Lakes expansion and emergence of potentially dangerous glacier lakes in Astore River Basin, Western Himalaya during 1993-2021

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Research Article

Keywords: Glaciers, GLOFs, Remote Sensing, Astore River Basin, Supraglacial lakes

Posted Date: November 2nd, 2023

DOI: https://doi.org/10.21203/rs.3.rs-3333294/v1

Abstract

Glaciers in High Mountain Asia ensure freshwater to billions of people downstream but this supply is dwindling owing to rapid melting due to climate change. On the same note, glaciers in the Astore River Basin, of the Upper Indus Basin (UIB), are rapidly melting leading to accelerated expansion of glacial lakes, emergence of new glacial lakes, and increasing the risk of Glacial Lakes Outburst Floods (GLOFs). This study investigates seasonal and decadal fluctuations in glacier lakes using Landsat data between 1993 and 2021 and differential Global Positioning System (dGPS) field observations. We found an increase in the number of glacial lakes and areal expansion of existing glacial lakes in the study area. During the 2021 ablation period (Jun-Oct), the number of contemporary glacial lakes grew fivefold (18 to 100), while the area expanded sixfold (0.62 to 3.86 km^2), the newly developed lakes were greater than 0.01 km^2. Over the past decade, PDGLs have doubled. To lessen the risk of GLOF, continuous monitoring of these lakes is necessary in the future. The implementation of GLOF monitoring and early warning systems, as well as sustainable water management practices, ought to be prioritized for mitigation and adaptation measures.

1. Introduction

Glaciers are the principal supply of freshwater in frigid locations and are critical for the water resources of billions of people, notably in High Mountain Asia (HMA) (Jones et al., 2019; Mohammadi et al., 2023; Nüsser & Schmidt, 2021; Rounce et al., 2023). Glaciers are key indicators of climate change (Kääb et al., 2007; Kaushik et al., 2022; Lama & Devkota, 2009), and the Himalayan region is one of the few regions where climate change effects are most prominent (Negi et al., 2021; Wester et al., 2019). Global warming poses a threat to glaciers (Compagno et al., 2022; Immerzeel et al., 2010) resulting rapid retreat globally (Shean et al., 2020), while warming reported in the Himalayan region is higher than the global mean warming (Bhutiyani et al., 2007; Negi et al., 2018; Shrestha et al., 2012), causing glaciers to lose mass at a faster pace (Nie et al., 2021; Sabin et al., 2020; Sharma et al., 2022). Although some advancing glaciers were observed in the Karakoram Mountains during the first decade of the twenty-first century but retreating rates differed greatly amongst glacial basins (Dehecq et al., 2019).

Glacier retreat causes melt water to collect as glacial lakes (Allen et al., 2016; Carrivick & Tweed, 2013; Lei et al., 2018), glacial lakes are also formed in glacier valleys and basins due to melting ice (Bajracharya & Mool, 2009; Muhammad et al., 2021) resulting in more melt and retreat and more lake expansion (King et al., 2019; Maurer et al., 2019; Watson et al., 2020). Outburst floods from glacial lakes pose a severe risk to infrastructure and humans (Allen et al. 2015). The physical condition of the lake, dam, source glacier activity, and surrounding stability all contribute to its resilience (Bajracharya et al. 2020). These lakes are frequently blocked by unstable moraine or glacier ice, and they are flanked by destabilizing permafrost slopes or hanging glaciers (Otto, 2019; Richardson and Reynolds, 2000). Slope failure can cause mass movement, displacing water and creating an impulse wave that overtops the frontal dam (Ambruster et al. 1978). Lake expansion raises the likelihood of overtopping failures and consequent flood volume, contributing to increased GLOF hazard (Bajracharya & Mool, 2009; Muhammad et al., 2021; Muhammad et al., 2020; Tian et al., 2017; Zhang et al., 2015). Moraine-dammed lakes are prevalent, consisting of loose, coarse moraines with low cementing content, makes them vulnerable to GLOFs, making them easy to erode. GLOFs can be caused by dam breach (Emmer & Cochachin, 2013; Rounce et al., 2016), overfilling (Allen et al., 2016a), and moraine/ice dam degradation (Majeed et al., 2021; Neupane et al., 2019), making it difficult to accurately quantify (Taylor et al., 2023), triggering is complex and can cause significant damage to property, infrastructure, and agricultural land, resulting in extensive loss of life (Carey, 2008; Emmer et al., 2020). The expansion of these lakes perils locale (Grant et al., 2021) due to GLOFs risk intensification (Frey et al., 2012; Shugar et al., 2020; Wang et al., 2021; Wieczorek et al., 2022).

Flooding increases turbidity, while surface signatures effect river landscapes (Meena et al., 2021). The Jinweng Co GLOF event in 2020 destroyed ten houses, bridges, and 43.9 km of road, causing damage to structures and agricultural land (Zheng et al. 2021). In 2013, a Chorabari lake debris flow and cloud-burst-induced landslides in Uttarakhand caused over 6,000 deaths and infrastructure damage (Allen et al. 2015). A catastrophic flood in the Rishiganga River occurred on 7 February 2021 due to a rockslide (Mao et al., 2022; Meena et al., 2021; Pandey et al., 2022), causing displaced materials, solar radiation, and glacier collapse, destroying infrastructure and lives (Pandey et al., 2022). Rising temperature may cause similar incidents in Himalayan valley (Pandey et al., 2022). Uncertainty exists on glacier lake evolution trends and future development over recent decades (Kumar et al., 2020). Remote sensing risk assessment aids in identifying flood hotspots in South Asia (Matheswaran et al., 2019). (Muhammad et al., 2021) predicted Shisper lake outburst due to terminus advances, lake developed a GLOF event in 2022. Shisper Glacier surges from 2017 to 2019 blocked Mochowar Glacier's tributary, forming an ice dammed lake, leading to GLOFs in 2019, 2020, and 2022 (Singh et al. 2023).

GLOF risk is highest in Himalaya, with potential to triple in future (Zheng et al., 2021) resulting in floods and scarce water resources that are of societal and ecological importance (Shugar et al., 2020). The impact varies significantly across the globe, requires urgent attention to reduce its impacts (Dubey & Goyal, 2020; Shugar et al., 2020).

Glaciers with steep slopes and lower altitude range lose more area (Pandey & Venkataraman, 2013). Temperature significantly impacts glacier melt (Bajracharya et al. 2020;Schmidt & Nüsser, 2009)). Increasing glacial retreat caused by climate change, results in glacial lakes growth and bursts (Nautiyal et al., 2022). Recent environmental and climatic disturbances impacts land surface temperature, which is the radiating temperature of the earth's surface (Yuan & Bauer, 2007). LST and air temperature are closely associated (Hachem et al., 2012; Vancutsem et al., 2010) may fluctuate by 1–2°C under cloud cover causing an increase in warming (Good et al., 2017). Previous studies have used LST to assess risks (Crago et al., 1995; Hu & Brunsell, 2013; Weng & Fu, 2014). Glacial lakes have grown rapidly since 1990, increasing by ~ 50% globally (Shugar et al., 2020). Climate change in Himalaya is causing an increase in glacial lakes, warming and discharge at high elevation, which could lead to increased flood events and reduced low flows (Chalise et al., 2006). The dearth of a long-term decadal inventory of glacial lakes with inter-annual assessment in Northern Pakistan can be attributed to various factors. The advancements in spatial and temporal resolution have led to a significant transformation in the evaluation of mountain hazards through remote sensing (Deschamps-Berger et al., 2020; Huggel et al., 2002).

This paper focuses on the seasonal variability and decadal oscillations of glacial lakes in the Astore Basin in Northern Pakistan's western Himalayan range. The study examined the growth and changes in the basin's glacial lakes using multi-temporal satellite imagery Astore station climate data 1961–2021, third pole high resolution meteorological data by (He et al., 2020; Jiang et al., 2023) from 1979–2020 and MODIS LST data from 2010–2021. Climate data shows an increasing trend for temperature, LST, and decreasing precipitation, affecting glacial lakes in the region. Our results showed a consistent increase in the number and size of glacier lakes from June to September annually, as well as over the decadal period spanning from September 2001 to September 2014 to October 2021. Climatic fluctuations and LST enhancements are the key influencers causing rapid escalation in glacial lakes number and area. These findings demonstrate the utility of our two-way method for studying the evolution of glacier lakes and highlight the importance of monitoring these lakes to better understand the impacts of climate change on water resources.

2. Study Area

The Astore Basin, situated in the Nanga Parbat region of northern Pakistan, is located at 34°50'–35°40' N and 74°30'–75°10' E. It covers an area of approximately 3995 km^2. The basin's elevation spans from 1202 to 8126 meters above sea level and is located in the high-altitude northwestern Himalayan region, extending from valley floors to the Nanga Parbat range (Farhan et al. 2015). Data from Astore stations 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, with accumulated seasonal snow reaching 80-85%,while 45% glacier-covered area in the basin has small cirque-type glaciers (Muhammad et al. (2019). Over 75% of annual runoff is dependent on melt-water produced by seasonal snow and glacier ablation (Farhan et al., 2015). The Rama Lake, situated in the Astore Basin, has been experiencing environmental issues caused by human activities like deforestation, agriculture, and tourism. The study area map is illustrated in figure 1 highlighting Pakistan, Northern Pakistan and Astore Basin along with streams, glaciers, and Rama Lake in the Basin. From 1993 through 2021, the imagery utilized in this study was chosen based on the availability of minimal or cloud-free data.

