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# Spatio-temporal assessment of regional scale evolution and distribution of glacial lakes in Himalaya

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Glacial lakes are a potential threat to the livelihoods and precious infrastructures in the Himalayan region. The expansion of these lakes under the influence of global warming further poses a grievous risk of natural disasters in the form of glacial lake outburst flood (GLOF) that necessitates regular monitoring to reduce and mitigate its implications. This research focuses on the regional scale distribution and evolution of glacial lakes in the Himalayan mountain range with their causes. We used Landsat thematic mapper (TM) and operational land imager (OLI) images, Google Earth imageries, Shuttle radar topographic mission (SRTM) Digital Elevation Model, and Aphrodite climatic data to study lake evolution and its controlling parameters. A total of the 5,409 glacial lakes was taken for the size expansion analysis, which excludes supraglacial lakes. An expansion rate of 2.98%/yr and 1.01%/yr in glacial lakes number and size was found from 1990 to 2020, respectively. The glacial lakes are distributed mainly in Langtang, Bhutan, Sikkim and Everest region; while, new lakes are forming at higher elevations continuously. The highest lake size expansion was noted in 2015–2020 (36.51%) followed by 2000–2010 (21.72%) and 2010–2015 (10.65%), while 1990–2000 (3.36%) showed a lowest expansion rate. The highest expansion rate was noticed near an elevation band of 5000–5500 m. Moreover, lakes in the central and eastern Himalaya are highly decrease by climatic change, i.e., increase in temperature a decrease precipitation. The feature selection algorithm was used to identify the importance of various controlling parameters, which showed temperature change rate, glacier fed lake, glacier snout steepness, proximal distance, glacier calving frontal width, precipitation change rate and lake type gave higher weightage towards lake size change.

KEYWORDS

**glacier, glacial lake, hazard, Himalaya, GLOF**

# 1 Introduction

Glaciers in the mountains have extensively reached its maximum extent during the little ice age (Holocene epoch). After that, it started retreating due to global warming, as a result forming glacial lakes (Cramer et al., 2014; Harrison et al., 2018; Zhu et al., 2020). The rate of glacier retreat correspondingly matched with the new lake formation (Emmer et al., 2014; Rashid and Majeed, 2018; Pandey et al., 2021). The Himalayan region witnessed warming at a higher rate than the global average (Taylor et al., 2013), therefore experiencing significant consequences of lake size increase, glacial lake outburst flood, avalanches, etc (Emmer et al., 2016; Veh et al., 2019). The number and size of glacial lakes have been increasing since 1990 by 53% and 51%, respectively, globally (Shugar et al., 2020). Through literature, we noted a contrast in the evolution of glaciers and glacial lakes over the eastern and western parts of the mountain range. In the eastern part, the majority of glaciers are retreating at a higher rate in comparison to the western part where melting is not fast as western counterparts (Kargel et al., 2005; Gardelle et al., 2011; Gardelle et al., 2013; Worni et al., 2013). Besides, glacial lake size and number are increasing faster in different parts of the Himalaya at a higher rate: Bhutan (Veettil et al., 2016; Wessel et al., 2018), Sikkim (Aggarwal et al., 2017; King et al., 2018), Nepal (Shrestha and Aryal, 2011), Uttarakhand (Raj and Kumar, 2016), Jammu and Kashmir (Govindha Raj, 2010; Mir et al., 2018; Watson et al., 2018; Yao et al., 2018).

Zone of lake with higher growth rate and future lake formation is a potential threat to the downstream (Mohanty and Maiti, 2021b). These increases in lake size could attribute to GLOF caused by global warming. A lake growth has possibly happened at a long glacier tongue with flat slope (Agarwal et al., 2014; Song et al., 2017). Lake characterization also indicates the GLOF possibility as ice dam followed by moraine dam lakes are more prone to GLOF (Veh et al., 2018). Moreover, lesser proximal distance, moraine dam and glacier fed lakes are more prone to lake size increase (Gardelle et al., 2013; Zhang et al., 2015). Besides, in the Nepal Himalaya, the majority of present-day large moraine-dammed lakes did not exist before the 1950s (Harrison et al., 2018). Many of these lakes started forming in the mid-1950s–1960s as small supraglacial lakes, which coalesced and started growing rapidly in the 1970s (Mohanty and Maiti, 2021a). A little is known about where a lake can be formed and to what extent a lake can be grown. Regional scale lake formation pattern and lake size change related to climatic, topographic and glacial lake parameters has not been discussed in detailed.

The glacial lakes are not stable due to the underlying formation mechanism, and hence very prone to the outburst in many circumstances, such as failure of the moraine dam by avalanches, landslide, earthquake, and extreme rainfall, *etc*. This outburst flood of glacial lakes is known as glacial lake outburst flood (GLOF). GLOF is the phenomenon of sudden release of huge amounts of water and sediment in the downstream river channel by the dam breach of glacial lake. Most of the GLOF events were experienced in lakes that have a larger lake size with a higher expansion rate. It was also noted that the majority of the GLOF events were concentrated in the Himalaya (Worni et al., 2013; Aggarwal et al., 2017; Nie et al., 2017). Furthermore, most of the GLOF has occurred from breach of the ice dam lake followed by the moraine dam lake (Carrivick and Tweed, 2016; Veh et al., 2019). These GLOF events pose grave threats to the societal and infrastructural setup along with significant risk to the livelihoods. Therefore, identification of lakes that have larger size and greater expansion rate is crucial. Notably, it is found that most of the critical lakes are present in the eastern and central Himalaya (Mohanty and Maiti, 2021b), due to the faster melting of glaciers in this region.

The simulations of the integrated impact on the glacial lakes of rugged topography, changing climate and variable response of glaciers to the climate change are challenging due to the dynamics of glacial lakes, which is complex in nature. An alternate choice is to be ready with the inventory datasets to understand these processes and dynamics of lakes. Therefore, lake inventory was firstly proposed for more than 300 glacial lakes from 1966–1975, further updated in 1980 taking lake morphometry and depth (Anselin and Getis, 1992; Worni et al., 2013). After that much work has been conducted in the Himalaya on glacial lake inventory. Besides, a study jointly carried out from 1999 to 2003 by the International Center for Integrated Mountain Development (ICIMOD), United Nations Environment Programme (UNEP), and Asia Pacific Network (APN) reported a total of 9,000 glacial lakes for 15,000 glaciers in Bhutan, Nepal, Karakoram, China, and India. Moreover, Zhang et al. (2015) reported the number of lakes in different basins: the Amu Darya, 594, Indus, 1,607, Ganges, 364, and Brahmaputra, 2,247; estimated using 2010 Landsat images. These lake numbers are relatively smaller in comparison to other published papers, Such as (Bhambri et al., 2011) mapped 1,266 glacial lakes in Uttarakhand (India), Aggarwal et al. (2017) showed 1,104 glacial lakes in Sikkim (India), Jeelani et al. (2011) estimated 1,466 glacial lakes in Nepal, and Nie et al. (2013) showed 4,950 lakes in the Himalaya. These inconsistencies could be a result of the distinctive conduct of these studies during different time frames. Therefore, these lake inventories should be updated in regular intervals to know the implication of climate change on glacier/glacier-lakes and the lakes' expansion/reduction dynamics in this region (Mool et al., 2001; Wang et al., 2013; Nie et al., 2017). The specific objectives of our study are therefore: (1) to examine the detailed evolution of glacial lakes size and number since 1990 in the Himalaya; (2) to investigate glacial lake evolution related to topography, lake characteristics and climate, and (3) to simulate possible future lake growth and zone of lake formation based on the glacial topography that are considered as being potentially dangerous.

