

Review article: Mountain Flash Floods: From Hazard Formation to Disaster Risk Reduction Pathways

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Abstract. Mountain flash floods pose growing risks under climate and environmental change, yet cross-regional understanding of their triggering mechanisms, cascading impacts and governance remains fragmented. This review synthesises 1,967 studies published during 2000–2025 using bibliometric and topic analyses with qualitative synthesis. By integrating these approaches, we reveal pronounced geographical and thematic imbalances, with research concentrated in Europe and Asia. Flash-flood initiation and impacts are strongly state-dependent, emerging from interactions among storm intensity, duration and spatial concentration, antecedent hydrological conditions, surface controls, and hillslope–channel connectivity. These interactions limit the transferability of fixed rainfall thresholds and support dynamic, multi-source early-warning approaches. The review further shows how hazards are transformed into disaster risk through exposure, vulnerability and capacity conditions, leading to realised economic, social and ecological impacts and cascading disasters. Evidence across non-structural, structural and Nature-Based measures indicates that effective risk reduction requires coordinated portfolios rather than isolated interventions. We develop an adaptive governance framework integrating prevention of new risk, reduction of existing risk and management of residual risk, while addressing exceedance uncertainty, warning-to-action effectiveness, and long-term costs and trade-offs. Overall, this synthesis provides a cross-regional basis for more effective mountain flash-flood risk reduction across mountain regions facing uneven evidence and response capacities worldwide.

1 Introduction

Flash floods are rapid, short-lived events with high peak discharges, typically occurring within four to six hours of rainfall and confined to small watersheds of a few hundred square kilometres (Murray et al., 2021). Flash flood disasters arise from the interplay of multiple drivers, including climatic triggers (e.g. extreme rainfall, rapid snowmelt), surface conditions (e.g.

slope, soil moisture, land cover), and anthropogenic disturbances (e.g. engineering failures, unregulated development near rivers) (Brázdil et al., 2024; Terry et al., 2023). These factors interact non-linearly, forming cascading disaster chains characterised by high uncertainty in triggering mechanisms and disaster responses, leading to secondary hazards (Hemmati et al., 2020; Rindsfuser et al., 2024). In the USA, flash floods represent a persistent and recurring hazard; between October 2007 and October 2015, approximately 28,826 events were documented, averaging 3,603 incidents annually (Gourley et al., 2017). Similarly, China experiences significant impacts, including heavy economic losses and high mortality, with an average of 984 flash-flood-related deaths occurring each year (Ma et al., 2018). For terminological consistency, this review uses mountain flash flood as the principal term for rapid-onset flooding in steep catchments. Mountain torrent is retained only where it reflects the terminology used in the source literature and is not treated as a separate hazard category. Hyperconcentrated flow and debris flood denote sediment-rich flood regimes, whereas debris flow is treated as a related but distinct gravity-driven mass-flow process; these terms are therefore not used interchangeably (Wang et al., 2009; Ilinca, 2021; Baggio et al., 2024).

Mountains, covering nearly 24% of the Earth's land surface, provide vital ecosystem services and play a critical role in the global water cycle (Farinotti et al., 2019; Hock et al., 2022). Physical features such as steep slopes, diverse geological conditions, and orographically-enhanced rainfall render these regions highly susceptible to flash flooding (Stäubli et al., 2018). During intense storms or rapid cryospheric melt on rugged terrain, runoff can converge into peak flows within mere hours (Manoj et al., 2024; Palumbo et al., 2024). Furthermore, under a 1.5°C warming scenario, extreme rainfall is projected to increase, while accelerated glacier and snowpack melt will further intensify flood hazards at high elevations (Myhre et al., 2019; Wang et al., 2023).

In disaster research, risk is shaped by the interaction of hazard, exposure, vulnerability and capacity (HEVC) (IPCC, 2023; UNDRR, 2017). Flood hazard describes the physical characteristics of an event, including its frequency, intensity, duration and spatial extent, whereas disaster risk depends on how these characteristics intersect with exposed populations, assets, infrastructure and ecosystems under different vulnerability and capacity conditions (Birkmann et al., 2013; Fuchs et al., 2013). In mountain catchments, rapid runoff generation, sediment mobilisation and downstream propagation determine the physical hazard, while settlement patterns, infrastructure, livelihoods and response capacity determine how that hazard is translated into potential loss. Once an event occurs, this risk is realised through economic, social and ecological impacts, which may be further amplified through cascading hazard and infrastructure failures. Rapid development and expansion onto steep slopes and valley floors can further increase exposure and constrain response capacity (Shi et al., 2025).

Existing research on flash floods in mountainous regions is still dominated by site-specific observations and single-basin analyses, which limits the comparability of evidence across climatic zones, geomorphic settings, and development contexts (El-Magd et al., 2021; Maqtan et al., 2022). As a result, comprehensive perspectives that connect rainfall forcing, runoff generation and convergence, peak formation, cascading impacts, and hazard chains remain scarce, and insights on triggering conditions and downstream consequences are difficult to transfer across regions (Abegaz et al., 2024; Fowler et al., 2021; Liu et al., 2018). Moreover, existing reviews have rarely explained systematically how mountain flash-flood hazards are

transformed into disaster risk through exposure, vulnerability, and capacity conditions. Although relevant studies have addressed hazard assessment, early warning, vulnerability assessment, and disaster impacts, this evidence remains fragmented and has not been sufficiently integrated into a complete chain from hazard formation to risk construction and realised impacts (Gan et al., 2018; Hao et al., 2022; Roy et al., 2024; Ashraf et al., 2024; Buchenrieder et al., 2021). Evidence on prevention and control measures is also fragmented: many studies evaluate single engineered interventions in specific settings (Maqtan et al., 2022), while the opportunities and limits of Nature-Based measures (Tian et al., 2025), as well as systematic comparisons and coordinated portfolios that combine non-structural (Al-Rawas et al., 2024a), structural, and Nature-Based approaches, are still insufficiently assessed (Adhikari et al., 2023; Lombardi et al., 2021).