Fig. 1 Study Area map of Astore River Basin highlighting the RGI 6.0 glaciers boundaries (RGI Consortium. (2017)), streams and Rama Lake

3. Data and Methods

3.1 Data

Landsat data is a valuable resource for studying the Earth's surface, and can be used to monitor natural resources, track glacial lakes changes, and investigate climate change. Landsat has provided data for various applications, including mapping. Landsat 5 collected data in seven spectral bands, while Landsat 7 is still operational and has an 8-day repeat cycle. (Hansen & Loveland, 2012; Ju et al., 2012; Roy et al., 2014; Tucker, 1979). Similarly, Landsat 8, which was 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). In Astore Basin, 2 Landsat 5 TM (resampled 30 meters resolution) for June 1993, 2 Landsat 7 ETM+ (30 meters resolution) for Sep 2001, and 8 Landsat 8 OLI (30 meters resolution, panchromatic bands is 15 meters), cloud-free level 2 scenes for June and Sep 2014 and June and Oct 2021 were obtained from the United States Geological Survey https://earthexplorer.usgs.gov/ based on the availability of Landsat data, scenes are enlisted in Table 1. Landsat has a 16 days repeat cycle. Pre-monsoon and post-monsoon seasons cover ablation and accumulation periods in Western Himalayas (Mondal and Bharti, 2022). (Kavan and Haagmans 2021) assessed seasonal snow ablation on glaciers, showing that glaciers lost 80% or more of their surface snow cover during the summer ablation season. therefore Jun and Sep/Oct data was processed to assess long term changes in the ablation and accumulation periods, as glacial lakes are clearly visible in ablation periods. Landsat-7 ETM + failure, causes gaps in data coverage (Markham et al. 2004). Due to unavailability of Landsat data for Sep/Oct 1993 and Jun/July 2001, only Jun 1993 and Sep 2001 were assessed to observe lake variations from 1993–2021.

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

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

Climate data was collected from Astore Station from 1961 to 2021. High-resolution near-surface meteorological forcing dataset for the Third Pole region (TPMFD, 1979–2020) by (He et al., 2020; Jiang et al., 2023) obtained from https://data.tpdc.ac.cn/ having a resolution of ~ 4 km (1/30°) encompassing of monthly daily and hourly data, monthly temperature data was acquired and minimum, maximum and average temperature was assessed. MODIS (MOD11A2) Land Surface Temperature (LST) data was obtained from https://modis.gsfc.nasa.gov/ for the period 2001–2021. Composite data spanning 8 days was acquired to mitigate the effects of cloud cover. In October 2021, dGPS field observations were conducted at Rama Lake to confirm the accuracy of satellite data. Analysis of climate data trends can facilitate the assessment of the effects of temperature and precipitation fluctuations on glacial lakes situated in the Astore Basin.

3.2 Methodology

Landsat data, climate data, and LST are used to map glacial lakes and study the impacts of climate. Preprocessing Landsat data is essential for remote sensing analysis, which can help researchers understand the Earth's surface and its changes over time. To do this, atmospheric correction, radiometric calibration, and geometric correction are performed to remove noise and artifacts and ensure correct registration of all bands (Jensen (1986). Once the data is pre-processed, it can be used for various applications such as classification and monitoring changes. The images preprocessing and analysis is given as follows. Images were preprocessed for correction of sensor errors and atmospheric disturbances through calibration algorithms. Layer stacking was performed by merging multiple Landsat images to create a composite image. Mosaicked images were created by merging multiple Landsat images to create a seamless image of the study area. This is useful for creating maps of large areas and identifying changes over time.

We used Landsat TM, ETM+, and OLI satellite data from 1993–2021 and dGPS field observations for Rama Lake in 2021, since glaciers in HMA are poorly observed in the field (Muhammad & Tian, 2016; S. Muhammad et al., 2019). To detect glacial lakes, we employed various techniques as classification, digitization, and validation with field observations. Among these techniques, maximum likelihood classification (MLC) was used for remotely sensed data. MLC is a popular algorithm that estimates the probability distribution of input data for each class and assigns a pixel to the class with the highest probability (Congalton & Green, 2019). We used the MLC algorithm in ENVI to classify Landsat scenes for glacial lake mapping. We then compared our results with the 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.

3.3 Mapping Uncertainties

The accuracy of glacial lake outlines obtained through Landsat imagery depends on the resolution and conditions at the time of acquisition, such as snow, cloud cover, and shadow (Wangchuk & Bolch, 2020).

The present study involved the estimation of uncertainty for individual glacial lakes, which was accomplished through the utilization of ground truths and comparison with high resolution Google Imagery. The kappa coefficient measured improves classifier accuracy, resulting in more applicable data selection approaches (Vieira et al., 2010). Classification limitations are frequently solved using confusion matrix (Kulkarni et al., 2020). The error matrix is used to calculate accuracy by dividing the total correct pixels by the total number of pixels in the error matrix. Accuracy of individual categories can be calculated by dividing the number of correct pixels by the total number of pixels in the row or column (Congalton, 1991). The classification accuracy was assessed with confusion matrix and the accuracy was obtained to be 99.3 with a kappa coefficient 0.97. Table 2 elaborates confusion matrix using ground truth region of interests (rois).

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

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

3.4 Statistical tests for the trend Analysis

We applied the MK test to climate data obtained from Pakistan Meteorological Department (PMD), station located in Astore Basin for the month of June and September from 1961–2021, to analyze trends and detect changes. MK test was also applied to high resolution meteorological data set TPMFD (He et al., 2020; Jiang et al., 2023) for maximum air temperature analysis 1979–2020. The Mann Kendall Trend Test (MK test) is a non-parametric test used to analyze data collected over time for trends analysis Trend analysis is used to detect changes in climatic and hydrologic time series, with the MK trend test (Hamed & Ramachandra Rao, 1998). However, the presence of serial correlation in the raw data can lead to inaccurate or spurious trend detections. To address this problem, pre-whitening of the raw data was performed before applying the MK test. Studies have demonstrated the importance of pre-whitening, such as (Serinaldi & Kilsby, 2016) finding that failure to pre-whiten can lead to significantly biased trend estimates, and (Yue & Wang, 2002) showing that pre-whitening can improve the accuracy of trend detection in hydrological time series data. Before applying MK test, pre-whitening was applied to minimize serial correlations. Then, MK test was used to analyze climate data to detect trends over time in data.

3.4.1 Land surface temperature data statistical tests, trend analysis

Glaciers are indicators of climate change, and mountain glaciers have been experiencing instrumental changes due to global warming (Yuanqing et al., 2008). LST is an important parameter in understanding Earth processes (Williamson et al., 2014). An in-depth study of the influence mechanism LST is essential to promote stable development. Using MODIS time series data, the MK nonparametric tests were used to analyze and predict the trend of LST changes in northern slopes of the Tianshan Mountains (Zhang et al., 2022). LST is an important factor to consider when assessing trends in time series (Panwar et al., 2018). The MK nonparametric test, a popular method used to measure the significance of trends (Dinpashoh et al., 2011). LST data was also pre-whitened before applying MK test, significant increasing trends were observed verifying climatic influence over glaciers and glacial lakes alterations in Astore Basin.

4. Results and Discussion

We estimated lakes fluctuations in last 28 years from 1993–2021 using Landsat Satellite Imagery. Along with satellite imagery climate data was also analyzed from 1961–2021 indicating an increase in overall temperature in the last three decades and decrease in the precipitation. Fluctuations were analyzed at seasonal and decadal intervals. Our results indicated an increase in seasonal as well as decadal changes in glacial lakes area. During the early melting season, we found a significant quantity of frozen lakes. However, as the season progressed, these lakes transformed into gigantic water reservoirs towards the conclusion of the season. Increase in temperature and decreased precipitation over the last three decades has resulted in an increase in glacial lake area, with frozen lakes becoming water reservoirs.

4.1 Climatological trends variability

We observed the Astore Station Precipitation and Temperature on a monthly and annual scale for two different periods: 1961–2019 and 1993–2019, accompanied by the high-resolution air-temperature data 1979–2020 by (He et al., 2020; Jiang et al., 2023). All the test were performed with confidence level > 95% with a significance less than 0.05. The first period was chosen to observe the overall trends variability within decades from 1961–2021, 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 Fig. 2.

Figure 2 *Precipitation Trend Analysis 1961–2019 showing an overall negative trend, followed by 1993–2019 annual mean precipitation indicating a decreasing trend.*

Higher temperatures cause a decrease in extreme rainfall intensity (Roderick et al., 2019). Temperatures have increased, but precipitation has decreased. 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, expanding lakes (Xu Wang et al., 2013; Wang Xin, 2011; Zhang et al., 2015), the 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 3 evidence temperature trend analysis.

Figure 3 *Temperature Trend analysis 1961–2021, annual maximum temperature 1993–2021 followed by maximum temperature 1961–2021, both indicating an overall increasing trend*

High resolution temperature data from the National Tibetan Plateau Data Center showed an increasing trend for maximum temperatures, demonstrating the impacts of warming on the Astore basin, enhancing glacial melt resulting lakes formation and expansion. As the Himalayan region is highly vulnerable to climate change (Khadka et al., 2018) and of great concern (Liu & Chen, 2000). 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 (He et al. 2020; Jiang et al. 2023) trends depicted Fig. 4.

Figure 4 *High-resolution near-surface meteorological forcing dataset for the Third Pole region (TPMFD, 1979–2020) overall positive trend for 1979–2020, followed by 1993–2020*

LST increased significantly from 2010 to 2021, influencing glacial lake alterations in northern Pakistan, there was an increasing trend for LST in Astore Basin, coupled with an 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. The results of MK test performed on pre-whitened data with a confidence level greater than 95%. LST data obtained from MODIS analyzed from 2010–2021. LST recorded an overall 2.3 K increase. Indicating a significant positive trend with a confidence of 99%. LST trend analysis illustrated in Fig. 5.

