BAMS Article

A Monitoring Network for Mitigating Himalayan Glacial Lake Outburst Floods

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ABSTRACT: Glacial lake monitoring is urgently needed across the Himalaya due to the threat of glacial lake outburst floods (GLOFs). Furthermore, both the population and the infrastructure exposed to or dependent on these glacial lakes are increasing. However, there are a substantial number of glacial lakes in the Himalaya with potential transboundary GLOF impacts, and their remote, high-altitude locations make monitoring extremely challenging, so existing field measurements are limited. Here, we propose a benchmark Himalayan glacial lake monitoring network "HiGLMN" that will characterize glacial lakes by combining geomorphological signatures of GLOFs, monitoring triggers and mechanisms of dam failure, and downstream impacts using in situ observations, remote sensing, and hydrodynamic modeling, and feed into early warning for disaster mitigation. We also provide existing practices to support the effectiveness and necessity and propose strategies for future data management. The monitoring network will contribute to robust GLOF risk management, early warning, and mitigation.

SIGNIFICANCE STATEMENT: The proposed glacial lake monitoring network aims to mitigate the escalating threat of glacial lake outburst floods in the Himalaya, where growing populations and infrastructure are at risk. The network will use a combination of in situ observations, remote sensing, and hydrodynamic modeling to better understand and predict outburst floods. The resulting data will support early warning systems and strengthen disaster risk management strategies. We also propose effective data management approaches to ensure the long-term success of the network in mitigating the damage caused by glacial lake outburst floods.

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1. Introduction

Glacial lakes form as glaciers retreat and proglacial or ice-marginal basins are filled by meltwater (proglacial, ice-marginal lakes), or when water is blocked by advancing glaciers (ice-dammed lakes). These lakes can be the source of destructive glacial lake outburst floods (GLOFs) (Carrivick and Tweed 2013, 2016; Tweed and Carrivick 2015; Westoby et al. 2014; Zhang et al. 2024). The Himalaya [briefly the Hindu Kush, Karakoram, Himalayan subregions (western, central, and eastern), Nyainqêntanglha, and Hengduan mountains] contains the largest volume of mountain glacier ice on Earth (~4000 km^3) outside the polar regions (Farinotti et al. 2019). As Himalayan glaciers retreat and thin (Hugonnet et al. 2021; King et al. 2019; Yao et al. 2022) at an increasing rate in recent decades compared to since the Little Ice Age (Lee et al. 2021), the resultant meltwater feeds ~9000 glacial lakes (larger than 0.0036 km^2) (Zhang et al. 2023) (Fig. 1).

In addition to the increase in area and water volume of existing lakes, new lakes have emerged (Chen et al. 2021; Wang et al. 2020; Zhang et al. 2015, 2023). Some of these glacial lakes are dammed by poorly consolidated moraines of past glaciers (Zheng et al. 2021b), and the whole mountain environment is becoming more dynamic as frozen parts thaw out, changes in precipitation regimes and extreme events increase, and water is much more available to move sediment and cause instability (Carrivick and Tweed 2021; Dubey et al. 2023; Tweed and Carrivick 2015). More than 200 GLOF events dominated by those from ice- and moraine-dammed lakes have so far been recorded in the Himalaya (Lützow et al. 2023; Shrestha et al. 2023). Indeed, the Himalayan region is a prominent hotspot of GLOF hazard and risk (Carrivick and Tweed 2016; Emmer et al. 2022; Nie et al. 2023; Taylor et al. 2023; Zhang et al. 2024). Historical events and future projections indicate that GLOFs are frequent in the Himalaya, and damage from them has been reported to be substantial, causing geopolitical as well as economic problems, especially for those in transboundary river basins (Dubey et al. 2024; Zhang et al. 2024; Zheng et al. 2021b).

The high population density downstream of the glacial lakes, together with critical transport infrastructure such as the Karakoram Highway and numerous hydropower reservoirs,

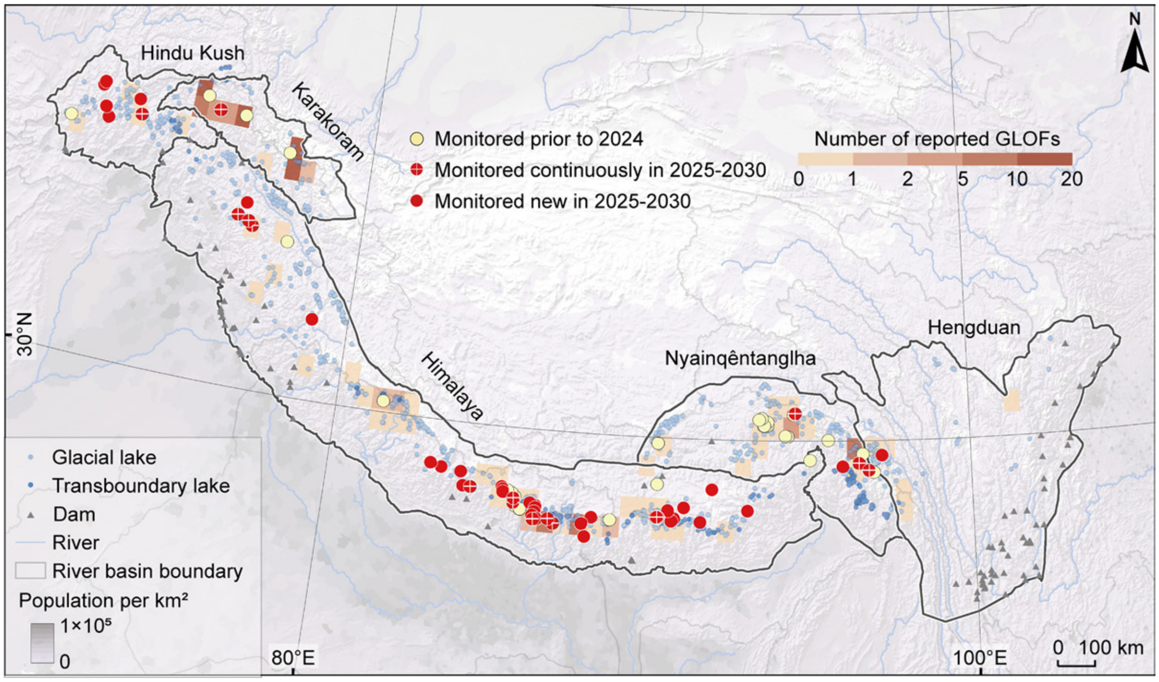

Fig. 1. Need for the establishment of a glacial lake monitoring network and historical and future monitored glacial lakes. The distribution of glacial lakes, historically reported GLOFs, transboundary lakes, dams, and population across the Himalaya supports the need and urgency for establishing a glacial lake monitoring network. Glacial lakes monitored before 2024 were compiled from literature and reports, and glacial lakes planned for monitoring in 2025–30 include some lakes with historical monitoring and some newly selected lakes with high hazard potential (Furian et al. 2021; Zheng et al. 2021b). Data sources include known glacial lakes (Zhang et al. 2023), recorded GLOFs (Lützow et al. 2023), transboundary lakes (Dubey et al. 2024), dams and reservoirs (J. Wang et al. 2022), and population data (Center for International Earth Science Information Network-CIESIN-Columbia University 2018).

