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Postprint: Exposure assessment of glacier hazards along the China-Pakistan Pamir Highway

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Abstract

Based on remote sensing and GIS techniques, we obtained the spatiotemporal distribution characteristics of glacier changes and glacier disasters in areas along the China-Tajikistan highway from 2000 to 2021, and conducted an exposure assessment of glacier disasters using the range transformation method and entropy weight method. The results indicate: (1) Since 2000, the glacier area shrinkage rate in areas along the China-Tajikistan highway has been 0.20%·a-1±0.06%·a-1, the mass balance has been -0.25±0.04 m w.e.·a-1, and the glacial lake area expansion rate since 1992 has been 0.45%·a-1, all of which are several times higher than the overall levels of the Pamir Plateau. (2) The enhanced glacier instability has directly led to the widespread prominence of glacier disaster risks along the China-Tajikistan highway, with medium- and high-risk areas for disaster occurrence mainly concentrated in the western section of the highway. (3) The macro-scale pattern of glacier disaster exposure in areas along the China-Tajikistan highway is primarily related to factors such as the distribution density of hazard-inducing factors and disaster-bearing bodies, the complexity of topographic and geological environments, and spatial differences in climate warming and wetting trends. The research results preliminarily reveal the macro-scale pattern of glacier disaster exposure along the China-Tajikistan highway, which can provide references for studies on disaster vulnerability, impact, and scenario prediction.

Full Text

Assessment of Glacier Disaster Exposure in the Areas Along the China-Tajikistan Pamir Highway

1.1 Study Area Overview

The China-Tajikistan Pamir highway traverses southern Tajikistan, extending from the Karasu Port—the sole open border crossing between China and Tajikistan—in the east to the Tajikistan-Afghanistan border town of Khorog in the west, with a total length of approximately 410 km. The highway runs west-east through the Gunt River valley and the Oksu River (upper Balandkiik River) valley in the southern Pamir Plateau, with elevations ranging from 2065 to 4365 m and an average of about 3550 m, making it one of the highest highways globally. Taking the central town of Alchur as a dividing point, the highway can be broadly divided into eastern and western sections. The western section primarily passes through narrow, deeply incised alpine valleys, where oases, settlements, and infrastructure such as road networks and water conservancy facilities are densely distributed along the valley bottoms, while large valley glaciers and glacial lakes are present in the surrounding mountains. The eastern section mainly traverses gently undulating plateau valleys, with only scattered hanging glaciers and minimal human activity except in a few areas.

[Figure 1: see original paper]

1.2 Data Sources

1.2.1 Landsat Imagery This study utilized Landsat TM/ETM+/OLI imagery, primarily for glacier inventory preparation and feature identification. These images were obtained from the United States Geological Survey (https://earthexplorer.usgs.gov/). As Level-1 products, they have undergone systematic radiometric, geometric, and terrain corrections, and were pan-sharpened using ENVI software, fully meeting the analytical requirements for glacier change and glacial hazard assessment. To facilitate glacier boundary interpretation and feature identification, we selected images from the late ablation season with minimal cloud cover and short temporal spans whenever possible.

1.2.2 Glacier Mass Balance Data We employed the Qinghai-Tibet Plateau mountain glacier mass balance dataset based on ZY-3 DEMs (2000–2018), updated and released in November 2023 by Jiang Liming et al., to analyze glacier mass balance conditions along the China-Tajikistan highway since 2000. This product, available from the National Earth Observation Data Center (https://www.doi.org/10.11878/db.202311.011644), integrates ZY-3 stereo imagery with SRTM DEM data using digital elevation model spatial matching and correction techniques to obtain surface elevation changes and mass balance of mountain glaciers. In the study area, the product' s average accuracy is ± 0.04 m w.e. · a ^{1}, lower than its overall accuracy across the Tibetan Plateau (± 0.06 m w.e. · a ^{1}).

1.2.3 Glacial Lake Inventory This study analyzed glacial lake distribution and changes along the highway using the High Mountain Asia glacial lake inventory prepared by Wang et al., which is available from the National Cryosphere Desert Data Center (https://cstr.cn/11738.11.ncdc.nieer.2020.11). Based on Landsat imagery, this inventory extracts glacial lake boundaries larger than

0.005 km² through visual interpretation. Field validation shows that the average interpretation accuracy remains within half a Landsat pixel. In the study area, the boundary interpretation error for glacial lakes is ±13.5%, still lower than the overall level for High Mountain Asia (±8.3%).

