Spatio-temporal Evolution of Glacial Lakes and Glacial Lake Outburst Flood Susceptibility in the Koshi River Basin

Internship Report

UNDER THE GUIDANCE OF

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Abstract

Glacial Lake Outburst Floods (GLOFs) represents one of the most severe cryospheric hazards in the Himalayas, with catastrophic consequences for the downstream communities and infrastructure. This study investigates the spatio-temporal evolution of glacial lakes and assesses their GLOF susceptibility in the transboundary Koshi River Basin from 1994 to 2024. Using multi-temporal satellite imagery (Landsat-8, Sentinel-2), ASTER DEM, and high-resolution Google Earth validation, we mapped 755 glacial lakes ($\geq$0.01 km^2) and quantified their decadal changes. Results observed a marked accelerated expansion of lakes, particularly between 2014 and 2024, with the 5000–5500 m elevation zone exhibiting the most rapid growth. A subset of 299 lakes ($\geq$0.05 km^2) was further analyzed for susceptibility using morphometric, topographic, seismic, and climatic parameters. The Analytic Hierarchy Process (AHP) was used to assign weights to various parameters and the highest weights were assigned to moraine width-to-height ratio, freeboard, and extreme precipitation events. Susceptibility mapping classified 150 lakes as low, 89 as medium, 45 as high, and 15 as very high risk. Notably, highly susceptible lakes cluster in the eastern sub-basins, where steep valley topography and glacier proximity exacerbate hazard potential. The findings highlight critical hotspots for monitoring and early warning systems, providing a scientific basis for disaster preparedness, infrastructure planning, and climate adaptation strategies in the Koshi basin.

1. Introduction

A Glacial Lake Outburst flood (GLOF) may be described as the sudden release of a significant amount of water retained in a glacial lake, irrespective of the cause (Emmer, 2017). The accelerated melting of glacial ice causes formation and expansion of glacial lakes. Existing lakes, often dammed by unstable moraine deposits left by the retreating glaciers, expand in both area and volume as meltwater input increases. The impounded water, held back by moraine or ice dams, can be unleashed with tremendous force, creating flash floods. These floods have high peak discharge, and immense erosive power, which are capable of transporting huge quantities of sediment and debris, including massive boulders and drastically changing the valley bottom and river channel across tens to hundreds of km (Richardson and Reynolds, 2000).

The triggering of a GLOF is a complex process that can be initiated by a variety of factors, which can act independently or in combination. These triggers can be broadly categorized as related to the dam, the lake, or the surrounding environment. Dam-related triggers include the melting of buried ice cores within a moraine, which reduces the dam's structural integrity, or seepage and piping, which can erode the dam from within (Richardson and Reynolds, 2000). Lake-related triggers often involve a sudden displacement of water, most commonly caused by an ice or rock avalanche into the lake, generating a displacement wave that overtops and breaches the moraine dam (Haeberli, 1983). Extreme Precipitation Events or seismic activity from earthquakes that might destabilize the moraine dam, are examples of environmental triggers (Fischer et al., 2021). Determining the susceptibility of a particular glacier lake requires an understanding of these possible triggers.

Globally the mountain glaciers are experiencing thinning and retreat at an accelerated rate. The effects are more evident in the High Mountain Asia region, often termed the "Third Pole" for holding the largest volume of ice outside the polar regions. In 2020, a GLOF from the Jinwuco moraine-dammed lake in the Tibetan Himalayas caused significant damage as a transboundary threat destroying downstream infrastructure (Zheng et al., 2021). Recent studies indicate that glaciers in the Himalayas have been losing mass at an exceptional rate, with the pace of loss doubling in the 21st century compared to the period from 1975 to 2000 (Maurer et al., 2019).The vast network of glaciers and rapidly developing valleys makes the Himalayan region a hotspot for GLOF risk. The transboundary nature of the Himalayan River basin means a GLOF originating in one country can cause a devastating impact on the other countries downstream. China, particularly in the Tibetan Plateau, has witnessed numerous GLOF events, threatening crucial infrastructure like the Sichuan-Tibet highway (Chen et al., 2020). Following severe GLOFs in the past, like the 1994 Luggye Tsho event, which took an estimated 5,000 lives, Bhutan has started taking important mitigation initiatives at many of its most vulnerable lakes, including Thorthormi Tsho (Watanbe and Rothacher, 1996). In Pakistan repeated GLOFs in its northern regions, such as the 2018 event from the Shisper Glacier, have destroyed homes, agricultural land, and critical infrastructure like the Karakoram Highway (Sattar et al., 2021). In Nepal, the 1985 Dig Tsho GLOF is a landmark event that destroyed a nearly completed hydropower project and caused widespread damage, serving as a wake-up call for the entire region regarding the severity of the threat (Vuichard and Zimmermann, 1987). Similarly, India too has seen multiple episodic events of GLOFs, for instance the catastrophic 2013 GLOF that occurred in the Uttarakhand state of India resulted in extensive damage to infrastructure including buildings, bridges, and roads along the 14-km pilgrim route between Gaurikund and Kedarnath. Around 120–190 buildings were destroyed, and the Sitapur hydropower site was also washed away (Bhambri et al., 2016). Similarly, in 2021 a GLOF event in the Chamoli district of Uttarakhand, initiated by a massive rock and ice avalanche, further underscored the complex and cascading nature of these hazards, where the initial trigger like a distant avalanche can lead to devastating flood impacts far downstream (Shugar et al., 2021). This recurring pattern of devastating events along the whole Himalayan arc shows there is a need for an evaluation on a whole basin-scale.

