Changes in Glacial Lakes on the Northern Slope of the Kunlun Mountains and Their Outburst Risk Assessment Postprint

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Abstract

Investigating the spatiotemporal variations of glacier lakes and assessing Glacier Lake Outburst Flood (GLOF) risks on the northern slope of the Kunlun Mountains is of great significance for regional water resource security and ecological development. Based on the Google Earth Engine (GEE) remote sensing computing platform, this study analyzes the change characteristics of glacier lakes on the northern slope of the Kunlun Mountains over the past 30 years and conducts hazard and risk assessments for current moraine-dammed lakes using a GLOF risk assessment model. The results indicate: (1) From 1990 to 2023, glacier lakes on the northern slope of the Kunlun Mountains exhibited a significant increasing trend, with the number of glacier lakes increasing from 248 in 1990 to 925 in 2023 (a 2.73-fold increase), and the area expanding from 14.99 km2 in 1990 to 54.83 km2 in 2023 (a 2.66-fold increase). Glacier lakes increased most significantly in the high-altitude mountainous regions of the western part of the northern slope of the Kunlun Mountains. (2) Analysis of the 2023 GLOF risk assessment reveals that the hazard level is highest in the Yarkant River basin (accounting for approximately 47.2%), followed by the Hotan River basin (accounting for approximately 15.7%). The risk level is also higher in the Yarkant River basin (accounting for approximately 50.8%), with high-risk glacier lakes in the Yarkant River basin comprising 60.7% of all high-risk glacier lakes across the entire northern slope of the Kunlun Mountains. (3) The increasing trend of glacier lakes from 1990 to 2023 is correlated with regional climate change, with increased precipitation in mountainous areas and melting of glacial snow and ice being the primary drivers of glacier lake expansion. Conducting GLOF risk assessments can provide scientific basis and support for sustainable water resource utilization in arid regions and for disaster prevention and early warning in downstream areas.

Full Text

Abstract

The exploration of spatiotemporal changes in glacial lakes on the northern slope of Kunlun Mountains and the risk assessment of glacier lake outburst floods (GLOF) are of great significance for regional water resource security and ecological development. Using the Google Earth Engine (GEE) remote sensing platform, this study analyzed changes in glacial lakes on the northern slope of Kunlun Mountains over the past 30 years and applied a GLOF risk assessment model to evaluate current moraine lakes for disaster risk. The results indicate the following: (1) From 1990 to 2023, the number and area of glacial lakes on the northern slope of Kunlun Mountains increased significantly. By 2023, the number of glacial lakes had risen to 925, marking a 2.73-fold increase from 248 in 1990. Similarly, the area of glacial lakes expanded to 54.83 km^2, a 2.66-fold increase from 14.99 km^2 in 1990. This growth was particularly notable in the high-altitude mountainous regions of the western part of the northern slope. (2) The 2023 GLOF risk assessment indicates that the Yarkant River Basin poses the highest disaster risk, accounting for approximately 47.2% of the assessed area, followed by the Hotan River Basin at 15.7%. In terms of risk levels, the Yarkant River Basin shows a relatively high-risk, accounting for about 50.8%, and high-risk glacial lakes in the Yarkant River Basin account for 60.7% of the high-risk glacial lakes on the entire northern slope of the Kunlun Mountains. (3) The increasing trend in glacial lakes from 1990 to 2023 is closely related to regional climate change. Rising temperatures have led to increased precipitation in mountainous areas and accelerated the melting of glaciers and snow, which are the primary drivers of glacial lake expansion. The GLOF risk assessment contributes to the sustainable management of water resources in arid regions and provides a scientific basis for disaster prevention and early warning systems in downstream areas.

Keywords: glacial lakes; outburst flood disaster; risk assessment; northern slope of Kunlun Mountains

1 Introduction

Glacier lake outburst floods (GLOF) refer to sudden dam failures or overflows of glacial lakes (including glacier-dammed lakes, moraine-dammed lakes, supraglacial lakes, and subglacial lakes) under glacial action, triggering outburst floods. These events are characterized by strong suddenness, extensive impact range, and severe damage potential, posing significant threats to lives, property, and infrastructure in downstream areas []. Therefore, investigating GLOF disasters not only provides authentic records of regional climate and glacial changes but also enables timely and accurate monitoring of glacial lake distribution and development trends. Scientific and rational assessment of GLOF risks in arid regions is crucial for future regional economic development and disaster prevention and early warning systems [].

