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Genesis and spatio-temporal analysis of glacial lakes in the peri-glacial environment of Western Himalayas

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Abstract

Glaciers are retreating in the highest mountainous regions of the world, like Himalayan region as a result of climate change and global warming. This leads to the formation of different types of glacial lakes. These lakes are not only the source of fresh water but it also causes disaster in the form of Glacial Lake Outburst Flood (GLOF). Astore Drainage Basin is located in north eastern mountainous region of Himalayas. This area is prone to GLOFs because of the increasing number of glacial lakes and the growth of existing lakes as a result of global warming. To provide a detailed information about the spatial and temporal information of glacial lakes detailed inventories has been developed for the study area using Landsat images for the year 1989, 1999, 2009 and 2019. Glacial lakes were mapped and identified by using Normalized Different Water Index, Normalized Difference Snow Index and high-resolution Google Earth images. It was found from the analysis that the number of the glacial lakes increased from 120 to 128 in a period of thirty years (i.e., from 1989 to 2019). During the study period two lakes disappeared whereas ten new lakes were formed. There were 21 lakes which show area expansion more than 100% representing high susceptibility for GLOF. The results also showed that smaller lakes expanded more rapidly in area than the larger lakes.

1. Introduction

Glaciers store a massive volume of water in the form of ice. Glaciers form naturally as a result of the interaction between relief and climate and are majorly formed from solid precipitation [1]. These are an important renewable source of fresh water and supply water for many purposes; drinking, irrigation, agriculture, industrial and hydropower development. Meltwater from glacier is not only the part of hydrological processes but also responsible for the global sea level rise [2]. About 1/6th of the world population is dependent directly on the water coming from these glaciers [3].

There are several glaciated mountainous places in the globe, but the Himalayan and Karakoram regions, after the Polar Region, are the most glaciated [4]. This region is known as the "Third Pole" because it contains the largest concentration of glaciers and snow after the Polar Regions [5], and it covers an area of 40,800 km^2 [4]. The Hindukush-Himalayan (HKH) area has around 54,252 glaciers with total ice reserves of 6,127 km^3. These glaciers and snow provide water to the region's major rivers [6]. This mountainous terrain is extremely vulnerable to global warming and climate change, and the stability of the glacier is determined by slope, aspect, elevation, and the geomorphology of the surrounding area [7].

Global warming patterns are causing glaciers to retreat [8-9]. As a result, several glacial lakes form in, around, and under the glacier [10-11]. According to previous research, glaciers with low flow velocity or those that are stationary and have a low surface slope angle are more vulnerable to lake formation [12]. Glacial lakes are the lakes "which form as a result of glacier retreat or which are primarily supplied by glacier meltwater" [13]. Glacial lakes are common in high mountain ranges across the world [14]; in the Rockies and Coastal Mountains of Alaska, of North America [15], in the Andes of South America [16], in the Alps and Caucasus of Europe [17-18] and in the Karakoram, Himalayas and Tien-Shan mountains of Asia [19-21].

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Glacial lakes are considered as the indirect indicators of glacier changes, as most the lake formed and the existing lakes increases in size as a result of glacial melting [2]. These lakes provide fresh water and have drawn a significant number of people to the hilly areas for a variety of activities [20]. The majority of the lakes are unstable and located in remote, inaccessible places. Glacial Lake Outburst Flood (GLOF) is a catastrophic outpouring of water from these lakes that affects the living population and damages natural and man-made infrastructure downstream [22].

Glacial lakes are found in northern Pakistan's high mountain ranges. In the Hindu Kush Himalayas (HKH) area of the country, there are currently around 2,600 glacial lakes [23]. According to the inventory, developed by International Centre for Integrated Mountain Development (ICIMOD), 2,500 glacial lakes were identified in ten river basins of Pakistan's HKH region in 2005 [24]. Nonetheless, it was estimated to be 2,420 in 2010, with 52 of them being deemed potentially hazardous. Cirque type accounts for 25% of these lakes, while End Moraine Dammed accounts for 62% [25]. The Indus, Astore, and Gilgit River Basins form the bulk of these lakes. This study aims to conduct Spatio-temporal distribution of glacial lakes for the period of thirty years (from 1989 to 2019) in Astore Drainage Basin by using remotely sensed data through geospatial techniques. The findings of the proposed study will provide baseline information for future research.

2. Study area

The Astore Drainage Basin is situated in the Himalayan northwestern mountain ranges (Fig 1). The study area spans between 34º 46' 31" to 35º 38' 38" North latitude and 74º 24' 12" to 75º 14' 52" East longitude. The Astore Drainage Basin is bordered on the north by Gilgit district (Pakistan), on the south by Neelum valley (Pakistan), on the east by Skardu district (Pakistan), and on the west by Diamir (Pakistan). It covers a total area of 3,988.7 km^2. The basin's elevation varies between 1,237m and 8,105m above sea level. Astore, Rama, and Rattu are the three meteorological stations, while Doyian is the only hydrometric station. There are 372 glaciers in the study area, occupying a total area of 239.59 km^2. The Astore Sub-basin has the lowest ice reserves in the Upper Indus Basin (UIB), with just 16.88 km^3 of ice [22]. In the winter, this area gets heavy precipitation, and most of the peaks are snow-covered all year [26-27].

Topographically, the ground surface is uneven. The Astore Drainage Basin is flanked on all sides by mountains. The basin is wider at the bottom (South) and narrower at the top (North). The basin's mountains span from south to north, with abrupt elevation variations. The southern side has a higher elevation than the northern side.

