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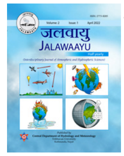

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Rapidly Expanding Glacial Lakes in Nepal Himalaya

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Abstract: The retreat and shrinkage of glaciers due to climate change are the causes for the formation and expansion of glacial lakes in the Himalayas. This study presents the rapidly expanding glacial lakes in Nepal Himalayas between 1988 and 2018 based on the published glacial lake inventories produced from Landsat imageries (30 m). Glacier-fed end moraine-dammed glacial lakes whose surface area was ≥0.1 km^2 in 2018 with an expansion rate of more than 30% in 1988-2018 were regarded as rapidly expanding glacial lakes. The results show that 19 rapidly expanding glacial lakes are heterogeneously distributed in different sub-basins of Nepal. Among the sub-basins, Dudh Koshi sub-basin has a maximum (5) number of rapidly expanding glacial lakes. The total surface area of these 19 glacial lakes expanded by ~133%, from 4.12±0.61 km^2 in 1988 to 9.62±1.04 km^2 in 2018. Regular monitoring of rapidly expanding glacial lakes is required because the rapid expansion heightens the risk of Glacial Lake Outburst Flood (GLOF) by developing more potential flood volume and the expanding lakes can reach sites of possible avalanches.

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1. Introduction

The warming and decreasing precipitation trend (except some regions) are the main causes of glacier retreat and melting in the Hindu Kush Himalayan region (HKH) (Azam et al., 2018; Gardelle et al., 2013; Bolch et al., 2012). The climate change is unequivocal, so some parts of the HKH, especially the western region (Karakoram) is experiencing the glacier advance or positive/neutral mass balance (Farinotti et al., 2020; Bolch et al., 2017; Gardelle et al., 2012). The status of glacier differs from one region to others (Yao et al., 2012); however, the glaciers are overall retreating and experiencing negative mass balance in the Himalayas (Bolch et al., 2012). The retreating and shrinkage of the glaciers cause the formation of new glacial lakes, merging and expansion of existing glacial lakes in the Himalayas (Song et al., 2017; Yao et al., 2012). If the glacial lakes are expanding rapidly and prone to possible hazards, they are assumed to be susceptible to burst, which may threaten downstream communities and infrastructure (Khadka et al., 2021; Nie et al., 2017).

Nepal Himalaya covers the central part of the Himalayan region hosting thousands of glacial lakes in the northern part (Khadka et al., 2018; Nie et al., 2017). Glacial lakes are formed in the vicinity of mother glaciers and some on the surface of glaciers, e.g., Imja Lake on the Imja Glacier, Khumbu, Nepal (Watanabe et al., 1994). Three main types of glacial lakes are found in the Himalayas: supra-glacial lakes/ponds located in the lower ablation areas, pro-glacial lakes linked with glacier termini, and other lakes which are disconnected (unconnected glacier-fed/non-glacier fed) but lie in the periphery to mother glacier (Otto 2019; Salerno et al., 2016; Zhang et al., 2015; Ageta et al., 2000). Supraglacial lakes form in areas of surface lowering where ablation depression occurs. Supra-glacial lakes (pools) are ephemeral, but they may reach several kilometres in diameter and be several meters deep. They may last for months or even decades at a time but can empty in the course of time (Benn et al., 2001). Pro-glacial lakes form due to glacier retreat leaving a basin up the valley of a moraine or ridge. The coalescence of supraglacial lakes with their further ice-cliff expansion and bed deepening gives rise to a single base-level moraine dam pro-glacial lake (Mertes et al., 2017). The formation of a large moraine dam glacial lake poses a threat to downstream communities since the moraine dam retaining water being naturally weak are prone to failure and the phenomenon is known as glacial lake outburst flood (Richardson and Reynolds 2000).

