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Glacier and Glacial Lake Dynamics in the Mo Chu Catchment, Bhutan: a Satellite-Based Analysis (1992-2022)

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Abstract

Melting glacier and glacier retreat are key indicators of climate change. However, there are no comprehensive documentation of the changes in the glacial lakes of the in the Eastern Himalayan region, particularly in Bhutan's Mo Chu catchment. Therefore, the aim of the study was to assess the impact of climate change on the glaciers and glacial lakes of the Mo Chu sub-basin. Remote sensing data from Landsat 5 Thematic Mapper (TM) and Sentinel-2 multispectral satellite imagery spanning three decades were used. Normalized Difference Snow Index was used to identify glaciers while Normalized Difference Water Index was used to delineate glacial lake boundaries. The findings from the analysis show a significant decline in the glacier area, from 183 to 109 square kilometres, over 32-year period, indicating a clear negative trend. Conversely, the study found that the glacial lake area increased by 5.5% over 30 years. Further, the analysis of POWER NASA data, indicate that temperature and precipitation are positively correlated, whereas temperature and glacier area exhibit a negative correlation. The findings of the study underline the impact of rising temperature on the glacier and glacial lakes of Mo Chu sub-basin, highlighting the need for continued monitoring and adaptation strategies.

Keywords— Remote sensing, Delineation, Climate, Glacier, Glacial lake

1 Introduction

Glaciers, those majestic features slowly sculpting landscapes over a millennia, are fundamental components of our planet's geophysical processes [1]. In mountainous regions like the Himalayas, glaciers and glacial lakes play pivotal roles in regulating water resources, supporting ecosystems, and influencing local climates [2]. However, recent decades have witnessed a concerning trend of glacier retreat in the Himalayas, as highlighted by studies utilizing satellite imagery, topographical maps, and field measurements [3]. Techniques such as remote sensing have been particularly instrumental in monitoring these changes, revealing significant reductions in glacier size and volume, especially in regions like the Mago Chu and Dangme Chu basins in Bhutan [4], [5].

The primary cause of glacier retreat in the Himalayas is attributed to climate change. Rising temperatures lead to an accelerated melting of ice [6], [7]. Reduced precipitation and warmer temperatures are believed to be key factors contributing to this phenomenon, though the exact mechanisms driving glacier retreat are complex and multifaceted [8]. Consequently, changes in glacier meltwater contributions can have profound impacts on downstream water resources, agriculture, and infrastructure thereby emphasizing the need to understand glacier dynamics in terms of water resource management and climate adaptation [9]. The major rivers of Asia, such as the Brahmaputra, Indus, and Ganges, receive their water from these high mountain glaciers [10].

Previous research on glaciers in Bhutan has provided valuable insights into glacier behaviour, retreat rates, and associated hazards like glacial lake outburst floods (GLOFs) [5], [11]. Studies have employed a combination of satellite data analysis, field measurements, and numerical modelling to assess glacier extent, volume, and behaviour [3], [5]. These methods have been validated through ground-truthing exercises, comparison with historical data, and cross-validation with other independent datasets [5].

The Bhutanese organization NCHM (National Center for Hydrology and Meteorology) has assessed potentially dangerous lakes in Bhutan by combining field observations with satellite imagery from 2016. They identified 12 lakes as potentially dangerous, considering factors such as depth, terrain, and previous inventory data. Nine of these lakes are primarily situated in the Pho Chu River Basin, which necessitates concentrated research efforts and the implementation of protective measures in this particular region [12]. Considering Bhutan's past occurrences of glacial lake outburst floods (GLOFs), notably the catastrophic event in 1994, proactive measures are imperative to address these risks [13].

In this study, we propose to utilize satellite data spanning from 1992 to 2022 to conduct a detailed analysis of decadal change in glaciers and glacial lakes within the Mo Chu catchment region. The concentrated study on the Mo Cho region will fill the evidence gap with the trend of change of glacier and glacier lake. Remote sensing offers a unique advantage in providing large-scale, synoptic views of glacier dynamics over extended periods which detects the long-term changes and trends [12]. Additionally, satellite data can complement ground-based observations, providing a comprehensive understanding of glacier behaviour and its implications for downstream water resources and hazards such as GLOFs.

2 Study Area

The Mo Chu catchment area is found in the northern part of Bhutan, specifically within the Lunana region. It extends from altitudes exceeding 6000 meters near the Chinese border (highest peak: Masang Kang at 6710 meters) to 1220 meters where it meets the Pho Chu River at Punakha Dzong. After this confluence, the river is known as Punatsangchu within Bhutan and Sankosh River in India before it gradually flows into the Brahmaputra River [14]. Figure 1 shows the map of the study area.

The latitude and longitude of the catchment are 27°37'59" N and 89°49'03" E respectively. Two potentially dangerous glacial lakes (PDGLs) identified by NCHM are "Mo_gl235" which is excluded due to lack of survey and Sintaphu Tsho.

