A Review of Glacial Lake Expansion and Associated Glacial Lake Outburst Floods in the Himalayan Region

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Abstract
Climate change is strongly affecting the Himalayas. Geologically young and fragile, the Himalayas are sensitive to even minor changes in the climate. Regional warming in Himalayas has been observed between 0.15 and 0.60 °C per decade, which is higher than the mean global warming rate of 0.74 °C per 100 years. Consequent to this warming trend, the glaciological changes in Himalayas are obvious, which has resulted in the formation, expansion and disappearance of various types of glacial lakes. The dangerous lakes among these pose threat to downstream community and infrastructure. In this study, an attempt has been made to critically analyze the progress in Glacier Lake Outburst Floods (GLOF) research and understand its dynamism from multiple approaches through a meta-analysis of peer-reviewed scholarly literature for a period of 2001–2020. The study has found that the glacial lakes in the study region are increasing in number and expanding rapidly owing to the climate change and anthropogenic causes as the Glacier Lake Outburst Floods (GLOFs) are becoming common. The expansion rates of pro-glacial lakes connected to glaciers and moraine-dammed lakes are faster than other type of lakes. Findings from the studies on area change analysis in the region reveal that a number of expanding glacial lakes can emerge as potential sites for future GLOFs, hence need immediate monitoring and observation. Geospatial tools and techniques coupled with field investigations have been found as a potent tool for mapping the evolution and propagation of GLOF hazards resulting from accelerated shrinking and thinning of glaciers and continued lake expansion. Further, the satellite-based remote sensing and modeling has been found as an excellent tool for GLOF management as well as reconstruction of previous GLOF events and prediction of future outburst potential. The idea of this study is linked to the increased incidence of GLOF events in the Himalayan region. This study will help in better understanding of glacial lake expansion and provide scope for future research in devising risk management action plans of potential GLOFs by selecting expanding glacial lakes as case studies.

Keywords Climate change · Glacier recession · Glacial lake expansion · GLOFs · Risk management

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1 Introduction

Climate change from the past few decades has significantly impacted the lifecycle of glaciers in the high-mountainous Himalayan region. The fragile Himalayan Mountains are sensitive to even minor changes in the climatic system (Lama et al. 2009). The temperature in the Himalayas during the past three decades has shown a constant increase (Shrestha et al. 2010; Dash et al. 2007; Wang et al. 2013, 2017; Khattak et al. 2011; Ali et al. 2018; Almazroui et al. 2020) causing glacier recession (Yongping 2004; Gardelle et al. 2011; Banerjee and Shankar 2013; Bolch et al. 2012a, b; Bajracharya et al. 2011; Cogley 2016; Sakai and Fujita 2017). Consequent to this climate change-induced glacier recession, glacial lakes have shown a significant increase both in terms of number and size. This has made them susceptible to Glacial Lake Outburst Floods (GLOFs) (Nie et al. 2013; Worni et al. 2012; Veh et al. 2020) with wide recognition (Yamada and Sharma 1993; Worni et al. 2013; Liu et al. 2014). Global warming is the major reason behind the changing climate and is believed to be the biggest threat to the living world. The impact of such warming has been mostly observed over the high mountains ice packs of the earth. Retreating of mountain glaciers and the development of glacial lakes has been reflected as one of the key factors for global warming. Therefore, glaciers in the high mountain regions serve as an important indicator for the monitoring and assessment of climate change (Haeberli et al. 1999; IPCC 1992; Kääb et al. 2012). In the context of rising temperatures, most of the glaciers in the Himalayan region have been receding at a greater pace, leading to increase in the volume of the glacial lakes and a concomitant rise of GLOF events. (Bolch et al. 2011a, b; Brahmbhatt et al. 2017; Bajracharya et al. 2007, 2008; Mir et al. 2017). Melt water from these glaciers makes an essential contribution to the development and expansion of glacial lakes in the Himalayas (Fujita et al. 2008; Harrison et al. 2018; Bolch et al. 2008). The Himalayan region which contains the largest number of glaciers outside the Polar region (Yao et al. 2012, 2014) is focus of this paper. Glacial lakes are water bodies existing in a sufficient amount influenced by the presence of glaciers and or retreating processes of a glacier (Jain et al. 2015; Fitzsimons and Howarth 2018). The sudden discharging of such lakes caused due to the ice/ moraine dam breach releases enormous volume of water and debris in a devastating manner is known as Glacial Lake Outburst Floods (GLOF’s) (Cenderelli et al. 2001; Worni et al. 2013).

