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Brief communication: A landslide-induced winter outburst from a frozen glacial lake in the Central Himalaya

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Abstract. Outburst floods from glacial lakes have predominantly occurred during ablation seasons, with few documented cases for frozen lakes during winter. The rarity of winter failures has led to the perception that glacial lakes with frozen surfaces and limited meltwater are generally regarded as safe. Here we report a winter-outburst flood from a frozen proglacial lake in the Central Himalaya on 16 December 2024. Two lateral rockfalls with a total volume of ~4.29 Mm^3 broken ~0.35 m thick lake ice below and triggered an "ice tsunami" at the lake terminus, unleashing a partial drainage of the ice-covered lake and triggering a flash flood that travelled roughly 140 km downstream. Although the lake-ice cover had blunted catastrophic overtopping by damping impact energy and wave amplitude, this winter outburst case suggests that the occurrence window for future GLOFs will temporally extend in high mountain areas as paraglacial slope failures increase and lake ice diminishes during winter. This single event therefore reveals a systematic blind spot in current GLOF risk assessments: frozen lakes are not inherently safe. We therefore urge a call to heighten public awareness of this emerging dangerous and future GLOF risk assessments/early-warning systems should incorporate lake-ice condition as one of monitoring parameters under relevant safety protocols.

1 Introduction

Glacial lake outburst floods (GLOFs) pose a growing threat to high mountain communities as global warming accelerates cryosphere shrinkage and increases water-mass movement in cold regions (Zhang et al., 2024a). Unlike periodic filling and drainage characteristics of ice-dammed or supraglacial lakes, outburst floods from moraine-dammed lakes are typically triggered by extreme external disturbances (Clague and O'Connor, 2021). Moraine dams are susceptible to breaching through either gradual degradation (e.g., permafrost thaw, ground ice melt) or abrupt erosion (e.g., wave overtopping, high rate waterflow incision), resulting in the sudden release of substantial volumes of lake water. Consequently, the timing and

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magnitude of a moraine-dammed GLOF are influenced not only by the inherent stability of the lake and its dam itself, but also by the frequency and intensity of external disturbances (M. J. Westoby et al., 2014). A better understanding of GLOF timing or their seasonal distribution is essential for the strategy of mitigation preparation or developing efficient early warning system (EWS).

