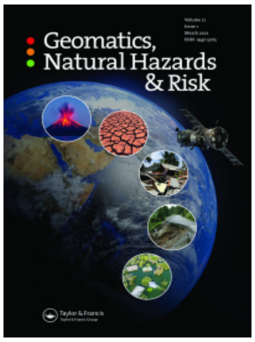

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The growth and emergence of potentially dangerous glacier lakes in Astore Basin, Western Himalaya during 1993–2021

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ABSTRACT
The recent retreat of glaciers in High Mountain Asia is a major issue for downstream communities. Similarly, glaciers in the Astore Basin are melting, causing glacial lakes to expand faster, new lakes to form, and increasing the risk of glacial lakes outburst floods (GLOFs). The present study uses Landsat data from 1993 to 2021 to explore seasonal and decadal changes in glacier lakes, which are validated using an *in situ* differential Global Positioning System (dGPS). During the ablation period (June - October) of 2021, we observed a five-fold increase (18 to 100) in the number of glacier lakes, as well as a six-fold increase (0.62 to 3.86 km^2) in lakes larger than 0.01 km^2. Over the last decade, from 2011 to 2020, the number of potentially dangerous glacial lakes (PDGLs) has doubled. GLOF risk must be reduced through continual monitoring of these lakes. Prioritizing the deployment of GLOF monitoring and early warning systems, as well as sustainable water management practices, is critical for mitigation and adaptation measures in mountainous regions.

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Glaciers; glacial lake outburst floods; remote sensing; dGPS; Astore Basin; Himalaya; LST

1. Introduction

Glaciers are important indicators of climate change and provide freshwater to billions of people in High Mountain Asia (HMA) (Jones et al. 2019; Mohammadi et al. 2023; Rounce et al. 2023; Kaushik et al. 2022). The Himalayan region is one of the few regions where climate change becomes particularly observable (Negi et al. 2021; Kiani et al., 2021; Wester et al. 2019). Global warming poses a threat to these glaciers (Compagno et al. 2022), resulting in rapid global retreat (Shean et al. 2020), while warming reported in the Himalayan region is higher than global mean warming (Negi et al. 2018;), causing accelerated mass loss (Nie et al.

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2021; Sabin et al. 2020; Sharma et al. 2022). The stable glaciers in the Karakoram that existed throughout the first decade of this century began to melt in the second decade (Jackson et al., 2023).

Glacier retreat leads to the formation of glacial lakes (Carrivick and Tweed 2013;), posing risks downstream when they experience outbursts. The resilience of lakes is influenced by various factors such as their physical condition, dam stability, glacier activity, and surrounding stability (Bajracharya et al. 2020). Unstable moraine or glacier ice, as well as destabilizing permafrost slopes or hanging glaciers, can increase the risk of slope failure and subsequent flooding (Muhammad et al., 2019a; 2021). Moraine-dammed lakes, which consist of vulnerable moraines, are particularly susceptible to glacier lake outburst floods (GLOFs). GLOFs can occur due to dam breach, overfilling, and moraine/ice dam degradation (Majeed et al. 2021). The triggering of GLOFs is complex and can result in significant damage to property, infrastructure, and agricultural land, as well as loss of life (Emmer et al. 2020).

The number and size of glacier lakes are expected to grow, especially in regions like HMA (IPCC: Ocean, Cryosphere and Sea Level Change., 2023). Glacier-related floods, mainly from lake outbursts, are a significant hazard in glacierized mountain ranges (Zhang et al. 2023; Mondal et al. 2023). Specific events, such as the Jinweng Co GLOF in 2020 and the Chorabari lake debris flow in 2013, have caused major damage to infrastructure and loss of life (Zheng et al. 2021). The catastrophic flood in the Rishiganga River in 2021 was caused by a rockslide and resulted in the destruction of infrastructure and loss of lives. There is an uncertainty in the present trends and future development of glacier lakes (Kumar et al. 2020). Muhammad et al. (2021) evaluated the physical processes and downstream impacts of Shisper glacier lake outburst resulted in GLOFs between 2019 and 2021 three times.

In the Himalayas, the probability of GLOFs could rise thrice in the future (Zheng et al. 2021). GLOFs have varying worldwide impacts and require immediate response to reduce their effects. Climate change in the Himalaya region is causing glacial lakes to expand due to warming and increasing discharge at higher elevations, perhaps leading to more flood occurrences and reduced low flows (Chalise et al. 2006). Glacial lakes have expanded quickly since 1990, expanding by almost 50% worldwide (Shugar et al. 2020). This research investigates the development and evolution of glacier lakes in the Astore Basin, Northwestern Himalayan.

To assess the growth and changes in the glacier lakes of Astore Basin, the study employs remote sensing data, National Tibetan Plateau Data Center (TPDC) climate data, Pakistan Meteorological Department (PMD) station data, and differential global positioning system (dGPS) field observations. Previous regional-scale research used lake volume as a proxy to assess the possible danger of GLOFs (Zheng et al. 2021). However, a more recent study by Taylor et al. (2023) used a consequence-based method, employing total lake area as a proxy to evaluate the intensity of possible GLOFs. According to this theory, larger lakes may have more intense GLOFs. We identified eleven glacial lakes in the Astore Basin that cover more than 0.1 km^2.

The extent of these lakes has increased in the recent past. The study emphasizes the importance of monitoring these lakes to better understand the consequences of climate change on water resources. However, the study is limited in its capacity to accurately simulate GLOFs and evaluate their downstream implications.

2. Study area

The Astore Basin is situated in the Nanga Parbat region of northern Pakistan, between 34°50′–35°40′ N and 74°30′–75°10′ E. It covers an area of approximately 3995 km^2 with an elevation range from 1202 to 8126 metres above sea level, located in the northwestern Himalayan region (Farhan et al. 2015). Astore meteorological data show an annual mean temperature of 9.8 °C and precipitation of 464 mm from 1961 to 2019. The basin area is mainly covered by glaciers and accumulated seasonal snow. Glaciers cover 14% of the basin area 320 km^2 according to RGI 6.0 (RGI Consortium, 2017), and seasonal snow reaches up to 80–85% (Muhammad et al. 2019b). Over 75% of annual runoff is dependent on melt-water from seasonal snow and glacier ablation (Farhan et al. 2015). The study area map is illustrated in Figure 1.

3. Data and methods

3.1. Data

Landsat data has widely been used for studying the Earth's surface, natural resources, cryosphere changes, and many other applications. Landsat 5 collected data in seven spectral bands, while Landsat 7 is still operational and has an 8-day repeat cycle