The GLOF events are likely to cause huge consequences in terms of human and infrastructural loss in the downstream regions (Emmer et al. 2018; Nie et al. 2013; Quincey et al. 2005; Yao et al. 2012). Therefore, it is important to understand the behavior of the glaciers, consequent lake development and expansion in the Himalayan region under changing climate to mitigate risks to protect the society living downstream. In the Himalayas, complete in situ observation to all the glacial lakes seems impractical due to remote locations, erratic weather conditions and rough terrain. However, the combined approaches of Remote sensing, GIS and hydrodynamic models act as a viable alternative to identify and monitor such lakes regular intervals (Huggel et al. 2003; Huggel et al. 2004; Komori, 2008; Bajracharya and Mool 2009; Bolch et al. 2011a, b; Govindha 2010; Raj et al. 2013; Worni et al. 2013; Klimes et al. 2014).

Climate change and glacier research has traversed a long path with some path-breaking studies that give details about paleoclimate and future climate scenarios as well as keep a check on present situation. Climate crisis and water-related disasters is a world problem. It is a serious challenge for developing and developed countries that are responsible for high carbon emissions. With the progress in earth, atmospheric and environmental sciences, use of ultramodern (geospatial and computer) technology and conventional (in situ) measurements, our approach towards assessing and addressing challenges posed by natural or human-induced processes that triggers disasters like GLOFs has undergone tremendous changes. The purpose of this study was to critically analyze the recent research on the subject concerning Himalayan region. To identify issues, underlying causes, gaps in knowledge, track shift in approach and provide some new insights into the management of GLOFs in the region with an intention to guide future research on the subject.

The next sections of the paper include materials and methods with description of study region and selection criteria for previous studies; analysis of findings from literature, GLOF events in the past, lake mapping and classification; discussion with a synthesis of similarities and dissimilarities on the subject and concluding remarks at the end that encapsulates this study with some suggestions to guide future research.

2 Materials and Methods

2.1 Description of Study Area

The Himalayan mountain system, is extended over 2500 km from south of the Indus Valley to Nanga Parbat in the west and Namcha Barwa in the east. Himalayas are the loftiest and geologically young mountain ranges in the world as compared to the Alps and Appalachians. These mountain ranges are crescent shaped with a projecting southward convexity, which borders the whole northern margins of the Indian sub-continent (Roy and Purohit 2018). It spreads
across the five Asian countries, namely India, China, Pakistan, Nepal and Bhutan, housing around 52.7 million people. Due to its vast size, huge altitudinal variation and complex topography, the Himalayas experience variable climate.

The Himalayan region including great ranges of central Asia is home to thousands of glaciers and glacial lakes and contains third largest snow and ice deposits in the world (Fig. 1). There are about 15,000 glaciers and 9000 glacial lakes in the Himalayan region (Mool 2005). The region contains permanent fields of snow, and during the winter season, most of the high-elevation regions receive snowfall (Kumar et al. 2005).