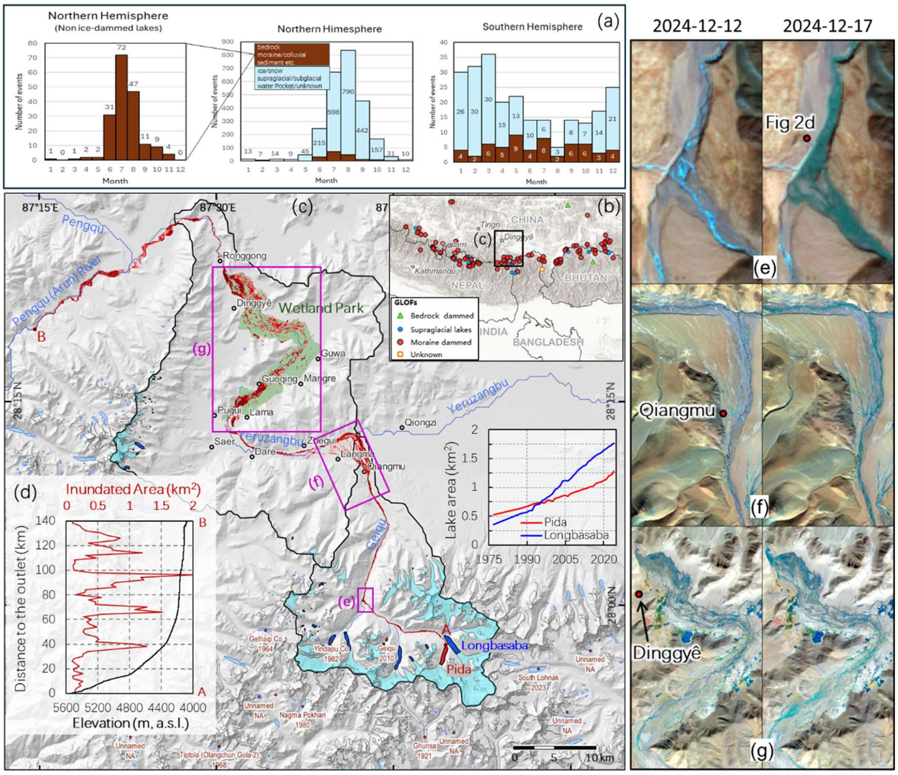

Fig 1. (a) Seasonal distribution of global reported GLOF events in the Northern and Southern Hemispheres. The plot incorporates 2,753 month-confirmed events out of 3,151 reported worldwide GLOFs (Lützow et al., 2023), grouped into (1) non-ice dams (bedrock, moraine, colluvial, etc.) and (2) ice-dammed sources (ice, snow, subglacial, supraglacial, water pocket, etc.); totals are given on each bar. Icelandic cases (590) are excluded because >95% were by geothermal/volcanic activity or ice-dammed lakes. (b) GLOFs in the Central Himalaya coloured by different dam types. (c) Location and distribution of glaciers and glacial lakes in the Geiqu River basin and surroundings, including historical GLOFs texted with red. The flood-inundated area of the 2024 Pida Lake GLOF (derived from the Sentinel 2-NDMI change detection between 12 and 17 December 2024) is overlapped on the map. Charts showing the 1975–2024 expansion history of the two neighbouring proglacial lakes, Pida and Longbasaba. (d) Longitudinal-profile of inundated area along the ~140 km flow path from the Pida Lake outlet (point A) to the Pengqu–Arun confluence (point B). Sentinel-2 image pairs in the right panel highlight the surge of valley

water content at (e) the upper reach (valley mouth), (f) the middle reach (Qiangmu Village) and (g) the lower reach (Dinggyê Wetland Park). Mapping methods are described in the Supplementary file.

Although the timing of most historical GLOFs is unknown (Zhang et al., 2024a), most destructive GLOFs happened in summer melt seasons (Carrivick and Tweed, 2016). Globally, only 15 GLOFs from moraine-dammed lakes were reported in cold seasons, including one in the Northern Hemisphere and 14 in the Southern Hemisphere (Fig.1a). In High Mountain Asia (Shrestha et al., 2023), of all 687 GLOFs total events less than five were in November to March, and all 325 date-confirmed failures of moraine-dammed lakes took place between March and November (further 74% of cases occurred between June and August). The only one case of moraine-dammed lake failure in the Northern Hemisphere is the non-frozen Passu lake outburst flood in Karakoram reported on 06 Jan 2008 (Tariq et al., 2014). During summer melt seasons, the glacial lake and dam system is prone to be disturbed when accompanied by fluctuating and high lake levels (Zhang et al., 2023) meet with external triggers such as peri- and paraglacial landslides/debris flow, ice avalanche, or rainstorms, which all are expected to be intensified under global warming (Haeberli et al., 2016). In addition, the cascading/compound effects during warm and monsoon seasons would be enhanced when outburst floods overlapping with high down-valley water discharge (Ng et al., 2007). During cold seasons, frozen glacial lakes are generally stable with minimal or no lake level fluctuations, and a frozen lake ice with enough thickness is supposed to buffer the impacts from external disturbances. Communities downstream are psychologically “off-guard” during winter when temperature is below freezing as they are not anticipating flash floods and no warning initiated (Ahmed et al., 2025). Here we reported an unprecedented winter outburst from a frozen proglacial lake in the central Himalaya (Fig. 1b) at the Pida Lake on 16 December 2024, highlighting the need to update our perception of cold-season GLOF risk as high mountain warming intensifies. Given the rarity of this phenomenon and its immediate implications for hazard assessment, we present this event as a sentinel case to rapidly alert the cryospheric community to an emerging winter GLOF risk that current monitoring frameworks overlook.

2 Glacial lakes in upper Geiqu, Central Himalaya, and the GLOF problem

The Geiqu in Dinggyê, Tibet, China, is a tributary of the Yeruzangbu River, situated in the upper reaches of the China-Nepal-India transboundary Pengqu/Arun Koshi River Basin (Fig. 1c). It is a highly permafrost-affected catchment with numerous glaciers and glacial lakes in the Central Himalaya Kanchenjunga region, where at least 22 historical GLOFs have been documented, two of which (the 1982 Yindapu and the 2010 Geiqu failure events, Fig. 1b) were occurred within the Geiqu catchment (Shrestha et al., 2023; Zheng et al., 2021a). The most recent incident was the catastrophic failure of South Lhonak Lake in October 2023, located just on the east side of the Geiqu in India’s Sikkim, triggered by a lateral moraine collapse (Sattar et al., 2025; Zhang et al., 2024b).

