

Remote Sensing Monitoring of Glacier and Glacial Lake Changes in the Yeru Zangbo Basin, Himalaya (Postprint)

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Abstract

The Yeru Zangbo basin is characterized by numerous glaciers and glacial lakes. Glacier meltwater serves as a vital freshwater resource locally and constitutes a critical supply for glacial lake expansion, while glacial lake outburst floods represent potential natural hazards in the region. Therefore, analyzing the current status and variation 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 characteristics of glaciers and glacial lakes in the Yeru Zangbo basin from 1990 to 2020. The results indicate that: (1) Over the past 30 years, the glacier area in the Yeru Zangbo basin has exhibited an overall retreating trend, decreasing from 167.80 km² in 1990 to 128.92 km² in 2020, with a total retreat of 38.88 km² and an average annual retreat rate of 0.77% · a⁻¹. Furthermore, glaciers in the study area are predominantly distributed at elevations between 5800~6400 m and concentrated on slopes of 5°~20°. (2) In contrast to the glacier variation trend, glacial lakes demonstrated 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 years and an average annual growth rate of 1.80% · a⁻¹. (3) Glacial lakes are primarily distributed at elevations ranging from 5000~5600 m, with greater areal distribution on slopes of 0~10°. Debris-covered glaciers and clean glaciers exert differential influences on glacial lakes. (4) From 1990 to 2017, temperature and precipitation in the Yeru Zangbo basin fluctuated substantially, with temperature showing an overall rising trend while precipitation exhibited a fluctuating decline, resulting in glacier ablation and glacial lake expansion in the basin. Through this research, we aim to provide detailed baseline data on the distribution and variation characteristics of glacier and glacial lake areas for the Yeru Zangbo basin region, offering certain support for disaster prevention and mitigation.

Full Text

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

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Abstract

There are numerous glaciers and glacial lakes in the Yairu Zangbo Basin. 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 change characteristics of glaciers and glacial lakes in 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 km² in 1990 to 128.92 km² in 2020—a total reduction of 38.88 km² 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 an expansion trend during the study period, increasing from 5.72 km² in 1990 to 8.81 km² in 2020—a total increase of 3.09 km² with 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°. Debris-covered and debris-free glaciers exert different influences on glacial lakes. (4) Temperature and precipitation in the 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. These findings provide detailed baseline data on the distribution and change characteristics of glaciers and glacial lakes, offering support for disaster prevention and mitigation efforts in Yairu Zangbo Basin.

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

1 Introduction

Glaciers are often referred to as 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 2017. Affected by climate

change, glaciers continue to retreat. Previous studies have demonstrated that glaciers on the Tibetan Plateau and surrounding regions have generally decreased to current levels from those at the end of the 20th century. Rising temperatures have accelerated glacier melting. As an important freshwater source in arid regions, glacier meltwater plays a vital role in local ecological environments and economic development. Although glacier meltwater can temporarily alleviate water shortages, it also poses potential hazards, as some glaciers store pollutants from historical periods, and their melting releases these contaminants into aquatic environments, affecting human health. Glacial lakes, as important recharge sources, also serve critical functions in regulating river runoff, protecting biodiversity, and providing tourism value.

The Himalayan region contains extensive glacier coverage and is a major disaster area for glacial lake outbursts, with numerous outburst events having caused tremendous threats to lives and property. However, the high altitude and steep terrain of the Himalayas greatly 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 using Landsat satellite data across the entire Himalayas, revealing rapid glacier retreat with a total area reduction of 29.34 km² between 1990 and 2015. Gong et al. monitored glacial lakes in the Koshi River Basin and found that the number of glacial lakes increased by 180 and their area expanded by 13.91 km² between 1990 and 2014.

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

2 Study Area and Methods

2.1 Study Area

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 km². The terrain rises gradually from north to south, with elevations ranging from 4122 to 7440 m. The region features high altitude, low temperatures, and a plateau mountain climate with precipitation concentrated in summer. According to China's second glacier inventory, the basin contained 139 glaciers covering 139.39 km² in 2015, predominantly distributed in the southern part of the watershed.

2.2 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 and minimize impacts from snow cover and clouds, 15 scenes with minimal cloud cover were selected (Table 1). The ASTER GDEM digital elevation model was also employed, downloaded from the Geospatial Data Cloud.

