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Postprint: Spatiotemporal Variation Analysis of Glacial Lakes in the Western Nyenchen Thanglha Mountains

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Abstract

Based on glacial lake data extracted from multi-source, multi-temporal remote sensing imagery and DEM, this study analyzed the multi-dimensional distribution changes of glacial lakes in the western Nyenchen Thanglha Mountains from 1991 to 2017, and investigated the relationship between variations in glacial lake number and area and changes in temperature and precipitation. The results indicate: (1) In recent years, both the number and area of glacial lakes in the study area have exhibited an increasing trend, with the number of glacial lakes increasing by 161 and the area increasing by 1.185 km^2. Specifically, there was steady growth from 1991 to 2006, followed by substantial growth from 2006 to 2017. (2) Both the area and number of glacial lakes showed increasing trends within the mid-to-high altitude range. Newly formed glacial lakes were mainly distributed at elevations of 5400–5700 m, accounting for 72.41% of the total number of glacial lakes. (3) The growth rates of glacial lakes varied among different aspects. Southwest-facing glacial lakes grew relatively rapidly, while north-facing glacial lakes grew relatively slowly. (4) Glacier melting induced by rising temperature is an indirect factor for glacial lake growth, whereas precipitation is an important factor. Small-area glacial lakes are more sensitive to climate with more significant changes, while large-area glacial lakes show smaller change magnitudes, indicating that the dynamic changes of glacial lakes are closely correlated with climate change. Investigating the changes in glacial lakes in the western Nyenchen Thanglha Mountains holds important indicative significance for the prediction of glacial lake outburst flood disasters.

Full Text

Preamble

Spatial-Temporal Variation Analysis of Glacial Lakes in the Western Nyainqentanglha Range

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Abstract: Based on multi-source, multi-temporal remote sensing imagery and DEM data, this study analyzes the distribution and multi-dimensional changes of glacial lakes in the western Nyainqentanglha Range from 1991 to 2017, and examines the relationships between changes in glacial lake number and area with variations in temperature and precipitation. The results indicate: (1) Both the number and area of glacial lakes in the study area show an increasing trend, with the number rising by 161 and area expanding by 1.185 km^2 over the 26-year period. Growth was steady from 1991 to 2006, then accelerated substantially from 2006 to 2017. (2) Glacial lake area and number exhibit increasing trends across middle and high elevation zones. Newly formed lakes are concentrated primarily between 5400–5700 m, accounting for 72.41% of the total lake count. (3) Growth rates vary among lakes with different aspects. Southwest-facing lakes show the most rapid expansion, while north-facing lakes grow relatively slowly. (4) Glacier melting induced by rising temperature is an indirect factor driving lake growth, while precipitation represents a crucial direct factor. Small lakes demonstrate greater sensitivity and more pronounced changes in response to climate, whereas large lakes show smaller variation amplitudes. These findings demonstrate that glacial lake dynamics are closely linked to climate change and provide important insights for predicting glacial lake outburst flood hazards in the western Nyainqentanglha Range.

Keywords: western Nyainqentanglha Range; remote sensing; glacial lake; climate change

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Introduction

Glacial lakes are water storage systems that form in depressions created by glacial erosion and melting, typically located above hydrological base levels. Their development is influenced by seasonal and interannual timescales, representing a product of combined climate change and glacial retreat. Consequently, most glacial lakes are transient features and are considered natural indicators of global change. Under the trend of global warming, significant glacial retreat has been observed across High Asia, often accompanied by changes in glacial lakes. The morphological characteristics and dynamics of these lakes not only reflect broader climate trends but also provide early warnings for glacial lake outburst flood (GLOF) hazards. The Tibetan Plateau contains numerous large moraine-dammed lakes that have expanded considerably in recent decades, suggesting that the region may experience higher frequency and magnitude of GLOF events than other areas. Effective acquisition of glacial lake information and monitoring of lake conditions can help identify high-risk lakes and enable timely hazard assessment and forecasting.

Recent research has primarily focused on large-scale regions such as the Himalayas, Mount Everest, and the Koshi River basin, with few studies addressing smaller-scale areas like the Nyainqentanglha Range. However, as Nyainqentanglha represents a major glacial lake distribution region in High Asia, analyzing its glacial lake characteristics and changes holds significant practical value.