Under global warming, alpine glaciers are experiencing widespread retreat and melting [], which promotes the formation of new glacial lakes []. As temperatures continue to rise, permanent snow cover and permafrost are also accelerating their thaw [], leading to further expansion in the area, number, and water storage capacity of glacial lakes []. For the arid high mountain regions of northwestern China, the expansion of glacial lakes and increased water storage have, to some extent, mitigated the loss of regional glacial water resources caused by climate warming [], providing valuable water sources for arid mountainous areas and effectively promoting sustainable economic and ecological development []. However, the continuous expansion of glacial lakes and increasing water volume also entail heightened GLOF risks [], threatening residential areas, infrastructure, and lives and property across thousands of kilometers in upstream and downstream regions [].

GLOF has become one of the major natural disasters in high-cold mountainous regions, attracting considerable attention from scholars in recent years. Current GLOF research primarily focuses on: dynamic change analysis of relatively active glacial lakes at regional scales []; simulation of outburst processes based on hydrodynamic models []; identification of potential glacial lake hazards and reconstruction of GLOF events []. In China, GLOF studies have concentrated on the “Third Pole” region [], including the Kunlun Mountains, Tianshan Mountains, Tibet, and the northern slope of the Kunlun Mountains, particularly in the Yarkant River Basin. These studies mainly involve: extraction of glacial lake information based on remote sensing []; analysis of climate change characteristics and driving factors of glacial lakes in different regions and watersheds []; reconstruction of outburst disasters for relatively active glacial lakes []; and identification, simulation, and early warning of potential GLOF hazards [].

Research indicates that glaciers and snow cover in the Asian high mountain regions and globally are universally retreating and melting. Glacial lakes fed by glacial meltwater account for 70% of the total number and area of lakes in the Third Pole region []. Climate warming-induced glacial meltwater is the direct cause of increased glacial lake numbers and expanded areas []. The northern slope of Kunlun Mountains, located on the southern edge of the Taklamakan Desert, represents the most concentrated distribution of glaciers in the mid-low latitude zones worldwide. Investigating the spatiotemporal distribution characteristics of glacial lakes on the northern slope of Kunlun Mountains can provide references for regional water resource security, ecological benefits, and future land use planning, while quantitative assessment of GLOF risks can offer theoretical foundations for disaster prevention and early warning in this region.

1.1 Study Area Overview

The northern slope of Kunlun Mountains is situated on the southern edge of the Taklamakan Desert in northwestern China, with geographical coordinates ranging from 34°83 –40°55 N to 74°80 –93°02 E. The region exhibits rich biodiversity and serves as an important protected area in the arid western region of China

[]. Numerous rivers originate here, including the Yarkant River, Hotan River, and Keriya River, forming a crucial corridor in the southern part of the core area of the Silk Road Economic Belt. This region also ensures the sustainable utilization and support of water resources in arid areas. The northern slope of Kunlun Mountains comprises five watersheds and basins: the Kumukuli Basin, Qarqan River Basin, Keriya River Basin, Hotan River Basin, and Yarkant River Basin. Precipitation shows strong seasonality, concentrated mainly in summer with minimal winter precipitation, and the average annual precipitation is 34.8 mm.

1.2 Data Sources

Remote Sensing Data: Sentinel-2A/B MSI data and Landsat series remote sensing images were obtained from the United States Geological Survey (http://earthexplorer.usgs.gov/) and the Copernicus Open Access Hub (https://dataspace.copernicus.eu/) for glacial lake boundary extraction. Given the difficulties in acquiring long time-series remote sensing images, images from the peak glacial melt period (June–September) with cloud cover less than 10% were selected to minimize impacts from cloud cover, terrain factors, and snow cover. Five time windows were extracted to construct a dataset of glacial lakes on the northern slope of Kunlun Mountains.

