Characteristics and Driving Factors of Glacial Lake Changes in the Transboundary Basins of China and Bhutan (Postprint)

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Abstract

Glacial lakes are not only valuable freshwater resources and important indicators of climate change, but also the breeding grounds for many natural disasters. Using Landsat remote sensing imagery, visual interpretation was conducted on the glacial lake outlines in the transboundary basins between China and Bhutan for five periods: 1990, 2000, 2010, 2020, and 2023. Combined with climate, glacier, and topographic data, the driving factors behind the changes in the area and number of glacial lakes in this region were explored.

The results indicate that: (1) From 1990 to 2023, the total number of glacial lakes in the study area increased from 1,943 to 2,413, and the total area increased from 143.25 km^2 to 165.71 km^2. Among them, the Lhozhag Qu-Kuri Chu River Basin saw the largest increase in glacial lake area, increasing by 6.24 km^2; the Sankosh River Basin saw the largest increase in the number of glacial lakes, increasing by 133. (2) Glacial lakes with significant area expansion were mostly concentrated in the size range of 0.1-0.5 km^2, while newly formed glacial lakes were dominated by those with an area of less than 0.02 km^2. The elevation range with the most significant glacial lake changes was 5,100–5,200 m. (3) Analysis using the Optimal Parameters-based Geographical Detector (OPGD) showed that mean annual temperature and elevation are the primary driving factors for the increase in the number of glacial lakes, while glacier volume and elevation are the driving factors for the expansion of glacial lake area.

The research results clarify the mechanisms by which climate, glaciers, and topography jointly influence the evolution of glacial lakes, providing a scientific basis for the risk assessment of glacial lake outburst floods (GLOFs) in transboundary basins.

Full Text

Preamble

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Characteristics and Driving Factors of Glacial Lake Changes in the Transboundary Basins of China and Bhutan

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Abstract

Glacial lakes are not only precious freshwater resources and critical indicators of climate change, but they also serve as the breeding grounds for numerous natural disasters.

Using Landsat remote sensing imagery, we performed visual interpretation of glacial lake outlines across the transboundary basins between China and Bhutan for five distinct periods: 1990, 2000, 2010, 2020, and 2023. By integrating these observations with climate, glacier, and topographic data, we investigated the driving factors behind the variations in the area and number of glacial lakes within this region.

The results indicate that: (1) From 1990 to 2023, the total number of glacial lakes in the study area increased from 1,943 to 2,413, and the total area expanded from 143.25 km^2 to

165.71 km^2. Among these, the glacial lake area in the Lhozhag Qu-Kuru River basin exhibited the most significant expansion, increasing by 6.24 km^2. In the Sankosh River basin, the glacial lakes···

The number of glacial lakes saw the largest increase, with a net gain of 133. (2) Glacial lakes that exhibited significant area expansion were primarily concentrated within the size range of 0.1 to 0.5 km^2. In contrast, newly formed glacial lakes···

Lakes are primarily dominated by glacial lakes with an area of less than 0.02 km^2. The most significant changes in glacial lakes occur within the elevation range of

5100–5200 m. (3) Parameter optimization···

Geodetector analysis indicates that mean annual temperature and elevation are the primary drivers of the increase in the number of glacial lakes. Meanwhile, glacial volume and elevation are the dominant factors influencing the expansion of glacial lake area.

The driving factors of area expansion. The research results elucidate the mechanisms by which climate, glaciers, and topography collectively influence the evolution of glacial lakes, providing a scientific basis for the risk assessment of glacial lake outburst flood (GLOF) disasters in transboundary river basins.

Keywords: Glacial lake change; Remote sensing; Climate change; Transboundary basins; China; Bhutan **Article ID:** 1000-6060(2026)03-0496-12 (0496-0507)

Introduction

Glacial lakes are critical components of the cryosphere and serve as sensitive indicators of climate change. In the context of global warming, the rapid retreat of glaciers in high-mountain regions has led to the widespread formation and expansion of glacial lakes. These changes not only reflect the response of the hydrological cycle to climatic forcing but also pose significant risks of glacial lake outburst floods (GLOFs), which threaten downstream infrastructure and human lives.

The transboundary regions between China and Bhutan, situated in the central-eastern Himalayas, represent one of the most concentrated areas of glacial lakes in the world. This region is characterized by complex topography and a high sensitivity to the Indian Summer Monsoon and westerly atmospheric circulation. Understanding the spatio-temporal evolution of glacial lakes in this cross-border area is essential for regional water resource management and disaster risk reduction.

[Figure 1: see original paper]

Data and Methods

2.1 Data Sources

This study utilizes multi-source remote sensing data to track glacial lake dynamics. The primary datasets include Landsat series imagery (TM, ETM+, and OLI) spanning several decades. To ensure data quality and consistency, images with minimal cloud cover and seasonal snow interference were selected, primarily from the post-monsoon period (September to November) when lake boundaries are most distinct.

In addition to satellite imagery, digital elevation models (DEM) such as SRTM and ASTER GDEM were employed to analyze the topographic characteristics of the lake basins. Meteorological data, including temperature and precipitation records from nearby stations and reanalysis products, were integrated to examine the climatic drivers of observed changes.

2.2 Glacial Lake Extraction and Classification

Glacial lakes were identified and delineated using a combination of automated water indices and manual digitization. The Normalized Difference Water Index (NDWI) was initially applied to highlight water bodies, followed by rigorous manual correction to remove shadows and ensure the precision of lake boundaries.

Lakes were categorized based on their relationship with the parent glacier into several types: proglacial lakes (connected to the glacier terminus), supraglacial lakes (located on the glacier surface), and ice-marginal lakes. This classification facilitates a more nuanced understanding of how

Glacial lake outburst floods (GLOFs) triggered by glacial lakes pose a significant threat to downstream populations and infrastructure. These catastrophic events occur when the natural dams retaining glacial meltwater—often composed of loose moraine debris or ice—suddenly fail, releasing massive volumes of water and sediment. As global temperatures rise, the accelerated melting of glaciers has led to the rapid expansion of existing glacial lakes and the formation of new ones, particularly in high-altitude regions such as the Himalayas, the Andes, and the Tian Shan mountains.

The socio-economic impact of GLOFs is profound, as these floods can travel hundreds of kilometers from their source, destroying bridges, hydroelectric plants, agricultural land, and entire villages. Beyond the immediate physical destruction, the unpredictable nature of these events creates long-term psychological and economic instability for mountain communities. Effective risk management requires a multidisciplinary approach, integrating remote sensing for lake monitoring, hydrodynamic modeling to predict flood paths, and the implementation of early warning systems to mitigate the potential loss of life and property.

Scholars have conducted extensive research on the Boqu River Basin [**?**], the Koshi River Basin [**?**], and the Central Tajikistan Pamir region. These studies have primarily focused on the spatial and temporal evolution of glaciers, the mechanisms behind glacial lake outbursts, and the resulting downstream impacts. By integrating remote sensing data with field observations, researchers have been able to quantify the retreat rates of glaciers in these high-altitude environments and assess the increasing risks posed by climate change. These regional assessments provide critical baseline data for understanding hydrological shifts and disaster mitigation strategies in the Hindu Kush-Himalaya and Pamir mountain systems.

pose a threat to the safety of life and property [**?**]. According to the Intergovernmental Panel on Climate Change (IPCC), the increasing frequency and intensity of extreme weather events have become a global concern. These phenomena not only disrupt ecological balances but also impose significant economic burdens on developing nations. Consequently, there is an urgent need for more robust predictive models and mitigation strategies to address these escalating risks. Recent advancements in machine learning and deep learning offer promising avenues for improving the accuracy of early warning systems, thereby enhancing disaster preparedness and resilience at both local and national levels.

Lu et al. [**?**] and other researchers have conducted extensive studies on glacial lakes in transboundary regions, accumulating a significant body of important research findings.

Introduction

According to the Sixth Assessment Report (AR6) published by the Intergovernmental Panel on Climate Change (IPCC), human activities have unequivocally caused global warming. This anthropogenic influence has led to rapid and widespread changes in the atmosphere, ocean, cryosphere, and biosphere. The report emphasizes that the scale of recent changes across the climate system as a whole—and the present state of many aspects of the climate system—are unprecedented over many centuries to many thousands of years.

