Challenges in predicting glacial lake outburst floods and suggested pathways forward

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Ongoing rapid atmospheric warming is driving accelerated melting and retreat of mountain glaciers worldwide. Consequently, there has been a rapid expansion of glacial lakes. Sudden failures of the natural dams of these glacial lakes can generate glacial lake outburst floods (GLOFs), caused by both internal conditioning factors and external triggers. Some of these GLOFs have been catastrophic[1] due to steep elevation gradients and the presence of abundant sediment transport in mountain rivers. GLOFs produce powerful flows that cause substantial damage to infrastructure, including roads, bridges, hydropower stations, and settlements, and result in loss of life.[2]

Geoscientists worldwide have conducted extensive research on glacial lake mapping, field surveys, and the identification of GLOF mechanisms and triggers.[3] These datasets and the associated knowledge enrich risk assessments and projections.[4] Early warning systems (EWSs) have been established in some at-risk valleys, yet effective and timely warnings remain rare. For instance, the China-Nepal transboundary GLOF that occurred on July 8, 2025, in Jilong County, Xizang, China, caused around 29 fatalities and widespread infrastructure damage. This recent event, which originated from a small, overlooked supraglacial lake, illustrates persistent challenges in GLOF risk assessment and underscores the need to rethink the limits of EWS prediction.

COMPLEX TRIGGERS AND CONDITIONING FACTORS

GLOF risk assessment is challenging due to highly complex triggers, mechanisms, and flow characteristics. Lake type strongly influences response to external disturbances: supraglacial lakes can form or drain episodically through subglacial conduits; ice-dammed lakes are prone to sudden drainage triggered by dam thinning or flotation; and moraine-dammed lakes are vulnerable to ice avalanches, landslides, extreme rainfall, permafrost thaw, or piping that weakens the dam to sudden failure through compound events. This diversity of lake types generates multiple interacting processes, increasing uncertainty in predicting outbursts (Figure 1). Even minor disturbances can evolve into catastrophic floods under specific conditions.

Glacial lakes are widespread across high-mountain regions worldwide, spanning diverse climatic and topographic settings. Glacial lake susceptibility to a GLOF depends not only on large-scale climatic forcing but also on local geomorphology, climate, and glacier-lake interactions. Monitoring, modeling, and EWSs remain insufficient to capture extreme or compound triggers, while ongoing rapid climate change introduces additional uncertainties. As a result, accurate prediction of the timing, magnitude, and mode remains highly uncertain, limiting the reliability of conventional risk assessments and challenging disaster mitigation strategies.

CASCADING AND COMPOUND HAZARDS

Most GLOF events involve a cascade of processes. For example, ice avalanches or landslides enter lakes, generating displacement waves that overtop and erode moraine dams, resulting in downstream outburst floods. Sediment entrainment and interactions with complex terrain amplify flow power. However, critical uncertainties remain at each flow phase: the magnitude and timing of slope failures, dam erosion rates, and downstream entrainment of sediment are usually poorly constrained. Conventional models tend to represent these processes in a simplified or linear manner. However, the uneven and rapidly evolving nature of these uncertainties fundamentally limits the feasibility of deterministic prediction.

High-resolution remotely sensed imagery and high-precision digital terrain models can improve hazard detection, yet limitations persist. Optical imagery suffers from cloud cover; InSAR faces layover and foreshortening, and permafrost, glacier outline, and thickness data remain coarse; and downstream sediment datasets are often lacking. These limitations, coupled with rapidly changing cryospheric conditions, render GLOF source prediction highly challenging. As GLOFs propagate downstream, interactions with complex terrain, sediment, and human-made infrastructure dynamically modify flow volume, composition, and mobility, thereby amplifying uncertainty in flood magnitude, routing, and impact.

LIMITED FIELD OBSERVATIONS AND EWSs

Field observations remain indispensable for validating satellite data, constraining lake bathymetry, assessing dam stability, quantifying hydrological flows, and capturing real-time triggers. High-altitude mountain regions are characterized by harsh environmental conditions and limited accessibility, resulting in short field visits and high resource demands, while many transboundary areas introduce additional barriers to fieldwork and data exchange due to political reasons. Only a small fraction of global GLOF events incorporate site-specific fieldwork, limiting the in-depth understanding of the dynamic processes involved.

EWSs are essential for real-time monitoring of GLOFs and should be designed as probabilistic decision-support tools that integrate remote sensing with field observations. Many EWSs fail over time due to maintenance lapses, lack of local ownership, or misalignment with the dominant failure mechanisms of specific lakes. For example, the EWS installed in 1998 for the Tsho Rolpa in Nepal has become nonfunctional due to a lack of maintenance and insufficient local ownership. Detailed field observations and the development of effective EWSs are interrelated, as limited observations impede the design of robust EWSs, while the absence of these systems restricts the precise data collection during before, during, and after events.

SOCIAL-INSTITUTIONAL AND GOVERNANCE CHALLENGES

Effective GLOF prediction is frequently hampered by complex social, institutional, and governance challenges. These obstacles not only impede scientific forecasting but also intensify community vulnerabilities in downstream areas. Social challenges in affected communities, often marginalized with limited resources, significantly hinder their ability to engage in GLOF prediction and preparedness efforts. Further, cultural factors, such as spiritual connections to mountains and lakes, shape risk perception and can hinder community participation in monitoring efforts, as locals may be resistant to external interventions that challenge their traditional beliefs.

