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Spatio-Temporal Dynamics of Proglacial and Supraglacial Lakes in the Arun and Tamor Sub-Basins of the Kosi River Basin (2010–2025) Using Remote Sensing and GIS

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Abstract: *Glacial lake expansion is one of the most notable responses to glacier retreat in high-mountain environments. This study analyzes changes in the size and number of proglacial and supraglacial lakes in the Arun and Tamor sub-basins of the Upper Kosi Basin from 2010 to 2025. Landsat (5 & 8-9) imagery over different time periods and GIS were used to delineate the boundaries of the glacial lakes and estimate lake volume using area–volume scaling relationships. The results show a clear rise in both the number and size of glacial lakes from 2010 to 2025. The total area of these lakes grew from 22.13 km² in 2010 to 27.15 km² in 2025 and estimated lake volume also increased from 0.585 km³ to 0.781 km³. The larger volume growth suggests that lakes are becoming deeper as melting glaciers uncover deeper basins. Significant expansion of proglacial lakes was also observed near retreating glacier fronts and an increase in supraglacial lakes on debris-covered glacier surfaces. These changes emphasize the growing importance of glacial lakes in the Himalayan region and the need for ongoing geospatial monitoring to improve hazard assessments.*

Key Words: *Glacial Lakes, Remote Sensing, GIS, Proglacial Lakes, Supraglacial Lakes, Glacier Retreat.*

I. INTRODUCTION

Glaciers are active parts of the Earth's ice system and play a crucial role in regulating the environment and water systems. These large ice masses form when snow accumulates and compacts over time in high-altitude and polar areas. Along with serving as freshwater reservoirs, glaciers also shape landforms and provide important signs of climate change [1].

In recent decades, glaciers around the globe have been shrinking and thinning faster due to rising temperatures [1,7]. This trend is especially clear in high mountain regions like the Himalayas, where glaciers react strongly to climate changes. As glaciers pull back, depressions at their fronts or surfaces often fill with meltwater, resulting in the growth of glacial lakes [2,4].

The Himalayan region holds one of the largest groups of glaciers outside the polar areas and is often called the “Third Pole.” These glaciers greatly contribute to major river systems like the Ganga, Brahmaputra, and Indus, supplying freshwater to millions downstream. Changes in glacier size and mass have serious effects on regional water systems and security [1,3,7].

One of the most noticeable effects of glacier retreat is the growth of glacial lakes. These lakes are usually categorized based on how and where they form in relation to glaciers. Proglacial lakes, which form at the glacier's end, and supraglacial lakes, which form on the glacier's surface, are especially important signs of glacier behaviour [4]. Proglacial lakes typically appear in depressions from glacier erosion or behind moraine dams, while supraglacial lakes develop on debris-covered surfaces of glaciers due to melting.

The rise in glacial lakes has gained more attention due to their risk of causing Glacial Lake Outburst Floods (GLOFs) [5,8,9]. These floods happen when a natural dam holding back a glacial lake breaks, sending large amounts of water downstream. Such events can lead to serious damage to infrastructure, ecosystems, and communities.

Remote sensing and Geographic Information Systems (GIS) are now key tools for monitoring glacial lakes in hard-to-reach mountainous areas [6,10]. Satellite images help researchers map lake boundaries, measure changes in area, and analyze trends over time efficiently. Multi-temporal satellite data has been widely used to examine glacier retreat and the development of glacial lakes throughout the Himalayan region [2,4].

This study aims to examine the changes in proglacial and supraglacial lakes from 2010 to 2025 using remote sensing and GIS methods. The focus is on identifying newly formed lakes, measuring changes in lake area and volume, and understanding what these changes mean for glacier behaviour and potential hazards.

II. STUDY AREA

The study area is located in the upper Kosi River Basin, a key transboundary river system in the central and eastern Himalaya [11,13]. Arun and Tamor sub-basins begin in glacier-rich areas of the eastern Himalaya and play a significant role in the total flow of the Kosi River [11,12]. The basin covers parts of India, China and Nepal. It starts in the high-altitude regions of the Himalayas and Tibet, then flows through Tibet (China), Nepal, and northern India before merging into the Ganga River [11]. It is known for its complex water system, high sediment load, and changing river behavior [13].

