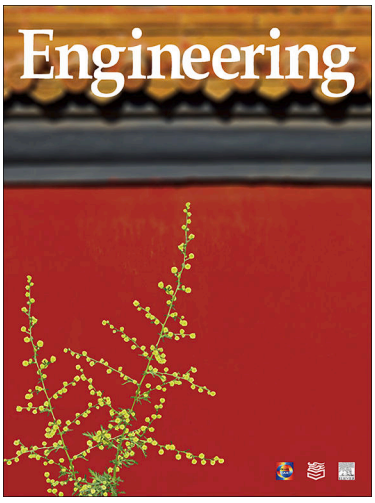
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Perspectives

Outburst Floods Redefine Design Floods for Critical Infrastructure in High-Mountain Rivers

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Hydraulic Engineering—Perspective Article

Outburst Floods Redefine Design Floods for Critical Infrastructure in High-Mountain Rivers

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ABSTRACT

Design floods serve as safety standards for critical infrastructure and flood protection. Conventionally, they are estimated from historical precipitation and streamflow records and therefore largely represent meteorological floods. However, in high-mountain rivers, this practice can severely underestimate actual flood hazards because the most catastrophic events are often geomorphically triggered outburst floods. Here, we present evidence that outburst floods can generate peak discharges that far exceed local 100-year meteorological floods and even surpass the global meteorological flood envelope. We further show that the

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dominant flood-generating mechanism shifts systematically along the river's longitudinal profile. Glacial lake outburst floods dominate in U-shaped paraglacial valleys, landslide lake outburst floods in V-shaped fluvial gorges, and meteorological floods in wide alluvial floodplains. Consequently, no single mechanism can adequately define basin-wide safety standards. To address this gap, we propose a unified design flood framework that probabilistically integrates the contributions of these distinct flood-generating processes. This framework redefines design standards to improve the resilience and safety of critical infrastructure in high-mountain regions.

1. The blind spot in high-mountain infrastructure design

In engineering planning, flood protection design codes require infrastructure to withstand floods of specific return periods, dictated by the importance of the infrastructure and the potential consequences of its failure. Conventionally, engineers derive the flood frequency curve (i.e., peak discharge–return period relationship) using historical streamflow records, assuming that extreme river flows result primarily from precipitation–runoff processes over the contributing catchment. The estimates derived from the established flood frequency curve are referred to as meteorological design floods. These design flood estimates directly determine critical structural parameters, including dam crest heights, spillway capacities, bridge elevations, and urban flood-defense levels [1,2] (Fig. 1).

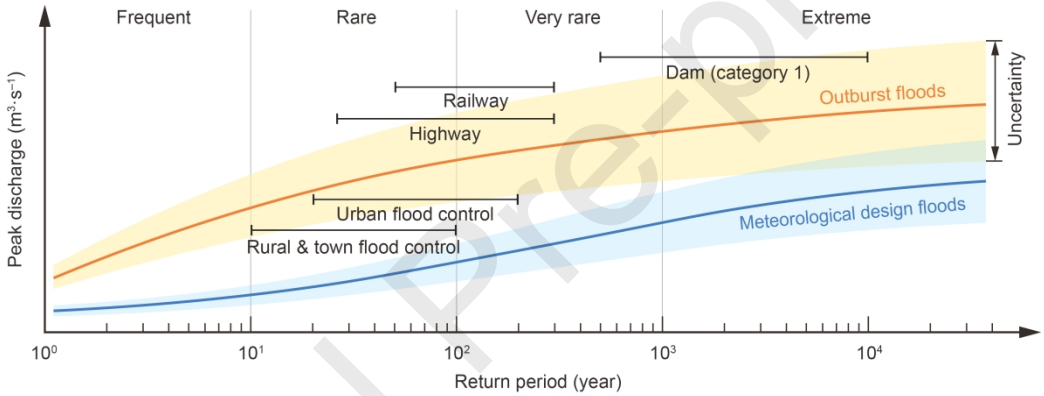


Fig. 1. Schematic comparison of meteorological design floods (used for infrastructure design) and outburst floods.

Although this method works well in lowland plains, where floods are indeed driven by precipitation, it fails in high-mountain gorges, particularly in High Mountain Asia (HMA). Characterized by intense tectonic activity, steep topography, and rapid deglaciation, HMA is highly susceptible to geomorphic hazards, particularly glacial lake outburst floods (GLOFs) and landslide lake outburst floods (LLOFs) [3–6]. As illustrated in Fig. 2, GLOFs and LLOFs have occurred widely across HMA. Furthermore, a growing number of existing and planned hydropower projects are located along the downstream propagation paths of these potential outburst floods [7–9]. This spatial overlap between outburst flood paths and major engineering projects highlights a fundamental issue: safety standards based only on meteorological design floods may underestimate flood hazards, leaving infrastructure vulnerable to changing mountain environments [8].