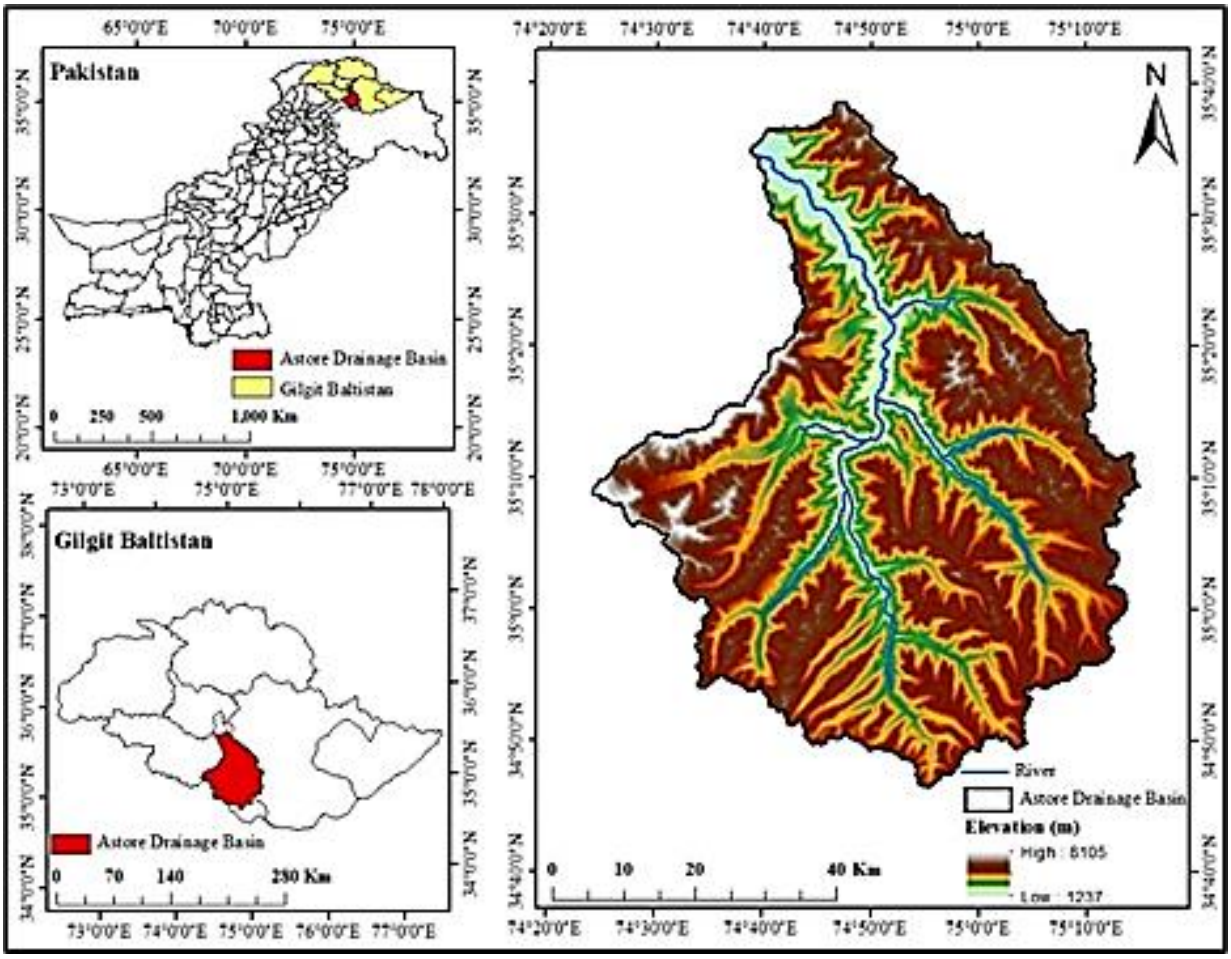

Figure 1. Location of Astore Drainage Basin, North Pakistan

3. Materials and methods

This section consists of the methods used for collection of data and mapping of the glacial lakes.

3.1. Collection of data and mapping of glacial lakes

Landsat satellite images with a spatial resolution of 30m and some with a resolution of 15m (panchromatic) were utilized in this work to create glacial lake inventories in the Astore Drainage Basin for the observation years 1989, 1999, 2009, and 2019. In ArcGIS, the Normalized Difference Water Index (NDWI) [28-30] and the Normalized Difference Snow Index (NDSI) were used to identify glacial lakes, as shown in Equations 1 and 2, respectively [31-32].

$$NDWI = \frac{GREEN - NIR}{GREEN + NIR} \quad (1)$$

$$NDSI = \frac{GREEN - SWIR}{GREEN + SWIR} \quad (2)$$

NDWI stands for Normalized Difference Water Index, and NDSI stands for Normalized Difference Snow Index, with GREEN representing the green band, NIR representing Near Infra-Red, and SWIR representing Short Wave Infra-Red. The NDWI scale runs from +1.00 to -1.00, with higher values representing water bodies and lower values representing non-water bodies. NDSI values also vary between +1.00 and -1.00, with all positive values indicating that snow is present.

High quality Google Earth pictures and the Hill Shading method were used to remove misclassified lakes and verifies lake location. The Google Earth images for various parts of the study area are available from 1984 to 2019. According to [22], glacial activity is responsible for the formation of all lakes over 3,500m. As a result, all glacial lakes over 3,500m were digitized and mapped in order to map the glacier lake. The lakes were designated from top to bottom of the basin for convenience, with identification numbers ranging from Astore-GL01 to Astore-GL130. Lakes that are not visible in the photos are not included in the inventories. All of these lakes were then classified based on the following characteristics:

i. ***Identity Number:*** To ensure uniformity, identity numbers ranging from Astore-GL01 to Astore-GL130 were allocated to each lake.
ii. ***Coordinates:*** The approximate center of the glacial lake was given World Geodetic System 1984 coordinates (Longitude and Latitude) by producing a point map.
iii. ***Area:*** The vector glacial lake layer was utilized to automatically compute the area of each lake using the raster calculator in ArcMap 10.5.
iv. ***Elevation:*** The elevation (in meters) above sea level for the lakes was obtained using the DEM.
v. ***Lake Type:*** Glacier lakes were categorized into two groups based on their hydrologic link to their mother glaciers: glacier-fed lakes and non-glacier-fed lakes.
vi. ***Volume and Depth:*** The volume and depth of each lake in this study were determined using the following formulae (Equations 3 & 4) devised by [31] to estimate the depth and volume of glacial lakes in the Swiss Alps:

$$V = 0.104A^{1.42} \quad (3)$$

$$D = 0.104A^{0.42} \quad (4)$$

Where V is the volume (m^3), D is the depth (m) and A represents area (m^2) of the lake.

