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Glacial lakes and GLOFs in a warming Himalaya-Karakoram region: current understanding, challenges, and the way forward



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The cryosphere of the Himalaya–Karakoram is rapidly retreating under climate change, leading to widespread formation and expansion of glacial lakes and increasing the risk of glacial lake outburst floods (GLOFs). To date, more than 388 GLOF events have been documented in the region, primarily from moraine- and ice-dammed lakes, with the highest frequency reported in the Karakoram, followed by the Central and Eastern Himalaya. Ice avalanches and extreme precipitation are the most common triggers. Growing exposure of settlements and infrastructure amplifies impacts, highlighting the need to integrate physical science with social vulnerability, preparedness, and adaptation strategies.

Global warming has heightened environmental concerns globally, with the accelerated melting of the Himalayan cryosphere emerging as one of the most critical challenges in the region¹. The geologically young and fragile Himalayas have experienced warming rates of 0.15 °C to 0.60 °C per decade, far exceeding the global average of 0.74 °C per century^{2–4}. Covering ~40,800 km² of glaciers (~22,800 km² in the Himalayas and ~18,000 km² in the Karakoram), the region is witnessing unprecedented glacial recession due to this warming trend^{5,6}. Projections under various RCPs indicate a temperature rise of 2.5 °C to 5 °C by the century's end, particularly in high-altitude zones⁷.

This warming has accelerated glacier retreat, driving the formation and expansion of glacial lakes^{1,8}. Under high-emission scenarios, 65% of the ice mass in High Mountain Asia could disappear by 2100, further increasing the number and size of glacial lakes⁹. Globally, since 1990, the number, area, and volume of glacial lakes have risen by 53%, 51%, and 48%, respectively¹⁰. Glaciers terminating in lakes retreat faster than land-terminating glaciers, amplifying glacial lake expansion and glacial recession rates¹¹. Consequently, Glacial Lake Outburst Floods (GLOFs) have emerged as a major hazard, particularly in the Himalayas. These sudden water discharges from glacier-fed lakes, located at the side, front, beneath, or on the surface of glaciers, pose a severe threat to downstream communities¹².

GLOFs are the most significant glacier-related hazard in terms of direct damage, having caused thousands of fatalities worldwide, including in the Himalayas^{13–15}, the Peruvian Andes^{16,17}, and the European Alps¹⁸. Despite

their sporadic occurrence, GLOFs are high-impact events that result in extensive economic and human loss. In Nepal, a study estimated potential economic damages ranging from 1.9 to 415 million USD for Imja, Tsho Rolpa, and Thulagi glacial lakes under worst-case scenarios, with hydro-power project losses reaching 8.98 billion USD for Imja Tsho, 2.4 billion USD for Tsho Rolpa, and 2.2 billion USD for Thulagi¹⁹. Similarly, a potential property damage of 159 million USD was estimated for a GLOF in Limu Chimi Lake, rising to 197 million USD in high flood scenarios²⁰.

Research on Himalayan glacial lakes has intensified in recent decades, driven by the increasing occurrence of GLOF disasters in the region²¹. This growing body of work has examined various aspects of the Himalayan cryosphere, with a focus on glaciers and glacial lakes in the context of climate change. In spite of all the progress so far, efforts to determine the precise number, spatio-temporal dynamics, and hazard levels of glacial lakes remain ongoing. Several datasets with varying spatial and temporal resolutions have been developed to map glacial lakes in the Himalayas^{22–24}. Given the dynamic nature of these lakes, regular updates to such inventories are crucial for monitoring their formation, expansion, shrinkage, and shifting over time.

The Himalaya-Karakoram (H-K) region is recognized as one of the most vulnerable regions to GLOFs^{8,13,18,25,26}. Continued glacier retreat in the region is projected to increase the frequency of GLOFs in the future¹². Approximately one million people live within 10 km of a glacial lake, highlighting the region's vulnerability²⁷. Historical GLOF events in this

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region, have demonstrated the significant destruction these sporadic but high-impact events can cause²⁸.

This study provides a comprehensive synthesis of existing research on glacial lake expansion and the rising GLOF hazard in the H-K region under climate change. We evaluated (a) current GLOF risks, (b) identified key drivers of GLOFs, and (c) assessed past research, future trends, and the mitigation strategies for GLOF disasters. Furthermore, we identified significant research gaps and limitations that continue to challenge GLOF studies in this vulnerable region.

Study area

The H-K region, stretching over 2400 km from northwest to southeast, is one of the youngest mountain systems in the world. Located along the southern edge of the Tibetan Plateau, it covers an approximate area of 0.65 million square kilometers (Fig. 1). Home to over 19,000 glaciers, the region boasts a total glacier area of around 29,500 square kilometers, including some of the largest glaciers in the world, such as the Siachen Glacier. The Himalayas are renowned for their abundant freshwater resources and serve as the source of major river systems like the Indus, Brahmaputra, and Ganges, which sustain the water needs of over a billion people across India, Pakistan, and Bangladesh. Seasonal precipitation patterns in the region are shaped by the Indian monsoon during the summer and the mid-latitude westerlies in the winter.

Temperature and precipitation vary significantly across the region, with mean annual temperatures and precipitation levels ranging from 1 °C and 66.1 mm at Shiquanhe station in the west, to 5.9 °C and 657.3 mm at Nyalam station in the center, and 0.4 °C and 442.6 mm at Yadong station in the east²⁹.

Data sources and methods

Data sources

This study used various datasets to study the different aspects of GLOFs in the H-K region. Key sources include the GLOF inventory from the International Centre for Integrated Mountain Development (ICIMOD), which details historical GLOF episodes and their triggers, as well as many glacial lake inventories that map and monitor glacial lakes throughout the Himalayas. The previous inventories^{10,22–24,30} provided valuable data on the spatial distribution, size, and dynamics of glacial lakes. These datasets, produced from remote sensing and GIS analysis, provide insight into the changing cryosphere and its potential hazards, allowing for comparisons across time periods and geographical regions in the Himalayas. We also relied upon the vast literature regarding Climate Change and GLOF, which includes case studies of previous GLOFs, studies modeling the potential threats and prospects of hazardous glacial lakes, and studies discussing the mitigation strategies for the GLOF disaster.