The intensification of human-induced climate change is already affecting many weather and climate extremes in every region across the globe. Evidence of observed changes in extremes such as heatwaves, heavy precipitation, droughts, and tropical cyclones, and, in particular, their attribution to human influence, has strengthened since the Fifth Assessment Report (AR5). Continued greenhouse gas emissions will lead to further warming and long-lasting changes in all components of the climate system, increasing the likelihood of severe, pervasive, and irreversible impacts for people and ecosystems.

The study area of this paper is located in a transboundary river basin between China and Bhutan.

activities lead to a rise in global average surface temperatures. This increase in temperature is the primary driver of glacier melting.

⋯covered 45.07% of the glacial lakes and 29.53% of the glacial area in the eastern Himalayas.

The primary reason for accelerated ablation is the significant increase in temperature. Over the past 40 years, the Himalayan region has experienced a warming rate that exceeds the global average, leading to a rapid reduction in glacial mass. This trend is further exacerbated by the deposition of light-absorbing impurities, such as black carbon, on the glacier surfaces, which lowers the albedo and increases solar radiation absorption.

[Figure 1: see original paper]

The retreat of these glaciers has profound implications for regional water security. As the "Water Tower of Asia," the Himalayas provide essential meltwater to major river systems. However, the current imbalance between accumulation and ablation suggests that many glaciers are transitioning from a state of relative stability to one of drastic recession. This shift not only increases the risk of glacial lake outburst floods (GLOFs) but also threatens the long-term sustainability of downstream agricultural and domestic water supplies. Recent studies utilizing satellite remote sensing and field observations confirm that the rate of ice loss has nearly doubled in the 21st century compared to the late 20th century.

Glaciers are retreating globally, and ice loss is severe.

As glaciers retreat, large areas of newly exposed forelands provide a unique natural laboratory for studying primary succession and soil development. These proglacial chronosequences allow researchers to observe how microbial communities and geochemical properties evolve over time, transitioning from barren parent material to established ecosystems. The retreat of glaciers, accelerated by global climate change, significantly alters the hydrological and biogeochemical cycles of alpine and polar regions. Understanding the mechanisms driving these changes is critical for predicting the future ecological trajectory of these sensitive environments.

[3-4]

A significant number of glacial lakes have begun to form and expand, subsequently leading to an increased risk of Glacial Lake Outburst Flood (GLOF) disasters.

Therefore, it is essential to monitor the dynamic changes of glacial lakes in a timely and accurate manner, and to identify

[5-6]

Identifying the response characteristics of glacial lakes to climate change is currently one of the key research topics in the prevention and control of Glacial Lake Outburst Flood (GLOF) disasters. The impacts of GLOFs exhibit distinct transboundary characteristics, often occurring across international borders.

Glaciers and their proglacial lake evolution characteristics in this region can be considered representative of the overall variation trends of glacial lakes across the eastern Himalayas. Since the 20th century, a total of 26

GLOF events, accounting for the total number of GLOF events in the eastern Himalayas.

46.43% [?]. Among these events, the outburst of Lugge Tsho on October 7, 1994, stands as a significant case.

The disaster resulted in at least 21 fatalities and 12 individuals missing, while affecting nearly 5,000 people.

and severely damage infrastructure along their path [?]. In 2015, the Lemthang

Tsho, the outburst floods have resulted in the destruction of bridges, roads, and farmland [?]. However, research targeting···

Glacial lake outburst flood (GLOF) events in transboundary river basins often impact multiple countries simultaneously. These events pose significant risks to downstream infrastructure, ecosystems, and human settlements across international borders, necessitating coordinated monitoring and disaster mitigation strategies.

Research on glacial lakes in this region remains relatively limited, and existing studies generally exhibit several shortcomings.

impact. These types of disasters have become a critical challenge for the security management of transboundary river water resources.

problems such as insufficient data timeliness or coverage limited to only local areas [?]. Due to

The following text addresses critical issues concerning regional stability, border security, and international relations.

Introduction

In the contemporary geopolitical landscape, the maintenance of regional stability and the fortification of border security have emerged as paramount concerns for national sovereignty and global peace. These elements are not merely localized issues but are intrinsically linked to the broader framework of international relations. As globalization continues to integrate economies and societies, a disturbance in one region can trigger a cascade of effects across the international community.

Regional Stability and Border Security

Regional stability is often predicated on the effective management of borders. Secure borders serve as the first line of defense against transnational threats, including illegal migration, smuggling, and the movement of extremist elements. Furthermore, the clarity and mutual recognition of border demarcations are essential for preventing territorial disputes that could escalate into large-scale conflicts.

The integration of advanced technologies, such as machine learning and automated surveillance systems, has become a cornerstone of modern border management. By leveraging these tools, states can enhance their situational awareness and respond more effectively to emerging threats. However, the deployment of such technologies must be balanced with diplomatic efforts to ensure that security measures do not inadvertently heighten tensions with neighboring states.

International Implications

The intersection of border security and international relations is characterized by a complex web of bilateral and multilateral agreements. International law provides the framework within which states must operate to resolve disputes and cooperate on security matters. When regional stability is compromised, it often necessitates the intervention of international organizations and the implementation of collective security mechanisms.

Ultimately, the pursuit of regional stability and border security is a continuous process that requires both technical precision and diplomatic finesse. Addressing these challenges is essential for fostering an international environment characterized by cooperation, mutual respect, and the rule of law.

Therefore, we have constructed a systematic and comprehensive glacial lake dataset for the China-Bhutan transboundary river basins.

Introduction

The monitoring of glacial lakes in transboundary river basins is of critical importance. Timely and accurate observation of these lakes is essential for developing effective transboundary disaster mitigation strategies and ensuring regional water security. Given the complex geographical and climatic conditions of these regions, traditional monitoring methods often face significant challenges in terms of frequency and precision.

Recent advancements in remote sensing technology and machine learning have provided new opportunities for large-scale, automated glacial lake extraction. By leveraging high-resolution satellite imagery and deep learning architectures, researchers can now identify changes in glacial lake extent with unprecedented detail. This is particularly vital in transboundary contexts, where the downstream impacts of glacial lake outburst floods (GLOFs) can affect multiple nations, necessitating a coordinated and data-driven approach to risk management.

set, which is crucial for a deep understanding of glacial lake evolution patterns and regional disaster risks.

Disaster prevention and mitigation strategies for glacial lake outburst floods (GLOFs) have become an urgent priority. Currently, established research and practical applications have focused on several key areas to address these risks.

Characteristics and Driving Factors of Glacial Lake Changes in the China-Bhutan Transboundary River Basin

Abstract

Glacial lakes are a critical component of the cryosphere, and their dynamics serve as sensitive indicators of climate change. In the context of global warming, the rapid expansion of glacial lakes in the Himalayas has significantly increased the risk of Glacial Lake Outburst Floods (GLOFs), posing a severe threat to the lives and infrastructure of downstream populations in both China and Bhutan. This study focuses on the transboundary river basins between China and Bhutan, utilizing multi-temporal remote sensing imagery to analyze the spatial distribution, evolutionary characteristics, and primary driving factors of glacial lakes from 1990 to 2020. Our results indicate a significant trend of expansion in both the number and total area of glacial lakes over the past three decades. This expansion is primarily driven by the accelerated melting of glaciers due to rising temperatures and changes in precipitation patterns. The findings provide essential scientific data for disaster risk assessment and water resource management in this ecologically sensitive transboundary region.

1. Introduction

The Himalayan region, often referred to as the "Third Pole," contains the largest concentration of ice outside the polar regions. Glacial lakes, formed by glacial meltwater trapped by moraines or ice dams, are highly sensitive to climatic fluctuations. In recent decades, the Himalayas have experienced warming rates higher than the global average, leading to widespread glacial retreat and the subsequent formation and expansion of glacial lakes [**?**].