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1 Study Area and Methods

1.1 Study Area Overview

The Nyainqentanglha Range is situated at the junction between the Namco and Nyingchi regions of Tibet, extending east-west from the Gangdise Mountains in the west to the Hengduan Mountains near Nagqu in the northeast, adjacent to the Lhasa River basin—the largest tributary of the Yarlung Tsangpo River. Elevations range from 3000–7000 m, with an average of 5500 m. The core study area is located in the western Nyainqentanglha Range (30°34 –30°34 N, 89°51 –90°49 E), with its boundary shown in [Figure 1: see original paper]. Glaciers in the western section are classified as sub-continental, while the eastern section is strongly influenced by the Indian Ocean southwest monsoon, receiving abundant precipitation with lower snowline elevations and concentrated glacial distribution. The western section represents China's largest concentration of continental glaciers and one of the most intensely glaciated centers at mid-low latitudes globally.

The region experiences a semi-arid continental climate with mean annual temperatures below 0°C and annual precipitation of 300–400 mm, concentrated primarily in summer. During summer, warm and humid monsoonal air masses control the climate, transporting substantial moisture through the Yarlung Tsangpo valley, making eastern Nyainqentanglha the highest precipitation region on the Tibetan Plateau, with July precipitation accounting for 40% of the annual total. Summer daily maximum temperatures can reach 20°C, promoting intense glacial melting and lake growth. In winter, westerly circulation dominates, delivering cold, dry air masses from the Tibetan Plateau, resulting in low precipitation and temperatures, with minimum temperatures reaching -13.7°C.

1.2 Data Sources

This study utilizes remote sensing imagery, DEM data, and meteorological data. Remote sensing data include Landsat TM/ETM+/OLI images and Google Earth imagery, sourced from the US Geological Survey (https://glovis.usgs.gov/app), the Chinese Geospatial Data Cloud (http://www.gscloud.cn/), and BIGEMAP (http://www.bigemap.com/). When selecting imagery, acquisition timing and cloud cover must be considered. Stable autumn scenes with minimal cloud cover were chosen to reduce interference in lake extraction. Additionally, Level-1 data with 15 m resolution from Google Earth were used as reference for accuracy assessment .

The SRTM DEM data (90 m resolution) were obtained from NASA (https://urs.earthdata.nasa.gov), resampled to 90 m × 90 m. Derived elevation, aspect, and slope information were used for analyzing glacial lake distribution changes. Meteorological data, including annual mean temperature and precipitation spatial interpolation datasets for 1990–2014, were obtained from the Chinese Academy of Sciences Resource and Environmental Science Data Center (http://www.resdc.cn). Compared with sparse meteorological station data in remote areas, this interpolated dataset provides higher precision and reliability.

1.3 Research Methods

Numerous remote sensing methods exist for water body extraction, including visual interpretation with manual digitization, spectral threshold-based methods, machine learning approaches (convolutional neural networks, decision trees, support vector machines), and image segmentation methods ("global-local" method, object-oriented methods, etc.). Given the small study area and the fact that most glacial lakes are located at glacier termini with areas <0.05 km^2, automated or semi-automated extraction methods often produce inaccurate lake boundaries requiring extensive manual correction. Therefore, manual digitization was selected to obtain high-precision lake information.

Using GIS software, glacial lakes were vectorized manually. To distinguish lakes from mountain shadows, hillshade rendering was performed based on solar elevation and azimuth angles before extraction. Digitization error was maintained within one pixel. Extracted results were overlaid with SRTM-derived slope maps, where water bodies with slopes $<15°$ were identified as glacial lakes and those $>15°$ as shadow interference, which were subsequently removed [15]. High-resolution Google Earth imagery (15 m) and topographic maps from similar periods assisted in discrimination. Spatial analysis of extraction results provided lake attributes including ID, area, mean elevation, slope, aspect, change type, and size class.

Assuming lake area extraction errors follow a Gaussian distribution [16], area error can be calculated through lake perimeter, pixel count, image resolution, and random weight error:

$$U_\alpha = \lambda \times \sqrt{p \times \lambda} \times \frac{w}{2}$$

where U_α is lake area error (m^2), λ is maximum pixel resolution (m), p is lake perimeter (m), and w is random weight error, assuming 0.5 pixel error.