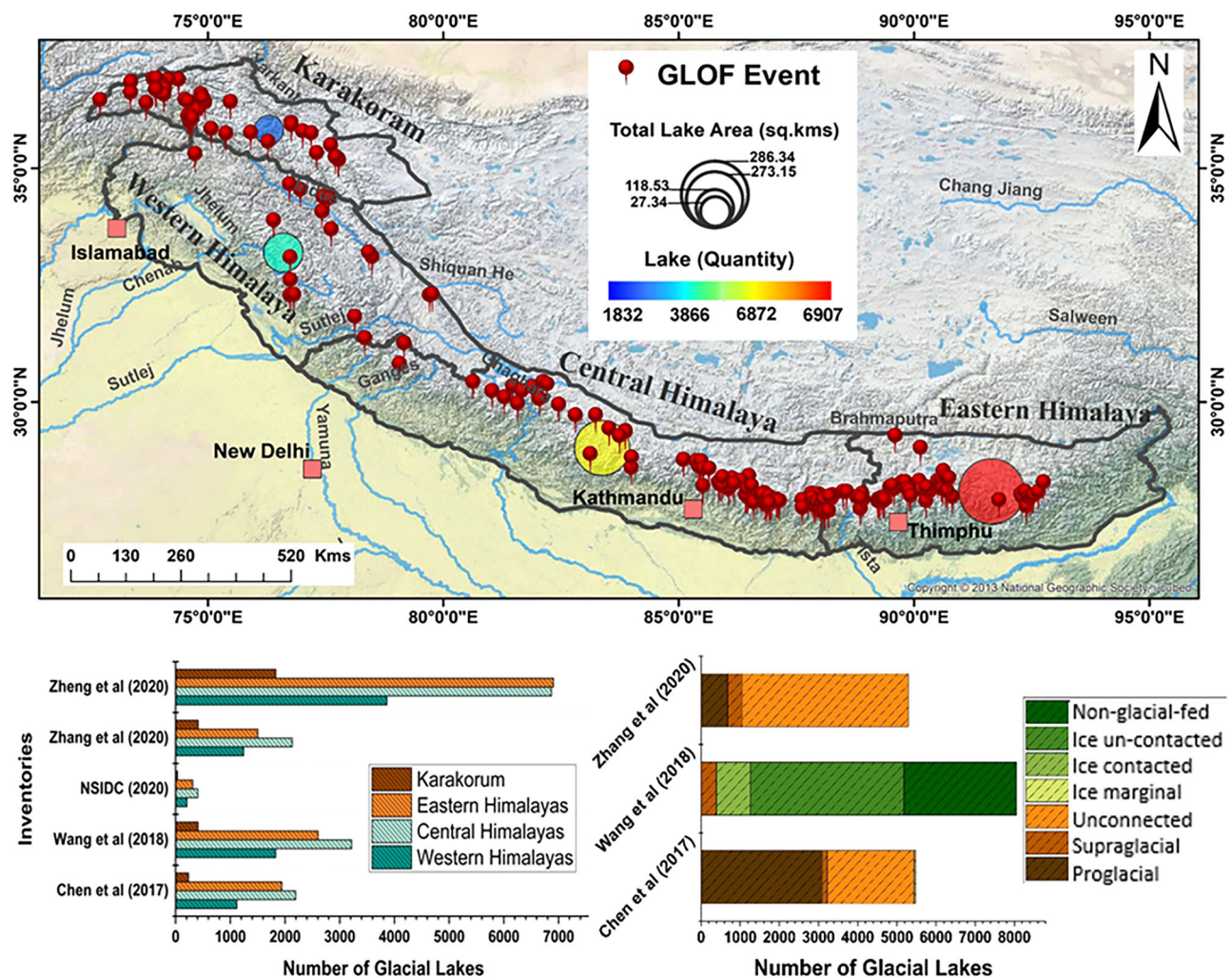


Fig. 1 | Study area map showing the spatial distribution of glacial lakes and documented past GLOF events across the H-K region, compiled from previously published glacial lake and GLOF datasets⁹⁴. The accompanying graphs illustrate (left) the number of glacial lakes reported in different inventories^{12,22,23,76}—note that

these datasets are not directly comparable due to differences in minimum mapping area thresholds—and (right) the classification of glacial lake types identified in the respective datasets^{12,22,23}.

Methods

The current study uses a comprehensive thematic analysis to investigate the various aspects of GLOFs in the H-K region, focusing on themes such as glacial lake changes, past GLOFs, triggers, and mitigating techniques. The methodology employs a systematic review approach, combining qualitative and quantitative analysis to synthesize findings from scholarly literature and previously produced datasets. The thematic analysis commenced with a detailed review of peer-reviewed journal articles, publications, and scientific databases focused on the H-K region. The study utilized the following keywords to identify relevant research: Climate Change in the Himalayas, Glacier Mass Balance, Glacial Lakes of the Himalayas, Glacial Lake Expansion, GLOFs, GLOF Risk, GLOF Triggers and Mitigation Techniques and Risk Evaluations for GLOFs.

Databases such as Web of Science, Scopus, Google Scholar, and GeoRef were employed to capture a broad spectrum of studies. Additionally, conference proceedings from the AGU, EGU, and AAG were examined to incorporate key studies and gray literature, ensuring a comprehensive understanding of research across the H-K region. Datasets on glacial lakes and GLOFs from prior studies were re-analyzed and synthesized to provide insights into their current distribution, dynamics, and historical and future trends. The study employed thematic analysis to organize findings into structured themes, following an inductive approach where themes emerged directly from the literature. This enabled an in-depth exploration of GLOF dynamics, historical patterns, and mitigation strategies specific to the Himalayas. The initial step involved coding articles to identify recurring patterns and topics. Characteristics of glacial lakes, GLOF triggers, climate change impacts, and mitigation strategies were systematically coded using qualitative data analysis software. These codes were then grouped into broader themes such as “GLOF triggers,” “glacial lake inventories,” and “mitigation strategies” (Table S1). Themes were refined and cross-referenced with pivotal studies such as systematic reviews and meta-analyses of glacial lake dynamics, GLOF triggers, mitigation techniques, and case studies of historical GLOFs to ensure consistency and uncover research gaps.

The quantitative aspect of the review examined the number and spatial distribution of glacial lakes, historical GLOF occurrences, and mitigation strategies at community, regional, and national levels. GIS-based maps and tables were used to visualize data, highlighting geographical and temporal trends as well as GLOF risk hotspots in the H-K region. The analysis revealed significant gaps in GLOF research, including limited social vulnerability assessments for populations near glacial lakes, insufficient studies on the impacts of climate change on GLOF frequency, and inadequate focus on mitigation measures like early warning systems (EWSs) in the region. These findings underscore the need for more integrated and region-specific research to address the growing risks of GLOFs effectively.

Climate change in the H-K region

Mountainous regions are among the most sensitive and highly vulnerable zones to climate change^{31,32} given that temperatures are rising faster than the global average and owing to their heterogeneous nature, both in terms of environmental and human factors³³. Since the H-K region encompasses developing countries, depending heavily on the Himalayan “water towers” for their human, agricultural and economic needs, the present and future human-induced climate change concerns are particularly high in the H-K region³⁴. The increase in the frequency of climatic extremes, and erratic patterns in precipitation and temperature^{35–38} together with the growing vulnerable population in and downstream of the Himalayan mountains³⁹, enhance the multifaceted threats from anthropogenic climate change^{40,41}. These multifaceted threats include floods (riverine, flash, and glacial), droughts, landslides, and debris flows⁴² affecting human lives and health, agriculture and food security, ecology and biodiversity, livelihood, and economic development⁴³.

Temperature trends. The H-K region is experiencing increasing temperature trends, as widely acknowledged by the research community^{44–46}.

The Himalayas and the adjoining Tibetan Plateau have warmed more rapidly in recent decades, with a 0.5 °C increase in annual maximum temperature from 1971–2005, compared to 1901–1960⁴⁷. However, the rates of warming vary across the region (Fig. 2 Table S2), with higher rates observed in elevated areas due to the phenomenon of ‘elevation-dependent warming’^{48,49}. In contrast, some sections, such as the Southern Himalayas, exhibit gradual warming or slight cooling trends⁵⁰. In the Western Himalayas, a 0.9 °C rise in temperature was recorded between 1901 and 2003, with most of the warming occurring post-1972⁵¹. Similarly, the NW Himalayas have witnessed a 1.6 °C rise (0.16 °C per decade) over the past century³. In the upper Indus basin, warming trends range from 0.07 to 0.55 °C per decade^{38,52}. Notably, nocturnal temperatures are rising faster than daytime temperatures across the region⁵³.

Regional Climate Model projections indicate continued warming in the Himalayas, with a median increase of 3.3 °C by 2100 under a moderate (RCP 4.5) scenario. However, the Tibetan Plateau and higher-altitude areas are expected to experience the greatest warming, with a projected rise of 3.8 °C⁵⁴. Seasonal variations in warming are also expected, with the largest increases projected for winter (3.6 °C) and monsoon months (2.7 °C).

Precipitation trends. Unlike temperature, there is an absence of spatially consistent long-term trends in the precipitation patterns. This is, in part, due to the impact of local thermodynamic and orographic processes on the synoptic-scale ocean-atmospheric processes⁵⁵. Seasonal variations further complicate precipitation patterns, with marked differences across regions⁵⁶. Long-term studies reveal a significant decline in monsoon and annual rainfall in the northwest Indian Himalayas from 1866–2006⁴⁴ and in the western Indian Himalayas from 1960–2006⁵⁷. In the western Indian Himalayas, winter precipitation has generally decreased since 1975, though with regional inconsistencies^{55,58}. Significant declines have been observed in Jammu & Kashmir and Uttarakhand from 1901–2003^{38,56}. By contrast, the upper Indus Basin has experienced increasing winter precipitation from 1961–1999⁵⁹. Pre-monsoon precipitation increases have also been noted in the western Indian Himalayas between 1901–2003⁵⁶. The Everest region displays contrasting trends, with the northern areas showing insignificant increases and the southern areas experiencing sharp decreases since the early 1990s⁶⁰. However, the precipitation simulations from Global Climate Models show greater uncertainty than the temperature simulations.

Analysis of some prominent regional studies (Fig. 2, Table S2) highlights consistent warming trends across all sub-regions of the Himalayas, particularly post-1980s, alongside varied precipitation trends. In the Western Himalayas, the mean annual temperature increases range from ~0.02 to 0.04 °C/year, with precipitation declines of 3–5.7 mm/year. In the Central Himalayas, the temperatures have increased by ~0.04 °C/year, while precipitation changes range from +3 to –9.7 mm/year. In the Eastern Himalayas, the temperatures have increased by ~0.01 to 0.03 °C/year, with an average precipitation decrease of 3.6 mm/year between 1950 and 2015. In the Karakoram Himalayas, the mean annual temperatures have risen by ~0.02 to 0.04 °C/year, though minimum temperatures in the Upper Karakoram show a slight decrease of 0.004 °C/year during 1980–2009. These diverse trends reflect the region’s varied climatic responses to physio-climatic regimes. While temperature trends are relatively homogeneous, precipitation shows more variability, with certain pockets exhibiting increases amidst a general pattern of decline across the H-K region.