2.2 Selection Criteria for Previous Studies

The climate-driven glacier recession and subsequent glacial lake expansion have increased the occurrences of Glacial Lake Outburst Floods (GLOFs) in the high glacierised basins of Himalayas. In this context, an extensive systematic review of peer-reviewed literature was conducted with a focus on glacial lake expansion and GLOFs in the Himalayan region. About 100 research articles and review papers, book chapters and institutional reports were collected from the internet-based databases like Web of Science, Google Scholar and ScienceDirect. The keywords, such as “glaciers”, “glacial lakes”, glacial lakes in the Himalayas”, “glacial lake expansion or assessment”, “GLOFs in the Himalayas” were used to extract the research articles that refer to the period 2001–2020. Out of which only 89 most relevant research items were shortlisted and later 76 were used. Old research on the subject was used to build the foundation and background while as the recent studies were utilized to develop current state-of-the-art and knowledge. Research articles that were not administered through a half, full or double-blind peer-review process were not considered for this study. The snowball technique was used with the intention that no original contributions on glacier and glacial lake studies concerning the region is left out.
3 Findings

3.1 Climate Change in the Himalayas

Global average temperatures have increased by about 1 °C since the dawn of pre-industrial times (IPCC 1992). In India alone, the mean annual temperature has increased by 0.56 °C during 1901–2009 (Attri and Tyagi, 2010) with average temperatures expected to rise between 3.5 and 5.5 °C by 2100 (Lal 2002). Regional warming in Himalayas has been observed between 0.15 and 0.60 °C per decade, which is higher than the mean global warming rate of 0.74 °C per 100 years (Shrestha et al. 2010; Negi et al. 2018; Bhutiyani et al. 2007). The warming rates are not solely attributed to the natural variability but are also a result of anthropogenic causes.

3.1.1 Western Himalayas

Western Himalayas receive precipitation (rainfall and snowfall) from westerlies and the southwest monsoon in the winter and summer season, respectively. Changes in temperature and precipitation are key indicators of climate change. The total observed increase in mean temperature for Western Himalaya from 1991 to 2015 was 0.65 °C. (Negi et al. 2018) (Fig. 2a). Snowfall for the same period has decreased with increase in rainfall. (Negi et al. 2018) (Fig. 2b). The glacier mass loss in the region has been observed as 13% from 1962 to 2000 with the possibility of glacial lake development (Kulkarni et al. 2014).

3.1.2 Central Himalayas

Kattle and Yao (2013) analyzed three decades (1980–2009) of data on annual maximum, minimum and average temperatures in the central Himalayas. Spatial analyses of the average temperatures show a warming trend with a dramatic increase in temperature is observed in the latest decade. The
southern slope of the central Himalayas shows variability in temperatures, especially for the minimum temperature due natural and anthropogenic causes. In Nepal, an increasing trend of temperature has been observed with an increase in mean annual temperature by 0.06 °C per year (Shrestha et al. 2010). The maximum temperature increased by 0.7 °C (Mohandas et al. 2015) (Fig. 3).

3.1.3 Eastern Himalayas

Eastern Himalayas are experiencing widespread warming and the rate is generally greater than 0.01 °C per year. Spatial distribution of annual and seasonal temperature trends shows that most of the region is undergoing warming trends as the annual mean temperature is increasing at the rate of about 0.01 °C/year (Li et al. 2016) (Fig. 4). Dash et al. (2007) observed that maximum temperature increased in the last 100 years over the North-Eastern region of India by about 1 °C during winter and post-monsoon months.

Therefore, based on the review of hydro-climatic trends and changes in observed temperatures and precipitation as highlighted through the present study, we have a strong evidence of warming over the entire Himalayan region. However, the warming rates vary across the sub-regions and seasons.

3.2 Synthesis of Existing Literature

Glacial lake expansion in the various parts of the Himalayas has been investigated with the help of satellite imageries, topographic maps and in-situ measurements (Nie et al. 2013, Ageta et al. 2000; Wang et al. 2015; Yamada 1993; Khadka et al. 2018; Komori et al. 2008). The Inventory of glaciers and glacial lakes in Nepal prepared by International Centre for Integrated Mountain Development (ICIMOD) has revealed that glacial lakes are increasing in number, size and volume due to glacier recession (Mool et al. 2001).