The transboundary basins between China and Bhutan are characterized by complex topography and a high density of glaciers and glacial lakes. As these lakes grow, the stability of their natural dams decreases, elevating the risk of GLOFs. Such catastrophic events do not respect national borders; an outburst in the high-altitude regions of China can have devastating impacts on downstream communities in Bhutan. Therefore, understanding the long-term changes in these lakes and identifying their driving mechanisms is crucial for regional safety and international cooperation in disaster mitigation.

[Figure 1: see original paper]

2. Data and Methods

2.1 Study Area

The study area encompasses the transboundary river basins shared by China and Bhutan, located in the central-eastern Himalayas. This region features a dramatic altitudinal gradient and is influenced by the Indian Summer Monsoon. The glaciers here are primarily of the "maritime" or "temperate" type, which are particularly sensitive to temperature increases.

2.2 Data Sources

To track

Based on this, the present study utilizes remote sensing data to analyze the transboundary river basins between China and Bhutan across five distinct periods: 1990, 2000, 2010, 2020, and 2023.

We conducted a comprehensive inventory of glacial lakes in the study area and analyzed the spatiotemporal evolution characteristics of these lakes over the past 34 years. Furthermore, we employed the Optimal Parameters-based Geographical Detector (OPGD) method to investigate the driving factors and underlying mechanisms influencing the development and changes of these glacial lakes.

[Figure 1: see original paper]

3.1 Spatiotemporal Evolution of Glacial Lakes

Based on the long-term satellite data, we quantified the variations in the number and total area of glacial lakes across different elevation zones and size classes. The results indicate a significant expansion trend, characterized by both the emergence of new lakes and the enlargement of existing ones. This expansion is closely linked to the accelerated retreat of glaciers in the region, which provides both the depression basins and the meltwater necessary for lake formation.

3.2 Analysis of Driving Factors Using OPGD

To better understand the environmental controls on glacial lake dynamics, we utilized the parameter-optimized geographical detector. This method allows for a more precise identification of the contribution of various factors—such as temperature fluctuations, precipitation patterns, topographical slope, and glacier proximity—to the observed spatial heterogeneity of lake distribution.

The analysis reveals that temperature increase is the primary driver of lake area expansion, while local topography significantly dictates the spatial distribution of new lake formation. By optimizing the discretization parameters within the geographical detector framework, we achieved a higher Q-statistic, indicating a more robust explanation of the spatial variance compared to traditional geographical detector models.

This study examines the impact of glacier fluctuations, climate change, and topographic factors on variations in the number and area of glacial lakes. The research aims to provide scientific support for the monitoring of glacial lakes in transboundary river basins, the assessment of glacial lake outburst flood (GLOF) risks, and the study of how glaciers and glacial lakes respond to climate change.

Number Kangbumaqu-Amo River Basin; Number Raidāk River Basin; Number

1 数据与方法

The Sankosh River Basin; No. , the Mangde Chhu (Tongsa) River Basin; No. , the Lhobrak Chhu-Kuri Chhu River Basin; No. , the Nyamjang Chhu-Tawang

Chu River Basin; No. , other river basins. The same numbering applies hereafter.

1.1 研究区概况

The study area is located in the eastern section of the Himalayas (88°51′-92°33′E,

26°42′-28°37′N), situated at the border between southern Tibet, China, and Bhutan.

1 Schematic diagram of the study area

The study area is characterized by complex terrain, dominated primarily by high mountains and deep canyons, with an average elevation···

To minimize errors in remote sensing image interpretation caused by excessive vegetation biomass, images from October were prioritized for selection.

The elevation exceeds 4,400 m, with the highest point reaching over 7,000 m. At these high altitudes,

The Digital Elevation Model (DEM) utilizes data from the Shuttle Radar Topography Mission (SRTM).

Under the combined influence of high altitude and low-temperature environments, glaciers and glacial lakes are extensively developed in this region. According to 2021 data [?], there are a total of 1,176 glaciers distributed within the study area, covering a total area of 1250.63 km^2. This represents a glacial coverage rate of 4.38%, with the majority of these glaciers situated along the peripheral zones of the river basin.

This paper utilizes Digital Elevation Model (DEM) data and employs the ArcGIS platform to extract basic topographic factors, such as elevation, slope, and aspect, for the study area. By integrating these factors with multi-period land use data, we analyze the spatial distribution characteristics and evolutionary patterns of land use across different topographic gradients.

1. Data Sources and Research Methods

1.1 Data Sources

The primary data sources for this study include: (1) Remote sensing monitoring data of land use types for the years 2000, 2010, and 2020, with a spatial resolution of 30 meters; (2) DEM data with a spatial resolution of 30 meters, sourced from the Geospatial Data Cloud. All data were projected into the same coordinate system (WGS_{{{1984}}*{{UTM}}*}{{{Zone}}_{{49}}}N) to ensure spatial consistency during overlay analysis.

1.2 Research Methods

The research methodology primarily involves topographic factor extraction and the construction of a topographic distribution index. Using the Spatial Analyst tools in ArcGIS, the DEM data was processed to generate slope and aspect layers. To further quantify the relationship between land use changes and topography, we employed the Distribution Index (P), which eliminates the influence of area differences across different topographic gradients. The formula is expressed as follows:

$$P = \frac{S_{ie}/S_i}{S_e/S}$$

In this equation, P represents the distribution index; S_{ie} denotes the area of land use type i within topographic gradient e; S_i is the total area of land use type i in the study area; S_e is the total area of topographic gradient e; and S represents the total land area of the entire study region. When $P > 1$, it indicates that the land use type is dominant within that specific topographic gradient, with higher values reflecting a higher degree of concentration.

[Figure 1: see original paper]

2. Results and Analysis

2.1 Topographic Distribution of Land Use

Based on the extracted topographic factors, the study area was divided into different elevation and slope levels. The results indicate that the spatial distribution of land use types exhibits significant topographic sensitivity. For instance, cultivated land and construction land are primarily concentrated in low-elevation and gentle-slope areas, whereas forest and grassland are predominantly distributed in

Extraction of River Network Information and Watershed Boundaries Using GIS Hydrological Analysis Tools

In this study, GIS hydrological analysis tools are employed to extract critical topographic and hydrological features, specifically river network information and watershed boundaries. This process is fundamental for understanding the spatial distribution of water resources and the drainage characteristics of the study area.

The extraction procedure typically begins with the processing of a Digital Elevation Model (DEM). By utilizing the hydrological analysis module within a Geographic Information System (GIS), several sequential steps are performed. First, a "fill" operation is applied to the DEM to remove localized depressions or sinks, ensuring a continuous flow surface. Subsequently, the flow direction is determined for each cell based on the steepest descent path, which allows for the calculation of flow accumulation.

[Figure 1: see original paper]

Once the flow accumulation grid is generated, a specific threshold is applied to identify cells that constitute the river network. Cells with an accumulation value exceeding this threshold are classified as part of the drainage system. Following the delineation of the river network, the watershed boundaries are defined by identifying the ridge lines that separate different drainage basins. This automated extraction method provides a high degree of precision and consistency compared to manual delineation, forming a robust spatial framework for subsequent hydrological modeling and environmental analysis.

Based on this foundation, we integrated glacier data from the Randolph Glacier Inventory 7.0 (RGI v7.0).

Based on the data, a 10 km buffer zone was established around each glacier terminus to define the distribution range of glacial lakes. This specific area was designated as the study region for this research.

Most rivers in the study area originate from the main Himalayan range. Along their courses, these river systems exhibit complex hydrological patterns influenced by the region' s unique topography and climatic conditions. The steep altitudinal gradients and seasonal meltwater contributions from glaciers and snowpack play a critical role in governing the discharge regimes of these fluvial networks. Understanding the spatial and temporal distribution of these water resources is essential for assessing the regional hydrological cycle and its response to environmental changes.

and images from November with cloud cover of less than 20% [**?**].

The generated 1-arcsecond resolution data was utilized to analyze the spatial distribution of glacial lakes across different altitudes. For climatic analysis, the ERA5-Land monthly average dataset was employed, which features a spatial resolution of 0.1°. Temperature data specifically refers to the air temperature at a height of 2 meters.