Figure 5 *Land surface temperature, trend analysis showing an overall positive trend.*

4.2 Seasonal and decadal Lake’s fluctuations June

Remote sensing is the most effective way to map glacial lakes in high-elevation zones (Huggel et al., 2002; Quincey et al., 2007). Satellite observations have been used to study glacial lake inventories at regional scales (Gardelle et al., 2011; How et al., 2021; Nie et al., 2017; Rick et al., 2022). Landsat archival images are the most widely used due to their high spatial resolution and public availability (Roy et al., 2014). In this study, Landsat 5 TM data from June 1993 with a spatial resolution of 30 meters were used to examine the glaciated area and glacial lakes in the Astore Basin. The study found that the Astore Basin had 06 glacial lakes with a total area of 0.35 km^2. Due to unavailability of data for June 2001, Landsat ETM + was utilized for September 2001. While for June 2014 and onwards Landsat 8 OLI was harnessed, witnessing the number of glacial lakes increase to 29, with a total area of 0.38 km^2. Understanding the changes in the glacier system is critical, and the quantity and area of glacial lakes are critical metrics for monitoring these changes. Glacial lakes form as glaciers melts. The analysis detected 18 glacial lakes in the Astore Basin with an aggregate area of 0.62 km^2 in June 2021, glacial lakes area rose dramatically. The study's results for June indicate a significant accretion from 0.35 km^2 in June 1993 to 0.62 km^2 in June 2021, showing an overall 56.4% increase in the glacial lake area throughout a 28-year period at the beginning of the melt season. Figure 6 indicates glacial lake from June 1993 to June 2021, with Rama Lake emphasized.

Figure 6 *Astore Basin Glacial Lakes June 1993-June 2021. A) June 1993, B) June 2014 and C) June 2021, Rama Lake encircled red circle*

4.2.1 Rama Lake and Lakes > 0.01 km^2 at the Start of melt Season.

The number of lakes having an area greater than 0.01 km^2 increased from 10 in June 1993, covering an area of 0.42 km^2, to 52 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 82% in number and 83.9% in area. From September 2014 to October 2021, the number of glacial lakes increased by 37%, while the area increased by approximately 12.5%. The high density of supraglacial lakes in the Astore Basin can increase the melt rate of the glacier, posing a risk to downstream communities and infrastructure. Understanding the changes in these features is essential for comprehending the effects of climate change on water resources in the region. In June 1993 among them, Rama Lake was recorded with an area of 0.16 km^2. Moreover, the study revealed that there were 05 lakes with an area greater than 0.01 km^2, covering 0.035 km. 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 9, with a total area of 0.26 km^2. This area changed to 0.25 with the lake numbers comprising of 8.

4.3 Seasonal and Decadal Fluctuations September/ October

In September 2001, the number of glacial lakes in the Astore Basin was recorded as 72, with a total area of 3.06 km^2. The number of glacial lakes in the Astore Basin recorded for September 2001 are 72, with a total area of 3.06 km^2. While the number of glacial lakes decreased for September 2014 to 63, with increase in its area of 3.23 km^2. The changes happened during the period of September 2001 to October 2021 are exemplified in the Fig. 7.

Figure 7 *Glacial Lakes statistics at the end of the melt season from left to right 2001–2021. On left Sep 2001, followed by Sep 2014, and to the right Oct 2021. Rama Lake encircled red to track the changes over the period.*

In September 2014, the number of glacial lakes increased to 63, with a total area of 3.23 km^2. This pattern continued and in October 2021, the number of glacial lakes increased to 100, with a total area of 3.86 km^2. This increase in the number and area of glacial lakes is attributed to the melting of glaciers and the accumulation of water in the depressions created by the melting process due to the rise in temperature from last few decades October is selected here for 2021, to detect the changes in the glacial lakes, because for the other months the availability of data was an issue. The detailed statistics of glacial lakes area and number changes from Sep 1993 to Oct 2021 are given in Table 3.

Table 3
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 0.01km^2

Month/Year	**Lakes Recorded**	**Lakes accumulated Area km²**	**Lakes Recorded with Area > 0.01 km²**	**Lakes Area > 0.01 km²**	**Rama Lake Area Changes**	**Seasonal Changes**
06/1993	06	0.35	05	0.35	0.16	Numerically 91.6% and area 88.56%
09/2001	72	3.06	52	2.93	0.07	
06/2014	29	0.38	09	0.26	0.03	Numerically 54% and area 88.2%
09/2014	63	3.23	50	3.14	0.14	
06/2021	18	0.62	8	0.25	0.13	Numerically 82% and area 84%
09/2021	100	3.86	75	3.69	0.15	
Decadal Increase	96% growth from June 1993-September 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 88%, Sep 2001-Oct 2021 20.6%	June 1993-Oct 2021 6.25%, Sep 2001-Oct 2021 53.3%	Average Numerically 75.8% and area 86.92% seasonal change

Table 3 *Detailed Statistics of Glacial Lakes in Astore Basin from 1993–2021, listed are the number of glacial lakes with their accumulated area and lakes having area greater than 0.01km^2*.

Global glacial lake numbers and total area have increased (Shugar et al., 2020). Our study demonstrates significant variations in the number and area of glacial lakes over the period from 1993–2021. The number of glacial lakes varies seasonally and annually, and their location and area changes over time. In June 1993, the total number of glacial lakes recorded was 06, with a total area of 0.35 km², which increased to 72 lakes with an area of 3.06 km² in September 2001. The period of 2014–2021 marked significant variations in the number and size of glacial lakes. In 2014, the number of lakes recorded in September was 63 with an area of 3.23 km², while in the start of the melt season, 29 lakes were recorded with an accumulated area of 0.38 km². In June 2021, the statistics showed 18 glacial lakes with an accumulated area of 0.62 km², while in October, the number of lakes increased significantly to 100 with an accumulated area of 3.86 km². Lake's alterations overall for Jun and Sep are illustrated in Fig. 8.

Figure 8 *Lakes area changes from 1993–2021, A) June, B) Sep*

Our data showed a significant rise in the number and area of glacial lakes, particularly those larger than 0.01 km^2. Small lakes were discovered with a significant increase in number and area seasonally, almost doubling in the last decade (2014–2021). This finding is consistent with prior research, which shows that glacier lakes are visible markers of global warming, with their extent and number growing dramatically in high mountain areas (Wieczorek et al., 2022).

4.2.1 Rama Lake and Lakes > 0.01 km² at the end of melt season

From September 2001-Oct 2021 Rama Lake's area was recorded as 0.07 km^2 in Sep 2001, and the total number of lakes having an area greater than 0.01 km^2 was 52, with a total area of 2.93 km^2. Rama Lake's area for September 2014 was recorded as 0.14 km^2, and the total number of lakes having an area greater than 0.01 km^2 was 50, with a total area of 3.14 km^2. For Oct 2021, the number increased to 75 with an accumulated area of 3.69 km^2. Our analysis of the Astore basin's water bodies reveals that understanding the number and area of lakes with a minimum size of 0.01 km^2 is crucial. In June, a total of 8 lakes with an area greater than 0.01 km^2, covering 0.25 km^2, were recorded. However, in October, the number of such lakes increased to 67, with a total area of 3.62 km^2. Alongside this, Rama Lake's area has undergone changes over time, with Landsat 8 OLI data showing an increase from 0.13 km^2 in June 2021 to 0.15 km^2 in October 2021. The cause of this increase is attributed to the melting of glaciers in the surrounding region caused by the increase in temperature and decreaseing precipitation. Landsat 8 OLI data was utilized to analyze the glaciated areas and lakes in the Astore basin for June and October 2021. The findings showed that the glaciated area decreased while the number and area of glacial lakes increased. Additionally, Rama lake's area increased, and the total number and area of lakes with an area greater than

0.01 km^2 also increased. These results are significant in understanding the changes in the glacier and lake systems in the Astore basin.

The area of Rama Lake, in the Astore basin, was determined using Landsat 8 OLI data for June and October 2021. The area of the lake was measured to be 0.13 km^2 in June and 0.15 km^2 in October of the same year, these variations from 1993–2021 are illustrated in Table 4. This expansion of the lake's area can be ascribed to the accumulation of water caused by the melting of glaciers in the surrounding vicinity (Ahmed et al., 2021).

Table 4
Rama Lake changes over the entire period from 1993–2021, alterations over the 28 years period

Year	June	Sep/Oct
1993	0.16 km²	
2001		0.07 km²
2014	0.03 km²	0.14 km²
2021	0.13 km²	0.15 km²

Table 4 *Rama Lake changes over the entire period from 1993–2021, alterations over the 28 years period*

4.2.2 GLOFs risks

Glacier lakes are formed due to melting of glaciers, accompanied by various obstructing elements such as rocky terrain, ice, loose moraine, and landslides. 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).

Bajracharya e t 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, 2019; Zheng et al., 2021). Generally, lakes larger than 0.1 km^2, increasing in size, and glacial fed lakes are considered potentially dangerous ((Bolch et al., 2012) ((Iribarren Anacona et al., 2014) (O'Connor et al., 2001; Xin Wang et al., 2013). (Bajracharya et al. 2007), (ICIMOD 2011), and (Mool et al. 2001) provided a set a criterion for 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.

6. Moraine Dammed lakes that have breached and refilled with water in the past can breach again.

7. Various physical conditions surrounding the lake, such as rockfalls, hanging glaciers, snow avalanches, neo-tectonic and earthquake activities, and the presence of large mother glaciers, can also contribute to a lake’s potential hazard.

8. Actively retreating and steep hanging glaciers on lake banks may also pose risks.

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 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 5.

Table 5
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

Table 5 *Lakes Statistics having area greater than 0.1 km^2 from 2001–2021, which maybe hazardous for GLOFs*

In previous regional-scale research, lake volume was utilized as a proxy to assess the potential risk of glacial lake outburst floods (GLOFs) (Zheng et al. 2021). However, a more recent study by (Taylor et al. 2023) adopted a consequence-based approach, using total lake area as a proxy to quantify the intensity of potential GLOFs. According to this approach, larger lakes may generate more intense GLOFs. In the Astore Basin, we identified 10 glacial lakes with an area greater than 0.1 km^2. Over a specific period, these lakes have experienced an increase in their area. 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 km2 have been classified as having a major risk for GLOFs. These high-risk lakes are clearly marked in Fig. 9.