makes the region particularly vulnerable to GLOFs, which can cause potentially severe damage (Li et al. 2022) (Fig. 1). Some of these past GLOFs have had catastrophic consequences for communities, including livestock and human casualties, and for infrastructure such as hydropower projects, bridges, and roads (Nie et al. 2023). For example, in 1985, a GLOF in the Khumbu region of eastern Nepal destroyed a hydropower plant, 14 bridges, ~30 houses, and a trail network (Vuichard and Zimmermann 1986, 1987). Two GLOFs, one in 2013 and the other in 2020, in the Nyainqêntanglha range of the Tibetan Plateau destroyed downstream infrastructure (roads, electrical facilities, bridges, buildings) and vegetation (trees), and eroded river banks along a flood path of more than 40 km (Peng et al. 2023). In 2013, a glacial lake outburst and debris flow cascade in the Indian Himalayan state of Uttarakhand killed more than 6000 people and damaged roads, bridges, and hydroelectric dams (Allen et al. 2016; Bhambri et al. 2016; Sati and Gahalaut 2013). A GLOF from South Lonak Lake in Sikkim, India in 2023 resulted in 55 deaths, 74 missing persons, and extensive infrastructure damage (Sattar et al. 2025), while another GLOF in 2024 devastated the village of Thame in the Everest region of Nepal (Press Trust of India 2024). The repeated failure of ice-dammed lakes has produced an even greater number of GLOF events than the moraine-dammed lakes that dominate the Karakoram region (Compagno et al. 2022; Veh et al. 2023), but damage is generally more limited due to their recurrent nature. Nevertheless, ice-dammed lakes in the region have repeatedly caused damage to infrastructure and less frequently to human life in the recent past (Nie et al. 2023; Rashid et al. 2020; Round et al. 2017).

For the case of proglacial lakes, GLOFs in the Himalaya are mainly triggered by heavy rainfall (Allen et al. 2016), snow avalanches (Poudel et al. 2025), ice avalanches (Wang et al. 2024), and landslides (Peng et al. 2023) from surrounding potentially unstable slopes. Ice avalanches have been shown to be the most common trigger of GLOFs for moraine-dammed lakes in the Himalaya such as at Ranzeria Co in 2013 (Peng et al. 2023). Lateral moraine failure has been shown to be the trigger for a GLOF at Jiwen Co in 2020 (Peng et al. 2023; Zheng et al. 2021a) and at South Lhonak Lake in 2023 in Sikkim, India (Sattar et al. 2025). Dam failure (e.g., breach, piping, seepage) and overtopping (including subsequent dam failure) are other important GLOF mechanisms for moraine-dammed lakes in the region (Lützow et al. 2023). The elucidation of causes and mechanisms and the reconstruction of historical GLOFs in the Himalaya (Emmer et al. 2022; Nie et al. 2018; Peng et al. 2023; Rinzin et al. 2023) provide insights into GLOFs and glacial lake evolution that should be addressed.

The risk of GLOFs in the Himalaya is expected to increase in the future due to the formation of new glacial lakes at higher elevations with greater energy potential, as well as the expansion of downstream infrastructure and population into the GLOF-prone area (Allen et al. 2022; Linsbauer et al. 2016; Medeu et al. 2022). As a result, the Karakoram and western Himalaya—where new glacial lakes are forming—are expected to become an additional GLOF hotspot, in addition to the existing eastern and central Himalayan hotspots (Dubey et al. 2023; Furian et al. 2021; Zheng et al. 2021b). Despite growing recognition of GLOF risks in the Himalaya, a comprehensive monitoring network has yet to be established. Existing observations remain fragmented, often focused on single events or specific regions. There is currently no unified framework, nor is there a centralized, harmonized database to support consistent monitoring. Observation standards vary widely, and data are frequently discontinuous, impeding systematic, multiscaled hazard and risk assessment. Moreover, there is a lack of strategic planning for sustained, long-term observations, and international cooperation remains limited, particularly in transboundary basins where collaboration is essential for effective disaster prevention. While initiatives like Glacier and Permafrost Hazards in Mountains (GAPHAZ) provide valuable technical guidance (GAPHAZ 2017), they fall short of delivering an operational, regionwide monitoring strategy. Here, we propose a benchmark Himalayan glacial lake monitoring network "HiGLMN" that addresses these critical gaps through the establishment of an integrated, parameter-harmonized framework designed to enable consistent, scalable, and collaborative monitoring across the Himalaya.

2. Strategy of glacial lake monitoring network

Our study proposes a strategy to establish a HiGLMN, with two key objectives:

1) Establishing a comprehensive database of field observations of glacial lakes: We propose to establish a glacial lake database that collects comprehensive field observations, including the characteristics of glacial lakes, the potential triggers and outburst mechanisms, and an assessment of downstream impacts. This monitoring network covers a wide spatial distribution of glacial lakes and types (proglacial lakes, ice-dammed lakes), which is important because of the different driving processes for their outbursts. For moraine-dammed lakes, the interannual change in lake level (predrainage) is not an indicator of hazard potential, as the lake level is relatively stable even though the lake volume increases due to terminal retreat (Wang et al. 2025; Zhang et al. 2023). However, ice-dammed lakes typically initiate a GLOF when a critical lake level is reached, and the ice tongue begins to float. Therefore, different variables need to be considered when setting up an early warning system (EWS). Further observations of the physical parameters of glacial lakes and the subaqueous topography are also the basis for quantitative estimates of their impact during outburst when using numerical modeling.
2) Mitigating GLOF risk in the Himalaya: Only a small number (about 10 lakes) of Himalayan glacial lakes with historically recorded GLOFs have been investigated in the

field over an extended period. More glacial lake surveys, monitoring, and GLOF hazard assessments can help to understand the patterns, causes, and mechanisms of GLOF occurrence. A comprehensive understanding of downstream settlement conditions, including structural and nonstructural vulnerabilities, is also needed. Indicators for the identification of potentially hazardous glacial lakes and hazard classification can be optimized based on the insights gained from the reconstruction of historical GLOF events and field assessment. An EWS can be established for lakes with a very high hazard level or in the catchment area of several hazardous glacial lakes. Our monitoring network HiGLMN can be used directly for planning potential engineering measures to reduce the risk of GLOFs (Emmer 2024), for land-use zoning in urban planning, and to support risk management in transboundary contexts, where timely communication and mutual understanding of the challenges are crucial.

3. Design of glacial lake monitoring network

a. Framework of monitoring network. The proposed glacial lake monitoring network integrates remote sensing, in situ observations, numerical modeling, and impact assessment (Fig. 2). It is designed to be multiscaled and parameter harmonized, enabling consistent and systematic hazard and risk evaluation across multiple valleys.