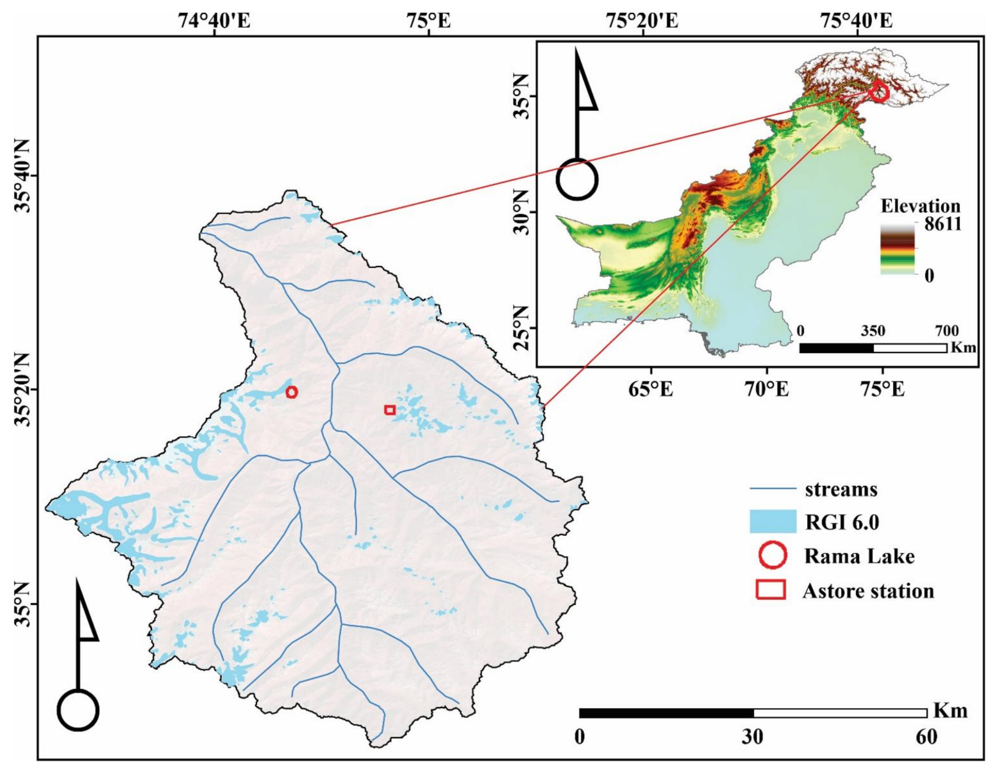

Figure 1. Study Area map of Astore River Basin highlighting Pakistan, Astore Basin with Randolph Glacier Inventory, RGI 6.0 glaciers boundaries (RGI Consortium, 2017), streams and Rama Lake.

(Hansen and Loveland 2012; Ju et al. 2012; Roy et al. 2014). Similarly, Landsat 8, launched in 2013, has a 16-day repeat cycle and covers the entire Earth's surface. The processed, calibrated, and archived data from Landsat is freely accessible to the public through the USGS (Zhu et al. 2019).

Landsat 5,7, and 8 between 1993 and 2021 were acquired from the United States Geological Survey https://earthexplorer.usgs.gov/ as shown in Table 1. Pre-monsoon and post-monsoon seasons cover ablation and accumulation periods in Western Himalayas. Therefore, the June and September/October data was processed to assess long term changes in the ablation and accumulation periods, as glacial lakes are snow free in the ablation season (Muhammad and Thapa, 2019c; Gul et al., 2017). Landsat-7 ETM + failure, causes scanned lines and gaps in data (Markham et al. 2004). This limitation affected the availability of data with complete coverage after May 2003. As a result, June 1993 and Sep 2001 data was used for these years. In addition, MODIS (MOD11A2) Land surface temperature (LST) data from https://modis.gsfc.nasa.gov/ from 2001-2021. Composite data spanning 8 days was acquired to mitigate the effects of cloud cover.

Besides remote sensing data, climate data was collected from Astore Station from 1961 to 2021 from PMD. High-resolution near-surface meteorological forcing dataset for the Third Pole region TPMFD, for 1979–2020 by Yang et al. (2023) was obtained from https://data.tpdc.ac.cn/ with a resolution of ∼4 km. Peng et al. (2019) developed a gridded dataset with a spatial resolution of 1 km for China and surroundings but uses meteorological observatories from China. This data could prove a valuable data source for similar studies within its geographic coverage. Monthly temperature data was acquired with minimum, maximum and average temperature. Also, dGPS field observations were conducted at Rama Lake in October 2021 to confirm the accuracy of satellite data. Analysis of climatic trends facilitate assessments of temperature and precipitation fluctuations on glacial lakes in the Astore Basin.

3.2. Methodology

Landsat data preprocessing is crucial for remote sensing, to understand the Earth's surface and its temporal changes (Jensen, 1987). This involves atmospheric correction, radiometric calibration, and geometric correction to eliminate noise and artefacts ensuring accurate registration of all bands.

Table 1. Landsat scenes with date, sensor, and tile number.

Year/Month	Landsat Sensor	Path/row
1993/Jun	Landsat 5 TM (Thematic Mapper)	149/035 149/036
2001/Sep	Landsat 7 ETM+ (Enhanced Thematic Mapper Plus)	149/035 149/036
2014/Jun	Landsat 8 OLI (Operational Land Imager)	149/035 149/036
2014/Sep	Landsat 8 OLI	149/035 149/036
2021/Jun	Landsat 8 OLI	149/035 149/036
2021/Oct	Landsat 8 OLI	149/035 149/036

The study utilized Landsat TM, ETM+, and OLI satellite data from 1993–2021, as well as dGPS field observations in 2021, to study glacial lakes in the region. Techniques including classification, digitization, and validation with field observations, were employed to detect glacial lakes. Maximum likelihood classification (MLC) algorithm was used to classify the remotely sensed data, which estimates the probability distribution of input data for each class and assigns pixels to the class with the highest probability (Congalton and Green 2019). MLC algorithm in ENVI was specifically used for glacial lakes mapping. Results were compared with High Mountain Asia Near-Global Multi-Decadal Glacial Lake Inventory, Version 1) (Shugar et al. 2020) and the GLOF Third Pole data set (Zheng et al. 2021). To overcome the uncertainties in large scale mapping our results suggest comparisons are needed to overcome these uncertainties and flaws in automated approaches, detailed methodology Figure 2.

3.3. Statistical tests for the trend analysis

The study utilized the Mann-Kendall (MK) test to analyze climate data obtained from the PMD and the TPDC dataset. The MK test is a non-parametric test commonly used for trend analysis in climatic and hydrologic time series data. It helps identify changes and trends over time. To ensure accurate trend detection, the study addressed the issue of serial correlation in the raw data by performing pre-whitening. Pre-whitening is an essential step in trend analysis as it reduces the impact of serial correlation on trend estimates (Serinaldi and Kilsby 2016). Previous research has demonstrated that failure to pre-whiten can result in biased trend estimates (Serinaldi and Kilsby 2016) and that pre-whitening improves the accuracy of trend detection in hydrological time series data (Yue and Wang 2002). After pre-whitening data, MK test was applied to analyze the climate data and detect trends over time.

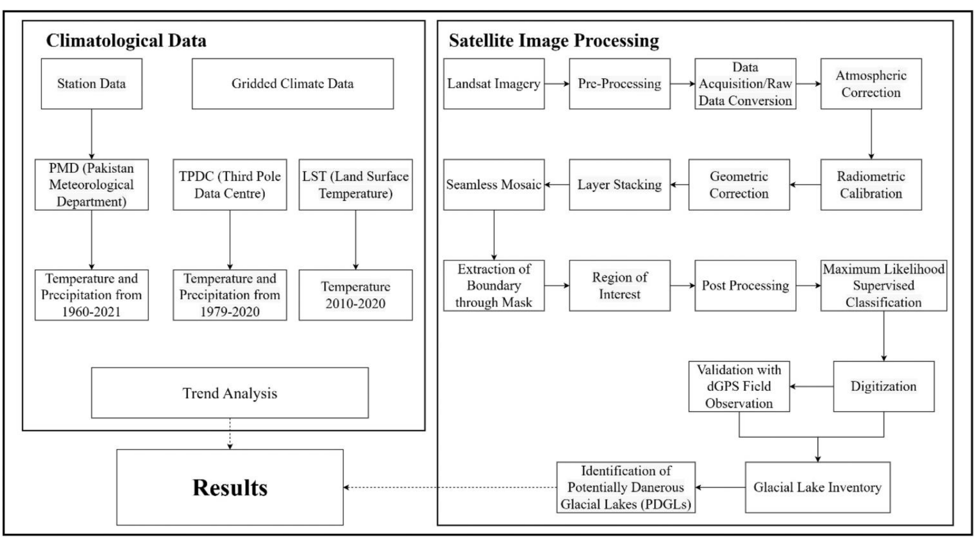

Figure 2. Methodology flowchart.

