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Glacial lake outburst floods threaten Asia's infrastructure

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People and infrastructure in the Tibetan Plateau and surroundings (TPS) face an increasing risk from glacial lake outburst floods (GLOFs) as the construction boom in transport and hydropower infrastructure coincides with a sustained and regional increase in outburst frequency. We have compiled an inventory of GLOF events since 1900 in the TPS, an area that acts as a key engine of environmental change in Asia [1], and examined the evolution and impact of recent floods from the surging Shisper Glacier that have destroyed homes and highways and could continue for several more years. We conclude that this ongoing increase in both exposure and glacio-climatic hazard poses a significant threat to Asia's economic development.

A boom in investment in transport and hydropower infrastructure is underway in Asia's high mountains while downstream populations are growing rapidly [2], and these two factors, combined with climate change, are raising the risk of disastrous floods from the region's mountain cryosphere [3, 4]. Flash floods (including GLOFs) descending from the mountains with high kinetic energy have recently damaged transport and power infrastructure (Table S1) such as the Upper Bhote Koshi hydropower plant [5], with a reconstruction cost of 57 million USD. Future flash floods are a potential threat to major new infrastructure, for example, hundreds more hydropower projects [6].

Sudden and catastrophic GLOFs in high mountain landscapes result from the failure of natural dams that impound glacial lakes. Such lakes have been both growing in extent and becoming more numerous through much of the Himalayas [7] and more widely across TPS [8], such that there are now 3745 glacial lakes larger than 0.1 km^2 across TPS [9]. Many of these are dammed behind ridges of glacial moraine left behind as glaciers have retreated, while in the Karakoram, a cluster of surging glaciers repeatedly advance across tributaries of the Indus and Tarim Rivers, creating ice-dammed lakes [6]. In addition, supraglacial and englacial lakes form on glacier surfaces and within the glaciers themselves. Such moraine- and ice-dammed lakes are inherently hazardous as the lakes grow, because unconsolidated moraine dams are mechanically weak and because ice within dams is both buoyant and prone to runaway channel enlargement by melting, as water-flow through a widening channel is able to increase and further accelerate channel growth [10].

Multiple GLOFs recorded from 1964 to 2022 have damaged Asian infrastructure (Table S1), but the character and therefore destructiveness of these floods are not well understood and they remain difficult to predict. From 1900 to 2022, a total of 298 GLOF events (categorized as moraine-dammed, ice-dammed or 'other' GLOF), were reported [4, 6, 10], with maximum affected distances exceeding 100 km (Fig. 1), and with increasing frequency through time. The various GLOFs are spatially heterogeneous and affect different basins in TPS: moraine-dammed GLOFs have caused the most severe damage while ice-dammed GLOFs are the most frequent (Fig. 1 and Table S1). Along with the Bhote Koshi disaster, moraine-dammed GLOFs (Fig. 1) are mostly located in the Himalaya, the Nyainqentanglha and Tien Shan, heavily affecting the Ganges and Brahmaputra basins, and have resulted in particularly severe damage to hydropower projects, bridges, and roads, such as the 2016 Gongbatongsha Tsho [5] and 2020 Jinwucuo [12] events. Ice-dammed GLOFs that dominate in the Karakoram and the Tien Shan and affect the Indus Basin and Tarim Basin, such as those at Shisper, Kyagar, and Merzbacher, have repeatedly destroyed local bridges, highways, and hydropower projects [4]. Outbursts from englacial or supraglacial lakes have been reported in the Himalaya, the Karakoram, the Pamir and the Tien Shan, but have caused less severe damage due to their more limited volume in TPS [4, 6].

Against the background trend of increasing GLOF risk [4] due to a combination of progressive climate and glacier changes and an upstream shift of people and infrastructure [2, 6] into GLOF-affected areas, sporadic extreme events also trigger GLOFs. Earthquakes, intense rainfall, ice avalanches, and landslides [4, 6], such as one in 2020 at Jinwucuo [12], have all been identified as such sporadic GLOF triggers. Recently, on 7th May 2022, a strong early thaw of snow and ice during an extreme heat wave appears to have triggered the outburst of a lake dammed behind the surging Shisper Glacier [13] in the Hunza Valley of the Karakoram. Each year since 2018, ice-dammed Shisper Lake has filled and persisted for up to several months before disappearing within hours to days when a drainage channel opens (Fig. 2a-b). This recent active phase of surging and repeated GLOFs at Shisper continues a record that spans more than a century: six major GLOFs were recorded during 1889-1904 as a result of surges, including one after an exceptional surge advance of 11 km from 1892-1893 [13]. A further five followed a large 1892-1906 surge (Fig. S1) [13], with floods in three consecutive years (1902-1904) that destroyed downstream bridges and irrigation channels. Smaller surges between 1954 and 1979 did not produce GLOFs.