Figure 9 *Lakes with area < 0.1km^2 are in blue, area 0.1–0.2 km^2 in yellow, and lakes with area > 0.2 km^2 are in red observed in Oct 2021*

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 intrinsic properties, dynamic characteristics, and overall magnitude of a site (Taylor et al. 2023). The Hindu Kush Himalayan region (HMA) was identified by (Taylor et al. 2023) as the most vulnerable area to glacial lake outburst floods (GLOFs) in 2020, with Afghanistan and Pakistan being the most vulnerable countries. Among all nations, China and Pakistan were found to have the highest global GLOF danger, with Pakistan having a larger lake condition score than China. In the Astore Basin, the classification of potentially dangerous glacial lakes (PDGLs) is based on several factors, including lakes with an area larger than 0.1 km^2, glacial fed lakes, lakes located within 10 km of a glacier, and lakes that have been observed to have an increasing area over time. Lakes with a red classification and an area larger than 0.2 km^2 are more likely to experience future GLOFs compared to lakes with yellow and blue classifications, which have a very low tendency for GLOFs due to their smaller area, less than 0.1 km^2. In 2012, (Ashraf et al. 2012) classified five lakes in the Astore Basin as PDGLs, each with an area larger than 0.1 km^2. Over the following decade, the number of PDGLs doubled, with these expanding lakes posing increasing risks due to their growing areas. Given the situation in Northern Pakistan's Astore Basin, continuous monitoring is crucial to mitigate potential hazards and protect the surrounding areas from the risks posed by these expanding glacial lakes.

4.3 Rama Lake, Landsat 8 data validation with dGPS data

Remote sensing data like Landsat 8 OLI can offer valuable insights for assessing changes in land use and land cover in the Rama Lake region. In this study, Landsat 8 OLI data for October 2021 was utilized to analyze modifications in the Rama Lake area, and dGPS field observations collected in July 2021 were used to validate the classification outcomes. Validation of research results is important to ensure the accuracy of results and the replicability generalization of findings. To validate our results, we used

Ground control points (GCPs) placed at known locations in the field and these coordinates were recorded using the differential Global Positioning System (dGPS). This method is widely used to validate the spatial accuracy of Landsat data. Comparison of the coordinates derived from Landsat image with the coordinates of these points is done to evaluate the accuracy of the image. This method has been successfully employed in various studies for validation of Landsat data, including land cover mapping and change detection analysis (Das & Angadi, 2022; Rawat & Kumar, 2015; Zhang et al., 2023).

Our dGPS field observations for Rama Lake in Astore Basin were validated using Landsat data for 2021. 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 along with the obtained overall is supported by Fig. 10. Landsat data collaborating with in-situ observations provides valuable information, proved instrumental for glacial lakes mapping.

Figure 10 *Rama Lake Landsat data validation with dGPS observations Oct 2021*

These results indicate the potential of remote sensing data for assessing changes in land use and land cover in the Rama Lake area. However, it is important to note that the accuracy of classification results may be influenced by various factors such as the quality of the remote sensing data, classification algorithms, and ground-truth data. Therefore, it is suggested that accuracy assessments should be conducted for each specific study area and application. 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 6 shows the overall accuracy obtained by validating the Landsat data with dGPS observations.

Table 6
Rama Lake overall accuracy obtained from validating Landsat data with the observations collected through dGPS

	Lake extent	**Landsat data**		**Total**
		lake	Others	
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		

Table 6 *Rama Lake overall accuracy obtained from validating Landsat data with the observations collected through dGPS.*

Landsat 8 OLI data and dGPS field observations can provide precise insights into mapping changes in the Rama Lake region, guiding sustainable management strategies.

4.4 Lakes fluctuations in June-September-October

Lake area changes at decadal and seasonal intervals, with large seasonal variations. Our study examined seasonal and decadal changes in glacier lakes. Every year from June to September to October, the rapid melting causes new lakes to grow and old ones to expand as suggested by (Shugar et al., 2020) Glacial lakes are growing due to climate change and glacier retreat. In June 1993, the number of lakes was only 06 with an area of 0.35 km^2, but by September 2001, the total had increased to 72 with an area of 3.06 km^2, indicating a 93% increase in lake number and an 88.5% increase in lake area. The number of lakes with an area greater than 0.01 km^2 grew seasonally to 52, with a total area of 2.93 km^2, which is particularly concerning. Likewise, in June 2014 lakes noted were 29 with an area 0.38 km^2, while in Sep 2014 at the end of melt season the number recorded was 63 with an area of 3.23 km^2 increasing the number by 54% and the area by 88%, seasonal variations is evident from such an enormous growth. Alike in June 2021 lakes sum was 18 with an area 0.62 km^2 and in Oct 2021 this hyped to 100 with an area of 3.86 km^2. Revealing the numeral increase to be 82% while the latter increased by 83.97%. Normal seasonal hype numerally is 74.8% while the average area change exhibited from 1993–2021 seasonally 86.3%. Alarmingly the seasonal variations are magnifying leading to the formation of new lakes and expansion of old ones endangering the mountainous communities as perceived by (Bolch et al., 2012; Haeberli et al., 2017; Huggel et al., 2002) GLOFs could threaten downstream residents, infrastructure, and environmental security. Figure 11 confirms the formations of glacial lakes from June 2021 to Oct 2021.

Figure 11 *Seasonal variations in glacial lakes from June 2021 to Oct 2021, representing how the frozen area changed to glacial lakes.*

4.5 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 Fig. 12.

Figure 12 *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.*

Upon comparing our glacial lake data in the Astore Basin with the HMA Multi-decadal Lake Inventory (Shugar et al., 2020) and the Third pole Glacial Lakes Inventory (Zheng et al., 2021), we observed that the latter has mapped all small lakes while the former has not considered lakes with an area less than 0.05 km^2. Our study identified differences in the number and area of glacial lakes in the basin and emphasized that satellite data can sometimes be inaccurate when studying small regions. Therefore, we conducted seasonal analysis from June to September to October each year. Our study found an increasing trend in the number and area of glacial lakes, with certain small size lakes developing in large numbers in the past decade.

The Third Pole dataset for 2014–2016 showed 242 glacial lakes in the Astore Basin with an area of 5.61 km², of which 107 had an area greater than 0.01 km² and covered 5.04 km² incrementally. Meanwhile, 26 lakes with an area greater than 0.05 km² were identified in the HMA inventory for 2015, covering an incremental area of 1.49 km². 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 km², of which 50 lakes had an area greater than 0.01 km² and covered an area of 3.14 km². Additionally, 18 lakes with an area greater than 0.05 km² were identified, covering an area of 2.39 km². These findings are presented in Table 7.

Table 7
Third Pole Glacial Lakes Dataset, HMA Inventory and Astore Basin Results 2014, number and area of lakes and the lakes having area > 0.01 km² 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 km²	1.49 km²	3.23 km²
No and Area greater than 0.01 km²	107	13	50
Cumulative Area of Lakes area > 0.01 km²	5.04 km²	1.49 km²	3.14 km²
Lakes > 0.05 km²	26 (3.34 km²)	13 (1.49 km²)	18 (2.39 km²)
Data source	Zheng et al., 2021	Shugar et al., 2020	This study

Table 7 *Third Pole Glacial Lakes Dataset, HMA Inventory and Astore Basin Results 2014, number and area of lakes and the lakes having area > 0.01 km² statistics.*

In summary, while the inventories by (Shugar et al., 2020) and (Zheng et al., 2021)provide valuable insights into glacial lakes on a large scale while for studying small regions such as Astore Basin we found out that the inventories data vary when considering a small region. As a result, we conducted a thorough investigation at seasonal and decadal scales. Our extensive analysis emphasizes the need to undertake field observations and detailed comparisons to overcome the uncertainties and flaws associated with automated approaches.

5. Conclusion

This study sought to analyze the phenomenon of glaciers and glacial lakes in Northern Pakistan's Astore Basin, utilizing Landsat data from 1993 to 2021, Climate data from Astore Station 1961-2021, TPDC temperature analysis 1979-2020, LST data from 2010-2021 and dGPS field measurements for Rama Lake in 2021. The investigation indicated considerable seasonal and annual variations in temperature, precipitation and LST influencing the quantity and extent of glacier lakes in the basin. Results indicated that the average intensification in lakes recorded seasonally from June to Sep./Oct integrally is 75.8%, whereas the average seasonal area changes were 86.29%. Compared to the results from the previous year, the density and quantity of glacial lakes in the region significantly increased seasonally and decadal. Analysis of seasonal changes in the number of lakes revealed an average increase of 75.8%, while the corresponding increase in lake area was 86.29%.

Decadal analysis from 2001 to 2021 showed a 28% increase in the number of lakes and a 20.7% increase in their area. Comparison of lake statistics between June and October from 1993 to 2001 revealed that Astore station temperature data (1961-2021) and TPDC temperature (1979-2020) showed an increasing trend for temperature. LST indicated an increasing trend from 2010-2021, enhancing the melt of glaciers causing a direct increase in the number and area of glacial lakes. Glacier melt patterns vary depending on seasonal approaches, particularly during September. The study identified 10 glacial lakes with an area greater than 0.1 km^2 and three with a major risk for GLOFs, the Himalayan region is the most vulnerable. Continuous monitoring is crucial to mitigate potential hazards and protect surrounding areas from these expanding glacial lakes. Policymakers and stakeholders should build monitoring and early warning systems for glacial lake outburst floods and encourage sustainable water management.

Declarations

Funding

This study was jointly funded by the Strategic Priority Research Program of the Chinese Academy of Sciences (Grant No. XDA2007010102), the National Natural Sciences Foundation of China (Grant No. 41877168), the Science and Technology Department of Tibet (XZ202001YD0013C, XZ202101ZD0006G).

Acknowledgement

The authors acknowledge the support of Sagax and ICIMOD for jointly conducting the pax Pakistan expedition. ICIMOD gratefully acknowledges the support of its core donors, including the Governments of Afghanistan, Australia, Austria, Bangladesh, Bhutan, China, India, Myanmar, Nepal, Norway, Pakistan, Sweden, and Switzerland. The authors thank the USGS for allowing free access to Landsat archive, MODIS archive, the TPDC for providing high-resolution temperature data, and the Pakistan Meteorological Department for providing climate data. The views and interpretations in this publication are those of the authors and are not necessarily attributable to their organizations.