Sintaphu Tsho is situated approximately 85 kilometres upstream from the junction with the Pho Chu River near Punakha. This location marks the first and largest settlement along the potential path of a Glacier Lake Outburst Flood (GLOF), with a population of 21,500 as reported by world population review. Further downstream, at distances of 22 kilometres and 36 kilometres from the confluence, two additional villages are found. Notably, these areas are also home to two significant hydropower projects which are known as Punatsangchhu I and Punatsangchhu II. These projects include building a concrete diversion dam that is 137 meters tall and 279 meters wide across the river. Despite the powerhouses being located underground, the projects may remain susceptible to significant GLOFs [12].

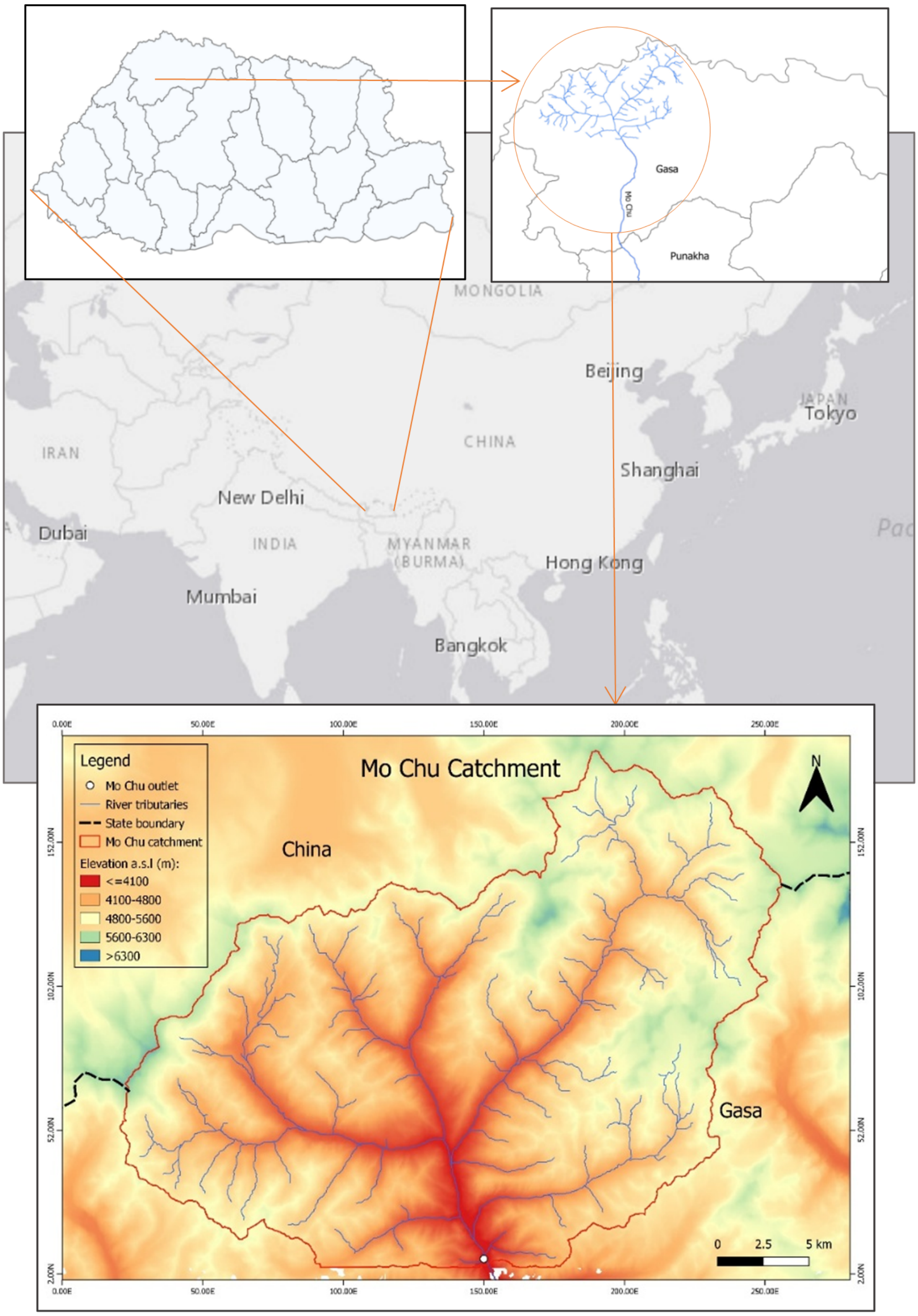

Figure 1: Study area map illustrating the catchment boundary and tributary network feeding into the Mo Chu River

3 Materials

3.1 Landsat-5 TM data

Landsat-5 measures a total of 7 different spectral wavelengths, each serving separate purposes. It divides the earth into different areas called scenes, identified by their path and row numbers. For the research, scene 138/41 was acquired which contained the data on the region of Gasa, among other areas.