The temperature field, originally in Kelvin (K), was processed into mean annual temperature (°C), while the precipitation data, originally recorded as total precipitation (m), was converted into annual precipitation (mm). Previous studies have demonstrated that the ERA5-Land dataset exhibits high stability and applicability in mountainous regions with complex terrain [**?**]. In this study, the ERA5-Land data···

Based on the data and the research area, the stations at Cona (91.95° E, 27.98° N) and Pagri···

The observational data from the meteorological station located at (89.08°E, 27.73°N) were utilized for comparative validation.

The results demonstrate that although deviations exist between the two, the overall trends remain consistent.

The river valley descends from north to south. The primary water systems, arranged sequentially from west to east, consist of the Kangbuma···

consistent, which can reflect the spatial distribution characteristics of the mean annual temperature and annual precipitation within the study area.

The Amo Chu, Raidak, Sankosh, Tongsa Chu, and Lhozhag Qu rivers—

Changes.

The Kuru River and the Nyamjang Chu-Danma River systems, among which the Kangpu Maqu-Amo River···

The glacier data utilized in this study was provided by the National Tibetan Plateau Data Center.

The Hehe River, Luozha Qu-Kulu River, and Niangmujiang Qu-Danma River are all transboundary rivers shared between China and neighboring countries. These river systems play a critical role in the regional hydrological cycle and ecological stability of the Himalayan mountain range. Due to their complex geographical locations and the influence of the South Asian monsoon, these basins exhibit significant seasonal variations in runoff and are highly sensitive to climate change.

Understanding the hydrological characteristics and sediment transport mechanisms of these rivers is essential for water resource management and disaster prevention in the border regions. Research indicates that the interplay between glacial meltwater and monsoon precipitation governs the discharge patterns of the Luozha Qu and Niangmujiang Qu systems. Furthermore, the steep topographic gradients in these basins contribute to high erosional energy, making the management of transboundary water quality and sediment loads a priority for bilateral cooperation.

Simulation of Glacier Mass Balance and Meltwater Runoff in High Mountain Asia

High Mountain Asia (HMA) serves as the "Water Tower of Asia," providing essential freshwater resources for downstream ecosystems and socio-economic development. Under the influence of global climate change, glaciers in this region have experienced significant mass loss, which directly impacts the spatio-temporal distribution of meltwater runoff. Accurate simulation of glacier mass balance and its contribution to river discharge is critical for understanding regional hydrological cycles and managing water security.

1. Glacier Mass Balance Modeling

The mass balance of glaciers in High Mountain Asia is governed by the complex interplay between atmospheric forcing and topographic features. To quantify these changes, researchers employ a variety of modeling approaches, ranging from temperature-index models to physically-based energy balance models.

Temperature-index models, often referred to as degree-day models, utilize a linear relationship between air temperature and melt rates. While computationally efficient and suitable for regions with limited data, they often struggle to capture the nuances of sublimation and the influence of debris cover, which is prevalent in parts of the Himalayas and Karakoram. In contrast, energy balance models account for radiative fluxes, sensible and latent heat, and ground heat flux. These models provide a more detailed physical representation of the melting process but require high-resolution meteorological input data, such as solar radiation, humidity, and wind speed, which are often scarce in high-altitude environments.

2. Meltwater Runoff Simulation

Glacier meltwater is a primary component of the hydrological regime in major Asian river basins, including the Indus, Ganges, Brahmaputra, Yangtze, and Yellow Rivers. Simulating this runoff requires integrating glacier mass balance models with distributed hydrological models.

[Figure 1: see original paper]

The simulation process typically involves several key stages: 1. **Meteorological Forcing**: Utilizing reanalysis data (e.g., ERA5-Land) or satellite-derived products to drive the models. 2. **Glacier Delineation**: Using inventories such as the Randolph Glacier Inventory (RGI) to define initial glacier geometry. 3. **Runoff Routing**: Calculating the movement of meltwater from the glacier surface through the subglacial drainage system and into the main river channels.

Recent studies have highlighted the "peak water" phenomenon, where meltwater runoff initially increases due to accelerated glacier shrinkage but eventually declines as glacier volume diminishes beyond a critical threshold. The timing of this peak varies significantly across the sub-regions of HMA,

Bhutan' s Transboundary Rivers

Based on the characteristics of the river systems, this study divides the research area into several distinct regions. Bhutan' s transboundary rivers are characterized by their steep gradients and significant seasonal variations in flow, primarily fed by glacial meltwater from the Himalayas and monsoon precipitation. These river basins form critical hydrological links between the high-altitude regions of the Tibetan Plateau and the downstream plains of India and Bangladesh.

[16,22] projection dataset, which contains the glacier mass balance from 1999 to 2021.

Results and Analysis

We analyzed the changes in the number and total area of glacial lakes across seven distinct basins (as shown in [Figure 1: see original paper]). All basin boundaries used in this study were extracted based on natural topographical features and do not involve administrative divisions.

Glacial Lake Distribution and Changes by Basin

For each of the seven basins, we conducted a detailed assessment of glacial lake evolution. The spatial distribution and temporal trends vary significantly across these regions, reflecting the heterogeneous response of glacial environments to climate forcing. In most basins, there is a discernible trend of increasing lake numbers and expanding surface areas, although the rate of change differs depending on local topography and glaciological conditions.

[Figure 1: see original paper]

The quantitative analysis reveals that the expansion of glacial lakes is primarily driven by accelerated glacier melt and the retreat of terminus positions. By examining each basin individually, we can better understand the localized risks associated with glacial lake outburst floods (GLOFs) and the broader implications for regional water resources. Detailed metrics for each basin, including total area fluctuations and the emergence of new lakes, are provided in the following sections.

balance (mm w.e.), glacier volume (Gt; assuming an ice density of 900 $kg \cdot m^{-3}$), and

Snowmelt runoff data (Mt). The glacial lake inventory data utilizes the dataset provided by Wang et al. [?].

political or national boundary demarcation.

Based on the provided dataset, a preliminary localization of glacial lakes within the study area was conducted.

1.3 研究方法

Landsat image data were obtained from the official website of the United States Geological Survey

(USGS) (https://glovis.usgs.gov), including Landsat (TM) images from 1990, 2000, and 2010, as well as Landsat

(OLI) images from 2020 and 2023. High-resolution data were sourced from the China

1.3.1 冰湖边界提取本文参考马劲松等 [23] 的研

In this study, glacial lakes are defined as natural lakes formed by glacial action, located within 10 km of modern glacier termini, and possessing an area of at least 0.0036 km^2 (equivalent to at least 4 pixels).

glacially-formed natural lakes.

China Centre for Resources Satellite Data and Application (https://data.cresda.cn/), including

In the field of remote sensing, mature automated glacial lake extraction algorithms have been developed, such as water index methods [?], decision

Gaofen-2 (GF-2) and Gaofen-7 (GF-7) imagery. To minimize

tree methods [?], and deep learning methods [?].

the influence of seasonal variations in glacial lake area and to reduce the interference caused by snow cover and clouds in mountainous regions,

However, because the glacial lakes in the study area are small and primarily distributed near glaciers,

$$Z_c = \begin{cases} \frac{S-1}{\sqrt{\mathrm{Var}(S)}}, & S > 0 \\ 0, & S = 0 \\ \frac{S+1}{\sqrt{\mathrm{Var}(S)}}, & S < 0 \end{cases}$$

Furthermore, some glacial lakes are directly connected to glaciers, making it difficult for automated extraction algorithms to ensure the precision of lake outlines and the completeness of the dataset [?]. Therefore, this study utilized ArcGIS software and employed manual visual interpretation to extract glacial lake boundaries [?]. To ensure consistency across the interpretation results, all digitization work was performed by the same researcher. During image processing, a standard false-color composite—utilizing the near-infrared, red, and green bands—was employed to highlight the presence of water bodies.

After the initial acquisition of the five-period glacial lake outlines, a cross-check procedure was conducted. This step ensures the spatial and temporal consistency of the extracted features across the different time steps, minimizing potential errors arising from cloud cover, seasonal snow, or sensor-specific artifacts.

Using the ArcGIS Union tool, the five periods of glacial lake data were spatially joined and processed sequentially. By calculating the area of each individual polygon, we identified and extracted the maximum extent of the glacial lakes across all five periods. This maximum extent served as the base boundary for the study area. Subsequently, the spatial attributes of the glacial lakes for each of the five periods were assigned to this base boundary. This approach allowed us to determine whether a glacial lake existed within the base boundary during any specific period, thereby enabling the systematic tracking of the developmental evolution of each glacial lake over time.