Climate change impacts on glacier dynamics

The Himalayas experience extreme temperature fluctuations, variable precipitation, and frequent extreme weather events. Glaciers in the region respond to climate change gradually, with flow rates and lengths adjusting over 10–200 years, while mass balance changes seem to occur more immediately^{61,62}. After meticulously documenting historical glacier changes, it has been determined that the mass balance of Himalayan glaciers has been negative since at least the 1970s⁵. Since the Little Ice Age, Himalayan glaciers have experienced a total volume loss ranging from 390 km³ to 586 km³⁶³.

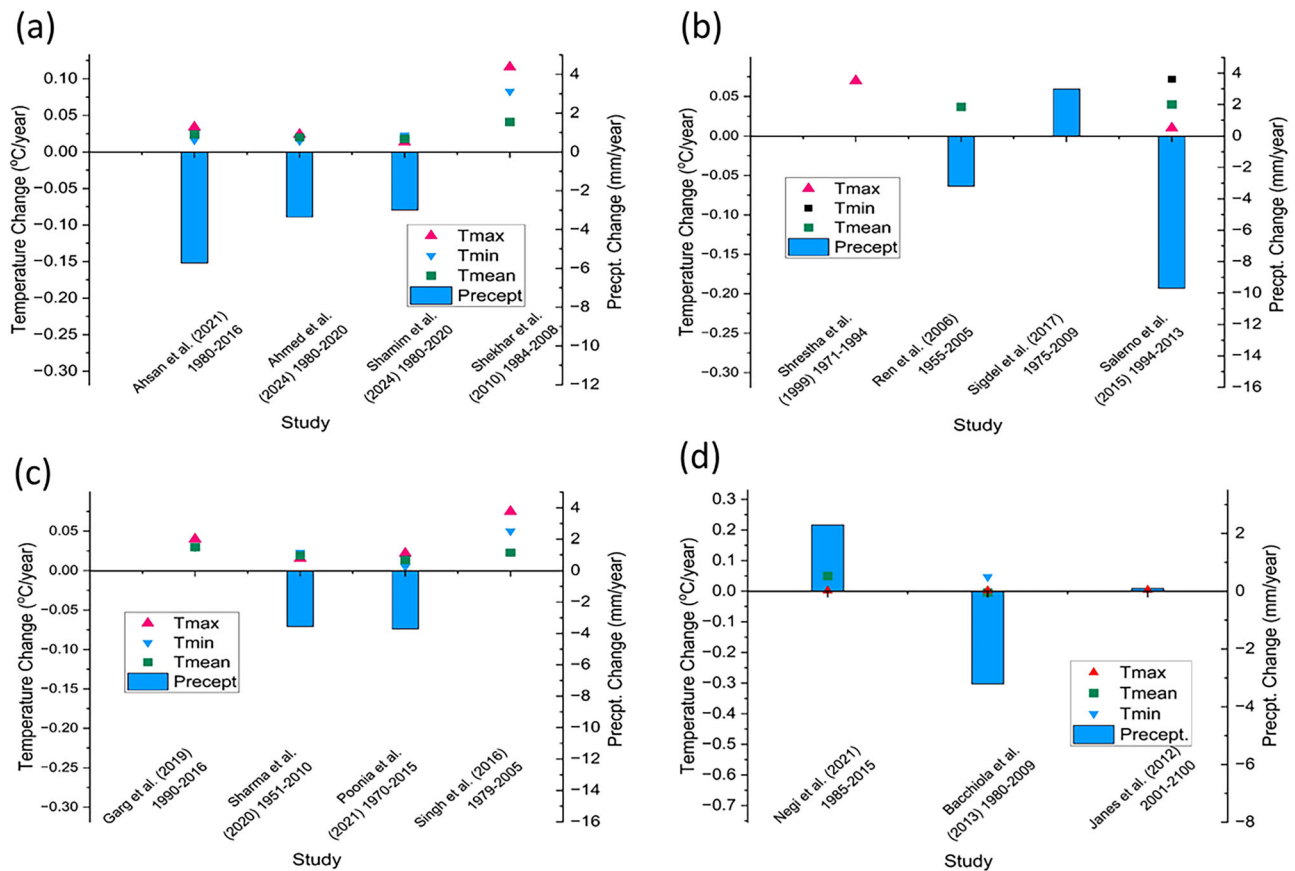


Fig. 2 | Per annum temperature and precipitation change rates across the Himalaya. Annual rates of temperature and precipitation change in **a** Western Himalaya, **b** Central Himalaya, **c** Eastern Himalaya and **d** Karakoram Himalaya, as reported in previous studies^{31,35,189–199}.

During this period, maximum glacier surface lowering occurred several kilometers up the glacier, especially on large valley floor glacier tongues, while minimum surface lowering was observed near the glacier terminus⁶³. Long-term mass balance records from well-studied glaciers across the H-K region reveal a general trend of glacier ice retreat, with notable regional variations (Fig. 3). Numerous studies highlight maximum glacier mass loss in the Western Himalayan region and more stable or less change in the Karakoram region^{63–67}. Both climatic factors (temperature, precipitation, albedo) and non-climatic factors (debris cover, elevation) influence glacier retreat. Black carbon has also been identified as a key factor accelerating glacier melt^{5,68}.

Glacial lakes in the H-K region: distribution and dynamics

Research on glacial lakes has gained significant attention over the past few decades, largely due to the hazards posed by GLOFs^{28,69}. The use of satellite imagery for monitoring the Himalayan cryosphere began in the 1990s with the advent of remotely sensed data, particularly from the Landsat series^{70,71}. Numerous inventories have since been developed to map and demarcate glacial lakes in the H-K region, with datasets prepared at regional, national, and global scales using remote sensing techniques. While glacial lake datasets now cover nearly all regions of the world, the challenging terrain and harsh climate of the Himalayas remain significant barriers to field-based glacier and glacial lake research. Consequently, most studies in this region rely heavily on remotely-sensed data, which often suffer from limitations such as coarse spatial and temporal resolution, introducing ambiguities in understanding ground-level processes. Furthermore, discrepancies in glacial lake definitions and varying size thresholds have resulted in significant inconsistencies among independently created datasets for the H-K region and the broader Third Pole region^{22–24,72}. Despite these challenges, remote sensing continues to be an indispensable tool for glacial lake research, offering valuable insights into this dynamic and critical aspect of the

Himalayan cryosphere. Some major glacial lake datasets are discussed below.

Review of previous glacial lake inventories

Several inventories have been developed for the H-K region and its associated mountain systems, each differing in scope, methodology, and mapping thresholds (Table S3). E.g., Maharjan et al.⁷³ compiled a comprehensive inventory of glacial lakes in the five major river basins of the Hindu Kush Himalaya using Landsat ETM+ imagery (2005–2007), identifying 25,614 lakes ($A \geq 0.003 \text{ km}^2$) with a total area of 1444 km^2 . Li and Sheng (2012)⁷⁴ mapped 11,056 and 11,289 lakes ($A \geq 0.0045 \text{ km}^2$) in the H-K region for 1990 and 2009, reporting a total area of 2890.38 km^2 . Fujita et al.⁷⁵ identified 2276 lakes (233.4 km^2) in 2010. Chen et al.²² mapped 8215 glacial lakes ($A \geq 0.008 \text{ km}^2$) in High Mountain Asia (HMA) for 2017 with a total area of 832.19 km^2 , while Wang et al.²³ documented 27,205 lakes (1806.5 km^2) in 1990 and 30,121 lakes (2080.1 km^2) in 2018 using a 0.005 km^2 threshold. Zhang et al.¹² identified 9208 lakes (779.01 km^2) in the H-K region for 2020 ($A \geq 0.003 \text{ km}^2$). Zheng et al.⁷⁶ produced the most extensive glacial lake inventory, mapping 63,727 lakes (2122.01 km^2) across the Third Pole using Landsat 8 OLI imagery ($A \geq 0.0009 \text{ km}^2$). Local inventories have also been prepared for specific administrative units^{77–80} and river catchments^{81–84}. Regional inventories offer higher accuracy and detail, making them more suitable for GLOF mitigation and regional planning.