Due to the scarcity of meteorological stations in the high-altitude glacier and glacial lake distribution areas, climate data from the University of Delaware (<http://climate.geog.udel.edu/~climate/>) were selected, providing temperature and precipitation data for the Himalayan region from 1990 to 2017 at 0.5° spatial resolution. This dataset has been widely used in Himalayan glacier research.

2.3 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. Google Earth was used to verify whether shadows existed, and glacial lake and stream locations were combined to identify glacier boundaries. Multi-temporal historical remote sensing images were compared to exclude the influence of snow on glacier boundary extraction.

To verify the accuracy of the extraction results, the buffer method was used to calculate the precision of glacier and glacial lake area extraction. The results indicated that the error margins satisfied research requirements (Table 2).

3 Results

3.1 Glacier Changes

3.1.1 Glacier Area Changes Glaciers in Yairu Zangbo Basin showed a clear retreat trend from 1990 to 2020 (Table 3). Glacier area decreased from 167.80 km² in 1990 to 128.92 km² in 2020—a total reduction of 38.88 km² with an average annual retreat rate of 0.77% · a⁻¹. The retreat process can be divided into three periods: 1990–2000, 2000–2010, and 2010–2020. During 1990–2000, glacier area decreased by 13.91 km² with an average annual retreat rate of 0.83% · a⁻¹. During 2000–2010, the area decreased by 8.24 km² with a slower retreat rate of 0.54% · a⁻¹. During 2010–2020, glacier retreat accelerated significantly, with area decreasing by 16.74 km² at an average annual retreat rate of 1.14% · a⁻¹, much higher than the previous two periods. Overall, the glacier retreat rate in Yairu Zangbo Basin showed a trend of first decreasing and then increasing, with accelerated retreat in recent years.

3.1.2 Glacier Distribution and Changes at Different Altitudes Using 200 m intervals, the distribution and changes of glaciers at different altitudes were analyzed (Fig. 3). Glacier retreat increased with altitude up to 5800–6000 m, where retreat was most significant at $1.15\% \cdot a^{-1}$. Above this elevation, retreat gradually decreased, becoming negligible above 6800 m. Although glacier retreat was greatest at 5800–6000 m, the retreat rate peaked at 5000–5200 m. As altitude increased, the glacier retreat rate gradually declined. In 2020, glaciers were predominantly distributed between 5800–6400 m, accounting for 64.25% of the total glacier area in the basin.

3.1.3 Glacier Distribution and Changes on Different Slopes Based on DEM data, slope information for glaciers in Yairu Zangbo Basin was extracted to analyze distribution characteristics. Using 5° intervals, the influence of slope on glacier distribution was examined (Fig. 4). Glacier area was primarily distributed on slopes of 5° – 20° , accounting for 46.02% of the total area, with the 10° – 15° slope range containing 26.18 km^2 (15.60% of the total). As slope increased, glacier distribution area gradually decreased while the retreat rate increased, reaching a maximum retreat rate of 32.77% on 55° – 60° slopes, where distribution area was minimal at only 1.55 km^2 (0.92% of the total).

3.1.4 Distribution and Changes of Debris-Covered and Debris-Free Glaciers Supraglacial debris thickness has a direct relationship with glacier melt rate. To comprehensively understand glacier distribution and change characteristics, glaciers in Yairu Zangbo Basin were classified as debris-covered or debris-free, and their area, number, and average size were statistically analyzed for 1990–2020.

Debris-covered glacier area decreased by 10.82 km^2 (a retreat rate of 27.72%), while debris-free glacier area decreased by 33.99 km^2 (a retreat rate of 10.82%). Debris-covered glaciers were fewer in number but larger in average size, with slower retreat rates. In contrast, debris-free glaciers were more numerous but smaller in average size, with faster retreat rates.

3.1.5 Glacier Area and Number by Size Class To examine the distribution and change characteristics of glaciers by size, glaciers in Yairu Zangbo Basin were divided into seven size classes (Table 5). The number of glaciers showed an overall increasing trend, with a net increase of 11 glaciers. The 0.2 km^2 class showed the greatest increase (16 glaciers), while the 0.5 – 1 km^2 class showed the greatest decrease (7 glaciers). The 5 – 10 km^2 size class had the largest area distribution at 51.17 km^2 (30.49% of the total), followed by the 10 – 20 km^2 class at 33.78 km^2 (20.09%). The smallest area proportion was in the $>50 \text{ km}^2$ class at 4.61 km^2 (2.74%). Only the 0.2 km^2 class showed an increasing area trend; all other classes exhibited decreasing areas, with the 0.5 – 1 km^2 class showing the most significant retreat and the $>50 \text{ km}^2$ class the least. This indicates that smaller glaciers are more numerous and experience greater fluctuations, while larger glaciers are fewer and more stable.