The primary data essential for the study consisted of all bands from Landsat 5 TM, except for band 6, obtained from the US Geological Survey (USGS) for earlier periods. The data acquired from Landsat has been used in mapping and monitoring the physical characteristics of the Earth's surface and its frozen components like glaciers and ice caps. In recent years, the launch of advanced satellites, the improvement of sensor technologies, and the creation of sophisticated tools have made remote sensing a more effective and efficient way to monitor, assess, and manage hazards that are related to glaciers [15]. It can also be used to study the trend of glacier and glacial lake changes in any region over long periods.

3.2 Sentinel-2 data

Similar bands to those of Landsat were acquired from Sentinel 2 as well for later periods. Sentinel-2 ensures frequent and timely acquisition of imagery for monitoring dynamic processes and changes over time. Sentinel-2, a key part of the European Space Agency's Sentinel program, has been pivotal in Earth observation since its launch on June 23, 2015. Equipped with the Multispectral Instrument (MSI), it captures detailed high-resolution imagery across different spectral bands, aiding in land cover analysis, vegetation monitoring, and environmental studies. Using several satellites within the Sentinel-2 group, the system achieves revisit intervals of 10 days at the equator with one satellite and 5 days with two, making it well-suited for obtaining cloud-free observations. Moreover, its swath width of 290 kilometres ensures extensive coverage during each pass.

3.3 Temperature and precipitation data from POWER NASA.

The multispectral raster data obtained from POWER NASA covers from 1992 to 2024, which is vital for analyzing major climatic drivers like temperature and precipitation. It was established by NASA and partners, where POWER (The Prediction of Worldwide Energy Resources) offers researchers reliable climate data for diverse applications, from climate modelling to renewable energy assessment. By utilizing this data, it helps gain insights into long-term climate trends and extreme weather events, aiding our understanding of Earth's climate system and its impacts. The details of satellite images that are used in the study are shown in Table 1.

Table 1: Details of satellite image employed in the study

Satellite sensor	Month of Acquisition	Bands used	Spatial (m)	Temporal (days)
Landsat 5 TM	Jan & Oct (1991, 1992, 1994, 1997, 1999, 2004, 2005, 2006, 2007, 2009, 2011)	B1 (Blue) B2 (Green) B3 (Red) B4 (NIR) B5 (NIR) B7 (MIR)	30	16
Sentinel 2	Jan & Oct (2015, 2018, 2020, 2022)	B2 (Blue) B3 (Green) B4 (Red) B8 (NIR) B11 (SWIR)	10	5

Table 2: Details of Temperature and precipitation data from POWER NASA

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperature at 2m (°C)	-8.37	-7.29	-3.9	-0.39	3.5	7.26	8.01	7.47	5.72	1.24	-2.75	-6.31
Precipitation (mm/day)	0	0.04	0.05	0.19	0.7	1.54	4.99	4.83	1.24	0.13	0	0.01

The spectral band images were performed with atmospheric correction and the creation of a composite band for the analysis followed by Depth of Image (DOI) correction. The Landsat and Sentinel satellite images were transformed from black and white to colour by merging certain bands (Landsat: 1-7 excluding 6; Sentinel: 2, 3, 4, 8, 11) and assigning red, green, and blue hues. Figure 2 shows the natural colour composite of the Mo Chu catchment. Subsequently, the Mo Chu area was isolated from these colourized images using a shapefile to generate a foundational map that is ideal for tracking and studying variations in glaciers and lakes.

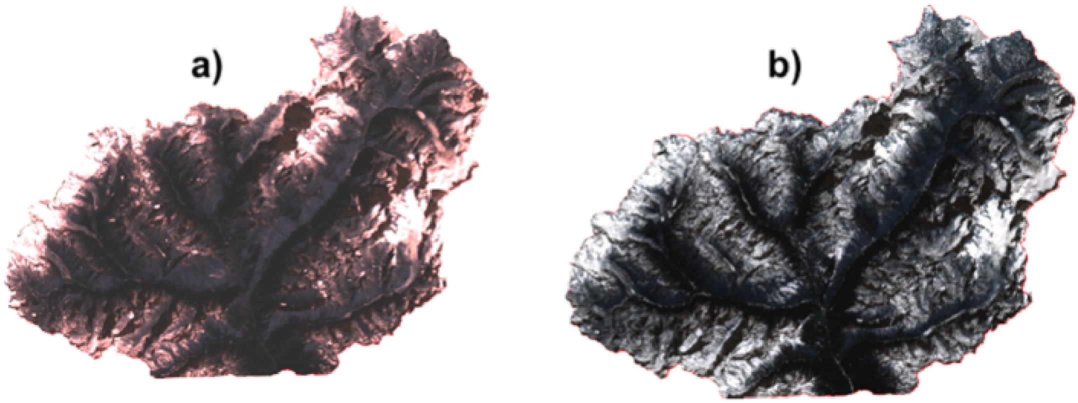

Figure 2: Natural color composites of the Mo Chu catchment: (a) Landsat image from 1992 and (b) Sentinel-2 image from 2022, used to observe glacier and lake extent.