Due to the intricate and multifaceted nature of GLOF susceptibility, researchers have created several risk assessment and susceptibility approaches. These methods frequently combine geospatial analysis, multi-criteria decision-making (MCDM) tools, and remote sensing data. For example, (Sattar et al., 2021) performed a GLOF susceptibility study using 15 triggering and vulnerability characteristics in an MCDM framework using the Analytical Hierarchy Process (AHP).Their work identified several lakes with very high susceptibility, providing crucial information for targeted monitoring. Similarly, (Rounce et al., 2023) developed a globally applicable framework that models the entire GLOF hazard chain, from lake susceptibility to downstream impact, identifying potential GLOF exposure hotspots worldwide. Other research has concentrated on thorough process-based modelling, simulating possible GLOF hydrographs and inundation scenarios for particular high-risk lakes using hydrodynamic models, and offering comprehensive insights for planning at the local level (Worni et al., 2012).

Furthermore, climate change is also altering the frequency and intensity of potential triggering events. Prolonged periods of exceptionally warm temperatures can accelerate the melt of buried ice within moraine dams, significantly weakening them over a short period. Since increased meltwater input from the rapidly melting glacier can trigger calving events. Analysis of climatic trends, especially Heatwaves, is a vital component for a comprehensive GLOF susceptibility assessment (Wang et al., 2018)

The Koshi river basin hosts a significant number of glacial lakes, many of which are moraine-dammed and situated near their parent glaciers (Nie et al., 2017). Moreoever, the basin has been subject to multiple episodic flood events, and its hydrology is strongly influenced by cryospheric melt. Additionally, the basin has been the site of several previous GLOF events, such as the well-known Zhangzangbo GLOF in 1981, which started in Tibet but caused significant damage downstream in Nepal (Khadka et al., 2024). Finally, and most critically, the Koshi basin houses a large and dense downstream population, particularly in the Terai plains of Nepal and the states of Bihar in India. This densely populated region, if hit by a GLOF event could have catastrophic human consequences. Considering this confluence of high hazard potential and high vulnerability, a detailed investigation into the temporal evolution of glacial lakes and an assessment of their GLOF susceptibility is therefore scientifically necessary for disaster risk reduction in the region.

Considering these factors, this study, therefore, aims to provide a comprehensive assessment of the GLOF susceptibility in the Koshi River Basin. The primary objectives are: (a)To analyze the spatio-temporal evolution of glacial lakes in the Koshi River Basin over the past three decades using multi-temporal satellite imagery. (b) To identify and characterize the key morphometric and glaciological parameters of the glacial lakes in the basin. (c) To identify the most susceptible glacial lakes by using a multi-criteria decision-making framework by ranking the lakes based on their potential to produce an outburst.

2. Study Area

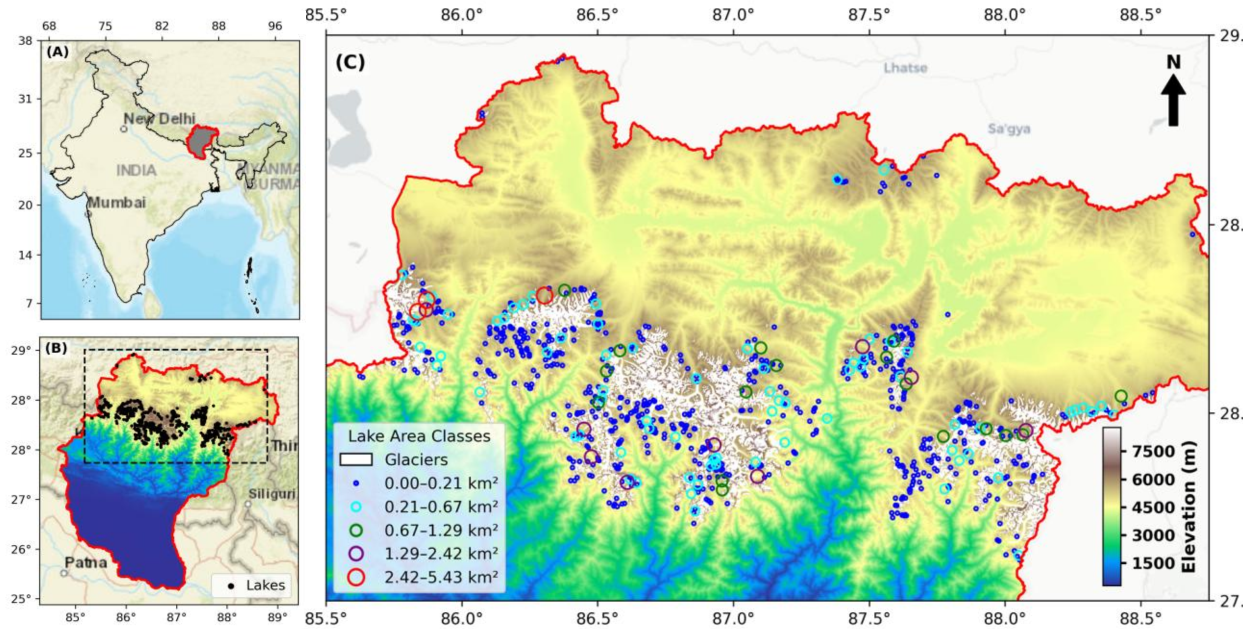

Fig 1: (A) Location of Koshi basin in Eastern Himalayas. (B) Koshi Basin and its glacier lakes (C) Distribution of glacial lakes (>0.001km^2 in 2024. Elevation from ASTERDEM 30m is used in the background.

