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Review

Climate-driven hydrogeological hazards: A growing threat to Asia's Water Tower [version 2]

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ABSTRACT

High Mountain Asia (HMA), known as Asia's Water Tower, faces unprecedented climate warming, resulting in accelerated glacier retreat, increased meltwater discharge, altered precipitation patterns, and permafrost degradation. These changes have intensified hydrogeological hazards such as ice–rock collapses, glacial lake outburst floods, landslides, and debris flows, which pose severe risks to infrastructure, ecosystems, and downstream communities. This review systematically summarizes the evolving hazard landscape in HMA, emphasizing the critical role of climate-driven factors in causing slope instability and flood risks. By integrating a multi-source hydrogeological hazard database, field observations, and literature reviews, we discuss the spatial variations, triggering mechanisms, and potential future trends of these hazards. Our findings highlight the need for enhanced early-warning systems, climate adaptation strategies, and transboundary cooperation to mitigate the increasing risks of hydrogeological disasters in HMA. Strengthening scientific research and policy frameworks is essential for boosting resilience and achieving sustainable water resource management in this vulnerable region.

KEYWORDS

Asia's Water Tower, climate change, hydrogeological hazards, distribution pattern, mitigation.

1 Introduction

The High Mountain Asia (HMA) region encompasses the Tibetan Plateau and its surrounding mountain ranges, including the Himalayas, Pamirs, Tianshan, Kunlun, Karakoram, and Hengduan Mountains (Lalande et al., 2021). This region contains extensive cryospheric and hydrological resources, with glaciers covering over 100,000 km^2 and glacial lakes spanning approximately 2,080.1 km^2 (Figure 1) (Bhattacharya et al., 2021; Dehecq et al., 2019). Additionally, HMA hosts significant groundwater reserves and receives substantial rainfall, collectively forming a vital freshwater reservoir (Cogley, 2017). These water resources are the primary source for several major river systems, including the Yarlung Tsangpo, Ganges, Indus, Lancang-Mekong, Yangtze, and Yellow River, which sustain billions of people downstream (Lutz et al., 2014; Miles et al., 2021). As a result, water security in the HMA region plays a pivotal role in supporting downstream socio-economic development, maintaining regional ecological stability, and shaping geopolitical dynamics, thereby influencing regional peace and sustainable development (Miles et al., 2021; Taylor et al., 2023).

In recent years, global climate change has emerged as a significant challenge for humanity, exerting a profound impact on the global water cycle (Li et al., 2022b). As one of the regions most sensitive to climate warming, High Mountain Asia (HMA) has experienced a temperature increase markedly higher than the global average, resulting in unprecedented hydrological changes (Azam et al., 2021; Nie et al., 2021). For instance, rising temperatures have accelerated glacier melt rates, contributing to the rapid expansion of glacial lakes (Chen et al., 2007; Wang et al., 2011). Concurrently, shifts in the temporal and spatial distribution of precipitation have intensified the frequency and magnitude of extreme rainfall events, enhancing surface runoff in mountain valleys (Kirschbaum et al., 2020; Luan Lan, 2022; Smith and Bookhagen, 2018). Furthermore, in alpine regions, permafrost degradation and enhanced ice and snow melt have increased groundwater flow and the hydrological dynamics within fractures in ice-rock masses, further altering the regional hydrological regime (Li et al., 2022a; Li et al., 2024a; Wang et al., 2024).

The intensified hydrological changes in High Mountain Asia have created favorable conditions for the occurrence of hydrogeological disasters, such as ice-rock collapses, glacial lake outburst floods, landslides, and debris flows, thereby increasing the risk of such disasters in the region (Bhambri et al., 2020; Kirschbaum et al., 2020; Luo et al., 2022b; Shrestha et al., 2023). For instance, in October 2018, the Sedongpu ice-rock avalanche in Tibetan Plateau was triggered by the combined effects of meltwater and rainfall infiltration from glacier crevasses, which induced a catastrophic ice-rock avalanche-debris flow disaster chain (Luo et al., 2022b). The event caused a disruption of the Yarlung Tsangpo River for three days, and the resulting outburst flood severely impacted downstream infrastructure, including roadways and construction projects (Li et al., 2024b; Wang et al., 2020). On October 3, 2023, the South Lhonak Glacial Lake in Sikkim, India, experienced a catastrophic glacial lake outburst flood (GLOF) after three decades of rapid expansion (Das et al., 2024; Sattar et al., 2025). The flood moving downward more than 200 km and caused the death of 109 individuals, the destruction of two hydropower stations, and significant damage to 25,900 buildings and 38 bridges (Sattar et al., 2025). These devastating events underscore the urgent need for comprehensive research on hydrogeological hazards in High Mountain Asia, as continued climate warming in the future is likely to exacerbate these risks (Wang and Zhou, 2017; Zheng et al., 2021a).

Previous studies on climate-driven hydrogeological hazards in HMA have predominantly focused on individual events, examining their formation and evolution, yet lacking a cross-regional, systematic synthesis, including classification systems for hydrogeological hazards and

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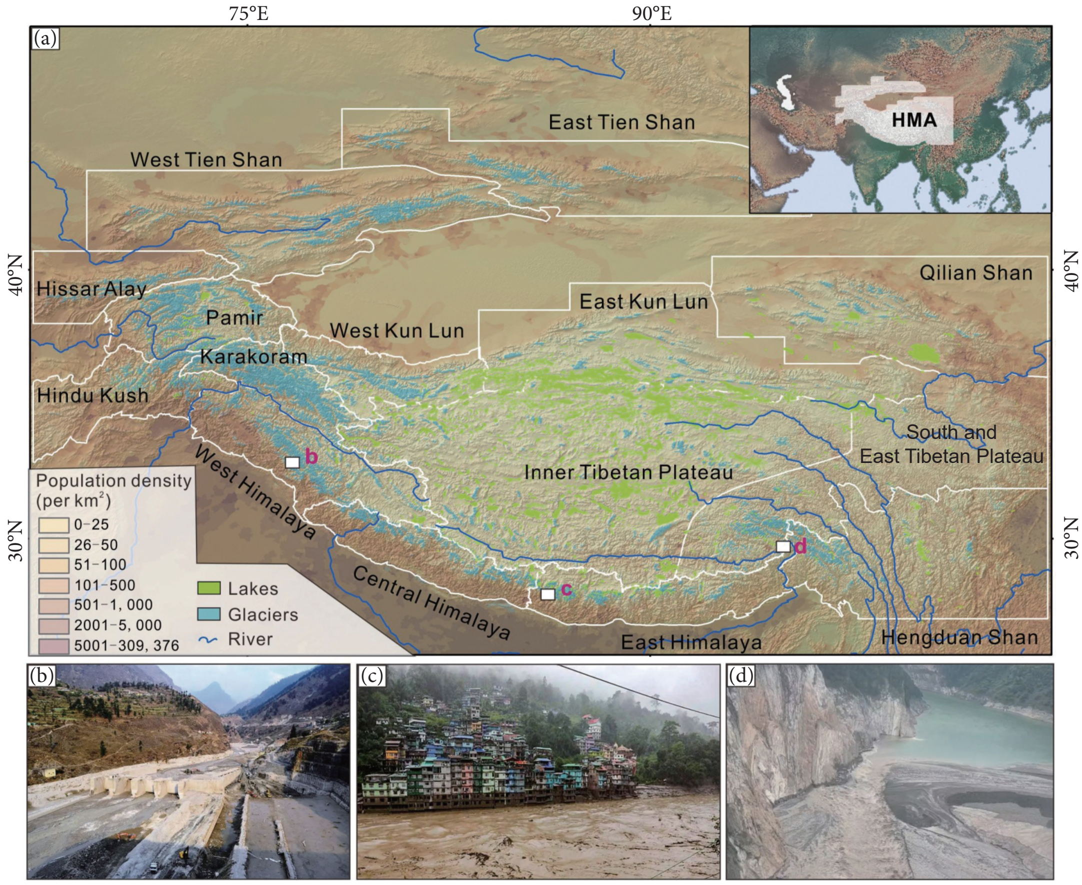