The Kosi Basin includes seven major tributaries: Indrawati, Sunkosi, Tamakosi, Dudhkosi, Likhu, Arun, and Tamor. Together, these make up the Sapta Kosi system [11]. The Arun and Tamor sub-basins begin in glacier-rich areas of the eastern Himalaya and play a significant role in the total flow of the Kosi River [11,12].

The basin has a varied landscape, from high glaciated mountains to low valleys. The upper areas are marked by steep slopes, active tectonics, and significant glaciation. These features lead to strong erosion, high sediment transport, and dynamic geological processes [13].

The regional climate is heavily affected by the South Asian monsoon, with most rainfall happening in the summer [13]. Higher areas have cold temperatures and snowfall, which helps form glaciers, while lower areas have conditions that promote melting [12]. The combination of steep terrain, monsoon rainfall, and glacier-covered land makes the Arun and Tamor sub-basins ideal for studying glacier and glacial lake dynamics.

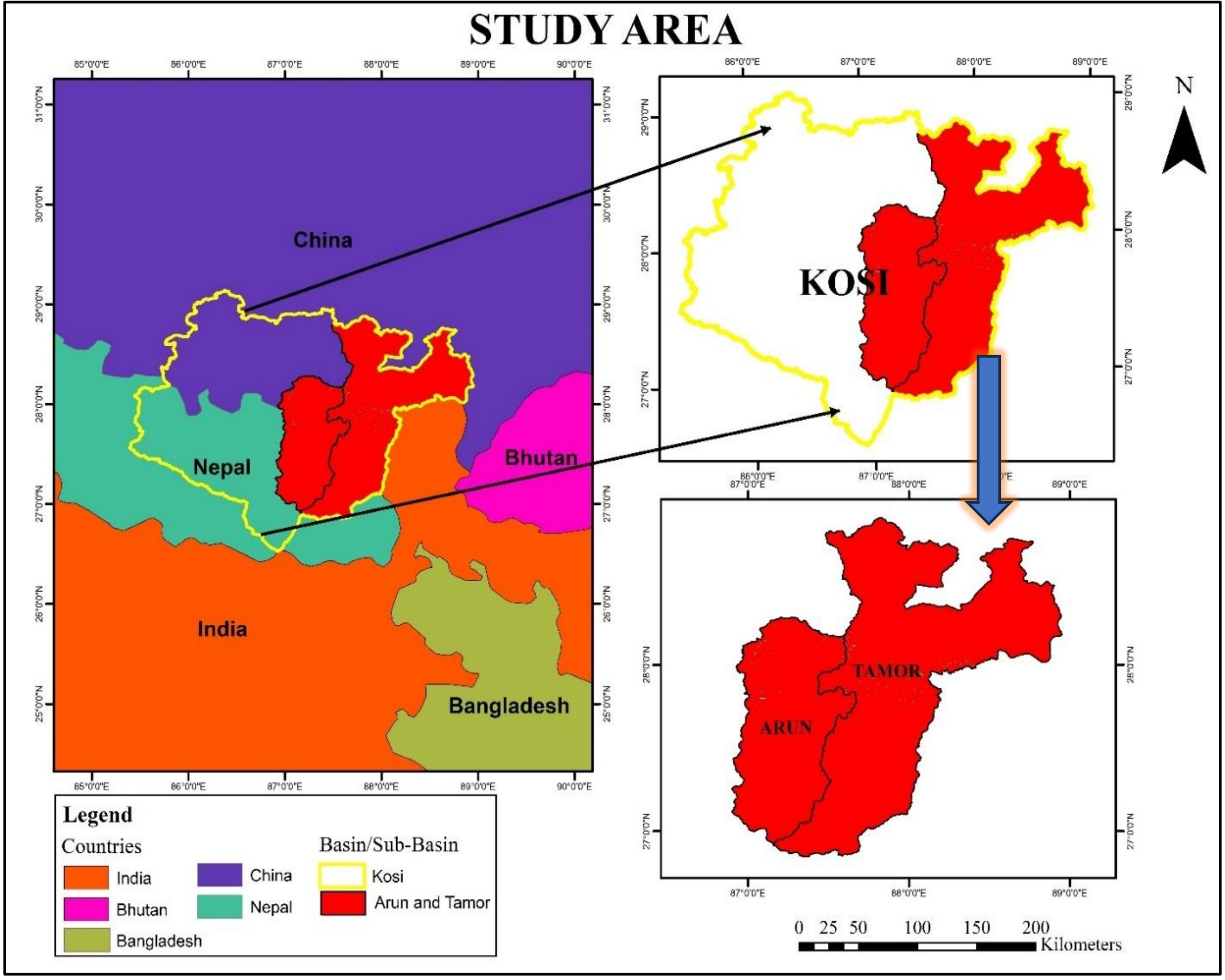


Figure 1: Location of the study area in the Upper Kosi Basin

III. METHODOLOGY

The methodology for mapping and analyzing glacial lake changes is shown in Figure 2.