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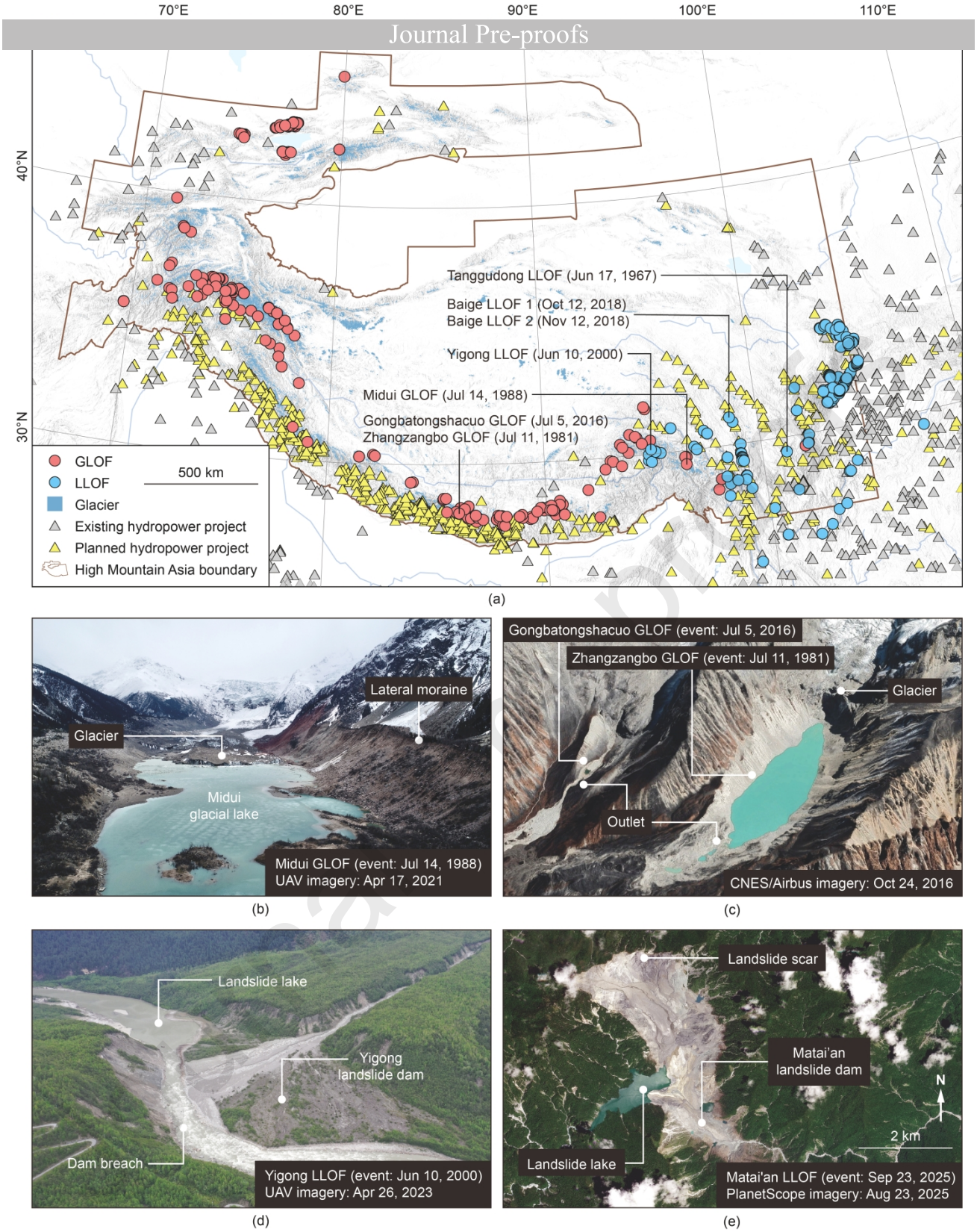