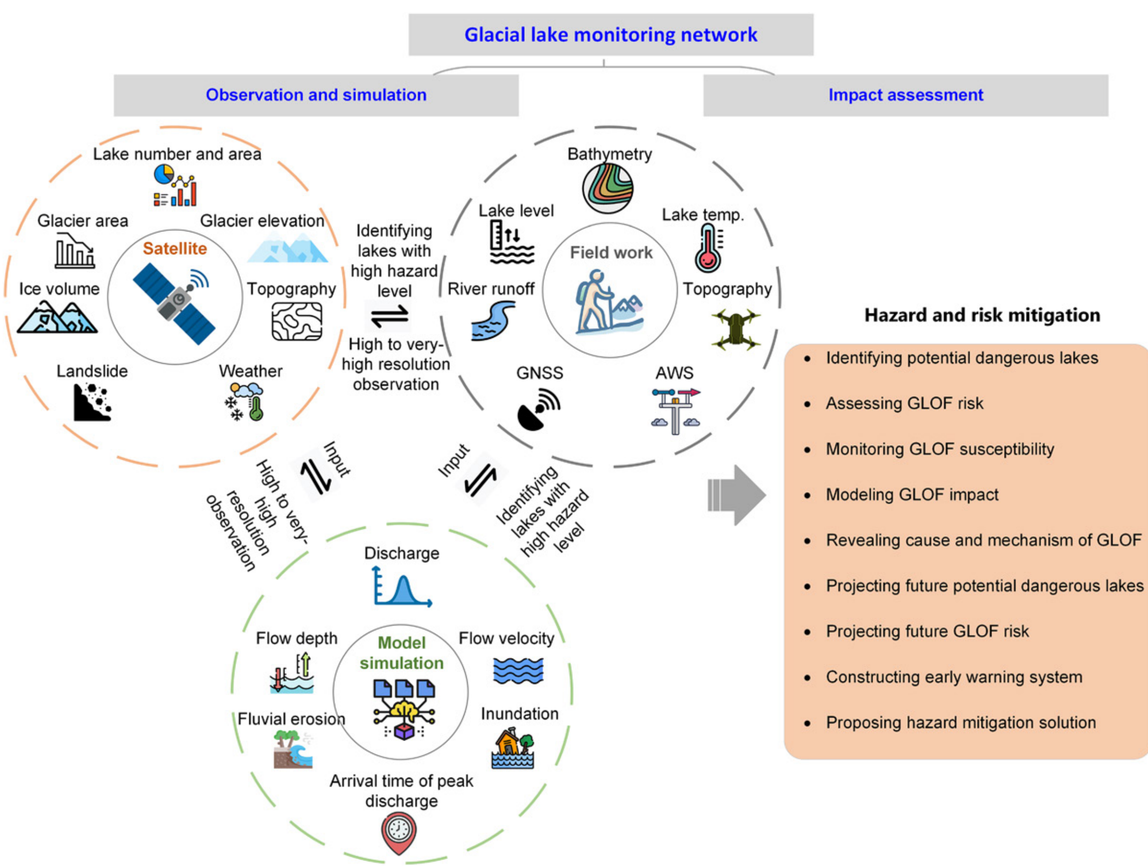

Fig. 2. Framework for establishing a glacial lake monitoring network. Satellite observations, field surveys, and hydrodynamic simulations are the key components of the network. First, medium- to high-resolution remote sensing and modeling are used to identify high-hazard lakes and provide information to guide the selection of sites for field surveys. Field work and modeling provide the feedback to identify those lakes that require high- to very-high-resolution remote sensing observations. Multisensor remote sensing observations and field surveys are the key inputs for hydrodynamic modeling. Hazard mitigation, including identification of potential GLOF risk and solutions to reduce risk and damage, is an output of this monitoring network.

Remote sensing enables the monitoring of nearly all glacial lakes at regional scales and of selected high-priority lakes at the catchment scale. Medium- to high-resolution remote sensing data (around 10–30 m, e.g., Sentinel-2, Landsat-8/Landsat-9), combined with numerical modeling, support the preliminary identification of lakes exhibiting high or emerging hazard potential, guiding the prioritization and selection of monitoring sites. For targeted lakes, high- to very-high-resolution imagery (around 0.3–5 m, e.g., PlanetScope, WorldView, Pléiades), together with modeling and field surveys, allows for detailed hazard assessments. Interferometric synthetic aperture radar (InSAR) and feature-tracking techniques provide high-temporal resolution monitoring of slope movement and moraine dam deformation (Van Wyk de Vries et al. 2024; Wangchuk et al. 2022).

Fieldwork remains the foundation of the monitoring network, supplying critical in situ measurements, including lake bathymetry, water level and temperature, dam geometry, basin topography, glacier mass balance and retreat rate, frontal calving, and downstream discharge. These parameters are essential for both site-specific analyses and for standardized hazard and risk assessments across valleys. The network emphasizes the harmonization of key parameters—such as lake volume, dam height and type, glacier-lake connectivity, and downstream exposure—to facilitate intercomparable risk evaluations and minimize observational redundancy. Identifying both essential and redundant parameters strengthens the network's robustness, interoperability, and scalability.

Hydrodynamic (or even morphodynamic) modeling relies on both field observations and remote sensing to provide quantitative assessments of river flows and floods (and geomorphological changes) in general, and, in particular, fluvial inundation, flow depth, and velocity in space and time (and bed shear stress and sediment transport) (Carrivick 2009; Carrivick et al. 2011, 2010; Sattar et al. 2021; Vázquez-Tarrío et al. 2024; Wang et al. 2024; Westoby et al. 2023). This hydrodynamic information can be integrated with inventories of downstream exposure and vulnerability data to better understand how the interaction between human activities, experiences, behaviors, and risk perception—with hazard mapping—shapes the extent and nature of damage caused by GLOFs (Watson et al. 2015).

Together, these interdisciplinary and harmonized approaches establish a structured, data-driven, and interoperable monitoring network. This network supports both localized EWSs and broader regional GLOF risk management strategies.

b. Site selection. The criteria for site selection include glacial lakes with documented historical GLOF events and those identified as posing a high risk. The glacial lakes selected for the proposed monitoring network HiGLMN include lakes with historical monitoring prior to 2024 and lakes planned for monitoring in 2025–30 (Fig. 1). Across the Himalaya, approximately 50 glacial lakes are known to have been monitored prior to 2024: for Tibet, China (32 lakes), Nepal (5 lakes), Bhutan (4 lakes), and the Indian Himalaya (4 lakes), as well as for the Karakoram and Hindu Kush [both Pakistan (4 lakes) and Afghanistan (1 lake)] (Table S1 in the online supplemental material). With the support of the Second Tibetan Plateau Scientific Expedition and Research (STEP 2017) launched in China, about 20 glacial lakes have been intensively surveyed during 2017–24, which is a significant progress compared to previous very limited lake monitoring, such as Longbasaba Lake (Liu et al. 2020b; Wang et al. 2018; Yao et al. 2012) and Chongbaxia Tsho (Nie et al. 2020). In Bhutan, several glacial lakes have been monitored since the Lugge Tsho GLOF event in 1994, and several subsequent smaller events have followed [National Center for Hydrology and Meteorology (NCHM) 2019; Watanbe and Rothacher 1996]. In Nepal, the bathymetries of several glacial lakes such as Imja Tsho, Tsho Rolpa, Thulagi Lake, and Lower Barun Tsho have been repeatedly surveyed (Haritashya et al. 2018; Shrestha et al. 2024). Similarly, the bathymetry of Lumding Tsho has been carried out at least once (Rounce et al. 2016). The bathymetry of proglacial lakes is important for estimating potential outburst volume. We are aware of more than 60 observations that now have bathymetric measurements (Zhang et al. 2023).