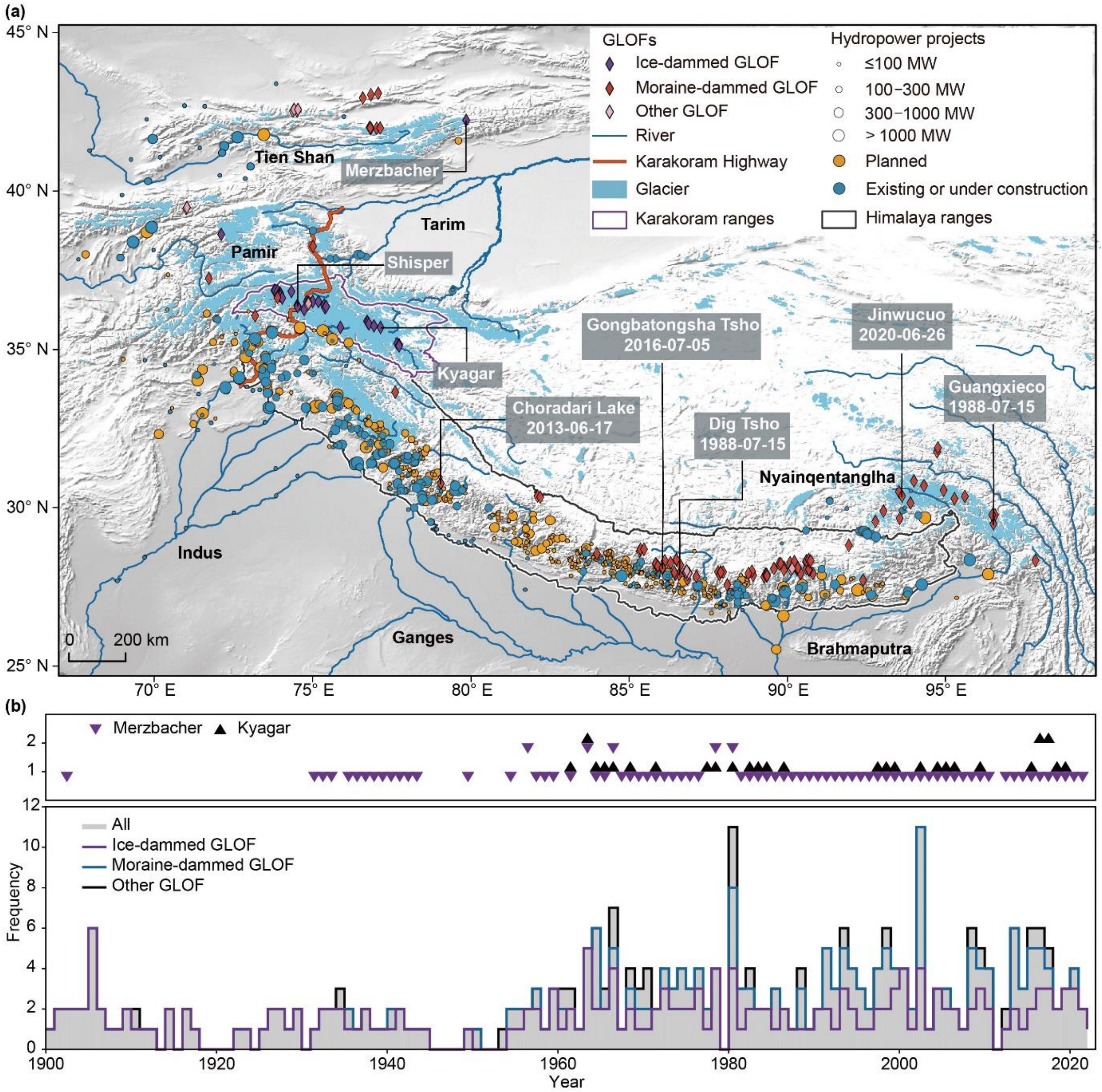

Fig. 1. Glacial lake outburst floods (GLOFs), hydropower projects (HPPs), and transport infrastructure across the Tibetan Plateau and surroundings. (a) Distribution of recorded GLOFs, HPPs [6], and major transport infrastructure. Historically-recorded GLOF events were compiled from the literature [4, 6, 10, 13] and satellite observations, including outburst floods from ice-dammed, moraine-dammed, englacial and supra-glacial lakes (herein called other GLOF). Gray boxes show GLOF-event names and dates for one-off moraine-dammed GLOFs, but no labels for ice-dammed GLOFs (Merzbacher, Kyagar, and Shisper events were ice-dammed GLOFs) due to their repeated occurrence. (b) Chronologically increasing frequency of GLOFs since 1900. Merzbacher and Kyagar are the most frequent ice-dammed GLOF sites.