The Koshi River is a major transboundary river system in the eastern Himalayas, it drains a vast catchment which spans the Tibetan Autonomous Region of China, Nepal, and India. Seven tributaries of the river system meet at Tribeni in eastern Nepal where it combines and carves a narrow Chatra Gorge. The river emerges from the gorge and enters the vast alluvial plains of northern India which has recorded frequent, devastating floods and catastrophic channel avulsions (Sinha et al., 2019). The basin exhibits extraordinary altitudinal variability in a relatively short distance from the summit of Mount Everest (~8,848 m) to the Gangetic plains at elevations below 100 meters (Agarwal et al., 2016).

The Koshi basin drains an area of approximately 74,500 km² and its catchment is distributed around 40% in Tibet, 46% in Nepal, and 14% in India (Mukul et al., 2024). The vast area is composed of diverse geological zones. The Higher Himalayas are composed of hard igneous and metamorphic rocks, as the river traverses southward it encounters the complex geology of the Lesser and Outer Himalayas. Tectonically active fault systems including the Main Central Thrust (MCT) and Main Boundary Thrust (MBT) determine the regional geology (Upreti, 1999). The combined effect of steep topography, active tectonics, and a fragile geological substrate leads to an area with high rates of natural erosion and frequent landslides, which makes the Koshi one of the most sediment-charged river systems in the world (Wasson, 2003).

The basin's climate varies dramatically with elevation, from alpine and tundra conditions at high altitudes to a humid subtropical climate in the southern plains. The south Asian Monsoon governs the regions hydrology and accounts for the 80% of the annual precipitation mainly during the period of June to September, This intense rainfall during the monsoon months lead to a seasonal peak in the river discharge (Talchabhadel et al., 2018). Moreover, future warming, especially at higher elevations, and alteration to monsoon precipitation patterns can exacerbate flood risk in the basin. The high-altitude headwaters of the Koshi basin are heavily glaciated and in response to regional warming are experiencing significant cryospheric changes.

Studies have documented widespread glacier retreat and an increase in the number and area of glacial lakes (Maurer et al., 2019; Nie et al., 2021). This proliferation in the number of glacial lakes in the region has made it the high risk region for Glacial Lake Outburst Floods (GLOFs), with inventories identifying at least 42 potentially dangerous glacial lakes (ICIMOD, 2025). High sediment load and the dynamic nature of the river causing frequent floods has earned it the moniker "Sorrow of Bihar". The 2008 Bihar flood, a catastrophic event triggered by an embankment breach in Nepal caused the river to abruptly shift its course eastward by over 100 km, displaced millions of people and caused widespread devastation (Sinha et al., 2019).

3. Data and Methodology

3.1. Data used

Remotely sensed data of medium to high spatial resolution and Digital Elevation Model (DEM) were used to study the evolution and dynamics of glacial lakes within the Koshi River Basin. An existing glacial lake inventory from Wang et al., 2020 served as the baseline for this study. To map the most recent lake outlines for the year 2024, we utilized Sentinel-2 Multispectral Instrument (MSI) imagery with a 10m spatial resolution. Lake extents for 2014 were delineated using terrain-corrected Operational Land Imager (OLI) Level 2 images from Landsat 8 (30m spatial resolution) for the historical analysis. All satellite images were taken during the post-ablation period, which is September to October, in order to reduce the impact of seasonal snow and cloud cover. To obtain the best view of glacial lake borders, this temporal window is frequently used in Himalayan cryosphere studies (Gardelle et al., 2011). The Normalized Difference Water Index (NDWI), a spectral index that is very useful for boosting the contrast between water bodies and surrounding land features, was calculated in addition to the manual delineation of lake shorelines (McFEETERS, 1996). For the derivation of key topographic and geomorphological parameters, the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) V3 was used, which provides a spatial resolution of approximately 30 meters. In addition, high-resolution imagery (<1m) available within Google Earth Pro was used extensively for the validation of lake delineations and the detailed manual analysis of moraine dam characteristics.

3.2. Morphometric parameters of glacial lakes

Key morphometric parameters were extracted from the digitized lakes and surrounding terrain features using satellite images and ASTER DEM. The individual parameters extracted are described below in more details: -

I. **The glacier-lake distance (F1):** The shortest distance between lake and glacier was calculated in QGIS.
II. **Slope analyses (F2)**: To assess potential downstream dynamics of a GLOF, slope along the shortest flow path was computed as Slope (°) = arctan (Rise/Run), where Rise is the elevation difference between the lake outlet and the downstream point, and Run is the horizontal distance. This slope indicator is used widely to estimate potential flood velocity and energy of the flow (Bajracharya and Mool, 2009).
III. **Moraine Dam Width-to-Height Ratio (F5)**: The Width-to-Height (W/H) ratio was measured using elevation profiles extracted from DEM. The maximum dam height and crest width were measured from these profiles. A low W/H ratio usually means a steep, narrow-crested dam, which is more susceptible to failure through various processes like piping, overtopping, or slope collapse (Clague and Evans, 2000).
IV. **Freeboard level (F6):** For the freeboard, the elevation of the lake (z_water) was extracted from the mean elevation data using Zonal Statistics tool over the extent of the lake (Nie et al., 2013; Veh et al., 2019). Then a negative buffer was applied along the lake boundary to delineate a rim of morraine from this the maximum elevation was extracted as the dam crest elevation (z_crest) (Rounce et al., 2023; Wang et al., 2020). The freeboard was then computed by Z_crest – Z_water. This approach, while not a substitute for in-situ field surveys, has been widely utilized in remote-sensing based susceptibility assessments of glacial lakes. Where field access is limited in Himalayan regions It provides a reasonable estimate of lake stability and potential overtopping risk (Emmer, 2017).
V. **Dam Distal Face Slope(F7)**: This was measured in QGIS from the elevation profiles derived from the ASTER GDEM data. This parameter is a critical indicator of dam stability, because during the overtopping event the steeper distal faces are easily eroded (Richardson and Reynolds, 2000). The initial measurements were cross validated using profiling tools in Google Earth Pro to ensure reliability.