Digital Elevation Model (DEM): The primary DEM data included the 30 m resolution AW3D30 v2.2 and MERIT DEM. AW3D30 v2.2 was derived from the Panchromatic Remote-sensing Instrument for Stereo Mapping (PRISM) onboard the ALOS land observation satellite, providing a global digital surface model (DSM). The high-resolution AW3D30 data enables acquisition of more detailed topographic characteristics and was therefore used to obtain relevant topographic attributes of glacial lakes. The MERIT DEM data, which removes various error components from existing DEMs, provided global high-resolution terrain data used primarily for GLOF hazard and risk assessment. Data sources included the National Aeronautics and Space Administration (https://nasadaacs.eos.nasa.gov/) and the ALOS World 3D-30 m Global Digital Surface Model website (https://www.eorc.jaxa.jp/ALOS/en/aw3d30/).

Meteorological Data: Due to the lack of meteorological observation stations in the study area, high-resolution (1/30°) daily-scale temperature and precipitation data from 1990–2020 for the "Third Pole" region were used to analyze the causes of glacial lake changes. Meteorological data were sourced from the National Tibetan Plateau Data Center (https://cstr.cn/18406.11.Atmos.tpdc.272763). The High Asia Glacial Lake Inventory data [] were obtained from the National Cryosphere Desert Data Center (http://www.ncdc.ac.cn).

Glacier Data: The Randolph Glacier Inventory 7.0 (https://www.globalglacierchanges.org/) was used to determine the distribution range of glacial lakes. OpenStreetMap (OSM) data (http://www.openstreetmap.org), which has high timeliness, were used to calculate the volume attribute characteristics of glacial lakes. The glacial lake volume formula was calculated as []:

$$V = 0.104 \times A^{1.42}$$

where V is the glacial lake volume (m^3) and A is the glacial lake area (m^2).

Given that the study area spans 18 degrees of longitude, corresponding to different Universal Transverse Mercator (UTM) zones, glacial lake areas were calculated based on UTM projection coordinates according to different longitudes. All glacial lake areas were obtained based on the UTM coordinate system. The relative change rate of glacial lake area was calculated as:

$$R = \frac{A_2 - A_1}{A_1 \times (t_2 - t_1)} \times 100\%$$

where R is the relative change rate of glacial lake area; A_1 and A_2 are the glacial lake areas at time points t_1 and t_2, respectively.

1.3.1 Glacial Lake Boundary Extraction Glacial lakes are mostly located in inaccessible high-altitude areas, making effective field survey and monitoring difficult. This limitation has led most current research to rely primarily on remote sensing techniques and methods. Leveraging the Third Scientific Expedition, the Scientific Investigation Project of Water Resources Potential and Development and Utilization Pathways on the Northern Slope of Kunlun Mountains was initiated in 2021. A glacial mass balance observation station and automatic meteorological observation station were successfully established in the Zitag Peak glacial region of East Kunlun in 2022 as a typical area for validation, based on regional grid data and remote sensing data.

This study extracted glacial lake boundaries for 1990, 2000, 2010, 2020, and 2023 based on Sentinel-2A/B MSI and Landsat series remote sensing images. A semi-automatic water extraction method using global-local threshold segmentation was applied on the GEE platform to extract glacial lake boundaries. The algorithm first performed binarization on grayscale images based on the Modified Normalized Difference Water Index (MNDWI) and labeled all possible water objects in the study area []:

$$\mathrm{MNDWI} = \frac{\mathrm{Green} - \mathrm{SWIR}}{\mathrm{Green} + \mathrm{SWIR}}$$

A buffer zone of the same size was then established for these labeled objects according to the remote sensing images. Finally, the Otsu algorithm (OSTU) was used for secondary segmentation of the buffered images to obtain more accurate glacial lake boundaries []. Pixels with slopes greater than 15° and terrain shadows greater than 50° were removed before calculation. Considering the impact of remote sensing image spatial resolution and climatic factors that can cause smaller glacial lakes to disappear, glacial lakes with areas smaller than 0.01 km^2 were deleted to ensure data accuracy.