## 2 Study area

Himalaya is a rugged topography ranging from 1,000 to 8848 m in elevation, and encompasses the highest elevation of the planet i.e. 8848 m. The Himalaya is a 2500 km-long orogenic zone which varies in width from 400 km in the west to 150 km in the east (Rubatto et al., 2013). The Himalaya was taken as a study area which is bounded by 69° 48′ 36.73″ E longitude to 98° 22′ 22.78″ E and 27° 12′ 16.89″ N to 39° 31' 26.89″ N latitude. Our study area expands over 4 important river basins: Indus, Ganges, Brahmaputra and the Mansarovar Interior Basin. The distributions of equilibrium line altitudes (ELA) are mainly fluctuating in the influence of summer Monsoon and Subtropical Westerly Jets with limited supplies from East Asian Monsoon (Yao et al., 2012). Besides, the Indian Himalaya has a glaciated area of 23,300 $km^2$ and a volume of 1071 $km^3$ (Bolch et al., 2012).

Himalaya gets snowfall due to three types of wind flow; (i) NW wind flow (westerly), (ii) SW monsoon, and (iii) NE wind flow (Bookhagen and Burbank, 2006). Eastern Himalaya is getting snowfall due to two types of wind flow: SW monsoon and NE wind flow (Bookhagen and Burbank, 2010). Moreover, these are mainly getting snowfall in the summertime, called summer accumulation type glaciers. The western side of the Himalaya (Karakoram, Pamir, and west Himalaya) is getting snowfall because of the westerly wind flow, which is prevalent during wintertime; so it is called winter accumulation type glacier. Summer accumulation glaciers are relatively more sensitive to the temperature rise because it will directly affect the snowfall and hence the feedback to the glacier system. The monsoonal precipitation decreases from east to west, and its divider from the westerly jet is present at 78° longitude near Sutlej valley (Aggarwal et al., 2016). The northern side of the eastern Himalaya is getting less snowfall than the southern side by monsoonal precipitation (Shrestha and Aryal, 2011).

## 3 Methodology

### 3.1 Data sources

#### 3.1.1 Satellite data and DEM

We used Landsat Thematic Mapper (TM) L1T and Operational Land Imager (OLI) data set to estimate the lake size. These datasets were obtained from the United States Geological Survey (USGS) Earth Explorer (https://earthexplorer.usgs.gov). A total of 90 scenes was used over the entire Himalayan region to delineate the lake boundaries for 1990, 2000, 2010, and 2015. We also utilized the Google Earth high-resolution images to outline the lake boundaries for 2020. The SRTM (Shuttle Radar Topography Mission) Digital Elevation Model (DEM) of 30 m spatial resolution provided the topographical information.

Cloud cover, solar elevation angle, and date of acquisition play a crucial role in data selection over a Cryospheric environment. Another critical aspect of the visible range satellite data is the presence of cloud cover, as it may significantly affect the accuracy. Thereby, we consciously chose cloud-free satellite datasets. However, the availability of datasets with absolute zero cloud cover is challenging; thus we chose the data with <5% of cloud cover, sun elevation angle>40°, and nadir facing. The data were obtained for the late summer period to melt the freshly fallen snow and provide us with a realistic representation of the glacial lakes. (Gardelle et al., 2011). Therefore, we selected satellite images of September to December (for the eastern part of Himalaya) and between June to October (for the western part of Himalaya), respectively.

#### 3.1.2 Climatic data

We used the APHRODITE (Asian Precipitation-Highly-Resolved Observational Data Integration Towards Evaluation) daily gridded precipitation data, a long-term regional-scale precipitation product. It is proven to be well-matched with the station data (Ali et al., 2012). It is interpolated from ground-based data from an *in-situ* rain-gauge-observation network (Sunilkumar et al., 2019; Taylor and Carr, 2019). These mean annual temperature and precipitation data were collected from https://www.chikyu.ac.jp/precip/english/for 1951–2007. The APHRODITE data was obtained which has a spatial resolution of 0.25°. Initially, APHRODITE - V1101 was available for 67 years (1951–2007) over the Asian monsoon region, but a new version - V1101EX_R1 extends the time range to 2015. In this study, we combined the two versions of the data to get an expanded time series of 64 years (1951–2015).

#### 3.1.3 Lake boundary data

We obtained the lake data from Zhang et al. (2015) for the years 1990, 2000, and 2010. However, after investigation, we found that this dataset is incomplete and does not incorporate many lakes in this region. Therefore, we modified this dataset with new additions of the missing lakes and some boundary corrections. We added 375, 144, and 403 lakes along with modifications in 11, 5, and 10 lakes for the years 1990, 2000, and 2010 respectively. Moreover, to extend this inventory further in time, we prepared the lake boundaries for the years 2015 and 2020 using a similar method as in Bajracharya et al. (2008). For an extended inventory, we have used Landsat OLI for 2015 and high-resolution images like Worldview, Quickbird, and GeoEye for 2020.

#### 3.1.4 Glacier boundary data

The glacier outline data were obtained from GLIMS (Global Land Ice Measurements from Space) webpage. RGI version 6.0 was downloaded, and some manual boundary corrections were performed.