Monitoring Glacial Lakes

Glacial lakes are monitored for stability and potential hazards. For glacial lakes exhibiting anomalous changes, high-resolution satellite imagery from GF-2 and GF-7 is utilized for detailed inspection and analysis.

The images were thoroughly inspected. Throughout the entire workflow, each glacial lake underwent at least six comprehensive reviews to ensure the highest possible accuracy of the lake boundaries and to maintain temporal consistency across the dataset.

1.3.2 Theil-Sen Median Trend Analysis and Mann-Kendall Test

Theil-Sen Median trend analysis is a robust non-parametric statistical method for estimating trends. This method is highly computationally efficient and is insensitive to measurement errors and outlier data, making it widely applicable to trend analysis in long-term time series data. The calculation formula is as follows:

$$\beta = \text{Median}\left(\frac{x_j - x_i}{j - i}\right), \forall j > i$$

In this equation, x_j and x_i represent the values of the sequence at times j and i, respectively. When $\beta > 0$, the time series exhibits an upward trend; conversely, when $\beta < 0$, the time series exhibits a downward trend.

The Mann-Kendall (MK) test is a non-parametric rank-based trend test used to determine the significance of a trend. Its primary advantage is that it does not require the data to follow a specific distribution and is unaffected by a small number of outliers. For a time series $X = \{x_1, x_2, \dots, x_n\}$, the test statistic S is defined as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sgn}(x_j - x_i)$$

Where $\text{sgn}(x_j - x_i)$ is the sign function:

$$\text{sgn}(x_j - x_i) = \begin{cases} 1, & x_j - x_i > 0 \\ 0, & x_j - x_i = 0 \\ -1, & x_j - x_i < 0 \end{cases}$$

When $n \geq 10$, the statistic S approximately follows a normal distribution. The standardized test statistic Z is calculated as:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\mathrm{Var}(S)}}, & S > 0 \\ 0, & S = 0 \\ \frac{S+1}{\sqrt{\mathrm{Var}(S)}}, & S < 0 \end{cases}$$

In this study, we set the significance level at $\alpha = 0.05$.

Testing Theil-Sen Median Trend Analysis and Mann-Kendall Test

Theil-Sen Median trend analysis and the Mann-Kendall test are two non-parametric statistical methods widely used in hydrology, meteorology, and environmental science for detecting and quantifying trends in time series data. Unlike parametric methods, these approaches do not require the data to follow a specific distribution (such as a normal distribution) and are highly resilient to outliers.

1. Theil-Sen Median Trend Analysis

Theil-Sen Median trend analysis, also known as Sen' s slope estimator, is a robust method for calculating the linear trend of a time series. It is particularly effective for long-term sequence data as it minimizes the influence of extreme values or noise.

The calculation involves computing the slopes between all possible pairs of data points in the time series. For a time series x with n observations, the slope Q_i between any two points x_j and x_k (where $j > k$) is defined as:

$$Q_i = \frac{x_j - x_k}{j - k}$$

For a series of length n, there will be $N = n(n-1)/2$ such slope estimates. The Theil-Sen estimator is the median of these N values:

$$\beta = \mathrm{Median}(Q_i)$$

A value of $\beta > 0$ indicates an upward or increasing trend, while $\beta < 0$ indicates a downward or decreasing trend. Because it utilizes the median, the estimator is insensitive to a small number of outliers or missing values, making it superior to simple linear regression in many geophysical applications.

2. Mann-Kendall Trend Test

While the Theil-Sen estimator quantifies the magnitude of a trend, the Mann-Kendall (MK) test is used to determine the statistical significance of that trend.

The MK test is a rank-based non-parametric test that evaluates whether a variable monotonically increases or decreases over time.

The test statistic S is calculated as follows:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \operatorname{sgn}(x_j - x_k)$$

where $\operatorname{sgn}(\theta)$ is the sign function:

$$\operatorname{sgn}(\theta) = \begin{cases} 1, & \theta > 0 \\ 0, & \theta = 0 \\ -1, & \theta < 0 \end{cases}$$

The Mann-Kendall test is a critical method for identifying trends in long-term time series data and has been extensively applied to analyze trends in temperature, precipitation, and glacial changes. Its primary advantages include high computational efficiency and robustness against measurement errors and outliers. Furthermore, the test does not require the time series to satisfy specific assumptions, such as a normal distribution or the absence of serial autocorrelation [**?**].

Theil-Sen Median trend analysis is a robust non-parametric statistical method used to estimate the slope of a trend over time. Unlike traditional ordinary least squares (OLS) regression, which is highly sensitive to outliers and assumes a normal distribution of residuals, the Theil-Sen estimator is insensitive to outliers and does not require the data to follow a specific probability distribution. This makes it particularly suitable for analyzing time-series data in environmental science, hydrology, and remote sensing, where data may contain noise or extreme values.

The core principle of the Theil-Sen estimator involves calculating the slopes between all possible pairs of points in a time series. For a given set of n data points (t_i, x_i), where t_i represents time and x_i represents the observed value, the slope S_{ij} between any two points at times t_i and t_j (where $t_i < t_j$) is defined as:

$$S_{ij} = \frac{x_j - x_i}{t_j - t_i}$$

The final estimate of the trend, often referred to as the Sen' s slope, is the median of all calculated slopes S_{ij}. This median approach ensures that the resulting trend line is not skewed by a small number of anomalous data points. Mathematically, the total number of slope pairs is $N = n(n-1)/2$, and the Sen' s slope β is expressed as:

$$\beta = \text{median}(S_{ij}), \quad 1 \le i < j \le n$$

A positive value of β indicates an increasing trend over the observation period, while a negative value indicates a decreasing trend. Because it relies on the median, the breakdown point of the Theil-Sen estimator is approximately 29.3%, meaning it can maintain its accuracy even if nearly a third of the data points are outliers. This robustness provides a significant advantage over linear regression models in long-term monitoring studies.

3.2 Trend Estimation Methods

The trend estimation method calculates the slopes between all possible pairs of data points within a time series. By determining the median of these slopes, the method provides a robust estimate of the overall trend. This approach is particularly effective in mitigating the influence of outliers and non-normal noise, which are common in complex datasets.

[Figure 1: see original paper]

The core principle involves analyzing the rate of change between observations at different time steps. For a given time series $X = \{x_1, x_2, \dots, x_n\}$, the slope S_{ij} between any two points x_i and x_j (where $i < j$) is defined as:

$$S_{ij} = \frac{x_j - x_i}{j - i}$$

By calculating S_{ij} for all pairs (i, j) such that $1 \le i < j \le n$, we obtain a set of $N = n(n-1)/2$ slope values. The final trend estimate, β, is the median of this set:

$$\beta = \text{median}(S_{ij})$$

This median-based estimator is highly resilient to anomalies, as a single extreme value does not significantly shift the median in the same way it would affect a traditional least-squares mean. Consequently, this method is widely utilized in machine learning and deep learning preprocessing pipelines to ensure that the underlying directional movement of the data is accurately captured before further modeling or forecasting.

In the equations above, S represents the test statistic; n denotes the number of data points in the time series; $\text{Var}(S)$ is the variance of S; Z_c is the standardized normal test statistic; and t_p refers to the number of ties in the p-th group of tied values. This study employs a two-tailed trend test with a significance level of $\alpha = 0.05$. Accordingly, the trend is considered statistically significant when $|Z_c| > 1.96$.

This study selects the annual average temperature and annual precipitation data from 1990 to 2023.

Theil-Sen Median trend analysis and Mann-Kendall tests were conducted on the glacier volume and glacier meltwater runoff data from 1999 to 2021. This approach allows for a robust assessment of the long-term changes in glaciological parameters, providing insights into the response of these ice masses to regional climate shifts. By employing these non-parametric statistical methods, the study ensures that the identified trends are less sensitive to outliers and skewed data distributions, which are common in high-altitude hydrological time series.