Despite their value, existing Himalayan glacial lake inventories face several limitations that constrain their direct comparability and application in risk assessments. The lack of standardized mapping thresholds, inconsistent lake definitions (e.g., inclusion or exclusion of supraglacial and ice-contact lakes), and varying classification schemes introduce significant uncertainty when comparing inventories across regions or time periods. Furthermore, most inventories are static snapshots in time and do not adequately capture seasonal variability, rapid lake evolution, or short-lived

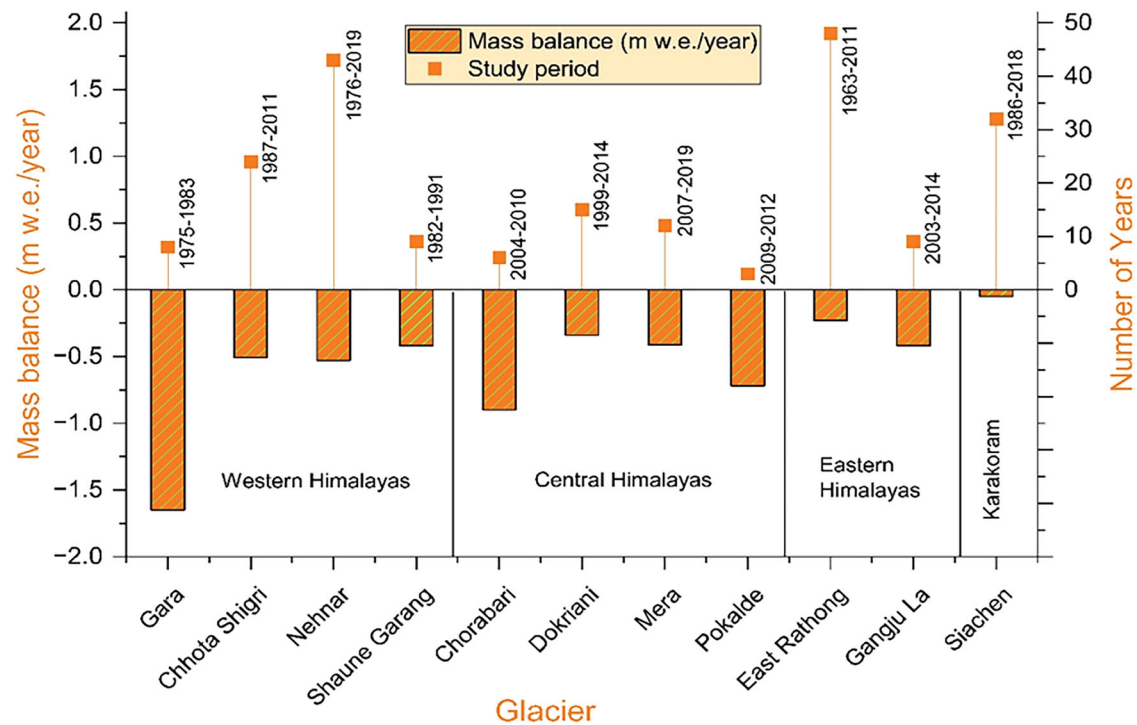


Fig. 3 | Specific mass balance of selected glaciers in different parts of the H-K region as estimated through long-term glaciological mass balance records derived from previous studies (except for the Siachen Glacier, whose mass change record is based on hydrological method)^{200–215}.

lakes that may still pose substantial GLOF hazards. Limited integration of lake characteristics critical for hazard assessment—such as dam composition, freeboard, lake volume, and upstream instability—also restricts their usefulness for quantitative risk analyses.

Spatial distribution of glacial lakes in the H-K region

Investigations based on previously published glacial lake inventories reveal pronounced regional patterns in glacial lake distribution across the H-K region (Fig. 4). We analyzed five inventories using GIS to derive the number and total area of glacial lakes reported in different sectors of our study area. While these inventories depict clear spatial patterns, they differ substantially in mapping years and minimum lake area thresholds and therefore are not meant for direct comparisons.

Earlier inventories consistently identified the Central Himalayas as hosting the highest number of glacial lakes and the largest cumulative lake area, followed by the Eastern and Western Himalayas. In contrast, the most recent inventory by Zheng et al.⁷⁶, updated to 2023 and employing a much smaller mapping threshold ($A > 900 \text{ m}^2$), indicates that the Eastern Himalayas now contain the highest number of glacial lakes and the largest total lake area, followed by the Central and Western regions (Fig. 4). The Karakoram region is reported to have the smallest number and area of glacial lakes among the sub-regions. This may reflect underestimation, as numerous small, newly formed moraine-dammed, ice-dammed, and supraglacial lakes in this region, because of the delayed response of this region to climate warming, are often excluded from inventories. With ongoing warming patterns, glacial lake numbers and area in this region are likely to increase significantly in the coming decades. This underscores the importance of regularly updating glacial lake inventories to capture the evolving nature of these dynamic systems.

Dynamics of glacial lakes

Numerous studies have examined the evolution and spatiotemporal dynamics of glacial lakes in the H-K region, utilizing diverse datasets, lake area thresholds, and mapping approaches, leading to variations in their findings^{29,74,85–88}. This study examines three widely used glacial lake inventories—Wang et al.²³, Chen et al.²², and Zhang et al.¹²—to assess

spatiotemporal changes in glacial lake number and area across the H-K region. All datasets were processed in a GIS environment and clipped to the study area to ensure consistent spatial coverage and facilitate robust comparisons. Despite methodological differences, these inventories generally report an increase in glacial lake numbers and area (Fig. 5, Table S4), which can be linked to a warming climate as reported by earlier studies.

Wang et al.²³, using a mapping threshold of $A > 0.005 \text{ km}^2$, documented an increase of 987 glacial lakes across the H-K region over 28 years, from 7077 lakes in 1990 to 8064 in 2018. This corresponds to an average annual increase of 0.67% in total glacial lake area, with the Karakoram showing the highest annual area change (1.31%), followed by the Central Himalayas (0.89%). In contrast, Chen et al.²², applying a higher mapping threshold of 0.008 km^2 , reported an increase of 1362 lakes in the same area over a much shorter period of 9 years, from 4136 lakes in 2008 to 5498 in 2017, accompanied by a 1.30% annual increase in total lake area. Within this dataset, the Central Himalayas exhibited the highest areal expansion annually (1.59%), followed by the Western Himalayas (1.41%). The third inventory by Zhang et al.¹², used a smaller mapping threshold of 0.003 km^2 and observed an increase of 999 lakes in 30 years, from 4297 in 1990 to 5296 in 2020, reflecting a 0.6% annual growth in total lake area. This dataset attributed the greatest area increase to the Central Himalayas (0.76%), followed by the Eastern Himalayas (0.66%), but uniquely reported a decline in the Karakoram region, with 52 fewer lakes and a 0.49% annual reduction in total lake area.

These contrasting rates and magnitudes of change highlight that glacial lake evolution varies across time periods and regions, and is also strongly influenced by differences in datasets, mapping thresholds, and methodological approaches. Our analysis shows that glacial lake behavior varies depending on the time period examined and the lake size classes considered. For instance, Zhang et al.¹² report a decline in the number of glacial lakes in the Karakoram, whereas other studies document an increase. This apparent contradiction largely stems from the higher mapping threshold adopted in that inventory, which suggests that actually the smaller lakes, which are excluded in that inventory, are increasing as suggested by other inventories, while the larger lakes are probably decreasing in number. Meaningful intercomparison, therefore, requires consistency in how glacial lakes are