Fig. 2. (a) Spatial distribution of historical GLOFs, LLOFs, and hydropower infrastructure across HMA. Data sources: GLOF database v4.1 from Lützow et al. [10]; LLOFs from Xiao et al. [11]; existing hydropower projects from Lehner et al. [12]; and planned hydropower projects from Zarfl et al. [13]. (b) Unmanned aerial vehicle (UAV) view of the Midui glacial lake (29.46626°N, 96.50137°E; GLOF occurred on July 14, 1988). (c) CNES/Airbus satellite imagery accessed via Google Earth, showing the source areas of the Gongbatongshacuo GLOF (28.07812°N, 86.06442°E; July 5, 2016) and the Zhangzangbo GLOF (28.06695°N, 86.06574°E; July 11, 1981); spatial resolution: 0.5 m. (d) UAV view of the Yigong landslide dam (30.17580°N, 94.94143°E; LLOF occurred on June 10, 2000). (e) PlanetScope satellite imagery obtained through the Planet Education and Research Program, showing the Matai'an landslide dam in the Taiwan region of China

(23.69814°N, 121.30108°E) and the impounded lake before its outburst on September 23, 2025; spatial resolution: 3 m.

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2. Diverse flood-generating processes

High-mountain rivers function as more than just drainage paths for precipitation, and high-mountain floods are driven by diverse physical processes with distinct mechanisms, magnitudes, and durations [14–16]. Meteorological floods are bounded by an envelope curve defined by the world's largest measured meteorological floods (Fig. 3(a)) [17]. This curve represents an empirical upper bound of observed meteorological flood discharges for a given drainage area. However, outburst floods are governed by a fundamentally different mechanism: the sudden release of stored water from glacial or landslide-dammed lakes. As these floods are not determined by precipitation–runoff processes, their peak discharges can exceed the maximum values generated by precipitation alone for the same drainage area. Notably, LLOFs exceed the global meteorological flood envelope across a wide range of catchment areas (Fig. 3(a)) because landslide dams can form and breach along both upstream and downstream reaches [18]. By contrast, GLOFs in HMA can also produce peak flows above the meteorological envelope, but their impacts are typically confined to headwaters near glacial lakes (Fig. 3(a)) [10]. Thus, GLOF hazards are primarily an upstream concern, restricted to smaller drainage areas, whereas LLOF hazards persist much further downstream, threatening infrastructure even in gorges with large drainage areas.