Similarly, the glacial lakes in Central Himalayas have shown a significant increase in area and number from 1990 to 2010. The number has increased by 123 and the total area of glacial lakes expanded by 28.81 km² (17.11%) as studied by (Nie et al. 2013). Wang et al. (2016) analyzed remote sensing data and long-term climate variables to examine the hydrological response of lakes in Nam Co Basin. The results show that the number of new formed glacier lakes increased by 36% and the area of glacier lakes increased by 36.7% (0.97 km²) from 1991 to 2011. According to Shrestha et al. (2017), in 2010 there were a total of 2168 glacial lakes with a total area of 127.61 km² and average size of 0.06 km² in the Koshi basin.

The number and area of the glacial lakes increased consistently over the study period from 1160 and 94.44 km² in 1977–2010 and 127.61 km² in 2010, with an overall growth rate of 86.9% and 35.1%, respectively. Khadka et al. (2018) employed open access Landsat imagery to map and analyze the spatio-temporal dynamics of glacial lakes in Nepal from 1977 to 2017. The results revealed that the total area of glacial lakes in Nepal expanded by 25%. The investigation of glacial lakes in the Chandra basin of Himalayas as studied by Prakash and Nagarajan (2018) shows an increase in the total number and area of glacial lakes in Chandra basin from 28 to 46 and area from 1.91 to 3.26 km².

The number of glacial lakes in Sikkim Himalayas has increased from 425 to 466 during 1975 and 2017 showing a discernible increase of about 9%. The total glacial lake area has also showed a significant increase of 24%, it has increased from 25.17 to 31.24 km² (Shukla et al. 2018). As reported by Begam et al. (2019) the glacial lakes in the central and eastern Himalayas have been identified and mapped, with a total surface area of 37.9 km², these glacial lakes (moraine-dammed) as a whole were observed to have expanded by 43.6% from 1990 to 2015 using multi-temporal Landsat data.

During 1964–2017, the total glacial lake area in the Poiqu River basin of central Himalaya has increased by
110% and glaciers retreated with an average rate of 1.4 km$^2$ a$^{-1}$ between 1975 and 2015 (Zhang et al. 2019). In the three river basins that form the Ganga river, the total area of glacial lakes has increased from 179 square kilometers in 2000 to 195 square kilometers in 2015 (UNDP, Nepal). The growth of glacial lakes in the Bhutan Himalayas has continued over a 20–70 years of study period, growing at a rate of less than 70 m per year in length and less than 0.04 km$^2$ per year in area (Komori et al. 2008). The glacial lake area change in the various parts of Himalayas is reflected in Table 1.

### 3.3 GLOF Events in the Himalayas

Glacial Lake Outburst Floods (GLOFs) have emerged as a serious hazard from the past few decades due to increase in the human settlements, anthropogenic activities and unplanned infrastructure development in to the fragile ecosystem of high mountain regions, which were not earlier inhibited (Khanal et al. 2015). Himalayan region contains approximately 9000 glacial lakes and around 200 lakes which are potentially hazardous resulting in about 40 GLOF events from the last four decades (Yamada and Sharma 1993; Ives et al. 2010). The onrushing water from the 1994 Lugge Tsho outburst flood devastated the number of villages downstream, such as Chozoz, Thanza, Tenchey and Punkha (Watnabe et al. 1996). In 1929 GLOF event resulted due to the outburst from Ice-dammed lake (Chog Kumdan) in Shyok basin of Ladakh region, affected about 48 villages in the downstream regions (Gunn 1930). On 17th of June 2013 Chorabari GLOF event, resulted due the dam breach has caused widespread damage to the region (Allen et al. 2016). Similar events have been witnessed in the Tibetan Himalaya Cirenacmo (1981), Ghulkin GLOF (1981) in Karakoram Himalayas, (Dig Tsho (1985) and Tampokhari (1998) in Nepal Himalayas has resulted in to the extensive human loss and property downstream (Vuichard and Zimmermann 1987; Richardson and Quincey 2009; Xu 1988).