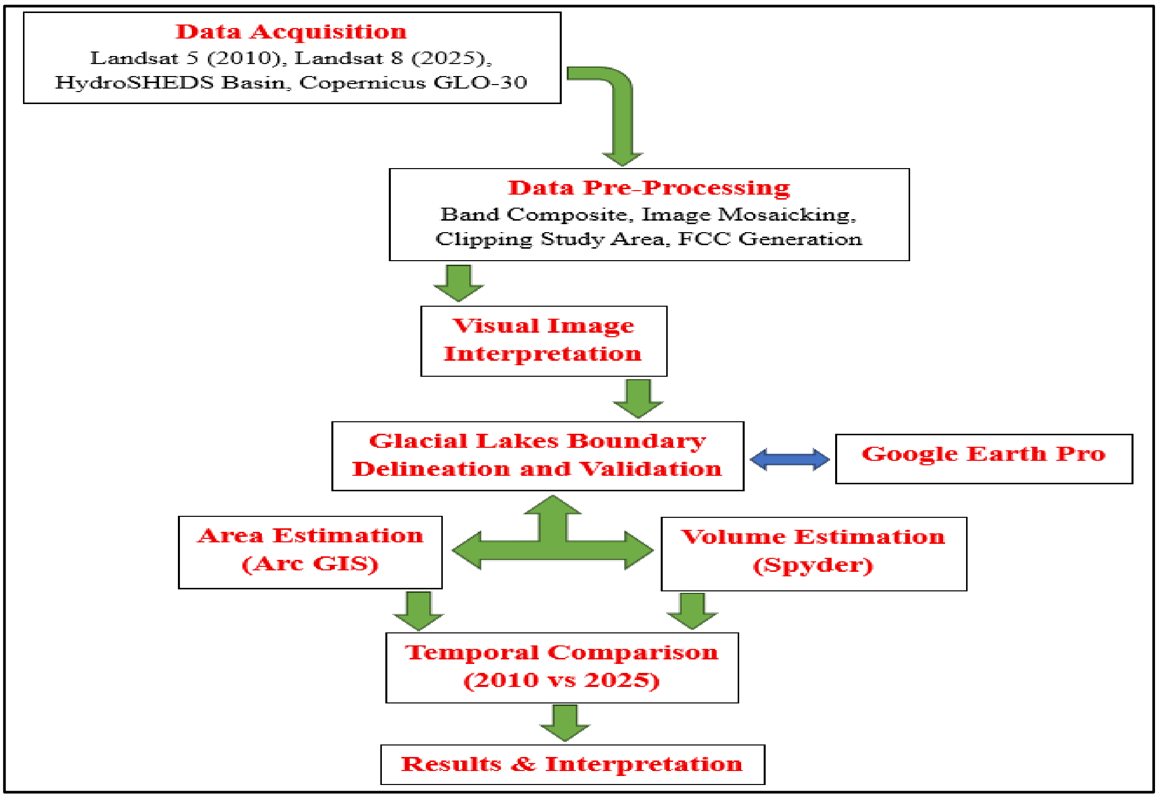


Figure 2: Workflow of glacial lake mapping and analysis

Multi-temporal Landsat images were pre-processed through layer stacking, radiometric correction, and subsetting to fit the Kosi Basin boundary in ArcGIS. All different datasets were projected to the same coordinate system (WGS 84 UTM Zone 45N) for consistency. Glacial lakes were identified using visual interpretation based on spectral properties, shape, location, and their closeness to glacier edges. The lake boundaries were delineated manually to make mapping more accurate in debris-covered areas. The lake polygons help compute area statistics for each period. Lake volume was estimated from area–volume scaling relationships often used in glaciological studies ($V=cA^{\wedge}\gamma$). Furthermore, the mapped lake areas were verified using high-resolution images available in Google Earth Pro to reduce errors.

IV. DATA

Landsat 5 images from (2010-2011) and Landsat 8, 9 images from 2025 were used in this study which were downloaded from the USGS EarthExplorer portal (https://earthexplorer.usgs.gov/). Table 1 provides details about the satellite data. The shapefile for the Kosi Basin came from HydroSHEDS (https://www.hydrosheds.org/). The Copernicus GLO-30 Digital Elevation Model (DEM), used for estimating elevation, was downloaded from the OpenTopography platform (https://opentopography.org/). Google Earth Pro was also used as a reference to verify the visual interpretation of glacial lakes. These datasets provided reliable information over time for mapping changes in glacial lakes in the study area.

Satellite	Sensor	Resolution (m)	Year	Path/Row	Scene ID
Landsat 5	TM	30	2010	139/041	LT51390412010348KHC00
Landsat 5	TM	30	2010	139/040	LT51390402010316KHC00
Landsat 5	TM	30	2011*	140/040	LT51400402011278KHC00
Landsat 5	TM	30	2010	140/041	LT51400412010339KHC00
Landsat 8	OLI/TIRS	30	2025	139/040	LC81390402025021LGN00
Landsat 8	OLI/TIRS	30	2025	139/041	LC81390412025021LGN00
Landsat 9	OLI-2/TIRS-2	30	2025	140/040	LC91400402025020LGN00
Landsat 9	OLI-2/TIRS-2	30	2025	140/041	LC91400412025004LGN00

Table 1: Details of Landsat

All selected scenes were taken during the late ablation season, under clear skies, to ensure reliable glacier boundary mapping. *One Landsat scene from 2011 was included because there were no cloud-free images for 2010.

V. RESULT

The analysis revealed significant changes in both the number and size of glacial lakes from 2010 to 2025. Both proglacial and supraglacial lakes experienced notable increases in area and distribution. The total number of glacial lakes grew during the study period, showing that glaciers are still retreating and more meltwater is accumulating. Proglacial lakes made up the bulk of the total lake area, while the count of supraglacial lakes increased significantly.

