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Dynamics of Vulnerable Glacial Lakes in the Sikkim Himalayas Under Changing Climate Scenario

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Abstract: Expanding glacial lakes and associated potential for catastrophic Glacial Lake Outburst Floods (GLOFs) are growing concerns globally. With above-average warming rates (0.3 ± 0.2 °C per decade), the Hindu Kush Himalayan (HKH) region is witnessing significant glacier mass loss, reduced snow cover, and increased permafrost thawing, all of which increase meltwater availability, leading to formation and expansion of glacial lakes. Glacial lakes, in turn, further accelerate glacier mass loss through calving and subaqueous melt, creating a vicious feedback loop of glacial melting and expansion of glacial lakes. Lake with larger areas has a higher probability of interception of mass movements. Additionally, it exerts greater hydrostatic pressure on moraine dams and therefore higher magnitude of GLOF which can be extremely destructive, arriving unnoticed and destroying property, infrastructure, and agricultural land, often resulting in extensive loss of life and property. Sikkim Himalayas hosts a large number of glacial lakes and has received considerable scientific attention due to the potential GLOF hazards. This study focuses on 13 vulnerable glacial lakes (VGLs) in the Sikkim Himalayas, analysing their decadal dynamics from 1962 to 2020 using declassified Corona and Hexagon KH-9 imagery and Landsat satellite data. Our analysis revealed a significant increase in the total area of the VGLs, expanding from 3.594 km² in 1962 to 8.664 km² in 2020. However, individual lakes exhibited highly variable dynamics and growth histories, falling into either of the two categories, quasi-stable and dynamic lakes. Most VGLs were quasi-stable, with minimal growth over a decade, while dynamic lakes, connected to parent glaciers, showed continuous growth. Based on modelled future lake expansion, South Lhonak and KhangchungTsho were found to have future expansion potential of 0.472 km^2 and 0.333 km^2, respectively. With growing infrastructure and population downstream, the risk of future GLOF events is exceptionally high. Understanding glacial lake expansion is crucial for effective risk assessment and policy development in these vulnerable areas.

Keywords: Glacial lakes; Lake expansion; Glacial lake outburst floods; Sikkim Himalayas.

Introduction

Silently expanding glacial lakes foretell a tragedy that threatens numerous downstream communities. The Hindu Kush Himalayan (HKH) region hosting a large number of glacial lakes is experiencing an increased development and expansion of glacial lakes(Chen et al., 2020), mirroring global trends (Shugar et al., 2020). This is coupled with significant glacier mass loss, declining snow cover extension and degrading permafrost, albeit with strong regional variation and these changes are projected to continue through the 21st century (IPCC, 2022).

The region is expected to lose up to 87% of its glacial ice mass over the next 70 years (Shean et al., 2020). Such drastic glacier mass loss is closely associated with

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the formation and expansion of glacial lakes (Farinotti et al., 2019; Haritashya et al., 2018). Glacier movement erodes the valley floor through abrasion and plucking, creating over deepening that can later fill with meltwater forming glacial lakes. A total of 25,285 over-deepening with an area larger than 10^4 m^2 that could transform into future glacial lakes was reported in the HKH region covering another 2683 ± 773.8 km^2 of area (Furian et al., 2021). Glacial lakes exacerbate glacier mass loss through calving and subaqueous melting, creating a vicious cycle of melt and retreat (King et al., 2019; Taylor et al., 2023). Several controlling factors drive the expansion of glacial lakes. Temperature rise is the primary driver, with regions like HKH experiencing above average warming rate of 0.3 ± 0.2 °C outpacing the global 0.2 ± 0.1°C per decade (IPCC, 2018). Additionally, permafrost thaw releases previously frozen water, contributing to increased meltwater runoff and further fuelling the growth of these lakes (Liu et al., 2020).

These glacial lakes can rapidly release large volumes of glacial lake water either through over-topping or failure of the dam causing glacial lake outburst flood (GLOF). GLOFs have the potential to be extremely devastating, strike without any notice, seriously damage infrastructure, and agricultural land, and cause a large number of fatalities (Taylor et al., 2023). Downstream communities often struggle with effectively planning, managing and funding mitigation projects (Thompson et al., 2020).

For effective risk reduction information on factors pertaining to the conditioning of the lakes, possible triggers and magnitudes in case of an outburst are crucial (GAPHAZ, 2017). Mass movement-induced displacement of the lake waters is reported to be responsible for more than half of the GLOF in HKH while intense rainfall events triggered another 18% (Emmer & Cochachin, 2013; Shrestha et al., 2023). The outburst from South Lhonak Lake in Sikkim Himalayas, where the failure of a portion of the moraine triggered a GLOF is a case in point (Yu et al., 2024). The predisposition to mass movements is higher in larger lakes, and this likelihood is expected to increase with the projected expansion of glacial lakes. Increased warming and glacial retreat also aggravate slope instabilities at higher elevations and higher altitudes due to melting permafrost and the loss of stabilisation along the glacier flanks (Deline et al., 2015; Schaub et al., 2013). Steeper slopes reveal increased vulnerability towards rainfall-induced deformation(Yu et al., 2024). Slopes greater than 20° are considered potentially dangerous, while slopes less than 20° degrees have a far lower probability of mass movement (Hermanns et al., 2012). Slopes can be grouped based on angle range for a predisposition towards failure and impact where slopes with 0-20° slope angle have very low, 20-40° have moderate, 40-60° have high and 60-90° have a very high predisposition (Furian et al., 2021).