Without comprehensive knowledge about an area's topography, lake water volume cannot be computed directly from remotely sensed data or any other data source [33]. It is important to note that the volume and depth obtained using the above methods are simply estimates because they are dependent on a number of other parameters.

Glacial lakes are divided into two kinds in current inventories. They are classified as glacier-fed lakes or non-glacier-fed lakes based on whether they are in direct touch with the parent glacier and get glacial meltwater or not [34]. To do this, the Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM) was employed in ArcGIS to outline the watershed for each lake. If glaciers lie within a lake's watershed, it signifies that the lake receives meltwater from the glacier, and so the lake is termed glacier-fed, and vice versa.

4. Results and Discussions

This section deals with the analysis, results and discussions. Section one explains glacial lake inventories for the year 1989, 1999, 2009 and 2019 whereas, section two elucidates Spatio-temporal distribution of glacial lakes.

4.1. Glacial Lake Inventories

4.1.1. Glacial Lake Inventory 1989

Based on Landsat imagery, there were 120 glacial lakes in the Astore Drainage Basin in 1989, covering a total area of 4.75 km^2. According to the classification, there were 54 glacier-fed lakes and 66 non-glacial-fed lakes with a total area of 2.227 km^2 and 2.523 km^2 respectively (Fig. 2). The lakes ranged in size from 0.0009 km^2 and 0.468 km^2. There were 31 lakes with an area of less than 0.01 km^2 and others with an area of more than 0.01 km^2. Only three lakes (two non-glacial-fed and one Glacial-fed) had an area greater than 0.02 km^2, and only one (Astore-GL108) had an area greater than 0.4 km^2.

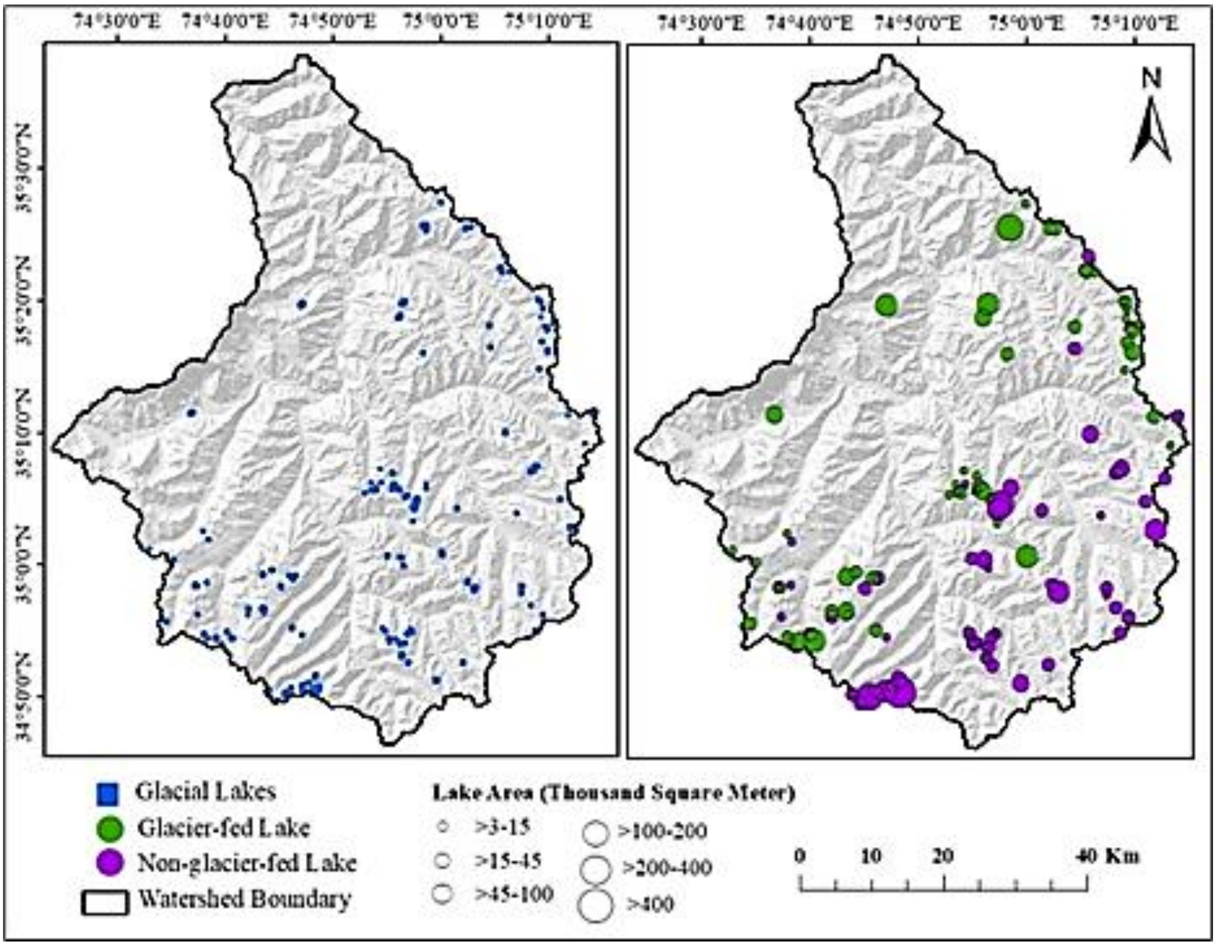

Figure 2. Astore Drainage Basin, 1989 (a) Distribution of glacial lakes (b) Lake types and area

4.1.2. Glacial Lake Inventory 1999

According to a 1999 inventory, the study area had 126 glacial lakes, with 59 Glacial-fed and 67 non-glacial-fed lakes (Fig 3). Glacial lakes occupied a total area of 5.457 km^2. Non-glacial-fed lakes occupied 58.18 percent (3.175 km^2) of the total glacial lakes area, while Glacial-fed lakes accounted for 41.82 percent (2.282 km^2). The lakes' surface area ranged from 0.0035 km^2 to 0.520 km^2 while their volume ranged from 1,545.55 m^3 to 223,821.3 m^3. There were 23 lakes with an area of less than 0.01 km^2 (18.25%). Just two lakes, both non-glacial-fed, had an area greater than 0.2 km^2. The only lake with a surface area greater than 0.5 km^2 was Astore-GL108. The lakes' elevations ranged from 3,501m to 4,949m above mean sea level (M.S.L), with an average of 4,354.95m. There were 41 lakes above 4,500m (M.S.L) with a maximum number of Glacial-fed lakes. The depth of the lakes varied from 3.20m to 26.17m.