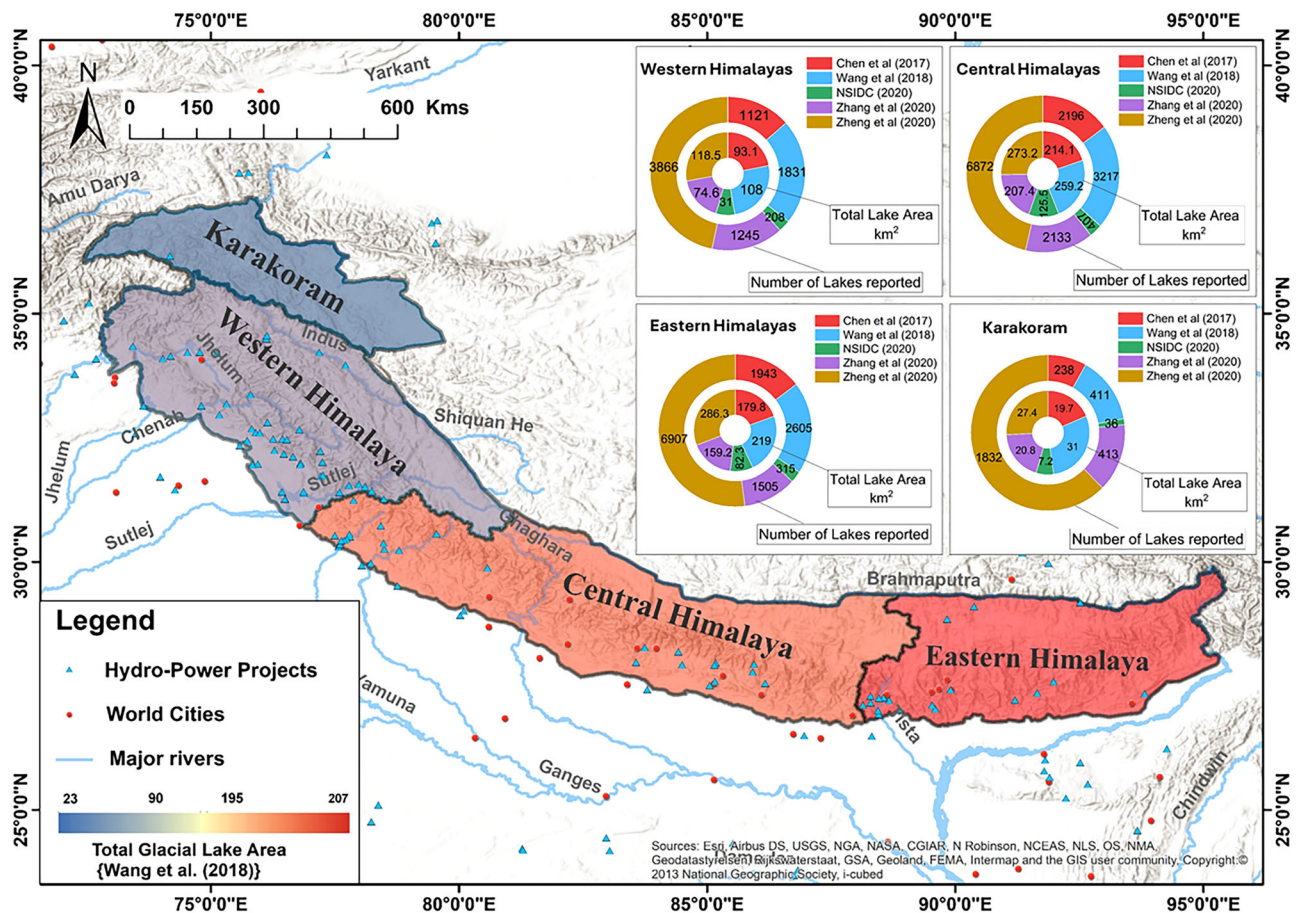


Fig. 4 | Spatial distribution of glacial lake number and total area across different sectors of the H-K region derived from different existing glacial lake inventories^{12,22,23,76,216}. Although all datasets were clipped to the H-K region, they differ in mapping year and minimum lake area thresholds and therefore are not

directly comparable. The year of mapping for each dataset is indicated in brackets in the legends of the embedded charts, while the corresponding mapping thresholds are provided in Supplementary Table S3.

defined, the minimum mapping area thresholds applied, and the temporal frameworks used. Despite such differences, most inventories indicate an overall increase in glacial lake numbers and areas across the H-K region, underscoring the strong influence of climate change on the regional cryosphere. However, establishing a more unified and standardized methodological framework would substantially improve the accuracy and comparability of glacial lake datasets, enabling more reliable assessments of glacial lake dynamics and associated hazards. Such a framework should explicitly incorporate observational and model uncertainty, and furnish values with confidence intervals. This can be achieved by developing standardized and transparent mapping protocols, harmonized minimum area thresholds, and consistent lake typologies across studies in the region. Furthermore, coupling inventories with field-based lake volume estimates, dam stability indicators, and process-based hazard information is essential to move beyond descriptive mapping toward inventories that directly support GLOF forecasting, early warning, and risk-informed adaptation planning in the Himalayan region.

Recent analytical studies^{1,21,89} provide strong quantitative evidence that atmospheric warming is the dominant driver of glacier retreat and subsequent glacial lake expansion in High Mountain Asia, including the Himalaya-Karakoram region. Geodetic mass-balance analyses show a marked acceleration of glacier mass loss since the early 2000s, closely correlated with rising air temperatures⁶. Global and regional trend analyses further demonstrate statistically significant increases in glacial lake number, area, and volume since 1990, with lake expansion strongly linked to enhanced glacier thinning and terminus retreat under warming

conditions^{10,11}. Process-based climate-glacier modeling confirms that temperature increases exert a far stronger control on glacier mass balance and lake formation than precipitation variability in the Himalayas^{9,90}. While trends in reported GLOF frequency are influenced by historical under-reporting⁹¹, quantitative assessments indicate that expanding lake volumes, unstable dam types, and increasing downstream exposure are collectively driving a rise in GLOF hazard and potential impacts²⁷. Together, these analytical findings substantiate the causal link between warming climate, glacial lake expansion, and escalating GLOF risk, while highlighting the need for future regionally consistent statistical analyses that explicitly integrate climatic drivers, lake evolution, and event occurrence.

Historical GLOF events in the region

The H-K region has witnessed numerous GLOF events in the past. These events have been documented by different previous studies^{24,92–94}. Lutzow et al.⁹⁵ report 516 historic GLOF events in the High Mountain Asia region, out of which 293 events could be traced back to the H-K region in our analysis. Of these 293 events whose exact locations could be identified, 8 were reported from the Western Himalayas, 49 from the Central Himalayas, 35 from the Eastern Himalayas, and 201 events from the Karakoram region. Nie et al.⁹² compiled an inventory of 62 previous GLOF events. Eleven of these GLOF incidents were classified as unpersuadable, and the other fifty-one as persuadable. Most of the convincing incidents were reported in the eastern (26) and central (25) Himalayas, within the borders of China (28), Nepal (8), Bhutan (13), and India (2). These occurrences varied in elevation from 3669 meters to 5527 meters with an average elevation of 4831 meters.

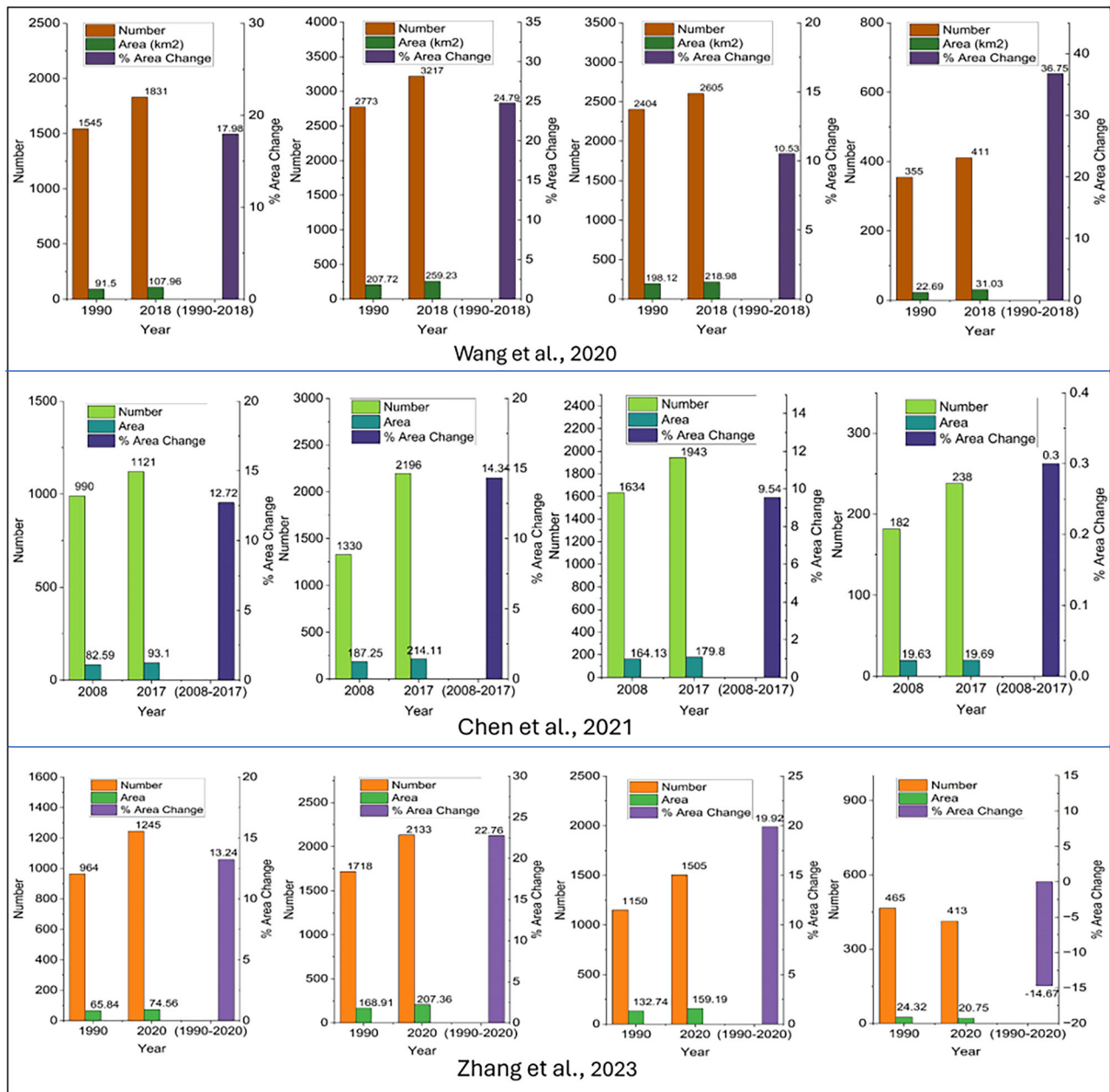


Fig. 5 | Sector-wise glacial lake changes in the H-K region (derived from three prominent glacial lake inventories mentioned in the figure^{12,22,23}). The graphs in each row (left to right) correspond to Western, Central, Eastern, and Karakoram Himalayas, respectively.