Due to the 30-year time series of remote sensing images being manually downloaded and then extracted through detailed manual interpretation, after completing the glacial lake dataset extraction, the results were manually visually interpreted using historical satellite images, online maps, and the High Asia Glacial Lake dataset. Incorrectly extracted portions were removed, and missing glacial lakes were supplemented. Interactive checks were performed on the multi-period glacial lake datasets using ArcMap to ensure data accuracy and completeness.

The uncertainty in glacial lake boundaries is related to remote sensing image characteristics (such as spatial resolution, terrain shadows, and image quality), researcher interpretation experience, and the minimum area threshold selection. According to the glacial lake area uncertainty estimation method by Hanshaw et al. [], the uncertainty error of glacial lake area was calculated as:

$$\delta = P \times G$$

where δ is the glacial lake area error; P is the glacial lake perimeter (m); and G is the satellite image resolution used for glacial lake area extraction (m).

1.3.2 Glacial Lake Type Classification Different types of glacial lakes typically exhibit different changes. To distinguish these variations and considering terrain complexity and image temporality, glacial lakes were classified based on dam type into moraine-dammed lakes and other dam-type glacial lakes. Moraine-dammed lakes refer to glacial lakes with moraine as the primary dam material, typically including terminal moraine lakes and lateral moraine lakes based on their location. Other dam-type glacial lakes include glacial erosion lakes, landslide-dammed lakes, bedrock-dammed lakes, and various other types. Glacial lake types were primarily identified using the Randolph Glacier Inventory and remote sensing images.

1.3.3 Glacial Lake Outburst Flood Risk Assessment Based on global GLOF records, most outburst flood disasters are dominated by events from moraine-dammed lakes []. Analysis of GLOF events on the northern slope of Kunlun Mountains reveals that outburst floods caused by moraine-dammed lakes and ice-dammed lakes are predominant. Since ice-dammed lakes are formed by glacier blockage with high repeatability and frequent outburst characteristics, while moraine-dammed lake outburst floods are directly related to climate warming and glacial retreat, this study focuses on risk assessment of moraine-dammed lakes.

An improved GLOF risk assessment model was used to evaluate the hazard and risk levels of 490 existing moraine-dammed lakes on the northern slope of

Kunlun Mountains []. Considering that this model is not applicable to moraine-dammed lakes covered by moraine debris or located on glacier sides, such lakes were excluded. The model operates through iterative runs on individual glacial lake objects, avoiding errors caused by overlapping lake watersheds. The model defines three indices: the hazard index represents the likelihood and potential magnitude of GLOF occurrence; the exposure index represents the degree of flood impact on downstream residents and infrastructure, calculated by converting the latest OSM data into raster data for model input; and the risk index is a function of the hazard and exposure indices [].

GLOF hazards are defined by five factors: lake volume, upstream glacier area, potential triggers (described by terrain potential) such as ice avalanches or rockfalls that may initiate GLOF, and average slope of the moraine dam. The dam slope is considered a crucial factor controlling dam stability or self-destruction. These factors integrate currently recognized triggers for GLOF. After calculating these factors, the percentage ranking method was used to normalize all factors influencing GLOF hazard and risk levels to 0–1, assuming equal weight (i.e., weight = 1) for each factor in triggering outburst floods for every glacial lake. Final hazard values were calculated accordingly, and risk values applied the same classification method, categorized as very low, low, medium, high, and very high using the natural breaks method.

2 Results

2.1 Current Status and Historical Changes of Glacial Lakes on the Northern Slope of Kunlun Mountains

Analysis of glacial lakes from 1990 to 2023 reveals significant increases in both number and area. The number of glacial lakes grew from 248 in 1990 to 925 in 2023 (a 2.73-fold increase), while the area expanded from 14.99 km^2 to 54.83 km^2 (a 2.66-fold increase). The most significant increases occurred in the high-altitude mountainous regions of the western part of the northern slope. From 1990 to 2000, the number and area of glacial lakes increased by 43.95% and 37.82%, respectively. From 2000 to 2010, they increased by 69.71% and 62.46%, respectively. From 2010 to 2020, the number and area grew by 40.85% and 33.48%, respectively. From 2020 to 2023, the number and area increased by 18.85% and 11.62%, respectively.

