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Glacier Lake Inventory and Lake Outburst Flood Hazard Assessment in Kanchenjunga Conservation Area, Nepal

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By

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Abstract

This study presents a comprehensive assessment of glacial lakes and land surface temperature (LST) dynamics within the Kanchenjunga Conservation Area (KCA) from 2010 to 2023. The KCA holds significant ecological importance, serving as a critical habitat for diverse flora and fauna, while also playing a vital role in regional hydrological systems. Additionally, its stunning landscapes attract tourists and mountaineers from around the world, further emphasizing the need for understanding environmental changes within the area. Utilizing medium to high-resolution satellite imagery from PlanetScope for glacial mapping and Landsat for LST analysis, the research aimed to achieve two primary objectives: creating an updated inventory of glacial lakes and conducting a thorough assessment of Glacial Lake Outburst Flood (GLOF) hazards associated with these lakes. Focusing on a 200-meter buffer around Randolph Glacier Inventory (RGI) boundaries ensured precise analysis within the glacial zone.

In 2023, a total of 140 glacial lakes covering 3.37 km² were identified, revealing their spatial distribution and characteristics. Of these, 76 were supra-glacial lakes and 27 were proglacial lakes, highlighting their dominance in the region. Analysis of elevation profiles highlighted the prevalence of lakes at higher elevations, while size distribution analysis showed dominance of small to medium-sized lakes, with larger classes contributing significantly to total lake area. Furthermore, the study assessed the trends in land surface temperature (LST), revealing mean temperatures of -8.73°C in 2010, -7.28°C in 2015, and -7.09°C in 2023. These temperature variations have significant implications for glacial melt rates, vegetation dynamics, and local climate patterns.

Additionally, hazard assessment of glacial lakes identified varying levels of GLOF susceptibility, with one lake categorized as 'Very High,' one as 'High,' five as 'Low,' and three as 'Very Low' hazard levels. This assessment was conducted using the Analytic Hierarchy Process (AHP). Overall, this study contributes to understanding the complex dynamics of glacial lakes and LST in the KCA, highlighting the importance of continued monitoring and assessment for informed decision-making and mitigation strategies in the face of changing environmental conditions.

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List of Abbreviations

Abbreviation	Description
DEM	Digital Elevation Model
GEE	Google Earth Engine
GLOFs	Glacial Lake Outburst Floods
HMA	High Mountain Asia
KCA	Kanchenjunga Conservation Area
masl	Meters above sea level
NDWI	Normalized Difference Water Index
NIR	Near-Infrared
PDGLs	Potentially Dangerous Glacial Lakes
RGI	Randolph Glacier Inventory
TAR	Tibet Autonomous Region
WWF	World Wide Fund for Nature

Introduction

The impacts of climate change are increasingly evident, with the global average temperature rising by 1.1 °C between 2011 and 2020 compared to the late 19th century (Pörtner et al., 2022). Nepal, particularly its Himalayan region, faces accelerated climate change, with an annual temperature increase of 0.06 °C (Upadhayaya & Baral, 2020). As the fourth most vulnerable country to climate change (Maplecroft, 2011), Nepal has witnessed temperature spikes, erratic rainfall, unpredictable monsoons, and heightened incidents of storms, landslides, and droughts (Gentle and Maraseni, 2012; Devkota et al., 2013; Khanal, 2014). Among these climate-induced challenges, glacier retreat and Glacial Lake Outburst Floods (GLOFs) emerge as significant threats. Himalayan glaciers have been retreating rapidly since 1970 (Bajracharya et al., 2006), contributing to a 24% reduction in glacier area in Nepal between 1977 and 2010 (Bajracharya et al., 2014a, 2014b). The alarming 31.2% increase in glacial lake area and a notable 15.76% rise in their total number between 2000 and 2020 (Hu et al., 2022) underline the urgency of understanding and mitigating GLOF risks. A 2011 study by ICIMOD reported 24 GLOF events, with 14 occurring in Nepal and 10 linked to flood surges across the China (TAR)–Nepal border (ICIMOD, 2011).

GLOFs pose significant risks in high mountain regions, and their study and identification are essential for effective hazard assessment and mitigation. GLOFs occur when large volumes of water are suddenly released from glacial lakes, leading to catastrophic downstream impacts (Somos-Valenzuela et al., 2015; Harrison et al., 2018). The Himalayan region is particularly susceptible to GLOFs due to its dense distribution of glacial lakes and ongoing glacier retreat (Carrivick and Tweed, 2016; Nie et al., 2018; Veh et al., 2019). Climate warming and environmental instability in high mountain areas have increased the frequency of triggers for

GLOFs, such as snow/ice avalanches and landslides (Ballesteros-Canovas et al., 2018; Clague and Evans, 2000). The presence of glacial lakes, including moraine-dammed, ice-dammed, and bedrock-dammed lakes, further amplifies the risks (Vi et al., 2013). These hazards have emphasized the need to understand the dynamics of glacial lakes, assess their potential for outburst floods, and predict their impacts on downstream areas (Anacona et al., 2015; Carrivick and Tweed, 2016).

Remote sensing technology and Geographic Information Systems (GIS) play pivotal roles in the study of glacial lakes and their associated hazards. These tools prove invaluable due to the remote and inaccessible locations of these lakes (Botch et al., 2008). Satellite imagery has been instrumental in investigating GLOFs across diverse mountainous regions, including the Rockies (Clague & Evans, 2000), Alps (Huggel et al., 2002), high mountains of Asia (Quincey et al., 2007), and the Andes (Emmer & Vilimek, 2014). GLOF studies necessitate a comprehensive approach, encompassing factors such as geomorphology, geology, and historical records (Huggel et al., 2004). The rapid economic growth and population expansion in mountainous regions heighten vulnerability to GLOFs. Despite the challenges associated with field surveys, GIS and remote sensing facilitate the identification and monitoring of glacial lakes (Prakash & Nagarajan, 2017b). These technologies support the creation of structured inventories (Nie et al., 2013), hazard estimation (Wang et al., 2012), and diverse modeling techniques, from empirical formulas (Huggel et al., 2002; McKillop & Clague, 2007) to advanced models such as Rapid Airborne Multibeam Mapping (RAMMS), SOBEK (Westoby et al., 2014), Monte Carlo Least Cost Path (MS_LCP) (Rounce et al., 2017), modified single flow (MSF) (Prakash & Nagarajan, 2017b), and Analytic Hierarchy Process (AHP) (Aggarwal et al., 2017; Prakash & Nagarajan, 2017a). The Himalayan region, witnessing a significant number of GLOF events, is a prime hotspot for such studies, emphasizing the efficiency of remote sensing in unraveling the complexities of glacial lakes and GLOF hazards.

In the Kanchenjunga-Sikkim region, a comprehensive study using Glacier mapping from 2000 Landsat ASTER data revealed a total glacierized area of 1463±88 square kilometers. Significantly, there was a recorded Glacier area loss of 0.50 ± 0.2% per year between 1962 and 2000 (Racoviteanu et al., 2015). Focusing on the more recent period from 1988 to 2017, the effects of this glacier retreat become apparent as deglaciated valleys have visibly expanded by 14.98 square kilometers, marking a substantial increase of 20.95%. This expansion underscores the noticeable recession of glaciers across the broader Kanchenjunga-Sikkim landscape (Kandekar et al., 2022). As glaciers retreat and deglaciated valleys expand, they often give rise to the formation or enlargement of glacial lakes. This study focuses on the KCA within the Kanchenjunga-Sikkim region. Recent mappings by Rounce et al. (2017) identified 11 lakes with areas greater than 0.1 km^2 as hazardous in the KCA region, with two categorized as moderate risk and nine as low risk. Notably, recent GLOF events, such as the one at Nupchu Pokhari, have occurred in lakes categorized as low risk, highlighting the need for enhanced risk assessment methodologies (Byers et al., 2023). Furthermore, Mohan Bahadur's inventory of glacial lakes in the KCA, utilizing Sentinel-2 imagery, identified a total of 303 glacial lakes with a combined surface area of 6.18 ± 0.75 km^2 in 2018. This study revealed traces of five GLOFs, of which only one was previously recorded. With the emergence of smaller glacial lakes alongside larger ones and the increasing urgency for effective GLOF risk mitigation, there is a clear imperative for comprehensive research focusing on smaller lakes and proactive risk management strategies.

This study is designed to achieve two primary objectives. Firstly, it aims to create an up-to-date inventory of glacial lakes within the KCA as of the year 2023, utilizing medium to high-resolution satellite imagery obtained from Planet Labs. Secondly, it seeks to conduct a thorough assessment of GLOF hazards associated with these lakes.

In the GLOF hazard assessment, a threshold value of $A > 0.05$ km^2 will be applied, drawing on recent GLOF events documented in Nepal (Byers et al., 2018) and the Indian Himalaya (Das et al., 2015; Rafiq et al., 2019), which occurred in lakes with areas < 0.1 km^2. This approach is supported by prior research advocating for the adjustment of threshold values (Nie et al., 2018; Veh et al., 2019; Khadka et al., 2021).

The assessment process involves the identification of key influencing factors, their prioritization, and the assignment of weights using the AHP method. Values for these influencing factors will be computed for each glacial lake, utilizing a combination of visual interpretation and statistical equations. The selected parameters for GLOF susceptibility assessment have been chosen based on their anticipated widespread recognition in the field, ease of interpretation and measurement through remote sensing, and expected versatility for both quantitative and qualitative evaluation.

Additionally, Land Surface Temperature (LST) analysis will be conducted using Landsat imagery to understand its role in driving mass loss within glacial systems. LST observations help in understanding land surface physical processes and estimating air temperature, particularly in mountainous regions (Zhang et al., 2018). Integrating LST analysis into this study will provide valuable insights into the environmental dynamics affecting glacial lakes and their associated hazards within the KCA, ultimately contributing to informed decision-making processes aimed at safeguarding downstream communities.

Study Area

The Kanchenjunga Conservation Area (KCA) covers 2,035 square kilometers in Nepal's Taplejung district. It hosts Mount Kanchenjunga, the world's third-highest peak, and spans from 27° 28' 48" N to 27° 56' 24" N latitude and 87° 39' 00" E to 88° 12' 00" E longitude. The KCA shares borders with China's Tibetan region to the north, India to the east, and other parts of Nepal to the south and west (Figure 1). Its diverse terrain ranges from 1,200 meters above sea level (masl) to towering heights of 8,586 masl, with summers bringing monsoon rains and winters consistent snowfall (Sherchan et al. 2017). The area maintains a mean annual temperature of 16.15 °C and receives an average annual rainfall of 1,981.4 mm (Bhatta et al., 2018). Around 18% of the KCA's land is covered by 206 glaciers including Yalung (81.91 km^2), Yamatari(14.08 km^2) and Kumbhakarna(18.13 km^2)(Mool et al. (2001)), contributing meltwater to rivers like Tamor, Ghunsa, Kabeli, and Yangma. Notable lakes in the region include Nangama, Tcherchen, Sinjema, and Pabuk. Additionally, the region is host to eleven hydropower stations, currently undergoing surveys and assessments for their environmental impact and sustainability (https://hydro.naxa.com.np/, accessed on: 10/06/2023).

Renowned for its conservation of glaciers and rich biodiversity, the KCA features eleven peaks exceeding 7,000 meters in height. KCA boasts 16% of Nepal's total floral species and seven mammals with conservation significance including the red panda, snow leopard, gray wolf, Himalayan black bear, Himalayan tahr, blue sheep, and musk deer (WWF 2007). It is recognized as a tri-national peace park, envisioned to extend to the TAR of China and Sikkim in India. Designated as a conservation area in March 1998, the KCA integrates biodiversity conservation with sustainable development initiatives (WWF 2007). Due to its unique mountain ecosystem, protected status, and the presence of hydropower infrastructure, the KCA is an essential site for researching GLOFs.