Approximately 33 additional glacial lakes are expected to be monitored over the next 6 years (2025–30), in addition to some lakes that will be monitored continuously (Fig. 1), supported by the continuation of the STEP and international cooperation, mostly located in the western and central Himalaya (Qi et al. 2022; Zhang et al. 2023). Among the glacial lakes planned for monitoring in the near future, special attention will be given to those identified as having high-hazard potential in previous studies (Allen et al. 2019; Furian et al. 2021; Khadka et al. 2019; Rinzin et al. 2023; Zheng et al. 2021b). Most of the selected lakes are proglacial lakes dammed by moraines.

c. Remote sensing observation. Satellite observations are an important complement to field surveys, especially for large-scale and high-frequency visits, and are the "telescope" of HiGLMN. Satellite data provide large-scale climate information that can be used to analyze extreme weather events. Glacier surges associated with glacier melt and hazards can be identified from glacier velocity products based on multiple optical, radar, and laser satellite sensors (Friedl et al. 2021; Gardner et al. 2022; Guillet et al. 2022). Permafrost data (Haeberli et al. 2017; Obu 2021) and topographic potential for ice avalanches and landslides (Allen et al. 2019; Majeed et al. 2021) can be used as proxies for the location of mass movements entering lakes. The number and area of glacial lakes and their changes are typically mapped from optical and synthetic aperture radar (SAR) imagery (Wang et al. 2020; Wangchuk and Bolch 2020; Zhang et al. 2015). InSAR from radar satellite remote sensing and other SAR-based techniques such as persistent scatterer interferometry (PSI) techniques can help to detect, monitor, and predict the potential landslide area, although they are difficult to apply in the complex topography of the Himalaya (Casagli et al. 2023; Wangchuk et al. 2022). Feature tracking techniques for surface deformation of surrounding slopes using optimal imagery, such as Sentinel-2, can be effective when cloud-free imagery is available (Van Wyk de Vries et al. 2024). The emergence of commercial providers, both optical and radar (e.g., Planet, IceEye, Capella), as well as some national providers (China: Gaofen, India: INSAT), has allowed much better coverage, making it possible to establish monitoring with almost daily repeat passes and up to ~1-m resolution (Kumar et al. 2020; Zhang et al. 2018). High-resolution satellite imagery such as Pléiades (0.5-m pixel size) can be used to map topographic features such as dam geometry and slope angles, as well as the geological structure of the lake basin slope (Allen et al. 2022). The OpenStreetMap and Open Buildings datasets, together with other remote sensing data and products, can be used to monitor downstream conditions (Allen et al. 2019). The launch of HiGLMN will identify hotspots of GLOF risk and provide the basis for detailed in situ surveys.

d. Hydrodynamic modeling. Hydraulic simulations using models such as HEC-RAS (U.S. Army Corps of Engineers 2010), r.avaflow (Mergili et al. 2017), BASEMENT (Vanzo et al. 2021), and FLO-2D (FLO-2D-Software 2018) provide a critical foundation for EWSs, particularly when integrated with downstream social data to reduce loss of life during GLOF events. By integrating downstream field observations and remote sensing, these models support disaster prevention efforts (Anacona et al. 2015; W. Wang et al. 2022) and function as the "sentry" of HiGLMN framework. Hydrodynamic modeling requires inputs such as dam stability and buried ice conditions (Schmidt et al. 2020), moraine and breach geometries and particle size and viscosity of debris flow samples (Liu et al. 2020a), and long time series of lake boundaries, downstream topography (Zheng et al. 2021a), and channel roughness (Amin et al. 2020; Sattar et al. 2019). Precipitation and soil moisture products are also important inputs to runoff modeling

(Nanditha et al. 2023). High-precision digital elevation models (DEMs) and lake bathymetry can improve modeling accuracy (Mergili et al. 2018). Model capabilities can be extended to simulate future floods based on predicted triggers (Sattar et al. 2023). Flood evolution and quantification characteristics such as flood depths, velocities, and inundation areas can be modeled, which can be used to assess flood damage downstream. For example, GLOF modeling demonstrates the potential threat of several lakes such as Poiqu No.1, Jialong Co, and Galong Co in the Poiqu River basin of the transboundary Himalayan basin (Allen et al. 2022; Wang et al. 2024) and Thorthomi Tsho in the Bhutan Himalaya (Rinzin et al. 2023), emphasizing the need for continued monitoring and establishment of EWS for disaster risk management. The HiGLMN will share the GLOF intensity of potentially high dangerous lakes and guide the detailed surveys and downstream development plan.

e. Field survey. Field surveys and detailed monitoring using a variety of instruments are the "heart" of HiGLMN (Table 1, Fig. 3). We divide the field observations into three classes, namely, those related to "external triggers," the "glacial lake" and "dam stability," and "downstream impacts," which are primarily concerned with GLOF disaster mitigation.

1) External triggers: including extreme weather, seismic activity, glacier stability, potentially vulnerable landslides, and rockfall areas are monitored using a variety of approaches. Extreme weather events can cause landslides from the surrounding hillsides to enter the lakes and generate a wave sufficient to damage the dam, or cause direct settlement of the dam, either of which can lead to dam failure, triggering the GLOF hazard chain and causing damage downstream (GAPHAZ 2017). Extreme weather conditions in the lake basin are monitored by automatic weather stations (AWSs), including air temperature, relative humidity, precipitation, air pressure, wind speed, mean total radiation, net total radiation, and daily mean water vapor pressure. In addition, shorter time periods, such as 15-day rainfall forecasts, can provide more time to prepare for potential events (Climate Hazards Center). Time series of precipitation, temperature, and evapotranspiration are important inputs to hydraulic models used to simulate GLOF hydraulics and assess downstream risk. Based on experience with GLOF events following extreme weather events, data from the AWS can be used to track extreme weather patterns. This information can be valuable in anticipating GLOF events and activating downstream risk reduction strategies, such as preparing for evacuation. Triggers from glacier surges and avalanches can be monitored using unmanned aerial vehicles (UAVs) and time-lapse cameras, which can also be used to monitor potentially vulnerable landslide areas such as lateral moraines.
2) Glacial lake and dam characteristics: including lake bathymetry, lake level, lake surface water temperature, lake surface to bottom temperature profile, lake shoreline, dam stability, ground surface temperature measurements, and buried ice are investigated using a variety of in situ methods. Lake bathymetry, typically measured by a unmanned surface vessel (USV) or rubber dinghy, is the basis and key data for estimating lake volume, which is a prerequisite for hydrodynamic simulation of downstream flooding. Lake level and surface water temperature, monitored by water-level and temperature loggers, can be used to quantify the seasonal dynamics of lake surface water conditions (Camassa et al. 2023; Falátková et al. 2014; Miles et al. 2017). Differential global navigation satellite systems (DGNSS) can provide precise validation for lake outlines derived from satellite imagery and enable detailed monitoring of dam stability beyond the capability of remote sensing alone. To assess the stability of terminal moraines, geophysical methods and borehole investigations will be used to detect subsurface ice content and melting. In addition, dam walls samples will be collected during fieldwork for geotechnical testing to further evaluate structural integrity. The stability of the dam will also be analyzed using