Institutional frameworks frequently fail to integrate GLOFs into disaster planning, especially in underdeveloped regions. In addition, transboundary data sharing remains limited; for example, the Poiqu-Bhotekoshi-Sunkoshi basin between China and Nepal suffers from limited data sharing and joint monitoring. Misalignment of agency priorities, poor coordination, and lack of recognition of local knowledge constrain effective risk reduction. Addressing these challenges

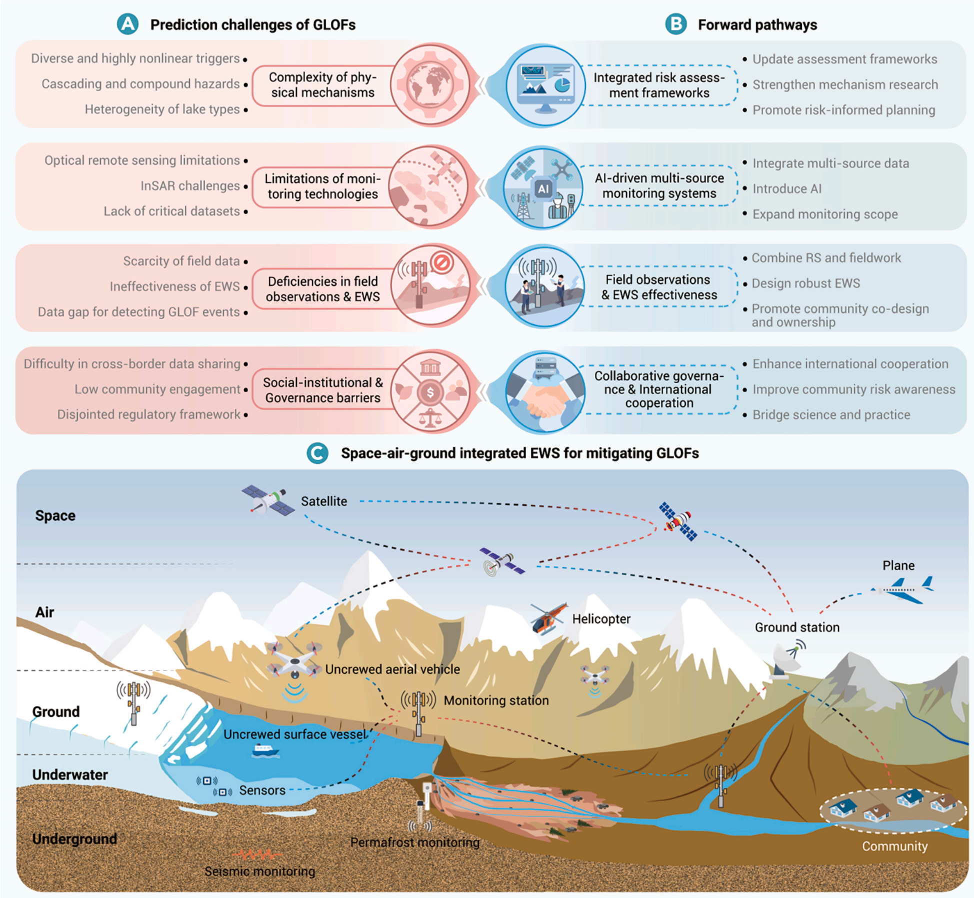

Figure 1. Challenges in predicting GLOFs and suggested pathways (A) Present challenges in GLOF prediction. (B) Proposed pathways to address these challenges. (C) An idealized framework illustrating how integrated space-air-ground observations can enable effective GLOF prevention and mitigation.

is essential for adaptive EWSs, targeted monitoring, and effective community engagement.

PATHWAYS TO IMPROVE PREDICTION AND RISK REDUCTION

In this commentary, we highlight how complex triggers and conditioning factors, cascading and compound hazards, sparse field observations, uneven EWS performance, and persistent social and governance constraints collectively limit the predictability of GLOFs. Therefore, improving GLOF risk reduction requires a shift toward updated risk assessment frameworks, process-informed modeling of cascading hazards, adaptive EWSs framed as decision support tools, and coordinated community-based risk governance.

- GLOF risk assessments vary widely depending on the parameters selected and thresholds determined. Future frameworks should place greater emphasis on probabilistically assessing the likelihood of GLOFs under extreme climatic and environmental conditions, including extreme warming, intense precipitation, mass movements, and permafrost degradation. This can be achieved by combining physically based process models with scenario-based and statistical approaches, including machine learning, to better represent uncertainty and low-probability high-impact events.
- Capturing the nonlinear interactions among triggers, dam stability, flood propagation, and sediment transport is essential for representing cascading hazards. Such models can simulate how initial perturbations amplify downstream and how sediment-water interactions alter flow dynamics. Scenario-based and hybrid modeling approaches, including probabilistic ensembles, allow for explicit accounting of uncertainty along the process chain and improve predictive robustness.
- AI-supported EWSs that integrate archived and real-time multi-source remote sensing data and field observations within a physics-informed framework have strong potential for addressing the complex nature of GLOF triggers. AI algorithms can automatically detect lake dynamics and glacier and slope activity and improve flood simulation. Advanced geophysical technologies, including distributed acoustic sensing,[5] can detect cryospheric structures and measure water content to assess dam stability.
- Transboundary collaboration is essential to overcome barriers to data sharing and enable coordinated early warning. This requires shared monitoring networks, open data repositories, and governance mechanisms that integrate local knowledge with scientific expertise. Further progress depends on co-designed community monitoring programs, capacity building, and effective governance frameworks that bridge science, government, and practice. Simulated GLOF flow paths can inform risk-aware urban planning and infrastructure development, making avoidance of hazard-prone zones an effective and cost-efficient mitigation strategy.

In summary, GLOF predictability remains fundamentally limited, and we need to rethink what effective prediction of GLOFs entails. This commentary argues that advancing risk reduction requires integrated strategies that combine probabilistic risk assessment, process-based hydrodynamics modeling, adaptive EWSs, and coordinated community-based governance to mitigate future GLOF impacts.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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