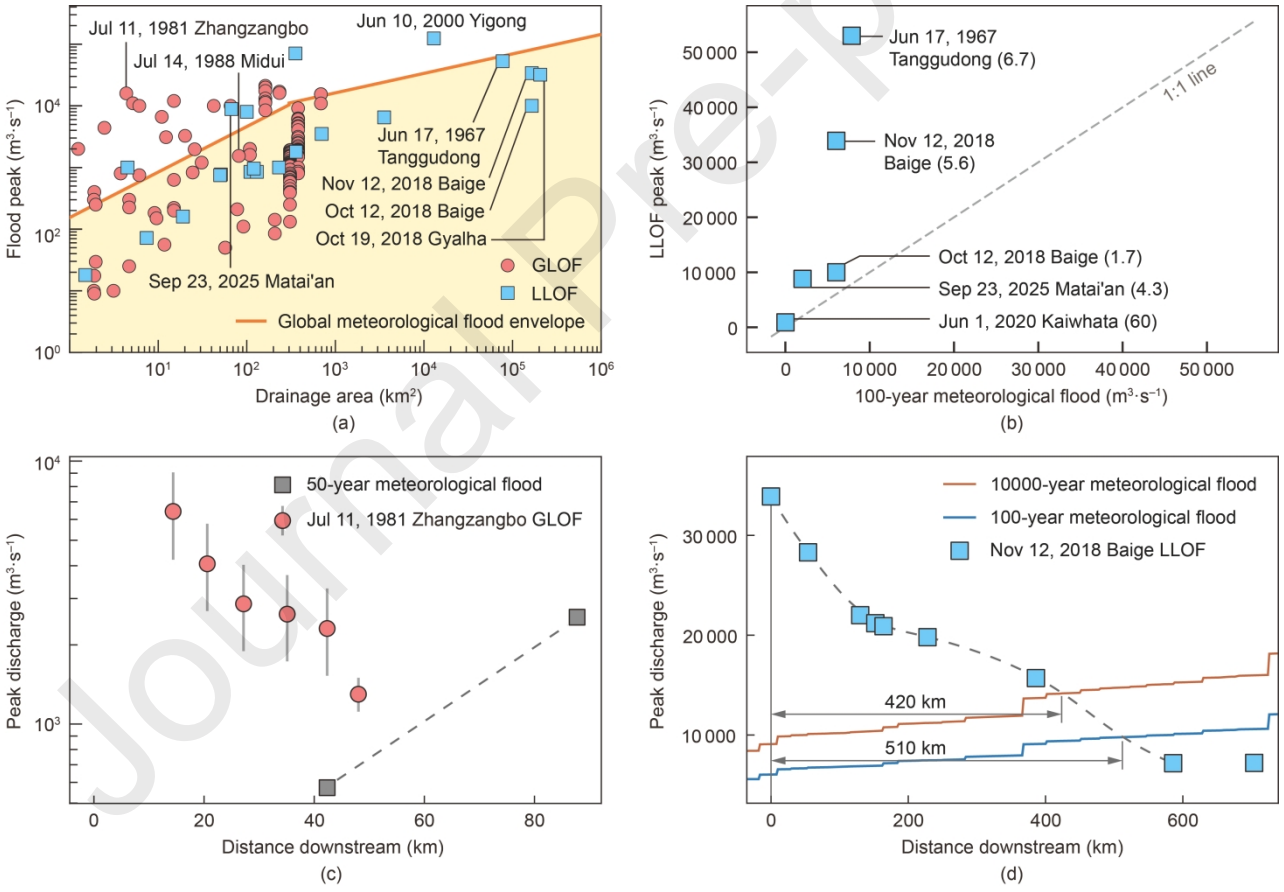


Fig. 3. Evidence of outburst floods exceeding meteorological design floods in high-mountain rivers. (a) Comparison of outburst flood peak discharges with the global meteorological flood envelope, highlighting that the sudden release of pre-stored water can generate peak flows exceeding the meteorological flood envelope for comparable drainage areas. (b) LLOFs with peak discharges exceeding local 100-year meteorological floods; values in parentheses denote the ratio of the LLOF peak to the local 100-year meteorological flood discharge. (c) The July 11, 1981, Zhangzangbo GLOF discharge compared with the 50-year meteorological flood; error bars indicate estimated uncertainty; data are from Cook et al. [3]. (d) The November 12, 2018, Baige LLOF discharge compared with the 100-year and 10 000-year meteorological

floods; data are from Xiao [19]. In panel (a), the envelope curve is adapted from the World Meteorological Organization [17]; LLOF data are from Fan et al. [18] and Froehlich [20]; GLOF data are the HMA subset of database v4.1 from Lützow et al. [10].

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Beyond peak discharge, the hydrographs of these events differ in shape and duration. Meteorological floods appear as broad, sustained waves lasting days, whereas outburst floods occur as high-magnitude, short-duration pulses lasting only hours [21,22]. This pulse-like behavior results in extreme impact forces and sediment transport capacity. The October 2023 South Lhonak Lake GLOF generated a peak discharge of 48 500 $m^3 \cdot s^{-1}$, which far exceeded historical regional meteorological extremes. As the flood propagated, it evolved into a hyper-concentrated flow, mobilizing ~270 million m^3 of sediment and overwhelming the 1200-MW Teesta III hydropower dam [23]. This event demonstrates that outburst floods can reshape riverbeds and erode dam abutments beyond the conditions considered in standard clear-water spillway design.

3. Outburst floods dwarf meteorological design floods

The extent to which outburst floods exceed meteorological design floods is alarming. Recent infrastructure failures illustrate this significant gap. In Nepal, the Bhotekoshi River experienced two GLOFs on July 11, 1981, and on July 5, 2016 (Figs. 2(a) and (c)). Among these, the July 1981 Zhangzangbo GLOF had an estimated peak discharge of 2300 $m^3 \cdot s^{-1}$ at the downstream town of Barabise, 4.4 times the local 30-year flood discharge of 525 $m^3 \cdot s^{-1}$ [3]. On July 5, 2016, the Gongbatongshacuo GLOF swept through the upper Bhotekoshi hydropower project with a measured peak discharge of 2576 $m^3 \cdot s^{-1}$, exceeding the project's probable maximum flood of 1750 $m^3 \cdot s^{-1}$ [24].

Similarly, LLOFs can greatly exceed the meteorological design floods used in standard engineering practice (Fig. 3(b)). On November 12, 2018, the Baige LLOF (location shown in Fig. 2(a)) on the Jinsha River peaked at 33 900 $m^3 \cdot s^{-1}$, 5.6 times the local 100-year meteorological flood and 3.7 times the local 10 000-year meteorological flood [19]. Despite being designed to withstand the local 100-year meteorological flood, at least 13 large bridges spanning the Jinsha River were destroyed. On June 17, 1967, the Tanggudong LLOF (see Fig. 2(a)) on the Yalong River, a tributary of the Jinsha River, peaked at 53 000 $m^3 \cdot s^{-1}$, 6.7 times the discharge of the local 100-year meteorological flood (7860 $m^3 \cdot s^{-1}$) and 4.7 times that of the 10 000-year meteorological flood (11 200 $m^3 \cdot s^{-1}$) [19]. On June 1, 2020, the LLOF on the Kaiwhata River in New Zealand generated a peak discharge of 900 $m^3 \cdot s^{-1}$, 60 times larger than the 100-year flood of only 15 $m^3 \cdot s^{-1}$ [25]. Most recently, on September 23, 2025, the Matai'an creek LLOF in the Taiwan region of China produced a peak flow of 8800 $m^3 \cdot s^{-1}$, 4.3 times the local 100-year meteorological flood of 2040 $m^3 \cdot s^{-1}$ [26].