Disclosure Statement

The authors have no potential conflict of interest.

Data availability Statement

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

Conflict of Interest

There is no conflict of interest.

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Figures

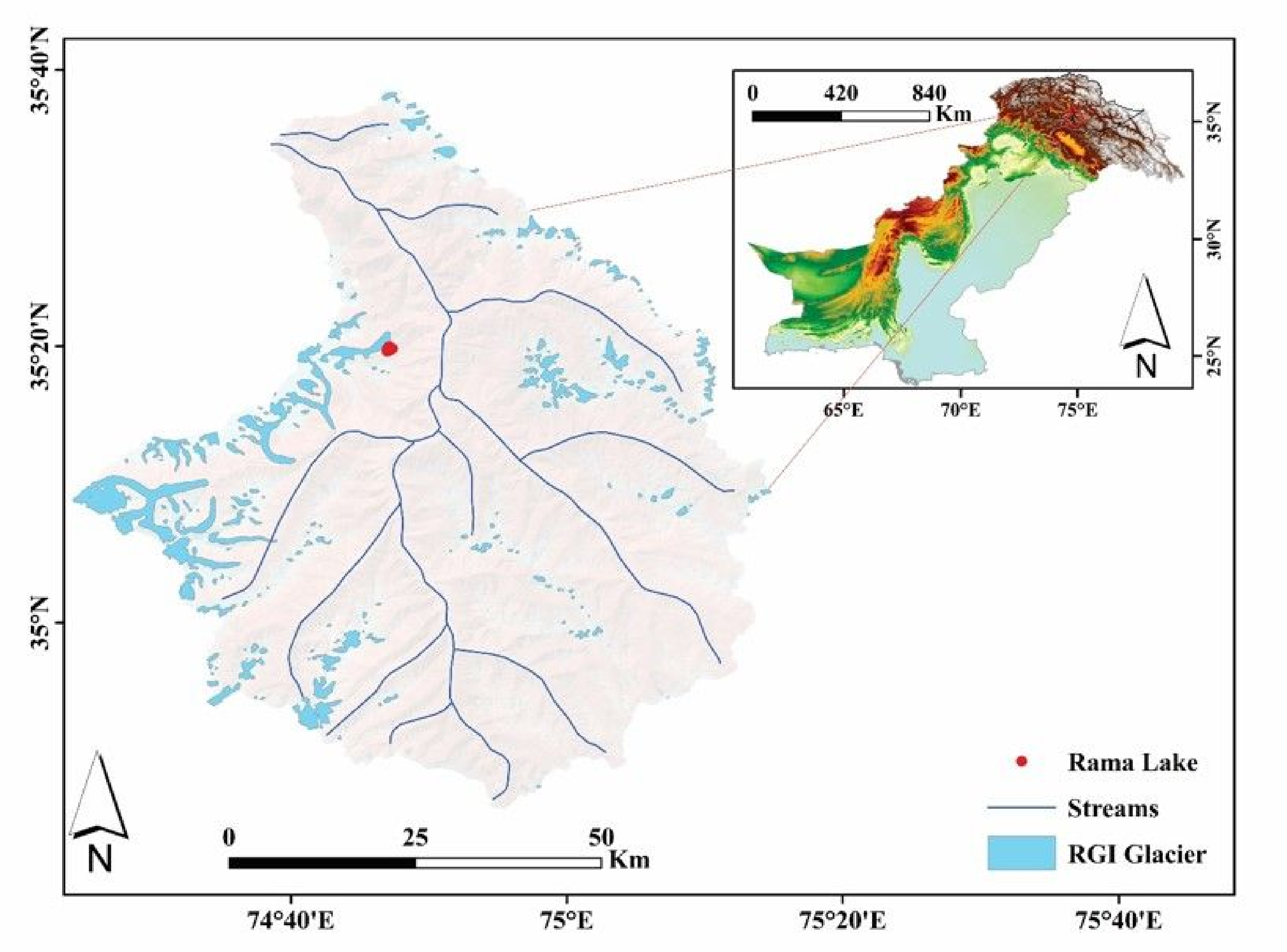

Figure 1

Study Area map of Astore River Basin highlighting the RGI 6.0 glaciers boundaries (RGI Consortium. (2017)), streams and Rama Lake

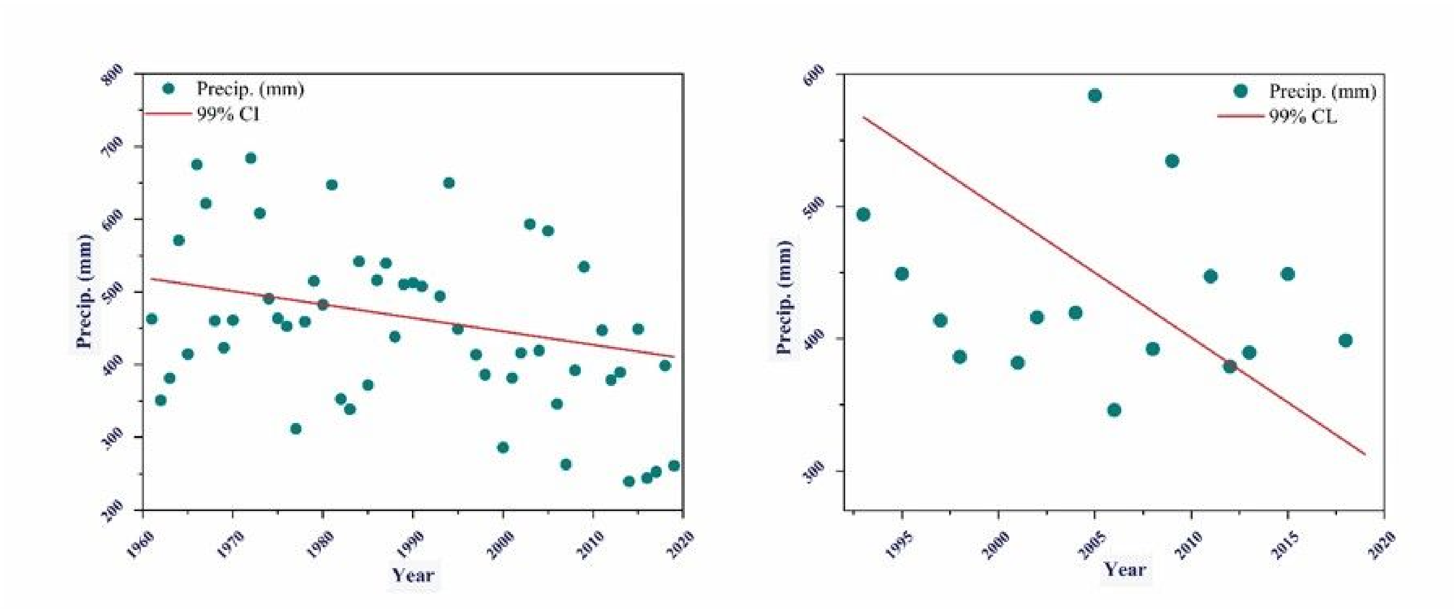

Figure 2

Precipitation Trend Analysis 1961-2019 showing an overall negative trend, followed by 1993-2019 annual mean precipitation indicating a decreasing trend.

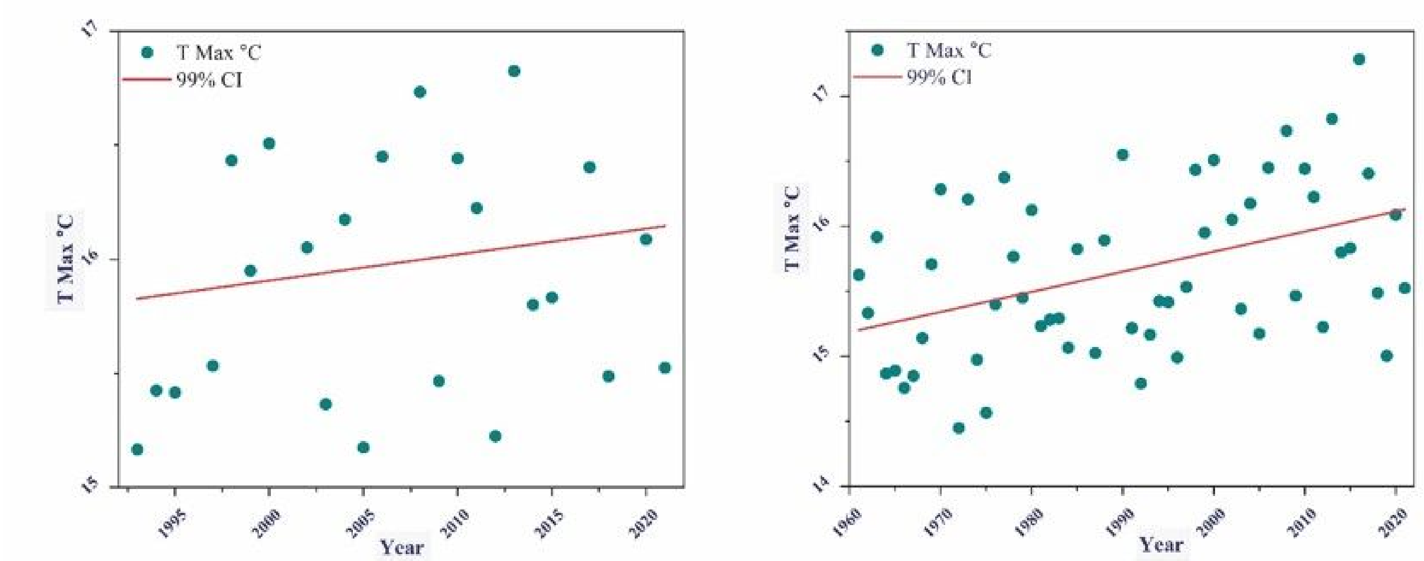

Figure 3

Temperature Trend analysis 1961-2021, annual maximum temperature 1993-2021 followed by maximum temperature 1961-2021, both indicating an overall increasing trend