Out of all the previous GLOF inventories, the most comprehensive inventory for the H-K region is the one compiled by Shrestha et al.⁹⁴ at the ICIMOD. According to our analysis of this inventory, 388 GLOF events have previously occurred in the H-K region, from which 21 have been reported in the Western Himalayas, 99 from the Central Himalayas, 72 from the Eastern Himalayas, and 196 events from the Karakoram region. The highest number of GLOFs were reported from the moraine-dammed lakes (163) followed by the ice-dammed lakes (144) and the supraglacial lakes (50) (Figs. 1, 6). The elevations at which these events were witnessed range between 2562 and 5982. The period between 1900 and 2000 witnessed the largest number of GLOFs (135) in the H-K region followed by the period after 2000 in which 85 GLOF events have been already recorded till date. However, there may be some bias in these figures owing to inadequate reporting and documentation of events in earlier times³⁶. Amongst the Himalayan countries, Pakistan has witnessed the largest number of GLOF events (131) followed by China (123), India (59), and Nepal (54).

The majority of the GLOF events, the dates of which are known, have been reported during the months June, July, and August (Fig. 6). This can be attributed to the fact that these months witness the highest temperatures, leading to peak glacier melting, in addition to the arrival of the rain-laden monsoon winds in the region. Extreme temperature and precipitation events in these months act as major triggers of GLOFs in this region⁹⁷. There are several glaciers, especially in the Karakoram region, known for recurrent GLOF events. Some of these glaciers have witnessed dozens of GLOF events till now (Fig. 7). The fact that the largest number of GLOF events have been recorded in the Karakoram region despite having the lowest number of glacial lakes is explainable through these ice-dammed lakes that witness recurring GLOF events. E.g. Khurdopin glacier has already witnessed 37 events while Kyagar glacier has witnessed 34 events of GLOF. Other glaciers such as Shisper, Hasanabad, Gulkhin, Batura, etc., have also witnessed multiple GLOF events in the past. These recurrent events are mostly witnessed from ice-dammed and supraglacial lakes that develop on and around these large-sized glaciers. Ice-dammed lakes are capable of causing recurrent

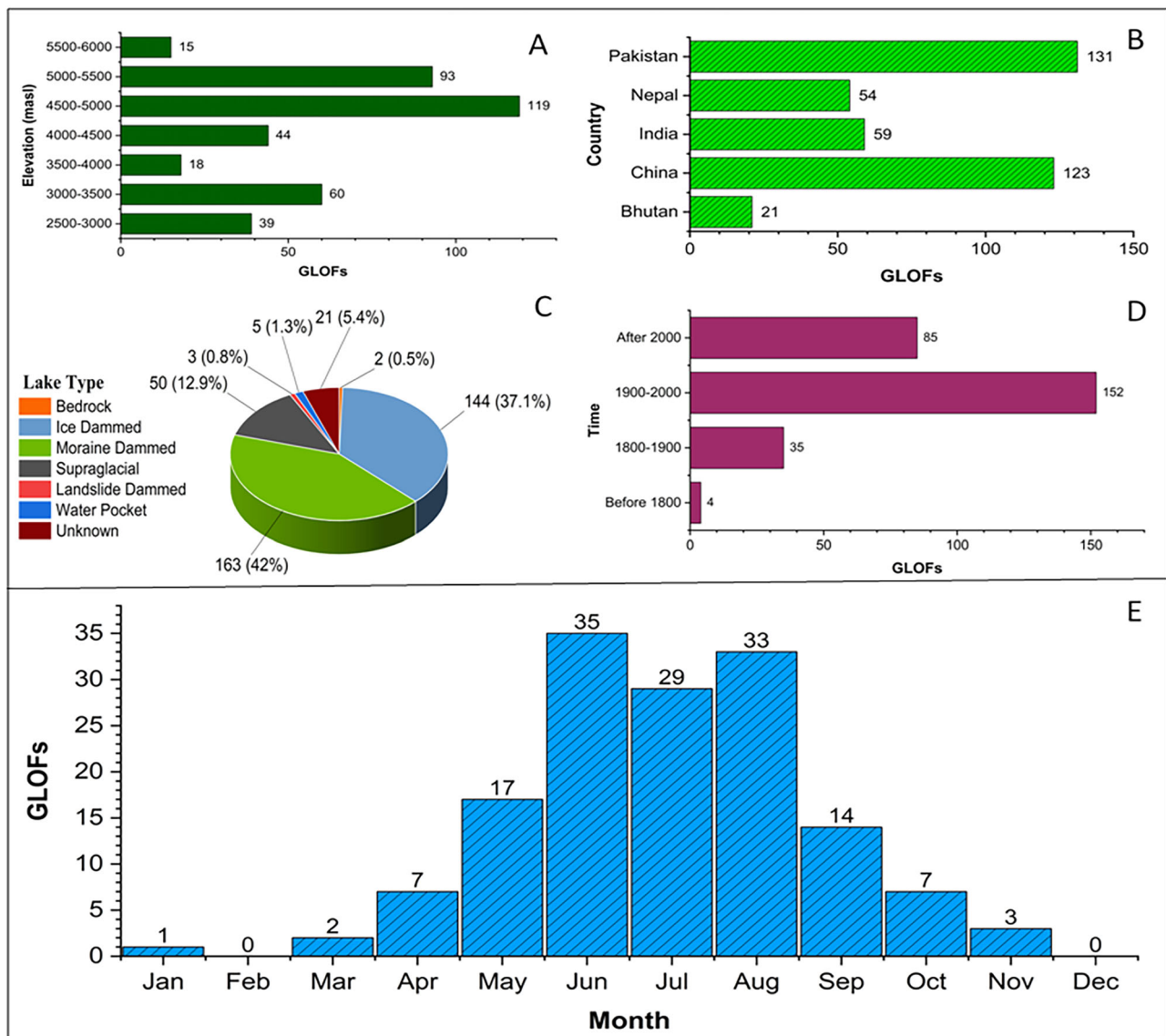
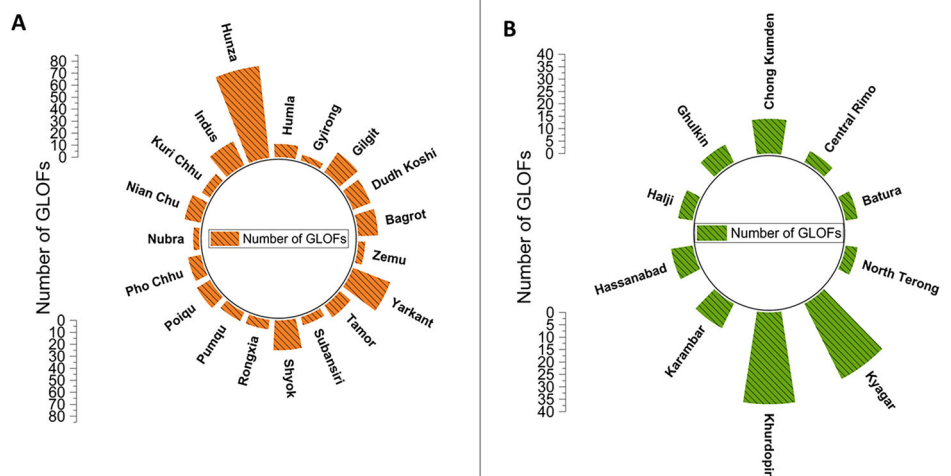


Fig. 6 | Distributional Characteristics of historical GLOF events in the H-K region. The figure depicts (A) Elevationwise distribution of historical GLOFs in the region (B) Country-wise distribution of historical GLOFs in the region (C)

Contribution of different lake types to past GLOFs in the region (D) GLOF frequency in different periods in the past (E) GLOF frequency in different months in the past. The figures have been prepared using the previous GLOF databases^{94,95}.

Fig. 7 | Glaciers and river basins that have witnessed multiple past GLOF events in the H-K region. A River basins that have witnessed 5 or more GLOF events B Glaciers that have witnessed multiple (5 or more) GLOF events. The data have been compiled from an existing GLOF database⁹⁴.



