM)	2000	3		0.63–0.69	30
Landsat 4–5 Thematic Mapper (TM)	2000		5	1.55–1.75	30
Landsat 4–5 Thematic Mapper (TM)	2010	3		0.63–0.69	30
Landsat 4–5 Thematic Mapper (TM)	2010		5	1.55–1.75	30
Sentinel-II Multispectral Imager (MSI)	2020	3		0.560	10
Sentinel-II Multispectral Imager (MSI)	2020		8	0.842	10

Table 2
High potential glacial lakes.

Lake ID	Area (km^2)	Volume (m^3)	Depth (m)	Elevation (m)
Chitral-GL2	1.5923	66,664,468.81	41.86774547	4493
Swat-GL31	0.7452	22,681,831.94	30.43638476	3507

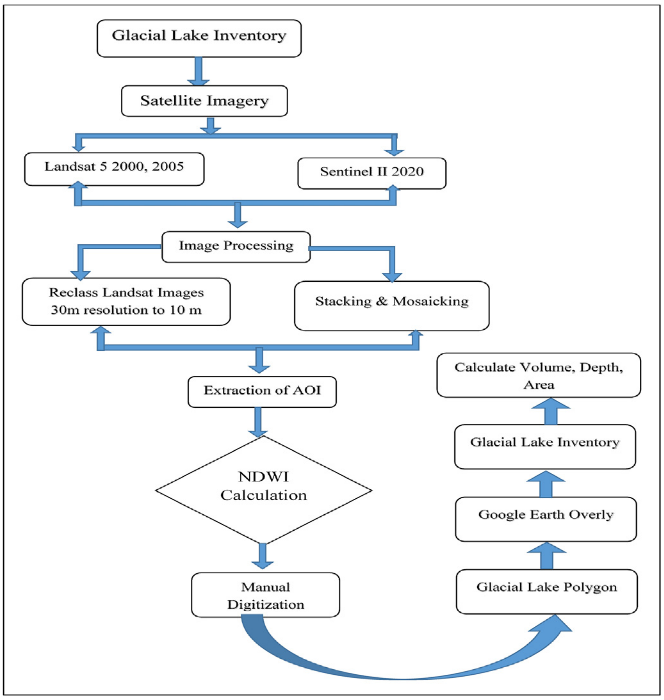

Figure: 2. Glacial lake inventory process.

delineation. The study by (Jilani and Haq, 2008) demonstrates the refinement achieved through manual editing. Both NDWI and MNDWI utilize the highest reflectance values from the green, NIR, and SWIR bands to extract water bodies.

The resulting ratio images from NDWI and MNDWI are further classified into specified intervals for delineating glacial lakes. These images are visually inspected and cross-referenced with Google Imagery. A manual land-water threshold is applied to classify the images into two classes: land and water. The determination of suitable thresholds for each index involves trial and error as well as observation of the histogram. Extensive manual editing and delineation of the lake boundaries are performed using Google Earth images, which are adjusted with reference data. The NDWI values range from −1 to +1, with water features predominantly found close to the +1 value. McFeeters (1996) established the threshold value of zero for water bodies. Values towards −1 indicate vegetation, bare soil, or land features (Sakai et al., 2000).

3.3. Estimation of lake volume and depth

Lake volume estimation is often conducted using empirical techniques, as suggested by Equations (3) and (4) in previous studies (Mahmood and Atiq, 2022). The relationship that established the links between lake depth, area, and volume for various types of lakes, including ice-dammed, moraine-dammed, and thermokarst lakes worldwide. This relationship has been widely applied in different research studies to estimate lake volume (McFeeters, 1996).

Several studies (McFeeters, 1996; Han-Qiu, 2005; Huggel et al., 2002; Bolch et al., 2012; Mergili and Schneider, 2011) have utilized this approach to estimate lake volume. These studies have adopted the empirical relationship to estimate the volume of lakes in various geographical contexts.

$$D = 0.104A^{0.42} \quad \text{Eq. 3}$$

$$V = 0.104A^{1.42} \quad \text{Eq. 4}$$

where D is the mean lake depth (in meters), the area is measured in m^2 and the volume in m^3.

4. Result, analysis and discussion

4.1. Glacial lakes inventory

The study conducted in the Eastern Hindu Kush region which identified and mapped 101 glaciers using Sentinel II imagery. The study provides valuable insights into the distribution and characteristics of the glaciers in the region.

The study found that the total surface area covered by the 101 glaciers in the Eastern Hindu Kush region was 9.72 km^2, with the largest lake having an area of 0.84 km^2 and the smallest lake covering only 0.003 km^2. It is interesting to note that the smaller lakes covered only 31.68% of the total lake area, while the remaining 68.32% were covered by larger lakes, with only 16 of them having an area greater than 0.15 km^2.