Fig. 1 Location of the High Mountain Asia (HMA) region and examples of recent hydrogeological hazards in the past five years. (a) The geographical extent of HMA. Glaciers (blue) and glacial lakes (green) are shown, along with population density distribution. The white solid line indicates the boundary of the Global Terrestrial Network for Glaciers (GTN-G) regions. **(b)** Hydropower station damaged by the 2021 Chamoli ice-rock avalanche in India (Photo: Irfan Rashid, Department of Geoinformatics, University of Kashmir). **(c)** Towns submerged by 2023 Sikkim floods (Photo: from the Facebook wall of Prem Singh Tamang-Golay, Sikkim CM). **(d)** The Yarlung Zangbo River partially blocked by the 2018 Sedongpu ice-rock avalanche in south and east Tibetan Plateau (Photo: Hao Wang, Institute of Mountain Hazards and Environment, CAS).

their distribution pattern (Byers et al., 2019; Jiang et al., 2021; Lei et al., 2021; Shugar et al., 2021; Zheng et al., 2021c). In this review, we analyze the environmental changes in HMA triggered by climate change and their impacts on hydrogeological hazard development. We first integrate multiple hazard types—including glacial, rainfall-induced, and permafrost-related events—into a unified framework based on a multi-source regional database (Shrestha et al., 2023; Veh et al., 2023). From the perspective of disaster-triggering factors, we systematically classify the hydrogeological hazards. We discuss the spatial statistical characteristics and distribution patterns of these hazards, summarizing the formation mechanisms of different subtypes of hydrogeological hazards. Finally, we explore future trends in hydrogeological hazard evolution. The regional synthesis, cross-hazard comparison and forward-looking discussion of future trend presented here aim to fill the current knowledge gap and support future mitigation and adaptation strategies.

2 Climate change and impacts on hydrogeological hazards

Climate change significantly influences hydrogeological hazards by altering precipitation patterns, accelerating glacier melt, and increasing extreme weather events. In this chapter, we review climate change trends in High Mountain Asia over the past 40 years and summarize the magnitude of changes in predisposing factors related to hydrological hazards (e.g., glacier mass loss rate, glacial lake area, and runoff).

2.1 Climate change in HMA

2.1.1 Trends in temperature and precipitation

Since the 1970s, HMA has undergone a series of climatic changes, characterized by rising temperatures and humidity levels and accompanied by decreasing solar radiation and wind speed (Liu et al., 2021b). The diminishing wind speed has notable implications for the exchange of water vapor between the Indian monsoon and HMA, leading to a significant increase in runoff in the southern and eastern regions (Bhattacharya et al., 2021). It is essential to recognize that HMA acts as a magnifier of climate change. ERA5 meteorological data show that near-surface temperatures in HMA have registered a maximum increase of approximately 0.48 K per decades from 1985 to 2020, whereas global temperatures have seen an increase of 0.20 K per decades (Figure 2(a)) (Khanal et al., 2021). The rising temperature trend has been associated with a reduction in near-surface wind speed by approximately 3.5%, thereby altering the precipitation mode. Consequently, there has been an increase in rainfall and a decrease in snowfall since 1987 (Ombadi et al., 2023; Smith and Bookhagen, 2018). In past for decades, HMA has been experiencing significant wetting trends in many regions due to climate change-driven shifts in precipitation patterns (Figure 2(b)) (Lalande et al., 2021).

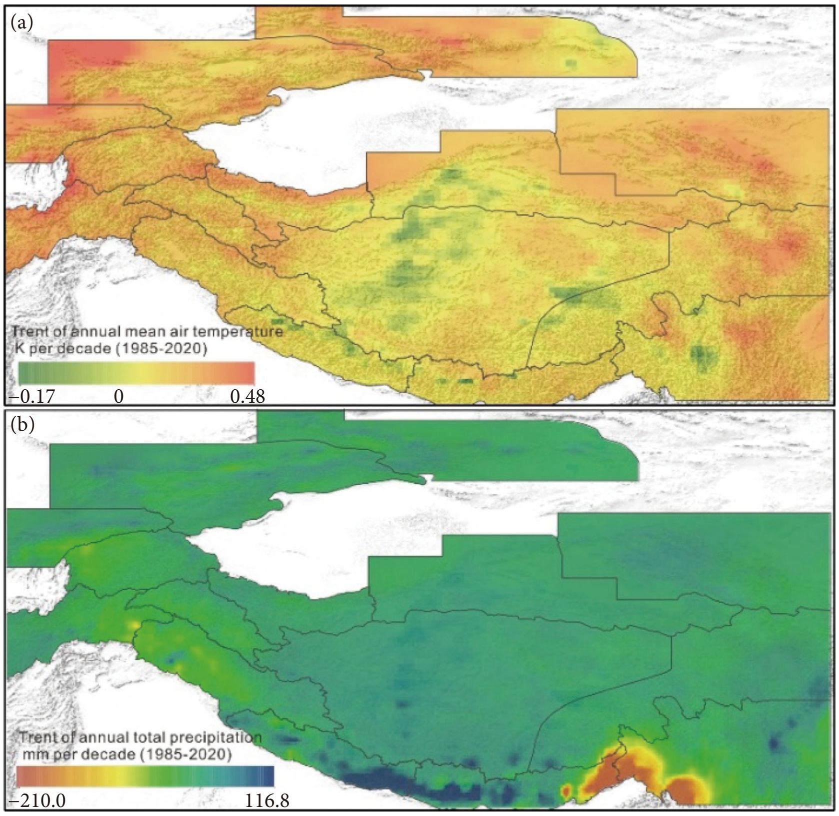

Fig. 2 Changes in annual average temperature and multi-year average total precipitation in HMA from 1985 to 2020, based on ERA5 reanalysis data. (a) Change in annual average temperature from 1985 to 2020. **(b)** Change in multi-year average total precipitation from 1985 to 2020. The black solid line indicates the boundary of the Global Terrestrial Network for Glaciers (GTN-G) regions.

2.1.2 Extreme weather events

In addition to the rise in annual average temperatures and the increasing spatial variability of precipitation, climate change also leads to alterations in extreme weather events, such as extreme air temperatures, rainfall, and snowfall. Statistical data indicate an increase in the frequency of extreme high-temperature events (≥90th percentile temperature), which have risen ~1.5 times between 1961 and 2020 (Gong et al., 2022). In contrast, the frequency of extreme low-temperature events (≤10th percentile temperature) has decreased, with a reduction of 1.0 days per decade between 1961 and 2020 (Gong et al., 2022). Changes in extreme precipitation patterns in HMA are also evident, with both the intensity and frequency of extreme precipitation events showing increases (Luan Lan, 2022). For instance, the extreme precipitation in the South and East Tibetan Plateau has risen by 6.66 mm per decades during 1991–2020 (Bai et al., 2022; Li et al., 2023). Extreme snowfall patterns in HMA also exhibit regional variations, with an increase in winter snowfall in the Pamir Plateau and Karakoram mountains, while the southeastern Tibetan Plateau has seen a decrease in extreme snowfall (Sun et al., 2024; Wang et al., 2024).

2.2 The impact on hydrogeological hazard preconditions

2.2.1 Release of solid material by shrinking glaciers and permafrost

Global warming has driven accelerated glacier retreat across HMA, consistent with world wide trends (Cogley, 2017; Dehecq et al., 2019; Miles et al., 2021; Rounce et al., 2023; Zhou et al., 2018). Remote sensing and field observations reveal widespread glacier recession in HMMA, with an average annual mass loss of −0.34 ± 0.07 m w.e. between 2003 and 2019 (Wang et al., 2021a). Notably, the eastern Himalayas and Hengduan Mountains experienced pronounced melting, at rates of −0.43 ± 0.01 m w.e. yr^{-1} and −0.62 ± 0.01 m w.e. yr^{-1}, respectively (Figure 3(a)) (Fan et al., 2023; Hugonnet et al., 2021). HMA also hosts 1.01×10^6 km^2 of permafrost, mainly on the Tibetan Plateau, which has seen accelerated degradation since 1970s, with decadal reductions of 3.62×10^4 km^2 in area and 0.055 m in average active layer thickness (Ran et al., 2022; Shen et al., 2024).