Besides, this similar destructive GLOF events have claimed large number of lives and caused enormous damage in various parts of the world, particularly Andes, European Alps, Canadian Cordillera and central Himalayan region (Huggel et al. 2003; Clague and Evans 2000; Mergili et al. 2011; Emmer and Cochachin 2013). In 1981, a GLOF event in Nepal damaged Friendship bridge of Nepal-China Highway and Koshi power station with heavy economic losses (Bajracharya et al. 2006).

A GLOF event that occurred during August 2000 damaged 98 bridges in the Tibetan Plateau and destroyed around 10,000 houses accounts about 75 million US dollars in terms of financial losses (Shen 2004). The major GLOF events that have been witnessed in the various parts of the Himalayan region are reflected in the Table 2.

### 3.4 Mapping of Glacial Lakes

Mapping of glacial lakes is essential to analyze the spatio-temporal distribution of the glacial lakes, which is perquisite for the management of potentially dangerous glacial lakes. Glacial lake mapping has been carried out by various researchers in the different parts of Himalayas using automated and semi-automated techniques, such as Normalized Difference Water Index (NDWI) (Prakash and Nagrajan 2018; Worni et al. 2012; Bolch et al. 2008; Zhang et al. 2020), Band ratioing (Bhambri et al. 2015), supervised and unsupervised classification (Zhang et al. 2020), object-oriented mapping and manual mapping (on-screen digitization) (Bhambri et al. 2018; Zhang et al. 2015; Nie et al. 2017). All these methods and techniques have been extensively used in the

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**Table 1** Expansion of glacial lakes in the various parts of Himalayas

| References                  | Time period | Change in area (%) | Study area                  |
|-----------------------------|-------------|--------------------|-----------------------------|
| Khadka et al. (2018)        | 1977–2017   | 25                 | Nepal                       |
| Chen et al. (2007a)         | 1986–2001   | 11                 | Poiqu basin Central Himalayas |
| Nie et al. (2013)           | 1990–2010   | 17                 | Central Himalayas           |
| Shukla et al. (2018)        | 1975–2017   | 24                 | Central Himalayas           |
| Wang et al. (2016)          | 1991–2001   | 36.7               | Namco basin                 |
| Wang et al. (2013)          | 1979–2009   | 173                | Central Tibet               |
| Shrestha et al. (2017)      | 1975–2010   | 31.5               | Koshi basin                 |
| Zhang et al. (2015)         | 1990–2010   | 23                 | Entire Third Pole           |
| Debnath et al. (2018)       | 1988–2014   | 8.38               | Kangchengyao-Pauhunri,Massif, Skkim Himalaya |
| Prakash and Nagrajan (2018) | 2000–2014   | 41.41              | Chandra basin               |
| Gardelle et al. (2011)      | 1990–2009   | 20–60              | Nepal and Bhutan            |
| Begam et al. (2019)         | 1990–2015   | 43.6               | Central and Eastern Himalayas |
past to extract the glacial lakes/water bodies in the Himalayan region (Shukla et al. 2018; Kumar et al. 2020; Mal et al. 2020; Ageta et al. 2000; Wang et al. 2015; Yamada 1993; Khadka et al. 2018). However, due to some uncertainties created by atmospheric and physical processes like mountain shadow, soil moisture, vegetation noise, cloud cover, built-up land noise and snow cover, they are sometimes misclassified as glacial lakes due to the spectral mixing (Zhang et al. 2015). In this context Xu 2006 has modified the Normalized Difference Water Index of Mc Feeters (1996), which has been extensively used by various researchers according to their purpose of study (Chen et al. 2021; Du et al. 2016; Sarp and Ozcelik 2017; Acharya et al. 2018). The Modified Normalized Difference Water Index (MNDWI) utilizes Green and Short-Wave Infrared (SWIR) bands to enhance open water features by efficiently diminishing and removing vegetation, soil and built-up land noise (Eq. 1). Accordingly, MNDWI seems to be more suitable for enhancing and extracting information of water region with a background dominated by vegetation, soil and built-up land noise.

\[
\text{MNDWI} = \frac{p_G - p_{SWIR}}{p_G + p_{SWIR}}
\]

where \(p_G\) and \(p_{SWIR}\) bands are the reflectance in Green and Short-wave infrared, respectively.