Based on these gaps, this review first analyses the formation processes and physical controls of mountain flash floods as hazards. It then examines how hazards are transformed into disaster risk through exposure, vulnerability and capacity, and how this risk is realised through economic, social and ecological impacts. The review further synthesises existing risk-reduction measures and develops an adaptive governance framework organised around preventing new risk, reducing existing risk and managing residual risk (UNDRR, 2017).

To address these gaps, this review makes three contributions:

- (1) To provide a structured synthesis of available cross-regional evidence of mountain flash-flood research by integrating bibliometric mapping, dynamic topic analysis, and qualitative synthesis across 1,967 studies, revealing persistent geographical and thematic imbalances.
- (2) To synthesise cross-regional process evidence on the formation of mountain flash-flood hazards, showing that flash-flood triggering and impacts are strongly state-dependent and coupled, arising from interactions among storm characteristics, antecedent hydrological conditions, and hillslope – channel connectivity, which limits the transferability of fixed thresholds.
- (3) To trace how physical hazards are transformed into disaster risk and realised economic, social and ecological impacts, and to integrate existing risk-reduction measures into a framework for comprehensive mountain flash flood governance.

2 Global research trends

2.1 Temporal and geographical patterns of research

This study adopts a structured literature search and screening strategy to identify research on mountain flash floods (Page et al., 2021). Publications were retrieved from the Web of Science Core Collection and Scopus databases for the period 2000–2025. To capture the diverse terminology used across disciplines, we applied a structured Boolean query constraining both hazard type and terrain setting; the complete database-specific search strategy is provided in Sect. S1.

Through strict inclusion and exclusion criteria, 1,967 peer-reviewed papers were selected for this study. Within this corpus, documented flash-flood events with reported quantitative rainfall information were further identified for the rainfall analysis in Fig. 3. Events with identifiable locations and timing and reported rainfall intensity, duration or accumulated rainfall were retained, yielding 42 event records; further extraction details are provided in Sect. S1. Dynamic Topic Modelling (DTM) was

applied to identify core research themes over the 25-year period, with deterministic training protocols ensuring reproducibility (Sect. S2). Author countries were derived from institutional affiliations, whereas study-location labels were assigned only when a country or identifiable region was explicitly supported by the title, abstract, or keywords. Publications without sufficiently reliable geographic evidence were left unlabelled.

The bibliometric analysis is used to identify temporal changes, spatial distributions, and thematic structures in mountain flash-flood research. Publication volume, study-location counts, and national distributions primarily indicate research visibility, evidence availability, and the current state of knowledge accumulation. These patterns are influenced by language, database coverage, monitoring capacity, and reporting standards. Accordingly, the bibliometric results are interpreted at the level of research patterns and evidence distribution. Within this interpretive scope, Figure 1 summarises the temporal, spatial, and academic landscape of global mountain flash-flood research from 2000 to 2025.

Journal of Hydrology contributed the largest number of publications (Fig. 1c), followed by Natural Hazards and Natural Hazards and Earth System Sciences. The publication trend (Fig. 1d) exhibits moderate growth between 2000 and 2010, followed by a rapid escalation thereafter, reaching a maximum of 181 articles in 2024. This volume of output highlights the status of flash floods as a significant interdisciplinary field bridging hydrology, geomorphology, and disaster science. Against the backdrop of global environmental change, increasing exposure, and growing demand for disaster-risk governance, this topic has received increasing attention from the international scientific community.

The geographic distribution of mountain flash-flood research partly reflects the occurrence of damaging events, but should not be read as a direct proxy for global flash-flood frequency or disaster risk (Fig. 1). Publication output and the number of papers associated with identifiable study locations are mediated by monitoring density, language and database coverage, institutional research capacity, funding priorities, and post-disaster reporting practices. The prominence of Europe and Asia therefore reflects not only recurrent flash-flood impacts, but also stronger monitoring systems and research capacity. Among publications with explicitly identifiable study locations, China and India have the largest evidence bases, followed by Italy, the United States, Egypt, France, Spain, and Saudi Arabia (Fig. 1b).

The distinction between author geography and study geography also reveals different forms of research concentration. China ranks first in both author-country output and study-location representation, while the United States ranks second by author affiliation and also has a substantial domestic study-location evidence base. By contrast, Switzerland makes a comparatively strong contribution through author affiliations but appears much less frequently as the study location, indicating a greater role in international and cross-regional research.