Within the HKH region Central and Eastern Himalayas have emerged as GLOF hotspots (Veh et al., 2019). Glacial lakes and associated hazards have attracted significant scientific attention with the Himalayan region emerging as the primary research focus of recent scientific studies (Emmer et al., 2022). Sikkim Himalayas which is a part of the Eastern Himalayan region and hosts a large number of glacial lakes has received considerable scientific attention. Multiple glacial lake inventories and glacial lake outburst flood risk assessments have been undertaken for the Sikkim Himalayas (Aggarwal et al., 2017; Allen et al., 2021; Dubey & Goyal, 2020; Islam & Patel, 2022; Mal et al., 2021). This study focusses on 13 vulnerable glacial lakes (VGLs) in the Sikkim Himalayas identified through previous risk assessment studies. By analysing their historical dynamics, the study aims to understand their future growth potential and susceptibility to mass movement triggers, ultimately contributing to improved GLOF risk management in the region.

Study Area

Sikkim Himalayas is a small region covering a total area of 7089 km^2 at the western end of the Eastern Himalayan regime. It hosts a total of 449 glaciers and 1104 glacial and high-altitude lakes covering a cumulative area of 705.54 km^2 and 30.49 km^2 respectively (Aggarwal et al., 2017; Raina & Srivastava, 2008). Sikkim is characterised by a steep elevation gradient, where the elevations rise from 213m to 8586m in the span of around 100 km with more than 43% of the total area consisting of rugged terrain characterised by steep slopes (Aggarwal et al., 2017).

Sikkim is divided into five fifth order basins i.e. Changme Khangpu, East Rathong, Talung, Zemu and Rangpo of which the first four are glacierised (Raina & Srivastava, 2008). While glacial and high-altitude lakes are widely distributed across all five basins.

Glacier systems in Eastern Himalayan glaciers have distinct accumulation and ablation patterns compared to central and western counterparts, largely controlled by climatic considerations (Garget al., 2019). Eastern Himalayas including Sikkim are dominated by the

Indian monsoon, accounting for >80% of annual rainfall during the monsoon months (Bookhagen & Burbank, 2010). The region receives additional precipitation owing to the western disturbances (Murari et al., 2014). An increase in the temperatures has been reported for the region with an increase of ~0.01° C a^{-1} between 1901 and 2016 (Shukla et al., 2018). The region receives additional precipitation owing to the western disturbances (Murari et al., 2014). The annual rainfall trend non-significant decline between 1901-2015, while rainfall in the monsoon period shows a negative trend (Kakkar et al., 2022).

Select glaciers in the region show substantial retreat rates at 17.78± 2.06 m a^{-1} along with the decrease in total glaciated area of about 5.44 ± 0.87% (Garg et al., 2019). The average glacier surface velocities in the region show a significant decrease from 15.7±5.69 (1994-96) to 12.88±2.09 m a^{-1} (2018-20) (Kaushik et al., 2022). Sikkim Himalayas also has one of the highest densities of glacial lakes (Campbell, 2005). A total of 419 glacial lakes with a total area of about 29.86 ± 6.85 km^2 were reported for Sikkim Himalaya in 2020 (Verma & Ramsankaran, 2022). The number of glacial lakes and total glacial lake area show growth rates of 9.64% and 4.93% respectively, between 1975 and 2017 (Shukla et al., 2018).

The 13 vulnerable glacial lakes identified for this study are distributed across the northern margin of the region (Figure 1(a)). It includes large moraine-dammed proglacial lakes, within close proximity to glaciers and