In summary, the KCA is a geographically diverse region with a unique ecosystem, making it a critical area for studying GLOFs and related hazards. This research aims to enhance our understanding of these risks and contribute to more effective hazard assessments within the KCA. The presence of glaciers, diverse flora and fauna, and the conservation efforts in the area underscore its significance not only as an ecological treasure but also as a key region for research that can inform conservation strategies and safeguard the lives and properties of those residing downstream.

Datasets

Optical Images:

Planet Labs, renowned for its high-resolution optical imagery, provides two main datasets: RapidEye and PlanetScope. RapidEye images, with a 5-meter resolution, encompass five spectral bands: blue (400–510 nm), green (520–590 nm), red (630–680 nm), red-edged (690–730 nm), and near-infrared (760–850 nm). PlanetScope images, offering a resolution of 3–4 meters, feature four spectral bands: blue (455–515 nm), green (500–590 nm), red (590–670 nm), and near-infrared (780–860 nm). These datasets were utilized to track changes in glacial lake areas, with images selected from the period between October and December. This selection facilitated more accurate mapping due to reduced cloud cover.

Additionally, to assess land surface temperature (LST) variations, Landsat imagery from different missions was integrated into the analysis. Landsat imagery provides moderate-resolution multispectral data, enabling the monitoring of land surface temperatures over large geographic areas. The specific bands used for LST analysis include the thermal infrared bands: Landsat 7: Band 6 (Thermal Infrared, 10.40–12.50 µm), Landsat 8: Band 10 (Thermal Infrared, 10.60–11.19 µm), and Landsat 9: Band 10 (Thermal Infrared, 10.60–11.19 µm). These bands enable the estimation of surface temperatures, contributing to a comprehensive understanding of environmental changes within the study area.

Glacier Inventory Data:

The Randolph Glacier Inventory (RGI) serves as a comprehensive database of glacier outlines worldwide, excluding ice sheets (Arendt et al., 2017). For this study, the latest version of the Randolph Glacier Inventory, version 7.0 (RGI v7.0) (RGI Consortium, 2023), along with version 6.0, were utilized. These versions offer improved coverage and reorganized flag attributes.

To assess the extent of glacial lakes, a 200m buffer was generated based on the glacier outlines derived from the RGI data. This buffer aims to encompass the majority of glacial lakes closely associated with glaciers in the region while excluding lakes located farther away from the glacier termini.

Digital Elevation Model (DEM):

The 8-meter resolution High Mountain Asia (HMA) 2018 Digital Elevation Models (DEMs) were downloaded from GLIMS (http://glims.org/download/, accessed on: 10/06/2023) to examine the vertical distribution of glacial lakes and derive terrain slope and relief information across the KCA region. Advanced techniques and methodologies, including remote sensing and data analysis, were employed to analyze key parameters such as lake area, distance between the lake and mother glacier, slope characteristics, changes in lake area, presence of lakes upstream or downstream, dam height, and other relevant factors (Bazai et al., 2021; Li et al., 2021). Challenges may arise during the mapping process when distinguishing glacial lakes from mountain shadows due to their similar spectral characteristics. To mitigate the impact of terrain shadows, slope and shaded relief maps derived from the DEM data were utilized.

Methods

Glacial Lake Mapping:

This research employed an enhanced method for extracting glacial lakes, specifically addressing challenges related to snow and shadow differentiation (Qi et al., 2020; Chen et al., 2017; Xu et al., 2006). The NDWI method was utilized, applying the formula (BGreen - BNIR)/(BGreen + BNIR) with the green and near-infrared bands to enhance water body identification (Xu et al., 2006). The methodology (Appendix 1) involved preprocessing PlanetScope satellite data and extracting potential glacial lake areas based on the NDWI threshold. NDWI was employed for glacial lake detection, leveraging its sensitivity to water content in the landscape. Initially, satellite images for the study area were clipped by the extent of the 200m buffer around the glacier and combined into a time-series dataset with a consistent time interval.

Furthermore, topographic shadows were identified in the back slope of mountains where sunlight was significantly obstructed. These shaded areas exhibited large surface gradients but small terrain reliefs. Detection of topographic shadows involved using slope (>10°) and shaded relief maps (<0.25) derived from DEM data (Li and Sheng, 2012; Quincey et al., 2007). The extraction of glacial lake polygons included setting a threshold value of Area > 0.001 km^2 to exclude insignificant water pixels and small patches that could lead to misclassifications.

Following the automatic mapping of glacial lakes, an interactive quality control process was implemented to correct any remaining errors in the mapping results. Mountain shadows and partial streams incorrectly classified as glacial lakes were manually removed by overlaying and visually assessing the extracted glacial lake boundaries onto the original satellite images. Furthermore, any missing glacial lakes were added using ArcGIS during the visual inspection.

This meticulous manual correction process ensured the accurate refinement of glacial lake polygons (Nie et al., 2017; Ahmed et al., 2022).

The accuracy of glacial lake extraction was influenced by various factors, including image quality, resolution, and registration (Paul et al., 2004; Hall et al., 2003). Addressing these challenges was crucial in this study due to the limited availability of high-quality remote sensing data and the complex topography of the glacial lake and glacier distribution area in Nepal. Additionally, the interpretation of remote sensing images introduced potential errors, particularly when dealing with mixed pixels that could include or exclude up to 50% of a feature.

To estimate the area uncertainties associated with glacial lakes, the method proposed by Wang et al. (2012) was employed. This method accounted for uncertainties arising from mixed pixels at the boundaries of lakes. The area uncertainty was calculated using Equation (1):

$$Q_a = \frac{\lambda^2 \text{ p}}{\mathbf{2}\sqrt{\lambda^2+\lambda^2}}$$

$$= \frac{\lambda\, p}{\mathbf{2}\sqrt{2}} \qquad \text{---------------}\ \mathbf{(1)}$$

where Q_a is the absolute area accuracy; λ is the spatial resolution of the satellite image; and p is the perimeter of the polygon.

The relative area accuracy, Q_r, is calculated as follows:

$$Q_r = \frac{Qa}{\boldsymbol{Ag}} \qquad \text{---------------}\ \mathbf{(2)}$$

where A_g is the area of the polygon.

By incorporating this approach, a comprehensive accuracy assessment of the glacial lake extraction results was provided, considering the limitations of the data and challenges associated with pixel interpretation.

Glacial Lake Water Storage Calculation

All glacial lakes in KCA are situated in elevated regions, which complicates field investigations significantly. This study employed the glacial lake area-volume calculation formula proposed by Qi et al. (2022) to ascertain the water storage capacity of each glacial lake. This formula (**Equation 3**) is practical for estimating the water storage of glacial lakes in Nepal because it's derived from measurements of 35 glacial lakes in the Himalayan region.

$$V = \begin{cases} 40.67 \times A^{1.184} - 3.218 \times Ratio_{(mxw/mxl)} & (A > 0.1km^2) \\ 40.67 \times A^{1.184} - 3.218 \times Ratio_{(mxw/mxl)} & (A > 0.1km^2) \end{cases} \quad \text{---------- } \mathbf{(3)}$$

where V represents the volume of water stored in the glacial lake (10^6 m³), A signifies the surface area of the glacial lake (km²), and the $Ratio_{(mxw/mxl)}$ denotes the ratio between the width and length of the smallest rectangle that fully encloses the glacial lake.

Land Surface Temperature (LST) Estimation using Landsat Imagery and Google Earth Engine

The process of estimating LST involved the utilization of Landsat 7, Landsat 8, and Landsat 9 imagery within the GEE platform, encompassing several key steps to ensure accuracy and reliability. Initially, Landsat image collections for the respective years, including 2010, 2015, and 2023, were filtered based on predefined temporal and spatial parameters to capture relevant data for the analysis. Cloud cover was effectively mitigated through robust filtering processes to maintain data quality. Subsequently, the selected imagery was median-composited and clipped to the study area boundaries to facilitate further analysis (Appendix 2).

Following preprocessing steps, the thermal infrared bands (Band 10 for Landsat 8 and Landsat 9, Band 6 for Landsat 7) were isolated from the Landsat imagery to enable temperature calculation. Employing the derived digital numbers from these bands, the formula for LST computation was applied, yielding temperature values in degrees Celsius. The standardized formula $LST=(DN\times0.00341802)+149-273.15$ was utilized for temperature calculation, where "DN" represents the digital number acquired from the respective thermal infrared bands (Puche et.al, 2023).

Upon computing LST, mean temperature values were obtained for each year of interest by reducing the region of interest to the 200m buffer of RGI and computing the average LST using GEE available functions. The resulting LST maps were then visualized alongside true-color imagery to provide comprehensive contextual information. Furthermore, to facilitate further analysis and dissemination, the LST maps and true-color images were exported to Google Drive. This methodology ensured the accurate estimation of LST while leveraging the capabilities of Landsat imagery and GEE for efficient data processing and analysis.

Identification of Potentially Dangerous Glacial Lakes

Various studies have proposed diverse sets of variables aimed at identifying and predicting PDGLs. Lu et al. (1999) put forth a specific set of 7 variables for PDGL prediction in Tibet, while McKillop Chague (2007) compiled 18 parameters from global moraine dam failure cases. Wang et al. (2011) focused on key factors such as mother glacier area, distance between the lake and glacier terminus, slope between the lake and glacier, mean slope of the moraine dam, and mother glacier snout steepness. Bolch et al. (2012) devised a General Workflow that allocated weights to various parameters for PDGL classification. Emmer and Vilimek (2013) conducted an exhaustive review of methods, elucidating the merits and limitations of each approach. Che et al. (2014) employed integrated criteria, whereas Kougkoulos et al. (2018) used multi-criteria decision analysis for PDGL identification.

In the Himalayan region, several studies have delved into parameters pertinent to glacial lake hazards. Investigations by Huggel et al. (2004), Fujita et al. (2013), Westoby et al. (2014), and Prakash and Nagarajan (2018) underscore elements such as lake area, lake connection with the feeding glacier, presence of supraglacial lakes, slope and dam conditions, seismicity, and topography. Recent studies by Allen et al. (2019), Islam and Patel (2020), Wang et al. (2021), and Zhang et al. (2022) have further scrutinized parameters like lake size, upstream watershed area, distal slope of the dam, connection with river channels, potential for ice and rock avalanches, and probable landslide zones. Collectively, these studies emphasize the importance of considering a multitude of parameters and their corresponding weights when assessing the hazard potential of glacial lakes, particularly in regions like the Himalayas, where the risk of GLOFs is high.

Consistently, factors such as lake area, expansion, downstream slope, slope between the glacial lake and mother glacier, and presence of supraglacial lakes have been recognized as pivotal indicators of potential hazards. Moreover, several studies have incorporated supplementary parameters, including lake depth, downstream characteristics, higher elevations, presence of ice cores, and dam conditions, to enhance the precision of PDGL identification. This comprehensive exploration underscores the complexity of assessing glacial lake hazards and highlights the need for meticulous consideration of a diverse array of variables. These endeavors not only enhance our understanding but also contribute to improved hazard assessment and risk mitigation strategies, bolstering the safety and resilience of vulnerable regions susceptible to the impacts of changing climatic conditions.

Table 2 provided a brief detail of the nine criteria along with their critical subclass values that were selected. In alignment with the chosen suitability criteria and by referring to various criteria utilized in previous studies worldwide, the AHP method was used to calculate criteria weights. AHP served as an effective tool in multicriteria decision-making, establishing a systematic hierarchy among the chosen criteria through pairwise comparisons. The methodological framework employed is presented in **Appendix 3**. It comprehensively integrated the concept of uncertain elements in judgments by employing established methods such as the consistency index and principal Eigen values (Saaty, 2004).