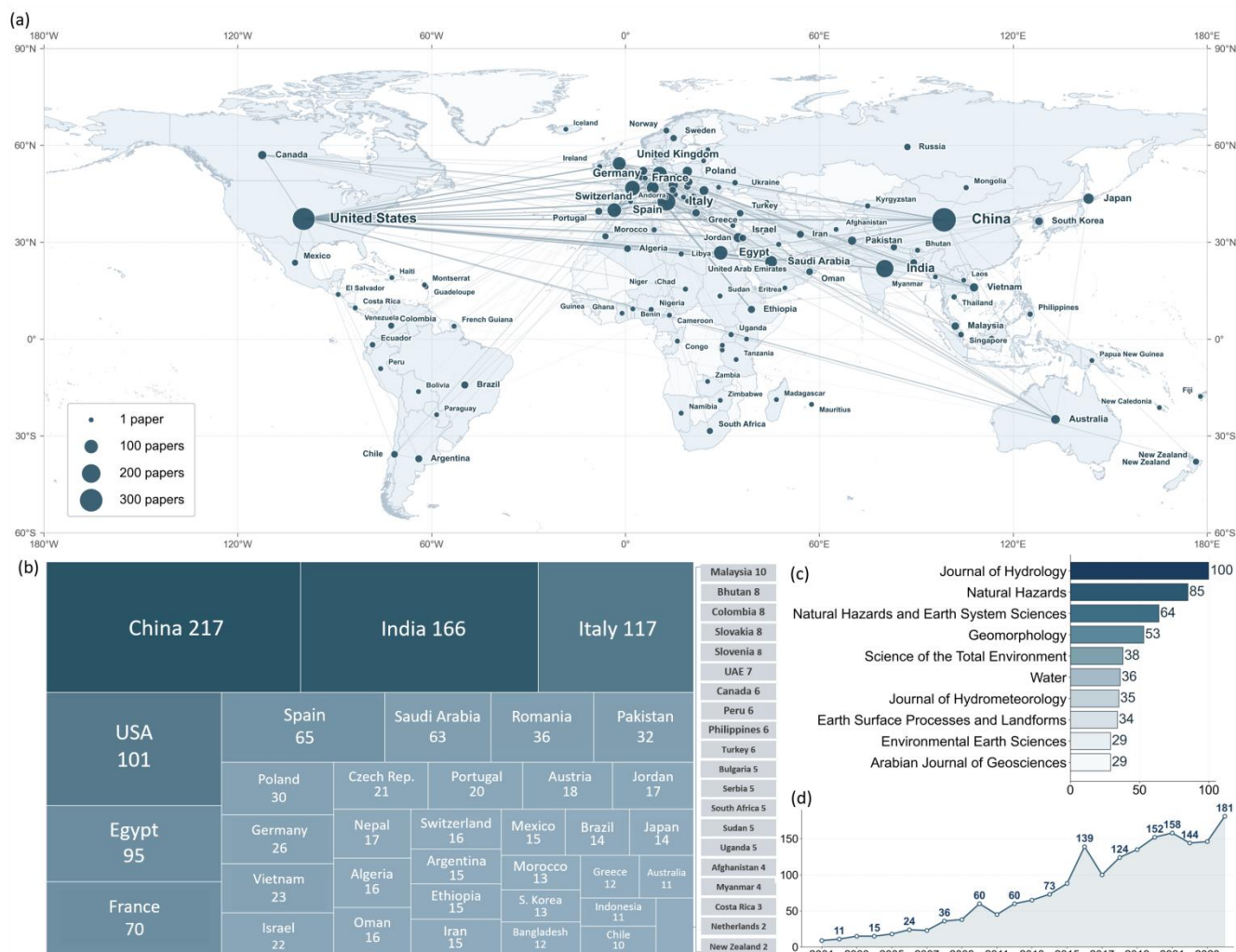


Figure 1: Spatial distribution and temporal trends in global flash-flood research in mountainous regions. (a) Global distribution of research outputs on mountain flash floods (2000–2025) and associated cross-border collaborations. Node size represents the total number of publications for each country, and connecting lines denote international co-authorship networks. (b) Countries in which flash-flood events were documented, as identified across all studies in the mountainous flash-flood corpus; labels show the number of documented cases per country. (c) The top ten journals contributing the highest number of publications to the corpus. (d) Annual publication counts from 2000 to 2025.

2.2 Regional variation in mountain flash-flood research

At the country scale, the Asian evidence base is dominated by China and India, while substantial South Asian research also occurs in Pakistan, Nepal, and Bangladesh. Arid-region studies are concentrated in Egypt, Saudi Arabia, Oman, Israel, and Jordan, reflecting sustained attention to wadi hydrology and ephemeral-channel flooding. In Europe, the largest study-location concentrations occur in Italy, France, and Spain, followed by Romania, Poland, Germany, and the Czech Republic. Clusters in Ethiopia, Morocco, and South Africa should be read against substantial monitoring and reporting gaps

140 across Africa and South America. This contributes to a north-south imbalance in research resources and attention, which ultimately hinders the development of locally tailored risk-reduction strategies.

National boundaries encompass mountain environments that differ substantially in climate, relief, land use, settlement patterns and observational coverage. Regional comparison was based on the formal hierarchy of the GMBA Mountain Inventory v2.0, using major mountain systems as the primary spatial unit and retaining sub-mountain systems where study locations could be resolved more specifically (Snethlage et al., 2022a, b). A total of 506 publications were assigned to at least one major mountain system, including 196 with a more specific sub-system assignment. Regional differences were compared in terms of evidence sources, analytical approaches and applied research focus (Table A1). Relative concentration was assessed using the location quotient (LQ; Isserman, 1977), with values above 1 indicating an above-baseline share of a given evidence category. Detailed coding and calculation procedures are provided in Sect. S1.