In the uppermost part of the Geiqu catchment lies lake Longbasaba (5450 m a.s.l.) and Pida (5530 m a.s.l.), two neighboring and rapidly expanding ice-contacted proglacial lakes (Liu et al., 2020) that have been evaluated as high risk (Allen et al., 2019; Wang et al., 2008). In recent years, both lakes have undergone significant expansion due to the rapid calving retreat at their lake-terminating terminus. A previous GLOF scenario study suggested that a worst-case failure of Longbasaba could inundate many houses, roads and farmlands downstream (Yao, 2014). Qiangmu village, the nearest Tibetan settlement located ~32 km downstream of Longbasaba and Pida, has a population of ~200 in 2024. Further 18 km and 30 km downstream, county Saer (population>2,000) and Dinggyê (population >20,000) are situated along the Dinggyê Wetland Park, a significant natural wetland ecological reserve in south Tibetan Plateau. Since 2006, local governments have implemented engineering measures to lower both lakes' levels, and have also conducted regular ground inspections by local villagers from Qiangmu. Several sets of ground monitoring systems (including AWS, moraine thermal sensors and lake water level sensors) have already been progressively installed thereafter, but an active EWS has not been set up mainly due to the logistical and real-time data transmission difficulties. Given the increasing risk posed by these two dangerous lakes, the Department of Emergency Management of Tibet, China, has planned to install an EWS in 2026 to mitigate their potential GLOF risks.

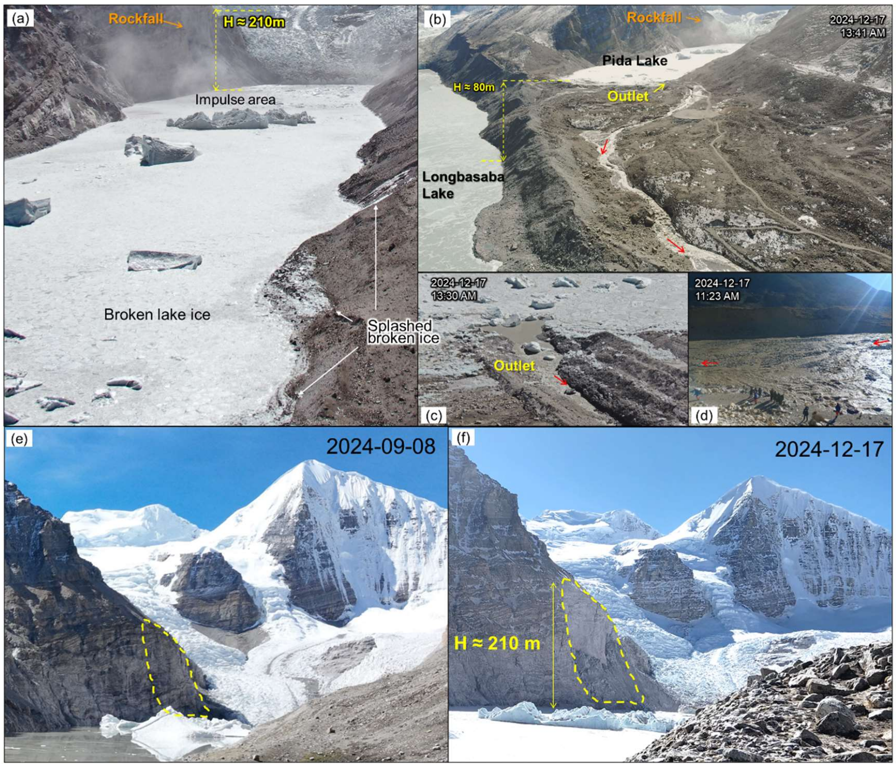

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Fig 2. Photographs taken by the local inspection team on 17 December 2024 showing the frozen Longbasaba Lake and fractured Pida Lake ice (a, b), with turbulent outburst floodwater originating from Pida Lake outlet (b, c) and surging to the valley mouth (d; also see Fig. 1e). Pictures (e) and (f) show the paraglacial rock slope before and after the collapse.

3 Observations of the 2024 winter GLOF from Pida Lake

On the evening (~21:00 pm) of 16 December 2024, local villagers from Qiangmu, Dinggyê, observed sudden water levelincrease, increased turbidity and drifting river ice blocks in the Geiqu River section near their village. The Geiqu river had already frozen over before 12 December, but the flash flood removed the river ice along its path (Fig.1d-f, seen from the Sentinel-2 image pairs captured on 12 and 17 December 2024). The local authorities promptly reported the unusual phenomena to the Shigatse Emergency Management Bureau. On the next day (17 December), an inspection team was dispatched to hike up the valley and investigate the source of the flood (Fig.2). Upon reaching the river junction (Fig. 1e and 2d) at about noontime, the team confirmed that the floodwater was from the Longbasaba and Pida Lake valley, not from Yindapuco Lake as they had initially assumed—the latter having experienced an outburst on 27 August 1982 (Nie et al., 2018).