To establish criteria weights, a pairwise comparison matrix was generated, with higher values assigned to criteria considered to have a greater impact on GLOF hazard, and lower values attributed to those with lesser influence. This matrix was subject to normalization to compute the weights for the chosen criteria and indicators. To ensure the method's reliability in subsequent applications, the consistency index (CI) and consistency ratio (CR) were calculated using established equations. The CI was calculated as **Equation 4**, where λmax represented the largest Eigen value of the pairwise comparison matrix, and n was the number of classes.

$$CI = \frac{\lambda max - n}{n-1} \quad ---------- \quad (4)$$

The CR was calculated as **Equation 5**, with RI denoting the random index (1.45 for n = 9). For the results to be considered valid, the CR value had to be below 0.1, necessitating adjustments to the matrix until consistency was achieved.

$$CR = \frac{CI}{RI} \qquad \text{----------} \qquad (5)$$

The CR value for the pairwise comparison in our matrix was found to be 0.09, which demonstrates that the pairwise comparison matrix is consistent. Three Critical Class index values (Ci values) of 1, 0.5 and 0.25 were picked for each of the criteria (Prakash and Nagarajan, 2017). The GLOF Susceptibility Index was calculated as **Equation 6**, where C_i stood for the criteria index, and W_i denoted the criteria weight.

$$\text{GLOF Susceptibility Index} = \sum_{i=0}^{n}(Ci * Wi) \qquad \text{----------} \qquad (6)$$

For this research, the following parameters were considered:

Criteria associated with Lake:

i. Lake area: The lake area was assessed to determine its size. This parameter was crucial in understanding the potential impact of a GLOF as larger lakes could store more water, leading to more severe floods (Huggel et al., 2004).

ii. Expansion rate: The expansion rate of the lake over a 13-year period was examined to identify significant changes in its size. Lakes that had expanded by more than 100% were considered at higher risk of GLOFs (Bolch et al., 2011; Aggarwal et al., 2017).

iii. Connection with glacier and river channel: The direct connection between the glacial lake, glacier snout, and river channel was investigated as it played a crucial role in facilitating water discharge during GLOF events. This connection provided a quick pathway for water transfer from the lake to the river, intensifying flood impacts (Wang et al., 2021; Islam and Patel, 2020; Rayees et al., 2022).

Criteria associated with Dam:

These criteria significantly influenced the susceptibility of dam breach during GLOF events.

iv. Dam type: Among different dam types, moraine-dammed lakes were given the highest preference as they were considered most prone to GLOFs. Moraine dams, composed of semi-consolidated material, could easily breach when triggered by GLOF phenomena (Westoby et al., 2015). Although there have been notable instances of GLOFs from ice-dammed lakes, bedrock-dammed lakes generally had a lower likelihood of experiencing dam breach (Vilímek et al., 2015). Therefore, this study assigned a lesser preference to bedrock-dammed lakes.

v. Dam front slope: The assessment also involved measuring the dam front slope, utilizing slope maps derived from the high-resolution DEM and terrain profiles extracted from Google Earth imagery. Quantifying the dam front slope, which identified steep or gentle slopes, provided insights into the stability of moraine dams and the potential for GLOFs.

Criteria associated with Feeding Glacier:

vi. Slope difference between glacier snout and lake outlet: This criterion aimed to understand the influence of the feeding glacier on glacial lake dynamics. A higher slope difference between the glacier snout and the lake outlet suggested that the lake was more likely to overflow its bounds, potentially leading to GLOFs. The steeper the slope difference, the greater the pressure on the lake's containment, increasing the risk of sudden releases of water. This parameter was evaluated using DEM to assess the relationship between the glacier and the lake and its implications for potential hazards (Wang et al., 2011).

vii. Proximity of glacier to the lake: This criterion considered how closely the feeding glacier was connected to the lake's snout and played a significant role in influencing the overall stability and behavior of the lake. A close connection between the glacier and the lake may also lead to increased ice melt, affecting the lake's water level and contributing to its dynamic changes. The extent of both the glacial lake and the feeding glacier was digitized using remote sensing imagery to analyze their spatial relationship. This information provided valuable insights into the interaction between the feeding glacier and the glacial lake, aiding in the assessment of potential hazards and dynamics associated with glacial lakes.

Criteria associated with the Environment:

viii. Presence of a supraglacial lake or other type of a lake in the upstream region: This parameter evaluated whether there was a glacial lake situated in the immediate upstream region of the target glacial lake. This assessment was crucial as the presence of a lake upstream could significantly increase the risk of dynamic failures and GLOFs (Islam and Patel 2022). Potential mass movements, such as avalanches, rockfalls, or GLOFs, in the upstream portion could pose a threat to the stability of the target glacial lake. By understanding the proximity and interaction between the two lakes, this parameter aided in identifying potential hazards and enhanced the overall assessment of glacial lake dynamics.

ix. Probability of Rock/Ice Avalanche: The "Probability of Rock/Ice Avalanche" parameter quantified the likelihood of probable ice or rock avalanches occurring in the vicinity of the target glacial lake. To assess this probability, two main factors were considered: slope angles and trajectories. Slopes with angles greater than 30°, whether covered by hanging ice or bedrock, were recognized as potential triggers for avalanches (Rounce et.a.,2017). Additionally, slopes with an overall trajectory exceeding 14° were deemed significant in determining the potential for avalanches to reach the glacial lake. By categorizing the presence of probable ice/rock avalanches as either "Yes" or "No," this parameter provided valuable insights into the likelihood of such events impacting the stability of the glacial lake and contributing to GLOFs. This consideration enhanced the overall understanding of the hazard assessment and helped identify potential triggers GLOFs.

Results

Glacial Lake Inventories and Database:

Spatial Distribution of Glacial Lakes:

In 2023, there were 140 glacial lakes with an area of ≥ 0.001 km² in KCA, having a total area of 3.37 km², an average area of 0.024 km². The water storage of glacial lakes was 76.55×10^6 m^3. Only four glacial lakes were larger than 0.2 km^2, of which the largest glacial lake was the Nagma Pokhari (87°51'55"E, 27°52'3"N), with an area of 0.67 km^2 and a water storage of 22.84×10^6 m^3.

Regarding the elevation profile of these lakes, 4 lakes with a combined area of 0.05 km² are found at elevations above 5,500 masl. Additionally, 73 lakes with a total area of 1.44 km² were found to be at elevations between 5,000 to 5,500 masl, and 51 lakes with a total area of 1.84 km² were found to be at elevations between 4,500 masl to 5,000 masl. Furthermore, 12 lakes with a combined area of 0.05 km² were found between 4,000 masl and 4,500 masl, and no lakes were found at elevations below 4,000 masl. This depicts an increasing inclination in the number of glacial lakes with elevation up to a certain level, after which the frequency decreases again. The largest number of glacial lakes is found in the elevation range of 5000-5500 masl. **Fig. 2** shows the trend of lakes in different elevation classes. In the middle Himalayas, the snow line lies within the range of 5800 to 6000 meters (X LI, 2021). This region experiences vigorous melting of glaciers and snow, which facilitates the expansion and formation of glacial lakes at altitudes ranging from 4500 to 5500 meters.

The glacial lakes were also analyzed with respect to their size (area). Five different lake size classes were created with areas less than 0.01 km², ranging from 0.01 to 0.05 km², from 0.05 to 0.1 km², from 0.1 to 0.2 km², and greater than 0.2 km². The results show that the highest number of lakes fall into the size class of 0.001-0.01 km², followed by the size class of 0.01 to 0.05 km², indicating the dominance of small and medium-sized lakes (A < 0.05 km²) in the region. However, the larger size classes, despite having the least number of lakes, contribute the highest to the total glacial lake area. The largest two classes contain only 10 lakes but contribute 68.3% to the total glacial lake area of the conservation area, indicating marked disparities in the size distribution of these lakes **(Fig. 3).**

Classification of Glacial Lakes:

Among these lakes, 4 were categorized as non-Glacier fed lakes, totaling an area of 0.05 km². Proglacial lakes constituted the largest proportion, with 27 lakes covering an area of 1.28 km². Additionally, there were 76 supraglacial lakes spanning 0.40 km², and 33 unconnected glacier-fed lakes occupying 1.64 km². These results reveal the varied distribution of glacial lakes in the KCA in 2023 **(Fig.4).** Understanding their locations and features is crucial for assessing risks, especially regarding GLOFs. **Fig. 5** displays the detailed distribution and sizes of these lakes, providing important geographic insights. Additionally, the presence of only 4 large glacial lakes, each with areas exceeding 0.2 km², underscores the relatively limited occurrence of such sizable water bodies within the region.

Spatio-temporal Evolution of Glacial Lakes from 2010 to 2023:

The investigation into the spatio-temporal evolution of glacial lakes within the study area, utilizing datasets from RapidEye and PlanetScope, revealed significant changes from 2010 to 2023. The analysis focused on glacial lakes exceeding 0.001 km² within a 200-meter proximity to RGI glacier boundaries within the KCA. In 2023, the total area covered by glacial lakes in the region was 3.37 km², marking a noteworthy 110.62% increase from the Hi-MAG inventory in 2017, demonstrating rapid growth over just six years. Over the span of 13 years, from 2010 to

2023, the lake area expanded from 2.89 km^2 to 3.37 km^2, representing a 17.30% increase. The number of glacial lakes with areas greater than 0.001 km^2 rose from 113 in 2013 to 140 in 2023, showing a net increase of 23.89% over the period. Additionally, the water storage capacity of these lakes increased from 69.97 $\times 10^6$ m^3 to 76.55 $\times 10^6$ m^3, marking a 9.40% increase over time **(Fig. 6).**

The analysis of glacial lake distribution within the KCA from 2010 to 2023 reveals significant transformations in the prevalence of different lake types. In 2010, supraglacial lakes were the predominant category, constituting 55% of the total lakes (62 out of 113). By 2015, the total number of lakes increased to 129, with supraglacial lakes maintaining dominance at 56% (72 lakes). In 2023, the total number of glacial lakes rose to 140, with supraglacial lakes continuing to dominate at 55% (76 lakes) **(Fig. 7).** From 2010, the number of unconnected glaciers decreased from 27 to 22 in 2015 and further to 21 in 2023. Similarly, the count of proglacial lakes decreased from 20 to 16 in 2015 and then to 14 in 2023. The 62 supraglacial lakes in 2010 decreased to 15 in 2015 and 10 in 2023. Moreover, 4 of the non-glacier-fed lakes from 2010 decreased to 3 in both 2015 and 2023. Overall, the total number of lakes decreased from 113 in 2010 to 56 in 2015 and 48 in 2023. Interestingly, compared to 2010, 2023 witnessed the emergence of 12 new unconnected glacial lakes, 13 new proglacial lakes, 66 new supraglacial lakes, and one new non-glacial-fed lake **(Fig. 8).** The significant proportion of newly emerged supraglacial lakes in 2023 is notable, given their substantial presence. However, it is equally striking that a considerable number of these lakes have vanished over the years. This observation underscores the dynamic nature of glacial landscapes and highlights the complex interplay between glacial retreat and the formation and disappearance of supraglacial water bodies.

Land Surface Temperature (LST):

The mean LST for the years 2010, 2015, and 2023 was -8.73°C, -7.28°C, and -7.09°C, respectively. Notably, the temperature decrease was more pronounced between 2010 and 2015, as evident in the data, correlating with a significant change in water storage during the same period **(Fig. 9).** However, the temperature change between 2015 and 2023 was relatively lower compared to the previous period, despite consistent changes in water storage. This suggests a more complex relationship between temperature variations and glacial lake dynamics than initially anticipated, highlighting the need for further investigation into the underlying mechanisms driving these changes.