Table 1. Instruments used for setting up a glacial lake monitoring network. Instrument name, picture, field observation frequency, measurement item, and application purpose are shown and described.

Instrument name	Instrument picture	Observation frequency	Measurement item and application purpose
Yunzhou USV (unmanned surface vessel, M70, and SL20), CarlVinson inflatable boat (CND-470A)	 	Once for each glacial lake, every 3–5-yr interval for potentially high-dangerous glacial lakes, and annually for easily accessible lakes	Bathymetry for estimating lake water volume
HOBO Water-Level Data Logger (U20)		Two water-level loggers for each potentially high-dangerous glacial lake with continuous real-time data recording and transfer	Lake level and lake water temperature
HOBO Water Temperature Logger (MX2204)		Vertical section from lake surface to lake bottom	Vertical lake water temperature profile
Campbell Radar Water-Level Sensor (CR300 datalogger)		One set of radar water-level sensor for each potentially high-dangerous glacial lake	Lake and river water level
Acoustic Doppler Current Profiler (M9)		Five to six annual measurements of river discharge for each potentially high-dangerous glacial lake combined with water-level measurement	Outflow of a glacial lake, river discharge downstream
DJI UAV (unmanned aerial vehicle, Phantom 4 Pro)		Once for each glacial lake, every 2–3 years for potentially high-dangerous glacial lake and annually for easily accessible lakes	Geomorphological condition for DEM producing photo
RTK (real-time kinematic positioning, Trimble R12)		Once for each glacial lake, 2–3-yr interval for each potentially high-dangerous glacial lakes, and annual for easily accessible lakes	Lake surface elevation, lake shore topography
HOBO soil moisture sensor (S-SMC-M005) and temperature sensor (S-TMB_M006)	 	A set of soil moisture and temperature sensors for each potentially high-dangerous glacial lake with continuous data recording	Terminal and lateral moraine soil moisture and temperature
Forsafe Infrared Night Vision Timing-Lapse Camera (H6)		Two cameras for each potentially high-dangerous glacial lake with continuous data recording	Photo of parent glacier of the glacial lake
TCCORS-GNSS BeiDou monitoring system		One set of GNSS-BeiDou monitoring system for each potentially high-dangerous glacial lake	Displacement of the terminal moraine of a glacial lake
SmartSolo seismic sensor (IGU-BD3C-5)		One seismic sensor for each potentially high-dangerous glacial lake	Natural microseismical
Campbell AWS (automatic weather station, CR1000X)		A set of AWS for one potentially high-dangerous glacial lake	Wind speed and wind direction, air temperature and humidity, net radiation, air pressure

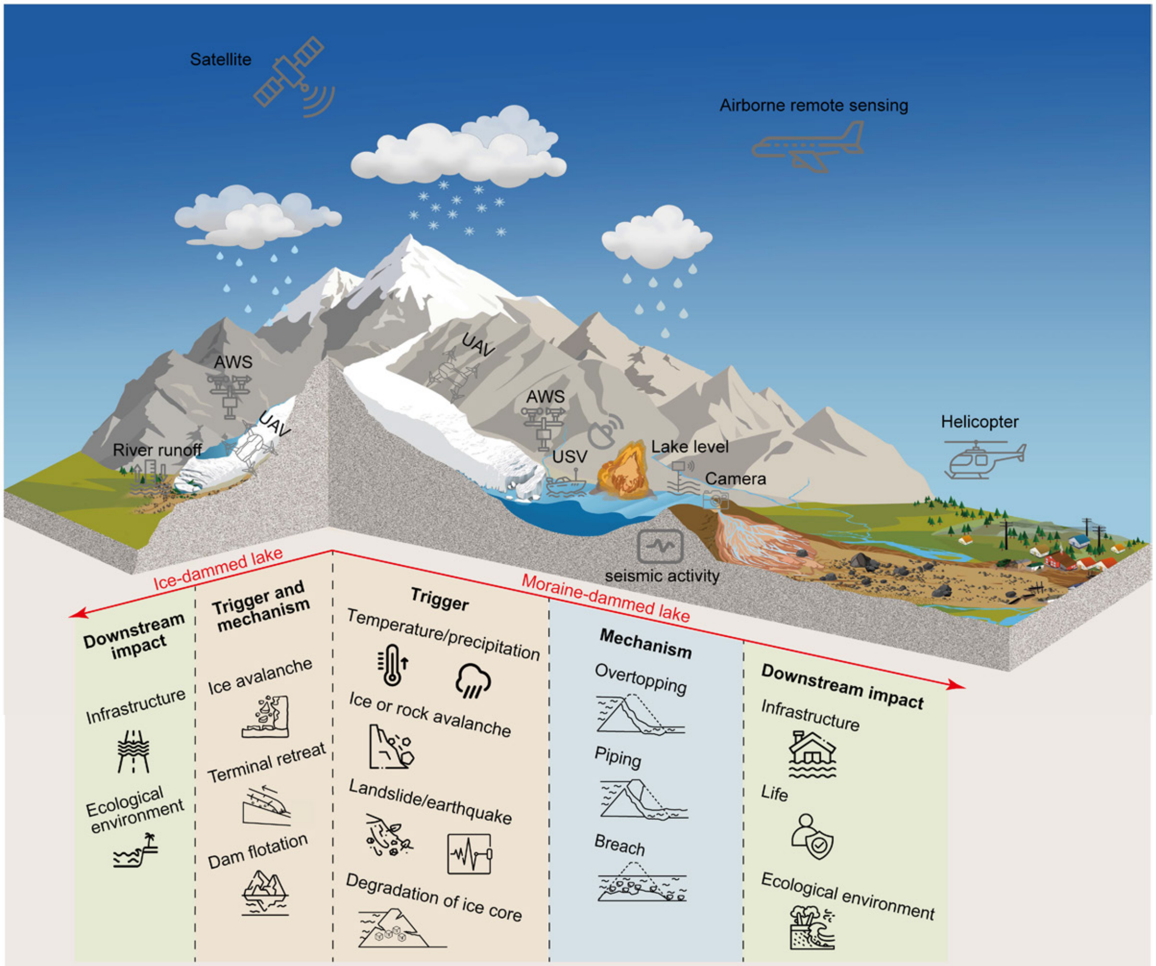

Fig. 3. Schematic of parameters to be monitored in a glacial lake monitoring network. The monitoring system is divided into moraine-dammed lakes and ice-dammed lakes. (top) The monitoring targets (glacier, lake, dam, and downstream exposure and flooding) by instruments such as satellite, UAV, AWS, USV, water-level logger, time-lapse camera, and helicopter. (bottom) The trigger, mechanism, and downstream impact of GLOFs for moraine-dammed lakes and ice-dammed lakes, respectively.

limited equilibrium or finite element analysis to determine the stability of the dam under different conditions.