The inspection team later confirmed that the flood originated from Pida Lake when they arrived at its lakeside in the afternoon. At the uppermost side of the Pida Lake, a fresh exposure slope after rock collapse was conspicuously noticed and wind-derived dust from the collapsing area indicated that the collapse occurred recently (Fig.2a). Turbid water was observed draining from the broken ice-covered lake and through the outlet channel (Fig.2b-c). This channel, spanning ~250 m across the end moraine, is an artificial and unsolidified waterway excavated in 2005 to lower the lake level (Liu et al., 2020). Although the channel has frozen in this season, the floodwater has removed the river ice. Both Longbasaba and Pida Lake had completely frozen over, but the Pida lake ice cover was totally broken, particularly at its uppermost and lower sections. Compared to the frozen and darker ice on Longbasaba lake, Pida Lake appeared as a uniform sheet of "white ice", a sign of low load-bearing strength riddled with widespread fractures and shattered plates. Numerous splashed broken ice blocks, elevated up to ~10 meters above the lake surface, were stranded on the inner slopes of end-moraine around the lake margin, as well as on the left bank of outlet channel. The extent of these splashed lake ice blocks was clearly visible in Sentinel-2 moisture index maps, which showed wetted moraine areas comparing before (12 December) and after (17 December) the event (See Supplementary File and Fig.S1). These observations provide clear evidence that a recent rock avalanche crashed into the frozen lake and triggered a small magnitude GLOF following the breakthrough of lake ice.

4 Triggers and chain process of the Pida Lake outburst

Satellite time series (PlanetScope, 15–17 December) reveal two distinct slope failures (Fig.3). The first, a small toe landslide detached from the lower part of the slope, fell on the glacier terminus area between 12:59 pm on 15 December and 13:03 pm on 16 December (Fig. 3d). This toe landslides calved ~2700 m^2 (~100m×27m) of glacier ice and raised the lake level by ~2.5

m (almost reaching the level observed on 08 September 2024 when comparing lake extents) but caused no additional water drainage at the outlet channel. The second, a ~4.29Mm^3 rock avalanche, occurred in the late afternoon of 16 December, struck the frozen lake with an estimated ~2.86 Mm^3 of rock directly impacting ice. This impact generated a sub-ice impulse wave that fractured the ~35 cm thick ice, produced an "ice tsunami" with ~10 m run-up, and triggered a flash flood. A large volume of permafrost rocks collapsed from the upper part of the same area, leaving a distinct scarped edge line on the cliff wall. The second collapse significantly disturbed Pida Lake, causing an additional slight rise in lake level (~1 m), an 'surged' lake terminus (~200 m, see supplementary file, Movie S1), fractured and whitened lake ice, and the relocation of floating icebergs in the middle part of the lake. Following this collapse, another section of frontal glacier ice (~250m×27m) across the entire ice tongue calved away. The observed repeated glacier terminus calving between 15 and 17 December indicated that both two lateral collapses had caused lake disturbance (i.e., lake water level fluctuations) but the second rock avalanche ultimately triggered the lake-wide ice fracture/displacement and the outburst flood.

The second rock avalanche, starting from approximately 210 meters above the lake surface, occurred directly above the current glacier terminus area (Fig. 3e). The absence of ice-laden debris on the lake surface, as observed in Fig.2a, suggests that the near-terminus lake ice was insufficiently thick to withstand the crashing impact of the rock avalanche. According to the field inspection team, the lake ice thickness near the end moraine and outlet area was approximately 35 cm. Based on the detached area extent (40,533.65 m^2) derived from pre- and post-event UAV images (Fig.3 and Fig.S2), roughly 2/3 of the collapsed rock block directly crashed on the frozen lake surface and the remaining 1/3 likely fell onto the glacier terminus surface. However, if the rock mass had not fragmented immediately upon impact, the entire rock block would have slid into the lake. Using two UAV DEMs surveyed on 08 September 2024 and 12 September 2025 (See Supplementary File), the volume of the collapsed rock block was estimated ~4.29±0.05 Mm^3, which means that at least ~2.86±0.05 Mm^3 rock hit the lake ice and fell into the lake. This volume of rock mass is significantly smaller than the 2023 collapsed lateral moraine into South Lhonak (14.7~16.75 Mm^3) but significantly larger than the 2020 landslide into Jinwuco (~1.2 Mm^3), both happened in summer ice-free situations and caused destructive floods to downstream (Sattar et al., 2025; Zheng et al., 2021b).