Moreover, these temperature changes exhibit a strong relationship with key parameters such as lake area, water storage, and the number of lakes in the vicinity. As depicted in the **Table 3** from 2010 to 2023, while the LST experienced a decline, the lake area expanded, and the number of lakes increased. This suggests a complex interplay between temperature variations and glacial lake dynamics, emphasizing the need for a comprehensive understanding of these relationships for effective environmental management.

Additionally, the observed temperature changes can inform future research and conservation efforts aimed at mitigating the effects of climate change on vulnerable environments. Furthermore, it's important to note that the LST analysis was conducted solely within the 200m buffer area of the RGI boundaries, ensuring a focused examination of the region surrounding the glaciers. **Fig. 10** showcases three different LST images corresponding to the years 2010, 2015, and 2023, providing a visual comparison of temperature distribution across the study area during different time periods. These visual representations offer valuable insights into the spatial and temporal variations in land surface temperature, contributing to a comprehensive understanding of the environmental dynamics within the region.

Hazard Assessment of Glacial Lakes:

In the evaluation of glacial lakes for potential hazards in 2023, 10 lakes with an area greater than 0.05 km² underwent multi-criteria hazard assessment using the AHP. Among these lakes, the distribution of GLOF susceptibility scores varied, indicating different levels of risk. Specifically, one lake was classified with a very high level of GLOF susceptibility, one with high susceptibility, five with low susceptibility, and three with very low susceptibility **(Fig 11).**

Lakes categorized as 'Very Low' hazard displayed notable patterns such as negative expansion rates, bedrock dams, minimal dam front slope gradients, and no upstream lake presence. These characteristics suggest reduced risk of sudden water volume increase and GLOFs. Conversely, lakes categorized as 'High' hazard exhibited larger areas, faster expansion rates, primarily moraine dams, and glacier proximity, collectively highlighting heightened risk of hazardous events. Lake 278813KCA878052, classified as 'Very High' hazard, showed moderate size and expansion rate but is connected to a glacier and dammed by a moraine. Its high susceptibility to avalanches further elevates the risk of glacial lake outburst floods, emphasizing the urgent need for monitoring and management **(Table 4)**.

The findings underscore the complex interplay of environmental factors in shaping the hazard levels of glacial lakes. While glacier proximity played a significant role, other factors such as dam type, slope gradients, and expansion rates also contributed to the varying levels of risk associated with these lakes. This comprehensive assessment provides valuable insights for understanding and mitigating potential hazards associated with glacial lakes.

Discussion

The dynamic nature of glacial lakes within the KCA and their susceptibility to GLOFs are highlighted in this study. Through a comprehensive analysis of parameters such as lake area, expansion rate, proximity to glaciers, and susceptibility to hazards such as rockfall, avalanches, and landslides, insights into the evolving risks posed by glacial lakes in the Himalayan region are provided. The inventory conducted in 2023 revealed a significant increase in both the total area and number of lakes compared to previous assessments in 2010, underscoring the urgent need for proactive GLOF risk mitigation in vulnerable mountainous regions. Furthermore, the analysis of LST indicates a warming trend in the region, suggesting ongoing climate change dynamics. The observed increase in temperature may have significant implications for glacial melt rates, vegetation dynamics, and local climate patterns, further exacerbating the risks associated with glacial lake expansion and GLOFs. It is imperative to consider these temperature variations in conjunction with other environmental factors when assessing the impact of climate change on glacial lake dynamics and implementing effective mitigation strategies.

Moreover, the integration of remote sensing technology, particularly high-resolution PlanetScope images with resolutions of 3 meters and 5 meters, and Geographic Information Systems (GIS) played a crucial role in inventorying and assessing the hazard of glacial lakes within the KCA. Additionally, it is noteworthy that this study included lakes within a 200-meter buffer area of the RGI glacier boundaries, addressing limitations observed in previous studies. By utilizing high-resolution PlanetScope imagery, the aim was to overcome these limitations and provide a more comprehensive assessment of glacial lakes within the KCA.

A comparative study on hazardous glacial lakes was conducted, analyzing findings alongside research by Rounce et al. The investigation revealed notable variations in hazard assessments.

Lahare Taal, previously deemed high-risk, has since been downgraded to very low risk. Similarly, Nangma Pokhari, initially categorized as medium risk, now presents low risk. Interestingly, both lakes have maintained consistent sizes since 2010. Our study, spanning 2010 to 2023, contrasts with Rounce's analysis, potentially explaining discrepancies observed. In addition to the comparative analysis, specific case studies were examined, building upon previous research. Nupchu lake, which experienced flooding in August 2022(Byers et al., 2023)., exhibits low hazard, likely due to decreased size post-flood. Conversely, despite minor expansion, Tilpile Taal presents elevated risk factors due to the presence of an upstream lake and a steep dam slope, which may increase the likelihood of avalanches. Also, lake with ID 278453KCA879625 is classified as high hazardous due to the high expansion rate. Regular monitoring of glacial lakes is imperative for early detection of changes and timely warnings to downstream communities, enhancing safety measures.

Conclusion

1. In 2023, the KCA region hosted 140 glacial lakes with areas ≥0.01 km², totaling 3.37 km² in area, with an average size of 0.024 km², and a combined water storage of approximately 76.55×10^6 m³. Predominantly, the number of smaller lakes (<0.01 km²) dominated at 102 (72.85%), while larger lakes (>0.2 km²) accounted for the majority of the total area at 1.51 km² (44.81%). Glacial lake concentration was observed within the altitude range of 4500–5500 m, housing 124 lakes (88.57%) and covering 62.04 km² (97.32%). Supraglacial lakes were the most numerous at 72 (51.42%), while unconnected glacial lakes dominated in terms of area, spanning 1.63 km² (48.37%).
2. Between 2010 and 2013, Nepal witnessed an overall increase in the number, area, and water storage of glacial lakes with areas >0.01 km². The count rose from 113 to 140, indicating a 23.89% increase, with 92 new lakes formed and 65 disappearing. The total area expanded from 2.89 km² to 3.37 km², marking a growth rate of 16.60%. Concurrently, LST increased from -8.73°C to -7.09°C, reflecting a 1.64°C rise over the 13-year period. Glacier retreat, attributed to climate warming, facilitated the formation and expansion of glacial lakes, driving the observed changes in Nepal.
3. The assessment of GLOF susceptibility identified 1 very high, 1 high, 5 low, and 3 very low susceptibility glacial lakes. Among these, the Tilpile lake (LakeID: 278813KCA878052) and the lake with LakeID of 278453KCA879625 pose the greatest risk of outburst flooding to downstream areas. Continuous reinforcement of remote sensing monitoring and basin investigation is essential, alongside the development of corresponding disaster prevention and reduction plans, particularly focusing on lakes situated above human settlements.

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TABLES

Year	Image Acquisition	Image ID	Satellite Name	Resolution
2010	October 8	e63b9cca-733c-4375-828e-b7b0c07553f9	Rapid Eye	5 m
2015	December 04	f7c16205-5bf2-42f5-b84e-3818535f57b1	Rapid Eye	5 m
2023	October 26	c45507e8-f4c8-4bbc-98c6-484e1de93ec6	Planet Scope	3m

TABLE 1 : DETAILS OF THE IMAGES USED IN THIS STUDY.

Category	Criteria	Critical sub-Class Values	Priority for GLOF	Index Values	Methods used	References
Factors associated with the lake	Lake Area	>0.5 0.5 - 0.1 <0.1	High Medium Low	1 0.5 0.25	Satellite Imagery	Khadka et al., 2021
	Expansion rate	>100% 50-100% <50%	High Medium Low	1 0.5 0.25	Satellite Imagery	Bolch et al. 2011; Aggarwal et al. 2017
	Connected with river channel	Yes No	High Low	1 0.5	Google Earth Imagery	Wang et al. 2021
Factors associated with Dam	Type of Dam	Moraine Dam Ice Dam Bedrock Dam	High Medium Low	1 0.5 0.25	Google Earth Imagery	Hegglin and Huggel,2008; Huggel et al. 2004
	Dam front Slope	>10 <10	High Low	1 0.5	DEM Google Earth	Che et al.2014, Ahmed et al.,2022
Factors associated with Mother glacier	Glacier proximity	Connected to snout <100 >100	High Medium Low	1 0.5 0.25	Satellite Imagery Google Earth Images	
	Slope difference between glacier snout and lake outlet	>20° 10° -20° 0-10°	High Medium Low	1 0.5 0.25	DEM, Google Earth, Satellite Imagery	Wang et al. 2011; Islam and Patel 2022
Other relevant factors	Probable Rockfall/Avalanche/Landslide	Yes No	High Low	1 0.5	Google Earth Images DEM	Allen et al. 2019; Islam and Patel 2022; Rayees et al. 2022
	Presence of Lake in upstream region	Yes No	High Low	1 0.5	DEM Satellite Imagery Google Earth	Jain et al. 2012; Che et al. 2014; Mir et al. 2018; Khadka et al. 2021

TABLE 2 : PDGLS FACTORS AND THE WEIGHTING SCHEME FOR AHP ANALYSIS.

Lake ID	Area Km²	Expansion Rate (%)	Connected to River	Type of Dam	DFSG	Distance to Glacier (m)	Lake Type	Slope to Glacier	Upstream Lake	Mass Movement	GLOF Suscep-tibility Index	Hazard Category	Elev (m)	Local Name
278813 KCA 878052	0.364	7.37	Yes	Moraine Dam	15.46	159	Unconnected Glacier-	0	Yes	Avalanche	0.743	Very High	4684	Tilpile Taal
278693 KCA 878664	0.665	-0.59	Yes	Moraine Dam	0	128	Unconnected Glacier-	8.75	Yes	Rockfall / Landslide	0.537	Low	4880	Nangma Pokhari
275451 KCA 880503	0.254	-1	No	Bedrock Dam	9.22	0	Proglacial Lakes	0	No	Rockfall / Landslide	0.472	Very Low	5021	
278161 KCA 877496	0.165	-3	Yes	Bedrock Dam	0	0	Proglacial Lakes	16.11	No	Rockfall / Landslide	0.488	Very Low	4896	Lahare Taal
278219 KCA 877395	0.060	-15	No	Bedrock Dam	14.23	144	Unconnected Glacier-	0	No	Rockfall / Landslide	0.501	Low	5188	

277905KCA879346	0.123	-0.3	No	Bedrock Dam	6.09	198.11	Unconnected Glacier-	44.69	No	Rockfall / Landslide	0.448	Low	4909	Nupchu Pokhari
277936KCA879749	0.228	-12	Yes	Moraine Dam	1.1	0	Proglacial Lakes	0	No	Rockfall / Landslide	0.531	Low	5149	
278011KCA881079	0.055	-1	No	Bedrock Dam	6.42	121.06	Unconnected Glacier-	44.27	No	Rockfall / Landslide	0.448	Very Low	5492	
277366KCA879416	0.053	2.17	No	Bedrock Dam	0	118.93	Unconnected Glacier-	26.46	Yes	Rockfall / Landslide	0.509	Low	5015	
278453KCA879625	0.127	122	Yes	Moraine Dam	5.94	0	Proglacial Lakes	0	No	Rockfall / Landslide	0.643	High	5191	

TABLE 3: DESCRIPTION OF FACTORS USED IN PDGL FOR EACH LAKE

Year	Total Lakes	Lake Area (km^2)	Water Storage (10^6 m^3)	LST (°C)
2010	113	2.89	69.97	-8.73
2015	129	3.05	76.47	-7.23
2023	140	3.37	76.55	-7.09

TABLE 4: TEMPORAL EVOLUTION OF GLACIAL LAKES, DEPICTING CHANGES IN TOTAL NUMBER OF LAKES, LAKE AREA, WATER STORAGE CAPACITY, AND LAND SURFACE TEMPERATURE (LST) IN 2010, 2015 AND 2023.