GLOFs as the dynamic glacier ice reforms the ice dams once the hydrostatic pressure has been released either through subglacial tunneling⁹⁸ or dam flotation⁹⁹.

Key triggers of GLOFs and failure mechanisms

GLOFs are intricate phenomena resulting from glacier recession and the accumulation of meltwater in depressions, often behind moraine or ice dams. However, the immediate outburst is often triggered by local and short-term factors, with the lake's intrinsic stability determining its susceptibility and the magnitude of the trigger required^{100–102}. Moraine and ice dams, being inherently less stable than bedrock dams, account for the majority of GLOFs in the H-K region. Ice cores within moraine dams, upon melting, create conduits for water flow, which can lead to piping failures. In ice-dammed lakes, subglacial tunneling dominates as the outburst mechanism, a phenomenon frequently observed in regions like Gilgit-Baltistan, where surging glaciers contribute to recurrent GLOFs. Lake geometry also plays a crucial role, with longitudinal or bullet-shaped lakes exerting greater hydrostatic pressure on dams, increasing the likelihood of failure¹⁰³.

Identifying precise GLOF triggers is challenging due to the loss of direct evidence, particularly in overtopping events involving bedrock-dammed or supraglacial lakes, where geomorphological markers or local accounts are often used as proxies^{96,104}. While 84% of triggers in past GLOF events remain unknown, extreme weather events, such as intense precipitation or extreme temperatures, and mass movements, including landslides or ice avalanches, are the most common known triggers, according to the dataset compiled by Shrestha et al.⁹⁴. Landslides can generate flood waves, causing dam outburst in moraine-dammed lakes or overtopping failure as seen in stable bedrock-dammed lakes^{105,106}. Although underreported, these events could intensify in the future as permafrost degradation increases mass movement activity in deglaciating valleys, as suggested by recent studies^{105,107–109}. Ice avalanches from glaciers, which have historically triggered numerous GLOFs^{28,110}, are expected to remain a significant hazard. Glaciers in direct contact with lakes not only recede faster¹² but also experience snout calving, increasing the likelihood of ice falls into lakes and subsequent GLOFs. Extreme temperature events exacerbate GLOF risk by inducing subglacial tunneling¹¹¹, ice core thawing¹¹², slope destabilization through permafrost melting¹⁰⁹, and increasing the hydrostatic pressure on dams by rapid meltwater accumulation¹¹³. While earthquakes are often considered potential triggers, their role in past GLOFs appears limited, despite their ability to cause mass movements in lake surroundings¹¹⁴, which may exacerbate the GLOF risk in the future.

Advancements and gaps in GLOF research

Glacial lake research in the H-K region has seen a boom primarily due to the rise of the Glacial Lake Outburst Flood disaster. The catastrophic GLOF events originating from glacial lakes, such as the Dig Tsho GLOF in Nepal or the Kedarnath GLOF in Uttarakhand, that killed more than 6000 people besides causing huge infrastructural damage in June 2013, caused the research community a serious concern regarding the climate-driven glacial lake expansion in the H-K region. Numerous studies have surfaced from then onwards that have attempted to understand this phenomenon of glacial lake expansion and the rising threat of the GLOF disaster. Such studies have been carried out in almost all parts of the H-K region on varying geographical scales. Here we will summarize some of the most prominent studies related to the GLOF hazard in the H-K region. These studies can be grouped under four major themes as follows:

Regional GLOF hazard assessments and risk mapping

Extensive research has focused on Potentially Dangerous Glacial Lakes (PDGLs) in the H-K region, either holistically^{13,30,75,115–117} or within sub-regions such as the Western^{118–120}, Central^{4,121–123}, and Eastern Himalayas^{124,125} as well as the Indian Himalayas^{26,126} and the Karakoram^{84,118}. Common assessment criteria include lake area, dam structure, slope gradients, and mass movement susceptibility. Many studies adopt

comprehensive risk assessments, integrating factors such as lake area with vulnerability and downstream exposure, both globally²⁷ and regionally^{12,15}. The encroachment of human settlements into fragile mountain zones further amplifies GLOF risk, establishing the Himalayas as a hotspot for GLOF hazards²⁷. Despite substantial progress, most of such assessments are based on static, snapshot indicators derived from medium-resolution optical imagery, inadequately representing dynamic processes such as rapid lake expansion, glacier–lake interactions, dam degradation, permafrost thaw, and transient triggers^{18,127}. Moreover, field validation is scarce due to extreme terrain^{12,15}. Socio-economic exposure and vulnerability are often simplified or outdated, and uncertainty is rarely quantified²⁷. Future improvements require standardized methodological frameworks, integration of multi-sensor remote sensing, and field-based assessments to analyze the hazard level of the lakes and the regional risk associated with them.

GLOF risk assessments for individual glacial lakes

Studies estimating the GLOF risk of specific glacial lakes are prevalent in the H-K region. These investigations utilize geospatial techniques and modeling approaches to assess the potential hazards posed by lakes deemed potentially dangerous. They often track lake evolution and surrounding conditions over time^{128–132} or simulate future GLOF scenarios using hydrodynamic models like HEC-RAS and MIKE 11^{121,133–138}. Others analyze past GLOF events to understand local risk dynamics^{139–143}.

These studies while needed for identifying local risk scenarios and informing mitigation strategies, such as EWSs for hazardous lakes, are often constrained by limited field data, including bathymetric data, dam composition, and downstream channel conditions¹⁴⁴. Hydrodynamic simulations frequently use assumed breach geometries and uniform roughness values, introducing substantial uncertainty in flood magnitude and timing estimates. Moreover, most studies focus on hazard characterization, with limited integration of downstream exposure, vulnerability, and cascading impacts. Focus should be on integration of multi-sensor remote sensing with bathymetric and geotechnical field measurements, uncertainty quantification in breach modeling, and closer coupling of hazard simulations with socio-economic risk assessments to support more robust and actionable GLOF risk management. While some research has addressed these socio-environmental dynamics^{145,146}, significant gaps remain in understanding the social aspects of GLOF risk in the Himalayas¹⁰⁴.

Historical GLOF Events and future trend predictions

Regional studies on the historical accounts of GLOF events^{24,79–81,95,147,148} and analyses of GLOF occurrence patterns^{14,21,78} also form a significant part of Himalayan GLOF research. The most comprehensive GLOF inventory to date, prepared by Shrestha et al.⁹⁴ for ICIMOD, identifies 388 GLOF events in the region. While studies show contrasting GLOF trends, with Veh et al.⁹¹ reporting no significant trend in the Himalayas and Zhang et al.¹² reporting an increase in the frequency of GLOFs globally, biases in historical reporting are evident. Research indicates that 2–4 out of 5 GLOFs in the early to mid-20th century likely went unnoticed or unreported^{96,149}. Nonetheless, these studies suggest an increase in GLOF frequency in the coming decades. Studies have also explored the future glacial lake development through modeling approaches^{150–152}. Furian et al.¹⁵² projected the formation of 2700 new glacial lakes ($A > 0.1 \text{ km}^2$) in the Third Pole region by the end of the 21st century, primarily in over-deepened glacial valleys likely to retain meltwater. Such forward-looking studies are crucial for anticipating and managing future GLOF risks effectively.

Studies on mitigation strategies for GLOF risk reduction

Numerous studies have examined GLOF mitigation and management strategies in various parts of the H-K region (Hanisch et al., Wang et al.)^{129,153–158}. These studies highlight that GLOF risks can be effectively managed or at least reduced to a large extent with the timely implementation of appropriate strategies, encompassing both structural and non-structural measures. Notable examples can be given from mitigation approaches adopted in Nepal on lakes such as Tsho Rolpa and Imja¹²⁸. Research also



Fig. 8 | Conceptual framework illustrating integrated GLOF risk management strategies in the Himalaya–Karakoram (H-K) region. The diagram highlights five complementary components: (1) *Early Warning Systems* based on satellite monitoring, automatic weather stations, and real-time surveillance for rapid alert dissemination; (2) *Structural measures* including spillways, controlled drainage, siphoning, and moraine-dam strengthening to reduce lake-outburst hazard; (3)

Non-structural measures and community preparedness emphasizing education, evacuation planning, simulation drills, and emergency response capacity; (4) *International collaboration* through data sharing, joint research, and regional cooperation for transboundary GLOF risk reduction; and (5) *Policy and planning integration* incorporating GLOF risk assessment, land-use zoning, and resilient infrastructure planning.

emphasizes the need for comprehensive strategies that coordinate actions across community sectors to mitigate GLOF impacts. Socio-economic vulnerability assessments of downstream populations, and identification of marginalized mountain communities are integral to GLOF risk mitigation^{159–161}. In the context of high population exposure to GLOFs in the region, non-structural and community-based measures, which are less technically and economically demanding, are pivotal. These approaches not only address social vulnerabilities but also offer sustainable and inclusive solutions for disaster mitigation in the developing Himalayan region.