4 Methodology

The study categorized characteristics in NDSI and NDWI maps by reclassify according to their index values. This resulted in the generation of new maps with colour-coded characteristics for simpler recognition. Analyzing these maps and their attribute tables enabled the calculation of the total area covered by each type of characteristic, unveiling the distribution and makeup of characteristics within the catchment area. To guarantee consistency between Landsat (30m) and Sentinel-2 (10m) data for precise area computations, Landsat images underwent resampling to a resolution of 10m. The monthly and yearly weather data covering more than thirty years from January 1992 to December 2022 for the area provides a detailed understanding of the climate patterns in the region from Power NASA. The information includes the air temperature recorded at a 2-meter height above the ground in Celsius and the daily precipitation in millimeters which are correlated in the results section. The methodology flowchart adopted for the study is shown in Figure 3.

4.1 Normalized Difference Snow Index (NDSI)

The process of identifying glaciers involves analyzing NDSI values [16], which focuses on the differences in reflectance between green and shortwave infrared bands. In this study, Landsat satellite images taken in January, a month with minimal cloud cover, were used for the year 1992. Band 2 (green) and Band 5 (shortwave infrared) were utilized to produce a raster band output with NDSI values for each pixel from Landsat 5TM for the year 1992. In addition, Band 3 (green) and Band 11 (shortwave infrared) were also used to create another raster band output, which helped in delineating glacier boundaries for the year 2024.

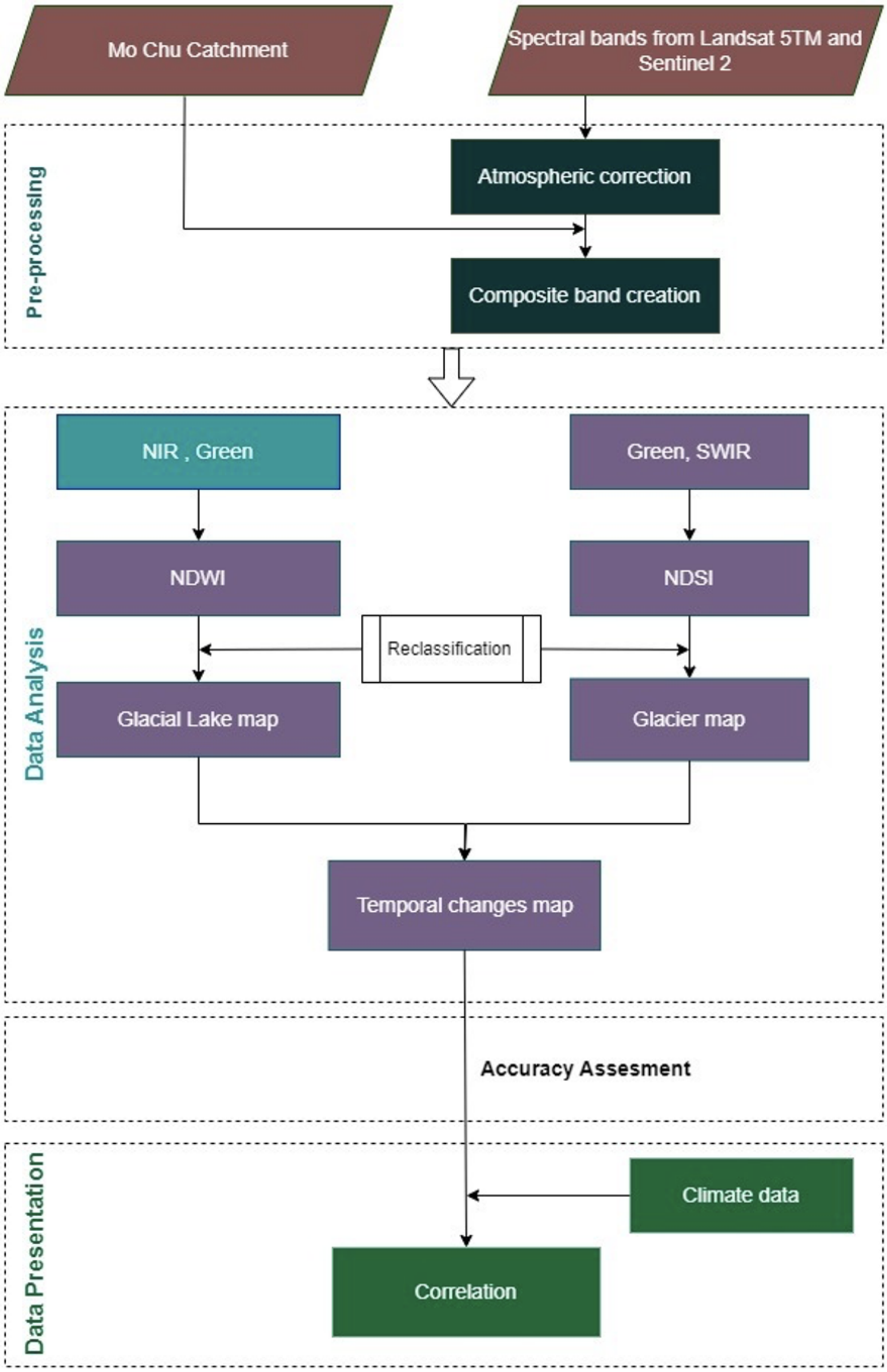

Figure 3: Flowchart outlining the methodological framework adopted for the analysis of glacier and glacial lake dynamics in the study area.