Table 2: List of parameters used for susceptibility analysis

Predictor groups	GLOF susceptibility and hazard predictors	Reference
Lake characteristics and dynamics	F1. Area 2024	Similar to Glacial Lake area: Aggarwal et al. (2016); Bolch et al. (2011)
	F2. Change rate %	Lake-area change (growth/shrinkage): Aggarwal et al. (2016); Wang et al. (2012)
	F10. Elevation	Glacial lake elevation: Mergili and Schneider (2011)
Dam stability	F5. Moraine W/H ratio	Width-to-height ratio: Aggarwal et al. (2016); Worni et al. (2013)
	F6. Distal face slope (°)	Moraine-wall steepness: Allen et al. (2019); Khadka et al. (2021)
	F7. Freeboard	Bolch et al. (2011); GAPHAZ (2017)
Potential triggering mechanisms (geomorphic)	F3. Glacier to lake distance	Distance from parent glacier snout: Aggarwal et al. (2016); Prakash and Nagarajan (2017)
	F4. Slope between lake and glacier	Steepness parent glacier snout: Bolch et al. (2011); Wang et al. (2011)
	F9. Seismic	Seismic activity: GAPHAZ (2017); Prakash and Nagarajan (2017)
Potential triggering events (climatic)	F8. Extreme precipitation events	GLOF triggering by extremes: GAPHAZ (2017); Prakash and Nagarajan (2017)

3.3 Derivation of geometric, topographic and Seismic susceptibility factors

To assess the GLOF susceptibility of the 299 selected lakes, multiple geometric and topographic parameters were derived. These parameters are widely recognized globally as primary controls on the stability of moraine dams and the potential magnitude of an outburst event (Richardson and Reynolds, 2000).

I. **Glacier-Lake Distance (F3):** The shortest distance between each glacial lake and the snout of its parent glacier was measured using tools in Google Earth Pro. This metric serves as one of the key indicators of lake's susceptibility. Lakes in direct contact with or near a glacier terminus are considered more susceptible due to their continuous and direct supply of meltwater, increased potential for ice calving or avalanches striking the lake (Sattar et al., 2019).

II. **Slope between lake and glacier (F4):** The average slope of the downstream channel below the lake outlet was calculated from the ASTER Global Digital Elevation Model (GDEM). A steeper downstream path corresponds to higher flow velocities and greater erosive power, during a potential GLOF event.

III. **Seismic Activity (F9):** Seismic activity is considered essential factor in modern hazard assessment frameworks (Ives et al., 2010; Kougkoulos et al., 2018). Earthquakes cause

GLOFs through the intense ground shaking which leads to the liquefaction or cracking of unstable moraine dams which reducing their structural integrity and results to a catastrophic failure. Moreover, co-seismic landslides and rock-ice avalanches are triggered on steep valley walls, which displaces large amounts of water upon impact on a glacial lake and thus causing an overtopping breach of the dam (Richardson and Reynolds, 2000). Since the Koshi basin is situated in one of the most tectonically active zones of the Himalayas, it is particularly vulnerable to such events. The catastrophic 2015 Gorkha earthquake (Mw 7.8) and its major aftershocks increased landslide activity across the region and it directly contributed to subsequent GLOF events, such as the 2016 outburst of Gongbatongsha Lake that turned into a destructive debris flow (Chen et al., 2023). This direct link between seismic events and GLOF initiation stresses the need for thorough assessment of seismic hazards for accurately predicting GLOF susceptibility in the Koshi basin.

IV. **Extreme Precipitation Events (F10)**: Extreme precipitation events, particularly cloudbursts, can rapidly raise lake water levels, increase hydrostatic pressure and potentially cause moraine dam failure and sudden outburst floods (Worni et al., 2014). Therefore, consistent with previous Himalayan GLOF assessments extreme rainfall was included as an important susceptibility factor, (Prakash and Nagarajan, 2017; Khadka et al., 2024).

3.5 Analytic Hierarchy Process (AHP)

The AHP technique was used to calculate the weights of the parameters used in our study for the generation of the final susceptibility index of each lake. The relative weights were assigned to the selected parameters to generate the final susceptibility index of each lake. AHP is a widely used multi-criteria decision-making (MCDM) approach that structures complex problems into a hierarchy of factors and uses pairwise comparisons to derive their relative importance (Saaty, 1987). It has been extensively applied in natural hazard assessments, including landslides, floods, and GLOF susceptibility (Prakash and Nagarajan, 2017; Khadka et al., 2024). Uncertainties may arise from satellite datasets and DEMs used for estimating factors, but similar datasets have been reliably used in Himalayan GLOF assessments (Rinzin et al., 2021). The consistency ratio (CR) was also evaluated to verify the reliability of pairwise judgments, with our CR value (0.0176) well below the acceptable threshold of 0.1. The calculated weights revealed moraine width-to-height ratio (0.2486), freeboard (0.1639), and extreme precipitation events (0.1639) as the most influential factors, while elevation (0.0219) contributed the least, aligning with previous studies on GLOF susceptibility.