A hybrid methodology which comprises the following five steps is much useful for the mapping of glacial lakes and water bodies.

- Automated extraction of glacial lake layer using techniques like NDWI, MNDWI, Band ratioing and supervised/unsupervised classification.
- Selecting the minimum threshold (based on the resolution of the data used)
- Manual editing or on-screen digitization
- Check and overlay with High-resolution Google earth images
- In situ field measurements

Post-checking and editing is almost necessary and suggested for all the automated methods and techniques for glacial lake mapping (Mergili et al. 2013). Therefore, automated techniques coupled with manual editing and check overlay with high-resolution Google earth images seems to be best method for the glacial lake mapping (Mool et al. 2001,2003). In addition to that, field-based observations to some of the bench mark glacial lakes may help to validate the results yielded from the remote sensing-based glacial lake mapping. Besides that, Digital Elevation Model based (DEM) derived slope, aspect and shaded relief values can be used to remove misclassifications of water bodies from topographic effects in the rugged terrain of Himalayan region. The field investigations that are essential part of the process are useful to validate the lake attributes and topographic parameters to generate the final database.

### Table 2  Major GLOF events in the Himalayan region

| No | Year | Lake           | Catchment/basin/mountain range | Source                                    | Country affected |
|----|------|----------------|--------------------------------|-------------------------------------------|------------------|
| 1  | 1929 | Chog Kumdan    | Shyok river                    | Gunn (1930)                               | India            |
| 2  | 1981 | Cirenamco      | Tibetan Himalayas              | Vuichard and Zimmermann (1987)           | China            |
| 3  | 1985 | Dig Tsho       | Nepal Himalayas                | Xu (1988)                                 | Nepal            |
| 4  | 1998 | Tampokhari     | Nepal Himalayas                | Yamada and Sharma (1993)                 | Nepal            |
| 5  | 1994 | Luggage Tsho    | Bhutan Himalayas               | Watanbe and Rothacher (1996)             | Bhutan           |
| 6  | 1964 | Gelhaipuco     | PumQu/Arun                     | Richardson and Quincey (2009), Bajracharya et al. (2006) | China and Nepal |
| 7  | 1977 | Nare           | Koshi                          | Yamada (1993), Ghimire (2004)            | Nepal            |
| 8  | 1980 | Nagma Pokhari  | Tamor                          | Raj and Kumar (2012)                      | Nepal            |
| 9  | 1981 | Zhangzangbo Boqu | Sun Koshi                     | Xu (1988), Shrestha et al. (2010a), Chen et al. (2013), Wang et al. (2018) | China and Nepal |
| 10 | 1998 | Sabai Tsho     | Khumbu Himal                   | Komori et al. (2012), Dwivedi (1999), Kattelmann (2003) | Nepal            |
| 11 | 2005 | Glacial lake    | Kara                           | Hussain et al. (2021)                     | Pakistan         |
| 12 | 2000 | Glacial lake    | Yigeong                        | Zhu and Li (2011)                        | China and India  |
| 13 | 2005 | Glacial lake    | Parechu                        | Zhu and Li (2011)                        | China and India  |
| 14 | 2013 | Chorabari      | Mandakani basin                | Allen et al. (2016)                      | India            |
| 15 | 2005 | Glacial lake    | Yigeong                        | Zhu and Li (2011)                        | China and India  |
3.5 Classification of Glacial Lakes

Classification of glacial lakes plays an important role to know the location and to understand the origin and evolution of glacial lakes. Glacier proximity, moraines, outwash plains and other geomorphological features should be taken into consideration at the time of classification of glacial lakes (Bhambri et al. 2015). Although, numerous approaches of glacial lake classification (Scheffers and Kelletat 2016; Cao et al. 2016; Mool et al. 2011; Wang et al. 2016; Yao et al. 2018; Wu et al. 2011) are available in the literature. However, as of now, there has been no internationally accepted method for the classification system of the glacial lakes.