This glacier retreat and permafrost degradation have released substantial amounts of loose moraine deposits at glacier terminal or slope, providing abundant material for debris flow development (Chiarle et al., 2007; Kumar et al., 2019; Tang et al., 2022; Wang et al., 2021b). Glacier retreat has also altered glacier and permafrost morphology in steep mountain range, promoting the development of hanging glaciers and increasing the probability of ice-rock avalanches and landslides (Fan et al., 2022; Huggel et al., 2005; Shugar et al., 2021). The 2018 Sedongpu ice-rock avalanche in southeast Tibetan Plateau has been attributed to the structural failure of a newly formed hanging glacier, which resulted from ongoing glacier retreat and destabilization processes (Li et al., 2024b; Wang et al., 2020).

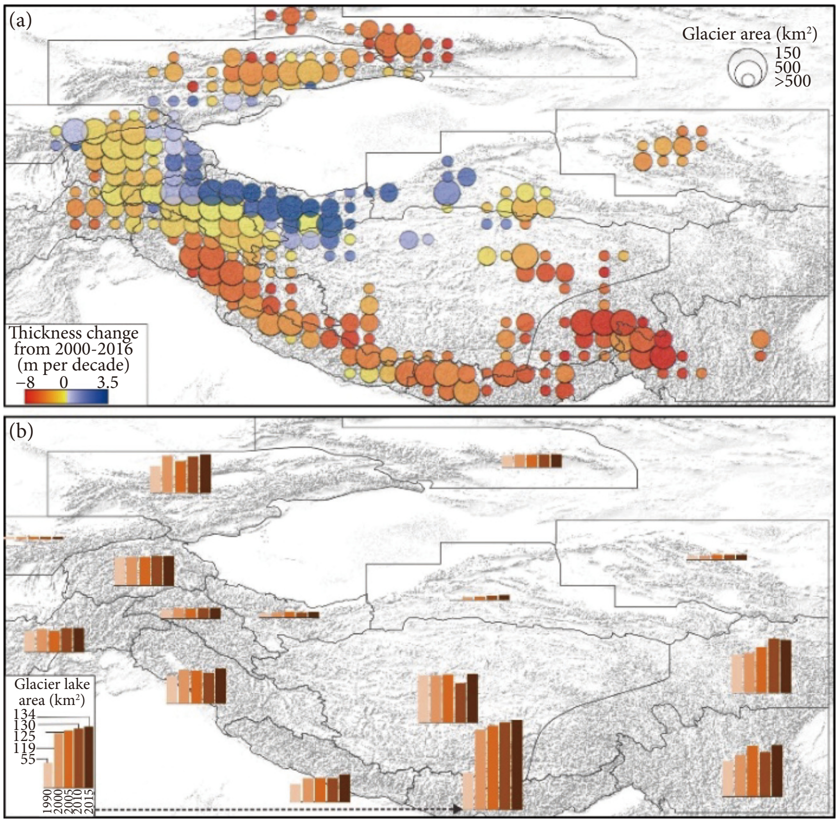

Fig. 3 Glacier mass balance and glacial lake changes in HMA. (a) Glacier mass balance rate, derived from ASTER DEM data. **(b)** Glacial lake changes, based on Landsat remote sensing data. The black solid line indicates the boundary of the Global Terrestrial Network for Glaciers (GTN-G) regions.

2.2.2 Increasing risk of outburst flood from expanding glacial lakes

Climate derived glacier retreat releases large amounts of meltwater that accumulate in moraine basins, leading to the formation of new glacial lakes or the expansion of existing ones (Wang et al., 2013; Yang et al., 2022). Over recent decades, High Mountain Asia (HMA) has experienced significant glacial lake expansion, both in terms of area and quantity. Between 1990 and 2020, the number of glacial lakes increased from 19,294 to 22,646, with the total lake area expanding by approximately 17.47% (257.23 km^2), reflecting an average annual growth rate of 0.58% (Figure 3(b)) (Zhang et al., 2022). The Central Himalayas are particularly significant among all the sub regions in terms of glacial lake expansion. In this region, the number of glacial lakes has increased by 43.39% since the 1990s, while the total lake area has expanded by 52.47% (Cheng et al., 2025). In these expanding glacial lakes, proglacial lakes, situated adjacent to glacier termini, have been the main contributors to lake area increasing, accounting for approximately 62.87% (56.67 km^2) of the total expansion. Conversely, regions such as the eastern Tibetan mountains and Hengduan Shan, where unconnected glacial lakes predominate, have exhibited stability or slight reductions in lake area (Chen et al., 2021). These expanding glacial lakes are becoming more prone to outburst floods due to the weakening of natural dams formed by terminal moraines and the increased instability of ice and debris dams (Taylor et al., 2023; Zhang et al., 2023a).

2.2.3 Increasing slope failure probability by intensified meltwater infiltration

Rising temperatures have accelerated glacier retreat and prolonged the melt season, resulting in greater meltwater availability and increased groundwater recharge. Studies indicate that the total meltwater in HMA has increased over the past few decades, with regional variations depending on glacier coverage and climatic conditions (Bolch et al., 2019; Lutz et al., 2014). In the Tarim Basin (Tien Shan), for instance, annual glacier meltwater discharge has risen by approximately 12.8% during 1991-2006 (Gao et al., 2010; Nie et al., 2021; Xu et al., 2025). Increased snowmelt has derived significant alterations in runoff patterns (Khanal et al., 2021), enhancing erosion to valley slopes and increasing sediment transport capacity of stream flow. Additionally, in some permafrost regions, increased meltwater has intensified groundwater activity. Infiltrating meltwater contributes to excess pore water pressure, weakening the shear strength of the soil (Ran et al., 2022; Shen et al., 2024). In the eastern Tibetan Plateau, an increase in thermokarst-related landslides has been observed due to intensified permafrost degradation and subsurface water infiltration (Luo et al., 2022a). These trends suggest that climate change is progressively altering the hydrological and geological conditions in HMA, leading to increased slope instability and a higher occurrence of landslides and debris flows (Kirschbaum et al., 2020).

3 Historical hydrogeological hazards and distribution pattern

The heterogeneity of the development conditions and the variety of triggering factors in HMA contribute to the diversity of hydrogeological hazard types. Here, we established a classification framework for hydrogeological hazards in HMA based on differences in material composition, dynamic characteristics, and triggering hydrological features. Subsequently, we compiled relevant databases of these hydrogeological hazards to analyze their spatial distribution patterns, providing insights into their regional variability and potential risk zones.

3.1 Hydrogeological hazard in HMA

Based on the development conditions and triggering factors, hydrogeological hazards in HMA can be categorized into three major types: glacier-related, rainfall-related, and permafrost degradation-related hazards (Table 1) (Bhambri et al., 2020; Dubey et al., 2023; Jiang et al., 2021). Glacier-related hydrogeological hazards include moraine-dammed Glacial Lake Outburst Floods (GLOFs) (Sattar et al., 2021), ice-dammed GLOFs (Bazai et al., 2021), glacier detachment events (Kääb et al., 2021), ice-rock collapses (Li et al., 2024b), and glacial debris flows (Wang et al., 2021b). These hazard types are among the most significant and widely studied in the region due to their considerable scale and extensive runout distances. Notably, the 2023 South Lhonak glacial lake outburst flood in Sikkim, India, exemplifies the destructive potential of such events, with the flood traveling over 385 km and impacting approximately 180 km of downstream human activity zones (Sattar et al., 2025). Rainfall-related hydrogeological hazards include rainfall-induced landslides and debris flows (Saha et al., 2024). These hazards are typically concentrated in low-altitude regions, particularly along the southern Himalayas and southeastern Tibetan Plateau, where the Indian Ocean monsoon and Southeast Asian monsoon exert significant influence. Although rainfall-induced hazards generally exhibit smaller magnitudes and shorter runout distances compared to glacier-related hazards, their occurrence in densely populated low-altitude areas poses substantial risks to infrastructure such as roads, hydropower stations, and residential communities (Bhardwaj et al., 2019; Dixit et al., 2024). The hazards associated with permafrost degradation include thermokarst landslides (Liu et al., 2024). Although typically of smaller scale, they often exhibit widespread distribution, frequently leading to significant impacts on transportation infrastructure (Mu et al., 2020). For instance, along a 550 km stretch of the Qinghai-Xizang Railway, which traverses the permafrost region of the Tibetan Plateau, the destruction of embankments due to permafrost-related hazards remains a persistent challenge (Wei et al., 2024).