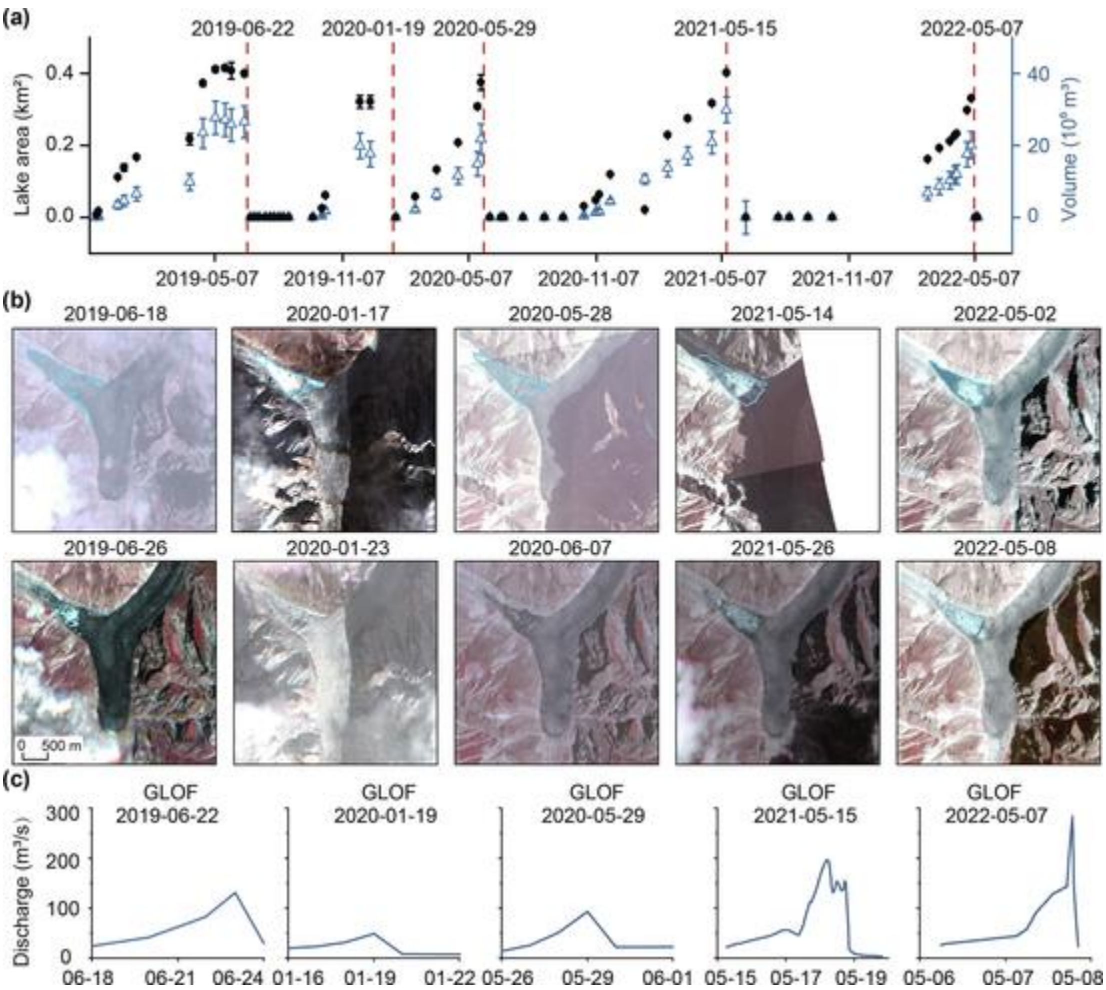

Fig. 2. Five Shisper GLOFs and associated peak discharge. (a) Changes in estimated area and volume for the Shisper ice-dammed lake during 2018-2022. The red dashed line represents the date of each GLOF. (b) Shisper Lake before and after each GLOF observed by the Planet satellite. (c) Measured hydrograph of each GLOF during 2020-2022.