3.2 Glacial Lake Changes

3.2.1 Glacial Lake Area Changes Glacial lakes in Yairu Zangbo Basin showed an overall expansion trend from 1990 to 2020 (Table 6). The minimum area of 5.72 km² occurred in 1990, increasing to 8.81 km² in 2020—a total increase of 3.09 km² with an average annual change rate of 0.96 km². The process can be divided into three periods: 1990–2000 (area increase of 0.63 km² at 1.68% · a⁻¹), 2000–2010 (area increase of 2.76 km² at 4.56% · a⁻¹, the fastest growth period), and 2010–2020 (area decrease of 0.30 km² at -0.94% · a⁻¹). Overall, glacial lake area showed a pattern of initial increase, followed by decrease, then increase again.

3.2.2 Glacial Lake Distribution and Changes at Different Altitudes

Glacial lakes in Yairu Zangbo Basin are mainly distributed between 4800–6600 m, with a relationship similar to glaciers—generally following a normal distribution with altitude. In 2020, glacial lake area peaked at 5000–5600 m, reaching 4.51 km² (78.84% of the total), with the 5400–5600 m interval accounting for 1.72 km² (30.10%). The expansion trend was altitude-dependent (Table 7), with the fastest increase occurring at 6000–6200 m (average annual change rate of 21.15%), corresponding to the altitude range with maximum glacier area distribution.

3.2.3 Glacial Lake Distribution and Changes on Different Slopes

Glacial lake distribution is significantly influenced by altitude, predominantly occurring in depressions or low-lying areas. Analysis of different slope classes revealed that glacial lake area is mainly distributed on gentle slopes of 0°–10°, accounting for 3.29 km² (57.50% of the total). As slope increases and terrain becomes steeper, conditions become less favorable for glacial lake development, causing lake area to decline rapidly. On slopes of 55°–60°, glacial lake area was only 0.023 km².

3.2.4 Distribution and Changes of Different Glacial Lake Types

Debris suppresses glacier melting, slowing melt rates and indirectly affecting the expansion of glacial lakes connected to debris-covered glaciers. By statistically analyzing the distance between glacial lakes and glaciers, lakes were classified as those influenced by debris-covered glaciers versus those influenced by debris-free glaciers.

From 1990 to 2020, lakes influenced by debris-covered glaciers increased in area by 1.03 km² (a growth rate of 34.80%), with unchanged numbers but increased average size of 0.20 km². Lakes influenced by debris-free glaciers increased in area by 2.76 km² (a growth rate of 74.64%), with numbers increasing by 8 (a growth rate of 88.89%) but average size decreasing by 0.01 km² (a reduction rate of 6.67%). This indicates that lakes connected to debris-covered glaciers experience slower changes, are fewer in number, and have larger average sizes, while

those connected to debris-free glaciers change more rapidly, are more numerous, but have smaller average sizes.

4 Discussion

4.1 Response of Glaciers and Glacial Lakes to Climate Change

The primary factors affecting glacier changes are temperature and precipitation, with temperature influencing melt and precipitation affecting accumulation. Analysis of temperature and precipitation data from 1990 to 2017 in Yairu Zangbo Basin revealed that temperature showed an overall upward trend (Fig. 7). Temperature fluctuated significantly, with an average warming rate of $0.06\text{ }^{\circ}\text{C}\cdot\text{a}^{-1}$ and amplitude of $2.45\text{ }^{\circ}\text{C}$. Temperature reached its lowest value of $0.81\text{ }^{\circ}\text{C}$ in 1992, then rose to a maximum of $2.18\text{ }^{\circ}\text{C}$ in 2016. When divided into three periods, temperature showed a decreasing trend from 1990–2000 (change rate of $-0.01\text{ }^{\circ}\text{C}\cdot\text{a}^{-1}$), an increasing trend from 2000–2010 ($0.05\text{ }^{\circ}\text{C}\cdot\text{a}^{-1}$), and a continued increasing trend from 2010–2017 ($0.08\text{ }^{\circ}\text{C}\cdot\text{a}^{-1}$). Overall, temperature in Yairu Zangbo Basin exhibited a fluctuating upward trend.