The analysis reveals significant fluctuations in both glacier volume and the resulting meltwater contributions over the past two decades. These findings are critical for understanding the hydrological cycle in the study area, particularly regarding the sustainability of water resources downstream. The integration of these datasets facilitates a comprehensive evaluation of how glacier retreat influences regional water availability and the overall stability of the mountain ecosystem.

By examining and analyzing the spatial distribution characteristics of the aforementioned factors and their relationship with glacial lake distribution, this study provides a foundational dataset for subsequent geographical detector analysis.

1.3.3 参数最优地理探测器地理探测器是一组用

Geographical detector is a statistical method used to explore spatial heterogeneity and reveal the underlying driving forces behind it [?]. Since the distribution and evolution of glacial lakes and their influencing factors exhibit distinct spatial differentiation, this method has been widely applied to identify the drivers of changes in glacial lake number and area [?, ?]. In this study, we employ the differentiation and factor detection module, as well as the interaction detection module of the geographical detector, to investigate the primary drivers of glacial lake changes and evaluate the explanatory power of different

The overall trend is estimated using the median slope between observations, which allows for the quantification of the magnitude of the trend

driving factors when they act synergistically on glacial lake changes. Factor

variation. The calculation formula is as follows:

differentiation and factor detection are used to detect the spatial heterogeneity of the dependent variable (Y), as well as to determine the extent to which a given factor (X) explains the spatial distribution of Y.

$$\beta = \text{Median}\left(\frac{x_j - x_i}{j - i}\right), \forall j > i$$

An upward trend in the time series is indicated when the value is positive, whereas a negative value represents a downward trend; here, x_i and x_j denote the data values at time points i and j, respectively. The Mann-Kendall test is a non-parametric statistical method.

It is used to determine the significance of a trend. The calculation formula is as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(x_j - x_i)$$

$$\operatorname{Var}(S) = \frac{n(n-1)(2n+5) - \sum t_p(t_p-1)(2t_p+5)}{18}$$

In the formula: L represents the stratification of variable Y or factor X, referring to its classification or partitioning; N_h and N denote the number of units in stratum h and the entire study area Y, respectively; σ_h^2 and σ^2 represent

the variances of stratum h and the entire area Y, respectively. The value of q ranges from $[0, 1]$; a higher q value indicates

whether it increases or weakens the explanatory power of the dependent variable, or whether the effects of these factors on

the traditional geographical detector method, when processing continuous variables,

the standardized statistic Z_c follows a normal distribution and is calculated according to the following formula:

the influence on the dependent variable is mutually independent.

$$Z_c = \begin{cases} \frac{S-1}{\sqrt{\operatorname{Var}(S)}}, & S > 0 \\ 0, & S = 0 \\ \frac{S+1}{\sqrt{\operatorname{Var}(S)}}, & S < 0 \end{cases}$$

Interaction detection can evaluate whether the combined effect of two factors is enhanced, weakened, or independent of one another. In statistical analysis and machine learning, this process is crucial for understanding complex relationships within data that cannot be explained by individual variables alone. By examining these interactions, researchers can determine if the influence of one independent variable on the dependent variable changes depending on the level of another independent variable. This approach is widely used to identify synergistic effects, where the joint impact exceeds the sum of individual effects, or antagonistic effects, where the factors interfere with each other.

$$\text{sgn}(x_j - x_i) = \begin{cases} 1, & x_j - x_i > 0 \\ 0, & x_j - x_i = 0 \\ -1, & x_j - x_i < 0 \end{cases}$$

A higher value indicates that the independent variable X has a stronger explanatory power for attribute Y, and vice versa.

In the formula: β represents the median slope of all data pairs; $\beta > 0$ indicates a temporal trend where···

···and the extent to which a specific factor (X) explains the spatial differentiation of Y.

Data processing typically requires the manual selection of classification methods and the number of intervals, which often leads to issues such as poor discretization and high subjectivity. In contrast, the Optimal Parameters-based Geographical Detector (OPGD) method can identify the maximum q-value for each variable across various classification methods and interval counts through comparative computation [?]. In this study, we utilized the R language···

···specifically the GD package, to apply classification methods and select the parameter combinations that yielded the maximum q-value for the spatial discretization of factors. Based on the seven···

···basins extracted via ArcGIS, combined with the HydroBASINS level-10 watershed data···

(https://www.hydrosheds.org), the study area was further subdivided to obtain 184···

···level-10 sub-basins. Data for these basins—including mean elevation, annual mean temperature change, annual precipitation change, cumulative glacier mass balance, glacier volume change, and meltwater runoff change—were aggregated using summation or averaging methods. Subsequently, the OPGD method was employed to analyze the influence of each factor on the changes in the area and number of glacial lakes across the different basins.

2 Changes in the total number and area of glacial lakes in transboundary basins between China and Bhutan from 1990 to 2023

Change in total number of glacial lakes (count)

Change in total area of glacial lakes (km^2)

2.1.2 不同流域冰湖变化研究区 7 个流域的冰湖

Both the quantity and total area exhibited an increasing trend from 1990 to 2023 [FIGURE:N].

2 结果与分析

Bing et al.: Characteristics and Driving Factors of Glacial Lake Changes in the Transboundary Basins of China and Bhutan

2). The Lhozhag Qu-Kuri Chu Basin (ID) exhibited the most significant area expansion.

2.1.1 冰湖数量与面积变化 1990—2023 年研究区

Changes in endoglacial lakes are characterized by four distinct states: disappearance, shrinkage, expansion, and stable area.

types. Among them, 41 glacial lakes disappeared and 4 glacial lakes shrunk. The disappearance and

The total area of shrinking glacial lakes is 0.8 km^2; meanwhile, 131 glacial lakes have undergone area expansion.

511 new glacial lakes were formed; meanwhile, the surface area of other existing glacial lakes remained unchanged. This type of glacial lake···

Most of the lakes in this region are non-glacier-fed lakes. From 1990 to 2023, the total number of glacial lakes in the study area increased from 1,943 to 2,413, representing a net increase of 470 lakes.

(6.24 km^2), while the Sun Koshi River Basin (ID) saw the largest increase in the number of new glacial lakes (133), with the second-highest increase in total area (5.99 km^2). In the Mangde Chhu River Basin (ID), 80% of the newly formed glacial lakes have an area of less than 0.02 km^2, primarily due to···

Although the number of glacial lakes in this basin has increased significantly (by 100), the overall expansion in surface area remains limited. In the Nyamjang Chu-Danma River basin (ID), 82 new glacial lakes were formed between 1990 and 2000, resulting in an area expansion of 4 km^2, which exceeds···

The increase in the area and number of glacial lakes across any given period and basin from 1990 to 2023.

increased by 13; the total area expanded from 143.25 km^2 to 165.71 km^2,

2.1.3 不同规模冰湖变化特征 1990—2023 年研

However, the formation and expansion of new glacial lakes represents the overall trend ().

5.91 km^2, while the remaining glacial lakes range in size from 0.0036 to 3.0 km^2 [FIGURE:N].

The total area of glacial lakes reached 22.46 km^2, with an average annual growth rate of 0.66 km^2. Although some glacial lakes have disappeared or are currently at different stages of development, there are notable differences in the expansion rates of the total number and total area of these lakes (Table 2). During the period from 1990 to 2000, the baseline number of glacial lakes was relatively small.

The largest glacial lake in the study area, She-e-tso, expanded from 5.63 km^2 to [missing value]. Classification standards for glacial lake scales (i.e., area classes) vary by region; however, they generally follow the principle of fine subdivision for small glacial lakes and coarse classification for large glacial lakes [**?**]. Based on⋯

The number of glacial lakes is small, but this period exhibits the fastest growth rate. During this stage, the number of glacial lakes increased by an average of 27 per year.

Regarding the scale distribution characteristics of glacial lakes in the study area, this paper adopts 0.02 km^2 as the minimum threshold for analysis.

During the first stage of growth, both the total quantity and the total area tend to stabilize, remaining in an ice-covered state.

Glacial lakes with an area of 0.02 km^2 are the most numerous across all periods of data and exhibit a consistent trend.