Here, we report for the first time on the destructive Shisper GLOF in Spring of 2022 (the fifth since 2019) that swept away the Hassanabad Bridge in Pakistan, severed the economically important Karakoram Highway, and destroyed homes and farmland (Fig. S2). It had a high peak discharge of approximately 280 m^3/s at the Hassanabad river gauge (Fig. 2c), 14 times greater than the annual mean discharge of 20 m^3/s, and a new record for this site. Counterintuitively, this recorded peak GLOF discharge was higher than each of those in the preceding years (e.g., peaks of 142 m^3/s and 197 m^3/s for 2019 and 2021 respectively) but involved a smaller total decrease in lake volume and area (Fig. 2a, c). Such a variable relationship between peak discharge and the volume of lake drainage is consistent with the repeated failure of an ice dam through flotation and/or melting of an ice-walled drainage channel, in contrast to the positively-correlated total and peak discharge associated with moraine-dammed lake outbursts [14] (Fig. S3). This variable relationship makes the risk posed by individual ice-dammed GLOFs difficult to predict, and this unpredictability in the GLOF mechanism is compounded by considerable changes in the position of the flood outlet channel through the active period, as evidenced in satellite images (Fig. S1b). However, at the average rate of retreat of 117 m/a for 1906-1954 (Fig. S1a, c), Shisper Glacier could take approximately 12 years to move back to its pre-surge position (on September 18th, 2017), hence the Hassanabad catchment could continue to be impacted by GLOFs throughout this period.

The hydrology and socio-economic damage of Shisper Glacier GLOFs are uniquely well observed, but similar GLOFs are not uncommon. Since 2019, peak GLOF flows have reached 2-14 times the base flow, leading to sustained, cumulative damage to infrastructure downstream of Shisper Glacier (Fig. 2 and S2). Satellite observations from Hassanabad show that the high 2022 peak led to the most substantial lateral river-bank erosion, especially at sections A-D of Figure S2 where the Hassanabad Bridge and hydropower station were heavily damaged. The river channel widened over this section by up to 63±3 m (uncertainty of 1 image pixel) due to rapid fluvial erosion, an impact similar to a 2016 GLOF report in the Himalaya [5]. Most Karakoram GLOFs also result from ice-dam failures following glacier surges, and five Karakoram valleys (Hunza Central, Shaksgam, Shimshal, Karambar-Ishkoman, and Kumdan-Shyok) account for more than 90% of recorded ice-dammed GLOFs [10]. Kyagar, in the Shaksgam, is another hotspot (Fig. 1) where 30 such events were recorded by ground and satellite observation from 1961-2019. Outside the Karakoram, the Tien Shan's Merzbacher Glacier has the most frequent ice-dammed GLOFs in the TPS [10], with 81 events recorded during 1902-2021. Many socio-economic loss records from ice-dammed GLOFs are missing or incomplete due to their relatively lower level of destruction and their typical remoteness from existing infrastructure, but we point out that the cumulative damage to downstream infrastructure from frequent ice-dam GLOFs should be of concern.

We emphasize that the nature of each dam and its mechanism of failure (Fig. S3) control the hydrograph of GLOFs, and hence the extent of related downstream damage. A high peak discharge is often more important in determining the erosive power and potential destructiveness of a GLOF than the total discharge. Though the nature of each dam is key to the GLOF risk that it poses, and as damaging as GLOFs from ice-dammed lakes (and englacial or supraglacial lakes) can be, the relatively slow drainage through ice dams, mostly via the melt-widening of an ice conduit, greatly reduces the peak discharge compared to typical hydrographs of catastrophic moraine-dam failure. Very rapid failure of moraine dams via overtopping or piping [6] generates a higher discharge in a shorter period, producing greater fluvial erosion and more damage to downstream infrastructure. The recorded highest peak discharge for a moraine-dam GLOF in the Himalaya [15] reached 15,920 m^3/s, destroying the downstream Sun Koshi hydropower plant. The observed maximum Shisper discharge peak (approximately 280 m^3/s) is only about 5% of the 5000 m^3/s moraine-dam GLOF peak estimated using empirical equations of peak discharge and lake volume [14]. Furthermore, a dam's material and failure mechanism control not only the magnitude but also the frequency of GLOFs. One-off moraine-dam failures are irreversibly catastrophic, unlike ice-dam GLOFs with their sometimes-cyclical fill-and-fail behavior (as at Shisper), boosting the frequency of ice-dam failures (Fig. 1). Moraine dams form as glaciers retreat, while ice-dammed glacial lakes form behind a surging glacier that advances across a channel [6]. As the climate-induced recession of glaciers occurs [16], a shift from ice-dam to moraine-dam GLOFs could take place in regions where ice-dammed GLOFs currently predominate, and this could lead to considerably more destructive GLOFs in these regions.