4.1.3. Glacial Lake Inventory 2009

In 2009, remotely sensed data revealed 127 glacial lakes with a total area of 5.576 km^2 in Astore Drainage Basin. These include 67 non-glacial-fed lakes and 60 Glacial-fed lakes occupied an area of 3.298 km^2 and 2.278 km^2, respectively, accounting for 0.082 percent and 0.057 percent of the basin's total area (Fig 4). The lakes ranged in size from 0.0036 km^2 to 0.521 km^2, with volumes ranging from 1,548.9 m^3 to 224,208.2 m^3. Only 23 (18.11%) of the lakes were smaller than 0.01 km^2, covering a total area of 0.18 km^2. Three lakes (two non-glacial-fed and one Glacial-fed) had an area greater than 0.2 km^2, with only one (Astore-GL108) exceeding 0.5 km^2.

4.1.4. Glacial Lake Inventory 2019

There were 128 glacial lakes in the study area according to a 2019 inventory. These lakes occupied 5.861 km^2 of area, accounting for 0.147 percent of the Astore Drainage Basin's total area. There were 61 Glacier-fed lakes with the remaining lakes listed as non-glacial-fed (Fig 5). The lakes ranged in size from 0.0036 km^2 to 0.54 km^2. Only three lakes had an area greater than 0.02 km^2 and 19 (14.84 percent) had an area less than 0.01 km^2. Astore-GL108 was the basin's largest lake with a surface area of 0.5400 km^2. Non-glacial-fed lakes occupied 3.370 km^2 area which was 0.88 km^2 more than the area occupied by Glacial-fed lakes. The lakes' volumes ranged from 1,548.9 m^3 to 232,340.79 m^3. Glacial lakes were located at elevations ranging from 3,501m to 4,947m above mean sea level with an average altitude of 4,358.09m. Above 4,500m above M.S.L, there were 42 lakes, the majority of which belonged to the Glacial-fed group of glacial lakes. According to the 2019 inventory, the depth of the glacial lakes varied from 3.24m to 26.59m.

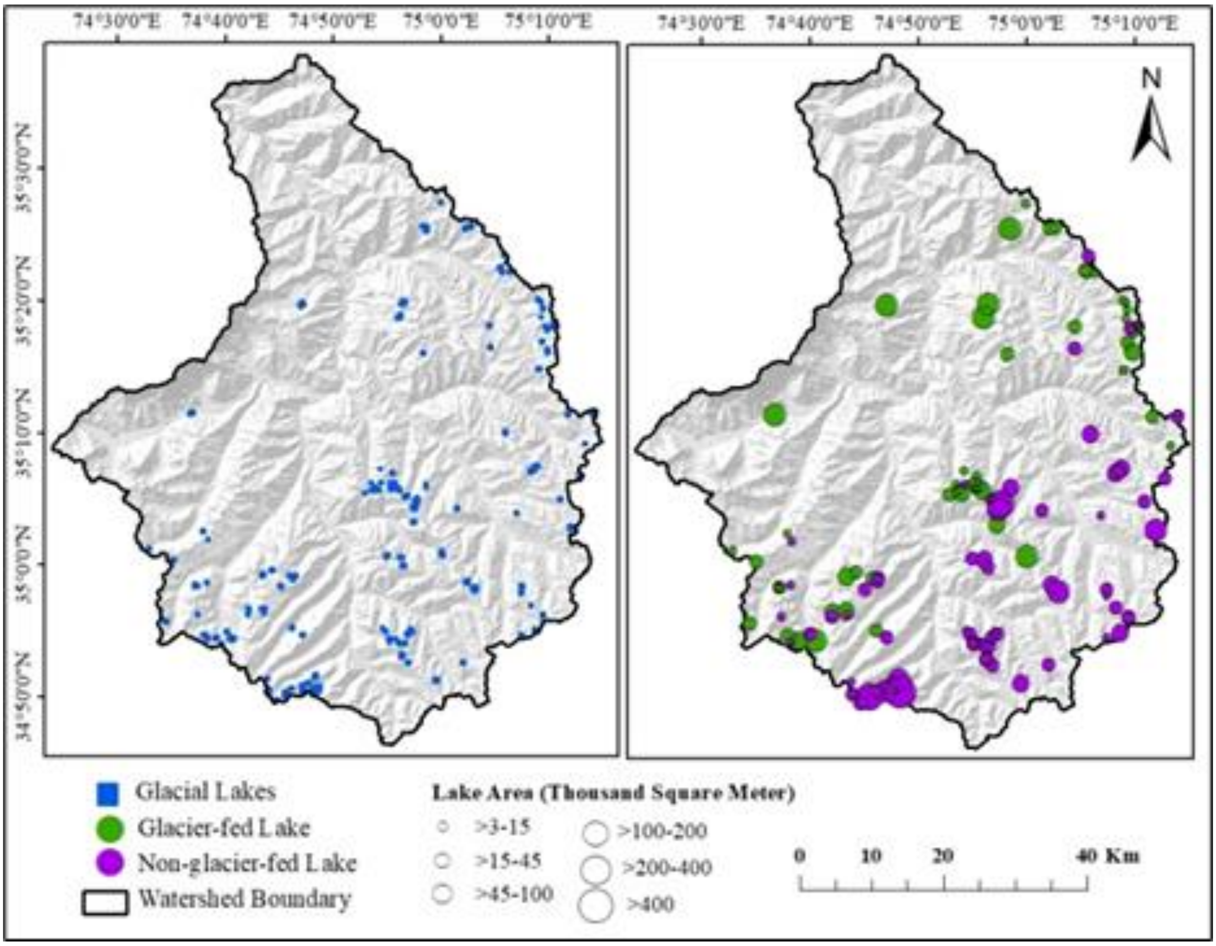

Figure 3. Astore Drainage Basin, 1999 (a) Distribution of glacial lakes (b) Lake types and area