The average annual area expansion was 1.04 km^2. From 2000 to 2010, the glacial lakes underwent⋯

The development stage of glacial lakes. From 2010 to 2023, both the total number and the total area of glacial lakes continued to increase steadily; however, the growth rate has slowed compared to the period between 1990 and 2000.

Total Number and Area of Glacial Lakes in Transboundary Basins Between China and Bhutan from 1990 to 2023

Based on the interpretation of multi-temporal satellite remote sensing imagery, the distribution and evolutionary characteristics of glacial lakes in the transboundary basins between China and Bhutan were analyzed for the period from 1990 to 2023. The results indicate significant changes in both the total number and the cumulative area of glacial lakes across these basins over the past three decades.

As shown in , the total number of glacial lakes in the study area has exhibited a consistent upward trend. In 1990, the region contained a specific number of identified glacial lakes, which increased steadily through the subsequent observation periods in 2000, 2010, and 2020, reaching its peak in 2023. This increase in number is primarily attributed to the fragmentation of larger existing lakes and the formation of new proglacial lakes resulting from accelerated glacial retreat.

[Figure 1: see original paper]

The total surface area of these glacial lakes has also undergone substantial expansion. [Figure 1: see original paper] illustrates the spatial distribution and the corresponding area changes across the transboundary basins. The expansion rate has not been uniform; rather, it shows an accelerating trend in recent years, particularly between 2010 and 2023. This expansion is a critical indicator of regional climate warming, as rising temperatures lead to increased meltwater production and the retreat of glacier termini, which in turn provides the necessary space and water source for lake growth.

The statistical analysis of the transboundary basins reveals that the growth in glacial lake area is often concentrated in specific altitudinal zones. Most of the expanding lakes are located in close proximity to glacier tongues, categorized as glacier-fed lakes. The continuous monitoring of these parameters—total number and total area—is essential for assessing glacial lake outburst flood (GLOF) risks and understanding the hydrological response of the Himalayan region to global climate change.

intervals were partitioned, with intervals appropriately increased for large glacial lakes. Glacial lakes with a size smaller than [missing value] exhibited a continuous growth trend, increasing from 884 in 1990 to 1,214 in 2023. This growth accounts for 70.21% of the total number of newly formed glacial lakes. In terms of area,

Glacial lakes with an area greater than 0.1 km^2 remain relatively stable in terms of quantity; however, they exhibit significant variability in terms of surface area.

The expansion is most significant in terms of area, with an increase of 14.94 km^2, accounting for 66.52% of the total newly added area. Among these, glacial lakes with a size ranging from 0.1 to 0.5 km^2 were the most prominent across all periods.

This category accounts for the largest proportion of the total area and exhibits the most rapid expansion rate, increasing by 6.02 km^2, which represents 26.80% of the total expanded area.

2.1.4 不同海拔冰湖变化特征高海拔地区气温

Total number of glacial lakes

Total area of glacial lakes/km^2

The formation and development of lakes [**?**]. More than 90% of the glacial lakes in the study area are distributed

Both the number and area of glacial lakes in the zone show an increasing trend [Figure 4: see original paper]. Glacial lakes in low, lacking supply sources such as glacial meltwater; in low-altitude areas, the temperature is high,

and glacier development is limited. Therefore, both excessively high and excessively low altitudes are unfavorable for glacial

within the altitude range of 4000–5550 m. From 1990 to 2023, across the 12 altitude

2 Changes in number and area of glacial lake in transboundary basins between China and Bhutan from 1990 to 2023

3 Changes in number and area of different scale glacial lakes in transboundary basins between China and Bhutan from 1990 to 2023

Lower altitude ranges (<4700 m) and higher altitude ranges (>5400 m).

Annual precipitation showed no significant change in 73.9% of the sub-basins, while the remaining sub-basins

The growth rate was fastest in this altitude range, with the number and area increasing by 98 and

The overall thermal distribution is characterized by a cold north and a warm south, with the multi-year average temperature in the glacial lake distribution areas generally remaining below 0 ℃.

Relatively stable, with minimal area expansion. Glacial lakes located at altitudes of 5100–5200 m

6.52 km^2, accounting for 20.85% of the increase in number and

29.03% of the increase in area. Notably, the average altitude of glacial lakes in 2023 was

4828.66 m, which, compared to the average altitude in 1990 (4790.19 m),

The annual precipitation variation ranged from 1.93 to 13.39 $mm \cdot a^{-1}$ [Figure 5: see original paper] (Fig. 5a). For the region as a whole,

0.015 to 0.064 $℃ \cdot a^{-1}$ (Fig. 5b). Rising temperatures accelerate glacial melting,

promoting the growth of both the number and area of glacial lakes. This phenomenon is particularly evident at glacier termini [?].

increased by 38.47 m. This trend is consistent with the upward migration of glacial lakes driven by glacier retreat.

In the Sankosh River Basin (ID: ···) from 1990 to 2023,

2.2 冰湖变化驱动因素分析

The annual average temperature variation in the basin is 0.031 $°C \cdot a^{-1}$. In the Lhozhag Qu-Ku···

This is consistent with the phenomenon of migration toward higher altitudes.

2.2.1 冰湖变化与气候波动冰湖变化与气候变化

closely related. Rising temperatures (leading to increased glacial meltwater), increased precipitation, and decreased evaporation all favor the expansion of glacial lake areas and an increase in their number [?]. The multi-year average precipitation in the study area exhibits a spatial pattern that is lower in the north and higher in the south.

) showed a net increase of 133 glacial lakes, 75.2% of which are located at glacier termini. The Gairu River Basin (No.) experienced the most significant expansion in glacial lake area. The mean annual temperature in this basin changed at a rate of 0.029 ℃ · a^{-1}, and by 2023, the glaciers within this basin

at the termini of four glacial lakes with areas exceeding 0.5 km^2 (Bailang Co, Yeyou Co, Angge Co, and Cuogalong Co) had expanded by a total area of 2.78 km^2.

Bing et al.: Characteristics and Driving Factors of Glacial Lake Changes in the Transboundary Basins of China and Bhutan

4 Changes in number and area of glacial lakes at different altitude in transboundary basins between China and Bhutan from 1990 to 2023

5 Distributions and variation trends of annual mean temperature and annual precipitation in transboundary basins between China and Bhutan from 1990 to 2023

2.2.2 冰湖变化与冰川变化冰川变化是一个系统

equilibrium state, indicating continuous glacier ablation. Among these, the Sankosh River basin

complex physical processes, covering stages such as "climate change -glacier mass balance change -glacier dynamic response -glacier volume change -glacier meltwater runoff change."

region (No.) experienced the greatest glacier loss, totaling 4048 m w.e., followed by the

change -glacier dynamic response -glacier volume change -glacier meltwater runoff change" and other stages.

In order to comprehensively analyze the impact of glacier changes on glacial lake variations,

this study examines the distribution characteristics of glacier mass balance, as well as the trends in glacier volume and meltwater runoff changes.

Nyamjang Chu-Danma River basin (No.), which recorded a loss of 3641 m w.e. ([Figure 6: see original paper]a).

Glacier loss during the periods 1999–2010 and 2011–2021 accounted for 45.32% and 54.68% of the total loss, respectively. This indicates that

glacier ablation has accelerated after 2010, which is consistent with global trends in glacier mass balance changes [**?**]

Glacier mass balance reflects the annual net change of a glacier. From 1999 to 2021, glaciers in 98.3% of the sub-basins in the study area were in a negative

(Figure 6b [Figure 6: see original paper]).

Glacier meltwater runoff and glacier volume reflect the ablation and

6 Distribution and changes of glacier mass balance in transboundary basins between China and Bhutan from 1999 to 2021

accumulation process. In the study area, glacier meltwater runoff increased in 82.1% of the basins.

Both the number and area exhibit an increasing trend, indicating that rising temperatures have led to

an increase in glacier meltwater. Among these, the Nyangmujang Qu-Danma River basin (ID) experienced the most significant change,

reaching 4.25 Mt·a^{-1} (Figure 7a [Figure 7: see original paper]), which highlights how increased glacier meltwater promotes glacial lake development.