3.4. GLOF risk identification

Bajracharya et al. (2020) outlined the key features and characteristics that contribute to dam stability:

1. No dam crest (nc) – the volume of inflow and outflow of the lake being equal.
2. Compressed and old dam material (co) – which provides more stability than loose debris.
3. Dam length greater than 200m (dl) – this reduces the erosional capacity of overflow
4. Outer slope of the is less than 20 degrees – a lower gradient results in less erosional capacity.

The likelihood of GLOFs occurring depends on local conditions, including topographic triggers, lake-dam geometries, and lake area/volume (Allen et al. 2016; Allen et al. 2019; Zheng et al. 2021). Generally, lakes larger than 0.1 km^2, increasing in size, and glacial fed lakes are considered potentially dangerous (Iribarren et al. 2014). ICIMOD, (2011), and Mool et al. (2001) provided a set a criterion for potentially dangerous glacial lakes (PDGLs) outlined as follows:

1. Water level rise in glacial lakes dammed by moraines poses a threat to the lake's breaching point.
2. Supraglacial lakes, formed over glacial surfaces, may merge over time, leading to larger and potentially dangerous lakes.
3. The stability of Moraine Dammed lakes is determined by damming material conditions and the nature of the mother glacier.
4. Valley lakes with an area larger than 0.1 km^2 and located within 0.5 km from the mother glacier are considered potentially dangerous.
5. Even cirque lakes even smaller than 0.1 km^2 associated with steep hanging glaciers are considered potentially dangerous.

4. Results and discussion

The investigation indicated considerable changes in the basin's glacier lakes from 1993 to 2021. Between 2001 and 2021, the number of glacial lakes increased from 72 to 100, and their total area expanded from 3.06 km^2 to 3.86 km^2. The growth of glacial lakes has environmental consequences, including the possibility of glacial lake outburst floods, hydrological changes, and downstream repercussions on settlements. The addition of seasonal and decadal analysis provides a more complete knowledge of lake dynamics, emphasizing the importance of ongoing monitoring and management methods. Continuous monitoring utilizing satellite imagery and field observations is critical for understanding and minimizing the risks associated with glacier retreat.

4.1. Mapping uncertainties

To assess the uncertainty of individual glacial lakes, our study used ground truths and compared the results to high-resolution Google imagery. To increase classification accuracy, the kappa coefficient can be used to assess classifier accuracy, resulting in more effective data selection procedures. The error matrix, produced from the confusion matrix, can be used to calculate accuracy by dividing the total number of correct pixels by the total number of pixels in the matrix (Congalton 1991).

The classification accuracy was examined using a confusion matrix, and it was determined to be 99.3% with a kappa coefficient of 0.97. Previously, Jamali (2019) and Gong et al. (2016) achieved higher classification accuracies Landsat data. While mapping on large scale Landsat accuracy is moderate for small scale it can achieve higher accuracies above than 99% (Li et al. 2020). Table 2 shows an elaborated confusion matrix

PDGLs in the Astore Basin are classified based on many parameters, including lakes having an area more than 0.1 km^2, glacially fed lakes, lakes within 10 km of a glacier, and lakes that have been documented to grow over time. Lakes classified as red with an area greater than 0.2 km^2 are more likely to encounter future GLOFs than lakes classified as yellow or blue, which have a very low tendency for GLOFs due to their smaller area of less than 0.1 km^2. Ashraf et al. (2012) designated five lakes in the Astore Basin as PDGLs, each having a surface area more than 0.1 km^2.

Over the next decade, the number of PDGLs increased, with these expanding lakes providing new threats due to their expanding regions. Given the scenario in Northern Pakistan's Astore Basin, ongoing monitoring is critical for mitigating possible dangers and protecting the surrounding areas from the risks posed by these developing glacial lakes.

4.2. Comparison with Third Pole GLOF dataset and HMA Lake Inventory

We compared our study with two existing datasets: the Third Pole Glacial Lakes Inventory by Zheng et al. (2021) and the High Mountain Asia Multi-decadal Lake Inventory by Shugar et al. (2020). These datasets provide valuable insights into the distribution and characteristics of glacial lakes at a large scale, their comparison with Landsat results revealed in Figure 3.

When our Astore Basin glacial lake data was compared to that of the HMA Multi-decadal Lake Inventory (Shugar et al. 2020) and the Third Pole Glacial Lakes Inventory (Zheng et al. 2021), we found that the latter had mapped all small lakes, whereas the former had not taken into account any lakes with an area smaller than 0.05 km^2. Our analysis highlighted the fact that satellite data might occasionally be imprecise when examining wide areas and revealed variations in the quantity and

Table 2. Confusion matrix elaborating product accuracy, user accuracy, overall accuracy percentage and kappa coefficients from 1993–2021.

Year		Product Accuracy (Percent)	User Accuracy (Percent)	Overall Accuracy (Percent)	Kappa Coefficient
1993		99.8%	99.9%	99.9%	0.99
2001		93.1%	99.5%	98.6%	0.95
2014	Jun	99.7%	99.9%	99.9%	0.99
	Sep	99.8%	99.5%	97.5%	0.95
2021	Jun	99.7%	99.9%	99.9%	0.99
	Oct	99.8%	99.9%	99.9%	0.99
Overall		98.6	99.8	99.3%	0.97

area of glacier lakes within the basin. As a result, every year from June through September to October, we performed seasonal analysis. According to our analysis, there has been a noticeable increase in the number and area of glacial lakes over the last ten years, with some small lakes seeing rapid growth.

The Third Pole dataset for 2014–2016 showed 242 glacial lakes in the Astore Basin with an area of 5.61 km^2, of which 107 had an area greater than 0.01 km^2 and covered 5.04 km^2 incrementally. Meanwhile, 26 lakes with an area greater than 0.05 km^2 were