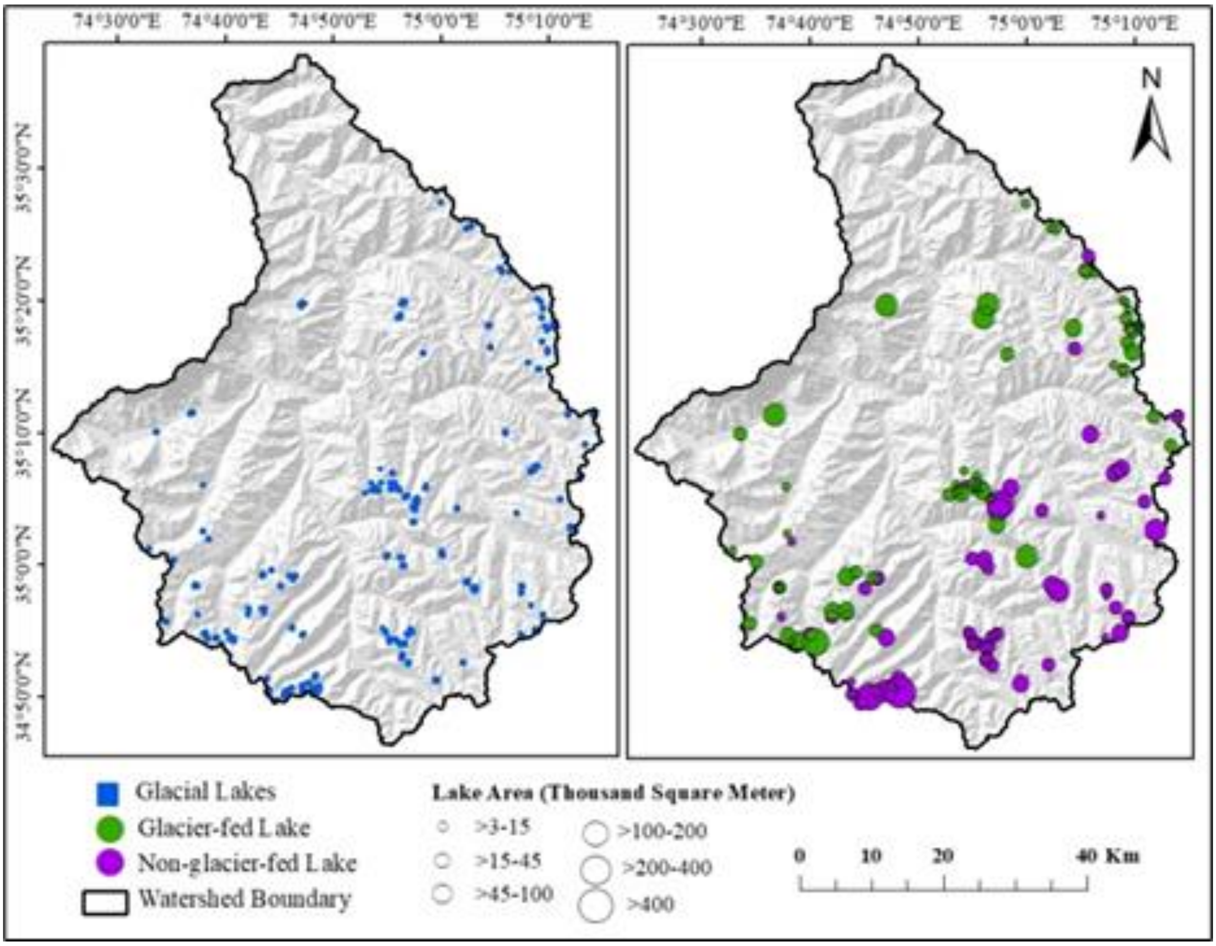

Figure 4. Astore Drainage Basin, 2009 (a) Distribution of glacial lakes (b) Lake types and area

