Postprint: Remote Sensing Monitoring of Glacier and Glacial Lake Changes in the Yeru Zangbu Basin, Himalaya

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Abstract

The Yeruzangbu River basin is characterized by numerous glaciers and glacial lakes. Glacier meltwater serves as a crucial freshwater resource for the region and constitutes an important supply for glacial lake expansion, while glacial lake outburst floods represent potential natural disasters. Therefore, analyzing the current status and changing characteristics of glaciers and glacial lakes in this region holds significant practical importance. Based on Landsat series remote sensing imagery, this study analyzes the distribution and changing characteristics of glaciers and glacial lakes in the Yeruzangbu River basin from 1990 to 2020. The results indicate: (1) Over the past 30 a, the glacier area in the Yeruzangbu River basin has exhibited an overall retreating trend, shrinking from 167.80 km2 in 1990 to 128.92 km2 in 2020, with a total reduction of 38.88 km2 and an average annual retreat rate of 0.77%·a-1. Furthermore, glaciers in the study area are primarily distributed at elevations between 5800–6400 m and concentrated on slopes of 5°–20°. (2) In contrast to the glacier change trend, glacial lakes showed an overall expansion trend during the study period, increasing from 5.72 km2 in 1990 to 8.81 km2 in 2020, with a total increase of 3.09 km2 over 30 a and an average annual growth rate of 1.80%·a-1. (3) Glacial lakes are mainly distributed within the elevation range of 5000–5600 m, with larger areas on slopes of 0°–10°. Debris-covered glaciers and clean glaciers exert varying degrees of influence on glacial lakes. (4) From 1990 to 2017, temperature and precipitation in the Yeruzangbu River basin fluctuated considerably, with temperature showing an overall upward trend while precipitation exhibited a fluctuating decline, leading to glacier ablation and glacial lake expansion in the basin. Through this research, we aim to provide detailed baseline data on the distribution and changing characteristics of glacier and glacial lake areas in the Yeruzangbu River basin region, offering certain support for disaster prevention and mitigation.

Full Text

Remote Sensing Monitoring of Glacier and Glacial Lake Changes in the Yairu Zangbo Basin, Himalayas

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Abstract

The Yairu Zangbo Basin contains numerous glaciers and glacial lakes. Glacier meltwater serves as a crucial local freshwater resource and constitutes an important supply for glacial lake expansion, while glacial lake outbursts represent potential natural disasters in the region. Therefore, analyzing the current status and changing characteristics of glaciers and glacial lakes in this area holds significant practical importance. Based on Landsat series remote sensing imagery, this study examines the distribution and variation patterns of glaciers and glacial lakes in the Yairu Zangbo Basin from 1990 to 2020. The results indicate: (1) Over the past 30 years, glaciers in the basin have exhibited an overall retreat trend, with area decreasing from 167.80 km^2 in 1990 to 128.92 km^2 in 2020—a total reduction of 38.88 km^2 at an average annual retreat rate of 0.77% · a^{-1}. Glaciers are predominantly distributed at elevations between 5800–6400 m and on slopes of 5°-20°. (2) In contrast to glacier trends, glacial lakes showed overall expansion during the study period, increasing from 5.72 km^2 in 1990 to 8.81 km^2 in 2020—a total increase of 3.09 km^2 at an average annual growth rate of 1.80% · a^{-1}. (3) Glacial lakes are mainly distributed at elevations of 5000-5600 m and on slopes of 0–10°. (4) Debris-covered and debris-free glaciers exert different influences on glacial lakes. (5) Temperature and precipitation in the Yairu Zangbo Basin fluctuated considerably from 1990 to 2017, with temperature showing an overall upward trend while precipitation declined, leading to accelerated glacier melting and glacial lake expansion. This research provides detailed baseline data on the distribution and changing characteristics of glacier and glacial lake areas in the Yairu Zangbo Basin, offering support for disaster prevention and mitigation efforts.

Keywords: glacier; glacial lake; remote sensing monitoring; Yairu Zangbo Basin

1 Introduction

Glaciers serve as critical indicators within the climate system and hold significant importance for understanding global climate change. In recent years, global temperatures have risen universally, with statistics indicating that the global average temperature increased by 1.09 °C in 2019 compared to pre-industrial levels. Affected by climate change, glaciers continue to retreat. Previous research demonstrates that glaciers on the Tibetan Plateau and surrounding regions have generally decreased to current levels from those at the end of the 20th century. The resulting meltwater represents an important freshwater source for arid regions, playing a vital role in local ecological environments and economic development. Although glacier meltwater can temporarily alleviate water shortages, it also poses potential hazards. Some glaciers store pollutants from historical periods, and their melting releases these contaminants into aquatic environments, threatening human health. As important recharge sources, glacial lakes also serve crucial functions in regulating river runoff, protecting biodiversity, and providing tourism value.