The inventories of the glacial lake show the spatial and temporal changes with an overall increase in the number, volume and expansion rate of glacial lakes in the Himalayas and surrounding regions (Nie et al., 2017; Zhang et al., 2015). The glacial lakes in the Nepal Himalaya have expanded by ~25% between 1987 and 2017 (Khadka et al., 2018). Furthermore, glacial lakes display patterns of change and a complex episodic disappearance and emergence (Khadka et al., 2018; Nie et al., 2017). Several previous reported and unreported GLOF events from the Himalayan region has occurred, marking the region susceptible to GLOF events in the world, with most GLOF events recorded in the central Himalayas being from moraine dam lakes (Zheng et al., 2021; Nie et al., 2018; Carrivick and Tweed 2016). Moreover, glacial lakes intensify glacier mass loss (King et al., 2019), pronounced glacier-lake interaction cause rapid glacial lake expansion likely increasing the susceptibility of GLOFs (Khadka et al., 2021). Thus, studying glacial lakes marks important. The examination of the surface area expansion rate of glacial lakes is regarded as one of the vital factors in assessing the burst potential of glacial lakes (Haritashya et al., 2018; Prakash and Nagarajan 2017). Regarding the rapid expansion of Tsho Rolpa and Imja Tsho glacial lakes in the Nepal Himalaya, these lakes were mitigated by the engineered lowering of the water level to reduce the possible GLOF risk. Therefore, identifying and mapping of rapidly expanding glacial lakes is necessary for individually focusing on their hazard and risk assessment, and appropriate mitigation. This study aims to identify rapidly expanding glacial lakes in the Nepal Himalaya between 1988 and 2018 and study their evolution.

2. Materials and Methods

2.1 Study area

Nepal is located in the southern part of the central Himalayas in between 26°22' to 30°27' N and 80°40' to 88°12' E. (Figure 1). The elevation of the country ranges from nearly 60 meters from the mean average sea level (masl) to the roof of the world, Mount Everest (8848.86 meters). This sharp rise in elevation in a short latitudinal span has provided a diverse landscape resulting in topographic complexity supporting the tropical to nival climatic zones (Karki et al., 2016). Koshi, Gandaki, and Karnali are three major river systems of Nepal in the east, central and west, respectively. The country has four distinct seasons pre-monsoon (March to May), monsoon (June to September), post-monsoon (October to November), and winter (December to February) (Sharma et al., 2020b). The northern part of the country is dominated by snow cover, glaciers, and glacial lakes (Khadka et al., 2020; Khadka et al., 2018; Bajracharya and Shrestha 2011). Most of the snow in the mountain ranges occurs in the winter (cold) season and melts in the pre-monsoon (hot-dry) season. The south Asian monsoon contributes to more than 80% of annual precipitation in the summer season, while the westerlies contribute to the remaining precipitation, especially snowfall in the high elevation in the winter season (Hamal et al., 2020; Sharma et al., 2020a). Almost 98% of the glacial lakes in Nepal Himalaya lie above 4000 m (Khadka et al., 2018). The study area is a region with a high number of reported and unreported GLOFs (Zheng et al., 2021; Nie et al., 2018)

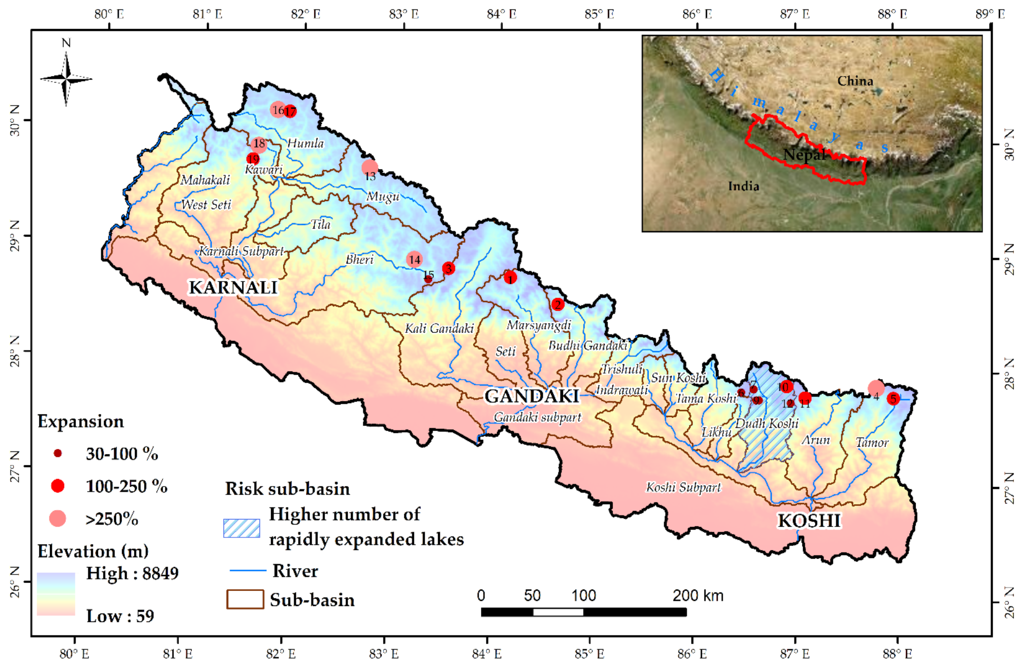

Figure 1. Distribution of rapidly expanding glacial lakes (1 to 19) from 1988 to 2018. The inset shows the location of Nepal in the Himalayas with a base map from ESRI.