1.2.4 Additional Data Due to sparse meteorological stations and frequent observation gaps along the highway, we used ERA5 climate reanalysis data from the European Centre for Medium-Range Weather Forecasts (https://cds.climate.copernicus.eu) to reconstruct regional climate change characteristics. With a spatial resolution of 0.25°, comparative studies demonstrate that ERA5 exhibits high simulation accuracy for temperature and precipitation changes in High Mountain Asia, including the Pamir Plateau. Seismic data (1980–2020) were obtained from the Central Asian Seismotectonic Map and Central Asian Seismic Hazard Zonation from the National Tibetan Plateau Data Center (https://doi.org/10.11888/Disas.tpdc.271301).

1.3 Methods

1.3.1 Extraction of Glacier Hazard Information We employed visual interpretation to extract glacier boundaries and construct a multi-temporal glacier inventory for the China-Tajikistan highway area from 2000 to 2021. Due to significant thermodynamic differences between ice/snow and bedrock, glacier boundaries can be directly digitized from false-color composite images (thermal infrared, red, and green bands). Building upon one complete glacier boundary interpretation, we modified only the changed portions using other temporal images to complete a multi-temporal glacier inventory with consistent interpretation methods and standards. Specific procedures and accuracy assessment methods are detailed in relevant literature.

Using hydrological analysis methods, we extracted tributary basins along the Gunt and Oksu valleys where modern glaciers and glacial lakes are distributed, and revised the extraction results using Google Earth imagery. Based on the spatiotemporal distribution and changes of hazard elements including glaciers, glacial lakes, debris flow gullies, and earthquakes, we aggregated glacier hazard information by tributary basin for exposure assessment.

1.3.2 Glacier Hazard Exposure Assessment Natural exposure to glacier hazards refers to the likelihood of glacier disasters occurring in the natural environment. Following principles of scientific rigor, objectivity, and operability, and referencing existing research with consideration of spatiotemporal distribution and changes of glacier hazard elements along the highway, we constructed a natural exposure assessment index system at the tributary basin scale (Table 2).

Since the units, magnitudes, and properties of indicator data differ, we standardized the data using range transformation before assessment to enable multi-dimensional comparison. We then determined indicator weights using the entropy method, commonly employed in natural hazard research. All indicators in this study are positive indicators, with the range transformation formula as follows:

$$X'_{ij} = \frac{X_{ij} - x_{min}}{x_{max} - x_{min}}$$

where X'_{ij} and X_{ij} represent the standardized and original values of the j-th indicator for the i-th assessment unit, respectively.

The entropy method is an objective weighting approach that determines weights based on indicator variability, suitable for multi-object, multi-indicator comprehensive evaluation. The calculation process is as follows:

$$Y_{ij} = \frac{X'_{ij}}{\sum_{i=1}^{m} X'_{ij}}$$

$$e_j = -k \sum_{i=1}^{m} Y_{ij} \times \ln(Y_{ij}), \quad k = \frac{1}{\ln(m)}$$

$$w_j = \frac{1 - e_j}{\sum_{j=1}^{n} (1 - e_j)}$$

$$T_{ij} = w_j \times X'_{ij}$$

where Y_{ij} is the proportion of the j-th indicator for the i-th assessment unit; e_j and w_j are the entropy value and weight of the j-th indicator, respectively; and T_{ij} is the exposure index. The final exposure index for each assessment unit is the sum of all indicator exposure indices.

2.1 Spatiotemporal Patterns of Glacier Changes

2.1.1 Glacier Changes Interpretation results show that 445 glaciers with a total area of 445.90 ± 20.81 km^2 were distributed along the highway from 2000 to 2021, primarily concentrated in the western section. During this period, glaciers experienced overall retreat, with a cumulative area loss of 20.03 ± 6.27 km^2 at a rate of 0.20% · a ^{1} ± 0.06% · a ^{1}—several times higher than the Pamir Plateau average. Meanwhile, the region experienced significant mass loss, with an overall mass balance of -0.25 ± 0.04 m w.e. · a ^{1}, showing spatial patterns consistent with area changes (Figure 2). Consequently, both metrics indicate substantial glacier retreat since 2000, with more pronounced retreat in the western section, implying greater risks of meltwater floods, glacial lake outbursts, and debris flows.

Glacier surging represents a major trigger for glacier hazards, but surging glaciers are sparsely distributed in the southern Pamir interior. Based on changes in glacier length, area, elevation, and velocity over recent decades, only G072526E37863N was identified as a surging glacier along the highway. Its surge phase occurred primarily during 2015–2018, during which the glacier tongue advanced 380 m and area expanded by 0.13 km^2. However, the surge magnitude was limited, the glacier has since stabilized, and no large glacial lakes or settlements are nearby, thus posing no significant hazard threat.