Here, we examine two representative events to demonstrate how far downstream outburst floods can persist above meteorological design floods. The July 11, 1981, Zhangzangbo GLOF attenuated as it propagated downstream from the breach site; however, even after traveling more than 40 km, its peak discharge remained above the estimated local 50-year meteorological flood discharge [3] (Fig. 3(c)). Similarly, the peak discharge of the November 12, 2018, Baige LLOF remained above the 10 000-year meteorological flood discharge as far as 420 km downstream and above the 100-year flood as far as 510 km downstream [19] (Fig. 3(d)).

4. Evolution of dominant flood-generating processes along the river profile

High-mountain basins function as continuous systems in which dominant flood-generating processes shift systematically from headwater to floodplain [16,27]. To capture this spatial evolution, we divide the river profile into three transitional geomorphic zones: U-shaped paraglacial valleys, V-shaped fluvial gorges, and wide alluvial floodplains (Fig. 4(a)). The transitions between these zones represent intersections where local environmental and topographic controls (e.g., deglaciation, valley geometry, and drainage area) dictate a shift in the dominance of different flood-generating mechanisms.

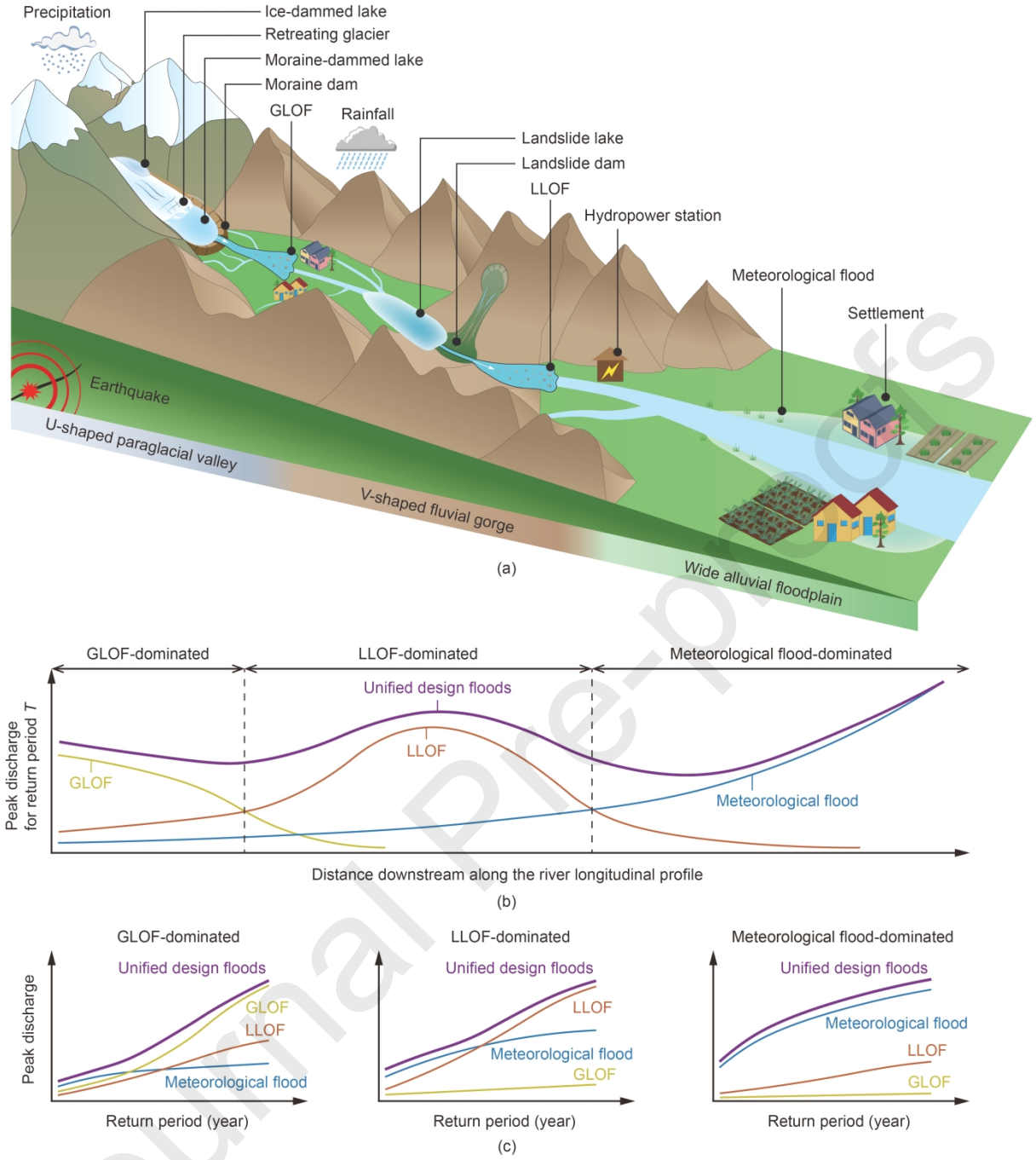


Fig. 4. Conceptual framework for deriving unified design floods. (a) Schematic of the three transitional geomorphic zones (i.e., U-shaped paraglacial valleys, V-shaped fluvial gorges, and wide alluvial floodplains). (b) Spatial evolution of dominant flood-generating processes and the unified design flood along the river's longitudinal profile. (c) Flood frequency curves illustrating the varying contributions of different flood types to the unified design flood across the three geomorphic zones.

(1) **U-shaped paraglacial valleys (GLOF-dominated).** In the uppermost paraglacial zone, the drainage area is typically insufficient to generate massive precipitation-driven floods. Instead, extreme hazards arise primarily from the instability of the cryosphere. Glacial retreat creates precarious glacial lakes, while permafrost degradation reduces the shear strength of rock slopes [7,28]. Although landslides occur frequently in this environment, their damming potential is limited by the local topography. As demonstrated by Argentin et al. [29], wide, flat, U-shaped deglaciated valley floors require large landslides to become fully dammed, and even such large landslides may create only small impoundments, limiting potential LLOF peak discharges. Therefore, extreme flood hazards in this uppermost zone are dominated by GLOFs.