### 3.2 Data analysis

#### 3.2.1 Lake size expansion rate

A few glacier lakes are not perennial, and have formed/disappeared after a specific year. Therefore, to account for this variability over the time, we determined the average lake size change

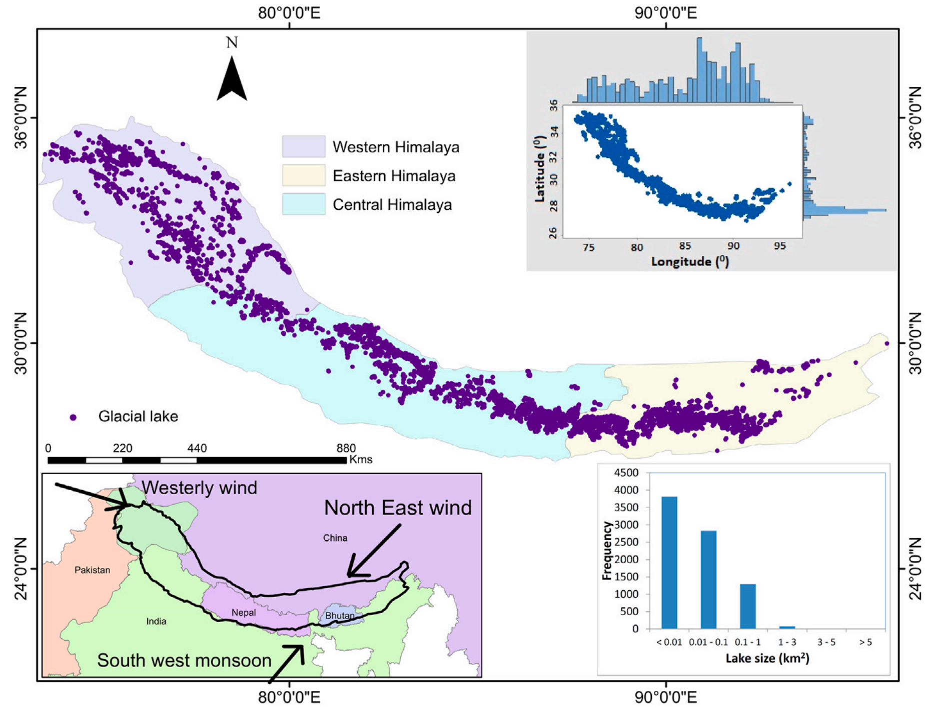


FIGURE 1
The Himalaya is taken as study area; here, dot with brown color shows the lake position in the study area. The violet color boundary shows the study area extent. Here, the scatter plot in the upper right corner shows the lake distribution along the latitude and longitude in the Himalaya, the histogram in the lower-left corner shows the lake size distribution in the Himalaya. Lake frequency distribution was also shown in another graph with respect to elevation.

TABLE 1 Lake size and number variation in different years.

| year | Lake size | | Lake number |
|---|---|---|---|
| | Total (km²) | Average (km²) | |
| 1990 | 262.45 | 0.132 | 2,406 |
| 2000 | 280.94 | 0.140 | 2,306 |
| 2010 | 304.59 | 0.132 | 3,015 |
| 2015 | 325.22 | 0.151 | 2,822 |
| 2020 | 342.08 | 0.136 | 4,420 |

rate. We took care of those lakes and calculated the average lake size change rate that has a different lifespan than the study period (i.e., 1990, 2000, 2010, 2015 and 2020) using the following formula:

$$\text{Average lake size expansion rate } (m^2/\text{year}) = \frac{\sum_1^n X_i - X_{i-m}}{n^* m} \quad (1)$$

Where $X_i$ and $X_{i-m}$ is the lake size between two consecutive times of 10 years interval. m is the total time interval of these years, and n is the number of lakes.

### 3.2.2 Lake attributes data derivation

Lake types (glacier-fed, connected, moraine-dammed) were marked in the lake polygon by visual interpretation with the help of the Google Earth platform. The proximal distance was calculated with the help of the near tool in ArcGIS 10.3, using the lake and glacier polygon as an input file. Northern side lakes and southern side lakes were classified in the GIS platform, referring to Nagai et al. (2013).

## 3.3 Statistical analysis

### 3.3.1 Cumulative frequency

The cumulative lake size was estimated by adding lake size continuously with an increase in elevation dataset (Mohanty and Maiti, 2021a). The last value will always be equal to the total (sum) for all lake size observations for that year since all frequencies have been added to the previous total. Cumulative lake size was studied concerning the elevation annually used for knowing the variation of lake size at certain elevation intervals in the Himalayas. A

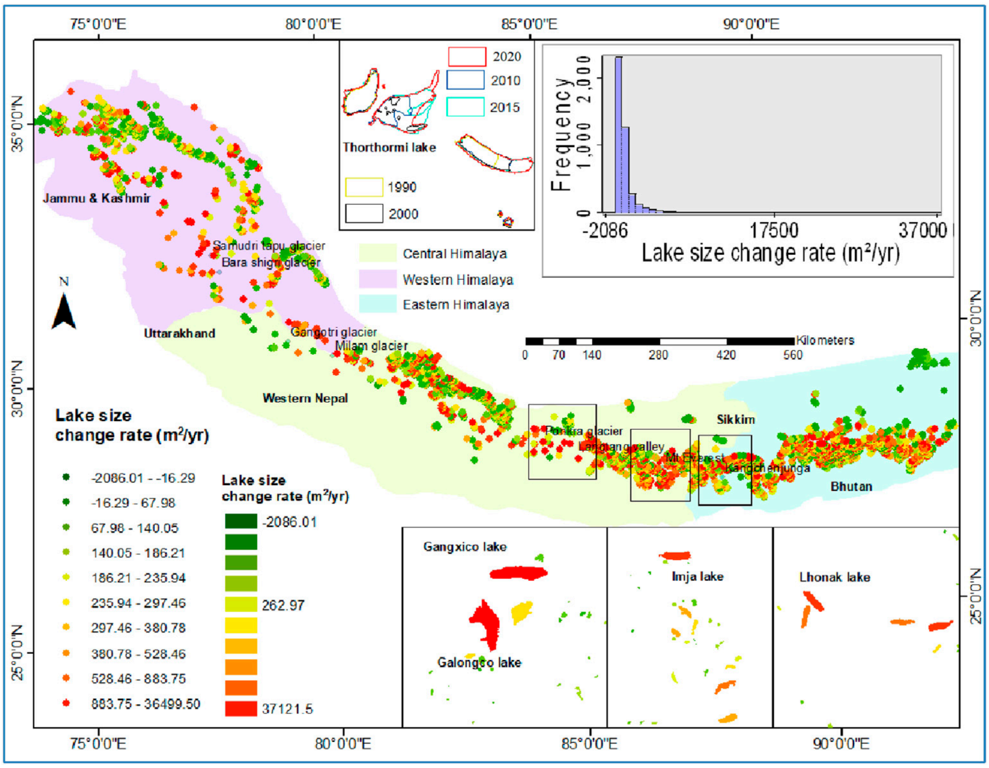


FIGURE 2
Lake size change rate map of the Himalaya; here, red color shows the highest positive, whereas green shows the lowest negative lake size change. In the zoom box important lakes were shown in different part of the Himalaya with their lake size change rate and different years of lake boundary polygon. In the histogram plot, the distribution of lake size change rate shown for the Himalaya.

cumulative graph was plotted between cumulative lake size and respective lake elevation.

## 3.4 Accuracy assessment

According to Zhang et al. (2015) and (Chand and Watanabe, 2019), the smallest detectable glacial lakes should be more than three pixels, i.e., 0.0027 $km^2$ in the Landsat TM/ETM + data. In addition to cloud and snow coverage, the accuracy of glacial lake areas can be affected by the spatial resolution of satellite data. As we did manual digitization error due to clouds and snow is very less here. Several studies have demonstrated that the accuracy of data derived from satellite imagery is within approximately 0.5 pixels (Ord and Getis, 1995; Clague and Evans, 2000; Salerno et al., 2016; Qiao and Zhu, 2019). The uncertainty of the glacial lake area was estimated in this study as an error of ±0.5 pixels on either side of the delineated lake boundary.