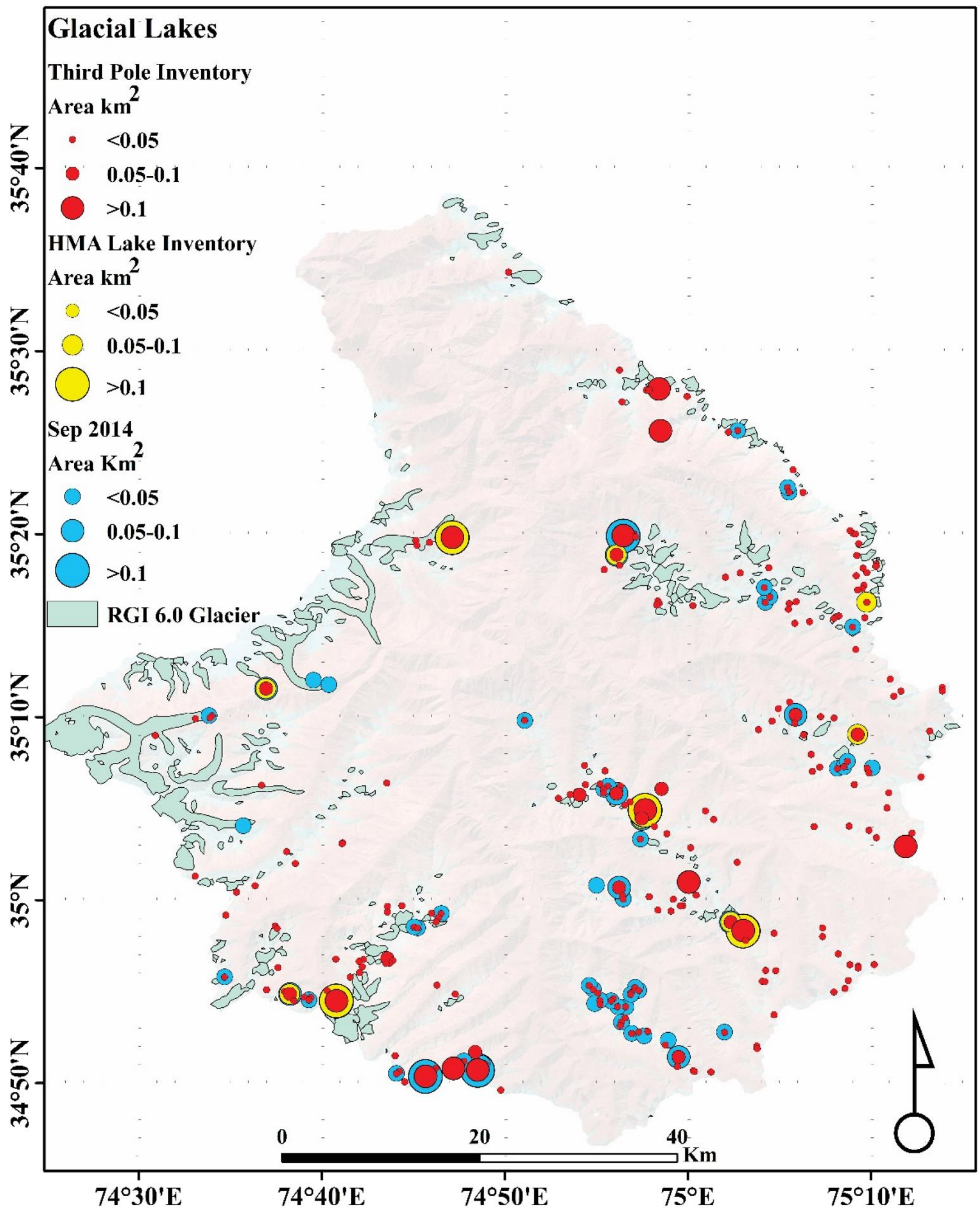

Figure 3. Third Pole, HMA and this study comparison, RGI 6.0 glacier boundary along with Third pole lakes represented red, HMA lakes as yellow, and 2014 results presented as blue.

identified in the HMA inventory for 2015, covering an incremental area of 1.49 km^2. Our detailed study, conducted through field observations and detailed comparison with other inventories, found that in September 2014, the Astore Basin had 63 glacial lakes with an area of 3.23 km^2, of which 50 lakes had an area greater than 0.01 km^2 and covered an area of 3.14 km^2. Additionally, 18 lakes with an area greater than 0.05 km^2 were identified, covering an area of 2.39 km^2. These findings are presented in Table 3.

In conclusion, while the inventories by Shugar et al. (2020) and Zheng et al. (2021) provide major insights into glacial lakes on an extensive scale, we found that the inventory data change when analyzing local locations such as the Astore Basin. As a result, we undertook a thorough investigation at the seasonal and decadal levels. Our extended research underlines the importance of conducting field observations and detailed comparisons to overcome the uncertainties and shortcomings associated with automated techniques.

4.3. Rama Lake, landsat 8 data validation with dGPS data

To validate our results, we used Ground control points (GCPs) placed at known locations in the field and these coordinates were recorded using the dGPS. The dGPS used in this study was previously used for changes in the ablation zones of glaciers in the region (Muhammad and Tian, 2016) and validation of mass balance of Guliya ice cap (Muhammad and Tian, 2020). Comparison of the lake extent derived from Landsat image with the coordinates of the dGPS points to evaluate the accuracy of the image. Our dGPS field observations in 2021 of Rama Lake in Astore Basin validated the Landsat data of the same time. During the field observations 37 dGPS observations were collected at elevation 3400-3502 m.a.s.l and the overall accuracy was found to be 91%. Validation results supported by Figure 4. Landsat data collaborating with in-situ observations provides valuable information, proved instrumental for glacial lakes mapping.

The dGPS shows 0.173 as lake in which 0.0026 is other in Landsat data, similarly, Landsat mapped 0.19 as lake area where 0.019 was not lake in dGPS data. Thus, the overall accuracy obtained was 91.07%. Table 4 shows the overall accuracy obtained by validating the Landsat data with dGPS observations.

Table 3. Third Pole Glacial Lakes Dataset, HMA Inventory and Astore Basin results 2014, number and area of lakes and the lakes having area > 0.01 km^2 statistics.

Glacial Lakes Elements	Third Pole Data Set (2014–2016)	HMA Inventory (2015)	Astore Basin Results (2014)
Number of Glacial lakes	242	13	63
Area(km^2)	5.61 km^2	1.49 km^2	3.23 km^2
Number and Area greater than 0.01 km^2	107	13	50
Cumulative Area of Lakes area > 0.01 km^2	5.04 km^2	1.49 km^2	3.14 km^2
Lakes > 0.05 km^2	26 (3.34 km^2)	13 (1.49 km^2)	18 (2.39 km^2)
Data source	Zheng et al. 2021	Shugar et al. 2020	This study

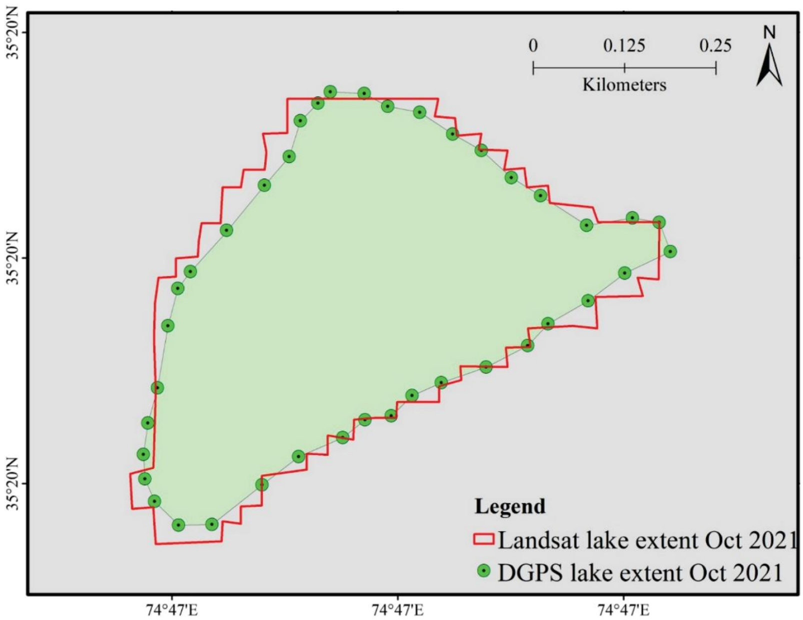

Figure 4. Rama Lake Landsat data validation with dGPS observations Oct 2021.