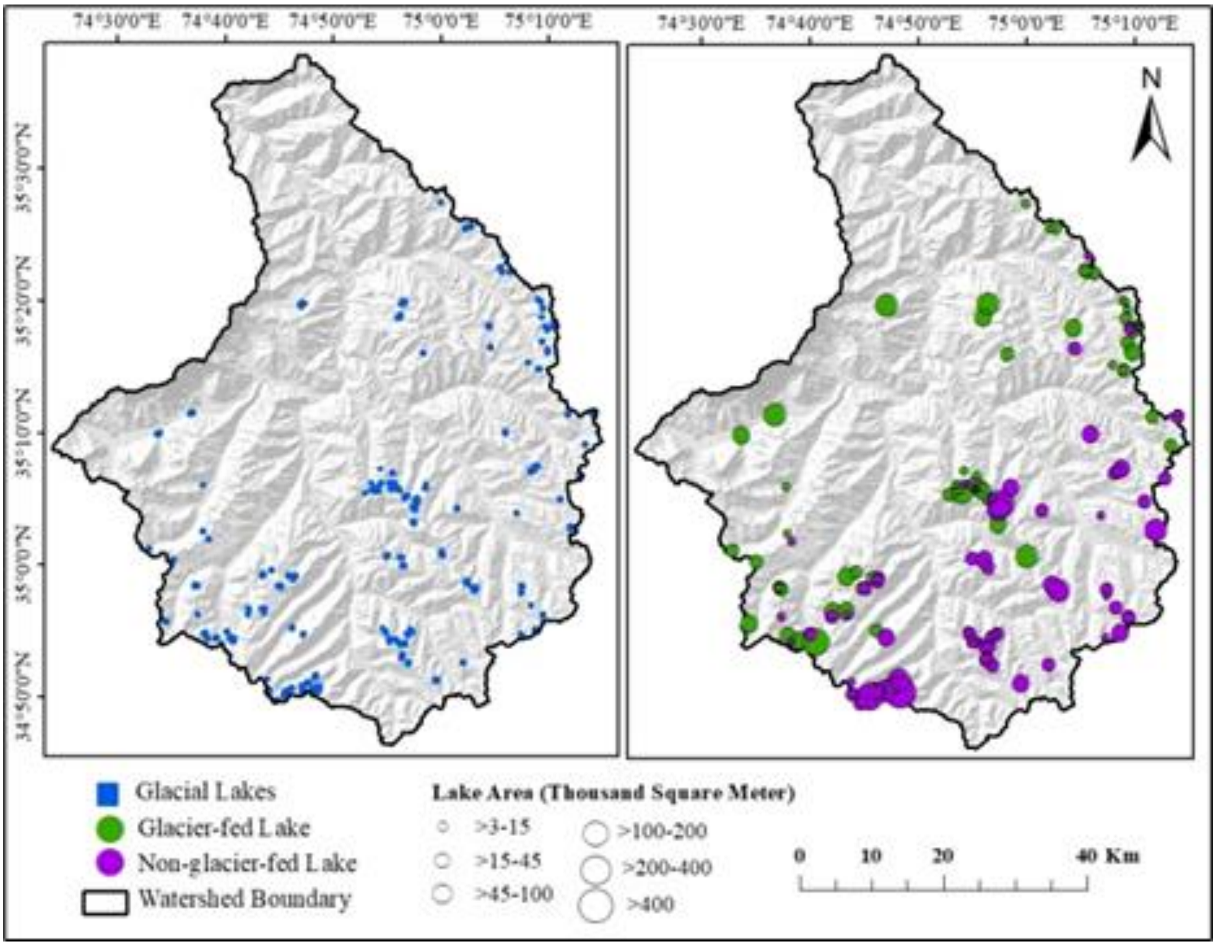

Figure 5. Astore Drainage Basin, 2019 (a) Distribution of glacial lakes (b) Lake types and area

4.2. Spatio-temporal Distribution of Glacial Lakes (1989-2019)

From 1989 to 2019, the evolution and development of glacial lakes in the Astore Drainage Basin was extremely complicated with the depletion of some lakes, the emergence of new ones, and the growth of existing glacial lakes. Between 1989 and 2019, the number and size of glacial lakes changed dramatically. The Astore Drainage Basin had 120 glacial lakes in 1989. In 1999, there were 126 lakes in the inventory. According to Landsat imagery, the number of glacial lakes increased from 127 in 2009 to 128 in 2019.

Over the investigated period, the volumetric and areal extents of the lakes also grew with the growing number. The lakes' total area grew from 4.75 km^2 to 5.86 km^2, and their approximate volume increased from 2,043,463.17 m^3 to 2,522,083.32 m^3. The specifics can be found in the Table 1.

Table 1. Areal and volumetric extents of the lakes

Year	Areal Extent (Km^2)			Volumetric Extent (m^3)		
	Glacial-fed Lakes	Non-glacial-fed Lakes	Total	Glacial-fed Lakes	Non-glacial-fed Lakes	Total
1989	1.93	2.82	4.75	830,241.01	1,213,222.16	2,043,463.17
1999	2.282	3.175	5.457	982,004.21	1,366,495.78	2,348,499.99
2009	2.278	3.298	5.576	980,046.56	1,419,182.01	2,399,228.57

From 2009 to 2019, the area of the glacial lakes expanded at a faster pace than the rest of the decades/years. Glacial-fed lakes have grown by 29.07 percent in the last 30 years from 1.93 km^2 in 1989 to 2.491 km^2 in 2019 which is considerably more than non-glacial-fed lakes which have grown by just 19.50 percent (from 2.82 km^2 in 1989 to 3.370 km^2 in 2019). Furthermore, the findings revealed that smaller lakes grew in size faster than larger lakes. The Himalayas have been warming at a rate of 0.15°C-0.6°C per decade over the last three decades [35], and as a result, the glaciers are melting over this mountainous area [2]. This retreat has resulted in the creation of new lakes as well as the expansion of the area and volume of present lakes. Glacial-fed lakes collect meltwater from the glaciers and increase in size because they are in contact with them. Non-glacial-fed lakes, on the other hand, have no glacier in their watershed and their area and volume are mostly dependent on precipitation or other sources. As the number of lakes grows and the glacier retreats, the results will lead to higher number of GLOFs. Non-glacial-fed lakes are mainly located in the basin's south-eastern side. Glacial-fed lakes, on the other hand, are located across the basin with the largest concentration in the study area's northwestern corner. Furthermore, there are almost no glacial lakes in the basin's upper reaches.

According to the findings of all inventories, there is a strong correlation between number of glacial-fed lakes and the elevation, i.e., the greater the quantity of glacially fed lakes, the higher the elevation. The finding is not surprising since it is commonly assumed that non-glacier-fed lakes are found in ponds left by Quaternary glaciers, which are lower in height than present glacier termini where Glacier-fed lakes are located [34].

4.2.1. Disappearance of Lakes

According to this study, two lakes in the basin are vanished within the thirty-year span (1989-2019). Both the lakes faded after 1999 and are only showed in inventories of 1989 and 1999. The detail of the lakes is:

i. Astore-GL02; in 1989, this lake had an area of 0.288 km^2 but by 1999, it had shrunk to 0.1944 km^2. This lake was 4,646m above mean sea level and belonged to the Glacial-fed Lake group.
ii. Astore-GL92; this non-glacier-fed lake was located at an elevation of 4,467m above M.S.L and had an area of 0.0063 km^2 in 1989 and 0.0045 km^2 in 1999.

The glacial lakes may become extinct in one of the following ways [18]:

i. In a non-catastrophic manner
ii. Because of sedimentation (lakes being filled with sediments)
iii. As a result of the lake's water intake being limited
iv. Without any Lake Outburst Flood as a result of dam incision
v. In a devastating manner (GLOFs)

According to the findings, the area of both lakes reduced between 1989 and 1999. So, it is possible that after 1999, the aforementioned two lakes were perished in a non-catastrophic fashion, either as a result of losing their primary source of water, alluviation, or as result of one of the reasons mentioned above.