NDSI is a band ratio technique used for mapping snow cover. It computes the normalized difference between the reflectance levels of the visible (green) and shortwave infrared (SWIR) wavelength bands. NDSI is particularly responsive to the presence of snow but does not effectively detect bare ice [17]. It is computed using the formula [17]:

$$\text{NDSI} = \frac{G - \text{SWIR}}{G + \text{SWIR}}$$

The range of NDSI values typically falls between -1 and 1. Positive values, particularly those above 0.4, generally indicate the presence of snow, while negative values suggest the absence of snow or the dominance of other surface types.

4.2 Normalized Difference Water Index (NDWI)

Field surveys for glacier lakes are challenging because of their remote and rugged locations in high mountain areas. NDWI (Normalized Difference Water Index) analysis was used to locate glacial lakes. The green band (band 2 for Landsat, band 3 for Sentinel-2) was merged with the near-infrared band (band 4 for Landsat, band 8 for Sentinel-2) to generate an image. This image assigns a unique NDWI value to every pixel, to identify regions with substantial water content, potentially indicating the presence of glacial lakes. Satellite-based mapping of these lakes frequently depends on the NDWI method [18], which relies on the water's sensitivity to the Green (reflectance) and Near-Infrared bands (absorption). A threshold of 0.2 was used to identify surface water features [18].

$$\text{NDWI} = \frac{G - \text{NIR}}{G + \text{NIR}}$$

where G = The spectral reflectance in the green wavelength NIR = The spectral reflectance in the near-infrared wavelength

Positive values represent water features, while negative values (or zero) indicate soil and terrestrial vegetation. For Landsat 5 TM data, Band 2 (green) and Band 4 (NIR) are utilized. The Band 3 (green) and Band 8 (NIR) are used from Sentinel 2.

4.3 Change analysis

To calculate the change in glacier and glacial lake areas within the given period is calculated using [19]:

$$\text{Rate of change} = \frac{A_a - A_b}{A_b \times P} \times 100$$

where A is the areas estimated in "a" which is the recent year and "b" for the older one and P is for the period.

5 Result

5.1 Glacier and their changes

Satellite data from the last thirty years indicates a significant decline in glacier area within the Mo Chu basin. A thorough examination of the entire basin indicates that in 1992, glaciers covered approximately 183 km2, constituting nearly 30% of the basin's total area. By 2024, this glacier-covered area had diminished to around 109 km2, accounting for almost 18% of the basin's total area. Most of the glaciers in the basin have clean ice, while debris cover is predominantly observed towards the glacier's terminus. Figure 4 illustrates the glaciers identified in 1992 and 2024, highlighting notable changes, while Figure 5 compares the glacier areas in 1992 and 2024. While the biggest changes in glacier area come from very large glaciers (since they cover more ground), smaller glaciers are disappearing or shrinking much faster in number [19].

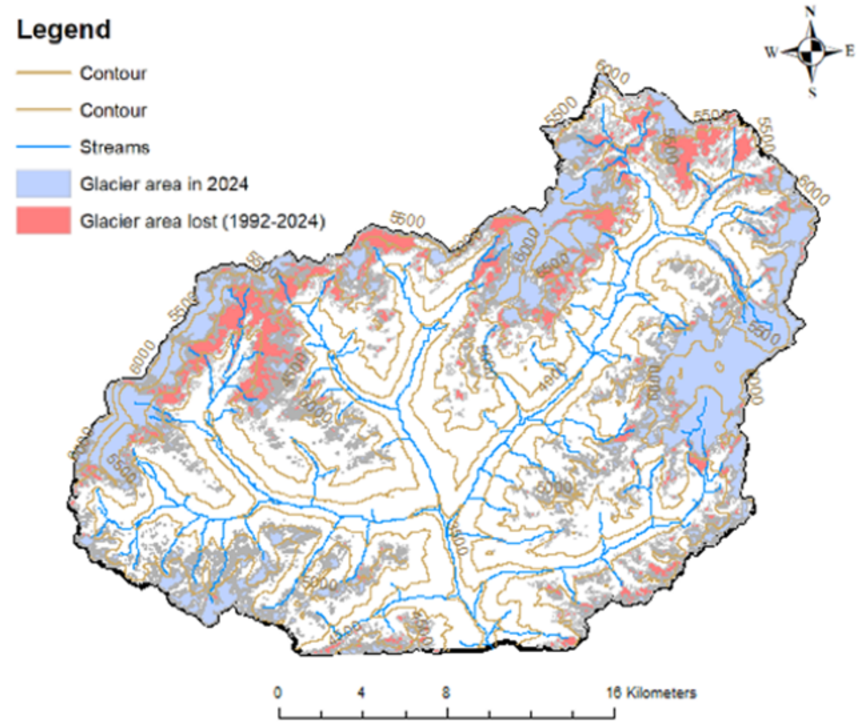

Figure 4: The extent to which the glaciers have diminished between 1992 and 2024.