150 Indian and Chinese studies differ in both their spatial concentration and evidence profiles. Of the 131 papers located in India, 127 are associated with the Himalaya. Exposure, vulnerability and disaster impacts are particularly prominent in the Himalaya (96 of 168 papers; 57.1%; LQ = 1.50), together with risk-reduction measures (52 papers; 31.0%; LQ = 1.31), including household and livelihood impacts, community response and mitigation practice (Arlikatti et al., 2018; Chouhan and Mukherjee, 2023). Chinese studies extend across several mountain systems. On the Tibetan Plateau (n = 28), remote sensing and spatial analysis and modelling and data-driven analysis each occur in nine papers, including remote-sensing interpretation and dynamic analysis of the 2018 long-runout disaster chains in the lower Yarlung Zangbo River (Zhang et al., 2022). In the Central China Mountains (n = 16), six papers address risk-reduction measures (37.5%; LQ = 1.58), and 11 studies are associated with the Chinese Loess Plateau, where erosion control, vegetation restoration and check-dam systems are prominent (Bai et al., 2022; Ke et al., 2025).

160 Ground observation and monitoring is comparatively concentrated in the European Alps (14 of 43 papers; 32.6%; LQ = 2.26) and Appalachian Mountains (5 of 12; 41.7%; LQ = 2.89), while historical event reconstruction is concentrated in the Carpathian Mountains (8 of 37; 21.6%; LQ = 2.23) (Anagnostou et al., 2018; Bates et al., 2015; Šilhán, 2015). The East Sahara Mountains show a markedly different profile, with remote sensing and spatial analysis occurring in 31 of 40 papers (77.5%; LQ = 2.70) and ground observation and monitoring in only five; modelling and data-driven analysis is also concentrated in this system (15 papers; 37.5%; LQ = 1.35) (Attwa et al., 2021). The smaller Atlas Mountains evidence base (n = 7) also includes remote-sensing and modelling studies, including work in the Moroccan High Atlas (Benkirane et al., 2022), but remains too limited to define a clear regional evidence profile. Madeira has a stronger applied component, with five of ten studies addressing exposure, vulnerability or disaster impacts (Leal et al., 2020). Evidence from the Andes and East African Highlands remains limited and fragmented. The Andean literature spans several evidence types without a clear dominant profile (n = 16). The East African Highlands are represented by only seven studies, five addressing exposure, vulnerability or disaster impacts and four risk-reduction measures; only one includes ground observation and monitoring, and none is classified as experimental evidence (Jacobs et al., 2016a; Addisie and Wassie, 2021). Direct observational and experimental evidence therefore remains sparse in the current East African literature.

These regional differences also affect the basis on which process relationships and management approaches can be transferred: evidence from sparsely monitored arid and tropical mountain systems relies more heavily on remote sensing, event reconstruction and site-specific modelling than the observation-rich evidence available for several European and Asian mountain systems.

2.3 Thematic structure of mountain flash-flood research

Dynamic topic modelling identified six interrelated research domains in global mountain flash-flood studies: Risk Management and Adaptation Strategy; Meteorological Forcing and Rainfall Drivers; Arid Wadi Flash Flooding; Sediment Processes; Special Geological and Topographic Settings; and Eco-Climate Impacts (Fig. 2). The corresponding topic cards are provided in the Supplement, including domain descriptions, anchor keywords, and inclusion/exclusion criteria.