Table 1 Classification system for hydrogeological hazards in HMA under climate change.

Type	Sub-type	Related triggers	Impacts related to climate change	Prone area or examples
Landslide	Rainfall induced landslide	Rainfall-related hazards	Increasing meteorological triggers	Himalaya, South and east Tibetan Plateau (Fan et al., 2025)
	Bedrock landslide	Glacier-related or Rainfall-related hazards	Enhanced freeze-thaw cycles Reduced rock strength due to meltwater infiltration	Baige Landslide (Li et al., 2020), Yigong landslide (Shang et al., 2003)
	Thermokarst landslide	Permafrost degradation-related hazards	Thickening of active layer Reduction in effective shear strength near the base of the active layer Increasing fluvial thermal erosion	Central Tibetan Plateau (Luo et al., 2022a)
Debris flow	Rainfall induced debris flow	Rainfall-related hazards	Increasing meteorological triggers Favorable run-off condition to initiate debris f low	Central Himalaya (Qiu and Geng, 2024)
	Glacial debris flow	Glacier-related hazards	Favorable run-off condition to initiate debris f low Substantial supply of loose or erodible sediment in the channel	The 2015 Peilong glacier debris flow (Wang et al., 2021b)
GLOF	Moraine dam GLOF	Glacier-related hazards	Rapid expansion of moraine-dammed glacial lake Enhanced ice melting inside the moraine dam Accelerate the destruction of lateral moraine	The 2023 Sikkim GLOF (Sattar et al., 2025)
	Ice dam GLOF	Glacier-related hazards	Rapid expansion of moraine-dammed glacial lake Enhanced ice melting inside the ice dam	The 2018 Khurdopin GLOF (Bazai et al., 2022)
Ice-rock avalanche	Glacier detachment	Glacier-related hazards	Increasing meltwater infiltration Lower friction between the ice bed and underlying bedrock	The 2016 Aru glacier detachment (Kääb et al., 2018)
	Ice-rock collapse	Glacier-related hazards	Lower friction between the ice bed and underlying bedrock Enhanced freeze-thaw cycles Reduced ice-rock strength due to meltwater infiltration	The 2018 Sedongpu Ice-rock collapse (Li et al., 2024b), 2021 Chamoli Ice-rock collapse (Jiang et al., 2021)

Based on the similarities in formation processes, material composition, and kinematic characteristics, the specific disaster types can be categorized into four main groups: landslides, debris flows, GLOF, and ice-rock avalanche. Table 1 offers a detailed comparison of these hazard types, including information on the climate factors that influence their occurrence and impact.

3.2 Relevant database collection and data cleaning

In the past two decades, significant progress has been made in the research community of HMA's hydrogeological hazards. However, these studies have often focused on specific types of disaster events, such as landslides or GLOFs, without systematically analysing the diverse range of hydrogeological hazards in the regional scale. This limitation has hindered the identification of overarching patterns in disaster distribution and the advancement of regional risk assessment and prediction efforts. To address this knowledge gap, it is crucial to construct a comprehensive and reliable HMA hydrogeological disaster database. Here we integrate existing hazard-related databases from both regional and global levels, incorporating a total of 10 databases and covering 8,209 disaster events (Table 2). The data sources include authoritative platforms such as the Global Landslide Catalog, the GLOF Inventory of HMA, and the Tibetan Plateau Data Center (TPDC).

Table 2 Open access hydrogeological hazard database. The table details the number of events recorded and those selected for inclusion in the current database, along with relevant references.

ID	Type of hazards	Study area	Period	Num. of events	Num. of events selected into our database (Since 1986)	Refs.
1	Landslide	Pamir, Hind Kush and Karakoram	1998-2018	127	>127	Liu et al., 2021a
2		Global	1901-2019	727	55	Zhang et al., 2023b
3		HMA	2007-2015	1750	1532	Kirschbaum et al., 2020
4		Tibetan Plateau	2008-2020	2669	1210	Luo et al., 2022a
5	GLOF	HMA	1560-2021	296	38	Zheng et al., 2021a
6		HMA	1560-2022	299	53	Li et al., 2022a
7		HMA	1822-2022	682	209 (including repeat events)	Shrestha et al., 2023
8		Himalaya	1980-2017	39	28	Veh et al., 2018; Veh et al., 2019
9		Global	1569-2021	1569	142 (including repeat events)	Lützow et al., 2023; Veh et al., 2023
10	Ice-rock avalanche	HMA	Prehistoric-2022	51	37	Zhong et al., 2024

We first standardized the data from various sources, including Excel, CSV, and KML formats, converting them uniformly into GIS-compatible shapefile format. Then, we clipped all events within the HMA boundary. Based on our hydrogeological hazard classification system, we filtered out events that did not meet the hazard definition or lacked essential attribute information. Duplicate records across different datasets were identified and removed through spatial and temporal matching using coordinate and event-year attributes. For temporal consistency, event timing was normalized to an annual scale, considering that most databases do not provide exact occurrence dates. In addition, we excluded earthquake-triggered landslides to focus on climate-driven hydrogeological hazards. To fill potential data gaps, we cross-checked records with published literature and official reports. Although we have integrated multiple authoritative datasets, some limitations remain due to incomplete temporal coverage and missing isolated events. Therefore, in subsequent trend analyses, only hazard types with relatively continuous time-series data (e.g., GLOFs) were used for discussion. Finally, we constructed a comprehensive database containing 3,254 hydrogeological hazards since 1986, including 2,758 landslides, 211 debris flows, 209 GLOFs, and 76 ice–rock collapses.

3.3 Distribution patterns

We have conducted a density analysis of hydrogeological hazards (HH) in the HMA since 1986, as depicted in the Figure 4. It reveals significant spatial variation in hazard distribution. The southern slopes of the Himalaya, particularly in the Central Himalaya and East Himalaya, show the highest density of hazards. This region's steep terrain, intense monsoonal precipitation, and active tectonic activity contribute to frequent occurrences of landslides, debris flows, and GLOFs. The Karakoram and Pamir ranges also exhibit concentrated hazard clusters, with numerous ice-rock avalanches and debris flows driven by glacier instability and rugged topography. Conversely, the Tibetan Plateau interior displays a lower density of events, with only some landslide events concentrated on the northern edge. These landslides, located in relatively stable landscape, were produced by permafrost degradation.

Hazard types show distinct spatial patterns. GLOFs (green circles) are concentrated in glacier-rich regions such as the Himalaya and Karakoram, while debris flows (orange triangles) are widespread, especially along river valleys. Ice-rock avalanches (yellow dots) are most prominent in the Himalaya, Karakoram and Pamir ranges, where unstable glaciers and steep slopes intersect. Landslides (white squares) are prevalent in high-relief zones along the Himalayan arc and extend toward the eastern Tibetan Plateau. The overall pattern highlights the influence of climatic, glacial, and geomorphic factors on hazard distribution, emphasizing the need for region-specific disaster mitigation strategies.