4.2.2. Formation of New Lakes

Between 1989 and 2019, the number and area of lakes in the Astore watershed increased dramatically. In all, 10 glacial lakes have appeared in the study area, marking a 6.67 percent rise in the entire number of lakes from 120 in 1989 (two of which vanished after 1999) to 128 in 2019 (Fig 6). Two of them are non-glacial while the others are Glacial-fed lakes. Non-glacial-fed lakes, as it is well known, are typically created in the ponds left by Quaternary glaciers. Two non-glacial-fed lakes (Astore-GL80, Astore-GL105) are shown to have formed after 1989 in this study. This may be due to one of the two possibilities:

i. These lakes may have existed in 1989 but were not apparent in satellite images due to various factors such as cloud cover, snow cover, and so on.
ii. The second explanation is, may be these lakes developed after 1989 as a result of rainwater runoff or significant amounts of snow melting.

The majority of the newly formed lakes are glacier-fed, indicating that the glaciers in the study region are constantly retreating. This supported numerous researchers' hypothesis that glaciers in the world's highest mountainous regions are melting, resulting in the creation of various forms of glacial lakes around, inside, or beneath the glacier [9-10]. Pakistan's average yearly temperature will rise by 4.3-4.9 Degrees Celsius by 2085, with the rise being greater in the north than in the south [36]. As a result, glacier retreat and lake formation will become more common in the future. 90% of the lakes appeared at altitudes greater than 4,000m above M.S.L. In research conducted in the Himalayas, Nie et al. [37] found similar findings. According to this report, because of rising temperatures, the greatest number of glacial lakes appeared at elevations greater than 4,000m between 1989 and 2019. In addition, the area of these newly developed lakes has varied over time Table 2.

Glacier retreat is related to the growth, progression, and extinction of lakes, which frequently modifies the vulnerability of glacial lakes with time [38-40]. The bulk of the lakes emerged after 1989, and glacial loss in the study region is estimated to have peaked between 1989 and 1999.

Table 2. Newly emerged lakes (1989-2019)

Name	Lake Type	Area (km^2)		
		1999	2009	2019
Astore-GL14	Glacial-fed	0.0063	0.0062	0.0063
Astore-GL17	Glacial-fed	0.0054	0.0054	0.0036
Astore-GL27	Glacial-fed	0.0072	0.0062	0.0107
Astore-GL28	Glacial-fed	_	0.0108	0.0108
Astore-GL35	Glacial-fed	_	0.0153	0.0567
Astore-GL54	Glacial-fed	0.0171	0.018	0.0242
Astore-GL63	Glacial-fed	_	0.0063	0.0063
Astore-GL80	Non-glacial-fed	0.009	0.0125	0.0125
Astore-GL86	Glacial-fed	_	_	0.018
Astore-GL105	Non-glacial-fed	0.0071	0.0098	0.0081

For a deeper understanding of the link between lake development and glacier ablation, more detailed knowledge about the glacier is needed. Despite all the uncertainties related with mapping of glacial lakes from satellite images, the appearance and development of lakes suggests that they are highly dynamic in nature, with a consistent growth pattern. The study area's fast fluctuation in the quantity and extent of glacial lakes can raise the danger of GLOFs.

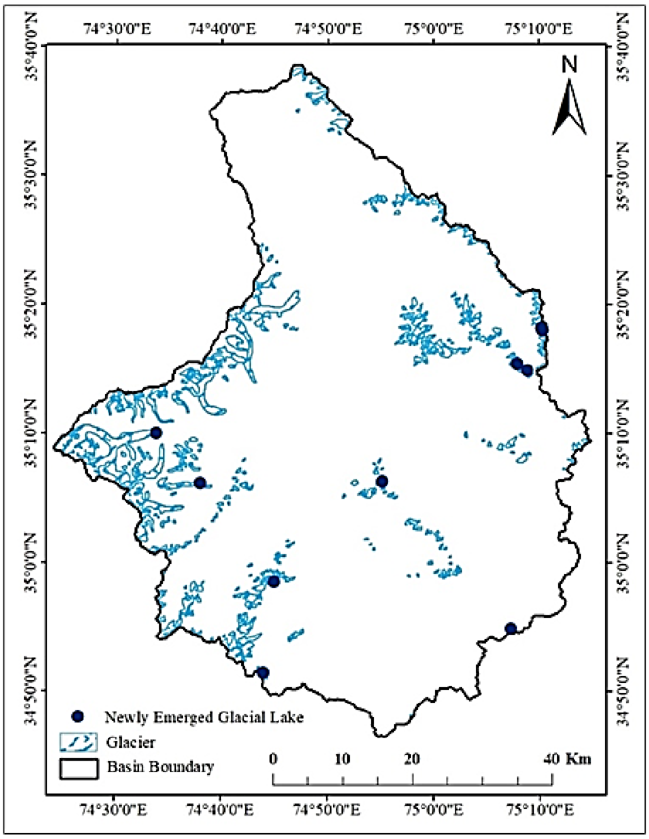

Figure 6. Newly emerged glacial lakes in Astore Drainage Basin (1989-2019)

4.2.3. Growth of The Existing Lakes

Over the study era, the area of the lakes fluctuates in Astore Drainage Basin. Some lakes have seen an increase in their area; some have seen a decline, while others remained unchanged.

The results indicate that 45 Glacial-fed and 47 non-glacial-fed lakes grew in size during the study period. This means that the glaciers in the region are rapidly melting. Twenty-two lakes have experienced negative growth in their area (16 non-glacial-fed and 6 Glacial-fed). According to Emmer et al. [35], the negative growth suggests that the production of these lakes is heading towards the non-glacial stage. Only four lakes, including one non-glacial-fed lake and three Glacial-fed lakes show no improvement. There are 21 lakes with an area expansion rate of more than 100% (7 non-glacial-fed and 14 Glacial-fed). Water spread boundaries of some lakes for different years are shown in Fig 7.