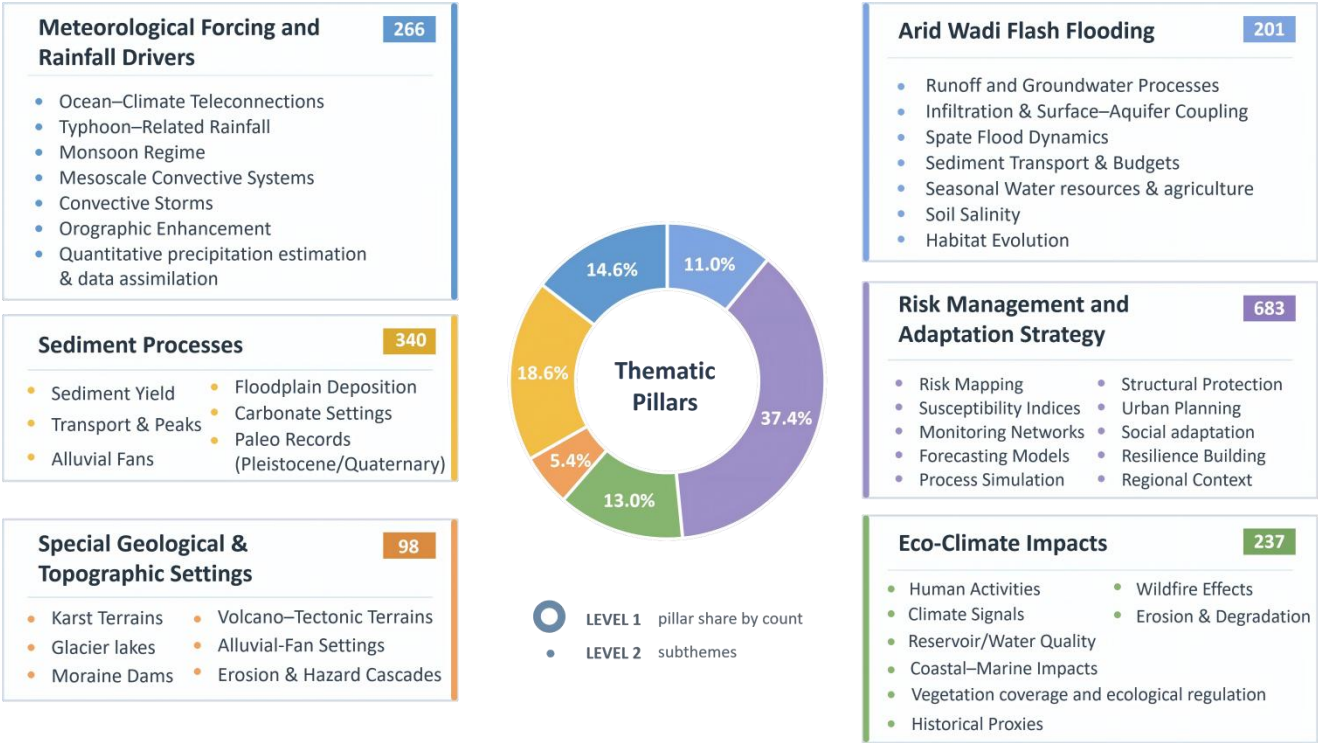


Figure 2: Literature-based hotspots of global mountain flash-flood research (2001–2025) and their thematic intensity. Studies aggregate into six major thematic pillars (outer wedges), and the inner ring shows the total number of publications for each pillar between 2001 and 2025. The pillars comprise: (1) Meteorological Forcing and Rainfall Drivers, covering ocean–climate teleconnections, typhoon-related rainfall, monsoon regimes, mesoscale convective systems, convective storms/thunderstorms, orographic enhancement, and advances in quantitative precipitation estimation and data assimilation; (2) Arid Wadi Flash Flooding, emphasising runoff–groundwater processes, infiltration and surface–aquifer coupling, spate-flood dynamics, sediment transport and budgets, seasonal water resources and agriculture, soil salinity, and habitat evolution in ephemeral channels; (3) Sediment Processes, focusing on sediment yield, transport and peak-flow metrics (including debris-flow dynamics), alluvial-fan and floodplain deposition, carbonate settings, and longer-term paleo-sedimentary records (Pleistocene/Quaternary); (4) Special Geological and Topographic Settings, highlighting karst terrains, glacier lakes and moraine dams, volcano–tectonic terrains, alluvial-fan settings, erosion and hazard cascades; (5) Risk Management and Adaptation Strategy, spanning risk mapping and susceptibility indices, monitoring networks, forecasting models and process simulation, structural protection, urban planning, social adaptation, resilience building, and regional context; and (6) Eco-Climate Impacts, addressing human activities, wildfire effects, climate signals, erosion and land degradation, reservoir regulation and water-quality impacts, coastal–marine impacts, vegetation coverage and ecological regulation, and historical proxies of flood frequency.

The resulting distribution of literature reveals a knowledge base that is fundamentally driven by practical problem-solving and application. Notably, the Risk Management and Adaptation Strategy sector represents the largest proportion of research, totaling 683 publications or 37.4% of the entire corpus. This domain has experienced a particularly robust and consistent growth trajectory since 2020, reflecting a broader academic shift toward tangible outcomes. These include risk mapping, the development of monitoring networks, forecasting and early warning systems, structural protection, urban planning, and the enhancement of community resilience. Such trends emphasize a clear prioritization of actionable research within the field. In contrast, Special Geological and Topographic Settings remains the least represented thematic pillar. This scarcity suggests that although certain factors are of high consequence, their location-specific nature (such as those involving karst hydrology, glacier-lake or moraine-dam hazards, volcano-tectonic terrains, and erosion-induced hazard cascades) leads to them being under-synthesized within global academic circles. Aside from this primary thematic imbalance, three further patterns characterize the current state of the literature.

First, process-centric research is substantial but fragmented. Sediment Processes represents 340 studies, reflecting sustained attention to sediment yield, transport and peak-flow metrics, and fan-floodplain deposition. Only 72 Risk Management and Adaptation Strategy studies explicitly address sediment-related factors, indicating scope for stronger linkage between process-based understanding and governance-oriented work. Second, the prominence of Arid Wadi Flash Flooding points to a distinct sub-community centred on infiltration losses, surface–aquifer coupling, and spate-flood dynamics, implying that ephemeral and highly seasonal channels in arid/semi-arid settings constitute a major empirical backbone of “flash-flood” research. Third, Meteorological Forcing and Rainfall Drivers accounts for 266 studies; its sub-topics (teleconnections, monsoon/typhoon regimes, mesoscale convective systems and convective storms, and orographic enhancement), together with advances in quantitative precipitation estimation and data assimilation, suggest a methodological shift toward improving precipitation representation—yet a clear opportunity remains to better translate large-scale climatic drivers and measurement improvements into event-scale hazard generation and downstream risk actions.