4 Formation and mechanism of different hydrogeological hazards

4.1 Glacier lake outburst flood (GLOF)

GLOFs in HMA are classified into two types: moraine-dammed GLOFs and ice-dammed GLOFs. The formation of moraine-dammed GLOFs is characterized by two modes: overtopping and piping. The piping failure mode occurs in supraglacial and fresh proglacial lakes, where the dam is composed of loosely consolidated debris with some undecomposed buried ice. When the glacial lake expands rapidly, high water pressure can cause particle migration within the dam, altering its skeleton and triggering a piping event. In addition, rising temperature can accelerate the melting of buried ice within the dam structure, further contributing to the formation of piping channels and compromising the dam's stability.

Overtopping is another failure mechanism in moraine-dammed GLOFs. This process is triggered by displacement waves generated by lateral moraine landslides (Figure 5(a)) (Sattar et al., 2025)or ice-rock avalanches (Figure 5(b)) (Zheng et al., 2021c) entering the glacial lake. A notable example is the GLOF event that occurred in Sikkim, India, on October 3, 2023, which was triggered by a lateral moraine landslide-induced displacement wave. Over the past 30 years, the mother glacier of South Lhonak Lake has retreated by approximately

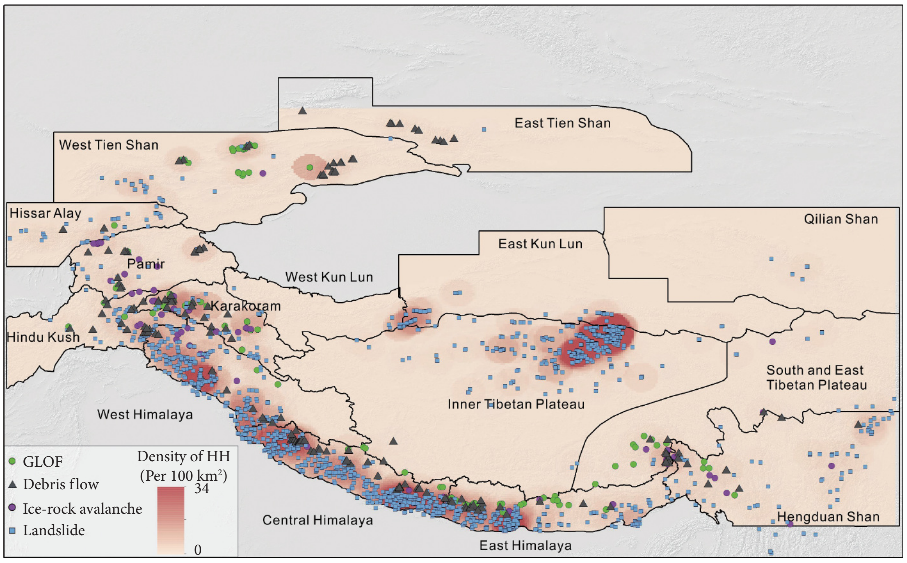

Fig. 4 Density distribution of hydrogeological hazards (HH) in the HMA since 1986. This map illustrates the spatial distribution of various hazard types, including glacial lake outburst floods (GLOFs, green circles), debris flows (black triangles), ice-rock avalanches (purple dots), and landslides (blue squares). Hazard density (per 100 km^2) is shown using an orange gradient, with darker shades representing higher hazard concentrations. The black solid line indicates the boundary of the Global Terrestrial Network for Glaciers (GTN-G) regions.

1,700 meters, causing the lake's area to expand nearly fourfold to 1.6 km^2 (Sattar et al., 2021). As the glacier retreated, the lateral moraine underwent obvious deformation due to the combined effects of meltwater infiltration from the upstream glacier and lake water saturation at the slope base (Saha et al., 2024). Optical remote sensing image displacement tracking indicates that the moraine experienced a maximum coherent displacement exceeding 15 meters per annum ($m \cdot a^{-1}$) between 2016 and 2023 (Sattar et al., 2025). Under prolonged heavy rainfall conditions, this deformation eventually triggered a landslide-wave-GLOF disaster chain. Additionally, a small proportion of moraine-dammed GLOFs are caused by overtopping events resulting from extreme rainfall or sudden inflows of glacier and snowmelt water.

Compared to the widely distributed moraine-dammed GLOFs, ice-dammed GLOFs are concentrated in the Karakoram region. Over the past 40 years, while most glaciers worldwide have experienced retreat, glaciers in the Karakoram have maintained a slightly positive mass balance, with some glaciers exhibiting surging behavior, a phenomenon known as the Karakoram Anomaly. During glacier surges, advancing glacier tongue can block river channels, forming ice-dammed lakes. In the early stages of river blockage, the ice dam undergoes continuous compression, resulting in a stable structure with relatively low outburst risk (Bazai et al., 2021). However, as the glacier

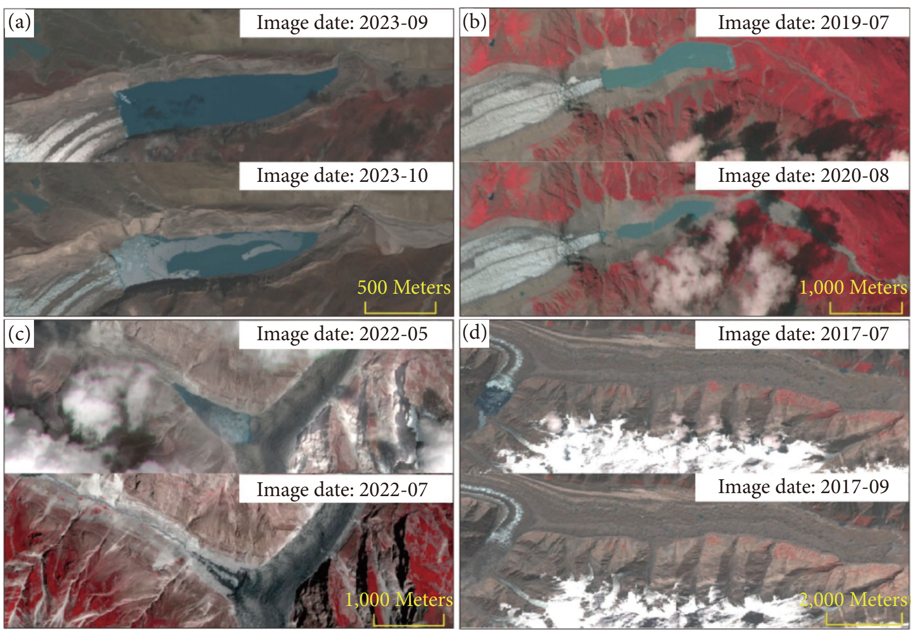

Fig. 5 Different glacier lake outburst flood (GLOF) in HMA remote sensing images were taken before and after the events. (a) The 2023 Sikkim GLOF in India (Sattar et al., 2025). **(b)** The 2019 Jinwucuo GLOF in Tibetan Plateau (Zheng et al., 2021c). **(c)** The 2022 Shiper GLOF in Karakoram (Bazai et al., 2021). **(d)** The Merzbacher GLOFs (Nie et al., 2023).

continues to exert pressure, new crevasses may develop within the dam, creating internal water conduit. As the impounded lake deepens and water pressure increases, these conduits can interconnect, weakening the dam structure and ultimately causing collapse (Bazai et al., 2022). Rising temperatures further accelerate internal ice melt, increasing the likelihood of ice-dam collapse and subsequent GLOFs. Following the termination of a glacier surge, the remaining dam material becomes loose debris that may either be transported downstream or persist until the next surge event forms a new ice dam (Cui et al., 2024). The frequency of ice-dammed GLOFs is consistent with the surge cycles of these glaciers, occurring less frequently than moraine-dammed GLOFs. A notable example is the Shisper Glacier (Figure 5(c)), where such processes have been well-documented (Bazai et al., 2021; Veh et al., 2023).

Another type of high-frequency ice-dammed GLOF occurs in glacial lake systems formed by main glacier and a tributary glacier interacting. A typical example of this process is observed at Merzbacher Lake in Kyrgyzstan (Nie et al., 2023). As the main glacier moves downstream, it blocks the meltwater draining channel from the tributary glacier. Subsequently, meltwater rapidly fills the ice lake at a rate of 2–3 meters per day. With high water pressure and temperatures rising together, the ice dam eventually breaks, forming a subglacial drainage channel and causing a GLOF. Statistical show this usually occurs once a year, though sometimes twice. The timing and frequency of these events and highly changeable, making them especially hard to predict (Figure 5(d)).