Table 4. Rama lake overall accuracy obtained from validating landsat data with the observations collected through dGPS.

		Landsat data		
	Lake extent	lake	Others	Total
DGPS	*Lake*	0.1704	0.0026	0.173
	other	0.019	0.05	0.069
	Total	0.19	0.0526	0.242
Overall accuracy (%)		91.07		

4.4. Seasonal and decadal lake's fluctuations in June

In this study, Landsat 5 TM data from June 1993 were used to derive changes in glacial lakes in the Astore Basin. The study found that the Astore Basin had thirteen glacial lakes with a total area of 0.28 km^2. Due to unavailability of data for June 2001, Landsat ETM + was only utilized for the month of September in 2001. While for June 2014 and onwards Landsat 8 OLI was employed, observing the number of glacial lakes increase to 29 with a total area of 0.38 km^2. The analysis detected 18 glacial lakes in the Astore Basin covering an area of 0.62 km^2 in June 2021. The results for June indicate a significant accretion from 0.28 km^2 in June 1993 to 0.62 km^2 in June 2021, showing an overall 54.8% increase in the 28-year period. Figure 5 indicates glacial lake from June 1993 to June 2021, with Rama Lake emphasized.

The number of lakes with an area >0.01 km^2 increased from eight in June 1993, covering an area of 0.26 km^2, to fifty-three in September 2001, covering an area of 2.93 km^2. This number increased to 75 in Oct 2021, covering an area of 3.69 km^2. Compared to June 1993, this represents an increase of 87% in number and 92.7% in area. From September 2014 to October 2021, the number of glacial lakes increased by

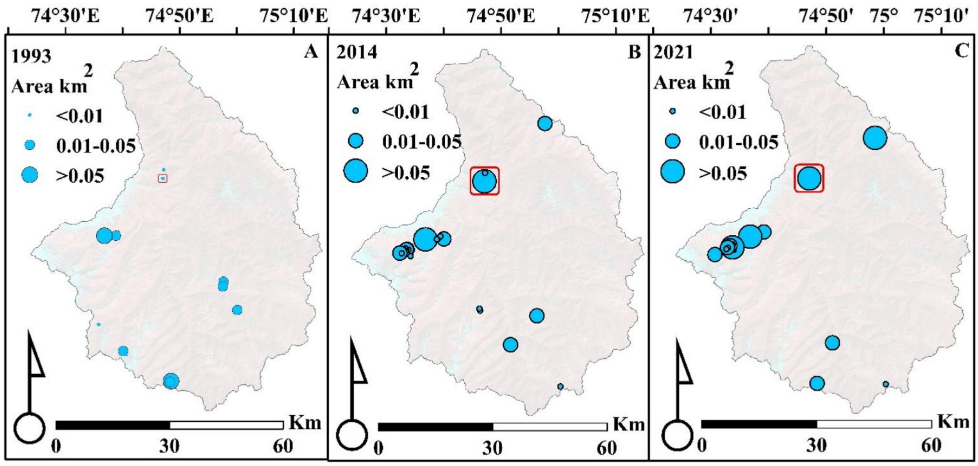

Figure 5. Astore Basin Glacial Lakes June 1993–June 2021. A) June 1993, B) June 2014 and C) June 2021, Rama Lake encircled red circle.

37%, while the area increased by approximately 12.5%. The high density of supraglacial lakes in the Astore Basin can increase melt rate of glacier, posing risk to downstream communities and infrastructure. In June 1993 among them, Rama Lake was recorded with an area of 0.16 km^2. Moreover, the study revealed that there were eight lakes with an area greater than 0.01 km^2, covering 0.26 km^2 in June 1993. Due to unavailability of data for June 2001 only September was analyzed for 2001, while in June 2014, Rama Lake area was recorded as 0.03 km^2, and the total number of lakes having an area greater than 0.01 km^2 was nine, with a total area of 0.26 km^2. The lakes greater than 0.01 km^2 hyped to ten with an area of 0.56 km^2 in June 2021.

4.5. Seasonal and decadal fluctuations in September/October

In September 2001, the number of glacial lakes in the Astore Basin were seventy-two with a total area of 3.06 km^2. In September 2014 the lakes area increased to 3.23 km^2. The changes happened during the period of September 2001 to October 2021 are shown in Figure 6.

This pattern continued and in October 2021 with an increase in the number of glacial lakes to one hundred with a total area of 3.86 km^2. Small lakes were detected with a significant increase in number and area seasonally, almost doubled in the last decade (2014–2021). This increase in the number and area of glacial lakes is attributed to the rise in temperature from last few decades (Chalise et al. 2006), The detailed statistics of glacial lakes area and number changes from Sep 1993 to Oct 2021 are given in Table 5.

The number and area of glacial lakes worldwide have increased globally Shugar et al. (2020). We found a significant increase in glacial lakes over the period from 1993–2021. The number of glacial lakes varied seasonally and annually, and their location and area changes over time. In June 1993, the total number of glacial lakes were thirteen, with a total area of 0.28 km^2, which increased to seventy-two lakes with an area of 3.06 km^2 in September 2001. The period of 2014–2021 marked

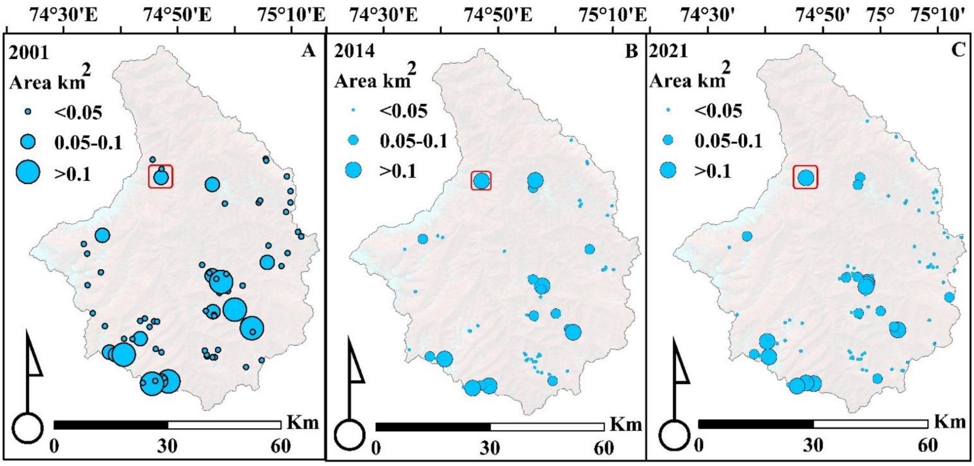

Figure 6. Glacial Lakes statistics at the end of the melt season 2001–2021. A) Sep 2001, B) Sep 2014, and C) Oct 2021. Rama Lake encircled red to track the changes over the period.

Table 5. Detailed statistics of glacial Lakes in Astore Basin from 1993–2021, listed are the number of glacial lakes with their accumulated area and also lakes having area greater than 0.01 km^2.