The distribution of glacial lakes on the northern slope of Kunlun Mountains shows a pattern of more lakes in the west and fewer in the east, with significant growth potential for future expansion. The western region, with its high elevation, extensive glacier coverage, and valley glaciers with perennial snow cover, provides suitable conditions for glacial lake formation and further expansion. The eastern region is relatively flat, dominated by larger glacial lakes and reservoirs, with less glacier coverage.

2.2.1 Impact of Climate Change on Glacial Lakes

Since 1990, the average annual temperature on the northern slope of Kunlun Mountains has increased from 4.35°C to 5.01°C, with a warming rate of 0.22°C · $(10a)^{-1}$. Precipitation increased from 169.47 mm to 206.59 mm, with a growth rate of 15.72 mm · $(10a)^{-1}$. Analysis of temperature and precipitation changes across different watersheds shows that the Hotan River Basin had temperature and precipitation increases of 0.26°C · $(10a)^{-1}$ and 15.30 mm · $(10a)^{-1}$, respectively; the Kumukuli Basin had increases of 0.19°C · $(10a)^{-1}$ and 30.67 mm · $(10a)^{-1}$; the Keriya River Basin had increases of 0.22°C · $(10a)^{-1}$ and 12.98 mm · $(10a)^{-1}$; the Qarqan River Basin had increases of 0.22°C · $(10a)^{-1}$ and 12.12 mm · $(10a)^{-1}$; and the Yarkant River Basin had increases of 0.29°C · $(10a)^{-1}$ and 22.34 mm · $(10a)^{-1}$ (Figure [Figure 2: see original paper]). The Kumukuli Basin showed the largest precipitation increase among all watersheds at 30.67 mm · $(10a)^{-1}$, though its temperature increase was the smallest. With climate warming, temperature and precipitation in the Kunlun Mountains have increased significantly, and the number and area of glacial lakes will continue to grow in the future.

Analysis of glacial lake numbers and areas across different watersheds (Figure [Figure 3: see original paper]) reveals that in the five watersheds of the northern slope of Kunlun Mountains, the Yarkant River Basin contains approximately 56.45%–64.23% of the total number of glacial lakes and about 55.97%–67.44% of the total area. The Keriya River Basin accounts for 11.76%–14.57% of the number and 13.18%–19.14% of the area. The Hotan River Basin has the largest proportion, with approximately 42.37%–49.07% of the total number and 31.89%–34.55% of the total area. The Qarqan River Basin and Kumukuli Basin have the smallest areas, accounting for only 8.67%–11.57% of the total area.

2.2.2 Glacier Area Changes in Different Watersheds

Using Landsat images and a ratio method combined with visual interpretation, glacier areas on the northern slope of Kunlun Mountains were extracted. From 1990 to 2020, the number and area of glaciers decreased by 0.87% and 0.88%, respectively, with overall stability in glacier area and number []. In different watersheds of the northern slope, as temperatures rose, glacier area showed an overall decreasing trend from 1990 to 2020. The Hotan River Basin and Qarqan River Basin exhibited the most significant negative growth trends at -13.33 km^2 · $(10a)^{-1}$ and -10.47 km^2 · $(10a)^{-1}$, respectively, followed by the Kumukuli Basin. However, from 2010 to 2020, glacier area in the Hotan River Basin and Keriya River Basin showed increasing trends at rates of 4.67 km^2 · $(10a)^{-1}$ and 14.93 km^2 · $(10a)^{-1}$, respectively. Notably, since the 21st century, glacier area in the Qarqan River Basin, Yarkant River Basin, and Kumukuli Basin has been continuously decreasing at rates of -6.61 km^2 · $(10a)^{-1}$, -6.88 km^2 · $(10a)^{-1}$, and -10.65 km^2 · $(10a)^{-1}$, respectively (Table).