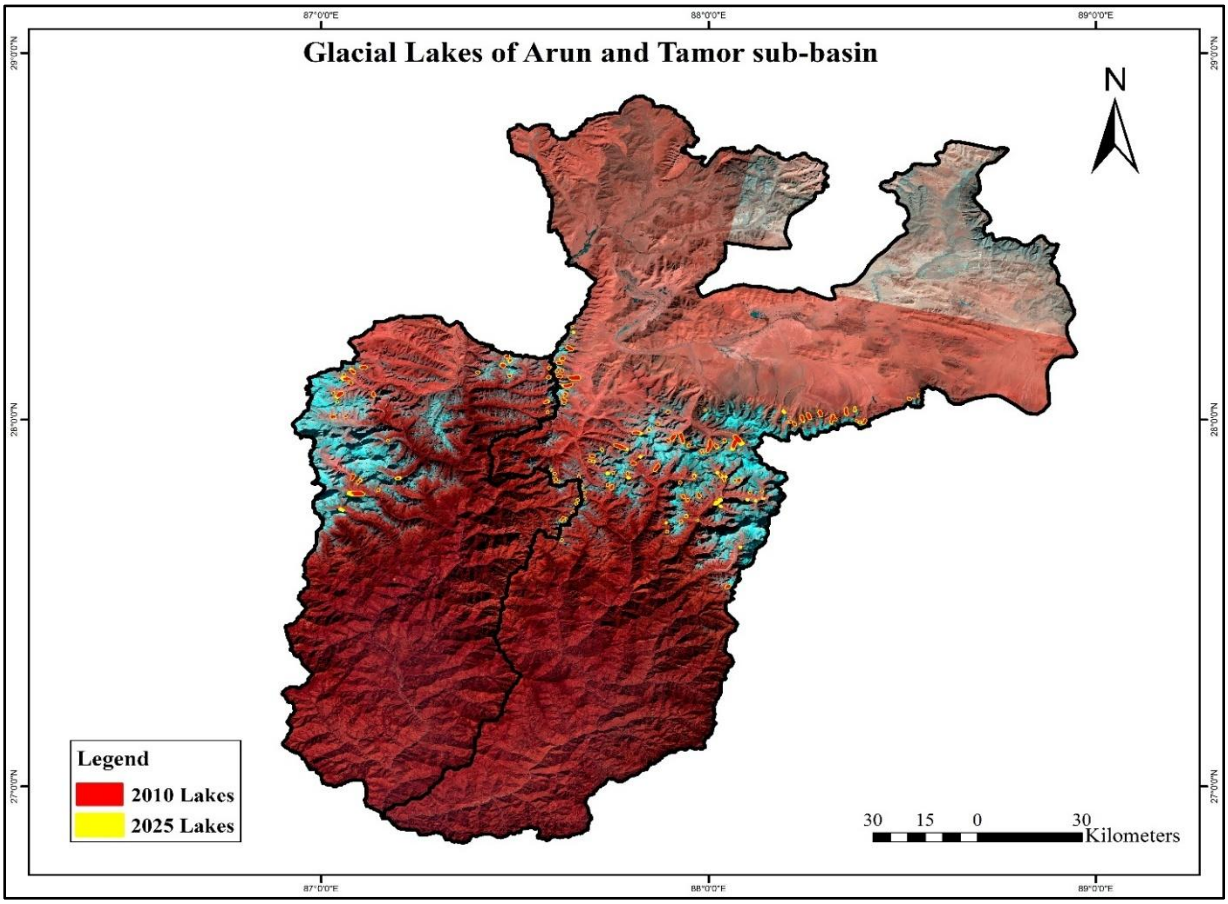
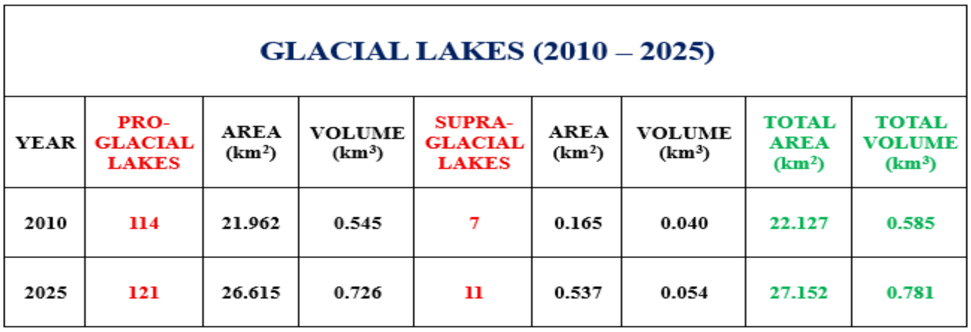


Figure 3: Distribution of lakes (proglacial and supraglacial) in the Arun and Tamor sub-basins (2010–2025).

The total area of glacial lakes rose from 22.13 km² in 2010 to 27.15 km² in 2025. Likewise, the estimated lake volume grew from 0.585 km³ to 0.781 km³. Proglacial lakes accounted for the majority of the total lake area, while supraglacial lakes saw a marked increase in number.