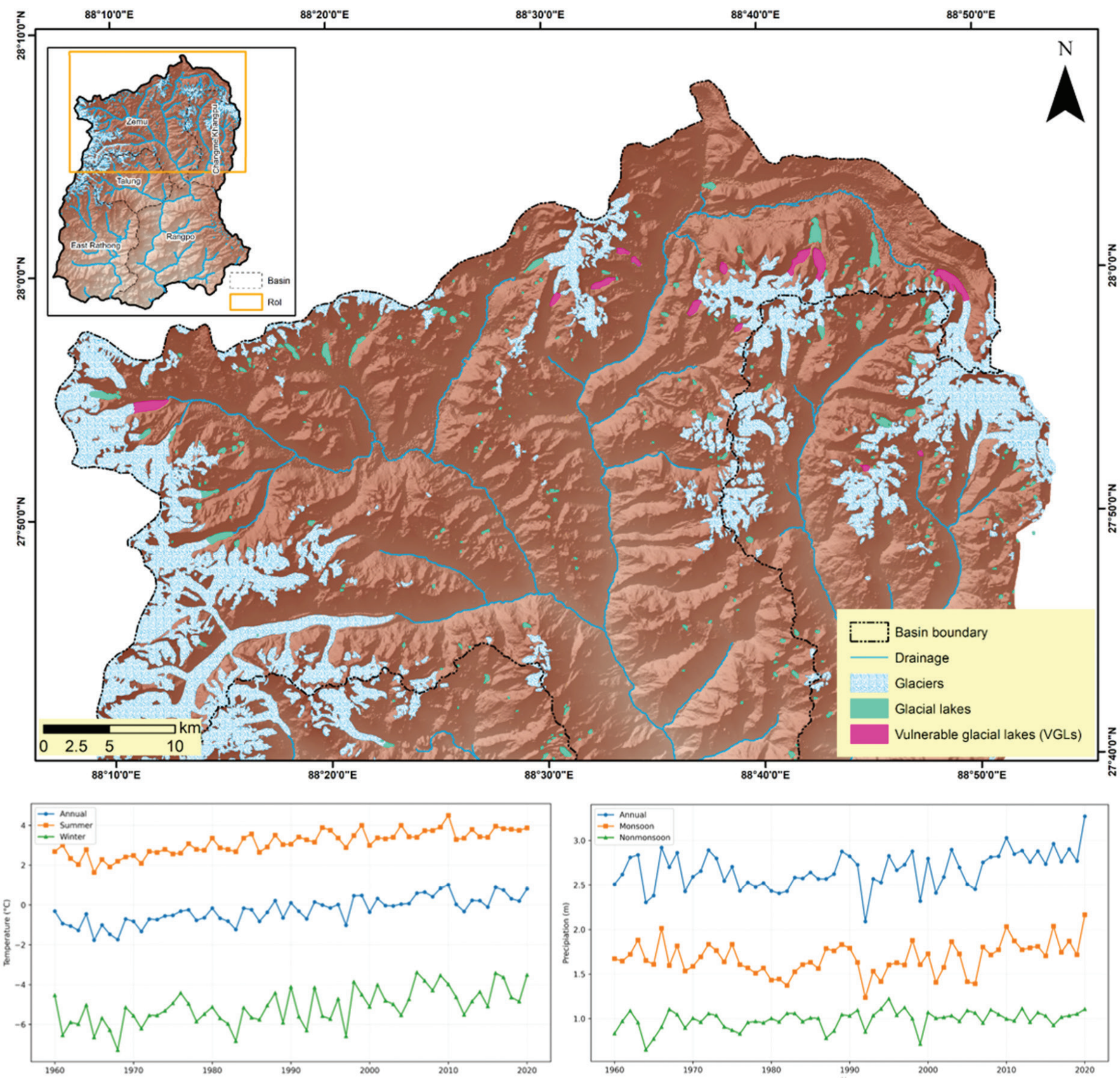

Figure 1: (a) Distribution of vulnerable glacial lakes, Sikkim Himalayas, and (b) and (c) showing the annual temperature (°C) and total precipitation (m) between 1960-2020, respectively.

steep slopes. Due to the lack of long-term observational meteorological data in the region of interest, this study utilises 2-meter air temperature and total precipitation produced by European Centre for Medium-Range Weather Forecast (ECMWF) obtained through Climate Data Store (Hersbach et al., 2018). The long-term 2m air temperature shows a rise of 0.019°C a^{-1} between 1960 and 2020 and while the total precipitation shows an increase of 0.013 m a^{-1} (Figure 1b,c).

Methods & Methodology

Identification of Vulnerable Glacial Lakes

To identify vulnerable glacial lakes (VGLs)we conducted a review of studies undertaken related to hazard and risk assessment for glacial lake outburst flood studies, encompassing Sikkim Himalayas. Based on a published research article, we compiled a list of 101 unique glacial lakes that were identified as being vulnerable with varying levels of risk towards a GLOF event. These lakes were then given scores based on the risk scale used in respective studies. We used the number of risk classes in each study to assign normalised scores between 0-1. For example, if a study divided lakes into three risk classes, low risk, medium risk, and high risk, we assigned the scores of 0.33, 0.66 and 1, respectively. Based on their cumulative scores13 glacial lakes were selected as vulnerable glacial lakes (VGLs) based on their high scores (Table 1).

Glacial Lake Mapping

A decadal-scale inventory of the vulnerable glacial lakes was created for the period of 1962-2020 utilising data from multiple platforms and sensors. To cover the span of the study period we combine declassified CORONA and Hexagon KH9 imagery with satellite imagery from Landsat missions. The region is marred with high cloud cover for the majority of the year, hence to get clear satellite imagery of the region is often hard. The post-monsoon months of September-November, which also corresponds to the end of the ablation period, provide the best images where the cloud, as well as snow cover, is minimal. For topographic data, we have utilised the Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM), which has good vertical accuracy in the study region (Debnath et al., 2018). Glacier boundaries were modified after the Randolph Glacier Inventory v7.0 outlines (RGI Consortium, 2023).

For the mapping of glacial lake difference in water reflectance and absorption in the different spectral bands is frequently utilised in multiple indices, such as normalised difference water index (McFeeters, 1996), modified normalised difference water index (Xu, 2006), automatic water extraction index (Feyisa et al., 2014). For the current study, we utilise a simple band ratio of the green band and NIR band (Eq.1) which improves the contrast between different values, thereby better-highlighting water features (Bazilova & Kääb, 2022). Since multiple images were used manual iteration was