Precipitation showed considerable fluctuation with an overall decreasing trend (Fig. 7). Total change amplitude was 188.53 mm , with a maximum of 1982.88 mm in 1990 and minimum of 1778 mm in 2016. From 1990–2000, precipitation decreased by 119.13 mm at a rate of $11.09\text{ mm}\cdot\text{a}^{-1}$. From 2000–2010, precipitation showed a slight increase followed by decrease, with an overall change rate of $-0.24\text{ mm}\cdot\text{a}^{-1}$. From 2010–2017, precipitation increased by 205.18 mm . Overall, precipitation in the basin showed a decreasing trend with significant fluctuations.

In summary, rising temperatures and decreasing precipitation from 1990–2017 promoted glacier melting and glacial lake expansion. During 1990–2000, precipitation was the main factor influencing glacier changes, while temperature and meltwater variation were important factors affecting glacial lakes. During 2000–2010, both temperature and precipitation increased, with temperature rise and precipitation increase respectively promoting glacier melt and accumulation, resulting in a slower glacier retreat rate compared to the previous period—indicating precipitation was the dominant factor. During 2010–2017, temperature rose while precipitation decreased. The reduced accumulation from precipitation decline, though small in magnitude, combined with temperature effects to accelerate glacier retreat, with temperature exerting a stronger influence than precipitation. For glacial lakes, accelerated glacier melting became the primary factor for lake expansion.

4.2 Co-evolution Characteristics of Glaciers and Glacial Lakes

Spatially, the vast majority of glacial lakes are directly connected to glacier termini. Glaciers are mainly distributed at $5800\text{--}6400\text{ m}$ altitude (accounting for 64.25% of total glacier area), while glacial lakes are concentrated at 5000--

5600 m (4.51 km², 78.84% of total lake area). The spatial pattern shows that as glaciers melt extensively, glacial lakes at their termini are directly affected. Analysis of area change trends reveals that while glacier area decreased year by year, glacial lake area continuously increased.

From 1990–2000, glacier area retreated by 13.91 km² at an average rate of $-0.83\% \cdot a^{-1}$, while temperature and precipitation both showed upward trends. Compared to this period, the 2000–2010 period saw slower glacier retreat (8.24 km² at $-0.54\% \cdot a^{-1}$) as temperature and precipitation continued rising, demonstrating that precipitation was the main influencing factor. During 2010–2020, glacier area retreated by 16.74 km² at an accelerated rate of $-1.14\% \cdot a^{-1}$, while temperature rose and precipitation decreased. The combination of temperature increase and precipitation reduction, though small in magnitude, led to accelerated glacier retreat, with temperature exerting a stronger effect than precipitation.

For glacial lakes, from 1990–2000, lake area increased by 0.63 km² at $1.68\% \cdot a^{-1}$, with both temperature and precipitation rising. From 2000–2010, lake area increased by 2.76 km² at $4.56\% \cdot a^{-1}$, corresponding to a period of accelerated glacier retreat, indicating that glacier melt was the dominant factor for lake expansion. From 2010–2020, lake area decreased by 0.30 km² at $-0.94\% \cdot a^{-1}$, while temperature rose and precipitation decreased. Although increased temperature enhanced lake evaporation and decreased precipitation reduced water supply, accelerated glacier meltwater input caused lake area to increase overall, demonstrating that glacier melting was the primary factor.

Additionally, debris cover significantly influenced glacial lakes in Yairu Zangbo Basin. Lakes connected to debris-covered glaciers showed smaller changes and lower change rates because the debris layer suppressed glacier melting, thereby reducing the magnitude and rate of lake expansion that is primarily driven by glacier melt.

5 Conclusions

From 1990 to 2020, glacier area in Yairu Zangbo Basin showed a retreat trend, decreasing by 38.88 km². Glaciers were mainly distributed at elevations of 5800–6400 m and on slopes of 5°–20°. Both debris cover and glacier size affected the number and area distribution of glaciers.

Glacial lake area showed an overall expansion trend from 1990 to 2020, increasing by 3.09 km² (a 54.02% increase). Glacial lakes were predominantly distributed at elevations of 5000–5600 m and on slopes of 0°–10°. Debris-covered and debris-free glaciers had different effects on glacial lakes.

Temperature and precipitation in Yairu Zangbo Basin fluctuated significantly from 1990 to 2017, with temperature rising by 1.49 °C and precipitation decreasing by 188.53 mm, promoting glacier melt and glacial lake expansion. This study provides detailed baseline data on glacier and glacial lake area distribution and

change characteristics, offering support for disaster prevention and mitigation in the region.

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