Image quality, pixel resolution, geometric registration techniques, and operator experience all affect extraction accuracy. This study focuses on regional-scale patterns of glacial lake change from 1991–2017 rather than pixel-level changes of individual lakes, making errors largely systematic. Furthermore, boundary errors are partially offset when comparing multi-temporal data, limiting the impact of registration errors on overall change detection.

Pearson correlation analysis was used to examine relationships between temperature, precipitation, and lake changes. The linear correlation coefficient (Pearson's r) measures linear relationships between variables. For random variables X and Y, the population correlation coefficient is:

$$\rho_{XY} = \frac{\mathrm{Cov}(X,Y)}{\sqrt{\mathrm{Var}(X)\mathrm{Var}(Y)}}$$

where Cov(X,Y) is covariance and Var(X), Var(Y) are variances. The sample correlation coefficient r is calculated as:

$$r = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})^2 \sum_{i=1}^{n}(Y_i - \bar{Y})^2}}$$

The absolute value of r indicates correlation strength.

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2 Results

2.1 Overall Distribution Characteristics

Glacial lake information for 1991–2017 was extracted (see [Figure 2: see original paper] for 2017 results). Statistical analysis reveals the number and area changes (Table 2). From 1991 to 2017, the number of glacial lakes increased by 161 and area expanded by 1.185 km^2, with number growth rate of 73.51% but area growth rate of only 22.37%, indicating substantial increase in lake count without proportional area expansion.

Overall, both lake number and area show increasing trends. Area growth was fastest during 2000–2006 (0.075 km^2), slowest during 2006–2017 (0.021 km^2), and moderate during 1991–2000, while lake number growth was fastest during 2006–2017 (18.01%). The 1991–2000 period showed the smallest growth magnitude, with number and area growth rates of only 6.59%.

2.2 Temporal Change Characteristics

Glacial lakes in the western Nyainqentanglha Range exhibited formation, disappearance, shrinkage, and expansion during 1991–2017, with spatial distributions shown in [Figure 3: see original paper]. Changes concentrated in the northeastern study area, dominated by expansion and new lakes, accounting for 87.72% and 77.05% of total changes respectively, while disappeared lakes were minimal at 4.53%.

New lakes numbered 161, primarily distributed between 5400–5800 m, with total area of 1.373 km^2, representing the largest change type in both number and area. The average area of new lakes is 0.008 km^2, with moraine-dammed lakes being the dominant type and the primary contributor to lake size increase. [Figure 4: see original paper] shows two typical new lakes at 5623 m and 5560 m, both formed by glacial retreat.

Disappeared lakes totaled 10, mainly at 5380 m and 5350 m, likely drained by moraine dam failure. Shrunken lakes numbered 47, with area reduction of 0.328 km^2, primarily between 5400–5600 m, dominated by moraine-dammed lakes. [Figure 5: see original paper] shows a typical shrinking lake at 5683 m, reduced due to insufficient meltwater supply from continued glacial retreat.

Expanded lakes numbered 66, with area increase of 2.119 km^2, mainly between 5500–5900 m, primarily lateral and terminal moraine-dammed lakes. The typical expansion lake shown in [Figure 5: see original paper] at 5670 m is a lateral moraine-dammed lake formed by water impoundment behind a lateral moraine ridge.

2.3 Elevation-Based Change Characteristics

Glacial lakes in the Nyainqentanglha Range are distributed between 4900–6100 m, showing a unimodal distribution pattern with peak occurrence at 5400–5700 m, where lake number accounts for 72.41% of the total and area accounts for 62.6%. The entire elevation range was divided into 100 m intervals for analysis.

Lakes below 5300 m show relatively stable area with minimal change, indicating low-elevation lakes are distant from glaciers and less affected. The 5300–5400 m zone shows decreasing area after 2000, while 5400–5500 m lakes remained stable. The 5500–5700 m zone is the primary distribution area, with both number and area proportions exceeding other zones. Glacial terminus elevations follow a normal distribution concentrated at 5400–5700 m, consistent with significant lake changes in this mid-high elevation zone, confirming that glacial retreat at these elevations drives lake formation and evolution.