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(2) **V-shaped fluvial gorges (LLOF-dominated).** As the river descends into deep, narrow gorges, the dominant extreme flood hazard shifts from GLOFs to LLOFs. This shift is driven by two key factors. First, the narrow V-shaped geometries of fluvial gorges provide high damming efficiency, allowing even small-to-moderate landslides to block the river and form high dams [11,29]. Second, the contributing drainage area here is larger than in the headwaters, providing greater volumes of water for impoundment.

However, high susceptibility to landslide dam formation does not necessarily result in a large LLOF. Morgan et al. [30] found that landslide dams are more likely to form in headwater river reaches where both drainage area and valley width are small. However, limited lake-storage space and small contributing drainage areas generally constrain the volume of impounded water, resulting in relatively localized LLOFs. Catastrophic LLOFs are therefore more likely when landslides impound deeply incised gorges with large drainage areas.

When such large landslide-dammed lakes breach, the resulting outburst floods can generate peak discharges far greater than those of meteorological floods. Furthermore, because GLOFs originating from the uppermost zone attenuate substantially as they propagate downstream, they lose their dominance in these reaches. LLOFs thus become the dominant extreme flood hazard in this zone. As landslide dams can form unpredictably at many locations along a gorge, LLOFs represent a major source of uncertainty in downstream engineering design.

(3) **Wide alluvial floodplains (meteorological flood-dominated).** Further downstream in the alluvial floodplains, the valley widens and the drainage area expands. In these reaches, upstream outburst flood peaks attenuate substantially because the gentle gradients and high flow resistance of the floodplains effectively flatten the flood hydrograph. Concurrently, runoff generated by basin-wide precipitation progressively overtakes outburst floods to become the dominant driver of flooding.

Although these three transitional zones represent a generalized geomorphic description typical of many Himalayan catchments, the exact zone boundaries and relative dominance of each flood type vary across different river basins. Therefore, future research should focus on basin-specific case studies to identify the specific river reaches where the dominance shifts from one flood mechanism to another.

5. Unified design flood framework

Engineering standards for high-mountain rivers must account for geomorphic instability. We therefore propose a unified design flood framework that represents flood hazards as a probabilistic mixture of diverse, overlapping flood-generating processes.