The characteristics of glacial lake changes in this basin demonstrate

2.2.3 参数最优地理探测器分析在冰湖面积变化

(the second highest in the entire basin). At the same time, 98.3% of the glaciers in the basin have experienced a decrease in volume.

and the *q*-values for glacier volume change rank among the top three. Among these factors, glacial meltwater

Currently, the area has expanded by 4.01 km^2 (ranking third in the entire basin), and the quantity has increased by 118.

In the total volume, the variation in glacier meltwater runoff and the cumulative glacier mass balance are critical components.

less, and its spatial distribution is consistent with the variation in meltwater runoff ([Figure 7b: see original paper]).

The explanatory power for runoff variation is the strongest; among the variations in the number of glacial lakes, the ice-contact lakes exhibit the most significant trends. These findings suggest that hydrological responses to climate warming are increasingly dominated by glacial meltwater contributions.

[Figure 1: see original paper]

The spatial distribution of these changes indicates a heterogeneous pattern across the study region. While some basins show a marked increase in total lake area, others are characterized by the fragmentation of larger glacial bodies into smaller, isolated units. This process is often preceded by the thinning of the glacier tongue and the subsequent formation of proglacial depressions that collect meltwater.

Quantitative analysis reveals that the sensitivity of runoff to temperature fluctuations has increased over the past decade. Using the relationship defined by $\mathcal{F}$, we can estimate the contribution of glacial retreat to the overall water balance. As shown in (1), the discharge Q is heavily influenced by the melt rate M and the precipitation P:

$$Q = \int_A (P + M - E) dA \tag{1}$$

where E represents evapotranspiration and A is the catchment area. Our results indicate that the term M has become the primary driver of seasonal peak flows, particularly in high-altitude catchments where permafrost degradation is also prevalent. These shifts in the hydrological regime have profound implications for downstream water security and the risk of glacial lake outburst floods (GLOFs).

The growth in the number of glacial lakes and the expansion of their surface areas are closely linked to glacial mass balance and the overall state of the cryosphere. As global temperatures rise, the accelerated melting of glaciers provides a continuous source of meltwater, which accumulates in topographic depressions to form new glacial lakes or expand existing ones. This process is a direct indicator of regional climate change and reflects the dynamic response of glaciers to thermal forcing.

[Figure 1: see original paper]

The relationship between glacial mass loss and lake evolution is characterized by a complex feedback mechanism. Negative mass balance leads to the thinning and retreat of glacier tongues, often leaving behind terminal or lateral moraines that act as natural dams. These dams impound meltwater, resulting in the formation of proglacial lakes. Furthermore, the expansion of these lakes can, in turn, accelerate glacier retreat through thermal undercutting and increased calving at the ice-water interface, creating a self-reinforcing cycle of mass loss and lake growth.

Monitoring these changes is critical for assessing regional water security and evaluating the risk of glacial lake outburst floods (GLOFs). As the volume of stored water increases alongside the degradation of permafrost and the weakening of moraine dams, the potential for catastrophic drainage events grows. Understanding the spatial and temporal patterns of lake expansion relative to glacial retreat is therefore essential for developing effective disaster mitigation strategies and managing water resources in high-mountain environments.

Abstract

The variations in glacier meltwater runoff, cumulative glacier mass balance, and glacier volume represent critical indicators of climate change and hydrological cycles in high-altitude regions. This study analyzes the fluctuations in glacier meltwater discharge and the corresponding accumulation of mass balance to understand the dynamic response of glacial systems to thermal and precipitative forcing. By quantifying the changes in glacier body characteristics, we provide a comprehensive assessment of the storage and release mechanisms of these "solid water towers." The results indicate a significant trend in mass loss, which directly influences the downstream water availability and the stability of regional ecosystems. These findings are essential for predicting future water resource security and developing adaptive management strategies in glacier-fed basins.

The variations in glacier volume and meltwater runoff exhibit a high degree of spatial consistency.

The q-values for the variation in cumulative volume rank among the top three, with the variation in glacier meltwater runoff being a primary factor.

2.2 Regional Characteristics

The climatic and hydrological characteristics of the study area exhibit significant spatial variability. In the Ladak River Basin (ID:), despite the relatively high annual average temperatures and annual precipitation levels, the region' s complex topography and specific moisture transport mechanisms lead to unique environmental dynamics. This basin serves as a critical point of observation for understanding how localized climatic factors influence broader hydrological cycles within the mountainous terrain.

The explanatory power of glacier-related factors is the most significant. Overall, glacier-related factors exhibit the strongest influence on glacial lakes.

Precipitation has increased significantly; however, due to the sparse distribution of glaciers, there is a lack of sufficient

The explanatory power of these changes is higher than that of both climatic and topographic factors ().

Due to the replenishment from snow and ice melt, the number and area of glacial lakes have remained relatively stable. In the Luozhaqu-Ku basin···

Significant interactions exist between various factors. As the number of glacial lakes changes, the underlying drivers exhibit complex synergistic effects. These interactions suggest that the evolution of glacial lake systems is not merely a response to individual environmental variables, but rather the result of a coupled mechanism involving multiple climatic and topographic factors.

The Lu River Basin (No.) and the Niangmu Jiangqu-Danma River (No.) flow ...

In the context of quantitative analysis, the q-value representing the relationship between the variation in mean annual temperature and the average elevation is 0.93.

Mountain glaciers are widely distributed, yet annual precipitation has not shown a significant trend of change.

maximum (Figure 8a [Figure 8: see original paper]), indicating that the increase in mean annual temperature and elevation characteristics are ice-related factors.

4. Discussion

4.1 Spatiotemporal Evolution of Glacial Lakes

The results of this study demonstrate a significant expansion of glacial lakes in the region over the past several decades. This trend is consistent with global observations of glacier retreat and lake formation in high-altitude environments. The spatial distribution of these lakes reveals a clear dependency on topographic features, particularly elevation and slope. As shown in [Figure 8: see original paper], the correlation between temperature rise and lake area expansion is most pronounced at higher elevations, where melting processes are accelerated.

4.2 Impact of Climate Change

Climate change remains the primary driver of glacial lake dynamics. The increase in mean annual temperature leads to enhanced meltwater production and the retreat of glacier termini, which in turn facilitates the formation of new lakes and the expansion of existing ones. Our analysis suggests that the sensitivity of glacial lakes to temperature fluctuations varies across different elevation bands. Specifically, lakes located in the transition zones between glaciers and permafrost exhibit the highest rates of change.

summarizes the statistical relationship between climatic variables and lake area changes. The high correlation coefficients indicate that temperature and precipitation are the dominant factors influencing the hydrological balance of these systems.

4.3 Hazards and Risks

The rapid expansion of glacial lakes poses significant risks to downstream communities and infrastructure. Glacial Lake Outburst Floods (GLOFs) are a major concern, as the increasing volume of water puts additional pressure on natural dams. Monitoring these changes is crucial for disaster risk reduction and water resource management in the context of ongoing climate warming.

5. Conclusion

In summary, this research highlights the dynamic nature of glacial lakes in response to regional climate warming. By integrating multi-temporal satellite imagery and topographic data, we have quantified the extent of lake expansion and identified key environmental drivers. Future studies should focus on high-resolution modeling of lake stability to better predict potential outburst events.

Against the climatic backdrop of a significant increase in mean annual temperatures, glacial lakes within the basin exhibit distinct evolutionary characteristics. These changes are closely linked to the accelerated melting of glaciers and shifts in regional precipitation patterns. As thermal forcing intensifies, the expansion of existing glacial lakes and the formation of new ones have become increasingly prominent, posing potential risks for glacial lake outlier floods (GLOFs) in the downstream regions. Understanding these dynamics is critical for assessing water resource stability and regional environmental security under a warming climate.

Drivers of Increasing Lake Numbers

The proliferation of glacial lakes is driven by a complex interplay of climatic and geomorphological factors. As global temperatures rise, the accelerated melting of glaciers provides a continuous source of meltwater, which accumulates in topographic depressions or behind moraine dams. This process is particularly evident in high-altitude regions where the warming rate exceeds the global average. The formation of new lakes is often initiated by the retreat of glacier tongues, leaving behind overdeepened basins that subsequently fill with water. Furthermore, the degradation of permafrost

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

Source: ChinaXiv —Machine translation. Verify with original.