Table 2: Pairwise comparison matrix and weight of factors computed using the AHP factors.

ID	Parameter	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	CW
F1	Area 2024	1	0.50	0.33	2	0.20	0.50	0.25	0.25	1	3	0.0470
F2	Change rate %	2	1	1	3	0.25	1	0.33	0.33	2	4	0.0798
F3	Glacier to lake dist.	3	1	1	4	0.33	2	0.50	0.50	3	5	0.1103
F4	Lake to glacier slope	0.50	0.33	0.25	1	0.17	0.33	0.20	0.20	0.50	2	0.0310
F5	Moraine W/H ratio	5	4	3	6	1	3	2	2	4	7	0.2486
F6	Distal face slope (°)	2	1	0.50	3	0.33	1	0.50	0.50	2	4	0.0826
F7	Freeboard	4	3	2	5	0.50	2	1	1	3	6	0.1639
F8	Extreme precipitation events	4	3	2	5	0.50	2	1	1	3	6	0.1639
F9	Seismic	1	0.50	0.33	2	0.25	0.50	0.33	0.33	1	3	0.0510
F10	Elevation	0.33	0.25	0.20	0.50	0.14	0.25	0.17	0.17	0.33	1	0.0219

4. Result and Discussion

4.1 Spatio-temporal evolution of glacial lakes from 1994-2024

To understand the spatio-temporal evolution of glacial lakes, the 2024 glacial lake inventory was created by updating the existing glacial lake inventory developed by Wang et al., 2020. A minimum area threshold of 0.01 km² was applied to the 2018 inventory, and only those lakes that were ≥ 0.01 km² were further updated (Rounce et al., 2021). These lakes were manually updated using high-resolution Sentinel-2 imagery from the September-October period as mentioned earlier. The delineation process was supplemented using a False Color Composites (FCC) and by calculating the Normalized Difference Water Index (NDWI), a highly effective technique to highlight the water pixels (McFEETERS, 1996). Lakes those that had drained or disappeared in the 2024 images were removed in the updated inventory, further where two or more lakes merged, the Lake ID corresponding to the bigger lake was kept and the smaller one was deleted to avoid confusion. This manual refinement felt necessary for ensuring high accuracy, correcting for classification errors, and accurately capturing lake boundaries (Gardelle et al., 2013). The newly created 2024 lake polygons then served as a reference layer for understanding the spatio-temporal variation compared to the historical 2014, 2004 and 1994 lake extents. A total of 755 lakes were present in our updated inventory with area ≥ 0.01 km². To analyze the evolution of these lakes, the rate of change in lake area between 1994, 2004, 2014 and 2024 was calculated. This metric serves as a critical indicator of lake stability, as rapid expansion is often linked to accelerated glacier melt and an increased likelihood of an outburst (Huggel et al., 2002).