Month/Year	Lakes Recorded	Lakes accumulated Area km^2	Lakes Recorded with Area > 0.01 km^2	Lakes Area > 0.01 km^2	Rama Lake Area Changes	Seasonal Changes
06/1993	06	0.35	05	0.35	0.16	Numerically
09/2001	72	3.06	52	2.93	0.07	91.6% and area 88.56%
06/2014	29	0.38	09	0.26	0.03	Numerically
09/2014	63	3.23	50	3.14	0.14	54% and area 88.2%
06/2021	18	0.62	8	0.25	0.13	Numerically
10/2021	100	3.86	75	3.69	0.15	82% and area 84%
Decadal Increase	94% growth from June 1993–Oct 2021, from September 2001 to October 2021 28% increase	June 1993–Oct 2021 90.9%, from Sep 2001–Oct 2021 20.7%	June 1993–Oct 2021 93.3%, from Sep 2001–Oct 2021 30.7%	June 1993–Oct 2021 90.5%, Sep 2001-Oct 2021 20.6%	Sep 2001–Oct 2021 53.3%	Average Numerically 75.8% and area 86.92% seasonal change

significant variations in the number and size of glacial lakes. In 2014, the number of lakes in September were sixty-three with an area of 3.23 km^2, while in the start of the melt season, twenty-nine lakes were recorded covering an area of 0.38 km^2. In June 2021, the statistics showed an area of 0.62 km^2, while in October 2021, the number of lakes increased significantly to one hundred with an area of 3.86 km^2. The changes in lake area for June and September are illustrated in Figure 7.

Our results showed a significant increase in the number and area of glacial lakes, particularly those greater than 0.01 km^2. These results are consistent with previous research, growing dramatically in high mountain areas (Wieczorek et al. 2022).

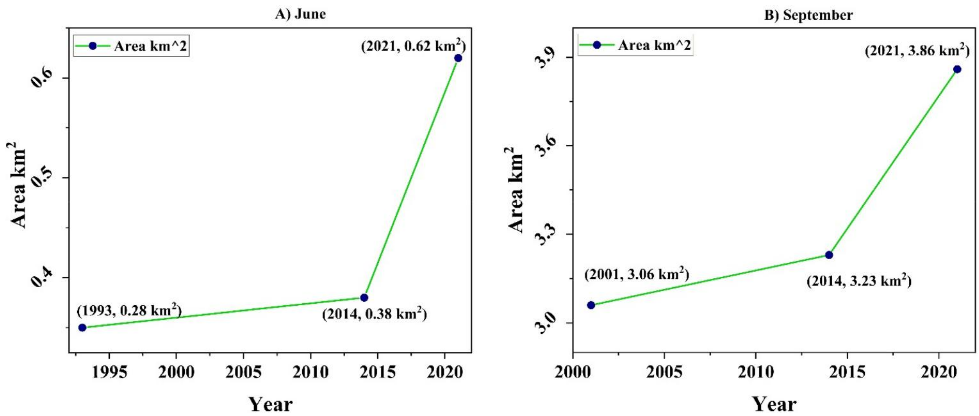

Figure 7. Lakes area changes from 1993–2021, A) June, B) Sep.

Table 6. Rama lake changes over the entire period from 1993–2021, alterations over the 28 years period.

Year	June	Sep/Oct	Percentage change
1993	0.16 km^2	No data	−56%
2001	No data	0.07 km^2	
2014	0.03 km^2	0.14 km^2	78.5%
2021	0.13 km^2	0.15 km^2	13.3%

T Rama Lake in the Astore basin has grown significantly, from 0.07 km^2 in September 2001 to 0.15 km^2 in October 2021. The number and area of lakes larger than 0.01 km^2 have also increased, with fifty-two lakes covering 2.93 km^2 in September 2001, fifty lakes covering 3.14 km^2 in September 2014, and seventy-five lakes covering 3.69 km2 in October 2021. The expansion of Rama Lake is attributable to glaciers melting in the surrounding region as temperatures rise and precipitation decreases. The analysis of Landsat 8 OLI data revealed that the area of glacial lakes had risen. These results provide valuable insights into the changes occurring in the glacier and lake in the Astore basin.

The area of Rama Lake was 0.13 km^2 in June and 0.15 km^2 in October. The lake area variations from 1993–2021 are illustrated in Table 6. This expansion of the lake area can be attributed to the accumulation of water caused by the melting of glaciers in the surrounding vicinity (Ahmed et al. 2021; Zhang et al. 2022).

4.6. GLOFs risks and climatological trends variability

We observed the Astore Station Precipitation and Temperature on a monthly and annual scale for two different periods: Temperature for 1961–2021, 1993–2021 and precipitation for 1961–2019 and 1993–2019, accompanied by the high-resolution air-temperature data 1979–2020 by Yang et al. (2023). The first period was chosen to observe the overall trends variability within decades, while the second data period is concerned with glacial lakes fluctuation from 1993–2021. The average precipitation trend was decreasing throughout the study period, specified in Figure 8.

Higher temperatures cause decrease in extreme rainfall intensity (Roderick et al. 2019). Temperatures increased, but precipitation has decreased (Hussain et al., 2022a), as has been observed in other regions around the world (Veh et al. 2022), glacier melt and temperature changes are main drivers of pond surface area changes. Rising temperature caused glacier melting and river runoff (Hussain et al., 2022b), expanding lakes (Wang et al. 2013; Zhang et al. 2015), lake areas fluctutaions along the Himalayan Mountains is caused by low precipitation (Sun et al. 2018) indicating a complex pattern. Since, the overall precipitation trend for Astore Basin from 1961 to 2019 is negative, the trend from 1993–2019 is also decreasing indicating drastically decreasing periods. This depicts the impacts of climate change which resulted an increase in number and size of glacial lakes. The MK test was then applied to the Astore Basin station maximum temperatures data from 1961 to 2021 and 1993 to 2021, respectively. Indicated an increasing trend in temperature. Positive relationship was observed between lakes number increase and increasing temperature trend, depicting the impacts of climate change over glacial lakes in Astore Basin. Figure 9 evidence temperature trend analysis.

High resolution temperature data from the National Tibetan Plateau Data Center showed an increasing trend for maximum temperatures, exhibiting impacts of warming in Astore basin, enhancing glacial melt resulting in lakes formation and expansion. As the Himalayan region is highly vulnerable to climate change (Khadka et al. 2018) and of great concern.

The accelerated melting of glaciers results in increased surface run-off and can lead to expansion of these lakes, posing potential risks of GLOFs. The stability of glacier lakes depends on various dam conditions, such as the presence of loose moraine material. Lakes with narrow crest moraines are at a higher risk of outbursts, while those dammed by more stable moraines structures are relatively safer. Ice-dammed and moraine-dammed lakes are particularly susceptible to instability, while bedrock-dammed lakes are more stable (Bajracharya et al. 2020).

Although there is no standard index for identifying potential GLOF lakes, factors like physical characteristics and their association with surrounding glaciers play a crucial role (Ashraf et al. 2012). In the Astore Basin, glacier lakes have significantly

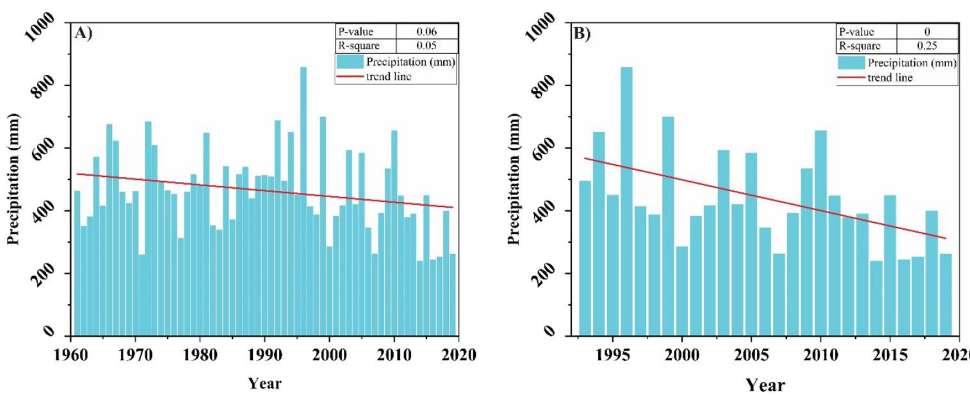

Figure 8. Precipitation trend analysis with R-square and *p*-values A) 1961–2019, B) 1993–2019 annual mean precipitation indicating a decreasing trend.