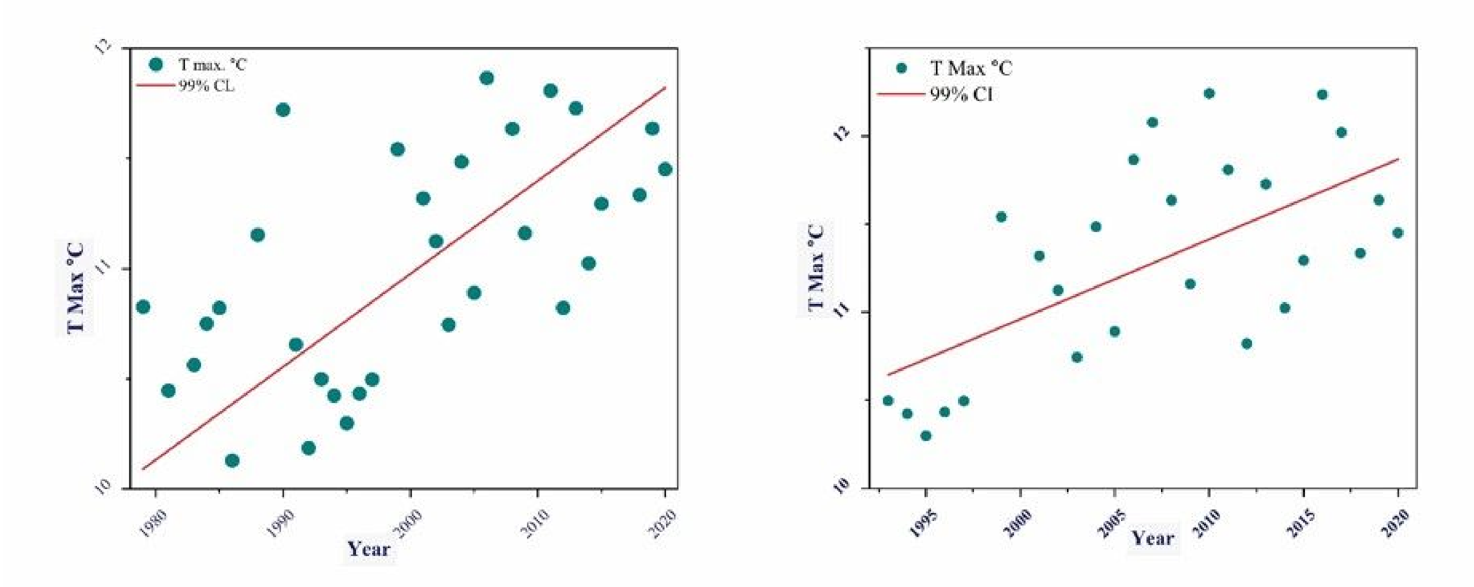

Figure 4

High-resolution near-surface meteorological forcing dataset for the Third Pole region (TPMFD, 1979-2020) overall positive trend for 1979-2020, followed by 1993-2020

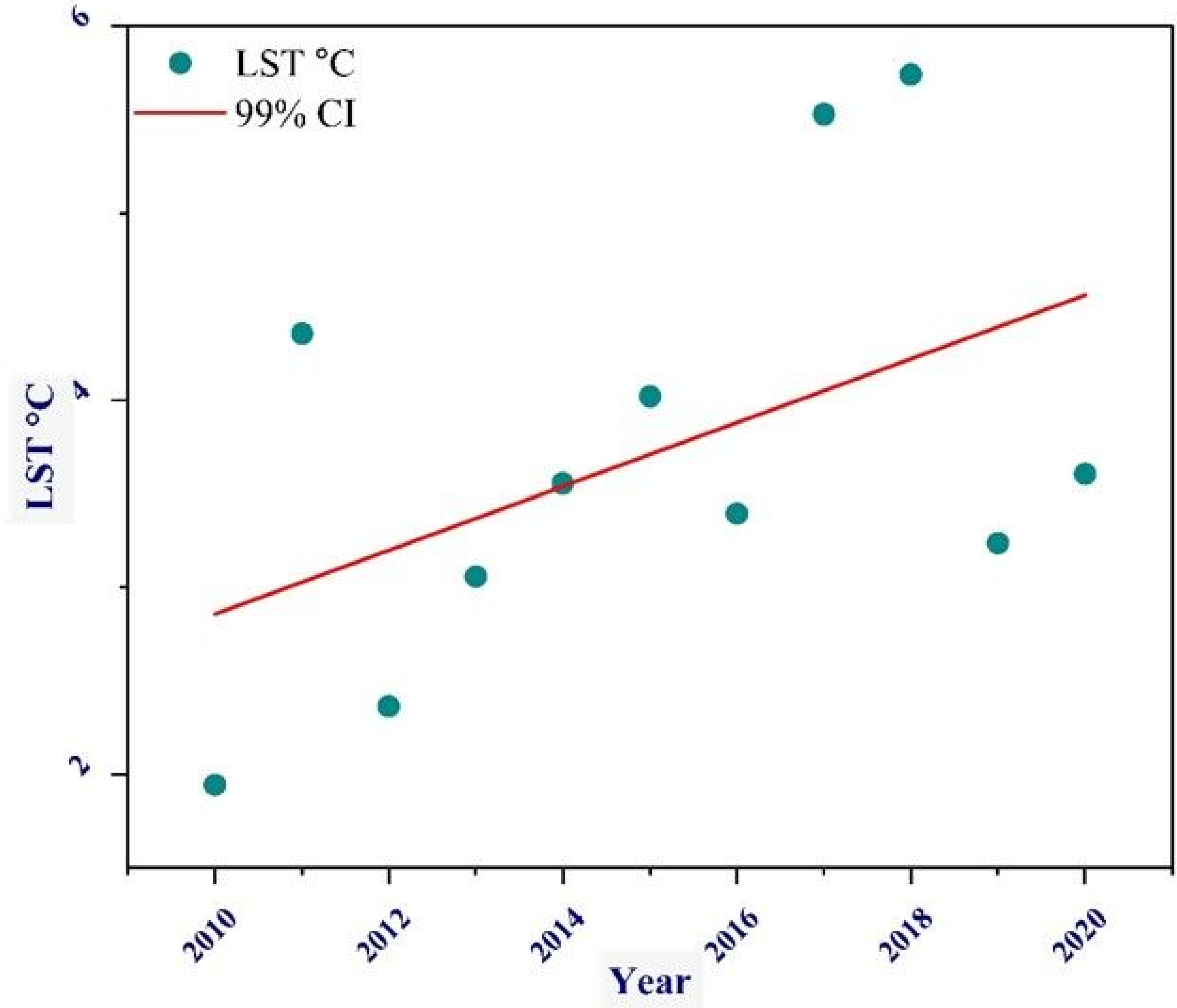

Figure 5

Land surface temperature, trend analysis showing an overall positive trend.

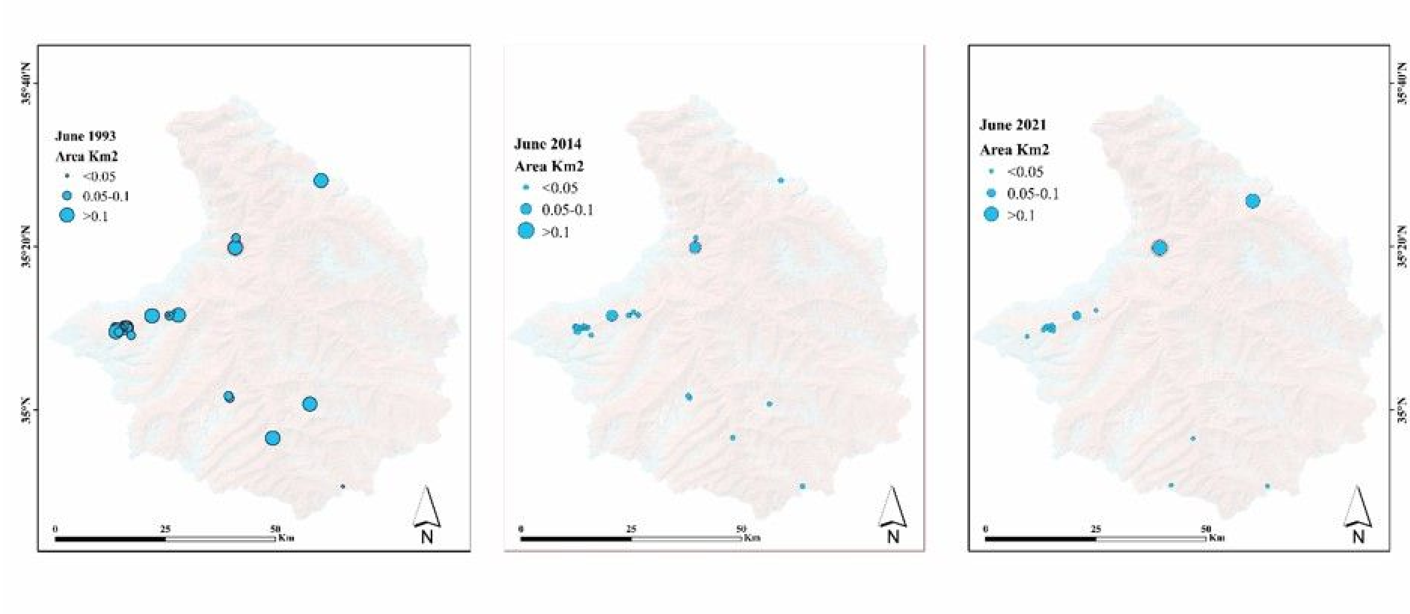

Figure 6

Astore Basin Glacial Lakes June 1993-June 2021 from left to right. Left June 1993, followed by June 2014 and to the right June 2021, Rama Lake encircled red circle