2.2. Data and methods

This study has used the glacial lake inventory datasets of 1988, 1998, 2008, and 2018 from Khadka et al., (2018) to identify the rapidly expanding glacial lakes in 30 years. These datasets were prepared by semi-automatic process of glacial lake boundary delineation utilizing normalized difference water index and visual confirmation and editing from Landsat images of 30 m resolution. Please refer to Khadka et al., (2018) for details of the glacial lake delineation methodology. Rapidly expanded glacial lakes between 1988 and 2018 were identified by undertaking the following steps:

i. Glacier-fed moraine-end dammed lakes of size ≥ 0.1 km^2 in 2018 were considered as big size lakes that can cause catastrophic damage upon their failure (Rounce et al., 2017; Wang et al., 2012).

ii. Their expansion rate was analyzed for the period of 1988 to 2018 (30 years).

iii. Glacial lakes whose expansion rate was more than 1% annually, i.e., > 30% in 30 years were considered as rapidly expanding lake (Khadka et al., 2021; Nie et al., 2017; Wang et al., 2015; Nie et al., 2013).

The other data used were the Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM, 30 m) data downloaded from the National Aeronautics and Space Administration's (NASA) web portal (https://urs.earthdata.nasa.gov) to study the topographic conditions of glacial lakes, such as, elevation. Data from the Randolph Glacier Inventory (RGI) version 6.0 were used to know the conditions of the parent glacier of glacial lakes, which were downloaded from the Global Land Ice Measurements from Space (GLIMS) website (https://www.glims.org/RGI/) released on 28 July 2017.

3. Results

3.1. Distribution of rapidly expanding glacial lakes

Nineteen glacial lakes were identified that had expanded rapidly between 1988 and 2018 (Figure 1). The details of the rapidly expanding glacial lakes is presented in Table 1. The highest number of rapidly expanded lakes lies in the Koshi basin (9), followed by Karnali (7) and Gandaki basin (3). These glacial lakes are distributed heterogeneously in different subbasins of Nepal. Among sub-basins, the Dudh-Koshi sub-basin (Everest region) has the highest number of rapidly expanded glacial lakes marking this basin as a potential high-risk basin in terms of rapidly expanded glacial lakes. Additionally, the Dudh-Koshi basin has large glacial lakes compared to other basins (Table 1). These rapidly expanded glacial lakes lies between 3596 m and 5578 m, with an average elevation of 4854 m.

Table 1. Details of the rapidly expanding glacial lakes. Lake number is the same as shown in Figure 1.

Lake No	Latitude	Longitude	Elevation (m)	Common name	Sub-basin	2018 Area (km^2)	Expansion (1988-2018, %)
1	84.151	28.824	5408		Marsyangdi	0.115	161.735
2	84.632	28.597	3632		Budhi Gandaki	0.256	113.534
3	83.529	28.888	5578		Kali Gandaki	0.350	198.423
4	87.808	27.880	4690		Tamor	0.374	380.478
5	87.976	27.791	5174		Tamor	0.235	221.588
6	86.465	27.847	4951	Kubung	Tama Koshi	0.116	94.329
7	86.588	27.874	4368	Dig Tsho	Dudh Koshi	0.413	87.508
8	86.642	27.778	5160		Dudh Koshi	0.288	42.186
9	86.618	27.778	4831	Lumding Tsho	Dudh Koshi	1.296	99.459
10	86.919	27.899	5003	Imja Tsho	Dudh Koshi	1.441	125.622
11	87.101	27.799	4530	Lower Barun	Arun	1.953	217.226
12	86.955	27.754	4924	South Chamlang Tsho	Dudh Koshi	0.859	62.991
13	82.705	29.742	5393		Mugu	0.121	268.874
14	83.186	28.956	5061		Bheri	0.257	320.548
15	83.329	28.788	4445		Bheri	0.441	46.397
16	81.757	30.215	5372		Humla	0.142	458.549
17	81.876	30.205	5519		Humla	0.118	116.617
18	81.579	29.896	3593		Kawari	0.325	326.632
19	81.525	29.775	4585		West Seti	0.520	130.521