Table 1: Vulnerable glacial lakes identified for Sikkim Himalaya

Glacial lake	*Latitude (°)*	*Longitude (°)*	*Name*	*Study*
VGL01	28.00500	88.71300	Gurudongmar B	1,2,3,4,5,6
VGL02	27.99300	88.54600		1,2,3,4,5,6
VGL03	28.01400	88.56100		1,2,3,4,5,6
VGL04	27.98200	88.50900		1,2,3,4,5,6
VGL05	28.00706	88.69776	Gurudongmar C	1,2,3,4,5,6
VGL06	27.96111	88.65026		1,2,3,4,5,6
VGL07	28.00200	88.63900		1,2,3,5,6
VGL08	27.97500	88.61600	Shako Chu	1,2,3,4,6
VGL09	27.86400	88.74700		1,2,4,5,6
VGL10	28.00737	88.57161		1,2,3,5,6
VGL11	27.91250	88.19510	South Lhonak	1,3,4,5,6
VGL12	27.87300	88.78900		1,3,4,5,6
VGL13	27.99000	88.81600	Khangchung Tso	1,3,4,5,6

[1]Dubey & Goyal, 2020, [2]Mal et al., 2021, [3]Islam & Patel, 2022, [4]Aggarwal et al., 2017, [5]Allen et al., 2021, [6]Worni et al., 2013.

applied for the determination of optimal thresholding to segment water and non-water pixels. The vectorised polygons were then manually corrected for improved accuracy and get the final lake boundary.

$$R_{\text{Water}} = \frac{X_{\text{Green}}}{X_{\text{NIR}}} \tag{1}$$

For panchromatic Corona and Hexagon KH9 imagery, no such band ratio was possible and the lake boundaries were mapped based on visual interpretation.

The accuracy of mapped lake boundaries is a function of the spatial resolution of the imagery used (Chen et al., 2020; Khadka et al., 2018; Shukla et al., 2018). Uncertainty was induced because the spatial resolution of the imagery used was estimated as ±1 pixel of error on both sides of the lake boundary. The percentage error of area delineation was calculated based on formulation by Krumwiede et al. (2014) as shown in (Eq. 2)

$$A_{\text{error}}(\%) = \frac{\sqrt{n} \times m}{A_{gl}} \times 100 \tag{2}$$

where, A_{error}= percentage error

n = number of pixels along the lake perimeter,

m = pixel area of the sensor

A_{gl} = area of the mapped lake

Future Lake Expansion

Glacial lakes connected with parent glaciers have the potential for future expansion due to glacier retreat. We estimated over deepening in the glacial subsurface by utilising modelled ice thickness and digital elevation models. For ice thickness data we utilise data from global ensemble models by Farinotti et al. (2019). This ensemble-based ice thickness estimate is derived based on up to five different thickness estimation models and helps reduce uncertainties sustainably, with a root mean squared error of 5m (Farinotti et al., 2017), the ice thickness raster data was subtracted from elevation data from Shuttle Radar Topography Mission (SRTM) to generate an ice mass free elevation model for the glacier extend. This raster layer reveals over deepening sites, which were then filled using the fill tool in QGIS. The ice mass free elevation raster was then subtracted from the filled overdeepening raster layer to generate the bathymetry of the overdeepening.

Result and Discussion

Thirteen vulnerable glacial lakes in Sikkim Himalaya were studied for their long-term decadal evolution between 1962 and 2020. Of the 13 vulnerable glacial lakes 11 have existed since the beginning of the study period, while VGL04 was first mapped in 1990 and VGL09 in 2000.

Most of the vulnerable glacial lakes are moraine-dammed, with a few having a combination dam type. The vulnerable glacial lakes largely represent moraine-dammed glacial lakes with just a couple of lakes that have a combination type of damming. These lakes are situated in very close proximity to very steep slopes. With the expansion of these lakes, the probability of any mass movement activity impacting the slopes increases. VGL 01 and VGL05, together with a third glacial lake, Gurudongmar Lake represent a combination system where initiation of an outburst flood in either lake can start a cascading flood. Similarly, VGL03 and VGL10 also form a lake system the failure of one can trigger the other. In cases where the parent glacier is still connected to the glacial lake or has recently detached the slope of the parent glacier is considerably gentle, however in some cases the lakes are now exposed to ice/snow masses perched at steep slopes.

The total lake area of the VGLs has increased from 3.594 km^2 in 1962 to 8.664 km^2 in 2020, a growth of about 130% in this period. This rate of increase is magnitude higher than the average growth rate of lake area in the region of ~5% (Shukla et al., 2018). The mean area of vulnerable glacial lakes has increased from 0.33±0.42 km^2 to 0.67 ± 0.577 km^2 during the period, the large standard deviation capturing the large variability in the lake areas. The lake outlines (Figure 2) and the area of the VGLs during the study period (Table 2) exhibit the large variance in the lake area of the different VGLs. It's noteworthy that VGL13, remained the largest glacial lake, over the study period, continuing to grow at a steady pace. The long-term growth of these glacial lakes changes the lake's predisposition to triggers such as proximity to steep slopes, and interception area in case of any mass movement in the lake catchment, in addition to the increased hydrostatic pressure on the lake dam.