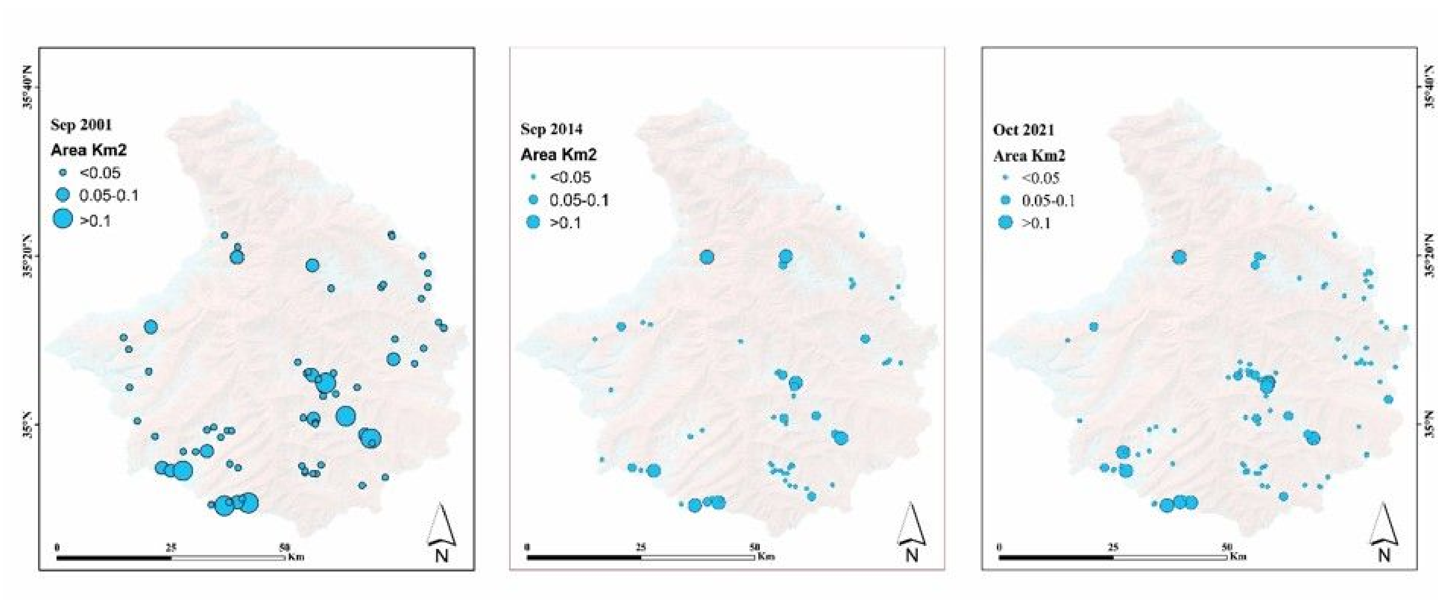

Figure 7

Glacial Lakes statistics at the end of the melt season from left to right 2001-2021. On left Sep 2001, followed by Sep 2014, and to the right Oct 2021. Rama Lake encircled red to track the changes over the period.

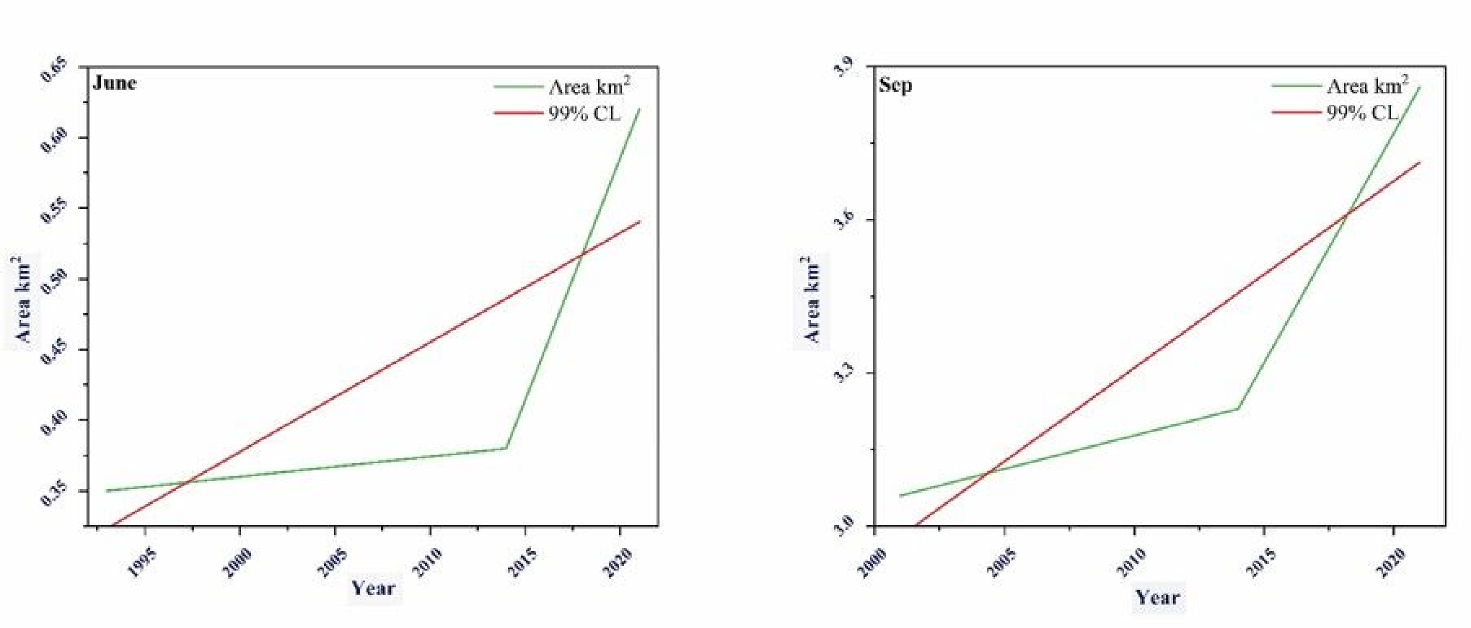

Figure 8

Lakes area changes from 1993-2021, A) June, B) Sep

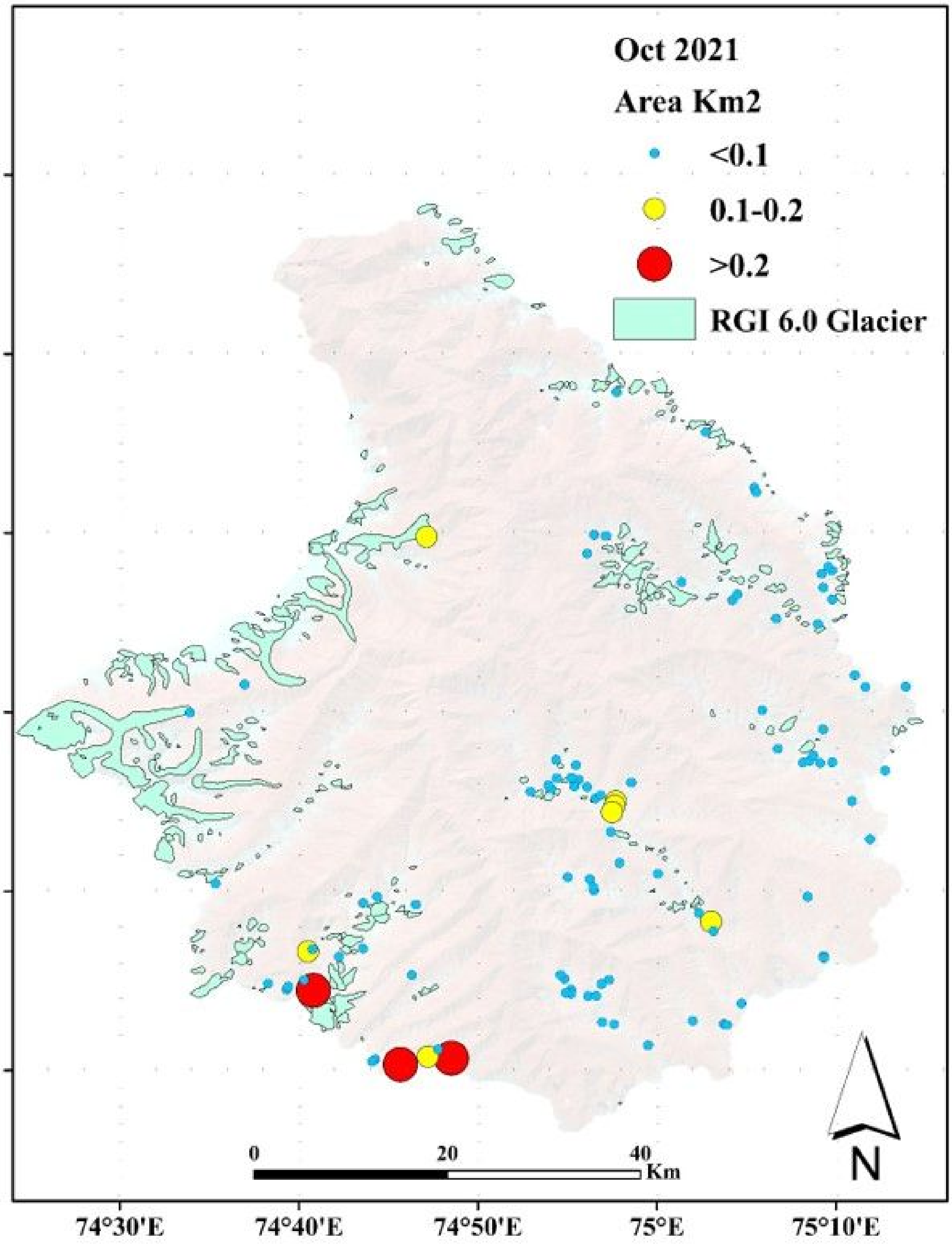

Figure 9

Lakes with area < $0.1km^2$ are in blue, area 0.1-0.2 km^2 in yellow, and lakes with area > 0.2 km^2 are in red observed in Oct 2021