Eco-Climate Impacts has shown a consistent upward trajectory since 2015, reflecting a growing cross-disciplinary strand that links flash floods to wildfire and land degradation, reservoir and coastal water-quality impacts, vegetation regulation, and historical proxies of flood frequency—thereby providing an emerging bridge between event-scale hydrology and longer-term environmental change.

3 Mountain flash floods hazard: formation processes and physical controls

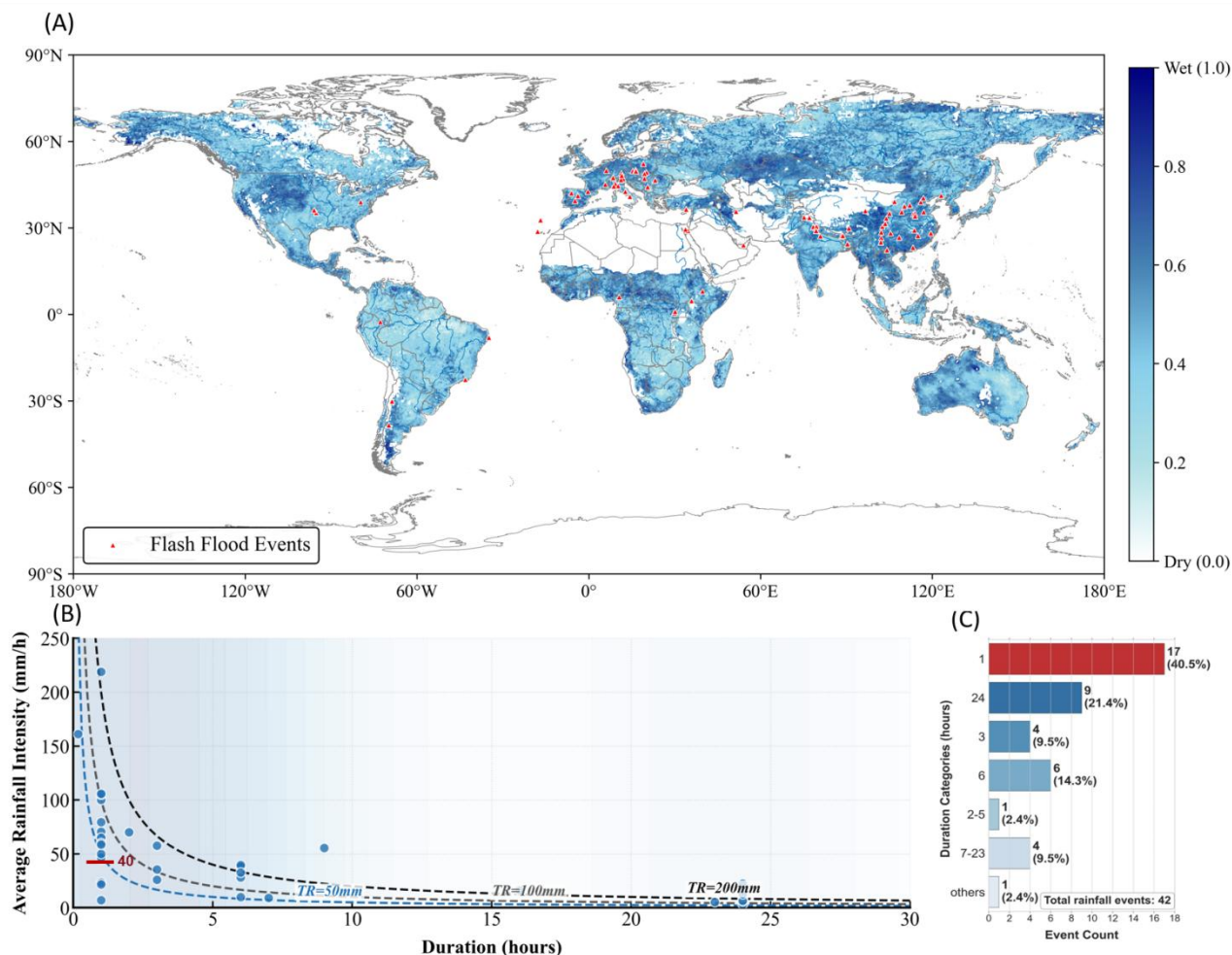
3.1 Climate–topography interactions and flood initiation

The most direct trigger of flash floods is intense rainfall that exceeds a basin’s infiltration capacity or storage capacity (Mukherjee et al., 2023). Traditional empirical thresholds typically rely on rainfall intensity-duration-frequency (IDF) relationships or cumulative rainfall totals. However, in mountainous areas, the strong spatial heterogeneity of rainfall and the sparse distribution of gauges complicates threshold calibration and hinders the transferability of empirical thresholds across

230 basins (Oo et al., 2023). For example, a 6-hour cumulative rainfall of 15 mm has been adopted as an operational threshold in parts of Europe (Spiridonov and Balabanova, 2021). By contrast, arid areas may experience flash flooding after relatively small rainfall totals. In the Wadi Al-Ambagi watershed in Egypt, only 10 mm of effective, spatially uniform rainfall generated a runoff volume of approximately $1.57 \times 10^7 \text{ m}^3$ (Attwa et al., 2021).

The spatiotemporal concentration of rainfall further exerts a major control on hydrological responses. In the Luanhe River
235 Basin, floods with 2-year and 20-year return periods tend to be rapid-rise, single-peak events driven by short-duration, high-intensity storms. In contrast, 5 – 10-year floods are more often associated with long-duration, moderate-intensity precipitation and exhibit multi-peak hydrographs (Gao et al., 2024). Importantly, flood recurrence intervals do not necessarily correspond to those of rainfall events.