3) Downstream impact: This refers to the exposure of the population and infrastructure within the hazard impact zone. The spatial distribution of the contemporaneous exposed population can be used to determine the locations of potentially affected populations in GLOF pathways (Allen et al. 2022; GAPHAZ 2017; Taylor et al. 2023). The distribution of people and livestock can be collected by local authorities during field surveys. The spatial distribution of exposed infrastructure provides basic information for the implementation of effective mitigation strategies. Infrastructure at risk, such as hydropower plants, roads, bridges, and buildings, can be surveyed using cameras and UAVs to provide accurate and up-to-date information. The granularity of the infrastructure inventory should be improved by adding details such as the type of use and construction of the structures. High-resolution DEMs of downstream river channels, used for flood simulation and inundation assessment, can be complemented by UAV imagery of critical areas.

4. Existing practices for identification and mitigation of high-risk lakes

GLOFs are one of the major natural hazards in the Himalaya due to the high-population densities downstream of the dangerous glacial lakes and the low economic development of these populations. Individual investigations of lakes at risk of outburst have been carried out in the region for decades, but comprehensive strategies to address the challenge regionally have only recently emerged (Emmer et al. 2022; GAPHAZ 2017). Lake-lowering interventions have been implemented at several potentially dangerous glacial lakes across the Himalaya, including Imja Tsho and Tsho Rolpa in Nepal (Cuellar and McKinney 2017; Khadka et al. 2019), Thorthormi Tsho and Raphstreng Tsho in Bhutan (NCHM 2019), and Jialong Co in China (Allen et al. 2022; Cuellar and McKinney 2017; Li et al. 2021). For GLOF early warning, in situ monitoring has been recommended through the installation of appropriate hydrometeorological observatories such as water-level gauges, pressure transducers, soil temperature dataloggers, time-lapse cameras, and AWS to continuously monitor lakes and downstream sites (GAPHAZ 2017). Information from other sources, such as satellite observations and hydrological models, could make the system more reliable and robust.

In the Chinese Himalaya, a number of studies have been carried out with the support of the China–Switzerland International Cooperation Project and the STEP. For example, the evolution of glacial lakes and glacier–lake interactions in the Poiqu River basin have been examined (Zhang et al. 2019), and the potentially hazardous glacial lakes in this basin have been identified (Allen et al. 2019) (Fig. 4). An EWS for Cirenma Co was established in 2022 (W. Wang et al. 2022). The future threat of two potentially dangerous lakes (Galong Co and Jialong Co), especially in the worst-case scenario, has been demonstrated (Allen et al. 2022). The GLOFs of Gongbatongsha Co happened in 2016 and Poiqu No. 1 in 2002 were reconstructed (Wang et al. 2024). Following several years of observational research

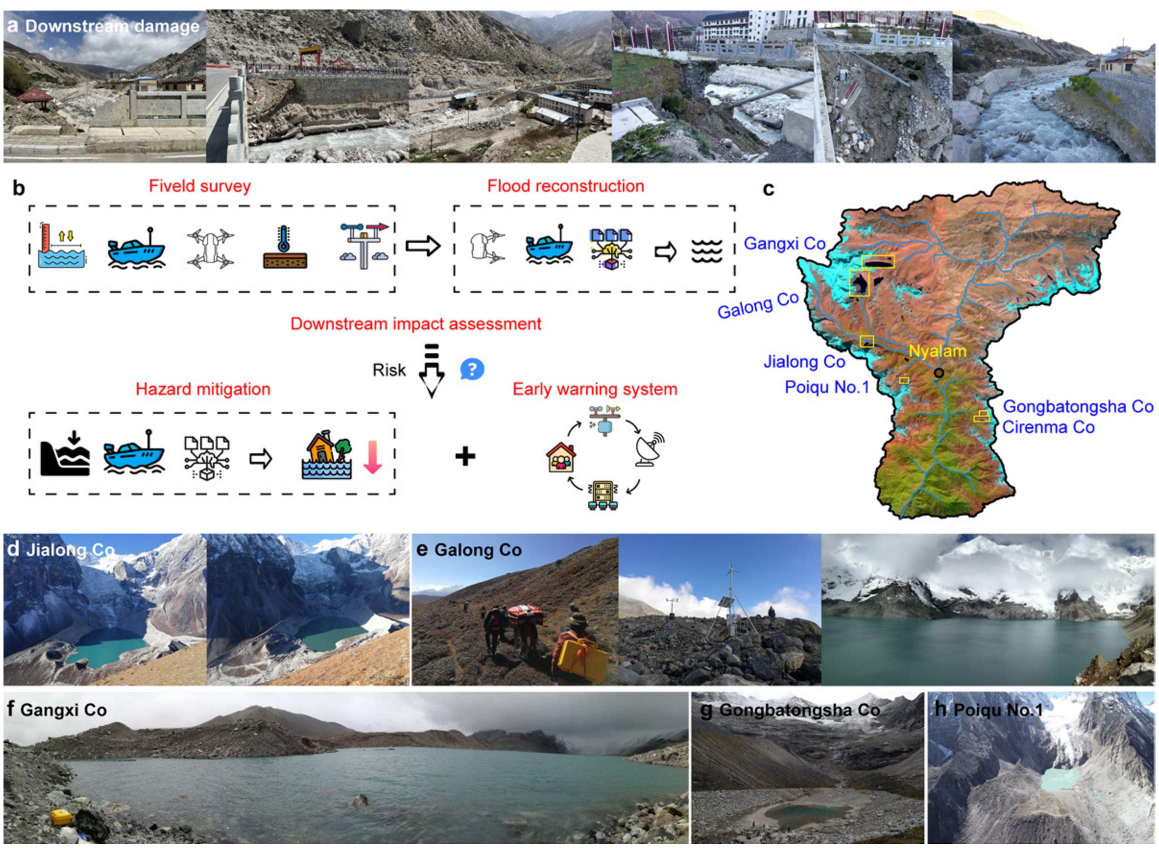

Fig. 4. Hazard mitigation practice from a glacial lake monitoring network. Application of a glacial lake monitoring network for hazard mitigation in the Poiqu River basin, central Himalaya, as an example. (a) Photos of downstream damage. (b) Framework of field survey, flood reconstruction, downstream impact assessment, hazard mitigation, and EWS construction. (c) Distribution of glacial lakes in the Poiqu River basin. (d) Photos of Jialong Co. (e) Photos of Galong Co. (f) Photo of Gangxi Co. (g) Photo of Gongbatongsha Co. (h) Photo of Poiqu No. 1.