Decadal Dynamics of Vulnerable Glacial Lakes

The vulnerable glacial lakes in the last six decades have exhibited dynamic growth with a wide range of annual growth rates (Table 3). The highest average annual growth rate (0.01 km^{2}a^{-1}) was recorded during 1975-1990, and the lowest (0.003 km^{2}a^{-1}) during 2000-2010. The highest annual growth rate for individual lakes was achieved by VGL01 at 0.616 km^{2}a^{-1} during 1975-1990. In terms of absolute growth rates, VGL11 and VGL01

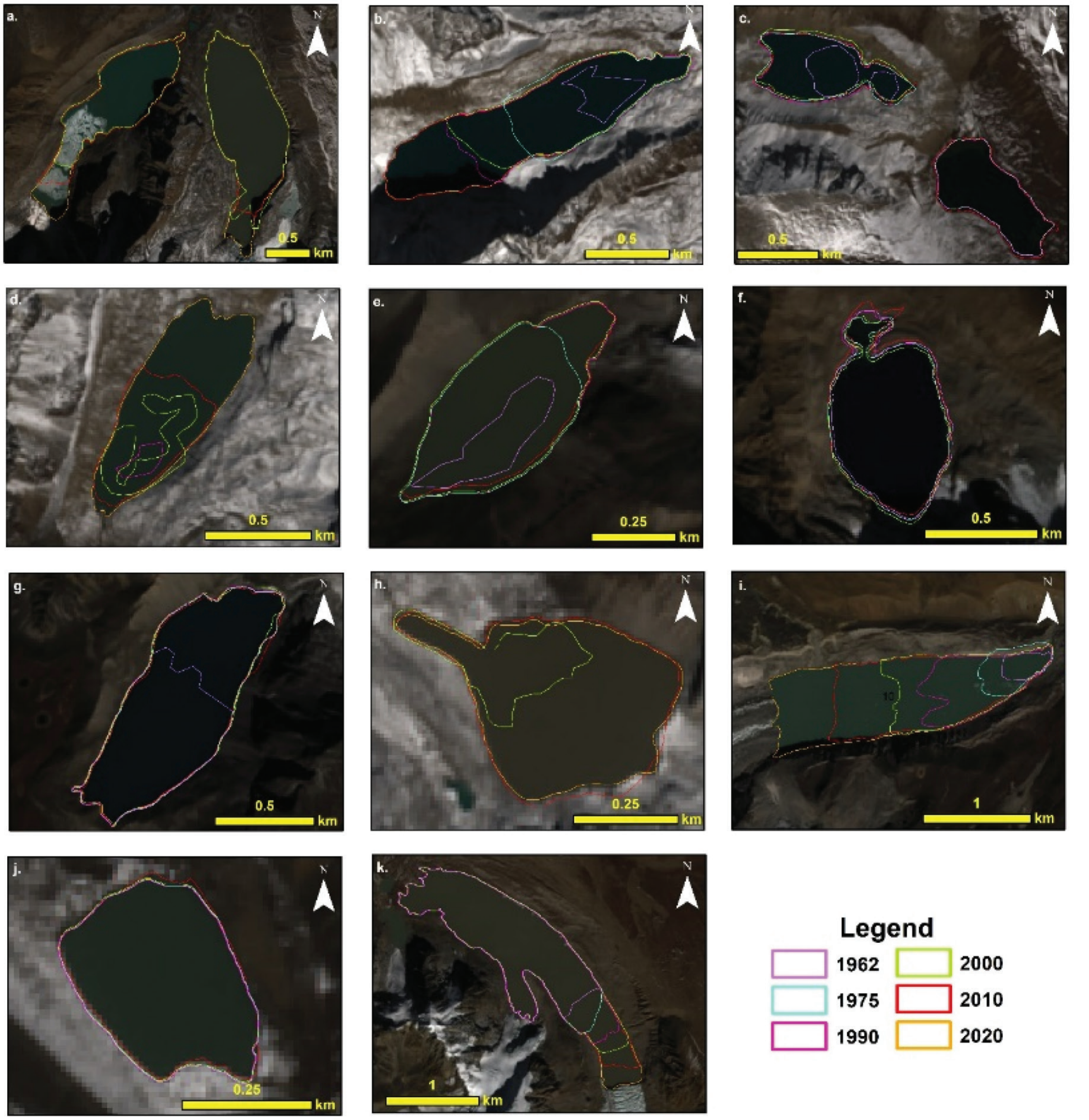

Figure 2: Long term areal evolution of vulnerable glacial lakes a) VGL01 and VGL05, b) VGL02, c) VGL03& VGL10, d) VGLO4, e) VGL06, f) VGL07, g) VGL08, h) VGL09, i) VGL11, j) VGL12 and k) VGL13.

seem to have the overall highest annual growth rates at 0.251 and 0.227 km^2a^{-1}.

Expansion of glacial lakes, such as the identified VGLs, is largely driven by the glacier-glacial lake interaction. Retreating glaciers not only exposes over deepening for the potential expansion of these lakes but also provides glacier meltwater for the expansion (Furian et al., 2021). Lake terminating glaciers also exhibit accelerated retreat, through calving and subaqueous melting aiding lake expansion (Carrivick & Tweed, 2013; Garg et al., 2019). Select lake-terminating glaciers Sikkim Himalaya exhibits retreat rates of 20.05±2.06ma^{-1} as compared to 17.34±4.28ma^{-1} for land-terminating glaciers between 1991-2015 (Garg