Error = ± 0.5* perimeter of glacial lake

We compare the lake boundary delineated uncertainty between ours and Zhang et al. (2015) for the year 2010. An uncertainty of <10% was found in this analysis.

# 4 Results

## 4.1 Lake characterization and its distribution in the Himalaya

A total of 5,409 separate glacial lakes with size >0.01 $km^2$ were selected for the calculation of lake size change rate. Moreover, glacial lakes within 5 km from mother glacier were included in this analysis. Glacial lakes are widely distributed throughout the Himalayan region with an elevation between 3000 and 6000 m (Figure 1). We noted that most of the lakes were formed in Langtang, Bhutan, Sikkim, and Everest region (near 90°E longitude and 29°N latitude) (Figure 1). Notably, nearly half of the lake in the Himalayas is relatively smaller in size (less than 0.01 $km^2$), identified through the modified and updated version of the glacial lake database of (Das et al., 2015; Dixit et al., 2021) We found 2,406, 2,306, 3,015, 2,822 and 4,420 glacial lakes during 1990, 2000, 2010, 2015, and 2020, respectively. Thereby, the number of glacial lakes in the region is rising rapidly with ~83.07% increase from 1990 to 2020 (Table 1). Most of the new lakes were formed in the eastern Himalaya, whereas in 2020,

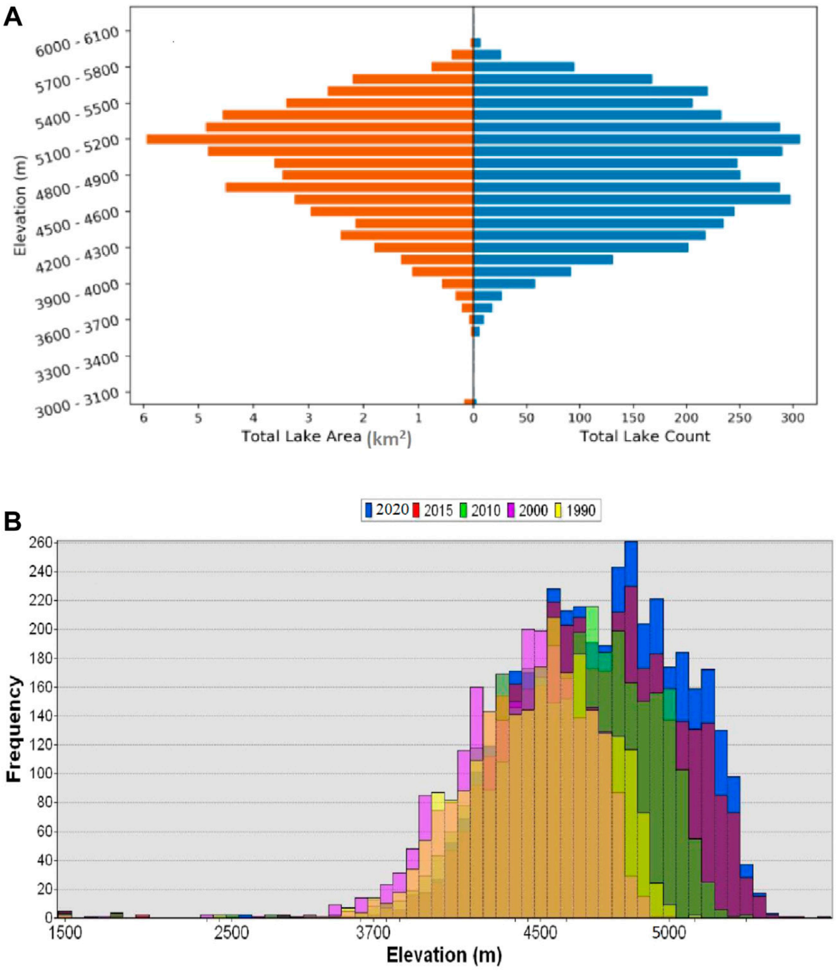


FIGURE 3
In **(A)** lake size and number distribution is shown for 2020 in different elevation band; while in **(B)** lake frequency distribution is shown in different color for various years (1990–2000-red, 2000–2010-cyne and 2010–2020-yellow) in different elevation zones of the Himalaya.

most of the new lakes were formed in the western Himalaya. However, these lakes were more prominent in the region of highest glacial retreat. The retreat depends on glacial topographic and climatic factors at different magnitudes (Bolch et al., 2008; Bhambri and Bolch, 2009; Racoviteanu et al., 2015; Pandey et al., 2017).

## 4.2 Characteristics of lake size expansion in the Himalaya

A total of 5,409 lakes was taken for the size expansion analysis, which excludes supraglacial lakes. We found a total lake size of 319.44 $km^2$, 329.14 $km^2$, 400.63 $km^2$, 443.31 $km^2$ and 605.31 $km^2$ in 1990, 2000, 2010, 2015 and 2020, respectively. Besides, stable lakes (lakes present throughout the study period) showed a change rate of 30.53% during the study period, while lake size of 262.45$km^2$, 280.94$km^2$, 304.59$km^2$, 325.22$km^2$ and 342.08 $km^2$ were found in 1990, 2000, 2010, 2015 and 2020, respectively. We also noted that during the recent decade (2015–2020) the change in lake size is relatively higher, followed by 2000–2010.

We found that the glacial lakes are increasing rapidly in the eastern side (i.e., middle Nepal, Bhutan, Sikkim and Everest region) than the rest of the Himalayas (Figure 2). The highest change was found in the Galongco lake (Nepal) followed by Gangxico (Nepal) and Thorthormi lake (Bhutan) (Figure 2). We also noted that 813 lakes were decreasing in their size over time. Upon manual investigation using high-resolution Google Earth images, we found that most of them are unconnected or glacier-fed lakes or erosional lakes. Moreover, some of the lakes were decreasing in size after the occurrence of the GLOF event (Tam Pokhari, some other lakes).