In the year 2010, there were 124 glacial lakes in the Eastern Hindu Kush region, with a total surface area of 11.08 km^2. These lakes were classified based on satellite data, and there were 27 Chitral-GL, 69 Swat-GL, and 28 Upper Dir-GL. The area of lakes varied from 0.003 km^2 to 1.58 km^2, with 67 lakes having an area smaller than 0.038 km^2. The smaller lakes covered only 54.03% of the total lake area, while the larger lakes covered 45.97% of the total area. Among the larger lakes, 18 lakes had an area greater than 0.15 km^2, and their total area covered only 14.51% of the total area (Fig. 3).

In the year 2020, there were 162 glacial lakes in the Eastern Hindu Kush region, with a total surface area of 12.36 km^2. These lakes were analyzed using Sentinel II imagery, and there were 44 Chitral-GL, 79 Swat-GL, and 39 Upper Dir-GL. Out of the total lake area, 95 lakes had an area smaller than 0.039 km^2, and the total area covered by these smaller lakes was not specified. The larger lakes covered only 12.34% of the total area, and only two lakes (Chitral-GL2 and Swat-GL31) had an area greater than 0.74 km^2. The distribution of lakes among the three regions remained similar to that in 2010, with Swat having the highest number of lakes followed by Chitral and Upper Dir (Fig. 4).

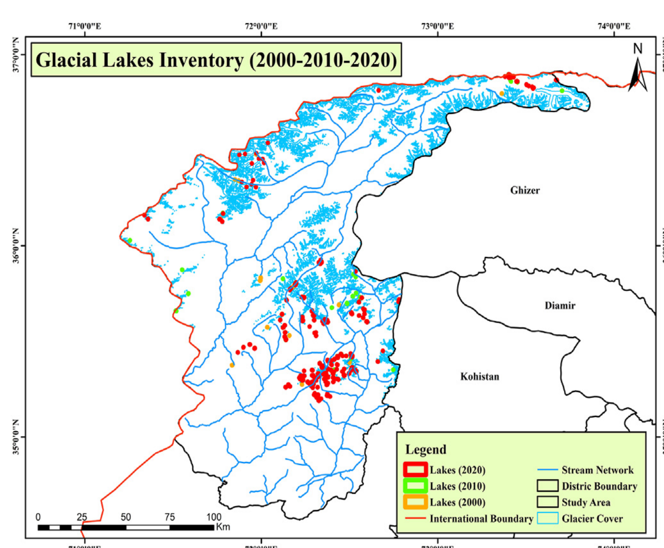

Fig. 3. Spatial inventory of Glacial Lakes.

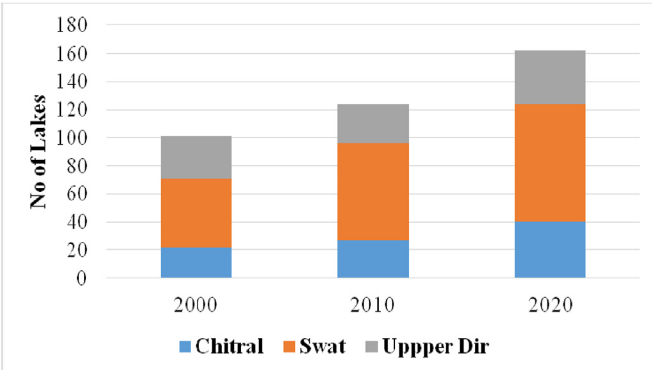

Fig. 4. Distribution of glacial lakes in eastern hindu kush region (2000–2020).

4.2. Disappeared Lakes

Based on the Lake Inventory of the Eastern Hindu Kush region, a total of 15 glacial lakes vanished between 2000 and 2020. These lakes became disconnected from their parent glaciers, resulting in their disappearance. Among these lakes, 7 were situated in Chitral, 3 in Swat, and 6 in Upper Dir. It is important to highlight that the disappearance of glacial lakes can have significant consequences for the environment and society. It can lead to the formation of hazardous glacial lake outburst floods (GLOFs) and affect water availability for communities reliant on glacial meltwater. Hence, the continuous monitoring and management of glacial lakes are essential to ensure the safety and well-being of local populations and the surrounding ecosystems (Fig. 5).

4.3. Newly formed lakes

The significant rise in the number and area of lakes in the Eastern Hindu Kush region from 2000 to 2020 is likely due to the melting of glaciers caused by climate change. As temperatures increase, glaciers in the region are retreating, leaving behind melt water that accumulates in depressions in the landscape, creating new lakes. According to the information provided, a total of 79 new glacial lakes appeared in the Eastern Hindu Kush region between 2000 and 2020. Out of these, 23 lakes appeared in 2010, while 3 lakes disappeared after 2010. This means that there was a net increase of 20 lakes in 2010. In 2020, a further 59 new lakes appeared, bringing the total number of new lakes to 138. The area of the lakes ranges from 0.0006 km^2 to 0.187 km^2 in 2020, indicating that they vary in size. The formation of these new lakes has significant implications for the environment and communities in the region. The accumulation of water in glacial lakes can increase the risk of glacial lake outburst floods (GLOFs), which can be catastrophic for downstream communities (Fig. 5).