This unified approach captures how the relative contributions of different flood types vary along the river's longitudinal profile (Fig. 4(b)) and across return periods (Fig. 4(c)). Specifically, GLOFs dominate the extreme flood quantiles in the uppermost paraglacial valleys, but their peak discharges attenuate rapidly downstream. The contribution of LLOFs varies non-monotonically, peaking in fluvial gorges before declining toward the floodplain. As drainage area expands downstream, meteorological floods grow in magnitude and ultimately dominate the design curve in the downstream floodplain.

5.1. Unified design flood (probabilistic)

To operationalize this conceptual framework, the unified design flood can be calculated by combining the probabilities of individual flood types. Here, the annual non-exceedance probability for a given peak discharge q is represented mathematically by the cumulative distribution function (CDF). As a practical baseline, if these flood events occur independently, the CDF of the unified design flood, $F_{\text{unified}}(q)$, is simply the product of their individual CDFs [31,32]:

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$$F_{\text{unified}}(q) = F_{\text{Met}}(q) \times F_{\text{GLOF}}(q) \times F_{\text{LLOF}}(q) \quad (1)$$

where $F_{\text{Met}}(q)$, $F_{\text{GLOF}}(q)$, and $F_{\text{LLOF}}(q)$ are the individual CDFs for meteorological floods, GLOFs, and LLOFs, respectively. The return period corresponding to the unified design flood, $T_{\text{unified}}(q)$, is defined as follows:

$$T_{\text{unified}}(q) = \frac{1}{1-F_{\text{unified}}(q)} \quad (2)$$

The individual CDFs are derived using different methods. For meteorological floods, the frequency curve is typically established by fitting extreme value distributions to nearby gauge records. In the absence of long-term observations, however, estimating both GLOFs and LLOFs relies on process-based flood frequency analysis [33,34]. For GLOFs, this involves estimating lake outburst frequencies, generating breach scenarios, and routing the floods downstream. By employing Monte Carlo simulations over thousands of synthetic years, $F_{\text{GLOF}}(q)$ can be derived directly by ranking the simulated annual maximum peak discharges at the site of interest. Similarly, $F_{\text{LLOF}}(q)$ can be derived by coupling regional landslide frequencies with dam formation, breaching, and downstream routing scenarios within a long-term Monte Carlo framework.

Although the independence assumption offers a practical baseline, it may underestimate the true hazard because these floods often share common drivers. For instance, all three types of floods are typically more frequent during the summer season [15]. Furthermore, extreme rainfall can cause a severe meteorological flood while simultaneously triggering a river-blocking landslide, ultimately leading to an LLOF. To move beyond the independence assumption, practitioners can extend the process-based flood frequency analysis to incorporate the spatiotemporal overlap of different flood types. This approach requires continuous, long-term stochastic weather generators coupled with physical hydrological and hydrodynamic models. The combined simulation of meteorological flood, GLOF, and LLOF processes naturally captures their shared seasonality and dependencies. A unified frequency curve is then constructed directly by ranking the annual maximum peak discharges from this integrated time series.

Implementing this framework highlights a disparity in data availability between GLOFs and LLOFs. The timing, frequency, and magnitude of GLOFs have been studied extensively [5,35,36], largely because their sources (i.e., glacial lakes) are relatively easy to detect and monitor via satellite imagery. In contrast, characterizing LLOFs is considerably more challenging. Landslide dams can form stochastically anytime and anywhere along a river network, making them difficult to detect. Consequently, historical LLOF databases suffer from a reporting bias toward catastrophic events and frequently lack precise coordinates, exact timing, or peak discharge measurements [18,37]. Although progress has been made, quantifying the timing, frequency, and magnitude of LLOFs requires further work.

A single basin may not experience all three flood types. For example, basins without glacial lakes naturally do not produce GLOFs, and the GLOF component can be omitted from Eq. (1). Conversely, some basins are subject to more diverse flood mechanisms. For instance, snowmelt floods are prevalent during spring in the Tianshan Mountains of northwestern HMA due to rising temperatures [15,38]. Additionally, rain-on-snow floods are frequent and intense across the mid-to-high elevation bands of the Tianshan Mountains, Pamir Mountains, and Himalayas during spring and summer when rain falls on sufficient snow cover [39]. Previous studies have shown that rainfall, snowmelt, and rain-on-snow floods originate from distinct physical processes, resulting in different statistical characteristics and tail behaviors [31,40]. In catchments with mixed flood regimes, Eq. (1) can therefore be expanded to represent these mechanisms as separate flood types through a mixed distribution.