Although the growing risk posed by GLOFs [12] across TPS is clear, the problem of managing them touches on several key knowledge gaps that scientists face. On the local scale, the strength of glacial-lake dams is difficult to determine because they are made of a poorly known combination of (melting) ice, unconsolidated sediment and rock. On larger scales, the rate of water supplied to many of the region's lakes by glacial melt depends on the thickness and thermal conductivity of rock debris on the glacier surface, and the nature of lakes in contact with the ice [6], but their properties are largely unknown. The water supply from melting snow depends on the volume of snow in each lake catchment, which is difficult to observe, and the snow melt rate which is difficult to model over rugged mountain terrain where few weather observations exist [6]. As glaciers retreat, the timing and location of new lake formation depends on their largely unmapped thickness, the poorly-known melt rate described above, and poorly understood patterns and trends in snowfall and rainfall that both sustain glacier mass and fill glacial lakes directly. For lakes that form behind surging glaciers, the timing and rate of glacier surging remain particularly difficult to predict. Adding to this tower of uncertainty are the difficulties of predicting extreme weather events like the 2022 Asian heatwave, and the even greater difficulties of predicting earthquakes, ice avalanches, and landslides. Overlying all of these issues lies perhaps the greatest uncertainty of all – the climate pathway that we choose to follow over the critical next few decades. In the face of such uncertainty, infrastructure planners and risk assessors must expect sudden catastrophic GLOFs, should design with this in mind, and so should invest in monitoring and warning systems in the mountain cryosphere that will likely be key in preventing future loss of life and infrastructure. Given the importance of infrastructure for Asian economic development, the imperative of proactive GLOF disaster reduction could not be clearer.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgments

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Author contributions

Yong Nie and Hamish D. Pritchard conceived the study, Yong Nie, Qian Deng, Wen Wang and Muchu Lesi performed data processing and analysis, and Yong Nie wrote the manuscript. All authors reviewed and edited the manuscript.

Appendix A. Supplementary materials

Methods, Fig. S1-S3, Table S1-S2 are introduced in the Supplementary document.

Supplementary materials can be found online at https://doi.org/10.1016/j.scib.2023.xxxx.

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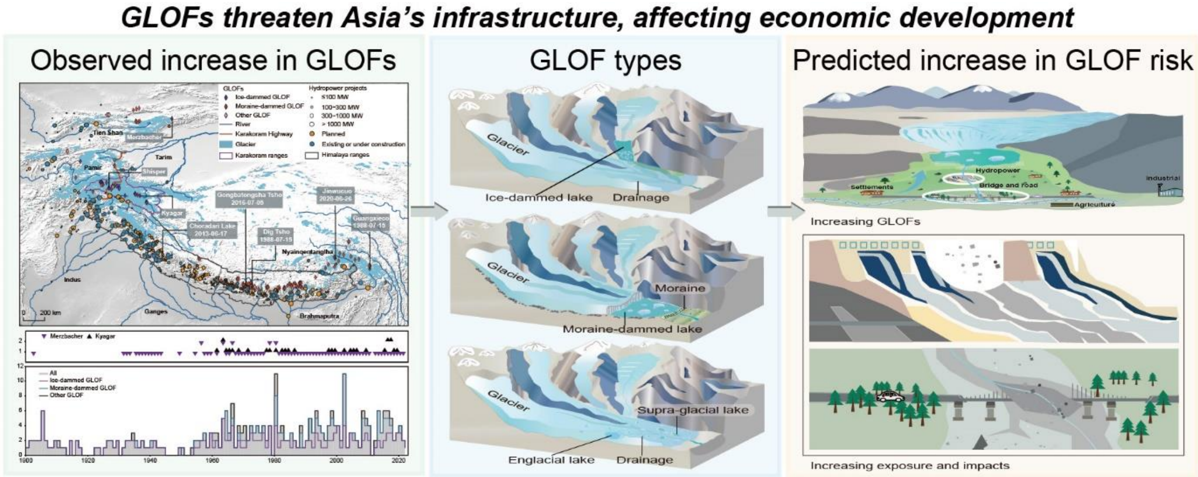

Graphical abstract