(2017–23) (Zhang et al. 2023), this region has been established as a demonstration site for GLOF mitigation planning. Successful practices of international field research to jointly promote transboundary GLOF assessment and disaster management have also been highlighted. The methods and lessons learned will be applied to the study of GLOF hazards in other transboundary regions.

In the Bhutanese Himalaya, the Lunana glacial lake complex, which includes Thorthormi Tsho, Lugge Tsho, Raphstreng Tsho, and Bechung Tsho, is the closest glacial lake system to human settlements (Rinzin et al. 2023). The 1994 Lugge Tsho GLOF caused 23 deaths and extensive downstream damage (Watanbe and Rothacher 1996). A project initiated in 2008 lowered the lake level of Thorthormi Tsho by ~5 m. Investigations have revealed an increased risk of cascading GLOFs from Thorthormi and Raphstreng Tsho (Rinzin et al. 2023), e.g., two GLOF events in 2019 and 2023 for Thorthormi Tsho, triggered by glacier block collapse and ice avalanche. Bhutan's NCHM has established an effective EWS for Lunana lake, which successfully alerted communities during recent events (NCHM 2023).

In the Nepalese Himalaya, the lake-level lowering project has been implemented for two lakes (Tsho Rolpa and Imja Tsho) (Shrestha et al. 2024). In 1998, the lake level of Tsho Rolpa was lowered by ~3 m, and a flood EWS was installed to warn vulnerable communities downstream in the Rolwaling Valley. In 2016, the water level of Imja Tsho was lowered by ~3.4 m through the construction of an artificial open channel, and hydrometeorological and water-level sensors were installed (Lala et al. 2018; Sattar et al. 2023).

In the Indian Himalaya, comprehensive EWS for GLOFs (and similar high-intensity mountain floods) has garnered increased attention, especially after the devastating events in Chamoli in 2021 (Shugar et al. 2021) and Sikkim in 2023 (Sattar et al. 2025). The National Disaster Management Authority (NDMA) has prepared detailed guidelines for mapping, monitoring, and mitigating GLOFs in the Himalayan region (NDMA 2020). These guidelines propose a two-step strategy that includes (i) a preliminary first-order Indian Himalaya-wide GLOF hazard and risk assessment and (ii) a detailed hazard and risk assessment. The first-order approximation will primarily utilize optical and SAR satellite data to provide an overview of risk hotspots, where detailed investigations can be prioritized and initiated. The detailed hazard, vulnerability, exposure, and risk analyses for a specific site will form the basis for the design and implementation of GLOF risk management strategies. In this regard, the document points out that some instruments including telemetry stations have already been set up in the Sutlej River basin to monitor and forecast flash floods, including those caused by cloudbursts and GLOFs (Ives et al. 2010). Drawing from the earlier efforts to mitigate the impact of landslide-dammed lakes formed by the blockage of the Phuktal River, ~90 km from Padum in Kargil, the NDMA has proposed controlled blasting of the dam of these hazardous lakes to safely drain the water in a controlled manner (NDMA 2020). In addition, based on modeling of the GLOF process chain, lowering the level of Gepang Gath Lake by ~10 m can reduce the high-intensity zone by more than half in both present and future scenarios (Sattar et al. 2023). Recently, the Government of India has also issued instructions to all dam authorities to assess the GLOF risk of existing and proposed dams in the Himalayan region. The Dam Safety Act 2021 mandates regular inspections, emergency action plans, and emergency flood warning systems for hydropower dams including potential transboundary GLOFs (Iyer and Bakshi 2023). The instructions also suggest installing the EWS for the dangerous lakes. However, as the structured guidelines are at a preliminary stage for this type of study, this work will serve as a baseline for such efforts.

In northern Pakistan (both in the Hindu Kush and Karakoram), the pilot GLOF risk reduction project (GLOF-I, 2011–15) helped to mitigate GLOF risks through identifying of locations at risk, improving infrastructure, and community-based disaster risk management, led by the United Nations Development Programme (UNDP) (2022) and government institutions (Rijal and Ali 2015). This was eventually followed by scaling up across the region (GLOF-II, 2017–24), under which monitoring equipment was installed in focus sites and further training conducted (UNDP 2022).

5. Long-term operation and maintenance of the monitoring network

The HiGLMN is a call and platform for monitoring and sharing data on Himalayan glacial lakes that can be used to prevent and mitigate GLOFs. Historical remote sensing imagery and model simulations show a rapid overall mass loss and retreat of Himalayan glaciers in the past (Azam et al. 2018; Hugonnet et al. 2021) and in the future (Rounce et al. 2023), resulting in the rapid expansion of glacial lakes and increased water volumes (Zhang et al. 2023). GLOFs pose a significant hazard potential, threatening downstream infrastructure and the safety of life and property (Fig. 5a). In the future, glaciers will continue to melt, new glacial lakes will form, existing glacial lakes will expand, and the risk of GLOFs is likely to increase in some regions. Increasing dependence of downstream populations on meltwater and the construction of new hydropower dams may contribute to increased disaster risk (Fig. 5b).