4.2 Debris flow

Debris flows in HMA include glacial debris flows, rainfall-induced debris flows. Rainfall-induced debris flows are distributed in low-altitude regions, where colluvium deposits or landslide accumulation materials in gullies serve as the main source. These materials, characterized by high porosity and loose structure, are susceptible to collapse under prolonged rainfall erosion. Such collapses can lead to blockages within the gully, which may subsequently trigger cascading outburst floods. As these floods travel downstream, they can further entrain and mobilize gully sediments, ultimately developing into large-scale debris flow events with destructive potential.

Glacial debris flows typically occur in high-altitude glacierized regions and can be classified into two types: rainfall-meltwater-induced glacial debris flows and moraine landslide-induced glacial debris flows (Wei et al., 2018). The rainfall-meltwater type is triggered by the combined effects of rainfall and glacier meltwater, which erode glacial moraine deposits or loose debris accumulated in gullies. These events are common during intense summer rainfall periods or abrupt autumn warming phases. Such debris flows are prone to occurring in glacier gullies with relatively gentle slopes and large catchment areas. In contrast, moraine landslide-induced glacial debris flows are characterized by their larger scale, longer runout distances, and greater destructive potential. These events are more frequent in gullies with steep gradients and extensive lateral moraine deposits. Prolonged gully erosion can destabilize the base of lateral moraines, resulting in moraine landslides that form temporary landslide dams. Following a brief period of blockage, dam failure can trigger a large-scale debris flow. Due to their bigger initial volume, these debris flows can entrain substantial amounts of loose gully sediments, often resulting in events larger than those triggered solely by rainfall and meltwater.

Peilong Gully in southeastern Tibetan Plateau is a typical glacier debris flow channel. The catchment area of Peilong Gully is approximately 87.54 km^2, with a glacier-covered area of about 18.16 km^2 (Wang et al., 2021b). The main channel extends 18.69 km with a channel gradient of 184 ‰. The gully contains an estimated 5.2×10^8 m^3 of glacial moraine deposits, providing abundant loose material for debris flow development. Since the 1980s, two notable glacier debris flow events have been recorded in this region: one on July 29, 1983, and another in October 2015 (Li et al., 2021). Both events resulted in the blockage of the Parlung Tsangpo River. The 1983 event was triggered by a large-scale landslide (Figure 6(a)), while the 2015 event was induced by increased rainfall and meltwater (Figure 6(b)). Remote sensing-based glacier velocity monitoring reveals that rainfall-meltwater-induced glacier debris flow events are often followed by reduced glacier activity (Figures 6(c)-6(d)). This reduction in glacier activity may be related to decreased internal glacier meltwater intensity, suggesting that glacier dynamics play a significant role in controlling glacier debris flow occurrences. These findings indicate that glacier activity can serve as a valuable remote sensing indicator for predicting glacier debris flow events.

4.3 Ice–rock avalanche

Ice-rock avalanche in HMA include two types: ice–rock collapse (Zhong et al., 2024) and glacier detachment (Kääb et al., 2021). Ice–rock collapse occurs in regions with well-developed hanging glaciers, such as the Himalayas and southeastern Tibetan Plateau. This process is accompanied by the development of cracks in hanging glaciers, where meltwater infiltration leads to bedrock degradation and the disruption of the glacier's water-thermal equilibrium, making it one of the most complex geomorphological processes in glacial areas (Faillettaz et al., 2015). As such, ice–rock collapses are controlled by a combination of factors, including the lithology and structural characteristics of the ice–rock mass, as well as the slope. Ice-rock collapses often trigger cascading chains. For instance, when an active glacier lies below the collapsing ice–rock, high-speed avalanches impact the glacier, causing it to disintegrate. The friction and heat generated by the collision contribute to the melting of ice within the disintegrated moraine, weakening its strength and leading to debris flow formation. The erosive effects of the debris flow can further increase its size. The debris flow rush into river, trigger a dam break flood. A notable disaster chain occurred on October 17, 2018, in the Yarlung Tsangpo River, Nyingchi, Tibetan Plateau. An ice-rock collapse in Sedongpu Gully triggered a series of events (Li et al., 2024b). The hanging glacier failure caused ice-rock debris to collide with the main glacier, generating a debris flow that entered the Yarlung Tsangpo River and formed a landslide dam. After 56 hours of blockage, the dam breached, releasing floodwaters (Figure 7(a)).

Glacier detachment happens when a big chunk of ice suddenly breaks off from a glacier. This is often caused by internal stress and changes in the environment. Rising temperatures lead to glacier thinning over time, making the ice less stable. Permafrost degradation also plays a role by reducing the glacier's grip on steep slopes. A good example of this occurred in July 2016 in the Aru Glacier region (Kääb et al., 2018; Lei et al., 2021). The Aru glaciers first went through a rapid advances experienced a period of rapid advance, probably because more meltwater at the base made sliding easier or due to changes in the water system under the glacier (Kääb et al., 2018). This surge increased internal stress as the ice deformed and pressure built up, weakening the glacier. Eventually, the accumulated stress and weakened

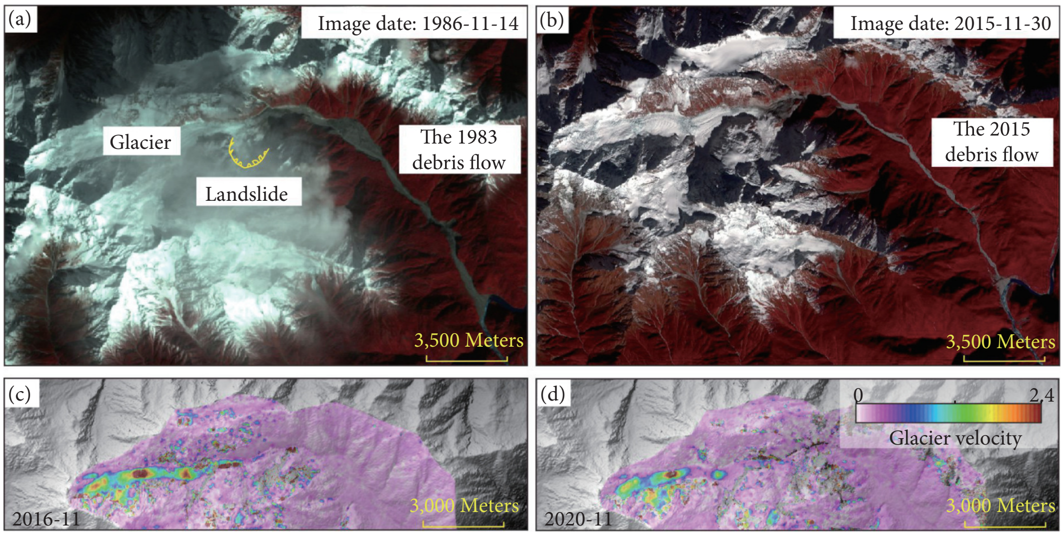

Fig. 6 Satellite imagery of the (a) 1983 and (b) 2015 glacier debris flow in Peilong Gully, Tibetan Plateau. (c) and (d) Panels show glacier velocity following the 2015 debris flow.

structure caused a sudden detachment. This led to a huge ice–rock avalanche that moved debris over a long distance (Figure 7(a)).

4.4 Landslide

Landslides affected by climate change in HMA include alpine bedrock landslides, rainfall landslides, and thermokarst landslides. The formation and mechanism of bedrock landslides in alpine mountainous areas are closely linked to glacial retreat and environmental changes (Li et al., 2022a). As glaciers shrink, the underlying bedrock loses critical support, increasing slope instability. This destabilization is further intensified as meltwater and precipitation infiltrate deep fractures in the rock (Liu et al., 2021a). During freeze-thaw cycles, water expands as it freezes, exerting pressure that widens fractures and weakens the rock's structural integrity (Zhang et al., 2023b). Over time, repeated frost cracking and the persistent weakening of bedrock strength can lead to slope failure, resulting in bedrock landslides. This process is particularly prevalent in regions experiencing rapid glacial retreat and climate warming.