GLACIAL LAKES (2010 – 2025)

YEAR	PRO-GLACIAL LAKES	AREA (km^2)	VOLUME (km^3)	SUPRA-GLACIAL LAKES	AREA (km^2)	VOLUME (km^3)	TOTAL AREA (km^2)	TOTAL VOLUME (km^3)
2010	114	21.962	0.545	7	0.165	0.040	22.127	0.585
2025	121	26.615	0.726	11	0.537	0.054	27.152	0.781

Table 2: Proglacial Lakes and Supraglacial Lakes Distribution (2010-2025)

Year	Sub-Basin	Proglacial Lakes	Area (km^2)	Volume (km^3)	Supraglacial Lakes	Area (km^2)	Volume (km^3)	Total Area (km^2)	Total Volume (km^3)
2010	Arun	35	5.834	0.153	3	0.074	0.031	5.909	0.184
2025	Arun	36	7.926	0.241	3	0.101	0.030	8.028	0.272
2010	Tamor	79	16.127	0.391	4	0.090	0.008	16.218	0.40
2025	Tamor	85	18.688	0.485	8	0.436	0.023	19.124	0.509

Table 3: Temporal variation (number, area, volume) of glacial lakes in the Arun and Tamor sub-basins
*Values are rounded to three decimal places; minor discrepancies may occur due to rounding.

Between 2010 and 2025, both pro-glacial and supra-glacial lakes showed noticeable growth in their individual area and volume. Pro-glacial lakes increased in area from 21.962 km^2 to 26.615 km^2 and in volume from 0.545 km^3 to 0.726 km^3, indicating a steady expansion of these lakes at glacier fronts. Similarly, supra-glacial lakes exhibited a significant rise, with their area expanding from 0.165 km^2 to 0.537 km^2 and volume increasing from 0.040 km^3 to 0.054 km^3. This trend reflects an overall intensification in meltwater accumulation both on and in front of glaciers over the study period.

Selected examples of glacial lake expansion and boundary changes observed during the study are shown in Figure 4.