Some researchers and organizations have proposed various classification systems of glacial lakes as per their own understanding and purpose of research. In the Inventory of glacial lakes in Uttarakhand, Govindha et al. (2016) have classified glacial lakes into 6 major types which include pro-glacial lakes, moraine-dammed lakes, blocked lakes, erosion lakes, cirque lakes and supra glacial lakes based on the methodology suggested by Mool and Bajracharya (2003) and Chen et al. (2007a, b). The schematic representation of different types of glacial lakes as given by Govindha & Kumar (2016) is depicted in (Fig. 5).

Pradeep et al. (2001) have also classified glacial lakes into 5 classes: glacial erosion lake, moraine-dammed lake, ice-blocked lake, Supraglacial Lake and subglacial lake. Bhambri et al. (2015) classified glacial lakes based on glacier process in to four major types as ice dammed, moraine-dammed lake, glacier erosion lake and other glacial lake. A detailed classification system which comprises 3 major classes and 10 sub-classes has been proposed by Wu et al. (2011).

Based on the hydrologic relationships between glacial lakes and their feeding glacier, Jain and Mir (2019) classified glacial lakes into 5 types as supraglacial lake, pro-glacial lake, periglacial lake, glacier fed lake and non-glacier fed lake. Yi and Cui (1995) in the glacial lake study of Altay Mountains suggested multiple classification schema. As per thermal and mechanical differences the glacial lake formation, they were classified as ice-blocked lake, moraine-dammed lake, glacial erosion lake, glacial thaw lake and glacial composite lake. Furthermore, glacial lakes were divided into ice-water lake and non-ice-water lake based on the water supply of glacial lakes. Rai and Mishra (2017) have categorized Glacier lakes into six types, namely blocked lake, moraine-dammed lakes, erosion lakes, cirque lakes, pro-glacial lakes and supra glacial lake. Wang et al. (2010) classified glacial lake into 7 types which include ice-blocked lake, moraine-dammed lake, glacial erosion lake, Cirque Lake, Supraglacial Lake, landslide-dammed lake and glacial valley lake. ICIMOD, 2018 has classified morphologically glacial lakes into three major types and divided them into 10 sub-classes. A complete classification schema proposed by Yao et al. 2018, which is based on the past research studies and principal of systematic, normalization, operability and scalability has incorporated almost all the types of glacial lakes in his classification system (Table 3; Fig. 6).