5. Conclusion

Glacial lakes are generated as glaciers recede. There are several forms of glacial lakes, and they pose serious dangers to downstream communities and properties. In all, 120, 126, 127, and 128 glacial lakes were discovered in the Astore Drainage Basin in the Himalaya's northwestern slopes in 1989, 1999, 2009, and 2019. During the research period, these glacial lakes encompass an area of 4.75, 5.457, 5.576, and 5.861 km^2. Lakes were divided into two types: glacially fed and non-glacially fed, and they were defined using quantitative and qualitative criteria. Glacial-fed lakes are more over 4,500m above mean sea level, than non-glacial-fed lakes which are present in lower elevation. The area growth rate of glacier-fed lakes that are in direct touch with the glacier's snout is greater than the area expansion rate of non-glacier-fed lakes that are not in direct contact with the parent glacier snout. During the research period, the quantity and size of lakes change. Between 1989 and 2019, two lakes vanished, while ten new lakes emerged. There were 21 lakes with an area expansion of more than 100%, indicating a strong vulnerability to GLOF.

In changing climate scenario, the list of glaciers in the study region is fluctuating. Therefore, the number of glaciers and Glacial Lakes are gradually increasing and pose serious threat to the downstream communities. Based on the mentioned facts, this study is a pioneering attempt in the region and it is very useful for decision makers, Disaster Risk Reduction experts and local communities in addressing and mitigating Glacial Lake Outburst floods.

Acknowledgement

This study is part of MPhil thesis of principal author and completed under the supervision of co-author. This research is not submitted to any other journal. All authors have declared that no conflicts of interests.

Author contributions

Fareeha Siddique: Conceptualization, Methodology, Software, Field study, Writing-Original draft preparation **Atta-ur-Rahman:** Data curation, Software, Validation., Field study, Visualization, Investigation, Writing-Reviewing and Editing.

Conflicts of interest

The authors declare no conflicts of interest.

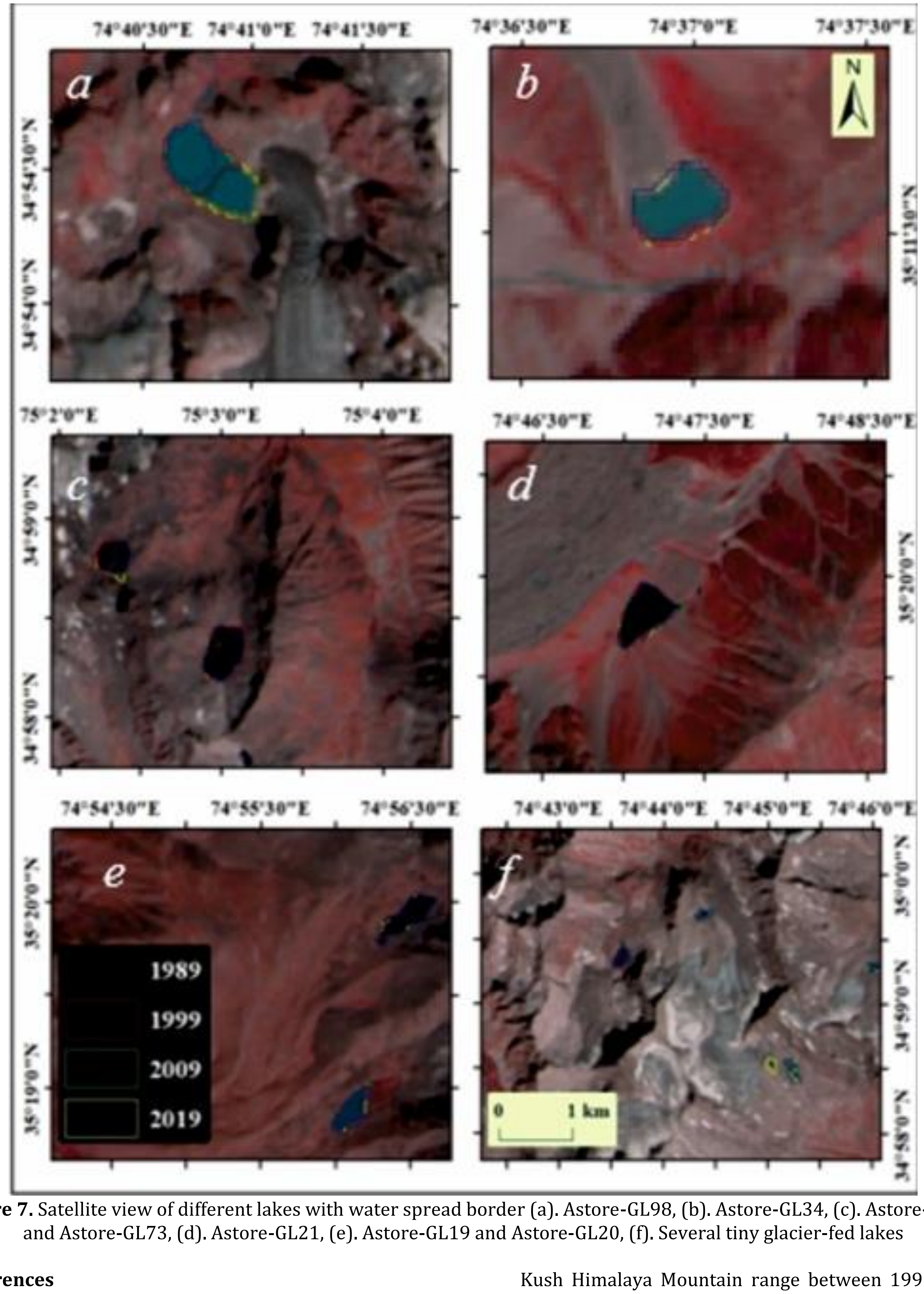

Figure 7. Satellite view of different lakes with water spread border (a). Astore-GL98, (b). Astore-GL34, (c). Astore-GL72 and Astore-GL73, (d). Astore-GL21, (e). Astore-GL19 and Astore-GL20, (f). Several tiny glacier-fed lakes

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