2.3.1 GLOF Risk on the Northern Slope of Kunlun Mountains

This study quantitatively assessed the risk and hazard levels of 490 moraine-dammed lakes on the northern slope of Kunlun Mountains using the risk assessment model. The evaluation results indicate that 30.7% of moraine-dammed lakes have very high or high hazard levels, with most distributed in the high-altitude mountainous areas of the west and fewer in the east. Approximately 43.6% of moraine-dammed lakes have low or relatively low hazard levels, while 25.7% have medium hazard levels.

From a risk perspective, approximately 20.7% of moraine-dammed lakes have relatively high risk levels (101 lakes), while 51.42% have low risk levels (252 lakes), primarily because there is no obvious downstream infrastructure within the flood outburst path in these areas, and they are located in high-altitude mountainous regions with sparse residential housing. In the western region, about 38.46% of moraine-dammed lakes have relatively high hazard levels, but their risk levels are low. Therefore, the GLOF risk is minimal in the eastern region, while higher risks occur primarily in the western part of the northern slope.

2.3.2 Current GLOF Risk Status in Different Watersheds

Analysis of GLOF risk and hazard levels across different watersheds shows that, in terms of hazard levels (Figure [Figure 5: see original paper]), the Yarkant River Basin has 47.2% of moraine-dammed lakes with high or relatively high hazard levels—4.2 times that of other watersheds—followed by the Hotan River Basin. The Qarqan River Basin and Kumukuli Basin have 42.6% of moraine-dammed lakes with relatively low or low hazard levels, while the Keriya River Basin has 38.46% with high or relatively high hazard levels.

Similarly, from a risk level perspective (Figure [Figure 6: see original paper]), the Yarkant River Basin has approximately 60.7% of moraine-dammed lakes with high or relatively high risk levels. In the Hotan River Basin, the number of relatively high-risk moraine-dammed lakes accounts for 50.8% of the total. Although the Qarqan River Basin has 15.7% of moraine-dammed lakes with high hazard levels, most are at low risk levels. The Kumukuli Basin has the smallest risk level, with the Qarqan River Basin and Kumukuli Basin having the highest proportions of low or relatively low-risk moraine-dammed lakes.

3 Discussion

3.1 Impact of Multi-Source Remote Sensing Images on Glacial Lake Extraction

Glacial lakes are primarily located in high-altitude mountainous areas with extensive glacial coverage, making manual field detection difficult. With the maturation of remote sensing technology, it has brought great convenience to field detection and large-scale data collection in high-cold mountainous regions. However, factors such as different spatial resolutions of remote sensing images, varying visual interpretation experience, and different threshold settings for glacial lake extraction introduce uncertainties in boundary extraction [].

To evaluate whether the glacial lake areas extracted using the GEE platform conform to reality, we conducted error analysis by comparing field-measured glacial lake areas in the northern part of Kunlun Mountains with those extracted via GEE. Three lakes were selected: Ayakekumu Lake, Aqikekule Lake, and Whale Lake. Based on 2020 remote sensing images, the extracted lake areas were compared with true values (Table). For Ayakekumu Lake, the true area was 1130.26 km^2, with an extraction error of 1.93% from Sentinel-2A/B MSI images (10 m resolution) and 2.11% from Landsat images (30 m resolution). For Aqikekule Lake, the true value was 596.65 km^2, with extraction errors of 2.22% from Sentinel-2A/B MSI images and 2.47% from Landsat images. For Whale Lake, the true value was 382.6 km^2, with an extraction error of 0.45% from 10 m resolution images and 0.86% from 30 m resolution images.

In summary, error analysis of glacial lake areas extracted from different spatial resolution images reveals that lower spatial resolution results in larger errors. In this study, all extracted glacial lake area errors were within the allowable range. Therefore, extracting glacial lake boundaries from different remote sensing images is entirely feasible.