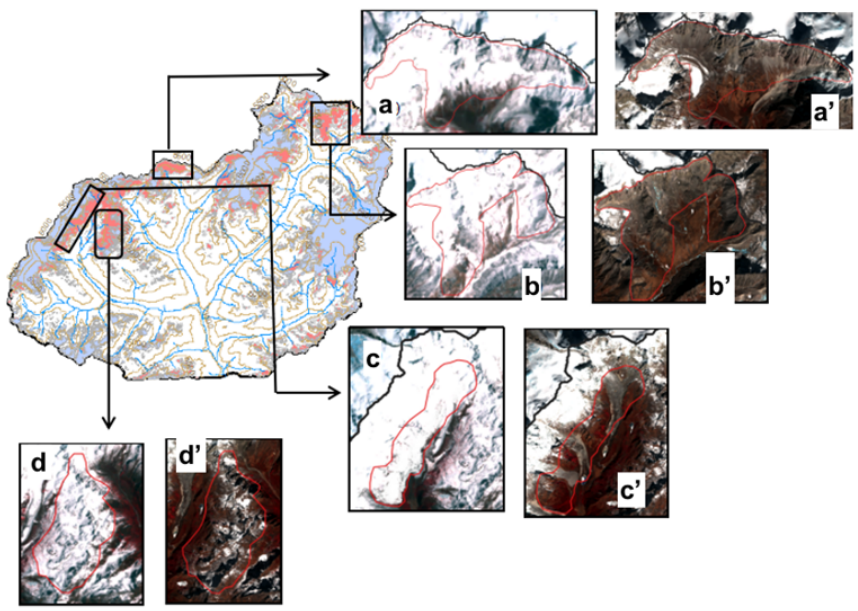

Figure 5: Comparison of glacier extent at four locations: (a–d) in 1992 and (a'–d') in 2024, showing significant glacier retreat and disappearance.

5.2 Glacial lakes and their changes

Analysis of glacial lake extent within the study area revealed a significant increase between 1992 and 2022. The area covered by glacial lakes in 1992 was 2.1 km^2. By 2022, this area had grown to 5.6 km^2, representing an increase of 3.5 km^2. These findings suggest a substantial expansion of glacial lakes within the catchment area, potentially linked to climate change and glacial retreat. With ongoing climate warming, these lakes could potentially increase in size [20]. Figure 5 illustrates the glaciers that vanished in 2024, which were present in 1992. Figure 6 shows the change in glacial lakes from 1992 to 2022. Figure 7 shows the lakes which were newly developed, which have undergone no change and which disappeared respectively.