Rainfall-induced landslides primarily occur on slopes and along riverbanks covered by loose accumulation layers. The formation and mechanism of rainfall-induced landslides in loose accumulation layers are driven by several interconnected processes (Saha et al., 2024). Intense rainfall accelerates surface erosion, displacing fine particles within the loose rock mass and destabilizing the soil structure (Lin et al., 2017). As rainfall infiltrates deeper, pore water pressure rises, reducing friction between soil particles and weakening the overall rock and soil skeleton (Kirschbaum et al., 2020). Simultaneously, rainfall promotes the expansion of cracks and sliding surfaces, further compromising slope stability. The combined effects of material migration, structural weakening, and increased pore water pressure significantly heighten the likelihood of landslide initiation in areas with loose accumulation layers. In terms of the slope along the river, increased rainfall intensifies surface runoff, enhancing river erosion of the loose deposits along riverbanks. This continuous erosion has accelerated slope instability and ultimately caused landslides.

Thermokarst landslides are associated with permafrost degradation. As temperatures rise, the shallow surface soil begins to thaw and the active layer gradually thickens, resulting in a loosening of the soil (Luo et al., 2022a). Under rainy conditions, meltwater starts to infiltrate along pores and structural interfaces, accumulating near potential sliding surfaces. This increases the saturation of the surface soil and the pore water pressure near the sliding plane, thereby reducing the effective stress and ultimately decreasing the soil's shear strength (Patton et al., 2021). Moreover, repeated freeze-thaw cycles lead to structural degradation of the soil under conditions of expansion and contraction, further reducing its shear strength (Hjort et al., 2022). When triggered by heavy rainfall, sustained meltwater input, or seismic activity, the saturated and weakened soil is prone to failure, ultimately resulting in a thermokarst landslide (Lewkowicz and Way, 2019).

5 Summary and implications

5.1 Future climate scenarios and impacts on hydrogeological hazard

Future climate change trends in High Mountain Asia (HMA) indicate significant warming, glacier retreat, and changes in precipitation patterns, posing major environmental and socio-economic challenges. Research shows that the region's average temperature is projected to increase by 2–4 °C by the end of the 21st century under high-emission scenarios (RCP8.5), with warming rates exceeding the global average (Kraaijenbrink et al., 2017). Precipitation patterns in HMA are also projected to undergo substantial changes. Climate models suggest an overall increase in annual precipitation, particularly during winter months, driven by intensified westerly winds and shifting monsoon patterns (Khanal et al., 2021; Lalande et al., 2021). However, this increase may be accompanied by greater rainfall variability and more frequent extreme weather events, such as intense storms and prolonged droughts. In some regions, snowfall is expected to decline, altering seasonal runoff patterns during warmer months (Lutz et al., 2014).

As the climate continues to warm, HMA glaciers are projected to experience substantial loss, with the rate of glacier retreat expected to accelerate in the coming decades, peaking between 2040 and 2060 (Li et al., 2022b; Rounce et al., 2023). This retreat is expected to regions

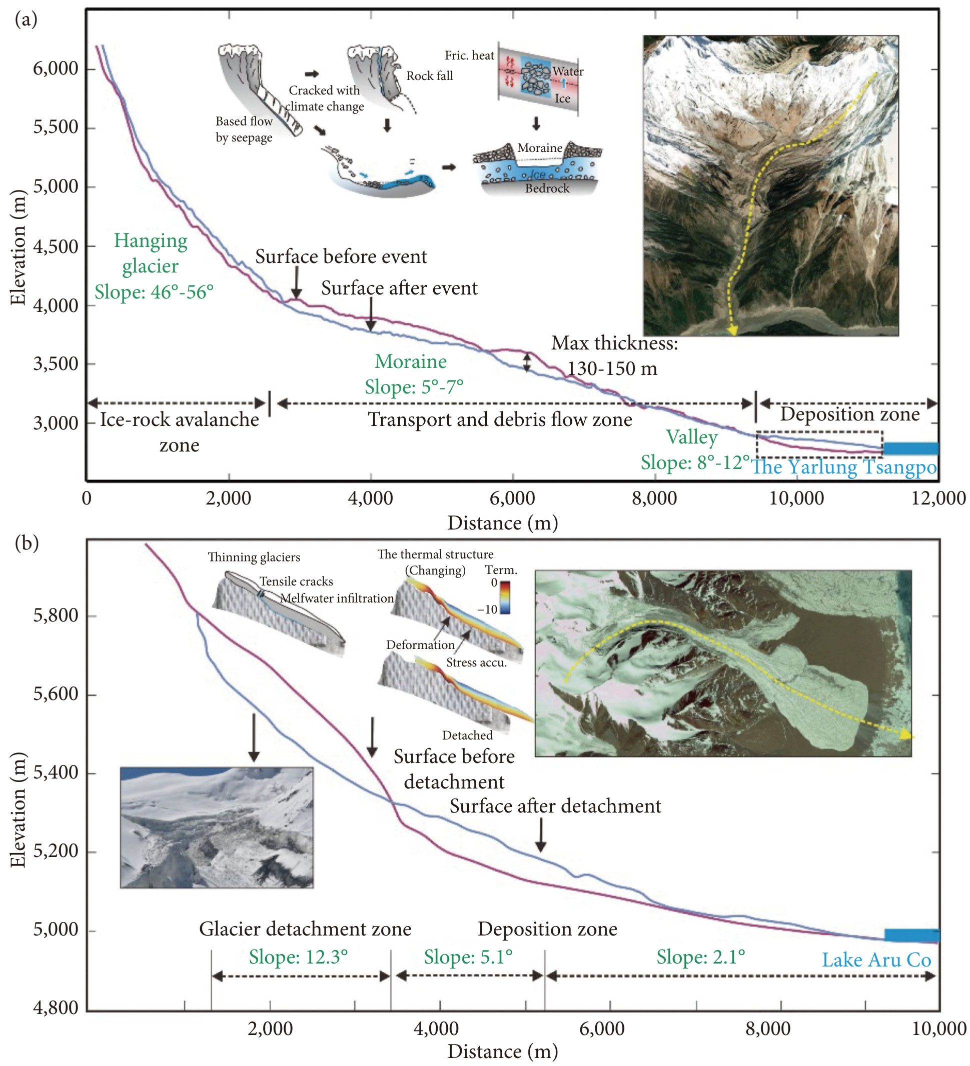

Fig. 7 Two types of ice-rock avalanche. (a) The Profile of 2018 Sedongpu ice-rock avalanche (Li et al., 2024b). **(b)** The profile of 2016 Aru glacier detachment (Kääb et al., 2018). Inset, lower left in (b), is reproduced with permission from Kääbet al., 2018, © Macmillan Publishers Limited, part of Springer Nature 2018.

with lower elevations and stronger monsoon influence. The eastern Himalayas and Nyainqentanglha ranges are identified as particularly vulnerable, with projected mass losses exceeding 60% by the end of the 21st century under high-emission scenarios (Rounce et al., 2023). Glacier retreat will continue to release solid materials and meltwater, facilitating the formation of landslides and debris flows. The increased meltwater will also contribute to the expansion of glacier lakes and the rise in runoff, thereby enhancing the risk of both GLOFs and monsoon floods (Zheng et al., 2021b). Furthermore, the retreat of glaciers leaves behind more hanging glaciers, which are prone to develop into ice-rock collapse events. In permafrost regions, evidence from various field studies indicates that a warming climate has progressively increased active layer depths and shifted the lower permafrost boundary to higher elevations. As the active layer thickens, shallow slope movements have been observed to increase, while the continued and deeper warming of high mountain permafrost is expected to contribute to a rise in large bedrock failures.