FIGURES

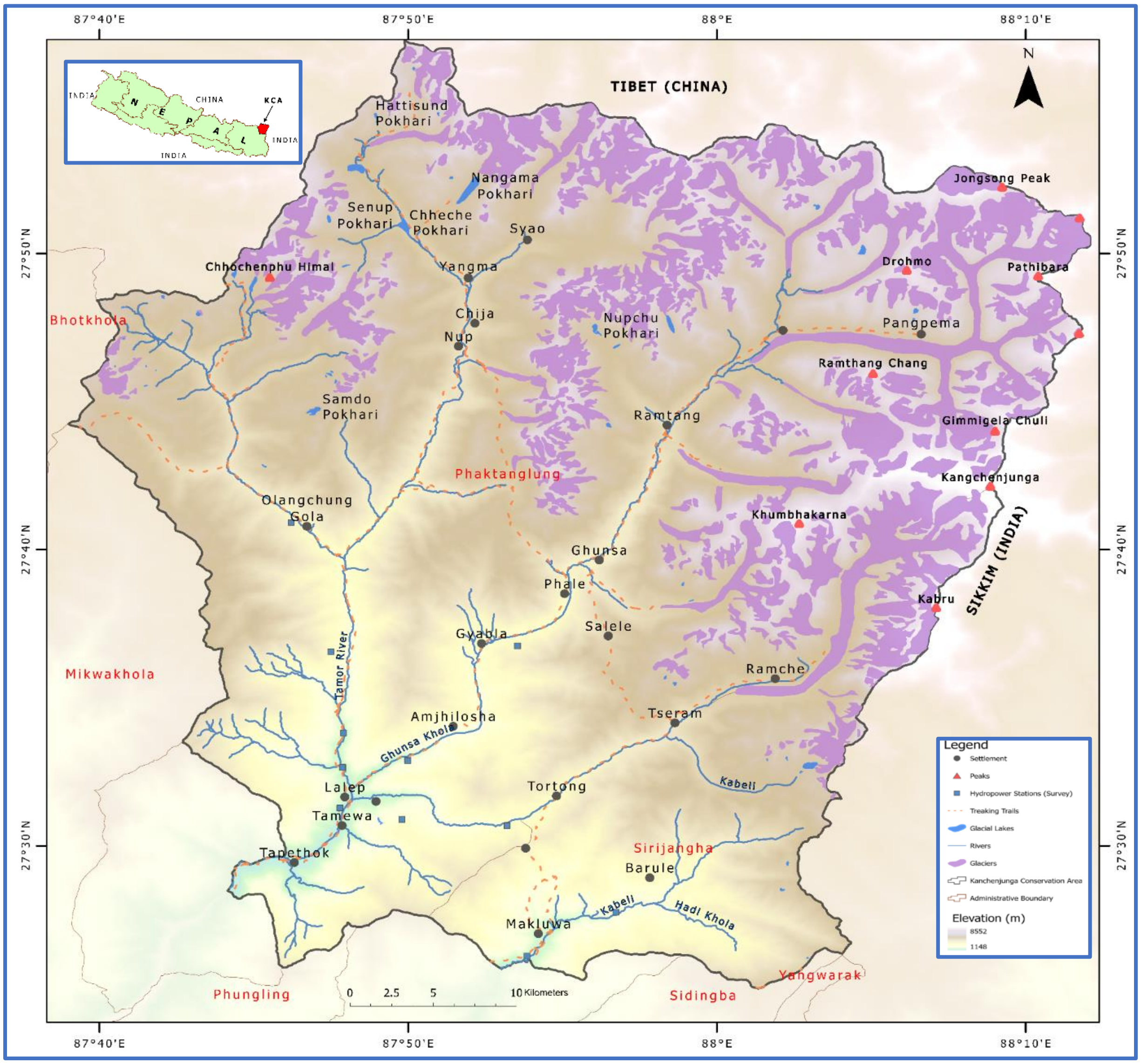

FIGURE 1 : MAP OF KANCHENJUNGA REGION, UPPER TAMOR RIVER BASIN, EAST NEPAL, INCLUDING ITS GLACIERS, GLACIAL LAKES.

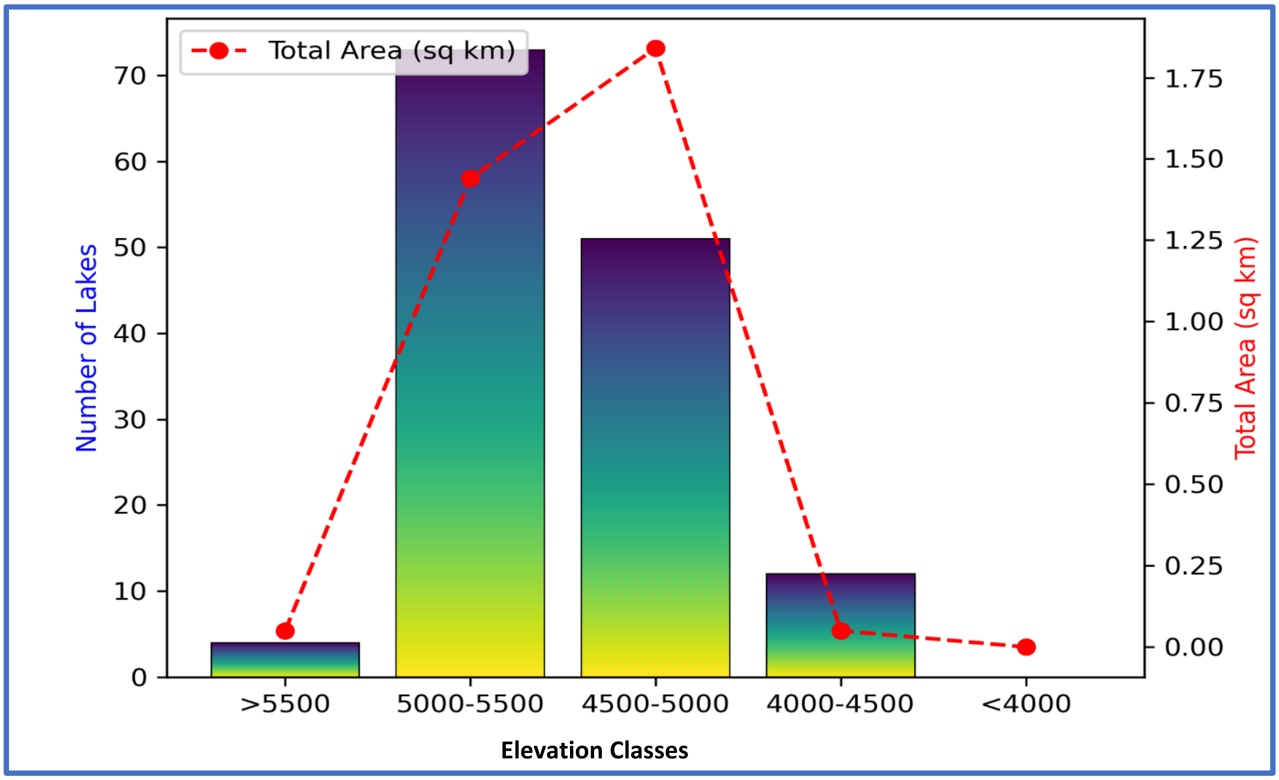

FIGURE 2: ELEVATION-WISE DISTRIBUTION OF GLACIAL LAKES IN KCA IN 2023.

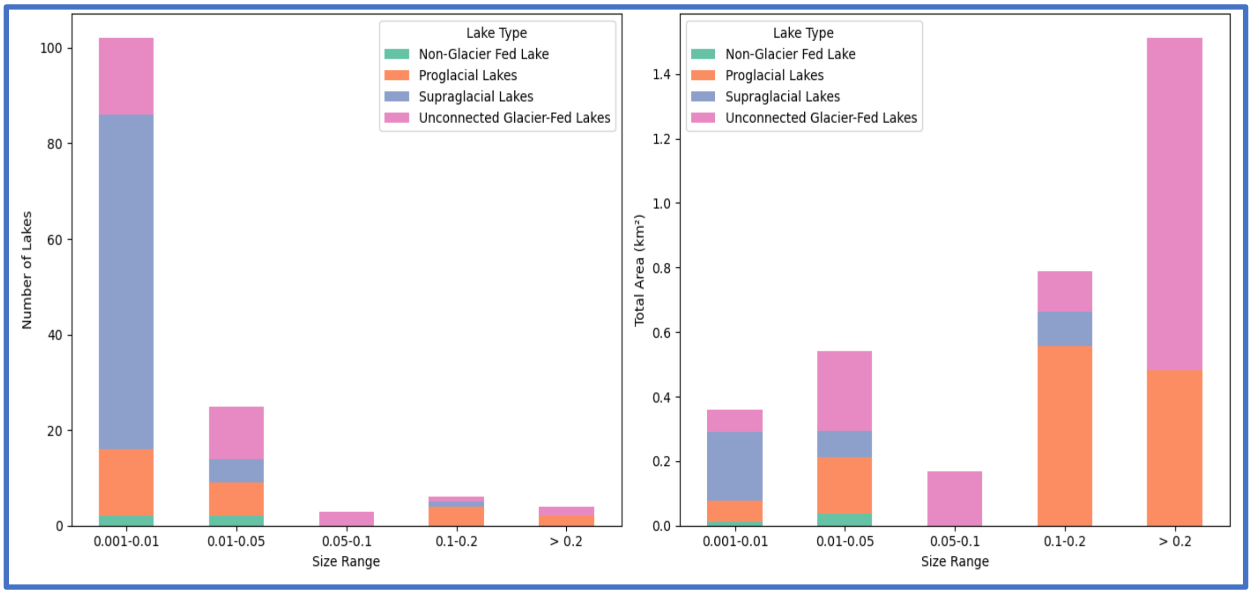

FIGURE 3: (A) CONTRIBUTION OF DIFFERENT LAKE TYPES, FALLING IN DIFFERENT SIZE CLASSES, TO THE TOTAL GLACIAL LAKE NUMBERS IN 2023.