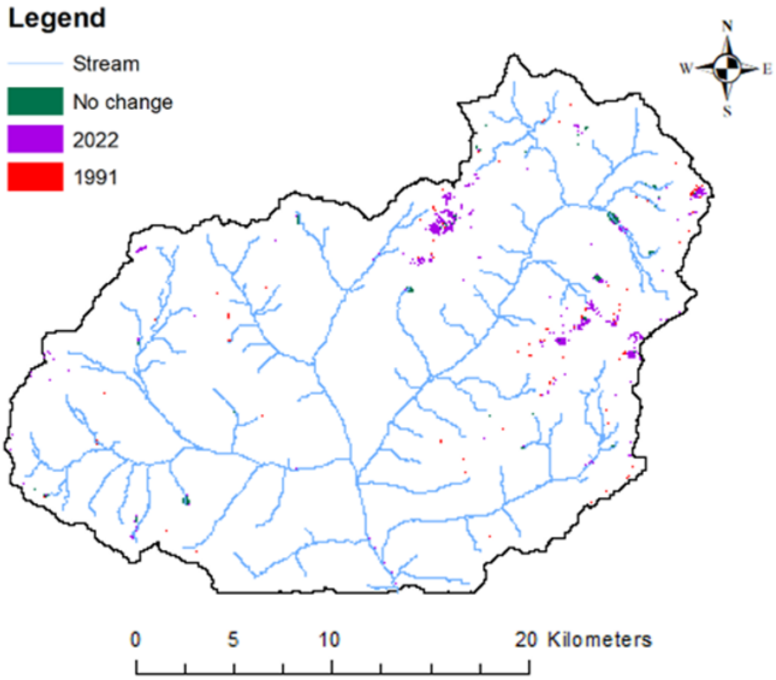

Figure 6: Glacial lakes were identified in 1992 to 2022

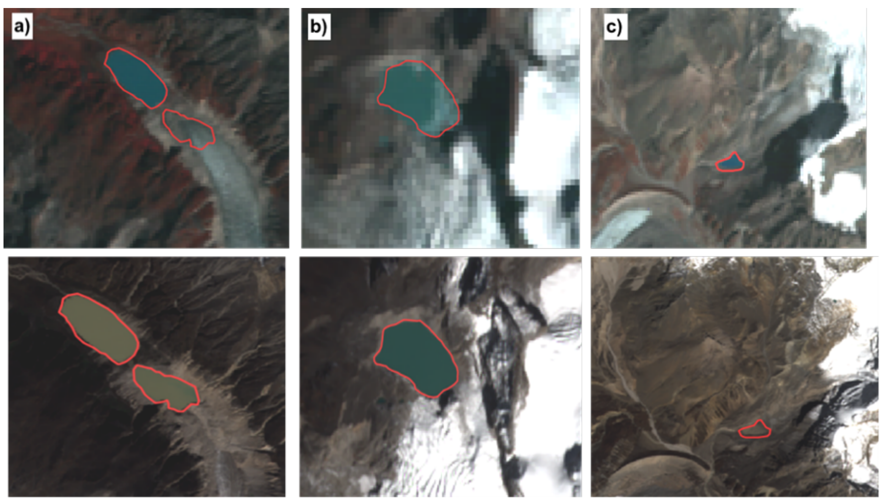

Figure 7: a) shows a new lake developed below the Sintaphu tsho, b) Mo_gl235 lake with no changes and c) shows the disappearance of the lake in 1992 and 2022.

Table 3: Attribute table of glaciers for January, 2024

Sl.no	Classification	No. of pixels	Area (sq. km)	Percentage area
1	Rock/debris/water	3440715	344.06	55.72
2	Snow	1652611	165.20	26.72
3	Glacier	1085261	108.53	17.56

Table 4: Attribute table of glaciers for January 1992

Sl.no	Classification	No. of pixels	Area (sq. km)	Percentage area
1	Rock/debris/water	2516202	251.62	40.74
2	Snow	1839301	183.93	29.80
3	Glacier	1822790	182.28	29.46

Table 5: Attribute table of glacial lakes for September 2022

Sl.no	Classification	No. of pixels	Area (sq. km)	Percentage area
1	Rock/debris/Glacier	6123049	612.2	98.2
2	Glacial lake	55538	5.6	1.8

Table 6: Attribute table of glacial lakes for September 1992

Sl.no	Classification	No. of pixels	Area (sq. km)	Percentage area
1	Rock/debris/Glacier	6158049	615.8	99.1
2	Glacial lake	21830	2.1	0.9

5.3 Change analysis

The glacier area has been shrinking at a rate of -1.26% per year from 1992 to 2024, showing the impact of climate change. This negative trend is a result of glaciers melting and retreating faster due to rising temperatures. Although the yearly decrease may seem minor, it accumulates over time, leading to a significant loss of ice mass. Conversely, the extent of glacial lakes has increased by 5.5% between 1992 and 2022, indicating substantial growth in these water bodies over 30 years.

5.4 Correlation analysis

Glaciers are very responsive to climate variations and serve as prominent markers of global warming [21]. Analysis of factors affecting glaciers in the Mo Chu catchment reveals a potential link between rising temperatures and glacial retreat. The graph suggests a positive correlation between temperature and precipitation, while a negative correlation exists between temperature and both glacier area and its rate of change. This indicates that as temperatures increase, glaciers shrink (glacier area decrease) while precipitation might increase. The correlation analysis graph between glaciers, glacial lakes, temperature and precipitation is shown in Figure 8.