5.2. Stress testing for "black swans" (deterministic)

For critical infrastructure (e.g., category 1 dams, strategic railways), the traditional precipitation-based

probable maximum flood is insufficient [24]. Designs must withstand a maximum credible geomorphic event, defined as the physically plausible worst-case flood scenario bounded by regional geomorphic constraints. Stress testing against these "black swan" events requires constructing extreme scenarios for GLOFs and LLOFs.

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GLOF scenarios consider upstream glacial lakes whose outburst paths could affect the site of interest, assuming a catastrophic trigger (e.g., a massive ice avalanche) that causes the release of the maximum potential drainage volume, estimated via bathymetry or empirical area–volume scaling [41]. In contrast, LLOF scenarios use historical analogues to define hypothetical landslide-dammed lakes in upstream gorges. The dimensions of these lakes are based on extreme past events in the basin of interest or nearby basins and constrained by the local valley topography. Simulating these scenarios involves computing the outburst hydrograph at the breach site using a dam-breaching model or assuming a simplified hydrograph, followed by routing the flood wave to the site of interest [22,42,43].

6. Future opportunities and challenges

The unified design flood framework can also account for climate-driven non-stationarity. Rather than assuming stationarity, design values should reflect changes in the frequency and magnitude of each flood type. For meteorological and snowmelt floods, historical observations can be supplemented with climate projections to capture intensifying extreme precipitation and changing snowmelt dynamics [44]. Meanwhile, ongoing deglaciation is expanding glacial lakes, and GLOF hazards in HMA could triple by 2100 [45]. Landslide hazards are also projected to expand into higher elevations and previously stable regions across HMA [46], altering the spatial probability of landslide damming. Long-term infrastructure planning should therefore account for the non-stationary behavior of these flood-generating processes.

Although this study focuses on natural geomorphic outburst floods (GLOFs and LLOFs) in high-mountain rivers, the mechanism of dam breaches releasing large volumes of pre-stored water also applies to engineered dams in lower-elevation and urban areas. For instance, triggered by the extreme rainfall of Storm Daniel in September 2023, the cascading collapse of two engineered embankment dams in Derna, Libya, generated a catastrophic flood that devastated the coastal city and claimed more than 5000 lives [47]. Similarly, during the record-breaking rainstorms in Zhengzhou (July 2021) and Beijing (July 2023), China [48,49], widespread overtopping and sequential breaching of small water-retention structures (e.g., pond dams and check dams) suddenly released impounded water, raising downstream flood levels and exacerbating the consequences of the disaster. In a non-stationary climate with more frequent record-breaking rainfall, artificial reservoirs with varying flood protection standards can fill rapidly and fail, generating short-duration flood pulses similar to those generated by natural outburst floods. Therefore, it is necessary to re-evaluate and upgrade traditional design flood methods to account for climate non-stationarity and the cascading failures of artificial infrastructure across diverse environments.

Although the proposed unified design flood provides a more realistic characterization of flood hazards, engineering risk also depends on exposure and vulnerability. Because considering multiple flood-generating mechanisms yields higher design flood values than traditional meteorological flood estimates, relying only on more stringent structural standards may be economically impractical. Water conservancy projects must balance hydropower, irrigation, and flood control under budget constraints. Rather than continually raising dam crests or increasing spillway capacities, decision-makers can combine structural and non-structural measures. Early warning systems, land-use controls that restrict development in high-hazard zones, and emergency evacuation plans can reduce exposure and vulnerability at relatively low cost [50–52]. Cost-benefit analysis can then identify strategies that balance construction costs against reductions in expected damage [53,54].

7. Summary

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Flood hazards in high-mountain rivers arise from multiple flood-generating processes, not precipitation–runoff alone. GLOFs and LLOFs can produce peak discharges many times larger than local 100-year meteorological design floods and can even exceed the meteorological flood envelope for catchments with comparable drainage areas. Therefore, failing to consider outburst floods in engineering design presents a major gap in current practice.

Furthermore, the dominant flood mechanism changes dynamically along the longitudinal river profile. River systems transition from GLOF-dominated U-shaped paraglacial valleys to LLOF-dominated V-shaped fluvial gorges and ultimately to meteorological flood-dominated downstream floodplains. Infrastructure design must therefore account for these spatially varying flood regimes.

To address this issue, we outline practical approaches for deriving a unified design flood that probabilistically integrates these diverse flood-generating processes. For critical infrastructure, this probabilistic framework should be complemented by deterministic stress testing against maximum credible geomorphic floods, thereby improving infrastructure resilience throughout its design service life in complex high-mountain environments.

Acknowledgments

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Declaration of interests

Journal Pre-proofs

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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