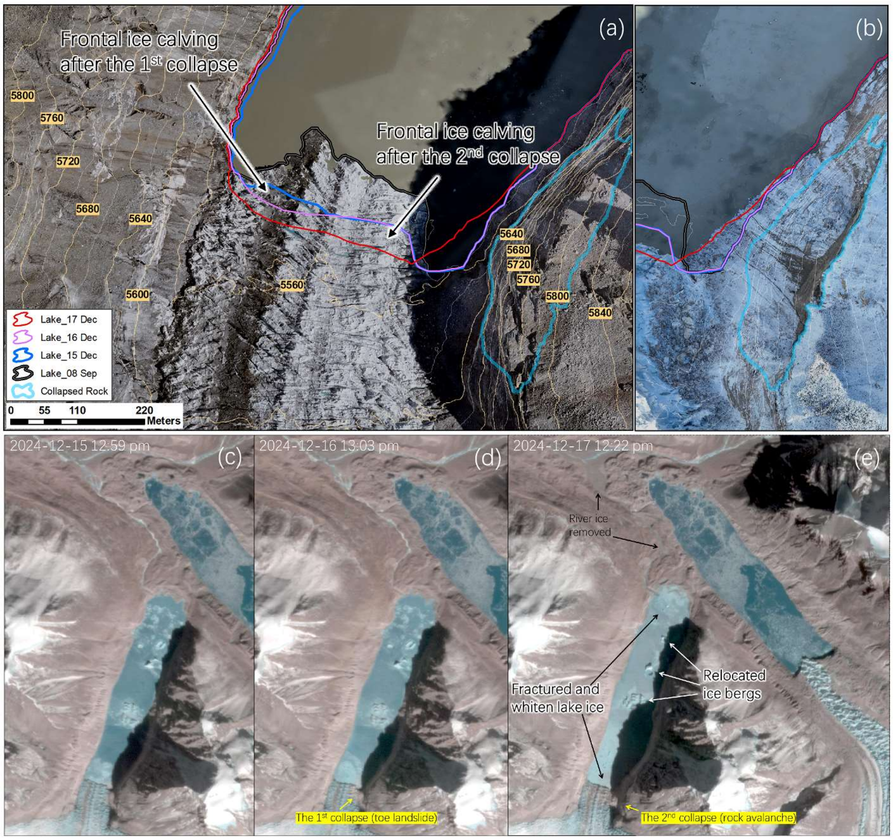

Fig 3. UAV orthographic images (a: 8 September 2024; b: 12 September 2025) and PlanetScope imagery groups (c, d, e) reveal the collapsed rock mass and the disturbed frozen surface of Pida Lake. Contours (20m interval) were derived from the September 2024 UAV DEM. The rock-avalanche scar (light-blue line) and the lake extents for 15-17 December were delineated from images shown below.

The combined ground and remote sensing evidence presented above elucidates the process chain leading to the 2024 winter outburst flood from Pida Lake. Satellite observations reveal that both Pida Lake and Longbasaba Lake experienced a multi-day period of lake ice growth between December 7 and December 10, during which the air and lake water temperature were observed with a noticeable drop (Fig.S3). Preceded by a warming period from 11 to 14 December, the significant daily temperature fluctuations (approximately between -12°C and 0°C) on 15 and 16 December are suspected to have induced a strong rock thermal shock and sharp stress gradients, finally triggering the rock failures. Between 15 and 16 December 2024, two cascading landslides/rock avalanches above the glacier terminus collapsed into the frozen lake and fractured the lake ice. The second rock avalanche occurred on 16 December and triggered a significant impulse wave that propagated beneath the lake ice and extended to the distal downstream areas of the lake. Although the wave pulse was limited, it lifted the marginal lake ice around the end moraine, creating an 'ice tsunami' with a maximum amplitude of ~10 meters. This amplitude was slightly less than the freeboard of the dam (~13-15 m), preventing a destructive overtopping process. However, a small volume of lake water spilled out through the outlet channel, forming a flash flood that propagated over ~140 km downstream. Channel erosion caused by the flash flood was primarily confined to the upper section of the flow path, and no damage to buildings or roads was reported following the flood. The most significant inundation occurred in the lower part of the wetland (Fig.1), but with limited sedimentation impact. Most of the debris was deposited in the upper valley between Qiangmu and Saer. Although the flash flood did not result in hazardous impacts downstream, it is conceivable that a much worse cascading hazard could occur without the buffer of lake ice, which might cause a single or combined failure of Longbasaba and Pida lakes.