Moreover, the increase in the number of lakes in the region can also have an impact on the local ecology and biodiversity. As such, it is important to monitor these changes closely and take steps to mitigate the potential risks associated with the formation of new glacial lakes.

4.4. Potential glacial lakes (PGL)

In the region, a total of 31 potential glacial lakes (PGLs) have been identified as having the capacity to trigger glacial lake outburst floods (GLOFs). Among these PGLs, 6 are located in Chitral, 16 in Swat, and 9 in Upper Dir (Fig. 6). The elevation of these PGLs varies, with 4 lakes situated between 3000 and 3500 m, 11 lakes between 3500 and 4000 m, and the majority, which is 18 lakes, positioned below 4000–4500 m. Out of the 31 PGLs, only 2 have been classified as having a high potential for GLOFs. These lakes are Chitral-GL2 and Swat-GL31, with respective areas of 1.59 km^2 and 0.74 km^2 (Table 1). The depth of Chitral-GL2 is recorded as 41.86 m, while Swat-GL31 has a depth of 30.43 m.

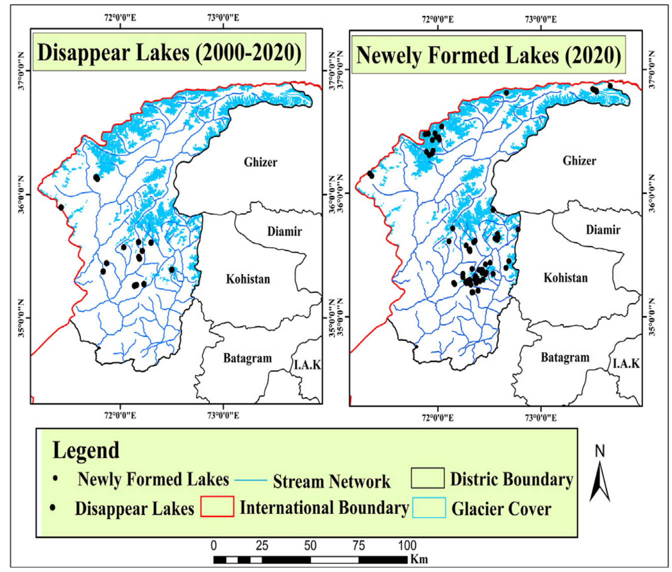

Fig. 5. Disappear lakes and newly formed lakes.

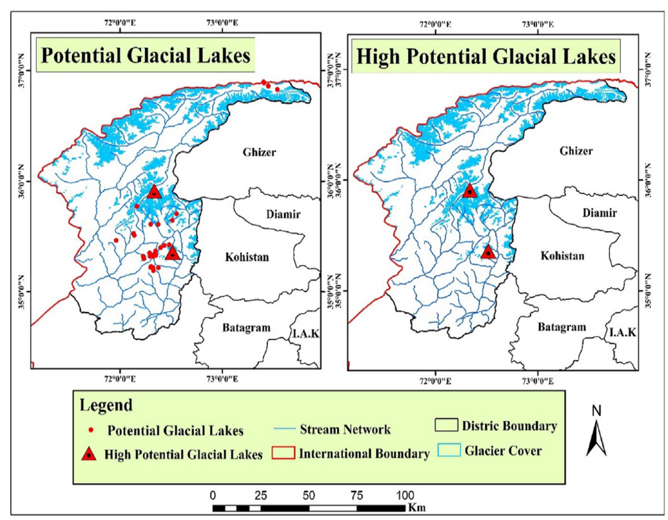

Fig. 6. Potential Lakes and High potential Lakes.

4.5. Discussion

The study used remote sensing data sets in a GIS environment to explore potentially dangerous glacial lakes in the Eastern Hindu Kush region. Specifically, the study utilized Sentinel II and Landsat 5 satellite imagery, as well as the Normalized Difference Water Index (NDWI) to achieve its objectives. The NDWI is a commonly used index for mapping water bodies using remote sensing data. It is based on the principle that water absorbs more radiation in the near-infrared region than in the visible region, resulting in a higher reflectance in the visible region than in the near-infrared region. In addition to using NDWI, the study also employed an empirical technique for the estimation of lake volume and depth. This likely involved using satellite imagery to measure the area of the lake and then using a relationship between area and depth or volume to estimate the lake's volume and depth. Overall, the use of remote sensing data sets and GIS techniques in this study allowed for a comprehensive assessment of potentially dangerous glacial lakes in the region, which is important for identifying areas that may be at risk of glacial lake outburst floods (GLOFs) and developing appropriate mitigation measures.