2.1.2 Glacial Lake Distribution and Changes From 2000 to 2021, 225 glacial lakes with a total area of 22.66 ± 1.83 km^2 were distributed along the highway, also concentrated in the western section. Most are moraine-dammed lakes with highly variable sizes—only 9 large lakes exceed 0.1 km^2, while the largest, Zaroshkul, covers 5.41 km^2. Since 1992, glacial lakes have expanded at a rate of $0.45\% \cdot a^{1}$, with a total area increase of 20.30 ± 1.71 km^2. As shown in Figure 2, most tributary basins with concentrated glacial lakes experienced overall expansion, with only a few showing stability or shrinkage—opposite to the spatial pattern of glacier area and mass balance changes. This indicates that sustained glacier retreat has caused widespread glacial lake expansion, increasing outburst risks.

2.2 Glacier Hazard Exposure

Based on the spatiotemporal distribution and changes of hazard elements, we assessed natural exposure to glacier hazards by tributary basin along the highway using natural breaks classification. Results show that natural exposure generally decreases from west to east, with medium and high-risk areas concentrated in the western section—consistent with the spatial patterns of glaciers, glacial lakes, and debris flow gullies (Figure 4). In the western section, tributary basins are generally short and steep, with larger and more significantly changing glaciers and glacial lakes, and more active geological environments, resulting in more prominent glacier hazard risks. The eastern section shows the opposite pattern.

Social exposure refers to the likelihood of human society facing glacier hazards, which together with natural exposure constitutes the exposure component in vulnerability assessment. Due to social and geopolitical factors, detailed socioeconomic data for individual tributary basins are unavailable. However, given that settlements and human activities are highly concentrated in oasis areas at gully mouths in the western section (Figure 2), we infer that social exposure—and thus overall exposure—follows a spatial pattern consistent with natural exposure. In the enclosed Gunt River valley, these oases and villages both depend on glacial meltwater for survival and face direct glacier hazard threats, making them critical nodes for maintaining highway operation and regional disaster prevention.

3.1 Influencing Factors of Glacier Hazard Exposure

The spatial pattern of glacier hazard exposure is primarily related to the potential distribution of various glacier hazards, human activity levels, and socioeconomic development. Spatially, the western section has higher densities of hazard-inducing elements (glaciers, glacial lakes, debris flow gullies, seismic activity) and disaster-bearing elements (infrastructure, population, economic activity). Temporally, the western section has also experienced greater changes in glaciers and glacial lakes, and larger increases in population and economic activity over recent decades, leading to more pronounced hazard risks.

Global warming-induced temperature rise and increased precipitation variability have enhanced mountain glacier instability, representing the main driver of widespread glacier hazard risk. Beyond these direct factors, the exposure pattern along the highway is also linked to climate background. Since 1981, the region has shown a warming and wetting trend, with temperature increasing significantly at 0.3 °C $\cdot$ $(10a)^{1}$ and precipitation increasing slowly at 1.5 mm $\cdot$ $(10a)^{1}$ (Figure 5). However, significant spatial heterogeneity exists: the western section experienced weak warming but substantial precipitation increases, intensifying glacier retreat and glacial lake expansion and highlighting hazard risks. The eastern section saw more significant warming but stable precipitation; however, sparse glacier distribution limited impacts on hazard risks.

3.2 Outlook

This study provides a preliminary assessment of glacier hazard exposure along the China-Tajikistan highway, offering a foundation for advancing research on hazard vulnerability, impact, and scenario prediction. Future work should consider: (1) integrating remote sensing with field observations to comprehensively monitor glacier changes and hazard elements, improving fundamental scientific data; (2) establishing China-Tajikistan cooperative research to leverage respective platform advantages and promote mutual sharing of field observation data and socioeconomic information; and (3) conducting vulnerability, impact, and prediction studies at larger spatiotemporal scales for the Pamir Plateau before gradually scaling down to sub-basins and individual tributaries.

4 Conclusion

(1) Since 2000, the glacier area shrinkage rate, mass loss rate, and glacial lake expansion rate along the China-Tajikistan Pamir highway are all several times greater than the Pamir Plateau average. Enhanced glacier instability has directly contributed to widespread glacier hazard risk.

(2) Glacier hazard exposure shows significant spatial heterogeneity, decreasing overall from west to east, with medium and high-risk areas concentrated in the western highway section.

(3) The macro-scale pattern of glacier hazard exposure is primarily influenced

by the distribution density of hazard-inducing and disaster-bearing elements, terrain and geological complexity, and spatial variations in climate warming and wetting trends.

[Figure 5: see original paper]

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