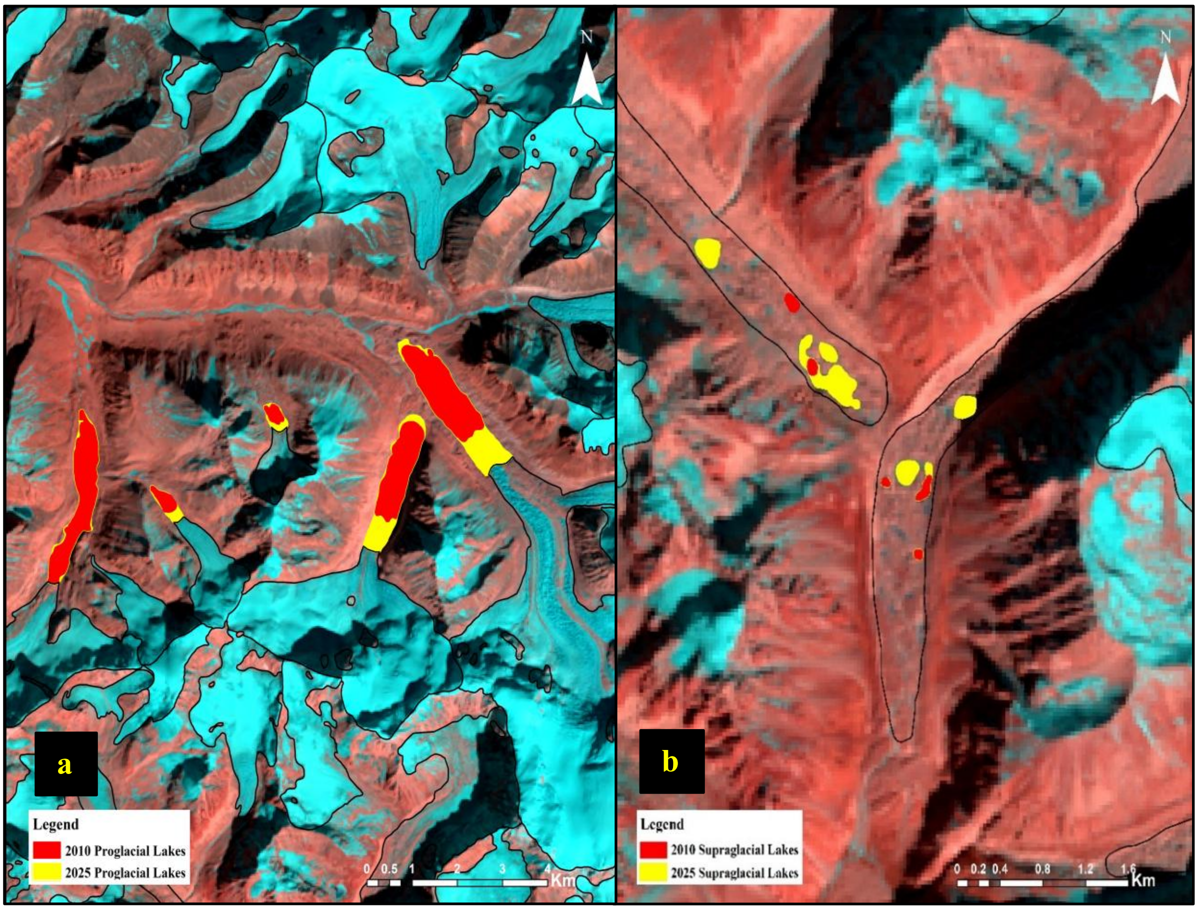


Figure 4: Representative examples of temporal changes in glacial lakes between 2010 and 2025 in the Arun and Tamor sub-basins: (a) expansion of selected proglacial lakes near retreating glacier termini; (b) development and enlargement of supraglacial lakes on debris-covered glacier surfaces. Lake boundaries for 2010 and 2025 are shown in red and yellow, respectively.

In summary, the area of glacial lakes increased by about 23%, and the volume grew by around 33% during the study period. The faster rate of volume growth compared to area growth suggests that lakes are becoming deeper as glaciers melt back and reveal deeper basins formed by prior glacial activity. At first, lakes expand horizontally as meltwater fills newly exposed pits, but as glaciers continue to thin, lakes deepen vertically, leading to quicker volume growth. This process is particularly clear in proglacial lakes, where receding glacier fronts leave behind basins that can hold more water.

As lake depth and storage capacity grow, the pressure on moraine dams increases. This could raise the risk of Glacial Lake Outburst Floods (GLOFs) due to dam instability, erosion, or sudden drainage. The growth of glacial lakes is closely tied to ongoing glacier retreat and heightened surface melting in the Himalayan region, fueled by rising temperatures and shifting precipitation patterns. The increase in supraglacial lakes further signals enhanced melting on debris-covered glacier surfaces. Overall, these trends suggest that glacial lakes are evolving into larger, deeper, and potentially more dangerous bodies of water in the melting mountain landscape. These changes highlight the increasing geological and water dynamics in the glacierized Himalayan basins.

VI. CONCLUSION

This study analyzed changes in proglacial and supraglacial lakes in the Arun and Tamor sub-basins from 2010 to 2025 using remote sensing and GIS techniques. The results show a clear increase in the number, area, and estimated volume of glacial lakes, with total area growing from 22.13 km² to 27.15 km² and volume from 0.585 km³ to 0.781 km³. The relatively larger increase in volume suggests that glacial lakes are deepening as retreating glaciers open up deeper basins.

These findings underline the growing significance of glacial lakes in terms of water management and hazard risks in the Himalayan landscape, especially regarding potential glacial lake outburst floods. Ongoing monitoring using multi-temporal satellite data is essential to enhance hazard assessments and comprehend ongoing changes to these icy systems. Future research that includes higher-resolution images and field observations could further improve the precision of glacial lake mapping and volume estimates.

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