The Himalayan region contains extensive glacier coverage and represents a major disaster area for glacial lake outbursts, with numerous outburst events recorded that have caused substantial threats to lives and property. However, the high elevations and steep terrain of the Himalayas severely limit field investigations of glaciers and glacial lakes. Remote sensing technology has become the primary means for glacier and glacial lake monitoring due to its advantages of large-scale synchronous observation and timeliness. For instance, Ji et al. conducted long-term monitoring studies on Himalayan glaciers using Landsat time-series data, revealing rapid glacier retreat with a total area reduction of 29.34 km^2 between 1990 and 2015. Gong et al. monitored glacial lakes in the Koshi River Basin, finding that the number of glacial lakes increased by 42 and their area expanded by 8.81 km^2 from 1990 to 2014.

The Yairu Zangbo Basin is located on the northern slope of the central Himalayas and constitutes the largest tributary of the Pumqu River (known as the Sun Koshi River outside China). The glacial lakes within this basin serve as headwaters for numerous rivers. While An Lina investigated the summer surface water chemistry and hydrogen-oxygen isotope characteristics of the basin, comprehensive studies on glaciers and glacial lakes remain limited. Therefore, this research focuses on glaciers and glacial lakes in the Yairu Zangbo Basin, combining Landsat series satellite data to analyze their changes over recent decades and integrating meteorological data to explore influencing factors.

2 Study Area Overview

The Yairu Zangbo Basin (27°50 -28°10 N, 87°50 -88°09 E) is situated on the northern slope of the central Himalayas, covering an area of 1627 km^2. The terrain rises gradually from north to south, with elevations ranging from 4122–7440 m. The region features high altitude and low temperatures, influenced by plateau mountain climate with precipitation concentrated in summer. According to China’ s second glacier inventory, the basin contained 139 glaciers in 2015 with a total area of 139.39 km^2, predominantly distributed in the southern part of the watershed.

3 Data Sources and Methods

3.1 Data Sources

This study utilized Landsat series imagery downloaded from the United States Geological Survey (https://earthexplorer.usgs.gov/) and the Geospatial Data Cloud (http://www.gscloud.cn/). To accurately extract glacier and glacial lake boundaries while minimizing interference from snow cover and clouds, we selected 15 scenes with low cloud cover (Table 1). Additionally, we employed the ASTER GDEM (Digital Elevation Model) with 30 m spatial resolution, also obtained from the Geospatial Data Cloud.

Given the scarcity of meteorological stations in the high-altitude glacier and glacial lake distribution areas, we selected temperature and precipitation data for the Himalayan region from 1990–2017 provided by the University of Delaware (http://climate.geog.udel.edu/~climate/), which has been widely applied in Himalayan glacier research.

3.2 Research Methods

Previous studies have employed ratio threshold methods, snow cover index methods, or convolutional neural networks for glacier boundary identification. While these methods play important roles in glacier boundary extraction, visual interpretation offers the highest accuracy. Therefore, this study adopted visual interpretation to extract glacier and glacial lake boundary information. Additionally, Google Earth was used for auxiliary verification.

To validate extraction accuracy, we applied the buffer zone method to calculate area extraction errors for glaciers and glacial lakes. The results indicate that error levels meet research requirements (Table 2).

4 Results

4.1 Glacier Area Changes

As shown in Table 3, glaciers in the Yairu Zangbo Basin exhibited a clear retreat trend during the study period. Glacier area decreased from 167.80 km^2 in 1990 to 153.89 km^2 in 2000, 145.66 km^2 in 2010, and 128.92 km^2 in 2020—a total reduction of 38.88 km^2 at an average retreat rate of $0.83\% \cdot a^{-1}$. The retreat rate varied across periods: $0.54\% \cdot a^{-1}$ during 1990-2000 and $0.77\% \cdot a^{-1}$ during 2000–2010, while the 2010–2020 period showed accelerated retreat at $1.15\% \cdot a^{-1}$, significantly higher than previous periods. Overall, the glacier retreat rate in the Yairu Zangbo Basin showed a decreasing trend followed by an increase, with accelerated retreat becoming most pronounced in recent years.

4.2 Glacier Distribution by Altitude

Analyzing glacier distribution by 200 m elevation intervals reveals that retreat magnitude increases with altitude up to 5800–6000 m, where maximum retreat occurs, then decreases at higher elevations. Above 6000 m, glacier retreat becomes negligible. Although glacier retreat is most pronounced at 5800-6000 m, the retreat rate peaks at 5000-5200 m. Previous research indicates that glacier area changes exhibit a positive correlation with elevation, and the Yairu Zangbo Basin shows similar patterns. Using 1990 glaciers as an example, elevations of 5800-6400 m contain the largest glacier area, approximately 64.25% of the total.