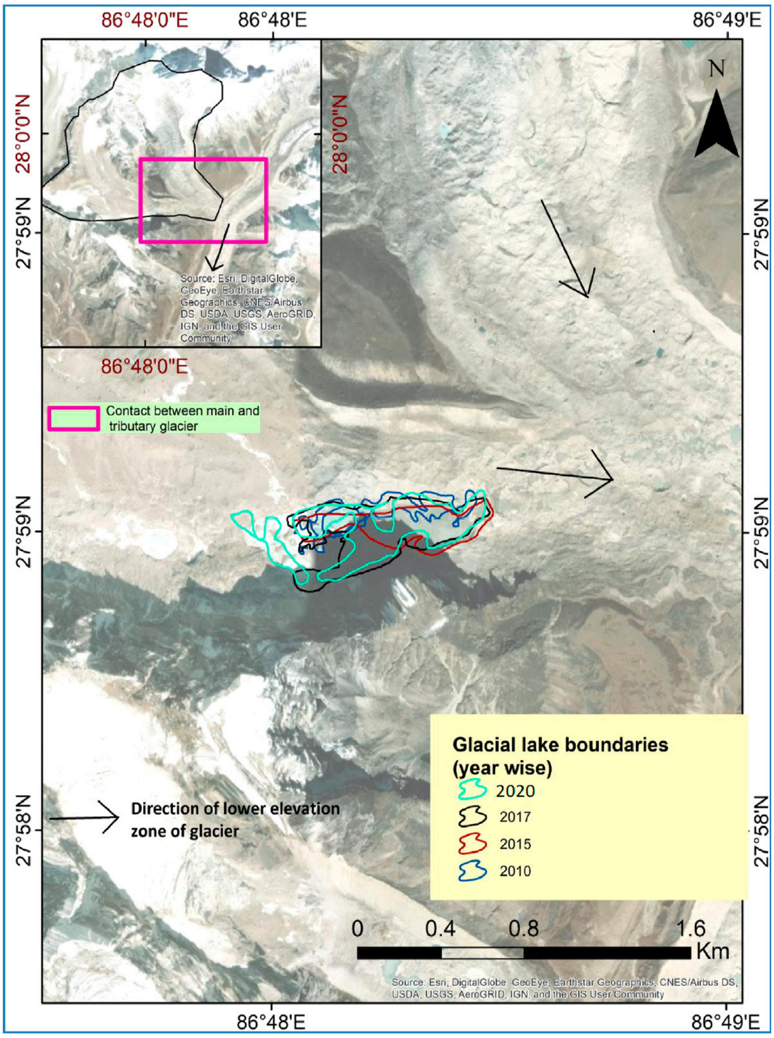


FIGURE 4
New proglacial lake is forming by coalensing at the tributary glacier (changri Nup) of Khumbhu glacier. Here, lake polygon in different years is shown in various color.

## 4.3 Altitudinal distribution in glacial lake number, size and expansion

The total lake count and size is highest at an elevation between 4500 and 5500 m (Figure 3A). Consequently, a cluster of new lakes was found to develop at the higher elevations (>5000 m) over the years (Figure 3B). This is due to the continual increase in glacier retreat, creating glacier fragmentation. The glacial fragmentation helps to form new lakes at the contact between main glaciers and its tributary (Figure 4). This contact zone is usually at a higher elevation than the ablation area of a primary glacier.

The average, standard deviation, and total lake size are continuously increasing since 1990 (Figures 5A,B). An increase in standard deviation refers to the higher variability in expansion over the time along with the formation of new smaller lakes. A sudden shift in lake size after the year 2000 was noticed due to the rapid increase in the lake size after the year 2000 (because of various underlying reasons such as faster glaciers melting). A crossover of the cumulative profile of lake size was seen for 2015 and 2020 at the elevation of 5000m, which shows that lakes are decreasing in size at elevation <5000 m. Additionally, for the elevation >5000m, an increase in the lake size was noticed in 2020, which happened because of the presence of a large number of proglacial connected lakes (Table 2). The highest and second-highest increase in lake size were found to happen between 2015–2020 and 2000–2010, respectively (Figure 5A). Moreover, out of 21 outburst phenomena (Table 3), seven occurred between 1990–2000; hence, these two cumulative profiles (2000 and 1990) are close to each

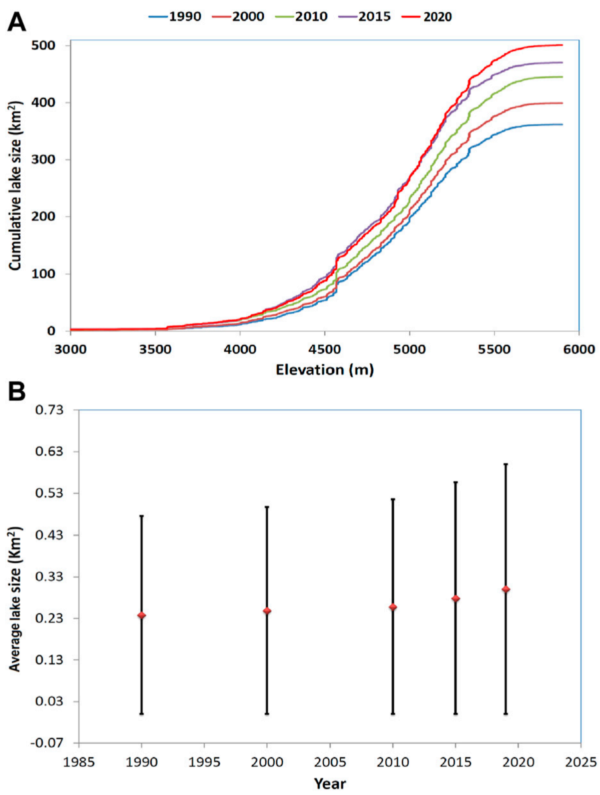


FIGURE 5
The graph plotted between elevation along *X*-axis with the cumulative lake size along *Y*-axis for different years (1990, 2000, 2010, 2015, 2020 and 2030) for the Himalaya glacial lakes **(A)**. In **(B)**, the average lake size was shown with standard deviation for different years.

other. The lake size expansion is higher between the elevation band 5000–5500m, followed by the elevation value >5500 m. The highest lake size change rate (819.17 $m^2$/yr) was found over the elevations 5000–5500m, possibly due to the presence of maximum proglacial connected lakes (731). However, at a higher elevation (>5500 m), a lesser number of lakes were present; mostly connected moraine-dammed lakes (Table 2). For the elevations lesser than 4500m, the glacial lake size change rate was relatively slower. However, a minimal number of lakes exist at elevation >5500 m (515), followed by <4500m and 5000–5500 m (Table 2). The average lake size is higher at 5000–5500 m (0.17 $km^2$) than the lakes present at 4500–5000 m (0.13 $km^2$) and >5500 m (0.09 $km^2$).

# 5 Discussion

## 5.1 Climatic control on glacial lakes distribution and expansion in Himalaya

Trend analysis of temperature and precipitation was calculated for the Himalayan region using APHRODITE dataset (Figure 6). It showed increasing precipitation mainly over the western Himalaya and central Himalaya. The temperature showed an increasing trend throughout Himalaya, having the highest warming trend over the central Himalaya. The western and eastern Himalaya showed warming, but with lesser intensity than central. At the same time, we found that the glacial lakes are increasing in number and size with a largest hotspot in the central Himalaya. The compound influence of both increased precipitation and temperature helped these lakes to grow in the central region of Himalaya. Albeit, the western region also received the increased precipitation, but due to the dominance of westerlies this precipitation falls mainly in a solid phase, however, over the central Himalaya, most of the precipitation falls in a liquid phase due to the dominance of the Indian Summer Monsoon. Therefore, the added energy flux through rain refreezing over the ice and increased temperature provide more water through melting to these glacial lakes that help them to grow further. Besides, we correlate the lake size change rate with the temperature and precipitation change rate in the Himalayan region and I got a $R^2$ value of 0.39 and 0.25, respectively.