(B) CONTRIBUTION OF DIFFERENT LAKE TYPES, FALLING IN DIFFERENT SIZE CLASSES, TO THE TOTAL GLACIAL LAKE AREA IN 2023

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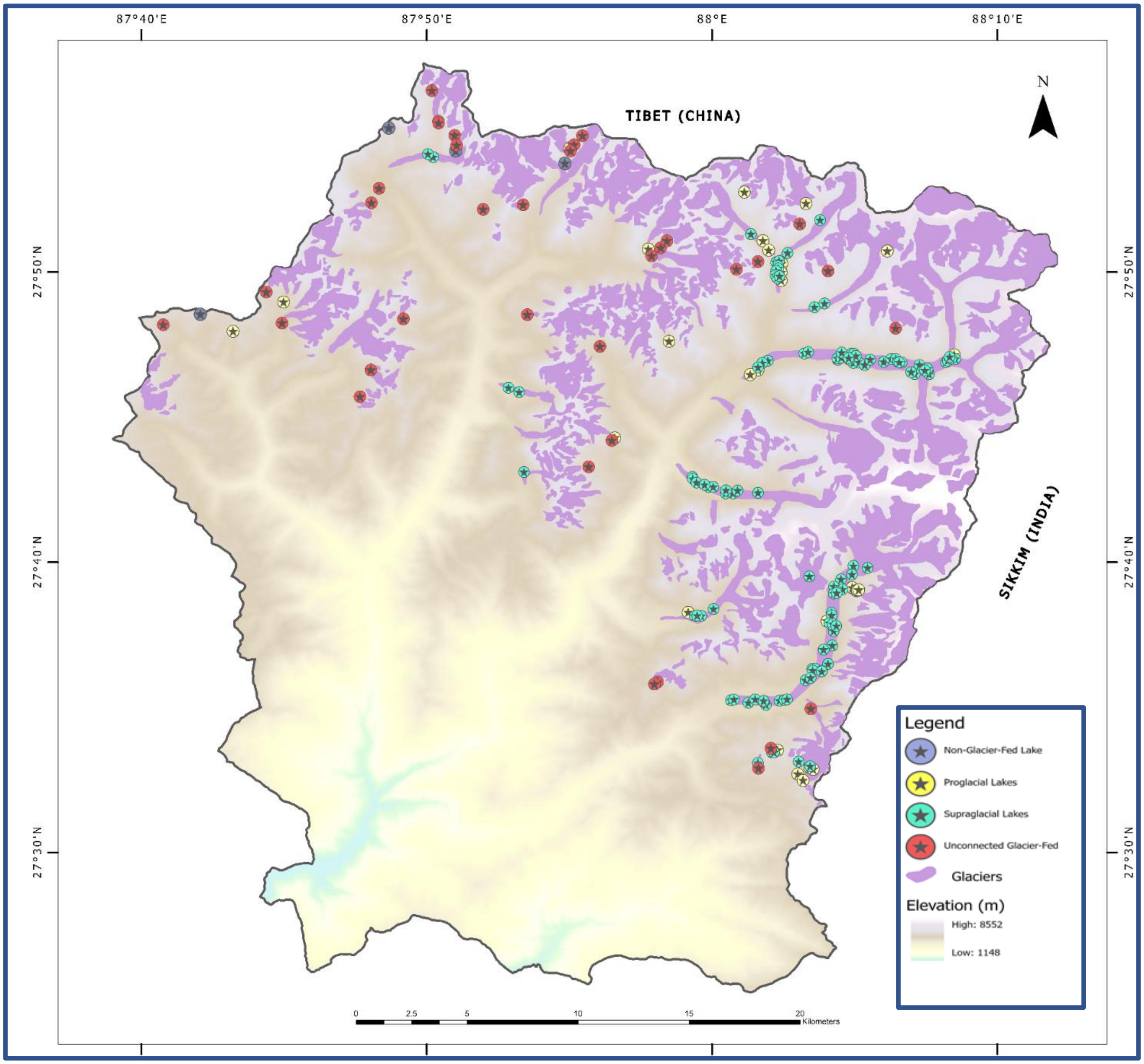


FIGURE 4: TYPE WISE DISTRIBUTION OF THE GLACIAL LAKES IN KCA IN 2023.

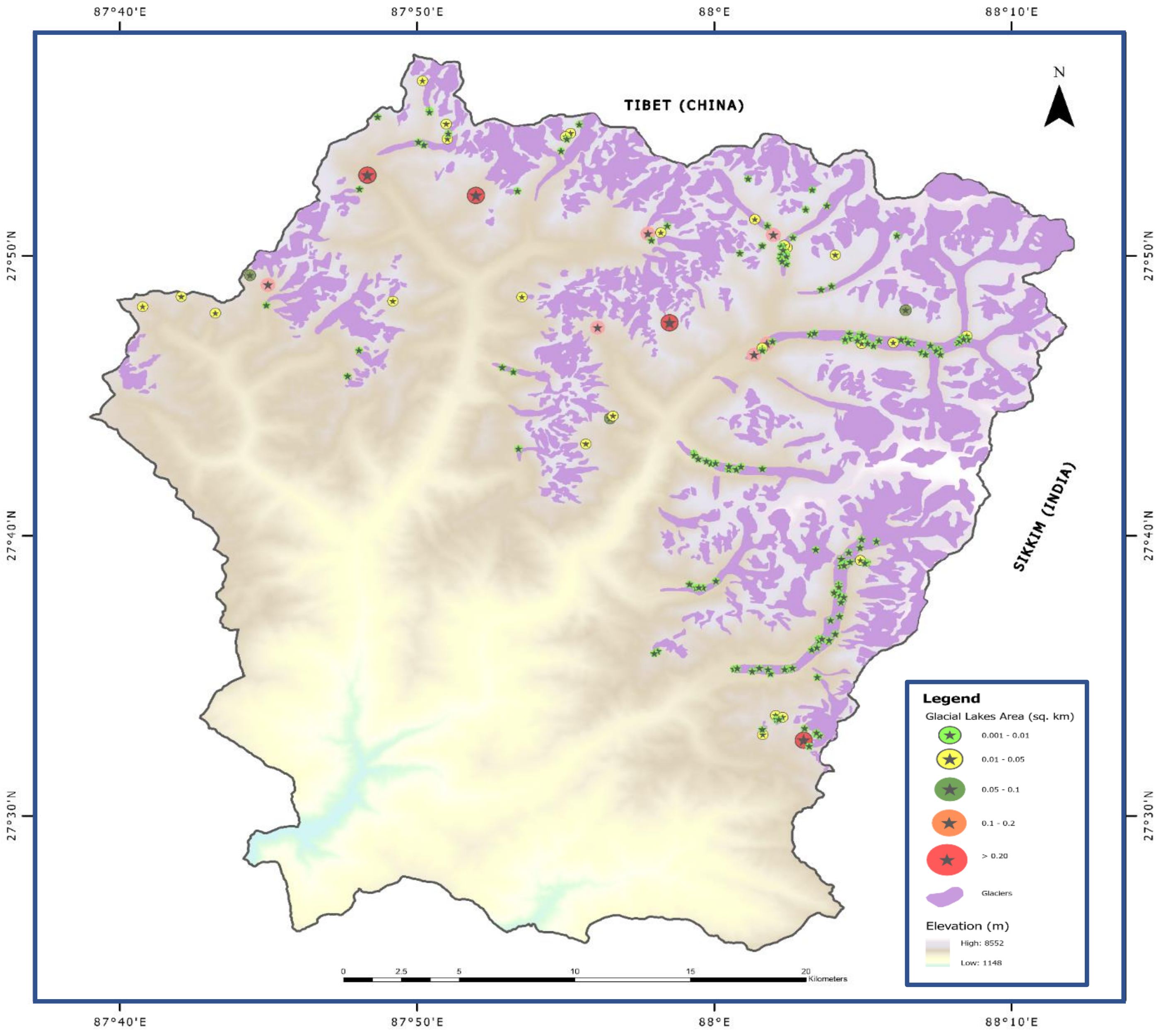


FIGURE 5: AREA WISE DISTRIBUTION OF THE GLACIAL LAKES IN KCA IN 2023.

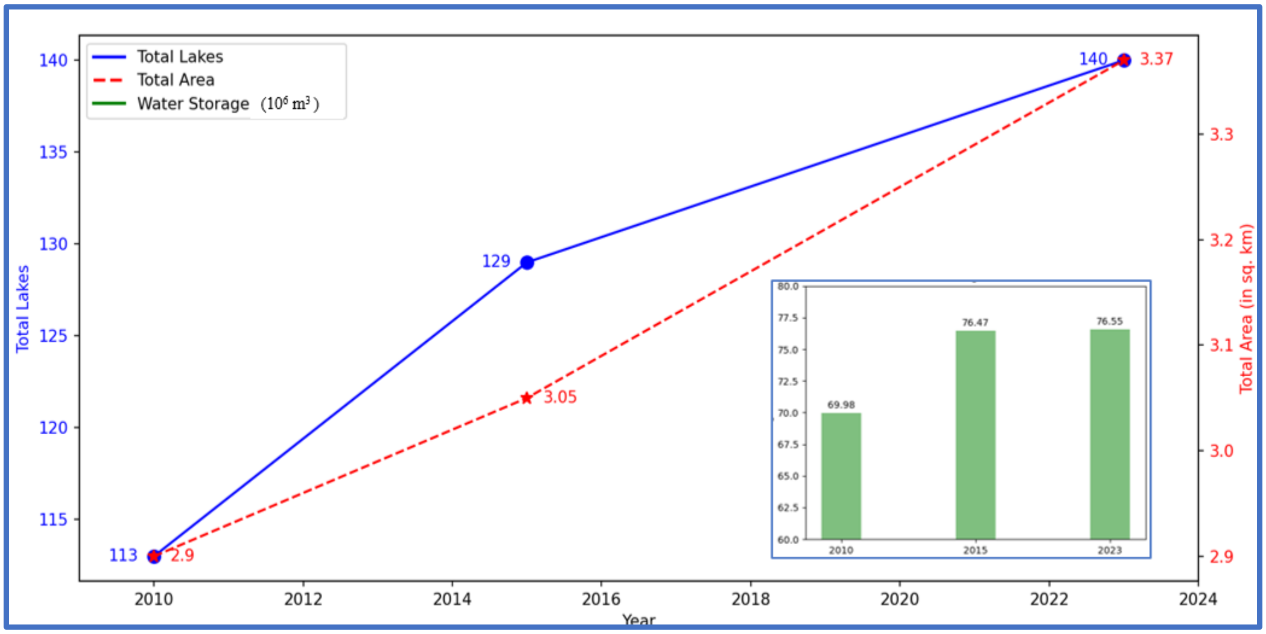


FIGURE 6: CHANGE IN AREA, NUMBER AND WATER STORAGE CAPACITY OF GLACIAL LAKES IN THE KCA, SPANNING 2010 TO 2023.

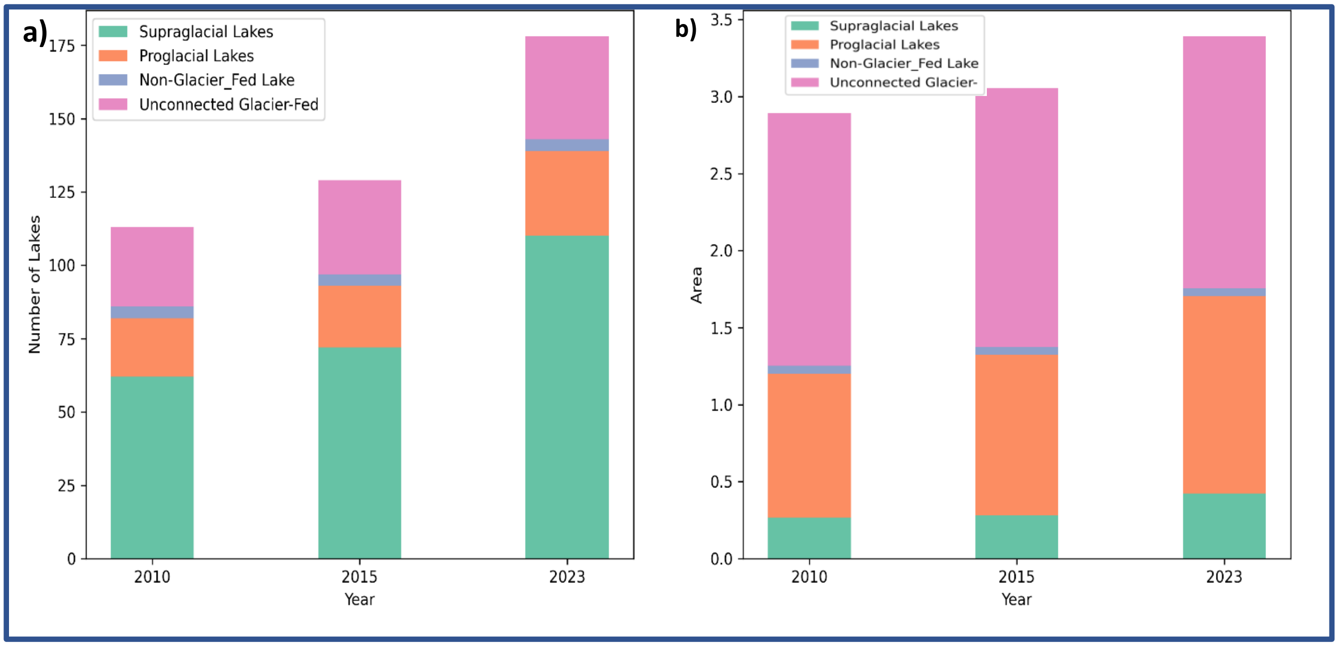


FIGURE 7: CHANGE (A) NUMBER AND (B) AREA OF DIFFERENT GLACIAL LAKE TYPES IN IN THE KCA, SPANNING FROM 2010 TO2023.