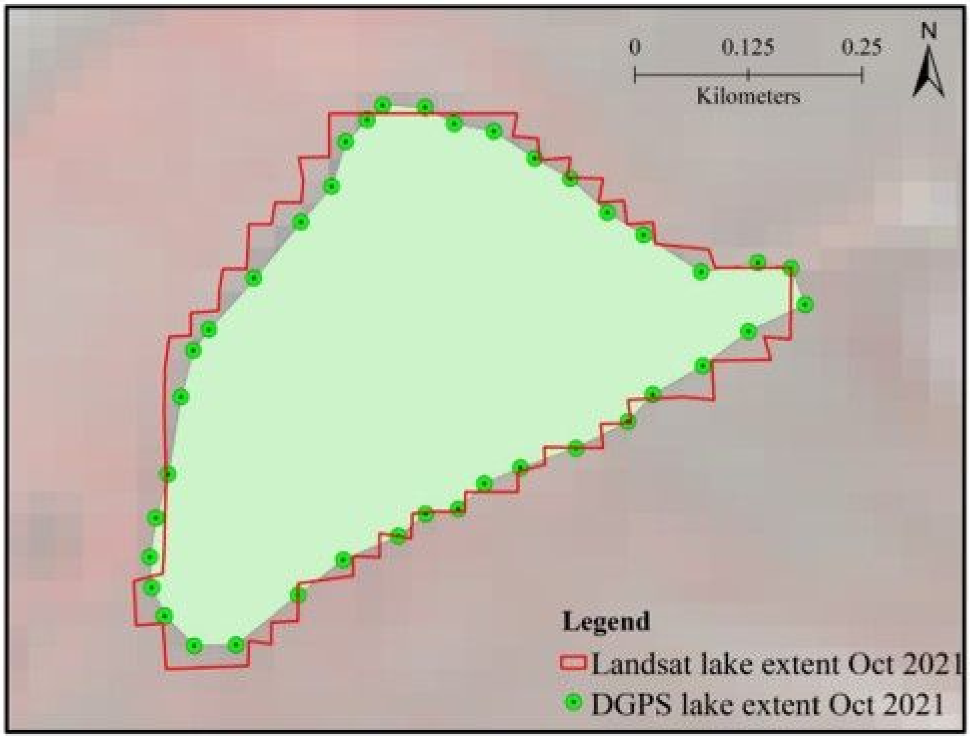

Figure 10

Rama Lake Landsat data validation with dGPS observations Oct 2021

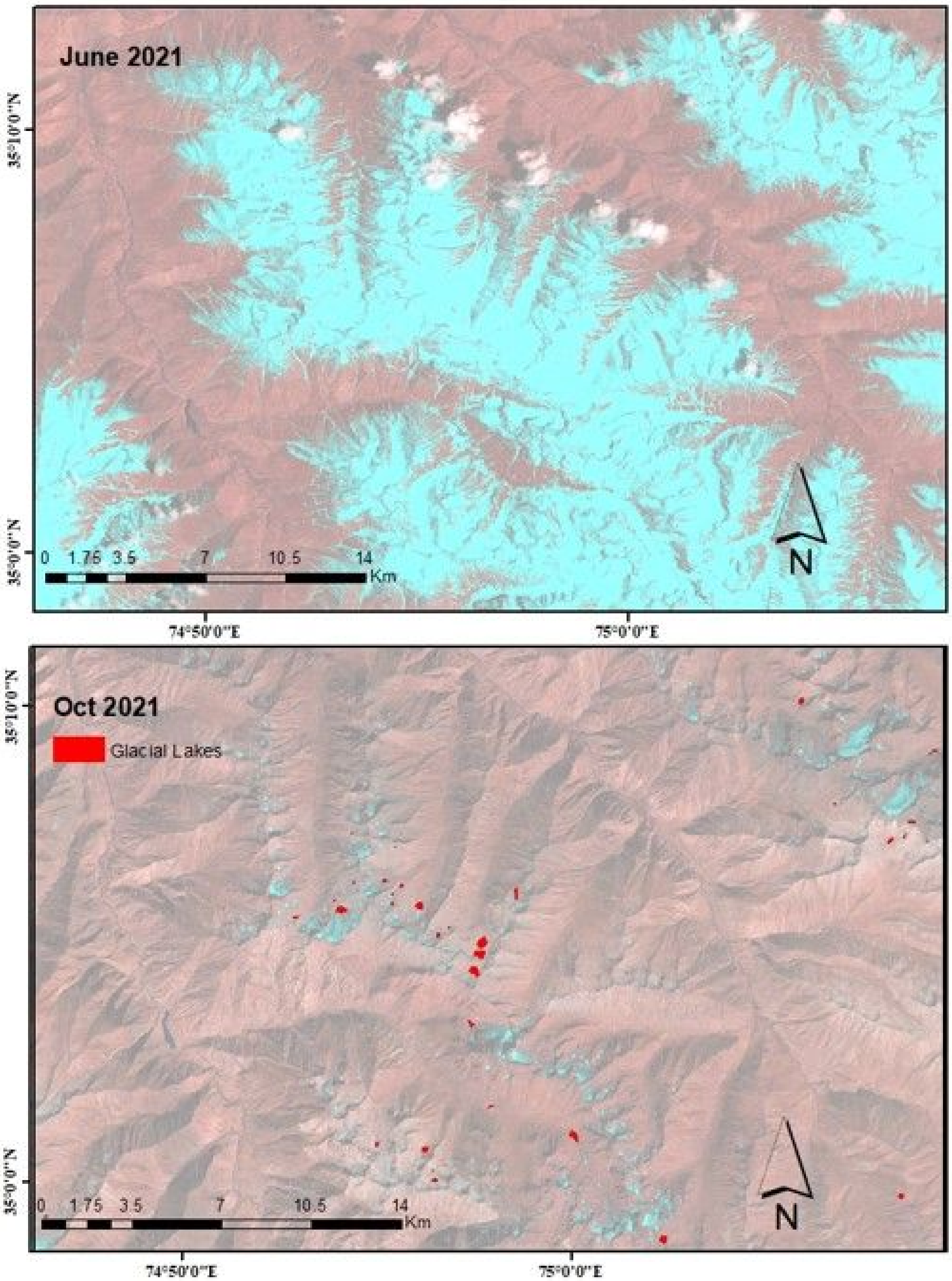

Figure 11

Seasonal variations in glacial lakes from June 2021 to Oct 2021, representing how the frozen area changed to glacial lakes.

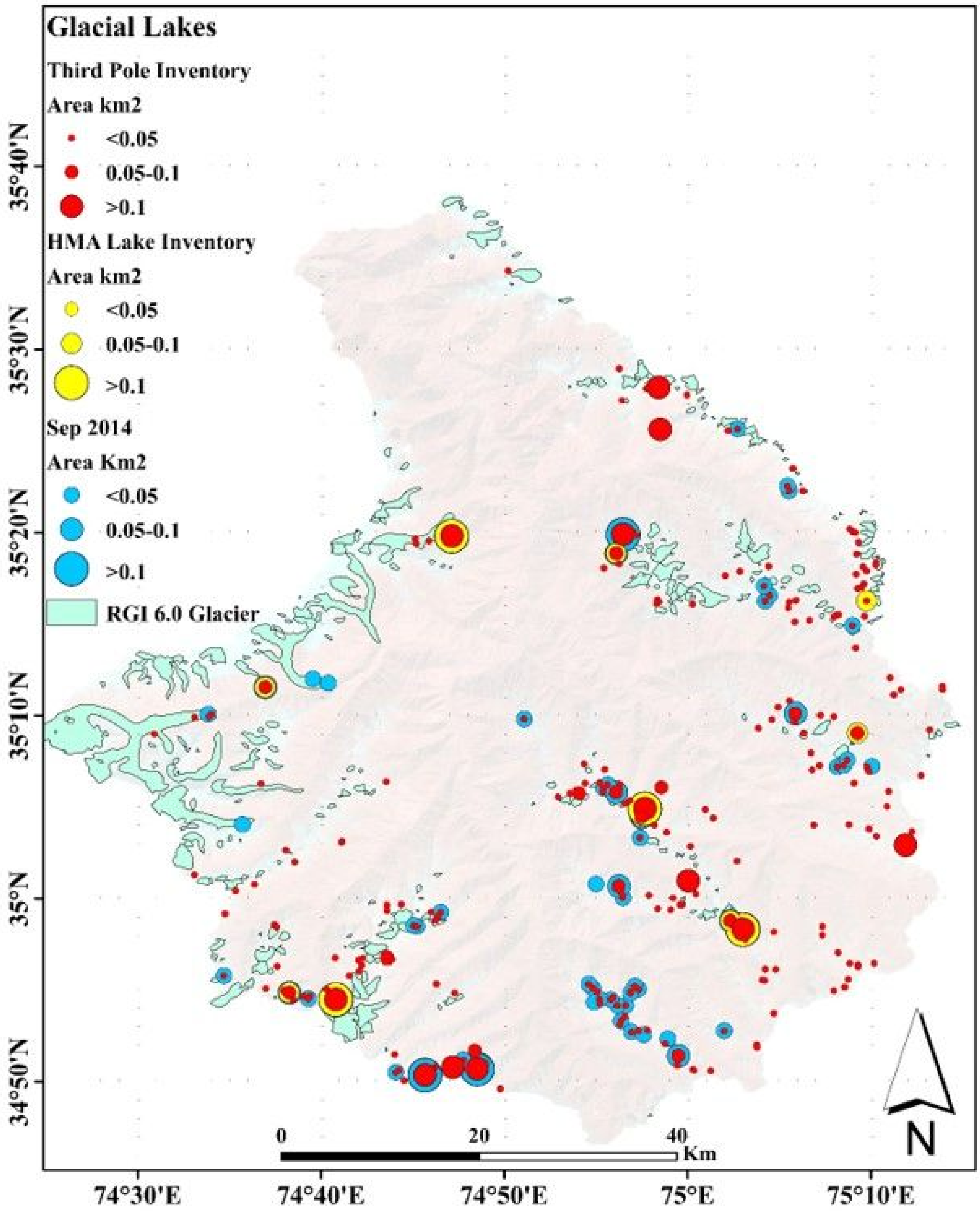

Figure 12

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.