Global Precipitation Climatology Project (GPCP) precipitation data showed a decreasing trend in the Himalaya from 1979 to 2010 (Huggel et al., 2002; Kaab, 2005; Kulkarni et al., 2011; Emmer and Vilímek, 2013). Moreover, Mohanty and Maiti. (2021b) showed a continuing decrease trend of precipitation amount in the Himalaya from 1998 to 2019. Moreover, Nie et al. (2017) also showed a decreasing trend of precipitation amount in

TABLE 2 Elevation wise lake characteristics distribution in the Himalaya.

| Elevation (m) | Lake count | Lake size change rate ($m^2$/yr) | Lake size ($km^2$) | Moraine dammed connected lakes |
|---|---|---|---|---|
| <4,500 | 1,000 | 457.33 | 0.11 | 342 |
| 4,500–5,000 | 1,374 | 526.58 | 0.14 | 501 |
| 5,000–5,500 | 1,309 | 819.17 | 0.18 | 731 |
| >5,500 | 515 | 570.19 | 0.12 | 307 |

TABLE 3 Number, causes and locations of GLOF events reported in the Himalaya since 1990.

| Name of the lake | Occurring date | Longitude | Latitude | Country | Causes of outburst |
|---|---|---|---|---|---|
| Chubung | 1991–07 | 86.47 | 27.88 | Nepal | Moraine collapse |
| Zanaco | 1995–6 | 85.37194 | 28.66222 | Nepal | Unknown |
| Kongyangmi La Tsho | 1995 | 88.78 | 27.90 | India | |
| Kab | 1994–10 | 89.58486 | 28.06667 | Bhutan | Unknown |
| LuggyeTso | 1994–10 | 90.30778 | 28.08333 | Bhutan | Moraine collapse |
| Sabai Tsho/Tam Pokhari | 1998–09 | 86.84 | 27.74 | Nepal | Ice avalanches |
| Tshojo glacier | 2009–07 | 90.16 | 28.10 | Bhutan | Ice deformation |
| South Lhonak | 2011–6 | 88.191,867 | 27.911,779 | India | Artificial pumping |
| Chorabari lake | 2013–17 | 79.681,259 | 30.747,866 | India | Landslide dam failure |
| Ranzeria Co | 2013–07 | 93.53 | 30.47 | China | Calving/ice avalanches |
| GongbatongshaTsho | 2016–07 | 86.06 | 28.08 | China | Ice avalanches |
| LemthangTsho | 2015–6 | 89.580,404 | 28.068754 | China | subglacial conduit |
| ChongbaxiaTsho | 2001 | 89.749,470 | 28.209,315 | China | Unknown |
| Unnamed | 2005–09 | 96.47 | 29.75 | China | |
| Jialongco 1st | 2002–5 | 85 51 07 | 28 12 85 | China | Ice avalanches |
| Jialongco2nd | 2002–6 | 85 48 24 | 28 13 53 | China | Unknown |
| Degaco | 2002–9 | 90 34 01 | 28 07 25 | China | Ice avalanches |
| Tsho Ga | 2009–07 | 94.00 | 30.83 | China | |
| Zhemaico | 2009–7 | 92 20 36 | 28 00 54 | China | Ice avalanches |
| Geiqu | 2010 | 87.99 | 27.95 | China | |
| Langmale lake | 2017–04 | 87.14 | 27.81 | China | Rock fall |

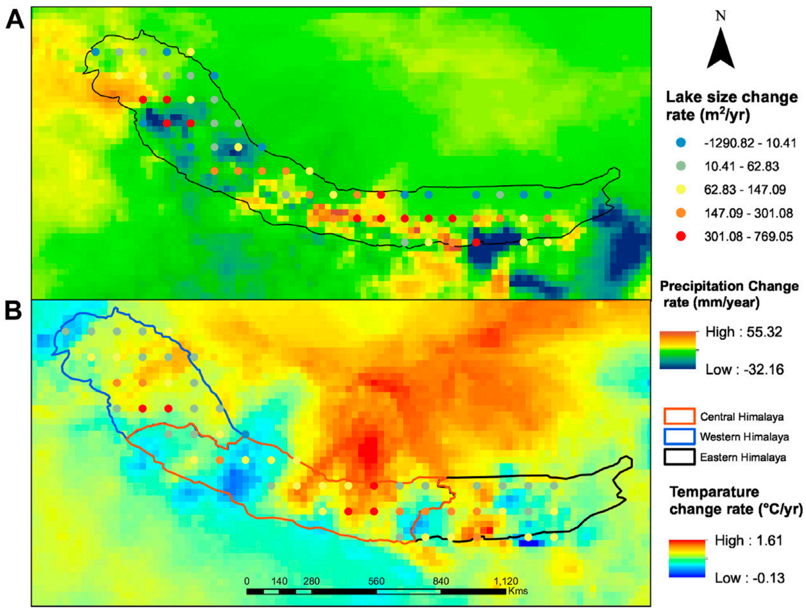


FIGURE 6
Precipitation **(A)** and temperature **(B)** change rate is shown with their corresponding average lake size change rate in the Himalaya.


FIGURE 7
The growth process of proglacial lakes is shown. Figure **(A)** shows proglacial lakes **(A,B)** became connected to unconnected with time, whereas in figure **(B)**, these proglacial lakes are remained connected.

most of the Himalayan from 1979 to 2014. The precipitation decrease in Himalaya was caused by the weakening in the Indian monsoon (Wu et al., 2005; Yao et al., 2012). The size of most of the non-glacial-fed lakes showed a declining trend caused by the decrease in the supply of precipitation; the same was observed in the Central Himalaya by Salerno et al. (2016) and Nie et al. (2017). However, most of the Himalayan glaciers are retreating at a higher rate, except for glaciers in Pamir, Hindu Kush, and the Karakoram in high Mountain Asia (Kaab et al., 2012; Gardelle et al., 2013; Vincent et al., 2016; Brun et al., 2017).