Table 2: Total lake area (km^2) of the VGLs between 1962 and 2020

LakeID	*1962*	*1975*	*1990*	*2000*	*2010*	*2020*
VGL01	0.012	0.269	1.193	1.213	1.181	1.292
VGL02	0.073	0.380	0.491	0.466	0.662	0.662
VGL03	0.102	0.265	0.273	0.266	0.261	0.273
VGL04	NA	NA	0.020	0.098	0.208	0.373
VGL05	0.817	0.851	0.868	0.868	0.932	1.042
VGL06	0.048	0.169	0.195	0.195	0.184	0.195
VGL07	0.331	0.320	0.331	0.323	0.343	0.320
VGL08	0.359	0.590	0.590	0.584	0.576	0.590
VGL09	NA	NA	NA	0.054	0.190	0.177
VGL10	0.255	0.255	0.255	0.255	0.272	0.255
VGL11	0.090	0.225	0.517	0.769	1.111	1.547
VGL12	0.103	0.103	0.103	0.103	0.102	0.103
VGL13	1.404	1.519	1.614	1.676	1.748	1.835

Table 3: Annual growth rate (km^2a^{-1}) for the VGLs between 1962 and 2020

LakeID	*1962-1975*	*1975-1990*	*1990-2000*	*2000-2010*	*2010-2020*	*1962-2020*
VGL01	0.0198	0.0616	0.0021	-0.0032	0.0111	0.0183
VGL02	0.0236	0.0074	-0.0025	0.0196	0.0000	0.0096
VGL03	-0.0042	0.0150	-0.0007	-0.0005	0.0012	0.0022
VGL04	NaN	NaN	0.0078	0.0110	0.0166	0.0118
VGL05	0.0026	0.0011	0.0000	0.0064	0.0110	0.0042
VGL06	0.0093	0.0017	0.0000	-0.0012	0.0012	0.0022
VGL07	-0.0009	0.0008	-0.0008	0.0021	-0.0024	-0.0003
VGL08	0.0178	0.0000	-0.0006	-0.0008	0.0014	0.0036
VGL09	NaN	NaN	NaN	0.0137	-0.0014	0.0062
VGL10	0.0000	0.0000	0.0000	0.0017	-0.0017	0.0000
VGL11	0.0104	0.0194	0.0252	0.0342	0.0436	0.0266
VGL12	0.0000	0.0000	0.0000	-0.0001	0.0001	0.0000
VGL13	0.0088	0.0064	0.0062	0.0072	0.0087	0.0075

et al., 2019), elucidating the role of glacier retreat and expanding glacier lake in Sikkim Himalayas. Once the glacial lake is disconnected from the parent glacier the expansion phase either ceases or is significantly reduced. With rapidly retreating and thinning glaciers in the Eastern Himalayas, the formation and expansion of proglacial lakes are going to increase while many glacial lakes will lose connection to their parent glacier and transform into glacial lakes (Bolch et al., 2019; Furian et al., 2021).

Based on areal evolution, the vulnerable lakes can be divided into two categories, quasi-stable glacial lakes and dynamic glacial lakes. Quasi-stable glacial lakes are those glacial lakes that, over an extended period, have remained largely unchanged in terms of size and shape. They appear stable under current environmental and climatic conditions, but they may change in response to shifting climatic or geological events. While dynamic glacial lakes show notable and ongoing changes in size and shape. Continuous climatic and environmental changes, including variations in temperature, precipitation patterns, and glacier melt rates, have an impact on their behaviour. The growth rates are related to firstly the glacier-glacial lake interface. Glacial lakes detached from parent glaciers stop growing when the overdeepening left by the glacier is filled. It's the overdeepenings that emerge out of retreating and thinning glaciers where the potential for growth lies.

In the context of the current study Lake VGL07, VGL10 and VGL12 are representative of quasi-stable glacial lakes. Their areal extent has remained stable since 1962. Their area and shape have not changed much. These lakes are also not connected to their parent glacier and rather are cirque glacial lakes. Lake VGL02, VGL03, VGL06 and VGL08 however appear as supraglacial lakes at different mapping periods but have attained a quasi-stable state with the study period. This type of lake represents the transition of glacier-connected lakes to glacier-detached lakes within the study period. VGL05, VGL11 and VGL13; however, are still connected to the parent glacier and grow continuously, representing the dynamic glacial lake category.

Glacial Lake Outburst Flood

The continued expansion of glacial lakes is projected to create new hotspots for glacial lakes vulnerable to producing GLOFs, and the Eastern Himalayas will emerge as a new hotspot (Wester et al., 2023). The selected VGLs are predisposed to many triggering and conditioning factors in terms of GLOF, such as exposure to steep slopes, large catchment areas, moraine dams and others. Expanding glacial lakes leads to larger lake volumes, increasing the hydrostatic pressure on the lake dam. The majority of the VGLs are moraine-dammed, where increased hydrodynamic pressure from expanding glacial lakes may cause 'self-destruction' of moraine dams (Emmer & Cochachin, 2013; Rounce et al., 2016), All the VGLs have large catchment area, which increases the potential precipitation entering the lake, especially during extreme events, potentially triggering outburst. Interestingly, the catchment areas for VGLs are either adjacent or lie very close together (Figure 3), which increases the possibility of multiple GLOFs in case of any extreme precipitation event in the area. Mass movement impacts, including avalanches, rock failure, moraine failure and upstream GLOFs, are among the most common triggers of GLOFs (GAPHAZ, 2017; Rounce et al., 2016). VGL03 and VGL10 present the case for possible cascading GLOFs in the case of upstream GLOF from VGL03. Slopes greater than 30° are considered prone to failure and among the VGLs all are surrounded and found to have significant regions