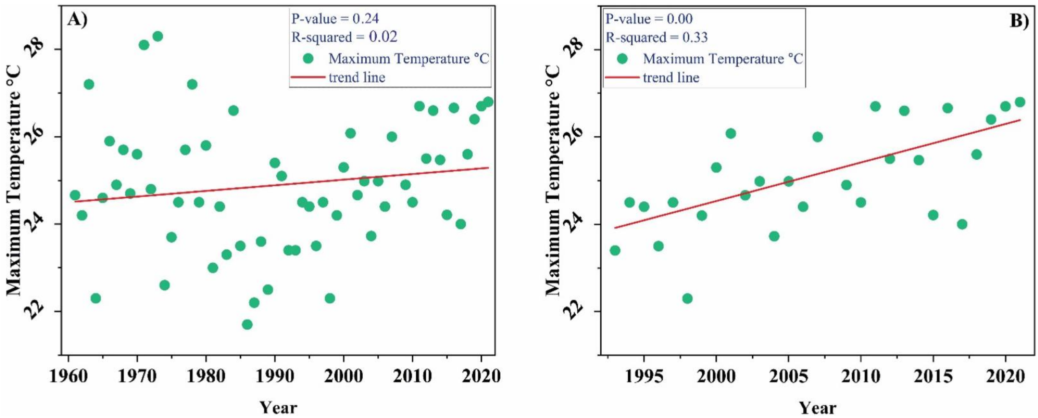

Figure 9. Temperature trend analysis 1961–2021 with R-square and *p*-values, A) annual maximum temperature 1993-2021 B) maximum temperature 1961–2021, both indicating an overall increasing trend.

Table 7. Lakes Statistics having area greater than 0.1 km^2 from 2001–2021, which are hazardous for GLOFs.

Year	No. of Lakes having Area > 0.1 km^2	Accumulated Area Km^2
2001	6/72	1.25 km^2
2014	7/63	1.57 km^2
2021	10/100	1.73 km^2

increased in size from 2001 to 2021. Following the criteria, 10 out of 100 lakes with an area larger than 0.1 km^2 were classified as hazardous glacial lakes in October 2021, as shown in Table 7.

Moreover, they are glacial-fed and located within a proximity of less than 5 km from the glacier, which indicates a potential risk of GLOFs. Among these lakes, three lakes with an area larger than 0.2 km^2 have been classified as having a major risk for GLOFs. These high-risk lakes are clearly marked in Figure 10.

Understanding natural hazards is of paramount importance as it involves comprehending the risk associated with events, which is a function of both event probability and intensity. This risk is influenced by the inherent properties, dynamic characteristics, and overall magnitude of a site (Taylor et al. 2023). The Hindu Kush Himalayan region, identified by Taylor et al. (2023) as the most vulnerable region to GLOFs in 2020, with Afghanistan and Pakistan being the most vulnerable countries. Among all nations, China and Pakistan have the highest global GLOF danger, with Pakistan having a larger lake condition score than China. According to Chalise et al. (2006) climate change could lead to increased melting, which leads to lakes expansion and formation. Similar trend analysis was performed for TPDC high resolution temperature data, depicting an overall positive trend for maximum temperature. As observed by Pang et al. (2021) rising temperatures have a greater impact on glacier meltwater causing glacial lakes alterations. High-resolution near-surface meteorological forcing dataset for the Third Pole region (TPMFD, 1979–2020) by Yang et al. (2023) trends depicted Figure 11.

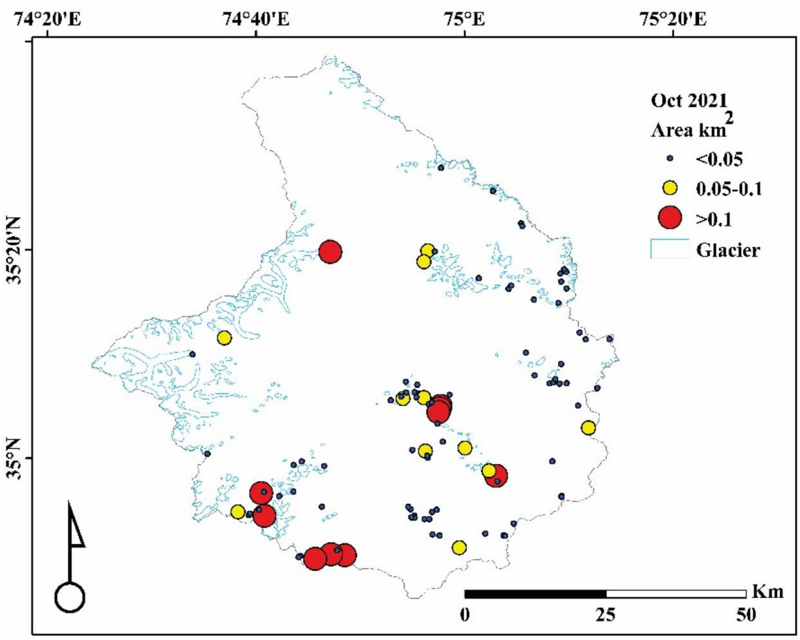

Figure 10. Lakes with area $< 0.1\,\text{km}^2$ are in blue, area $0.1\text{–}0.2\,\text{km}^2$ in yellow, and lakes with area $> 0.2\,\text{km}^2$ are in red observed in Oct 2021.

LST increased significantly from 2010 to 2021, an increasing trend for LST in Astore Basin, coupled with increase in glacial lakes. This suggests that climatic variability in the form of rising warming accelerated the expansion of existing and creation of new glacial lakes. LST trend analysis illustrated in Figure 12.

Increase in LST could enhance melting causing expansion of glacial lakes (Mondal et al. 2023). In Astore Basin LST increased notably, leading to enhanced melting which could be a cause of expansion and formation of glacial lakes. Our analysis indicate that maximum air temperature increased by 3.4 °C in last 28 years while average LST increased by 1.04 °C in last decade. This temperature hype is alarming and could lead to disastrous events such as GLOFs, necessitating further study to mitigate future hazards.

5. Conclusion

This study indicates a significant increase in glacial lakes, both seasonally and in long-term. From June 1993 to October 2021, the number of lakes increased by an average of 87%, while the lake area increased by 92.7%. Our results of decadal changes from 2001 to 2021 revealed a 28% rise in the number of lakes and a 20.7% increase in their area. The study also analyzed lake statistics from June to October from 1993 to 2001, demonstrating an upward trend in temperature based on data from the Astore station (1961–2021) and the TPDC (1979–2020).