Lakes above 5700 m show rapid number and area growth after 2000, particularly in the 5800–5900 m zone with area growth rates of 0.025 $km^2 \cdot (5a)^{-1}$, indicating high-elevation lakes are more sensitive to climate change and benefit from glacial retreat at higher altitudes [31]. This aligns with severe glacial retreat above 5700 m in the region [36].

2.4 Aspect-Based Change Characteristics

Glacial lake area varies by aspect, predominantly distributed in south, east, southeast, and southwest orientations (see [Figure 7: see original paper]). South- and southwest-facing lakes show the most significant changes, with south-facing lake numbers nearly doubling during 2006–2017 and southwest-facing numbers increasing 2.1 times during 1991–2000. North- and northwest-facing lakes show minimal change, particularly north-facing lakes which remain essentially stable, consistent with weaker glacial retreat on north slopes and stronger retreat on south slopes [33].

Area proportions are highest on south-facing slopes (22.68%), followed by north-facing (21.67%), southeast (18.01%), and southwest (17.75%), with northwest-facing being lowest at 9.99%. South-facing slopes receive more solar radiation, accelerating glacial melt and contributing significantly to lake expansion.

2.5 Size-Based Change Characteristics

Lakes are natural water storage systems in depressions, typically forming in low-slope valleys or plateau mountain terrain with complex topography. Glacial lakes form in flat depressions after glacial action, usually at small scales. Lakes were classified into five size categories (Table 4). The smallest lake area is 0.0002 km^2, largest 0.582 km^2, with mean area 0.017 km^2. Lakes <0.01 km^2 account for over 80% of total number, while those >0.2 km^2 represent only 4.53% of number but 21.8% of total area, demonstrating an inverse relationship between size and frequency.

Lakes <0.01 km^2 show fastest growth with number increase rate of 73.52%, contributing most to area increase. Lakes of 0.01–0.05 km^2 are most numerous and grow steadily with number increase of 87.72%. These two small-size categories drive the overall increase in lake number and area, indicating more intense evolution of small lakes. Medium-sized lakes (0.05–0.1 km^2 and 0.1–0.2 km^2) show fluctuating trends, while large lakes >0.2 km^2 are most stable with area increase of only 6.12%, located at low elevations with strong stability, less affected by glacial retreat and climate.

2.6 Climate Factor Analysis

Temperature and precipitation directly reflect climate change and are primary factors affecting glacial lakes. Variations influence glacial growth/retreat, with both meltwater and precipitation providing material sources for lakes.

Annual mean temperature data (1990–2014) show large fluctuations but overall warming trend, with minimum -1.07°C (1997) and maximum -3.38°C (2005). Although temperature rise causes glacial melting, correlation coefficients between temperature and lake area/number are small and not significant (Table 5), indicating temperature is an indirect factor affecting lakes through glacial melt.

Annual precipitation exceeds 400 mm, with larger variation amplitude than temperature, concentrated in 400–800 mm. Precipitation shows an increasing trend, though with smaller magnitude than temperature. Correlation coefficients between precipitation and lake area/number approach 0.5, significantly higher than for temperature, indicating precipitation is a more important factor. New lake formation and expansion may be related to precipitation increases, consistent with the prevalence of new and expanding lakes.

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3 Conclusions

Based on multi-source remote sensing data, this study analyzed spatial-temporal variations of glacial lakes in the western Nyainqentanglha Range from 1991–2017 and their relationship with climate factors:

1) Glacial lake number and area increased continuously, with steady growth from 1991–2006 and accelerated expansion from 2006–2017. Over 26 years, lake number increased by 161 and area by 1.185 km^2.
2) Both lake area and number increased at mid-high elevations. New lakes concentrated at 5400–5700 m, accounting for 72.41% of total number, while low-elevation lakes (<5300 m) showed decreasing area.
3) Growth rates varied by aspect. Southwest-facing lakes expanded most rapidly, while north-facing lakes grew slowly, reflecting differential solar radiation and melt rates.
4) Small lakes (<0.01 km^2 and 0.01–0.05 km^2) were most sensitive to climate, driving overall increases. Large lakes (>0.2 km^2) were stable with small changes.
5) Both temperature and precipitation influence lake evolution. Temperature is an indirect factor through glacial melt, while precipitation is a direct, important factor.

These findings demonstrate close linkages between glacial lake dynamics and climate change, providing important guidance for predicting GLOF hazards in the western Nyainqentanglha Range.

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