GLOF risk management strategies in the H-K region

The H-K region faces a serious threat of GLOF in the upcoming decades which underpins the need to devise robust mitigation and management strategies^{145,149}. Glacial Lake Outburst Flood risk management strategies involve a combination of different elements of disaster management such as EWSs, structural measures, and community preparedness^{158,162}. An integrated framework of GLOF risk management strategies in the Himalaya–Karakoram region, encompassing EWSs, structural and non-structural measures, policy integration, and international collaboration, is illustrated in Fig. 8.

Early warning systems

EWSs play a pivotal role in detecting potential GLOF events and issuing timely alerts to vulnerable communities¹⁵⁸. Comprehensive EWSs leverage high-resolution satellite imagery for monitoring hazardous glacial lakes, along with automatic weather stations and hydrological devices to track extreme weather conditions and water level

fluctuations¹⁶³. The integration of robust communication networks ensures rapid dissemination of warnings to authorities and local residents. Examples of EWSs in the H-K region include manual systems, such as those implemented at Raphstreng Tsho and Luggye Tsho in Bhutan, and automatic systems like the ICIMOD-designed EWS at Imja Glacial Lake in Nepal's Dudh-Koshi basin¹⁶⁴. Despite notable progress in Nepal, other nations, including Pakistan, Afghanistan, and India, require significant advancements to establish effective EWSs, highlighting a critical gap in regional preparedness. Mobile phones have proven effective in saving lives during several GLOF events and represent one of the most practical and affordable tools for disseminating early warnings in vulnerable communities, at least during daytime¹⁶⁵. This potential can be realized by strengthening and expanding mobile network coverage in high-mountain settlements at risk.

Structural measures

Structural measures aim to reduce GLOF risks by enhancing the stability and managing the water levels of glacial lakes¹⁶⁶. These measures often include constructing spillways, engineered channels designed to release water in a controlled manner to prevent overflow¹⁶⁷. For instance, artificial spillways and drainage systems have been implemented in Bhutan to mitigate GLOF risks, notably at Thorthormi Tsho, where a spillway lowered the lake level by 5 m, releasing ~14 million m³ of water over 4 years¹³. Controlled breaching of moraine dams is another effective method for reducing lake levels safely¹²⁸. Siphoning has also been widely used, as demonstrated at Lake Palcacocha in the Peruvian Andes and Tsho Rolpa Lake in Nepal, to lower water levels to reduce the immediate risk^{129,155}. Dam

reinforcement, which involves strengthening natural moraine dams using engineering techniques, is another key structural intervention. For example, reinforcing the outlet channel and dam of Jialong Co in the central Himalayas significantly reduced the likelihood of outbursts caused by ice avalanches or landslides¹⁶⁶. However, the vulnerability of glacial lakes is dynamic, influenced by changes in their surroundings over time^{168,169}. Thus, structural measures must be tailored to specific lake conditions at specific times. While these measures do not fully eliminate the risk of GLOFs, they can reduce the severity of potential disasters or delay them to buy time for comprehensive risk management programs¹⁷⁰. However, a major limitation of structural interventions in the H-K region lies in their high financial and technical requirements, which are often beyond the capacities of developing countries and especially the local communities directly threatened by such floods. These constraints frequently undermine the effectiveness of such measures, as demonstrated by cases in Nepal where inadequate funding impeded glacial lake level-lowering projects, thereby reducing their overall effectiveness¹⁷¹.

Non-structural measures and community preparedness

In addition to hazard mitigation, vulnerability mitigation forms a critical pillar of risk management in the H-K region^{159,172,173}. Strengthening the capacity of local communities to respond effectively to disasters through education and training is particularly vital in developing nations like India, Pakistan, Nepal, and Bhutan (Heath et al.)¹⁷⁴. Structural measures often face financial and technical challenges in these regions, but community-based non-structural approaches offer a feasible pathway to enhance resilience against cryospheric disasters such as GLOFs^{175–177}. Community-based approaches emphasize capacity building by educating vulnerable communities about GLOF risks, warning signs, and safety measures. For example, Bhutan's Department of Disaster Management has developed integrated disaster management plans, enabling communities to identify hazards and vulnerabilities effectively¹⁷⁸. In Nepal a 1-year Local Adaptation Plan of Action facilitated by HiMAP (High Mountains Adaptation Partnership) in the Khumbu region to support community-led climate adaptation is another example. Key components of community approach include well-formulated evacuation plans, regular simulation drills, and the provision of emergency supplies, first aid kits, and communication tools during GLOF events. In Nepal and Bhutan, local communities have actively participated in evacuation planning and drills as part of the Community-Based Flood and Glacial Lake Outburst Risk Reduction Project, significantly improving disaster preparedness¹⁷⁹.

However, cognitive biases and heuristics can undermine community preparedness efforts. For instance, at Tsho Rolpa Lake, repeated evacuations without subsequent events led to diminished trust in mitigation measures and monitoring institutions¹⁷³. This highlights a key limitation of community-centric programs, where unmet expectations can erode confidence and cooperation. Sustained engagement, transparent communication, and continuous capacity-building efforts are essential to ensuring long-term community participation in risk reduction initiatives.

Policy and planning integration

There is a need to incorporate GLOF risk assessments into regional and national development plans to ensure resilient infrastructure and land use¹⁸⁰. Comprehensive risk assessment studies are important to identify vulnerable areas and assess potential GLOF impacts in the future. However, risk assessment should be augmented with proper land use planning with zoning regulations to avoid construction in high-risk zones¹⁸¹. Environmental management in ecologically fragile mountain ecosystems should be given more attention to developing sustainable practices to reduce contributing factors such as deforestation and improper land use patterns in high-risk zones¹⁸². To encourage the building of robust infrastructure in glacial zones, the National Disaster Management Authority of India has included GLOF risk assessments in its national disaster management framework. More such efforts need to be incorporated into national and state disaster management plans.

International collaborations

Cross-border cooperation and knowledge-sharing among the countries of the H-K region that exhibit almost similar glacial environments are critical in enhancing the GLOF risk management practices^{183–185}. This includes the sharing and exchange of hydro-meteorological data among countries and collaborative research projects to study the glacial lake dynamics in the region^{186,187}. Capacity-building projects and workshops among the Himalayan countries, such as the HiMAP project in Nepal, which emphasized the need for interdisciplinary collaboration in building climate adaptation and resilience¹⁸⁸, can also prove beneficial in developing a region-wide disaster resilience framework. Such initiatives should be well-funded by National and International organizations dealing with the cryospheric hazards and the development of the mountainous areas. A pertinent example of such collaboration is through the ICIMOD, where member countries share data and expertise to develop regional GLOF risk reduction strategies.

Conclusion

This study provides a comprehensive review of past glacial lake research in the H-K region, with a specific focus on the GLOF hazard. By examining previous studies and analyzing various datasets, the research highlights trends in glacial lake dynamics under changing climatic conditions. We assessed trends in glacial lake dynamics across different Himalayan zones using datasets compiled previously by researchers. Our findings highlight a steady increase in both the number and size of glacial lakes across the region, driven by warming temperatures. Coupled with expanding human populations in fragile mountainous areas, this trend makes the Himalayas a hotspot for heightened GLOF risk. The region has experienced 388 GLOF events, primarily from moraine and ice-dammed lakes. The Central and Eastern Himalayas contain the largest number of glacial lakes, but the highest GLOF risk is found in the Eastern Himalayas, where large, potentially dangerous lakes exist. Climatic trends suggest a general rise in GLOF hazards, with high-risk zones extending from the Eastern to the Western Himalayas, including the Karakoram, which has exhibited a delayed response to climate change compared to other areas.

While research in the region has focused on identifying PDGLs, assessing GLOF risks, reconstructing past events, projecting future lake growth, and studying trends in GLOF frequency, social aspects of GLOF risk have been less explored. Flood risk management solutions should include EWSs using hydrological monitoring and remote sensing, structural measures like spillways and dam reinforcement, and community preparedness through building evacuation plans and robust public communication networks. Effective GLOF mitigation also requires integrating risk assessments into national planning and fostering international cooperation. This review highlights key gaps in glacial lake research in the Himalayas, contributing to a better understanding of the GLOF hazard and its mitigation in the region.

Data availability

No datasets were generated or analyzed during the current study.

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Author contributions

Every author has contributed to the successful compilation of this study. AFR, RA, TS: Conceptualization, Methodology, Software, Writing – original draft, Formal analysis. AF and SH: Formal analysis, Writing – review & editing. OW, PA, RAM: Writing – review, editing, Supervision. All authors read and approved the final manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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