The analysis also shows an increase in land surface temperature (LST) between 2010 and 2021, which leads to increased glacier melt and, as a result, an increase in the number and area of glacial lakes. In the Astore Basin, ten glacial lakes with an area more than $0.1\,\text{km}^2$ were detected, three of which are at high risk of GLOFs.

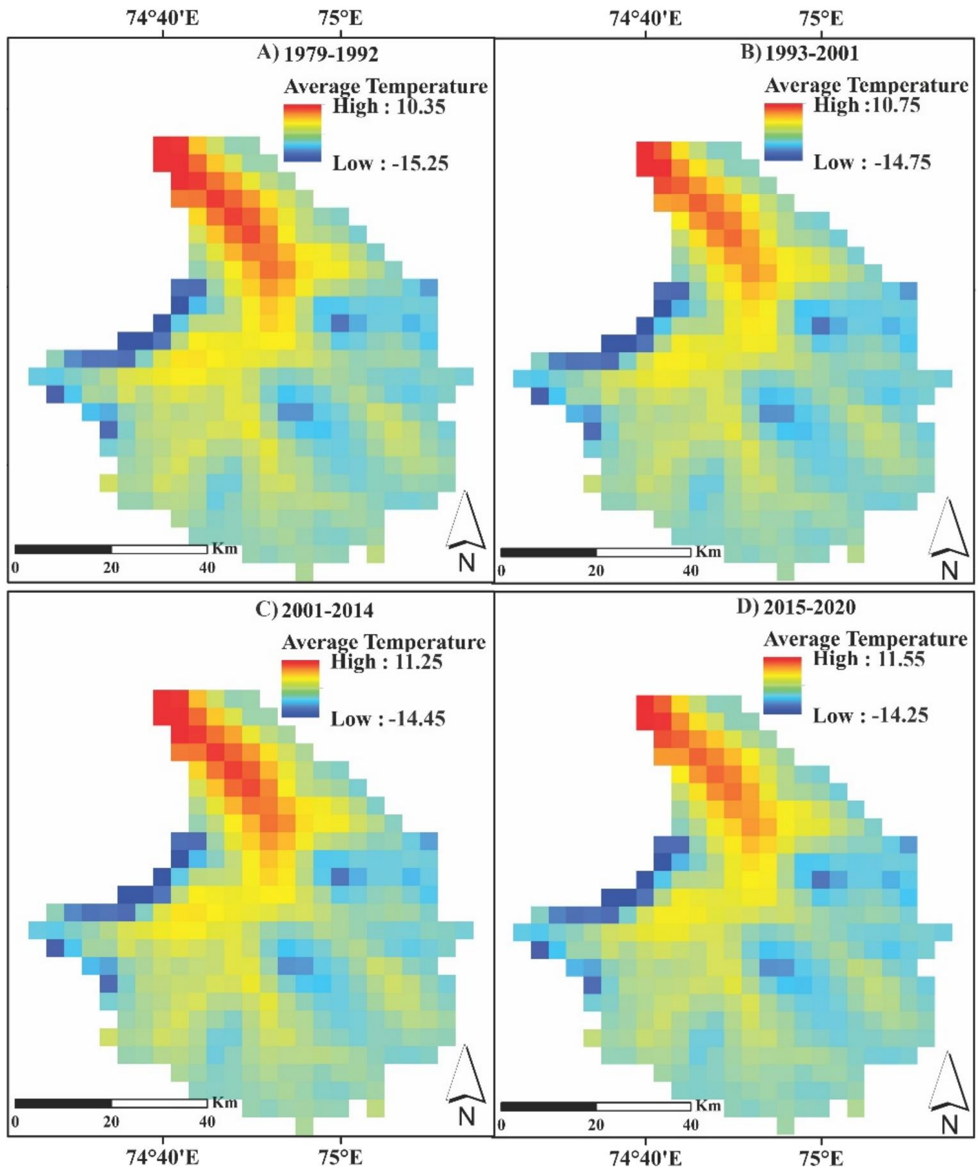

Figure 11. High-resolution near-surface meteorological forcing dataset for the third pole region (TPMFD, 1979–2020) average temperature gridded maps 1979–1992, 1993–2001, 2001–2014 and 2015–2020. An overall increasing temperature since last four decades.

Continuous monitoring is essential for reducing possible dangers and protecting adjacent areas from these developing glacier lakes. Policymakers and stakeholders should establish monitoring and early warning systems for glacial lake outburst floods, as well as promote sustainable water management practices.

Disclosure statement

No potential conflict of interest was reported by the author(s).

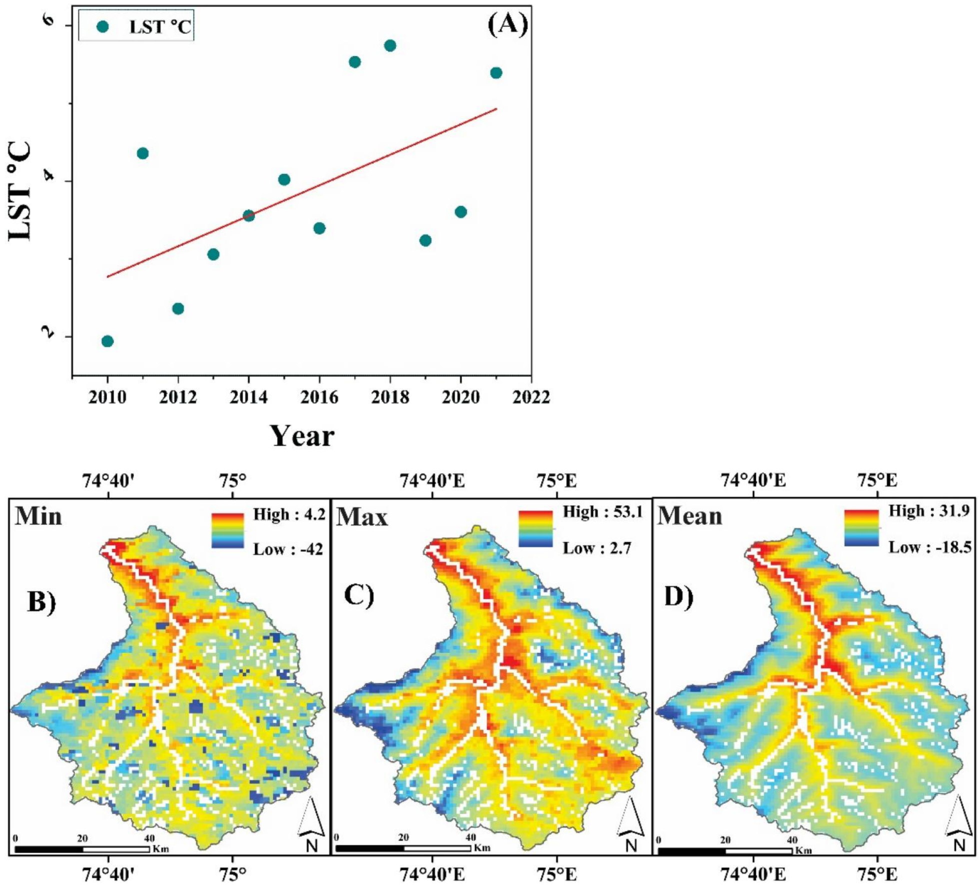

Figure 12. Land surface temperature, trend analysis showing an overall positive trend. Gridded map indicates average minimum, maximum and mean LST from 2010–2020.

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Data availability statement

The data in this study area available from the first and corresponding authors upon reasonable request.

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