The locations of the 95 documented events are shown in Fig. 3a. Approximately 70% of the 42-event rainfall subset occurred
240 between June and August. The 2022–2024 summer-mean Microwave Integrated Drought Index (MIDI) field in Fig. 3a provides broad spatial context and does not represent antecedent moisture conditions at the time of each event. Reported cumulative rainfall ranged from 43 to 1,631 mm, with a 25th percentile of 150 mm and only one event registering $< 100 \text{ mm}$ (43 mm) (Fig. 3). Hourly rainfall intensities exceeded 40 mm h^{-1} in 82% of the cases, whereas 18% recorded intensities below 25 mm h^{-1} , and one case recorded only 7 mm h^{-1} . These events were identified through the availability of sufficiently
245 complete published records. The subset is geographically uneven and dominated by Asian cases, whereas semi-arid Mediterranean basins, North Africa and South America are represented by fewer events. The resulting distributions are therefore treated as descriptive evidence of variability among the documented cases rather than as a representative global climatology or transferable rainfall thresholds.



250 **Figure 3: Spatial moisture context and rainfall characteristics of documented flash-flood events.** (a) Global distribution of the 95
 255 documented events identified from the literature. The background shows the Microwave Integrated Drought Index (MIDI) derived from
 FY-3 products as the 2022–2024 summer mean; it provides broad spatial context rather than event-specific antecedent moisture conditions.
 (b) Relationship between rainfall intensity and duration for the 42 events with quantitative rainfall information. Grey dashed lines indicate
 total-rainfall levels of 50, 100 and 200 mm, and the red horizontal line marks a reference intensity of 40 mm h⁻¹. (c) Distribution of the
 reported rainfall-duration categories for these 42 events.

The substantial differences in reported rainfall volumes and intensities indicate that effective early-warning systems cannot
 rely on a single rainfall threshold. Instead, warning systems need to combine rainfall intensity and duration with antecedent
 soil moisture and other catchment conditions, using locally calibrated and dynamically updated thresholds (Di et al., 2021;
 260 Zhao et al., 2025).

Observed changes also differ among regions and rainfall metrics. In Basilicata, southern Italy, station records for 2001–2024
 indicate increases in 1- and 3-h rainfall extremes, particularly in summer and autumn (Piccarreta et al., 2026). In Genoa, by
 contrast, long-term records show no marked change in annual rainfall totals but a clear decline in the number of rainy days

and an increase in rainfall rate (Faccini et al., 2015). Together, these cases illustrate that changes in short-duration rainfall intensity may not be reflected in annual precipitation totals.

Large-scale climate modes can modulate the background conditions associated with extreme rainfall, although the relationships are strongly region-specific. For the 2017 Mocoa disaster, Cheng et al. (2018) linked an antecedent El Niño-related drought to reduced vegetation cover and described increased rainfall following the transition towards La Niña. The exceptional dry-season rainfall over the United Arab Emirates in 2022 coincided with a negative Indian Ocean Dipole phase (Terry et al., 2023), while 84% of the reconstructed flash floods in a forested mountain catchment in central Spain were associated with negative monthly North Atlantic Oscillation indices (Ballesteros Cánovas et al., 2015). These cases indicate potential climatic modulation, but climate indices should be treated as regional contextual indicators.

At local to regional scales, mountain extreme rainfall is often produced by terrain-modulated convection (Chen et al., 2023; Zhu et al., 2024), where moist inflow and synoptic forcing interact with orography to organise and anchor convective cells on windward slopes (Buzzi et al., 2014; Miglietta and Davolio, 2022), yielding highly concentrated precipitation and strong windward-leeward contrasts (Pereira et al., 2010). Case evidence shows that synoptic forcing (cold-front/upper-level trough) can anchor orographically enhanced convection (Martín et al., 2007), whereas tropical-cyclone rainfall can be intensified and prolonged by valley channelling in complex terrain (Zou et al., 2023). Similar convergence features, including those induced by nearby islands or local thermal contrasts, can further shift rainfall maxima in complex terrain (Miglietta and Davolio, 2022). These dynamics imply that early-warning practice should combine mesoscale storm tracking with locally calibrated, terrain-aware precipitation estimates and thresholds to avoid systematic underestimation of peak rainfall and flash-flood potential (Mukherjee et al., 2023).

Synthesising the above evidence, mountain flash-flood initiation should not be reduced to a single rainfall threshold; rather, it is better conceptualised as a state-dependent triggering function that defines a “threshold surface.” This function couples storm forcing (intensity, duration, and spatial concentration/storm structure) with antecedent catchment states (soil moisture and subsurface storage, snow/ice storage and melt potential, and disturbance-driven shifts in infiltration capacity and sediment supply from wildfire, landslides, or earthquakes) and with hillslope–channel connectivity and tributary synchronisation that control peak formation. As such, warning practice should move from point-based rainfall thresholds to cross-scale, multi-level monitoring and dynamic threshold updating. This requires large-scale climate-weather diagnostics to identify periods of elevated hazard, including teleconnections, monsoon or typhoon regimes, convective systems and moisture transport. It also requires high-resolution precipitation observation and nowcasting to constrain storm location and concentration in complex terrain. At the basin scale, susceptibility states such as wetness, cryospheric conditions, recent disturbance and connectivity should be tracked so that conditional thresholds can be updated in real time. Building on this state-dependent framework, the next section shows how soil, vegetation, geology, and human alterations modulate storage–infiltration and connectivity, thereby systematically shifting conditional thresholds.