5 Lessons and implications

The delivery of rock avalanche-triggered impulse energy to sub-ice water and the amplitude of the consequent sub-ice wave surge are highly dependent on the presence and thickness of the lake ice. Although the frozen state of Pida Lake significantly mitigated the hazardous impact of the rock avalanche-induced GLOF, this winter-outburst flood observed in Central Himalaya sounded an alarm for high mountain communities. A single rock- or icefall can hit pre-cracked plates and trigger an impulse wave that shatters the lake ice cover and causes flood, like the chain reaction has already been documented in this study. Even when ice looks uniform, point-scale thinning driven by sub-ice seepage, snow insulation and thaw–freeze cycles can drop local thickness (Culpepper, 2024), while warming that shortens the cold season also destabilizes adjacent valley walls (Gruber and Haeberli, 2007). Changing glacial lake ice phenology (Woolway et al., 2020), which has not been thoroughly investigated or incorporated into most previous GLOF assessment studies, could play a critical role in influencing the process of ice/rock avalanche-induced lake disturbances and failures. As temporally shortening and quality weakening of lake ice cover (Culpepper, 2024; Huang, 2022), coupled with the increasing frequency of glacier/lake-adjacent slope failures (Islam et al., 2025), it is anticipated that the risk of glacial lake failures during cold seasons will increase under condition of atmospheric temperature rise in high mountain regions. We recommend enhancing public awareness and safety protocols for the visiting security of frozen glacial lakes, considering the potential for sudden lake disturbances and failures caused by nearby landslides and ice/rock falls. Cryospheric and hazards community should treat winter GLOFs as an emerging class of threat and to prioritize lake-ice monitoring in the next generation of early-warning systems.

While engineering interventions (etc. lake level lowering via siphon or channel excavation, and dam reinforcement using rockfill or gabion walls) can reduce risk associated with high-level glacial lakes, the increasing frequency and intensity of paraglacial slope failures, along with shifting weather patterns in high mountain areas, may trigger lake outburst more frequently. Recent catastrophic GLOFs, such as that from South Lhonak Lake in Sikkim, India (Sattar et al., 2025), and the successful evacuation from the Blatten landslide in the Swiss Alps (Islam et al., 2025), underscore the importance of timely and accurate EWS for saving lives. An effective EWS must continuously integrate up-to-date information on hazard-forming conditions. Current EWS may account for changing climate conditions, paraglacial rock/slope stability and glacier/glacial lakes dynamics; we further recommend that future EWS incorporate evolving lake ice conditions into warning protocols since before failure a frozen lake would have no or limited lake-level fluctuations, which usually be monitored as one of the key thresholds for GLOF warning. Moreover, since water-pressure-based sensors often become non-operational when a lake freezes, new sensing technologies or strategies are needed to monitor real-time lake and ice disturbances and integrate these into GLOF early warning systems.

Code and data availability

No code was generated during the current study. Satellite datasets analysed in this study are primarily derived from publicly accessible Earth observation sources. Sentinel-2A/B imagery is available from the European Space Agency (ESA) Copernicus Open Access Hub. PlanetScope images were provided by Planet Labs Inc. through the Education and Research Programme and accessed via Planet Explorer (https://www.planet.com).

Supplement link

The link to the supplement will be included by Copernicus, if applicable.

Author contributions

Q.L. developed this study and led the writing of the manuscript. Y.Y. and Q.L. carried out repeat UAV mapping and conducted flood analysis. J.Y., Y.L. and X.L. mapped the glacier/lake/slope changes and contributed to the development of the methodology. D.L. and X.W. analyze the local air and lake water temperatures. Q.Z., H.W. and Y.Y. collected pictures and videos from local villagers and contributed field expeditions. Y.F, B.Z., S.L., Y.N. and S.K. contributed to the discussion, writing and review of the manuscript.

Competing interests

The authors declare no competing interests.

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Review statement

The review statement will be added by Copernicus Publications listing the handling editor as well as all contributing referees according to their status anonymous or identified.

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