![Fig. 5 Types of glacial lakes: (EL) Erosion Lake, (CL) Cirque Lake, (MDL) Moraine-dammed lake (BL) Blocked lake, (SL) Supra glacial lake and (PL) Pro-glacial lake. Source: Adapted from (Govindha & Kumar 2016)](image-url)
Glacial lakes in the Himalayan region are increasing and expanding at an accelerated rate with increase in the number of potentially hazardous lakes. There is a strong evidence in the scholarly literature that the climate change-induced glacial retreat has resulted into the formation, development and expansion of different types of glacial lakes in the study region. Expansion rate of pro-glacial lakes connected to the glacier and moraine-dammed lakes is faster than other type of lakes. As reported by Begam et al. (2019), the glacial lakes in the central and eastern Himalayas have a total surface area of 37.9 km². These moraine-dammed glacial lakes were observed to have expanded by 43.6% from 1990 to 2015. The study was conducted using multi-temporal Landsat data. This gives us an indication that a limited number of such studies have been conducted using high-resolution satellite data. Use of high-resolution data will give better results. The growth of glacial lakes in the Bhutan Himalayas has continued over a 20–70 years of study period, growing at a rate of less than 70 m per year in length and less than 0.04 km² per year in area (Komori et al. 2008). According to the glacial lake inventory prepared by Shrestha et al. (2017), there were a total of 2168 glacial lakes with a total area of 127.61 km² and average size of 0.06 km² in the Koshi basin in 2010. The number and area of the glacial lakes increased consistently over the study period from 1160 and 94.44 km² in 1977–1986 and 127.61 km² in 2010, with an overall growth rate of 86.9% and 35.1%, respectively. The results indicate that the total surface area of glacial lakes in Nepal Himalayas expanded by 25% between 1987 and 2017 as studied by Khadka et al. 2018. The number of glacial lakes in the Sikkim Himalayas has increased from 425 to 466 during 1975 and 2017 showing a discernible increase of about 9%. The total glacial lake area has also showed a significant increase of ~24%, it has increased from 25.17 to 31.24 km² (Shukla et al. 2018). Dubey and Goyal (2020) of the Indian Institute of Technology Indore, India, employed satellite data, DEM and flood models to analyze the hazard risk of 329 glacial lakes in the Indian Himalayas. The glacial lakes in the region have increased by 16% during 1993–2018. Furthermore, they estimated that about 22% of these glacial lakes possess high hazard risk both in terms of GLOF event and downstream impacts. Although this is not an exhaustive study covering all the research studies carried out so far in the study region, but on the basis of the abovementioned literature, it is quite evident that glacial lakes in the Himalayan region are expanding and the formation of new glacial lakes has shown a considerable increase particularly in the form of supra glacial lakes.

The rate of growth of such glacial lakes may increase in the future due to the recession of the glaciers caused by the changing climate. The consequent changes may cause catastrophic events which can damage the people and infrastructure downstream.

### 5 Concluding Remarks

High-mountain areas are severely affected by climate change. The present study highlighted sequentially the glacial lake changes and prioritization of risk management for potential GLOFs by investigating into major GLOF events in the Himalayan region using existing literature. Glacial lakes in the Himalayan region are increasing in number and area; hence GLOF events are becoming common in the high-glaciered basins of Himalaya. The continued recession of glaciers under changing climate may lead to the drastic increase in glacial lake area which could be possible cause for GLOFs in the region. The consequences arising from such situations are inevitable, particularly due to less availability of adequate data pertaining to intensity of rainfall, landslide locations, and outburst potential of glacial lakes. The inferences drawn from the study suggest that there...
Fig. 6 Types of glacial lakes on Landsat Images on bands 5, 4 and 3 and Google earth images. Source: Compiled from (Yao et al. 2018)
is an urgent need to monitor and assess the expanding glacial lakes and potentially hazardous lakes in the Himalayan region with immediate impact on the mountain communities of countries like India, China, Pakistan, Bhutan and Nepal. Although various field investigations have been conducted in the area, they are usually limited by lack of in situ glaciological and meteorological observation sites and unfavorable environmental conditions. Integration of Remote Sensing (RS), Geographic Information System (GIS) and Global Positioning System (GPS) has been observed to be the best tool for mapping and monitoring dynamics of glacial lakes and the associated outburst scenarios in the Himalayan region. However, the updated and detailed glacial lake inventories for the region using high-resolution satellite data will be a resource-based for future studies to monitor the behavior of glacial lakes in the region to save many lives and reduce damages to infrastructures, such as houses, bridges, hydro-power projects, roads, etc. With the advancement in geospatial technology for polar and oceanic research, new technologies will open ways for effective management for GLOFs in the region; Geoinformatics is that specialized area where we need invest more to further the scope for cryospheric and climate research. The need has been felt to link the scientific knowledge on GLOF hazards into policy and planning at the local level as well as involve indigenous mountain communities in the GLOF risk prevention and mitigation programs.

Declarations

Conflict of Interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

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