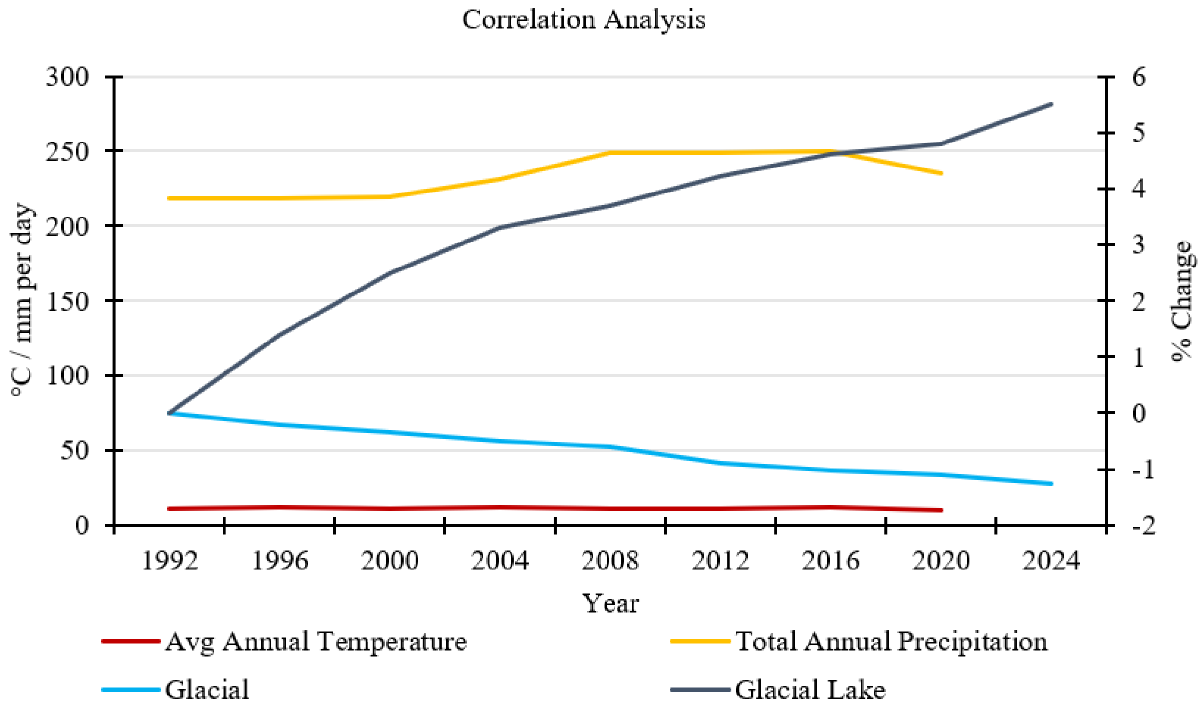

Figure 8: Correlation analysis graph between glaciers, glacial lakes, temperature and precipitation

5.5 Validation

The validation procedure involved utilizing the Randolph Glacier Inventory (RGI) as a benchmark dataset. The most recent subset of regional glaciers for the study area was acquired from the RGI website. After examining the data, the glacier extents mapped closely matched the data from the RGI. Most of the glaciers aligned well in terms of their location, size, and shape. However, a small number of glaciers had slight differences which could be due to changes in the glacier outlines or limitations in the satellite imagery resolution of both datasets. The accuracy of the result was verified by obtaining percentage errors [22] as shown:

Absolute Error (E):

$$E = \text{Observed Value (O)} - \text{Expected Value (T)}$$

Absolute Percentage Error (%E):

$$\%E = \frac{\text{Observed Value (O)} - \text{Expected Value (T)}}{\text{Expected Value (T)}} \times 100$$

$$= \frac{108.53}{106.3} \times 100$$

$$= 2.09\%$$

This validation is done for the area of glaciers of the year 2024 and the area of the glacier inventory map which shows an error of 2.09

6 Discussion

As global warming intensifies, there is increasing emphasis on tracking glacial changes as critical indicators of climate change [23]. The findings from this study indicate a substantial retreat of glaciers in the Mo Chu catchment declining from 183 km^2 in 1992 to 109 km^2 in 2024. This is consistent with previous work in the Dangme Chu and Mago Chu basins, where glacial retreat and lake expansion have been similarly observed [4].

The retreat rate observed in this study (1.26% per year) aligns with the findings from Hugonnet et al. (2021), who reported accelerated global glacier mass loss in the 21st century. Moreover, the observed growth of glacial lakes by 5.5% over 30 years supports patterns noted by Ahmed et al. (2021)[24], who documented lake expansion across the Himalayan region and highlighted the associated risks of glacial lake outburst floods (GLOFs).

Smaller glaciers appear to be retreating more rapidly, as also noted in Zhao et al. (2020)[25], who emphasized the vulnerability of small glaciers in the Himalayas due to their limited ice mass and greater climatic sensitivity. The emergence of new lakes and the disappearance of others mirrors similar transitions reported in the Kanchenjunga region and the Sikkim Himalaya, where changing topography and climatic shifts alter glacial hydrology [26], [27]. The patterns observed in Mo Chu thus not only confirm previously documented regional trends but also underline the urgent need for ongoing remote sensing-based monitoring to manage water resources and mitigate potential hazards.

7 Conclusion

This study reveals significant transformations in the Mo Chu catchment over the past three decades. Glacier area declined from 183 km^2 in 1992 to 109 km^2 in 2024, indicating a retreat rate of 1.26% per year, which reflects the increasing impact of climate change in the Eastern Himalayas [4], [6].

At the same time, glacial lakes expanded from 2.1 km^2 to 5.6 km^2 between 1992 and 2022. This increase of 5.5% suggests a growing hazard potential for downstream communities due to possible glacial lake outburst floods [20], [24].

Temperature and precipitation data from NASA POWER show a positive correlation with each other, while glacier area is negatively correlated with temperature. These trends underscore the complex interplay between climatic drivers and glacier-lake dynamics.

While this analysis contributes valuable insight into long-term changes in the Mo Chu basin, further research is needed to examine additional variables such as snow cover, humidity, and evaporation. Comparative analysis with adjacent basins and expanded field validation would enhance the understanding of broader regional cryospheric trends [19], [28].

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