The analysis revealed that lake is expanding at an unprecedented rate. Most of the glaciers are expanding that are located at an altitude of 3500 m a.m.s.l to 4000 m a.m.s.l. Average lakes surface area has been increased from 9.72 km^2 (2010) to 12.36 km^2 (2020) and 79 new lakes formed and some are disappeared. The analysis further reveals that 31 potential lakes and two highly potential lakes lie in the heavy rainfall area. The largest glacial lake in the Eastern Hind Kush region is 41.86 m, which lies in the Chitral district. Almost 67% of lakes mapped in the Eastern Hind Kush are less than 0.05 km^2, 25 lakes are larger than 0.11 km^2 the average size of the lakes in 2000 in the region is 0.09 km^2, size of lake in 2010 is 0.08 km^2 and 2020 the average size of lake is 0.07 $km^{2.}$

The analysis also revealed that the Eastern Hindu Kush region has a significant number of glaciers, the larger lakes cover a relatively small area of the total glacier area. This information could be useful in developing targeted conservation and management strategies for the region's freshwater resources, focusing on preserving and protecting the larger lakes that cover a more substantial portion of the glacier area. Overall, the study provides valuable information on the distribution and characteristics of glaciers in the Eastern Hindu Kush region, which can help in understanding the impacts of climate change on these vital freshwater resources. It is important to monitor these PGLs regularly to assess any changes in their size, depth, and potential for GLOFs. This information can then be used to develop early warning systems and contingency plans to minimize the potential impact of GLOFs on downstream communities and infrastructure. Moreover, the increase in the number of lakes in the region can also have an impact on the local ecology and biodiversity. As such, it is important to monitor these changes closely and take steps to mitigate the potential risks associated with the formation of new glacial lakes (Sharma et al., 2019).

It is clear from the analysis that high resolution satellite images can greatly improve the exploration and assessment of glacial lakes. High resolution images can help to identify small or newly formed lakes, which may have been missed by other methods. Machine learning techniques, such as the use of data-driven NDWI maps and random forest classifiers, have also been shown to be effective for mapping lakes on ice sheets (Wester et al., 2020; Chen et al., 2007). In future studies, the integration of machine learning techniques with high resolution data and NDWI maps could further improve the methodology for alpine glacial lake mapping and inventorying. The use of deep learning methods is also suggested as a potential avenue for advancing the accuracy and efficiency of glacial lake mapping (Ashraf et al., 2017b; Ahmed et al., 2022). The proposed method described in the analysis successfully integrates the random forest classifier and utilizes the strengths of existing methods. By incorporating machine learning techniques and high resolution data, the proposed method has the potential to improve the accuracy and efficiency of glacial lake mapping and inventorying (He et al., 2021; Chen et al., 2022; Wu et al., 2020). Finally, the results and finding of the study can further be improved by conducting field work. The impact climate change needs to determine in future studies. Similarly, the geo-spatial assessment of GLOF risk in the downstream communities is also highly required.

5. Conclusion

In conclusion, the study employed remote sensing data and GIS techniques to investigate potentially hazardous glacial lakes in the Eastern Hindu Kush region. The integration of Sentinel II and Landsat 5 satellite imagery, along with the use of the NDWI index, allowed for a comprehensive assessment of these lakes. The analysis revealed a notable expansion of lakes, particularly in glaciers located between 3500 m and 4000 m above mean sea level. The average surface area of lakes increased over time, with the formation of new lakes and the disappearance of others. The study identified 31 potential lakes, including two with a high risk of GLOFs, mainly concentrated in areas with heavy rainfall. Larger lakes covered only a small fraction of the total glacier area, suggesting the need for targeted conservation and management strategies. Monitoring of these glacial lakes is crucial to track changes and develop mitigation measures.

High-resolution satellite images proved invaluable for identifying small or newly formed lakes that may have been overlooked using other methods. Machine learning techniques, such as data-driven NDWI maps and random forest classifiers, demonstrated effectiveness in lake mapping. Future studies can further improve the methodology by integrating machine learning, high-resolution data, and NDWI maps. Deep learning methods also hold potential for enhancing the accuracy and efficiency of glacial lake mapping. Fieldwork and additional research are recommended to assess the impact of climate change and evaluate GLOF risks in downstream communities. Overall, the study provides valuable insights into the distribution and characteristics of glaciers in the region, aiding in the understanding of climate change's effects on freshwater resources.

Conflict of interest

The Author declared that they have no conflict of interest.

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This research article is part of Mariam Sarwar MS research work. Both authors contributed equally.

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