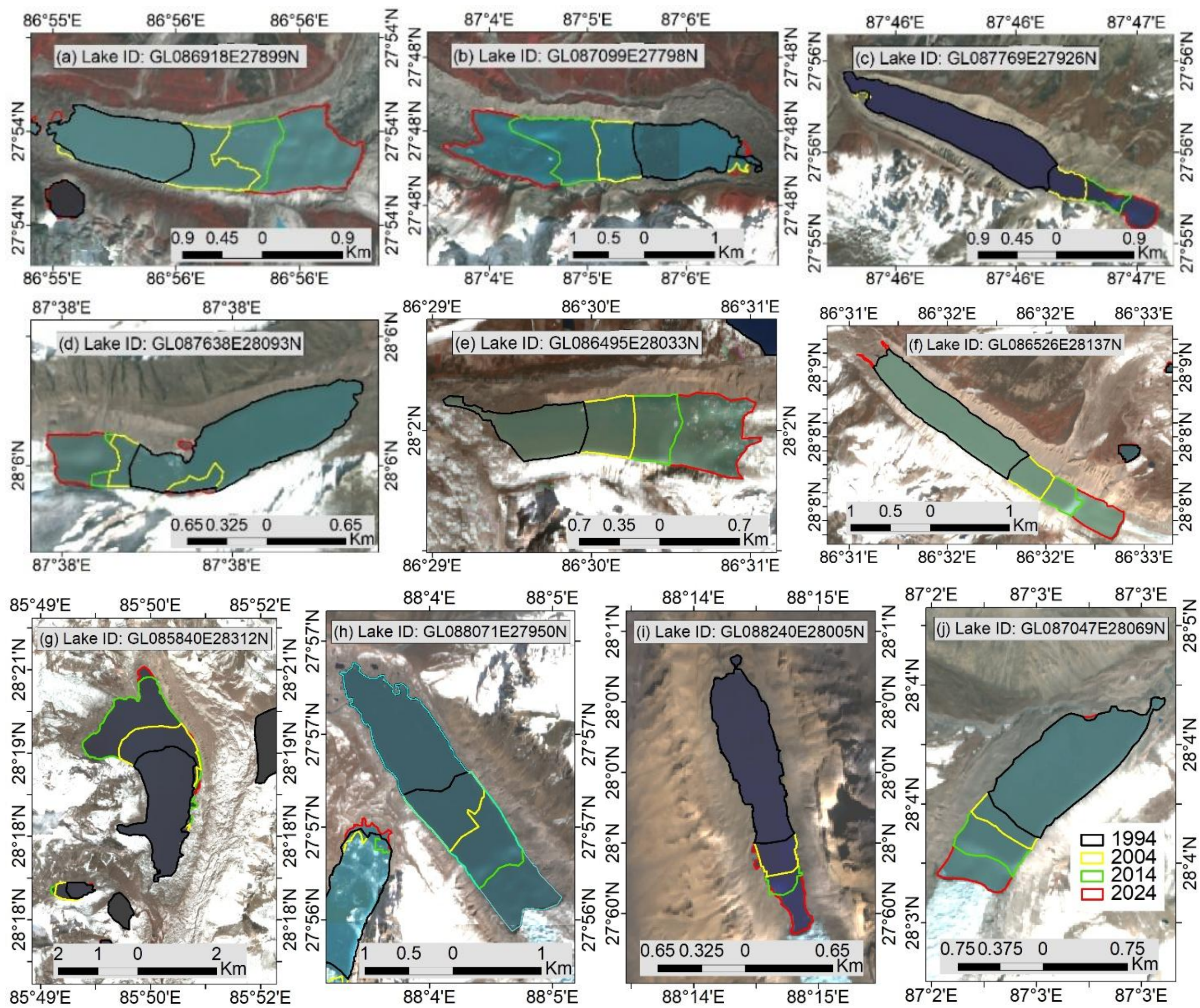

Fig 2: Surface area changes for some of the glacial lakes between 1994 and 2024.

The updated inventory for this study reveals a detailed altitudinal distribution of 755 glacial lakes. The vast majority are concentrated at high elevations: only one lake exists between 3500–4000 m, followed by 24 lakes from 4000–4500 m. The number increases sharply to 168 lakes in the 4500–5000 m band. The highest concentration of lakes is found between 5000–5500 m, with 444 lakes, after which the number decreases to 118 lakes in the 5500–6000 m zone.