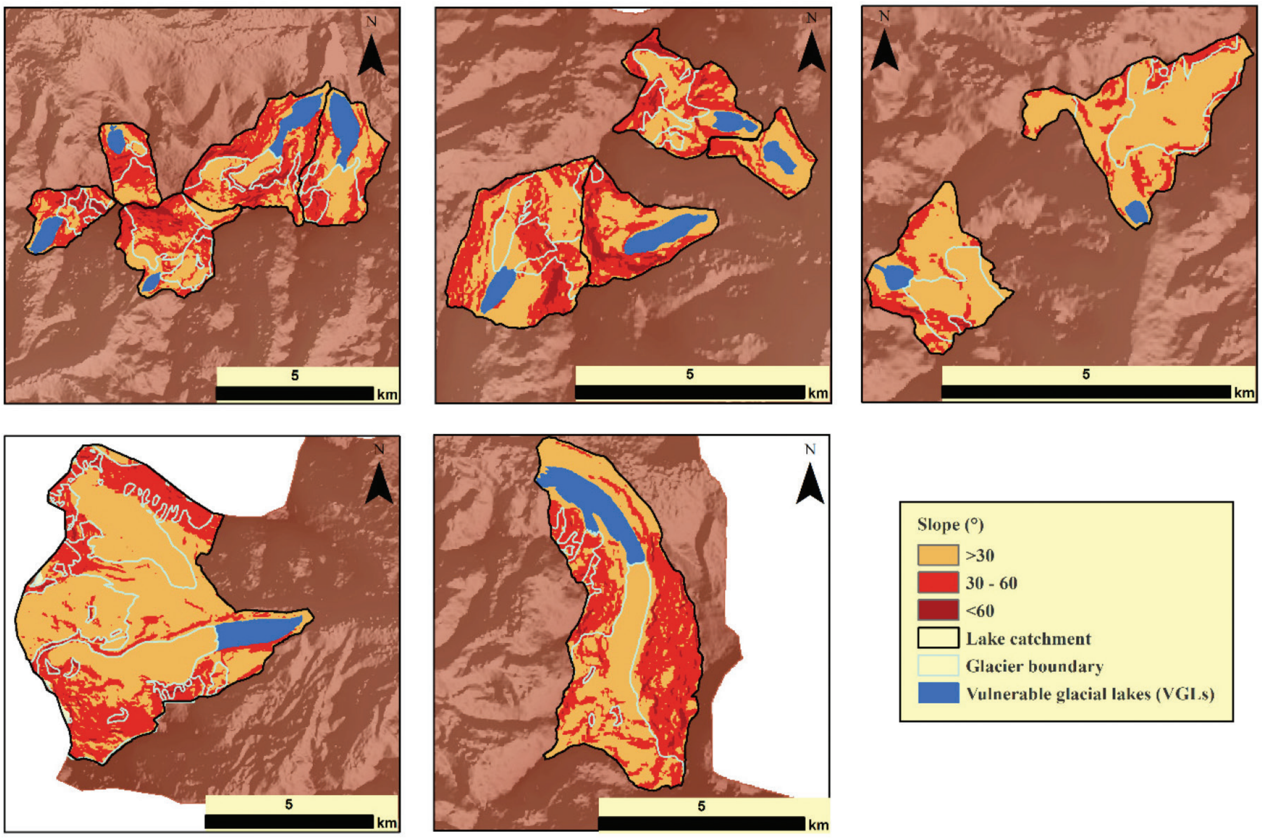

Figure 3: Lake catchment area and surrounding slope for glacierised and non glacierised area.

of steep slopes. The presence of steep glaciers and ice/snow mass increases the possibility of ice/snow avalanches impacting and triggering a GLOF, for many lakes such as VGL01, VGL02, VGL05 and VGL08 among others (Figure 3). Degrading permafrost-related failures may also produce mass movements triggering GLOF, such as in the case of GLOF from VGL11, South Lhonak Lake in 2023 (Yu et al., 2024). Future expansion of glacial lakes exposes them to possible newer areas of potential mass movement as well as provides a larger surface area for any such mass movement impacts.

Future Lake Expansion

Future expansion of glacier lakes is a function of available over deepening for the lake controlled by the glacier-glacial lake connection. Climate models predict a temperature rise of 2.5±1.5°C for RCP4.5 (moderate scenario) and 5.5±1.5°C for RCP8.5 (extreme scenario) in the HKH region leading to increased glacier retreat (Krishnan et al., 2019; Van Vuuren et al., 2011). Eastern Himalayan glaciers fare worst with a mass loss of about 63.7-94.7% by 2100 (Ohara et al., 2014). Under these changing climatic scenarios, the dynamic VGLs are set to expand. Of the vulnerable glacial lakes all except four glacier lakes are not connected to their parent glacier, providing no more possibility for further expansion. VGL01, VGL05, VGL11 and VGL13 are connected to their parent glacier, Gurudongmar Khangse (RGI2000-v7.0-G-15-0911), Kangchengyao-2 (RGI2000-v7.0-G-15-09107), South Lhonak (RGI2000-v7.0-G-15-07986) and Teesta Khangse (RGI60-15.02698), respectively. Overdeepenings derived from the ensemble ice thickness models show considerable growth for VGL10 and VGL13, while for VGL01 and VGL05 no potential overdeepening could be identified. Based on recent satellite imagery it can be observed that the glacier terminus has now retreated significantly, and parts of the bedrock are now exposed.