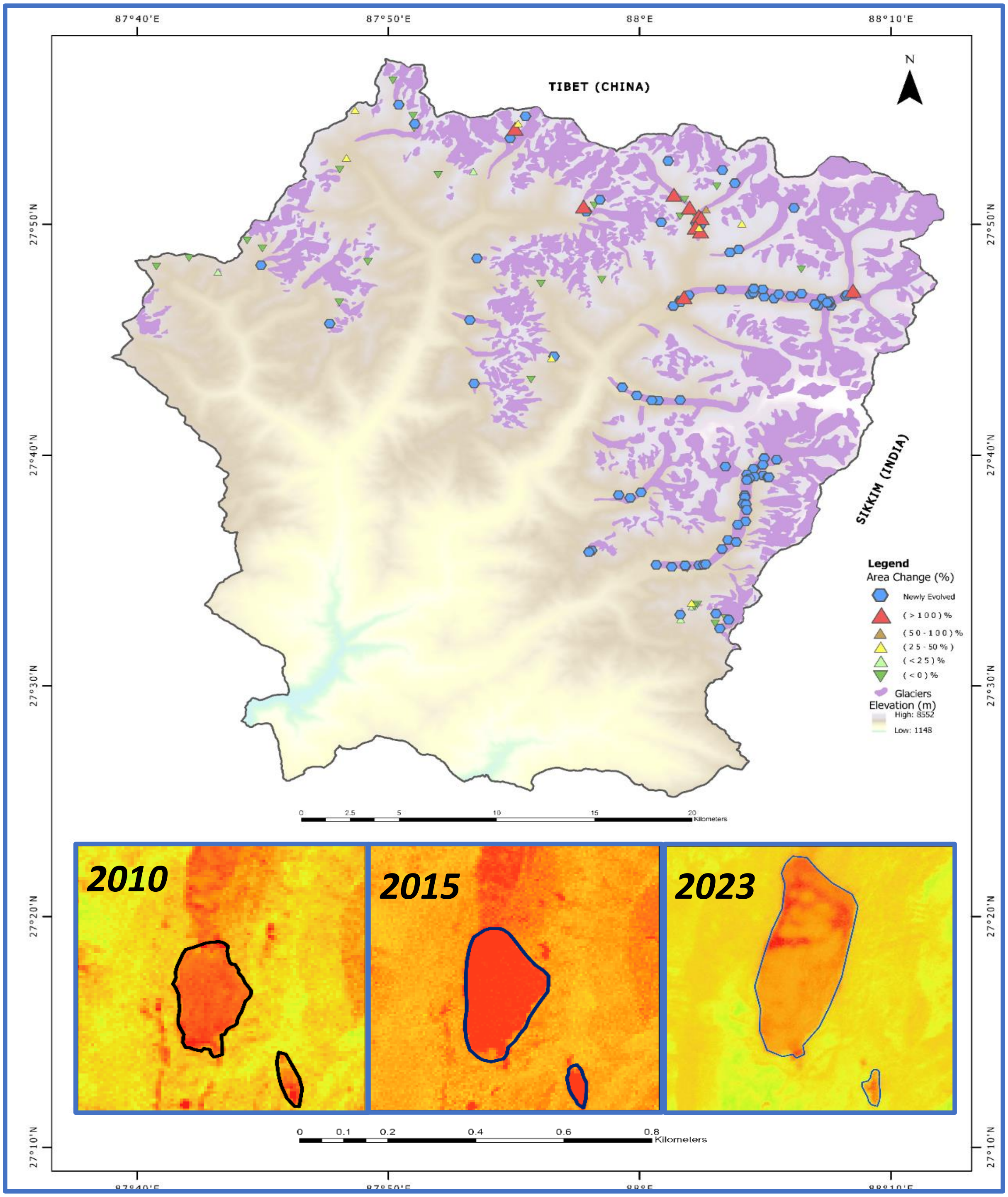


FIGURE 8: A) GROWTH (AREA CHANGE %) OF GLACIAL LAKES IN KCA (2010-2023).

B) OUTLINES OF LAKE 278453KCA879625 IN 2010, 2015, 2023

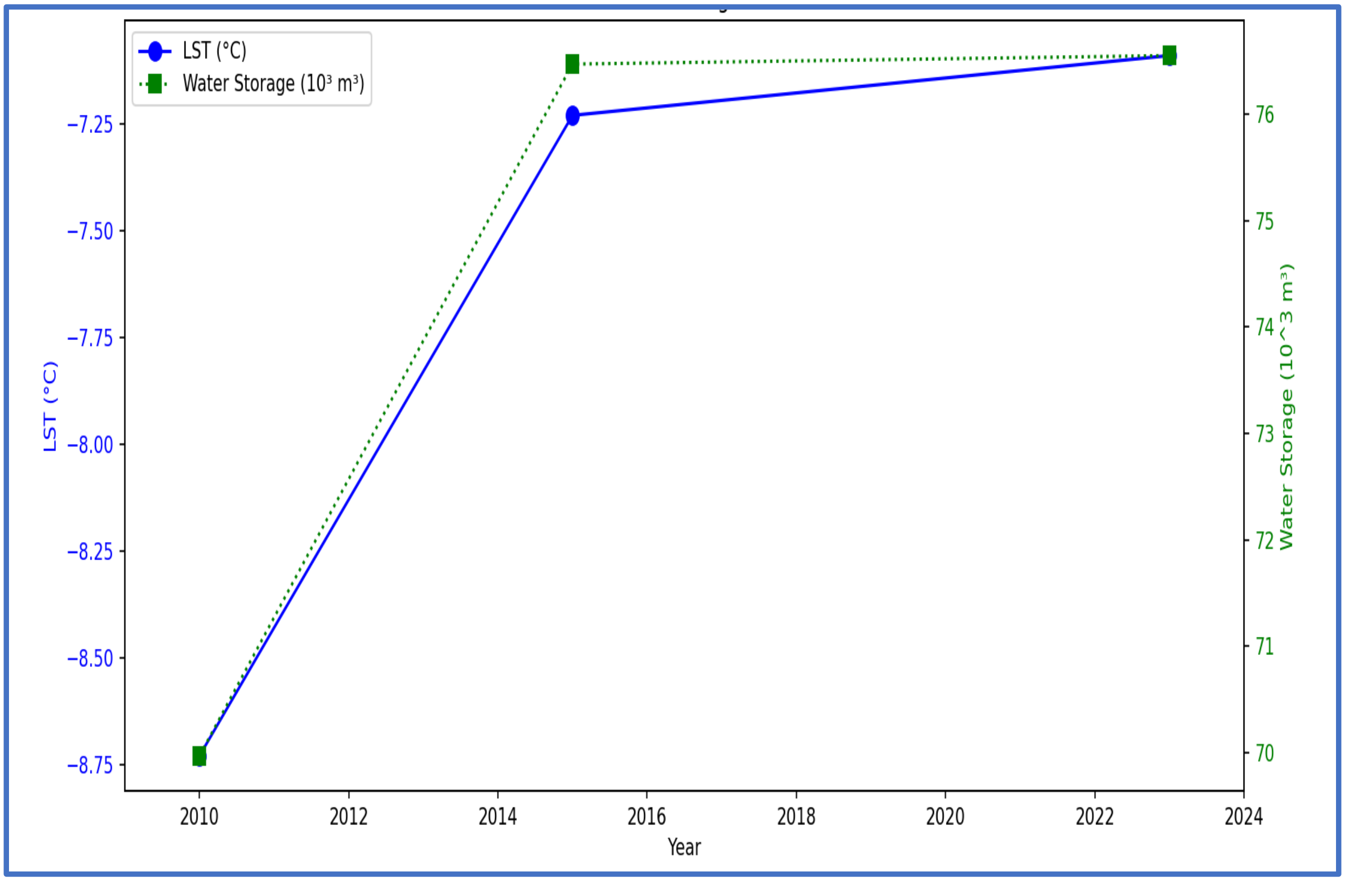


FIGURE 9: CHANGES IN LAND SURFACE TEMPERATURE (LST) FROM 2010 TO 2023.

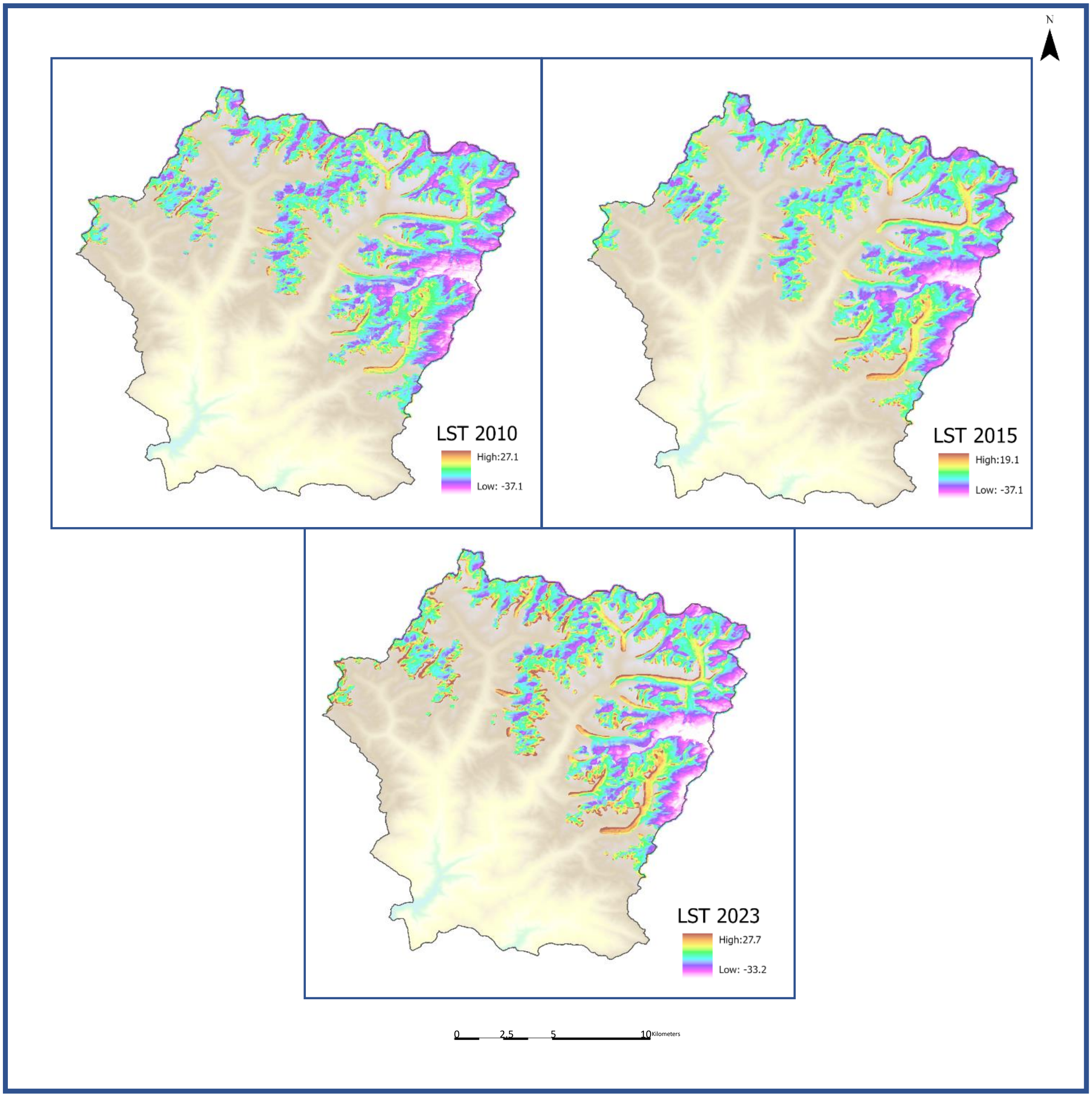


FIGURE 10: COMPARATIVE LST IMAGES FOR THE YEARS 2010, 2015, AND 2023, OFFERING INSIGHTS INTO SPATIAL AND TEMPORAL VARIATIONS IN LAND SURFACE TEMPERATURE ACROSS THE STUDY AREA.