3.2. Expansion rate and evolution map

The total surface area of 19 rapidly expanded glacial lakes increased by ~133% from 4.12±0.61 km^2 in 1988 to 9.62±1.04 km^2 in 2018 (Figure 2a). The majority (13) of the rapidly expanded glacial lakes have their present size (in 2018) double their size in 1988. Five glacial lakes have expanded by less than 100%, whereas seven glacial lakes have expanded by more than 250%. In this study, although, we choose end-moraine dammed glacial lakes directly fed by glacier melt water, only 11 rapidly expanded glacial lakes directly contacted with their parent glaciers, as observed from RGI glacier outlines. Here, we illustrated the decadal evolution map of six rapidly expanding glacial lakes directly connected with their parent glaciers, namely Imja Tsho, Lower Barun Tsho, Lumding Tsho, and Glacial lakes 18, 5 and 1 (Figure 3), to visualize the growth of glacial lakes. The notable size of lakes in 1988 confirms that the formation of lake has begun before 1988. These six glacial lakes expanded towards their parent glacier due to glacier-lake interaction (details in the Discussion section). Imja Tsho, a pro-glacial glacial lake in the Everest region had an initial area of 0.64±0.06 km^2 in 1998 and grew to 0.96±0.09 km^2 in 2008 and expanding rapidly towards the east with an area of 1.44±0.11 km^2 in 2018 (Figure 2b and 3). Similarly, Lower Barun Tsho and Lumding Tsho expanded by 0.045 and 0.022 km^{2}yr^{-1} from 1988 to 2018. Although Glacial Lakes 18, 5, and 1 have expanded by ~327, ~222, and ~162% between 1988 and 2018, their current size is small than Imja, Lower Barun and Lumding Tsho. Among 19 rapidly expanding lakes, Lower Barun Tsho has the largest surface area followed by Imja Tsho, while Glacial Lake 1 has the smallest surface area.

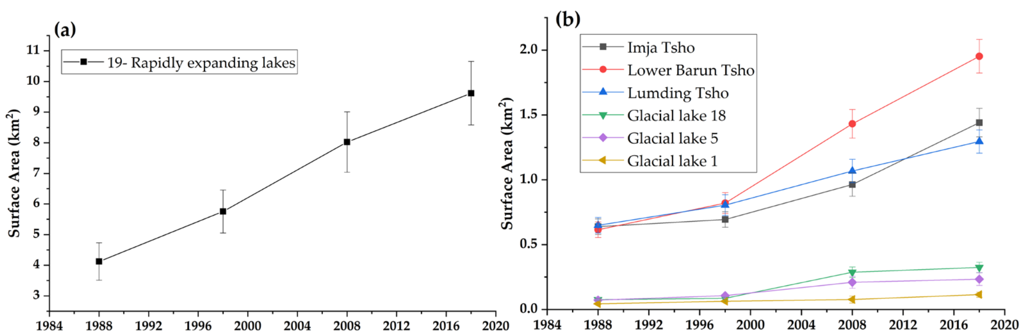

Figure 2. Decadal growth of 19 rapidly expanding glacial lakes (a) and selected six proglacial lakes (b).

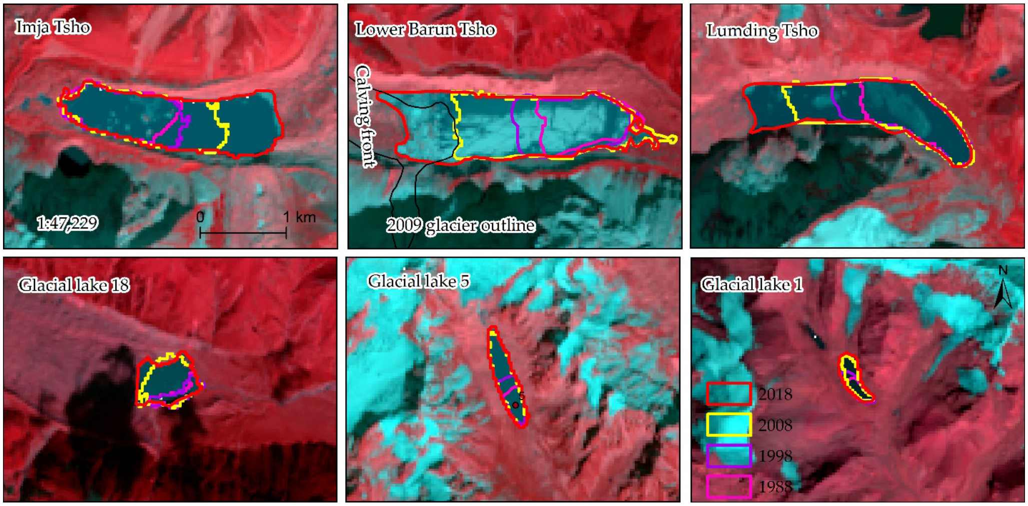

Figure 3 Decadal evolution map of selected six rapidly expanding glacial lakes in Nepal. Please refer to Figure 1 and Table 1 for the lake number. The background images are false color composite images of Landsat.