For VGL11 and VGL13 over-deepening depths of 84.75m and 41.67m was observed respectively (Figure 4). From the modelled data, the future lake expansion area is about 0.472 km^2 and 0.333 km^2. This expansion would account for additional annual growth of 77.14% and 16.84% growth compared to 2020. Areal expansion is directly related to growth in lake water volume which may increase the magnitude of future outburst floods (Allen et al., 2019; Rounce et al., 2016). Expansion of the lake area in turn is also associated with a larger area for interception in case of any mass movement, increasing the susceptibility of such triggers (GAPHAZ, 2017; Prakash & Nagarajan, 2017; Rounce et al., 2016). Increasing volume has an effect on the conditioning of the lake dam increasing the hydrostatic pressure on the moraine dam, which may lead to failure (Rounce et al., 2016).

The steady rising temperatures in the region effect glaciers in the region inducing more melting and increased meltwater flow (Wang et al., 2013), especially in summer accumulation-type glaciers, such as in Sikkim Himalayas (Basnett et al., 2013). This increase in the available meltwater provides for the rapid expansion of the connected glacial lake, throughout the

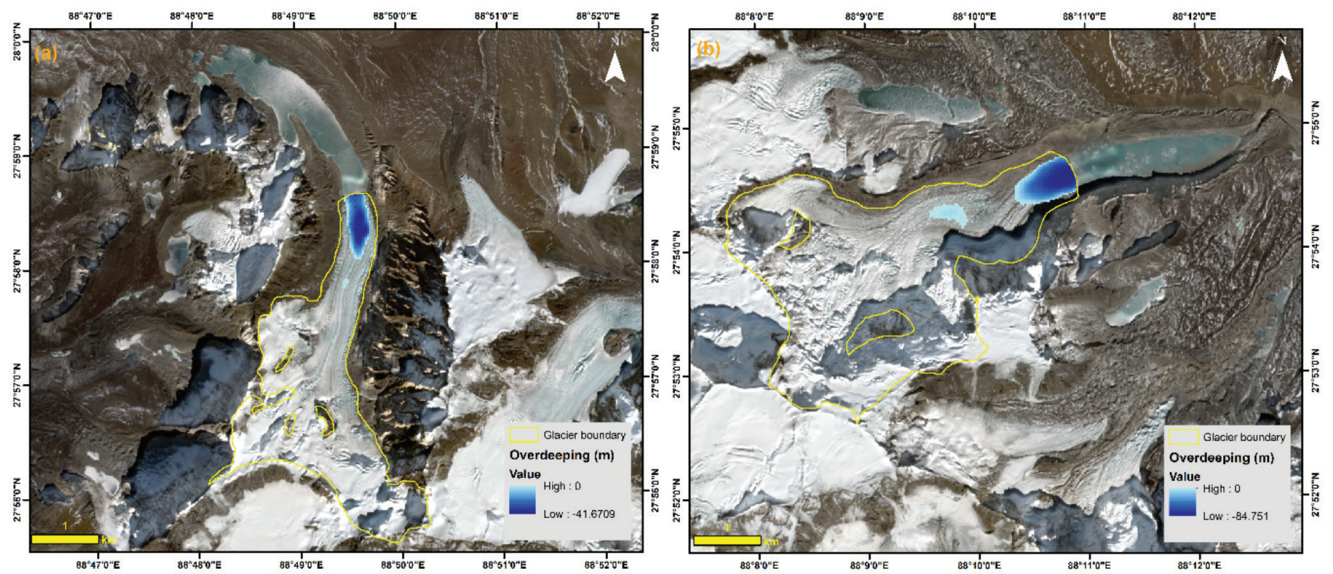

Figure 4: Future Lake extent possible for the parent connected glacier lakes (a) Khangchung Tso, VGL13, and (b) South Lhonak Lake, VGL11.

Himalayas (Ahmed et al., 2022; Kaushik et al., 2020). Sikkim experienced an increase in the annual mean air temperature at a rate of 0.019°C a^{-1} between 1960 and 2020, higher than the overall average in the Sikkim of ≈0.01°C a^{-1} (Shukla et al., 2018).

Conclusion

With the recent outburst of flood from South Lhonak Lake that devastated Sikkim, there has been a major thrust in the monitoring and management of vulnerable glacial lakes in Sikkim Himalayas. 13 vulnerable lakes in the region were selected based in order to understand their growth dynamics and future expansion potential. The total lake area shows a significant increase exhibiting varied patterns with highly dynamic growth rates. Two distinct categories of lakes were identified based on their dynamics, quasi-stable and dynamic lakes. Quasi-stable lakes which include most lakes that exhibit no areal growth and remain stable in terms of glacial lake area. Although the expansion of these lakes has ceased, vulnerability towards producing outburst floods remains. Some of the lakes are still exposed to steep slopes surrounding the lake, increasing the possibility of mass movement impact. VGL10 and VGL13 are representative of dynamic lakes, where there is continual areal growth. These lakes are still connected to their parent glaciers and their retreat provides overdeepening sites for future lake expansion. Expanding glacial lakes not only increases the possible magnitude but increases the interception area for any mass movement events triggering future outburst flood events.

With rapidly growing infrastructure and population in the downstream region, any future outburst events might possess high risk. In addition to regular monitoring and assessment of the glacial lakes, mitigation measures need focus.

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