3.2 Climate and Glacier Melt as Drivers of Glacial Lake Expansion

Due to diverse climate conditions and complex terrain, glacial lake distribution on the northern slope of Kunlun Mountains shows significant spatial heterogeneity []. Through climate analysis, it is evident that since 1990, against the background of global warming, the arid region of northwestern China has experienced significant warming, with average annual temperatures rising at a rate of $0.34°\text{C} \cdot (10\text{a})^{-1}$. The northern slope of Kunlun Mountains shows clear increasing trends in temperature and precipitation, while glacier area and number remain generally stable.

Notably, although glacier area on the northern slope of Kunlun Mountains has been decreasing since 1990, glacial melt has been increasing. The Hotan River Basin and Keriya River Basin have experienced the most significant glacier area reductions, decreasing from 5041.34 km^2 to 5074.61 km^2 (-0.66%) and from 1170.48 km^2 to 1163.84 km^2 (-0.57%), respectively. However, since 2010, glacier area in the Hotan River Basin and Keriya River Basin has begun to increase.

Analysis of glacial lake changes and climate factors reveals that climate change has led to significant regional heterogeneity in glacial lakes. Glacial lake changes are primarily driven by temperature and precipitation, with temperature fluctuations being the main factor causing increased precipitation, glacial retreat, and snowmelt. Under global warming, future glacial lake expansion will continue, and the potential threat of GLOF will increase.

3.3 Potential Hazard and Risk Assessment

Based on historical flood data from scientific expeditions and relevant literature, 15 GLOF events occurred in the Yarkant River Basin from 1961 to 2021, primarily fed by glacial meltwater with large interannual variations. Outburst events are prone to occur from May to September, causing extreme damage and potential threats to downstream areas. This study conducted quantitative risk and hazard assessments of 490 moraine-dammed lakes ($ 0.01km^{2}$) on the northern slope of Kunlun Mountains. The results show that current high-risk events are located in the western part of the northern slope (Yarkant River Basin and Hotan River Basin), while low-risk areas are distributed in the eastern part. The most significant hazard levels are found in the Yarkant River Basin, followed by the Hotan River Basin, with lower hazard levels in the eastern region.

Using the latest OSM data, downstream residential areas, transportation facilities, buildings, and land use types were converted into raster data and incorporated into the model to quantitatively analyze the exposure of moraine-dammed lakes. The results show that 28.57% of moraine-dammed lakes have relatively high exposure (140 lakes), while 51.42% have low exposure (252 lakes). The risk index was then derived from the hazard and exposure indices. The exposure index is influenced by future socio-economic development, ecological environment, and urban expansion. GLOF risk analysis for the northern slope of Kunlun Mountains can provide a basis for future regional land use planning and disaster prevention and early warning, promoting sustainable regional economic and ecological development.

4 Conclusions

1) By selecting glacial lakes with area $ 0.01km^{2}$ on the northern slope of Kunlun Mountains for analysis, the results show that since 1990, the number and area of glacial lakes have increased significantly overall. The number of glacial lakes increased from 248 to 925 (a 2.73-fold increase), and the area grew from 14.99 km^2 to 54.83 km^2 (a 2.66-fold increase). Glacial lakes on the northern slope of Kunlun Mountains exhibit obvious spatial heterogeneity, being mainly distributed in high-altitude western regions (such as the Hotan River Basin and Yarkant River Basin), with fewer glacial lakes in the eastern region.

2) In terms of temporal distribution, correlation analysis with climate data reveals that climate change has caused significant regional heterogeneity in glacial lakes. Glacial lake changes are primarily driven by temperature and precipitation, with temperature fluctuations being the main factor causing increased precipitation, glacial retreat, and snowmelt. Under global warming, future glacial lake expansion will continue, and the potential threat of GLOF will increase.

3) The GLOF risk assessment for moraine-dammed lakes on the northern slope of Kunlun Mountains indicates that high hazard and risk levels are

concentrated in the western region, particularly in the Yarkant River Basin and Hotan River Basin. The eastern region has relatively low hazard and risk levels. This assessment can provide a scientific basis for sustainable water resource utilization in arid regions and disaster prevention and early warning in downstream areas.

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