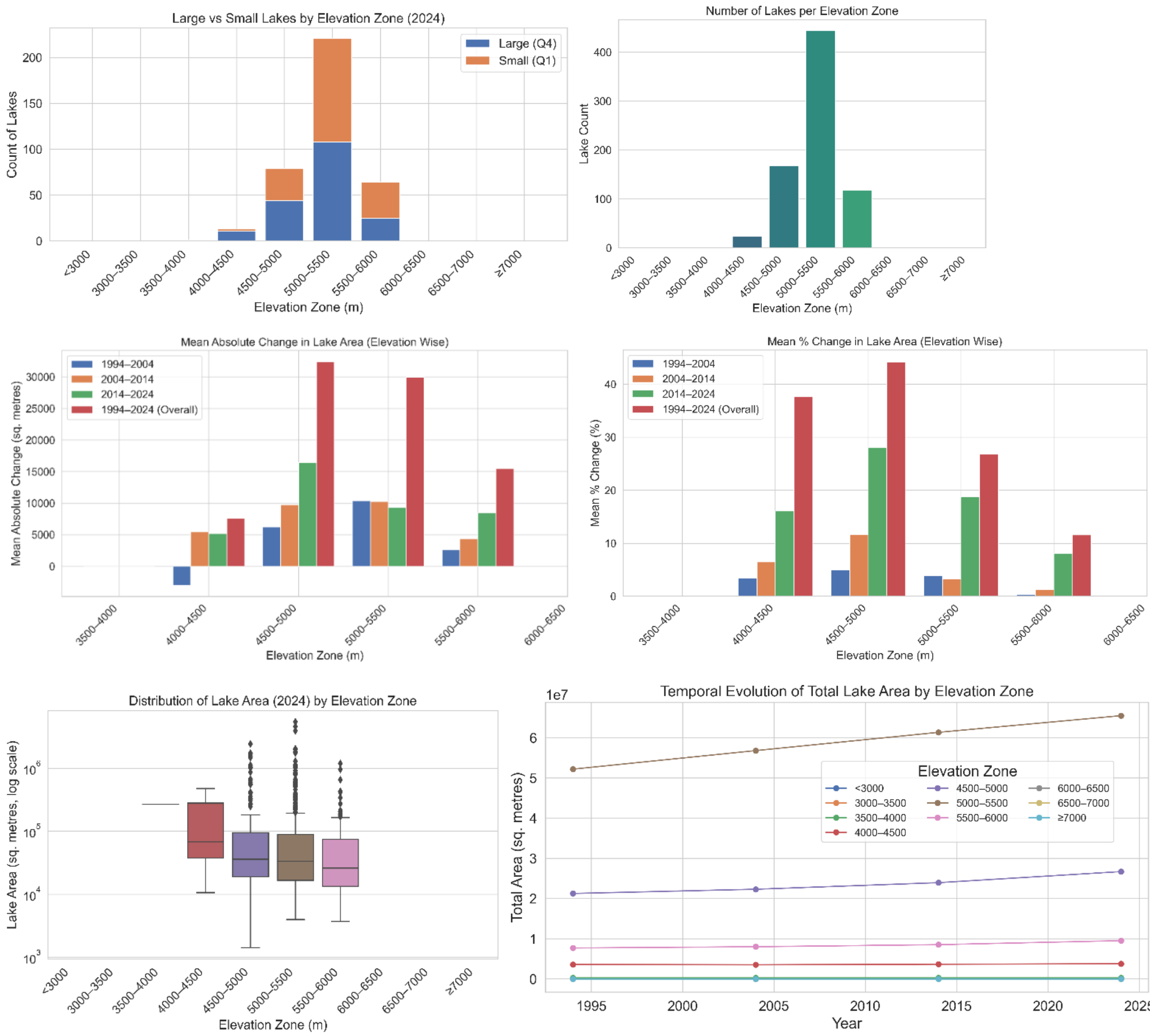

Fig 3: (A) Large vs small lakes by elevation zone (2024). (B) Number of lakes per elevation zone (2024) (C) Mean absolute change in lake area. (D) Mean percentage change in lake area (elevation wise) (E) Distribution of lake area by elevation (2024). (F) Temporal Evolution of total lake area by elevation zone.

Analysis of lake area change over the past three decades highlights an accelerating expansion, particularly in key elevation bands. The 4500–5000 m zone, for instance, has witnessed a dramatic and accelerating rate of growth. The mean percentage change in lake area for this band was 4.99% between 1994 and 2004, which more than doubled to 11.67% in the following decade (2004–2014). This trend has intensified significantly, with a mean change of 28.08% recorded between 2014 and 2024. This represents a cumulative expansion of 44.22% from 1994 to 2024, indicating that these mid-to-high altitude lakes are responding rapidly to climatic shifts, thereby increasing the region's overall GLOF hazard potential The spatial distribution of these lakes reveals a strong clustering in the eastern sub-basins, particularly along the Arun and Tamor tributaries, which coincide with higher glacier density and steep valley topography. Further glacial lakes with an area of ≥ 0.05 km² were selected, resulting in a total of 299 lakes for susceptibility analysis to a potential

GLOF event in the future. This threshold of ≥ 0.05 km² is consistent with multiple other GLOF susceptibility analysis around the world including the Himalayas (Prakash and Nagarajan, 2017).

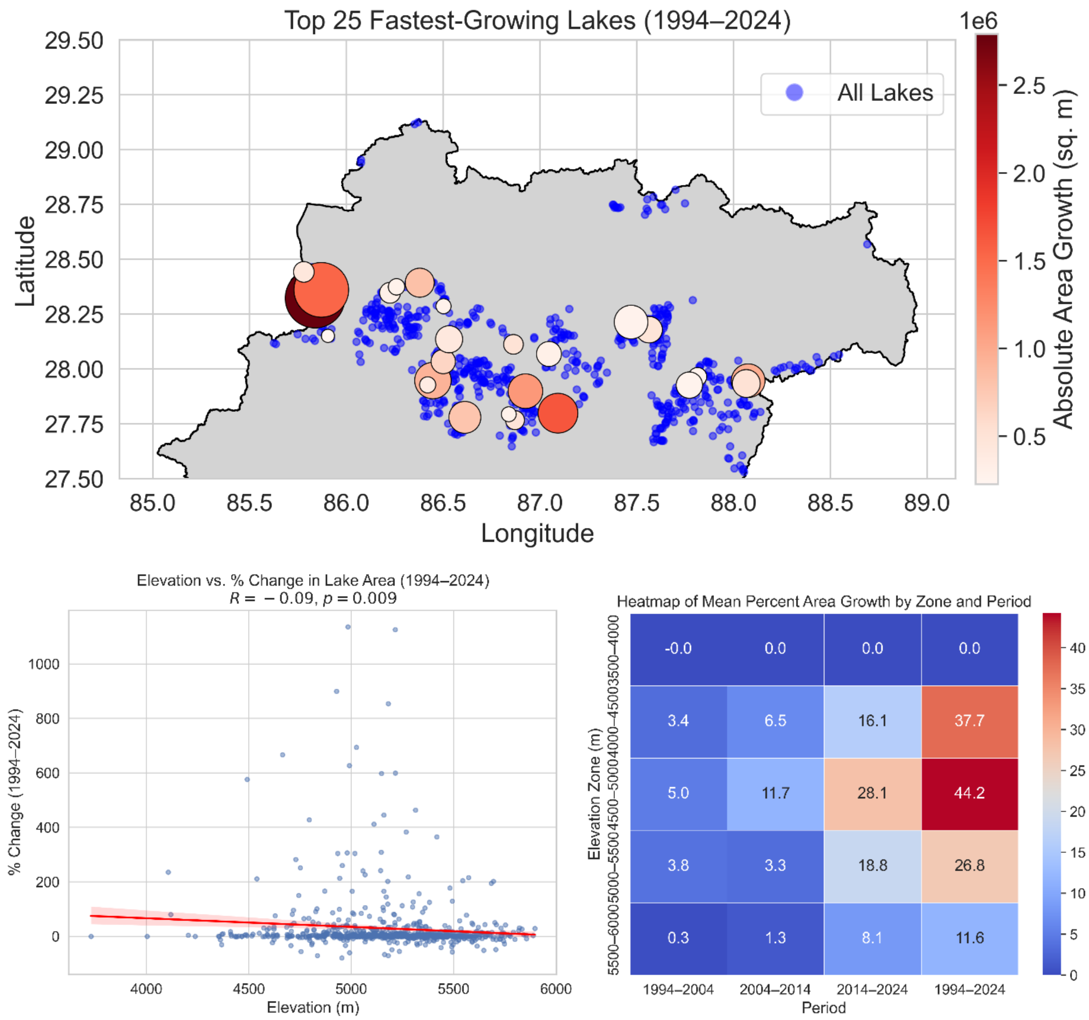

Fig 4: (A) Top 25 fastest growing lakes (B) Elevation Vs change in lake area (1994-2024) (C) Heatmap of mean percent area growth by zone and period.