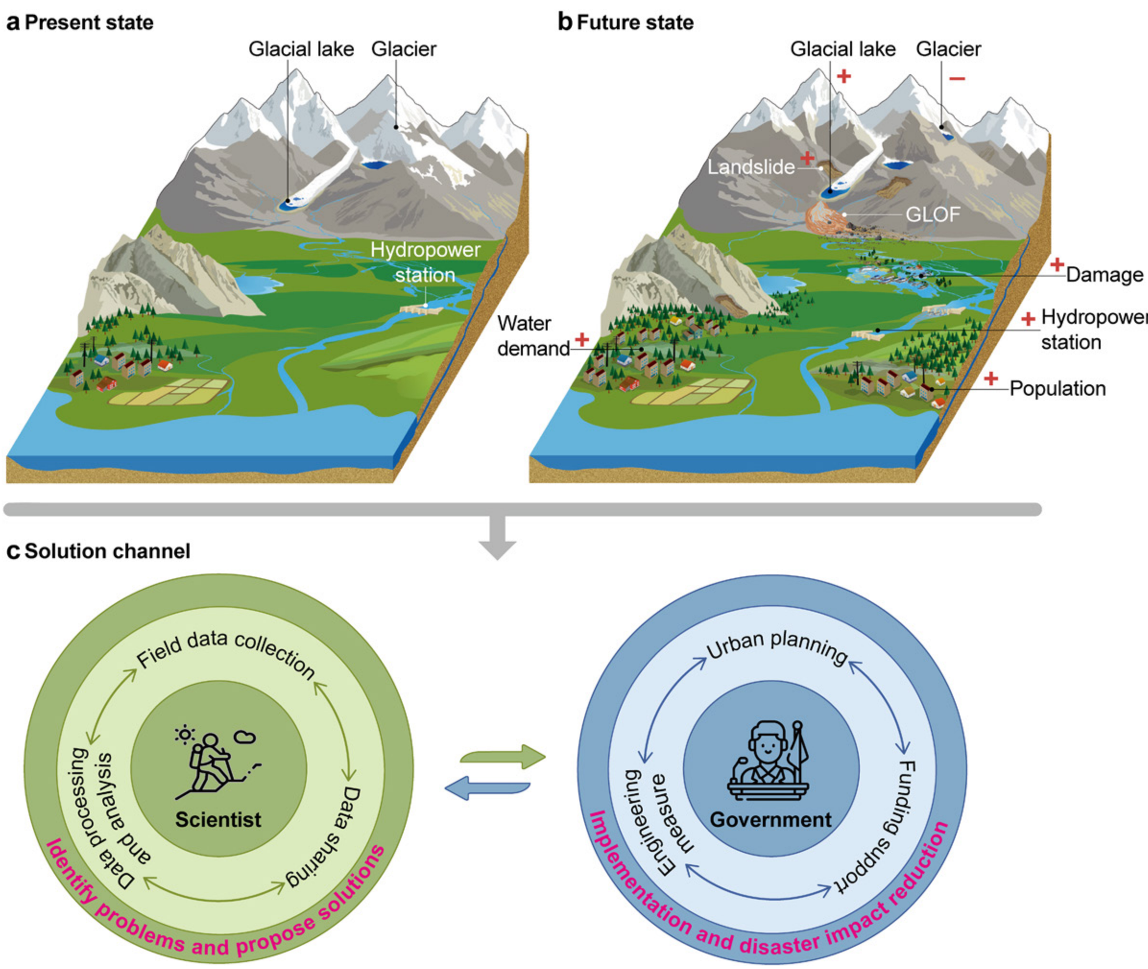

Fig. 5. Future recommendations for GLOF damage reduction based on the establishment of a glacial lake monitoring network. (a) Present state of glacial lakes and downstream conditions. (b) Future state of glacial lakes and downstream GLOF potential. (c) Solutions recommended by scientists and the government's view. The future reduction of GLOF damage depends on the identification of problems and proposed solutions by scientists and the implementation of policy, engineering, and future planning by the government department.

Operation and maintenance of the proposed glacier lake monitoring network will require sustained support from scientists, the governments of Himalayan countries, local communities, and international partners. Scientists play a key role in identifying critical situations and proposing solutions through systematic field data collection, data processing and analysis, and open data sharing (Fig. 5c). All collected data must undergo rigorous quality control and validation. The findings and recommendations derived from scientific analysis should be effectively communicated to government authorities and local communities to enhance GLOF risk awareness and support the implementation of mitigation strategies.

To ensure long-term sustainability, it is essential to explicitly address financial and human resource requirements. The operation and maintenance of such a network involve recurring costs, including instrument calibration and replacement, data storage infrastructure, and field logistics. Sustainable funding mechanisms must be established from the outset. Potential sources include international development and scientific collaboration platforms such as the Alliance of International Science Organizations (ANSO), the International Centre for Integrated Mountain Development (ICIMOD), the United Nations Educational, Scientific and Cultural Organization (UNESCO), and the Glacier Stewardship Program (GSP), particularly in the context of recent initiative such as the 2025 International Year of Glaciers' Preservation and the Decade of Action for Cryospheric Sciences (2025–34) led by the UNESCO, which strongly emphasize disaster risk reduction in high mountain regions.

Human resource development is equally critical. Strengthening local technical capacity—through training programs, engagement with universities and regional research institutions, and sustained knowledge exchange—is essential for the continued operation of the network. Involving local communities, particularly through citizen science, can enhance data collection, support the maintenance of instruments in remote high-altitude areas, plan bespoke risk mitigation activities, and foster local ownership of risk management efforts. Institutionalizing these partnerships within regional frameworks will ensure long-term operation, minimize redundancy, and enhance the network's resilience and scalability.

6. Summary and perspectives

There is an urgent need for establishing an overarching glacial lake monitoring network across the Himalaya, given the thousands of lakes, the transboundary nature of hundreds of lakes, the threat of GLOFs to downstream populations and infrastructure, and the low levels of economic development and resilience across the region. Field observations of glacial lakes, combined with remote sensing and hydrodynamic modeling, have important utility for GLOF disaster mitigation. Subsurface topography, water volume, GLOF triggers, and mechanisms represent essential information that can only be obtained through dedicated field observations and long-term monitoring.

To establish and maintain a comprehensive network covering the entire Himalayan mountain range, there are severe challenges that need to be overcome: 1) the remoteness and inaccessibility of the glacial lakes require substantial financial investment and human resources for monitoring and maintenance; 2) a lack of attention and awareness by stakeholders and policymakers of the risks associated with glacial lakes, and the lack of investment by hydropower companies, stakeholders, and other businesses to address these risks require appropriate science-policy dialogue; 3) geopolitical challenges of data sharing require effective intergovernmental dialogue and cooperation to overcome these barriers and ensure successful data collection and network management; 4) dynamic impacts of climate change, such as glacial lake expansion, retreating hanging glaciers, degrading permafrost, and increasingly unstable terrain, must be integrated into long-term monitoring strategies, requiring forward-looking approaches that account for future vulnerability under warming scenarios.

As part of this study and broader international collaborations, the HiGLMN will be established to document existing efforts, such as ongoing monitoring activities and initiatives, and to enable transparent and consistent data sharing. With continued and future atmospheric warming, the hazard posed by glacial lakes could increase across many world mountain regions (Carrivick et al. 2022a,b; Drenkhan et al. 2018; Emmer et al. 2020; Zhang et al. 2024; Zheng et al. 2021b). While HiGLMN will initially focus on the Himalaya, the framework is designed to be scalable and adaptable. Similar networks should be developed in other glacierized mountain regions facing comparable GLOF threats, such as the Tien Shan (Medeu et al. 2022), the Andes (Cook et al. 2016; Wood et al. 2021), and other high-altitude areas around the world.

This HiGLMN lays the foundation for future collaboration with other mountain regions, promoting knowledge exchange and supporting the development of a global glacial lake monitoring and early warning network. This would serve as an international coordination framework, aligning global scientific objectives with the operational priorities of national and regional missions. By expanding and enriching glacial lake observations worldwide, such a network would significantly enhance the capacity to anticipate, forecast, and mitigate GLOF risks. Ultimately, this global initiative could help protect millions of people, livelihoods, property, and infrastructure, thereby having social and economic benefit by strengthening climate resilience across some of the world's most vulnerable high mountain regions.

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Data availability statement. The data collected by the Himalayan glacial lake monitoring network will be available through the National Tibetan Plateau Data Center (https://data.tpdc.ac.cn/higlmn) through a special website "HiGLMN" entitled "Himalayan glacial lake monitoring network."

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