The impact of climate on glacial lakes is pretty complex. The addition of black soot particles to the glaciers causes darkening and accelerated glacier melting (Reynolds, 2000; Richardson and Reynolds, 2000; Scherler et al., 2011a; Ming et al., 2012; Vishwakarma et al., 2018). Black soot particles gather in the high altitude glaciers by the wind, after originating from industrial and fossil fuel combustion (Negi et al., 2019). Moreover, glaciers containing a lake/ debris content, and clean glaciers have different retreat rates and responses to climate change (Racoviteanu et al., 2015; King et al., 2018). The glacier type, debris content and local topography have great control on the thinning and retreat pattern of the glaciers, as well as the precipitation and temperature pattern (Bhambri et al., 2011; Racoviteanu et al., 2015). These heterogeneities in glaciers varied across different parts of Himalaya i.e., western, eastern, and central (Bolch et al., 2012; Yao et al., 2012; Kaab et al., 2015).

## 5.2 Verification of lake size expansion and process associated

The highest lake size expansion rates were observed for proglacial lakes viz, a (Galongco), b (Gangxico), present in the Chinese Himalaya (Figure 7A). This observation is aligned with (Mayewski and Jeschke, 1979; Chen et al., 2007). The lake size expansion rate is lowest for the lake (a, b) from 2015 to 2020 due to a shorter period and also for mountain base came, where the snout detachment happened from lake surface (Figure 7). This expansion rate increases till the lake touches the base of the mountain where the slope is steep (the average slope of the lower part of the ablation area is 25°); after that the expansion of lake size slows down, and only volumetric growth happens. Moreover, the lake 'c' is a permafrost lake where lake size expansion rate is always low. On the contrary, only the proglacial connected lakes will continue to grow at a higher rate, as in Figure 7B; these proglacial connected lakes also showed a higher lake size expansion rate. In Figure 7B, these lakes, possibly increase at a higher rate till the mountain base or higher relief zone comes. We noted the third highest lake size increase rate was shown by Thorthormi glacial lakes (Figure 2). This lake is present in

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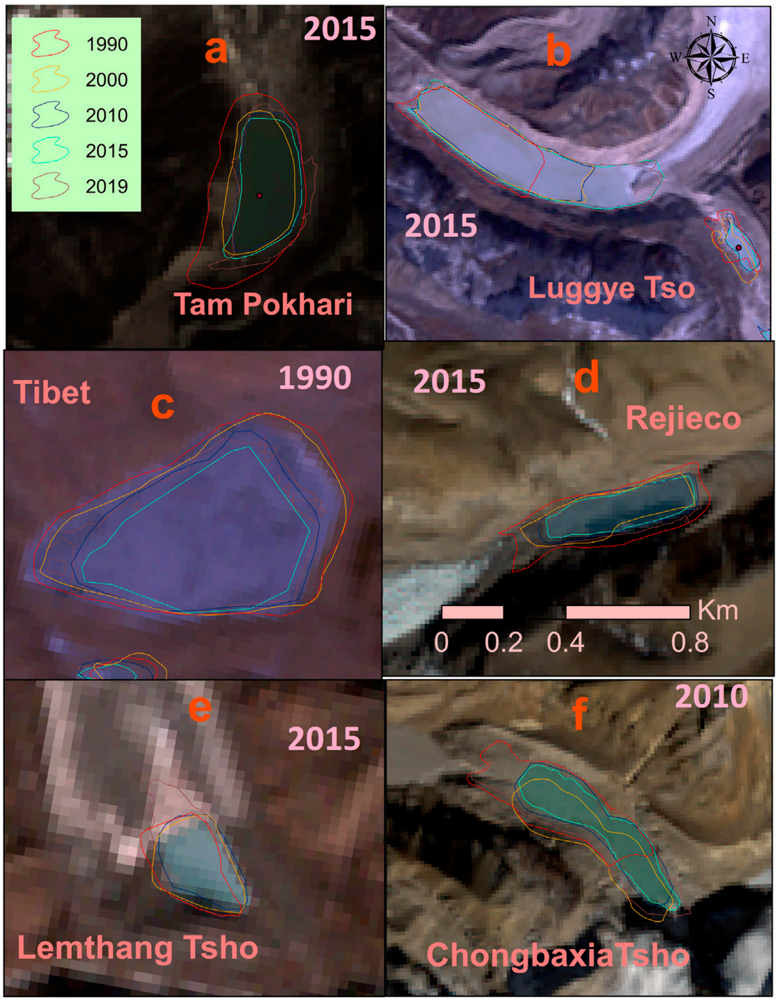


FIGURE 8
GLOF event verified in a different part of the Himalaya. Here, the GLOF occurrence in different parts of the Himalaya is shown: **(A)**-Tam Pokhari in Everest Himalaya, **(B)**-Luggey Tso in Bhutan region, **(C)** (Tibetan plateau close to Sikkim) sdown stream of lake-f, **(D)**-Rejico northern slope of Sikkim, **(E)**- Lamthang Tso southern slope of Bhutan and **(F)**-Chongbaxia Tso northern slope of Bhutan.

the southern slope of Bhutan and formed by the coalescing of supraglacial lakes. The highest expansion rate of this lake happens because of the higher calving frontal width and the smaller size of mother glacier with higher debris content. Moreover, lakes formed by cleansing have a higher increase rate (Komori, 2008; Mohanty and Maiti, 2021b).

A total of 813 (19%) lakes showed a negative lake size expansion rate in the whole Himalaya. Most of them are unconnected or erosion lakes or non-glacier fed lakes. Three types of processes can explain the reduction in lake size: lake outburst, partially drained by artificial draining, or natural and naturally dried by lowering in water input. The first and second type of lake size decrease is frequent in an ice-dammed or moraine-dammed lake, while the third happens only in unconnected or non-glacier-fed lakes. The lake becomes dangerous when lake volume increases; hence, artificially pumping could be done, as in Imja and Lhonak Lake (Kattelmann and Watanabe 1997). However, when lake water increases to higher extent, partial draining happens. A total of 21 lake outbursts events happened during the study period, and out of these, most of the GLOF occurred between the years 1990–2000. Moreover, many lake outbursts or partial draining phenomena were observed from previous studies and verified in this study (Table 3) (Figure 8).

## 5.3 Fate of proglacial lakes

The bedrock slope is closely related to the surface slope of a glacier, i.e., steeper the surface, thinner the ice, and *vice versa*