4. Discussion

In this study, the total number of rapidly expanding glacial lakes was limited by choosing glacier-fed end moraine-dammed glacial lakes of size ≥0.1 km^2 in 2018 with at least 30% expansion in 30 years. The number of rapidly expanding glacial lakes can increase/decrease if these thresholds, criteria, and study periods are altered. The expansion rate of glacial lakes is considered one of the essential factors in hazard and GLOF susceptibility assessments because the growing lake area increases the potential volume and hydrostatic pressure in moraine-dam (Khadka et al., 2021; Aggarwal et al., 2017; Prakash and Nagarajan 2017; Bolch et al., 2011). Furthermore, the rapid surface expansion of glacial lakes such as Imja Tsho will bring lakes closer to areas prone to avalanches (Watson et al., 2020), which will eventually heighten the risk of GLOF from them in the near future. Thus, monitoring of rapidly expanding glacial lakes are important. Rapidly expanding glacial lakes do not mean that they are likely to produce GLOF, as many rapidly expanding glacial lakes such as Lower Barun Tsho and Lumding Tsho have not yet produced GLOF concerning their high rate of expansion (Khadka et al., 2019). However, they require close monitoring. The nineteen rapidly expanding glacial lakes identified in this study are from the expansion rate calculated in the period of 1988–2018, thus, this does not necessarily mean they will continue to expand in the future. The future expansion of the glacial lake depends upon the topographic conditions (such as slope, surface cover, bed rock) and characteristics of parent glacier (glacier thickness and glacier and lake interaction) (Mertes et al., 2017; Linsbauer et al., 2016). For instance, Imja Tsho, Lower Barun, Tsho and Lumding Tsho have possibilities for future expansion (Khadka et al., 2021; Watson et al., 2020), whereas further expansion of South Chamlang Tsho is restricted by bedrock and lateral moraines

(Lamsal et al., 2016). Future studies should focus on whether these lakes would further expand or not.

The retreat and negative mass balance of glaciers due to the pronounced warming in high altitude regions of Nepal (Salerno et al., 2015) is favoring lake development and expansion. Glacier-fed glacial lakes expanded more than non glacier-fed glacial lakes in the Himalayas during the period 1990–2015 (Nie et al., 2017). Specifically, in Nepal Himalaya, pro-glacial lakes with ice contact exhibited the highest incremental changes in surface area (82%) compared to unconnected lakes between 1987 and 2017 (Khadka et al., 2018). This implies that pro-glacial lakes in contact with glaciers have a maximum expansion rate. Out of 19 rapidly expanding glacial lakes, 11 glacial lakes are in direct contact with their parent glaciers, as observed from RGI glacier outlines. The pronounced glacier-lake interaction not only intensifies lake expansion but also accelerates the retreat of glaciers (Figure 3) (Zhang et al., 2019). For example, in Figure 3, the 2009 glacier area of Lower Barun Tsho has been replaced by a lake due to glacier-lake interactions. Lacustrine terminating glaciers retreat faster than land terminating glaciers, providing space for lakes to expand (King et al., 2018). Transmission of thermal energy from fetch of glacial lakes connected to glaciers causes submerged ice melt resulting calving of glacier terminus, which provides space for upward pro-glacial lake expansion (Song et al., 2017; Sakai et al., 2009). Sub-aerial melting, water line melting, and ice calving are the drivers for the expansion of pro-glacial or supraglacial lakes in the Himalayas (Mertes et al., 2017; Thompson et al., 2012). The expansion of glacial lakes not directly connected with glaciers depends on water from glacier melt, ice melt, or precipitation (Salerno et al., 2016).

5. Conclusions

This study identified 19 rapidly expanding glacier-fed end moraine-dammed glacial lakes in Nepal Himalaya that expanded more than 30% in the period of 30 years (1988-2018). The majority (13) of the rapidly expanding glacial lakes (in 2018) have attended double their size in 1988. These glacial lakes are heterogeneously located in different sub-basins of Nepal. Among different sub-basins, the Dudh Koshi sub-basin has a maximum (5) number of rapidly expanding lakes, marking this basin as a high-risk basin in terms of rapid lake expansion. Rapidly expanding glacial lakes heighten the hazard level and eventually the risk of GLOF, thus, their continuous monitoring is needed.

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