4.2. Glacial Lake Dynamics

Our analysis reveals that over 60% of the lakes were in direct contact with glaciers, indicating a increase potential for lake growth due to constant meltwater supply from the glacier. Our analysis further revealed that many lakes are located along moderate to high downstream slopes (>15°), which, when combined with low moraine crest width-to-height ratios (F5), may indicate structural vulnerability of moraine-dammed lakes.

4.3 GLOF susceptibility

Table 4. Glacial lakes (>0.05km^2) with highest GLOF susceptibility rank in the Koshi basin.

GLAKE_ID	Susceptibility Index	Susceptibility Class	Longitude	Latitude
GL088049E27544N	0.768194	Very High	88.04999243	27.54527654
GL087581E27681N	0.723150	Very High	87.58298239	27.68153468
GL087740E27823N	0.718640	Very High	87.74080436	27.82319993
GL086952E27782N	0.716611	Very High	86.95785055	27.78339859
GL087720E27799N	0.712495	Very High	87.72017201	27.79945418
GL086951E27840N	0.710742	Very High	86.95132928	27.84045422
GL086565E27833N	0.705513	Very High	86.56503757	27.83315861
GL087940E27736N	0.702851	Very High	87.94140944	27.73676283
GL086839E27791N	0.701335	Very High	86.83901381	27.79325046
GL087631E27796N	0.700730	Very High	87.63129338	27.79689586
GL087100E27834N	0.699454	Very High	87.10034738	27.83475716
GL086975E27711N	0.697088	Very High	86.97749417	27.71110057
GL086791E27696N	0.696696	Very High	86.79198916	27.69648678
GL086928E27850N	0.696488	Very High	86.92832519	27.85012401
GL086913E27894N	0.695772	Very High	86.91375831	27.89393439
GL086682E27895N	0.694258	High	86.68292572	27.89588763
GL087632E27675N	0.693565	High	87.6331261	27.67544274
GL087081E27845N	0.688895	High	87.08181306	27.84496524
GL086675E27920N	0.688415	High	86.67526304	27.92071973
GL087302E27937N	0.688277	High	87.30347076	27.93822264

To analyse the GLOF susceptibility, the factors selected in the present study include lake area, area change rate, glacier to lake distance, Lake to glacier slope, dam freeboard, dam distal face slope, moraine width to height ratio, seismicity, extreme precipitation events and elevation. A relative weight was assigned to each factor based on expert judgment and literature. This determined weight reflects its importance in influencing the likelihood of a GLOF event. We then applied a weighted linear combination method, each lake was scored against these factors, multiplied by their respective weights, and aggregated to generate a composite susceptibility index. We used the Jenks natural breaks approach whereby the susceptibility index values were classified into four distinct categories. The resulting distribution showed 150 lakes in the Low class, 89 in the medium class, 45 in the High class, and 15 in the Very High class. Remarkably, lakes classified as Very High susceptibility exhibited critical characteristics such as large storage volume, unstable moraine dams, and exposure to extreme precipitation events, which makes them priority sites for monitoring and early-warning measures.

5. Conclusion and Future Scope

Our study has analyzed over 755 glacial lakes from 2024, 2014, 2004 and 1994 and we have found a general increase in each decade followed by the most rapid increase in 2014-2024 decade. Most of the larger lakes were confined to 5000-5500m elevation zones with 59% of the lakes having sizes larger than 1km^2 were confined to 5000-5500m elevation zone. Moreover, we found that the lakes situated in the 5000-5500m elevation zone witnessed the most rapid increase in size.

Furthermore, to conduct the GLOF susceptibility analysis we selected lakes with an area of ≥0.05 km^2 resulting in a total of 299 lakes. Key topographic, seismic, morphometric and climatic parameters for these lakes, were systematically derived using a combination of Google Earth, QGIS, aided by high-resolution satellite imageries and DEMs. These parameters formed a robust foundation for assessing Glacial Lake Outburst Flood (GLOF) susceptibility in a data-sparse, intricate topography and natural and climatic hazard-susceptible Himalayan region.

The GLOF susceptibility was conducted using 10 parameters. The ranks of each parameter were deduced using AHP and the final susceptibility score of each lake was computed. We found that a total of 15 lakes were found to be very highly susceptible, 45 lakes as high susceptible, 89 lakes as medium susceptible to GLOFs while 150 lakes were found to be low susceptible to a potential GLOF event in the near future.

Most of the highly susceptible lakes were located towards the eastern side of the basin. Additionally, majority of these GLOF-Susceptible lakes were in the 5500m - 5000m elevation zone indication that the lakes at higher elevation zones are more susceptible to a potential outburst event in the near future. This work not only addresses the urgent need for region-specific GLOF early warning assessment but also lays the groundwork for integrating remote sensing, hydrological, and probabilistic hazard modeling in future mitigation planning. The prediction component, now underway, will serve as a decision-support layer for disaster preparedness and climate adaptation strategies in the Himalayan region.

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