5.2 Future trend of hydrogeological hazards

There is no doubt that future climate warming and the resulting environmental changes will provide favorable conditions and intensify the magnitude of the triggering factors for the development of hydrogeological hazards (Wang et al., 2024). Nevertheless, the trends in frequency and scale remain an open topic for discussion. To date, no comprehensive study has thoroughly examined this issue. Nevertheless, consensus has been achieved regarding certain specific hazard types in some regions, such as GLOFs in the Himalayas (Veh et al., 2019) and thermokarst landslides in the Central Tibetan Plateau (Luo et al., 2022a). Researchers have analyzed historical GLOF events using remote sensing data and found that the average annual frequency of GLOFs, approximately 1.3 events, exhibits no significant trend in the Himalayas since the 1980s (Veh et al., 2019). Furthermore, a literature review of historical GLOF events (1990–2021) on a global scale (including HMA) suggested a decreasing trend in the extreme peak flows and volumes (10 per cent highest) of GLOFs, which they termed as an anomalous finding (Veh et al., 2023). In contrast, studies of thermokarst landslides in the Central Tibetan Plateau have shown that both the number of retrogressive thaw slumps (RTSs) and their affected areas have increased by 4 and 6 times from 2008 to 2021 (Luo et al., 2022a). Despite the differing trends in the frequency and scale of hydrogeological hazards across various regions of High Asia, researchers generally agree that, in the context of climate change, the risk of these hazards is likely to increase (Taylor et al., 2023;

Zhang et al., 2023a; Zheng et al., 2021a).

In the future, intensified magnitude of the triggering factors, such as extreme temperature and rainfall events, may lead to the occurrence of multi-hazard hydrogeological events (Wang et al., 2024). Consequently, the downstream community will be exposed to compound disaster events more frequently, such as landslide-debris flow chain and ice-rock collapse-debris flow-GLOF chain. Compared to single-hazard events, compound or cascading disasters are larger in scale and have a broader impact (Owolabi and Sajjad, 2023). The expansion of disaster impacts could even transcend national boundaries. Mitigating these cross-regional disaster risks will be a critical focus for future disaster management research.

There is considerable research focusing on the hydrological responses of HMA to climate change, identifying tipping points in glacier meltwater and runoff changes (Li et al., 2022b). However, no reliable models have yet to determine whether tipping points exist for the occurrence of hydrogeological hazards. What is certain is that future disaster-prone conditions related to hydrogeological hazards—such as glacier mass loss (Cogley, 2017; Rounce et al., 2023), glacier lake expansion, and critical runoff thresholds—will likely lead to peak frequencies of certain disaster types, including glacial debris flows, channel erosion landslides, and GLOFs. This peak frequency may, however, lag behind the corresponding peak in environmental changes that produce these events.

Although no robust models currently exist to reliably predict future trends of high-mountain hydrogeological hazards (HH), future research can improve predictive capabilities by prioritizing the integration of physically based process models with multi-source monitoring datasets, including remote sensing, in-situ observations, and numerical simulations. Developing coupled modeling frameworks that incorporate hydrological, thermal, and mechanical processes will enable more realistic simulations of slope stability, glacier dynamics, and glacial lake evolution under projected climate scenarios, thereby reducing uncertainties in projections of hazard frequency and magnitude.

5.3 Avenue for hazard mitigation

In low-altitude mountainous regions, many disaster-prone areas have adopted active protection engineering measures, such as retaining walls and drainage systems, alongside ecological measures like vegetation restoration and soil stabilization, to mitigate the impacts of hydrogeological hazards (Zhou et al., 2023). However, in HMA, characterized by high altitudes, the implementation of such disaster prevention techniques faces significant challenges due to the cold climate, steep terrain, and unstable landforms like permafrost and glaciers. For instance, freeze-thaw cycles can undermine the stability of traditional drainage systems, while continuous snowmelt poses greater erosion risks to retaining walls and embankments. Moreover, hydrogeological hazards in high-altitude regions tend to be on a larger scale compared to low-altitude areas, making conventional protective engineering systems prone to failure (Baggio and D'Agostino, 2022). A notable example is the 2018 Sedongpu ice-rock avalanche, which caused over 100 meters of erosion beneath the moraine (Wang et al., 2020). Therefore, active protection may not be the most effective mitigation strategy for hydrogeological hazards in high-altitude mountainous regions (Wang et al., 2020).

In addition to active protective engineering measures, early warning systems (EWS) also offer an effective approach for disaster mitigation (Sattar et al., 2025). In low-altitude regions, researchers utilize in-situ instruments (such as deformation and rainfall monitoring), satellite remote sensing, drones, and ground-based synthetic aperture radar (SAR) to conduct disaster monitoring and early warning (Cook et al., 2021; Dixit et al., 2024). However, in the inaccessible high-altitude mountainous regions, the implementation of traditional monitoring frameworks faces great challenges due to the harsh environment and poor signal transmission conditions. Therefore, innovation in monitoring techniques, including the introduction of new technologies, will be a key focus for future research. For example, the use of non-contact seismic monitoring technologies can effectively overcome issues related to equipment deployment difficulties and extreme environmental conditions, enabling remote and continuous monitoring in these areas (Cook et al., 2021; Faillettaz et al., 2015).

In addition, given the diverse triggers of hydrogeological hazards in HMA, Early Warning Systems (EWS) must integrate multiple monitoring methods to comprehensively capture the dynamics of different events triggered by factors such as precipitation, temperature fluctuations, glacier melt, and permafrost degradation. In terms of disaster analysis, the EWS should include phased analysis models to address different warning needs before, during, and after a disaster (Li et al., 2020). For instance, remote sensing surface deformation monitoring can be employed to identify potential hazards before their occurrences. Additionally, seismic monitoring, combined with numerical simulation techniques, can provide rapid assessments of disaster processes and impact ranges, improving the timeliness and accuracy of emergency response during a disaster. Most critically, the EWS requires an efficient and stable platform for information transmission, extraction, and scenario simulation visualization. This platform should integrate cloud-based data storage and retrieval modules, high-performance computing capabilities, and efficient 3D rendering features, allowing for rapid analysis and clear visualization of disaster evolution. Currently, Early Warning System platforms based on Digital Twin technology are considered the most promising solutions due to their advanced data integration, simulation, and visualization capabilities, making them worthy of further research and application (Cui et al., 2024).

In addition to engineering measures and monitoring systems, effective mitigation of hydrogeological hazards in HMA requires strengthened policy coordination and transboundary cooperation (Zheng et al., 2021a). Given that many glacial lakes, river basins, and hazard chains span multiple national borders, joint early-warning mechanisms, shared data platforms, and coordinated emergency response protocols are critical for reducing downstream risks. Establishing regional partnerships can facilitate real-time information exchange and promote integrated climate adaptation strategies across the HMA region.

6 Conclusion

High Mountain Asia, known as Asia's "Water Tower", is experiencing significant climate-driven changes. In the past 40 years, rising surface temperatures have altered precipitation patterns and intensified hydrological activity. These shifts have accelerated glacier retreat, expanded glacial lakes, increased meltwater runoff, degraded permafrost, and changed runoff regimes, all of which heighten the risk of hydrogeological hazards. The region is witnessing more frequent and severe ice–rock collapses, glacial lake outburst floods (GLOFs), landslides, and debris flows, threatening water security, infrastructure, and communities.

Currently, hydrogeological hazards are most prevalent in the Himalayas, where steep terrain and monsoon-driven precipitation increase the risks. However, as climate change progresses, the geographic extent of these hazards may expand, rising exposure and vulnerability across HMA. The cascading effects of climate-induced disasters highlight the urgent need for systematic research on the formation conditions and evolutionary mechanisms of hydrogeological hazards in HMA. Future research should focus on integrating multi-hazard assessments, improving early warning systems, and enhancing climate adaptation strategies to mitigate the risks posed by these hazards. Strengthening regional cooperation and leveraging advanced monitoring technologies will be critical to safeguarding HMA's stability ensuring the resilience of downstream communities dependent on its water resources.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration of competing interests

The authors have no competing interests to declare that are relevant to the content of this article.

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