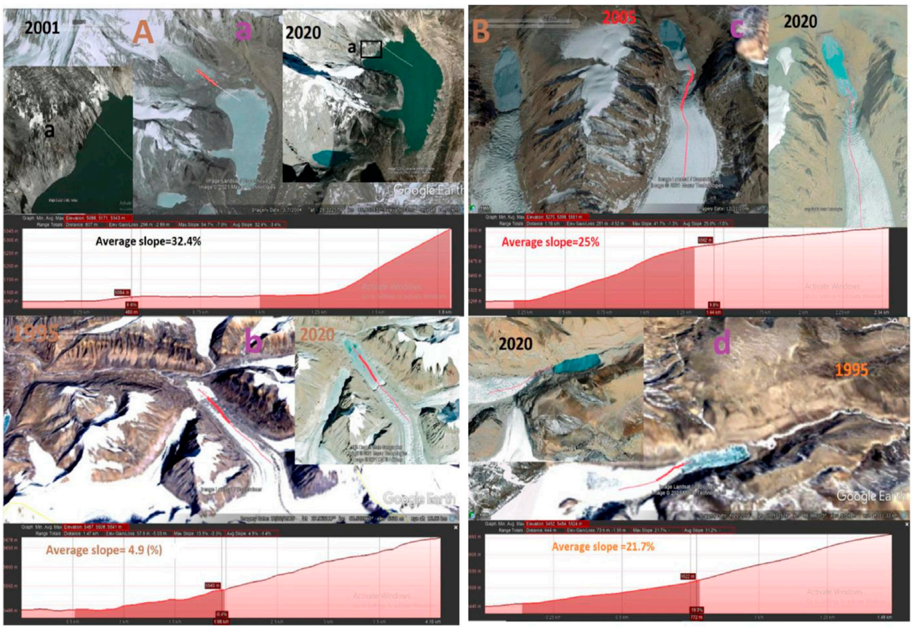


FIGURE 9
Surface slope of glaciers at lower part of ablation area, i.e., close to glacial lake. **(A)** Google Earth based observations of surface slope of glaciers temporarily **(A)** view in 2006 shows connected and **(B)** shows view in 2020 which became unconnected **(B)** GIS based procedures for future prediction of becoming unconnected based on slope of lower part of ablation area for Sikkim Himalayan connected lakes.

(Oerlemans, 2001). The continual increase in frontal loss leads to the detachment of proglacial-connected lakes when the glacier's front comes to a zone of higher relief (steeper slope) (Figures 9A,C,D). Besides, due to the lesser slope in north Lhonak lake (Figure 9B) snout detachment could not have happened, causing a higher increase in lake size. On the other hand, the snout detachment is seen in (Figures 9A,C,D) due to the higher slope. This detachment is prominent for clean glaciers with lesser ice thickness. The glacier is unable to erode when the glacier subsurface rock is very hard; as a result, the sub-glacial relief will be high. This process is a typical case of most of the northern flowing glaciers, mostly in the Bhutan and Sikkim region, which flows over hard crystalline rocks (Nagai et al., 2013; Racoviteanu et al., 2015). Moreover, those glaciers have higher frontal and area loss due to lesser size and debris content (Scherler et al., 2011b; Bolch et al., 2012; Nagai et al., 2013; Ojha et al., 2017). Therefore, many lakes may get unconnected with time in the eastern and central Himalaya, as the glaciers present in those areas have a higher retreat rate (Bolch et al., 2012; Kulkarni and Karyakarte, 2014; Kaab et al., 2015; Racoviteanu et al., 2015; Brun et al., 2017). This detachment is possible because of a higher surface slope (>20%) at the lower part of the ablation area, observed from Google Earth (Figures 9A,B,D). Additionally, after the detachment of the lake, its expansion rate will be slowed down with time, if the current trend of temperature and precipitation prevails.

## 5.4 Comparison with previous work

A higher lake size and number change of 25%, 36% and 25%, 47% was noticed for the Himalayan region from datasets of Zhang et al. (2015) and our data set, respectively. Wang et al. (2020) showed a 15% and 10% increase in size and number for the HKH region from 1990–2018. Likewise, Xin et al. (2012) showed a 29% increase in lake size in the Chinese Himalaya from 1970–2000. A total of 7.02% of lake size expansion rate was shown in the Himalaya from 1990–2010 (Li and Sheng, 2012). Nie et al. (2013) showed that the glacial lakes expanded rapidly by 17.11% from 1990 to 2010 in the central Himalaya. The Himalayan lakes grew continuously between 1990 and 2009 by 20%–65% (Gardelle et al., 2011). Shukla et al. (2018) showed a lake size expansion rate of 24% for the Sikkim region from 1975 to 2017. However, the Hindu Kush and Karakoram regions showed a decrease in lake size expansion rate (Gardelle et al., 2013). This is due to the current trend in temperature and precipitation in that region, i.e., increasing precipitation. Hence, we can conclude that the lake size and number are increasing with time.

The greatest expansions occurred in the latitudinal zones between 4800m and 5600 m on the northern side and between 4500m and 5600 m on the southern side of the Himalaya (Song and Sheng, 2016). Here, a higher lake expansion rate between elevation zones 5000–5500 m was identified in the whole Himalaya. The expansion rate of southern side lakes is higher than the northern side lake (Kanamitsu et al., 2002; Kattelmann, 2003; Kulkarni et al., 2007; Komori, 2008; Nie et al., 2013; Veettil et al., 2016). Besides, Debnath et al. (2018) showed higher lake growth for the North aspect lakes in the Sikkim region. Here, we found the lake size expansion rate is higher for the southern side lakes for the whole Himalaya. Besides, We have also found a higher rate for glacier-fed lakes as reported by (Songchitruksa and Zeng, 2010; Singh et al., 2015) and Song et al. (2014).

### 5.5 Feature selection techniques

The feature selection algorithm was used to identify the importance of various controlling parameters (Manepalli et al., 2011). Here, the multiple regression analysis was used with 1,680 numbers of observations and 16 independent variables (*viz.*, temperature change rate, precipitation change rate, proximal distance, calving width, size of mother glacier, lake size, lake type, lake width, lake length, slope, aspect and elevation), while lake size change rate was taken as dependent variable. Here, temperature change rate, glacier fed lake, glacier snout steepness, precipitation change rate and lake type gave higher weightage towards lake size change rate in regression analysis with a 95% confidence level. Besides, correlation matrix was created which showed lake type, proximal distance the glacier calving frontal width, mother glacier size, debris content, moraine dam and lake width gave higher weightage for lake size change rate.

## 6 Conclusion

- In the Himalaya glacial lake count (lake size >0.01 km$^2$) has increased rate by approximately 2.98%/yr (30.53%) from 1990 to 2020. Most of the glacial lakes are gathered in Langtang, Everest, Sikkim and Bhutan regions at an elevation band of 4500–55000 m. Moreover, new lakes are continuously forming at higher elevation in the Himalaya and these are prominent where glacier fragmentation happens caused by glacier retreat.
- Besides, the average lake size expansion rate of 1.01%/yr was estimated for the Himalaya region. Furthermore, the majority of lake size expansion was noticed at an elevation band of 5000–5500 m due to the presence of the maximum number of moraine dam lakes.
- The lakes present in central and eastern Himalaya (Bhutan, Sikkim, Everest and Langtang) gave higher expansion rates, which is due to the decrease in the amount of precipitation and increase in temperature. Therefore, these regions are going to face the GLOF events depending on the local geomorphology.
- In future, the rate of glacial lake size increase will be slowed down, as some of the glacial lakes are going to be unconnected with continual frontal loss when a steep glacier subglacial topography comes.

## Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

## Author contributions

LM original drafting, data generation and plotting ADtemperature and precipitation data analysis correction SM supervision and interpretation.

## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note



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