4.3 Glacier Distribution by Slope

Based on DEM data, we extracted slope information for glaciers in the basin. Analysis at 5° intervals shows that glacier area is predominantly distributed on slopes of 5°-20°, accounting for 46.02% of the total area. Specifically, the 10°-15° slope range contains 26.18 km^2, representing 15.60% of the total. As slope increases, glacier distribution area gradually decreases while retreat rate increases, reaching maximum retreat rates of 32.77% on 55°-60° slopes, where distribution area is minimal at only 1.55 km^2.

4.4 Debris-Covered vs. Debris-Free Glaciers

Supraglacial debris thickness directly affects glacier melt rates. To comprehensively understand glacier distribution and change characteristics, we classified glaciers as debris-covered or debris-free, analyzing their area, number, and average size in 1990 and 2020.

Results show that debris-covered glacier area retreated by 10.82 km^2 (27.72% retreat rate), while debris-free glacier area retreated by 33.99 km^2 (10.82% retreat rate). Debris-covered glaciers are fewer in number but larger in average size with slower retreat rates, whereas debris-free glaciers are more numerous but smaller in average size with faster retreat rates.

4.5 Glacier Size Distribution and Quantity

To analyze distribution and change characteristics across different scales, we categorized glaciers into six size classes. Table 5 reveals that glacier numbers increased overall by 16 during the study period, with the \$ $0.2km$^{2}\$ class showing the greatest increase (+13 glaciers) and the 0.5-1 km^2 class showing the greatest decrease (-7 glaciers).

In terms of area distribution, the 5-10 km^2 class occupied the largest proportion (51.17 km^2, 30.49% of total), followed by the 10-20 km^2 class (33.78 km^2, 20.15%). The smallest proportion occurred in the >50 km^2 class (4.61 km^2, 2.75%). Only the \$ $0.2km$^{2}\$ class showed area increase, while all other classes decreased, with the 0.5-1 km^2 class retreating most significantly. This demonstrates that smaller glaciers exhibit greater numerical fluctuation, while larger glaciers show greater stability.

4.6 Glacial Lake Area Changes

During the study period, glacial lakes in the Yairu Zangbo Basin showed overall expansion (Table 6). Lake area reached its minimum of 5.72 km^2 in 1990, increased to 6.35 km^2 in 2000 (0.96 km^2 increase, 1.68% $\cdot$ a^{-1}), decreased to 5.72 km^2 in 2010 (0.63 km^2 reduction, 0.94% $\cdot$ a^{-1}), then expanded to 8.81 km^2 in 2020 (3.09 km^2 increase, 4.56% $\cdot$ a^{-1}). The 2010-2020 period exhibited the fastest annual area change rate. Overall, glacial lake area showed a pattern of initial increase, subsequent decrease, then renewed expansion.

4.7 Glacial Lake Distribution by Altitude

Glacial lakes are primarily distributed between 4800-6600 m, with area showing a normal distribution relative to elevation. The 5000-5600 m interval contains the largest lake area, reaching 4.51 km^2 (78.84% of total) in 1990 and 1.72 km^2 (30.10%) in 2020. Analysis of annual area change rates shows that lake area increases most rapidly with elevation, peaking at 6000-6200 m with a rate of 21.15% $\cdot$ a^{-1}, corresponding to the elevation range with maximum glacier distribution.

4.8 Glacial Lake Distribution by Slope

Glacial lake distribution is heavily influenced by elevation, predominantly occurring in depressions and low-lying areas. Analysis by slope interval reveals that lake area is mainly distributed on gentle slopes of 0-10°, accounting for 57.50% of the total (3.29 km^2). As slope increases and terrain becomes steeper, lake area decreases rapidly, with only 0.023 km^2 on 55-60° slopes.

4.9 Different Types of Glacial Lakes

Supraglacial debris inhibits glacier melting, indirectly affecting expansion of adjacent glacial lakes. By analyzing distances between lakes and glaciers, we classified lakes as influenced by debris-covered or debris-free glaciers.

From 1990 to 2020, lakes influenced by debris-covered glaciers increased by 1.03 km^2 (34.80% growth rate) with unchanged numbers but 0.20 km^2 increase in average size. Lakes influenced by debris-free glaciers increased by 2.76 km^2 (74.64% growth rate), with numbers increasing by 8 (88.89% growth) but average size decreasing by 0.01 km^2 (6.67% reduction). This indicates that lakes influenced by debris-covered glaciers change more slowly, are fewer in number, and have larger average sizes, while those influenced by debris-free glaciers change more rapidly, are more numerous, and have smaller average sizes.