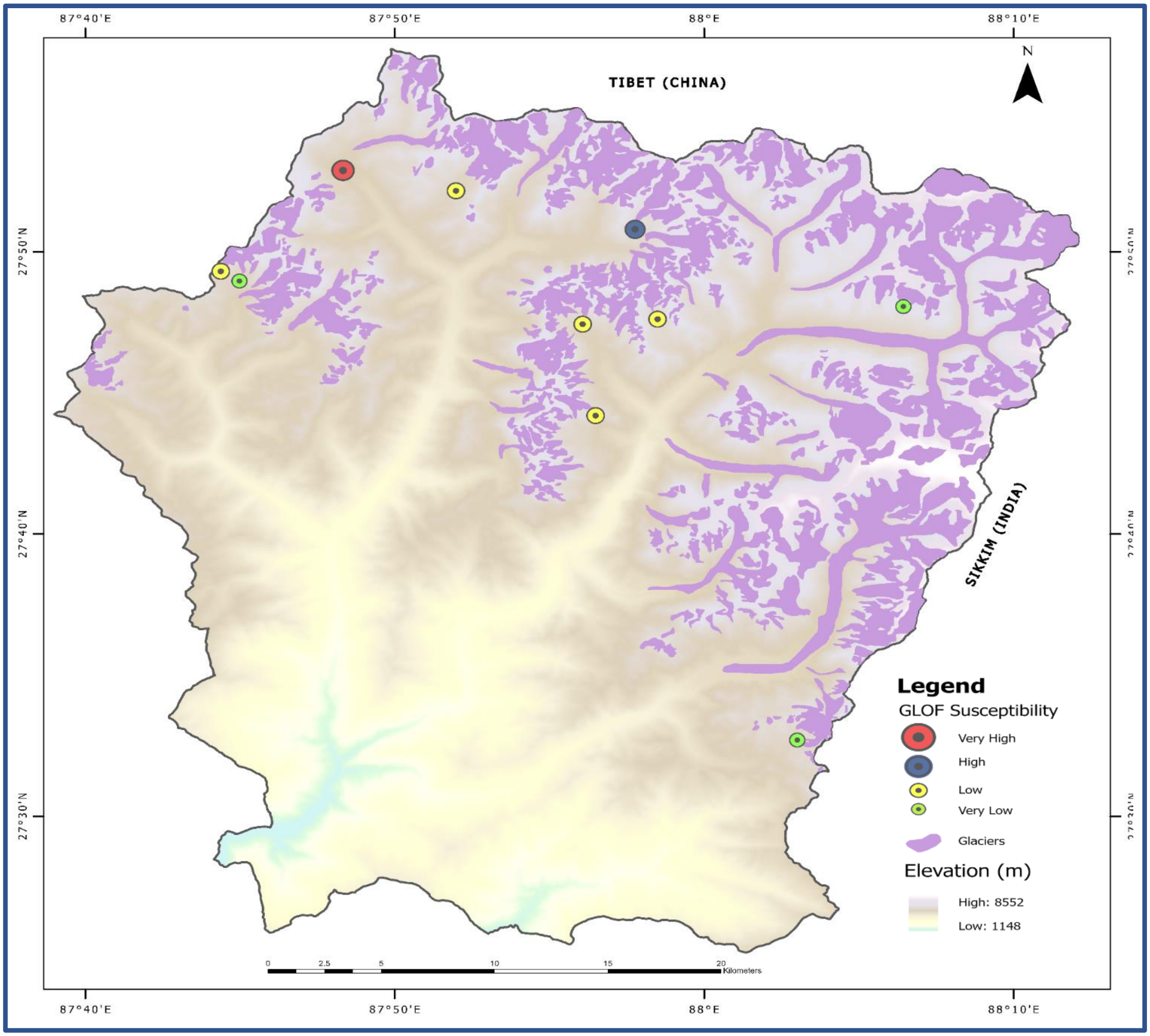
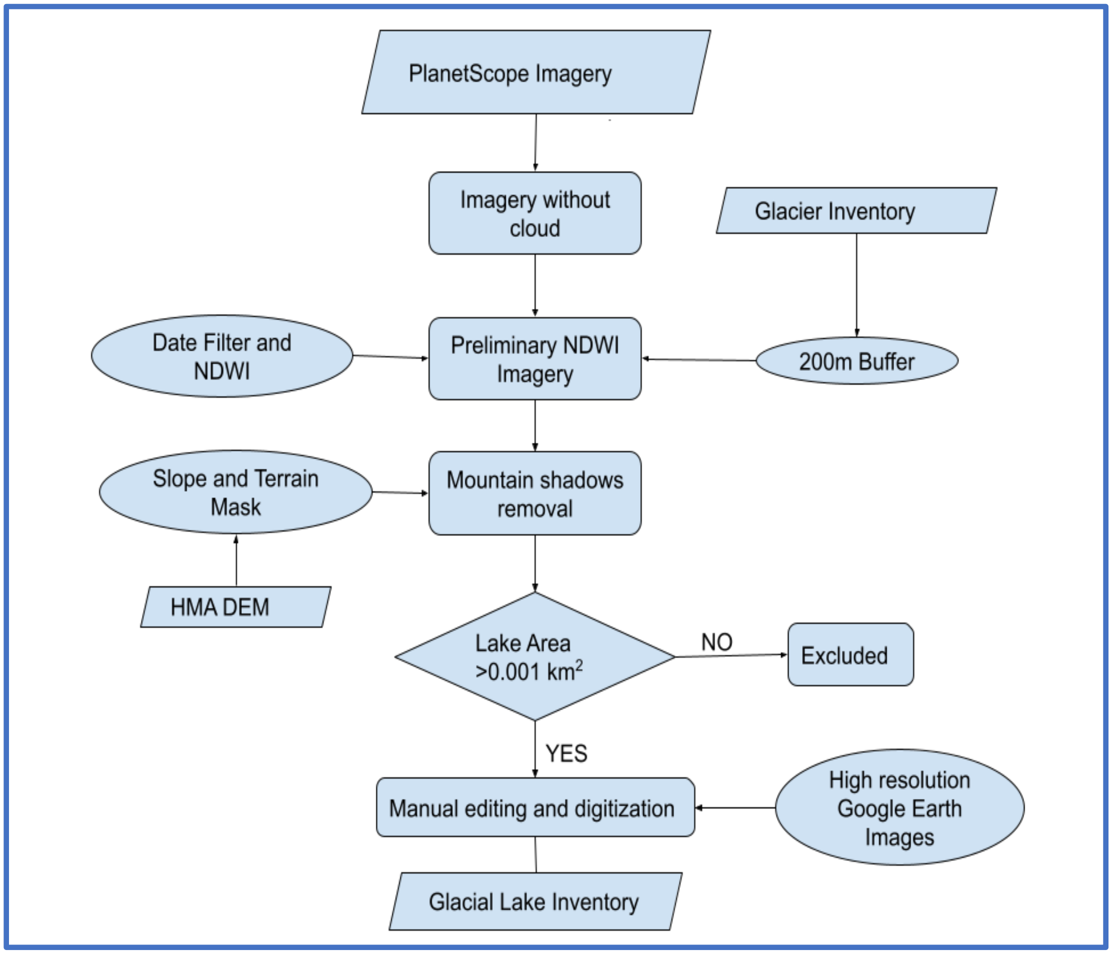


FIGURE 11: GLOF SUSCEPTIBILITY MAP FOR KCA

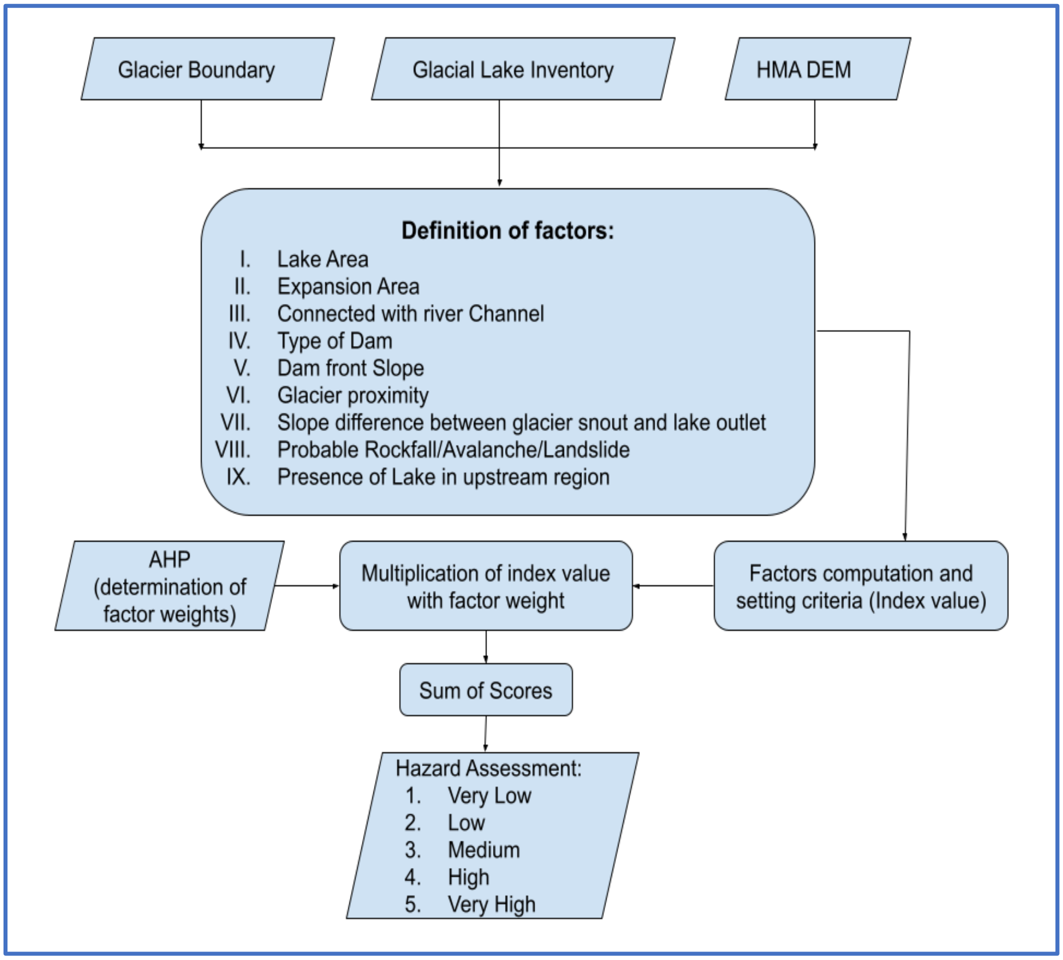
Appendix 1

Flowchart of the glacial lake extraction



Appendix 2

Workflow for hazard assessment of glacial lake



Appendix 3

Flowchart of the Land Surface Temperature (LST) Calculation