5 Discussion

5.1 Response of Glaciers and Glacial Lakes to Climate Change

The primary factors affecting glacier change are temperature and precipitation, with temperature influencing melt and precipitation affecting accumulation. Analysis of temperature and precipitation data from 1990-2017 in the Yairu Zangbo Basin reveals that temperature showed overall fluctuating increase while precipitation exhibited large fluctuations with a general decreasing trend, leading to glacier melting and glacial lake expansion.

Temperature increased by 1.49 °C overall, with a warming rate of 0.06 $°C \cdot a^{-1}$ and amplitude of 2.45 °C. Precipitation decreased by 188.53 mm overall, with an amplitude of 556.23 mm and a decline rate of 11.09 $mm \cdot a^{-1}$. During 1990-2000, both temperature and precipitation showed upward trends, reducing glacier retreat rates and decreasing meltwater supply to lakes, making temperature and meltwater changes important factors for lake variation. During 2000-2010, rising temperature and declining precipitation caused accelerated glacier melting; although increased temperature enhanced lake evaporation and reduced precipitation weakened lake recharge, accelerated glacier melt caused lake area to increase, making glacier melt the dominant factor. During 2010-2017, both temperature and precipitation increased, but temperature rise had stronger effects than precipitation increase, causing accelerated glacier retreat that became the main factor driving lake expansion.

5.2 Co-evolution Characteristics of Glaciers and Glacial Lakes

Spatially, most glacial lakes directly connect to glacier termini. Glaciers are mainly distributed at 5800-6400 m (64.25% of total area), while lakes are concentrated at 5000-5600 m (4.51 km^2). The spatial pattern shows that as glaciers melt extensively, lakes at their termini are directly affected. Temporally, glacier area decreased annually while lake area increased concurrently.

Analysis of temperature and precipitation data reveals that during 1990-2000, glacier area retreated by 13.91 km^2 at 0.54% $\cdot a^{-1}$ while lake area increased by 0.63 km^2 at 0.94% $\cdot a^{-1}$, with both temperature and precipitation showing upward trends. Precipitation was the main factor affecting glacier change, while temperature and meltwater variation were important for lake change. During 2000-2010, glacier area retreated by 8.24 km^2 at 0.77% $\cdot a^{-1}$ while lake area decreased by 0.63 km^2 at 0.94% $\cdot a^{-1}$, with temperature rising and precipitation declining. Glacier melt became the main factor influencing lake change. During 2010-2020, glacier area retreated by 16.74 km^2 at 1.14% $\cdot a^{-1}$ while lake area increased by 3.09 km^2 at 4.56% $\cdot a^{-1}$, with temperature rising and precipitation fluctuating downward. The combined temperature and precipitation effects caused accelerated glacier retreat, with temperature having greater influence than precipitation.

Supraglacial debris also significantly affects glacial lakes in the basin. Lakes connected to debris-covered glaciers show smaller changes and lower change rates because the debris layer inhibits glacier melting, reducing the glacier melt-driven lake expansion and thereby decreasing both the magnitude and rate of lake change.

6 Conclusions

This study reveals the following key findings about the Yairu Zangbo Basin from 1990 to 2020:

1. **Glacier Changes**: Glacier area exhibited a retreat trend, decreasing from 167.80 km^2 in 1990 to 128.92 km^2 in 2020—a total reduction of 38.88 km^2 at an average rate of 0.77% $\cdot a^{-1}$. Glaciers were predominantly distributed at elevations of 5800–6400 m and on slopes of 5°–20°. Both debris cover and glacier size affected the distribution of glacier numbers and areas.

2. **Glacial Lake Changes**: Glacial lake area showed overall expansion, increasing from 5.72 km^2 in 1990 to 8.81 km^2 in 2020—a total increase of 3.09 km^2 representing 54.02% growth at an average rate of 1.80% $\cdot a^{-1}$. Lakes were mainly distributed at elevations of 5000–5600 m and on slopes of 0–10°. Debris-covered and debris-free glaciers exerted different influences on lake development.

3. **Climate Impacts**: Temperature and precipitation fluctuated significantly from 1990 to 2017, with temperature increasing by 1.49 °C overall and precipitation decreasing by 188.53 mm overall. These trends promoted glacier melting and glacial lake expansion in the Yairu Zangbo Basin.

These findings provide detailed baseline data on glacier and glacial lake distribution and change characteristics, offering scientific support for ecological management, water resource utilization, and disaster prevention in the Yairu Zangbo Basin.

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Note: Figure translations are in progress. See original paper for figures.