3.2 Surface controls on flash-flood flow

Catchment retention depends on how soil storage, vegetation cover, slope and geology regulate infiltration, subsurface storage and drainage. Once rainfall exceeds this storage–infiltration capacity, runoff can be rapidly routed through short hillslope and channel pathways. In the arid, mountainous areas of the southwestern United States, small watersheds with steep slopes and deeply incised valleys exhibit short infiltration times and produce near-instantaneous flood peaks under strong monsoon thunderstorms (Saharia et al., 2017). The confluence zones of multiple tributaries represent additional high-risk areas (Jin et al., 2024), particularly in basins with short flow paths and fan-shaped convergence geometry (Chu et al., 2024). Flood magnitude is strongly dependent on synchronisation of tributary responses: isotope tracing in a semiarid basin in Arizona revealed that runoff from two alpine tributaries arrived at the main stem almost simultaneously, merging with pre-event baseflow at the flood bore on the rising limb (Desilets et al., 2008).

Landforms can impose distinct controls on flash-flood response and inundation patterns. In the karst catchments of the Cévennes and Jura Mountains in France, storm-event analyses show that interbasin groundwater flow can remove about 20% of event rainfall and approximately half of channel discharge to the subsurface, thereby lengthening response times and attenuating peaks (Le Mesnil et al., 2021). In contrast, post-fire experiments in steep mountain channels demonstrate that ash-laden flows form very steep flood fronts with enhanced density and sediment-transport capacity, promoting the transition from flash floods to progressively bulked debris flows (Gabet and Sternberg, 2008).

Geological disturbances further alter hydrological response. Landslides in the Rwenzori Mountains of Uganda (Jacobs et al., 2016a; Jacobs et al., 2016b) and earthquake-induced microtopographic changes in Jianpinggou following the 2008 Wenchuan event (Ran et al., 2015) removed topsoil, exposed bedrock, and left abundant loose debris. In Jianpinggou, modelling shows that when 6-hour rainfall exceeds around 235 mm, peak flows in local sub-catchments can rise by up to 87% before amplification saturates, while peak increases at the basin outlet remain comparatively modest (Jin et al., 2024; Ran et al., 2015). Similarly, kinematic-wave simulations on coupled alluvial-fan–piedmont plains in New Mexico indicate that sheet-flow depths rise non-linearly from the fan apex to the fan toe and reach maxima in the middle to upstream piedmont plain, indicating that the most severe flooding occurs downstream of the mountain front rather than at the fan apex (Mukhopadhyay et al., 2003).

Soil properties regulate infiltration, water storage, drainage and sediment delivery, and therefore play a central role in determining how rainfall is converted into surface runoff. Permeable substrates can attenuate flood peaks by increasing infiltration losses, whereas shallow, fine-textured or bedrock-limited soils favour rapid runoff generation. In the hyperarid Kuiseb River basin of Namibia, downstream increases in soil infiltration rate (from 8.5 to 50 mm h⁻¹) caused more than three-quarters of small and medium floods to disappear during transit (Morin et al., 2009). Rising antecedent soil wetness (expressed as a dimensionless soil saturation ratio, $S \in [0, 1]$) lowers rainfall thresholds for flash flooding: increasing S from 0.20 (dry initial condition) to 0.50 reduced threshold rainfall by 8–38% across the studied catchments and rainfall patterns (Zhai et al., 2018). At the Fernow Experimental Forest in the central Appalachians, crest-stage piezometers show highly

heterogeneous subsurface saturation, including rare but extensive perched water tables that exert a strong control on extreme flood peaks (Bates et al., 2015). Similarly, where shallow soils overlay impermeable bedrock, limited soil water storage leads to rapid conversion of rainfall to runoff (Sharif et al., 2010). In contrast, a comparative study in Luxembourg exhibited delayed and muted responses to intense rainfall (Douinot et al., 2022). Given the importance of soil-state monitoring, recent work in German headwaters demonstrates that assimilating remotely sensed soil moisture into operational hydrological models substantially improves flash-flood simulations (Liu et al., 2025b).

Vegetation acts as both a "green reservoir" and a roughness element, slowing overland flow and enhancing temporary storage. Along the Rift Valley escarpment of northern Ethiopia, peak discharges are strongly negatively correlated with forest and grassland cover ($R^2 \approx 0.80-0.85$), especially where vegetation is distributed across hillslopes rather than confined to riparian corridors (Asfaha et al., 2015). Flume experiments likewise show that turf and shrub cover prolong flow-concentration time, with turf producing a stronger effect (Peng et al., 2019). Vegetation-induced delays are almost insensitive to storm intensity on 5° slopes but diminish under high rainfall and steeper gradients ($15-45^\circ$) (Peng et al., 2019). Mechanistically, vegetation promotes infiltration, maintains a permeable litter and humus layer, and forms root macropores that enhance storage and delay drainage (Bates et al., 2015). Increased vegetative cover also raises surface roughness and soil cohesion, reducing sediment entrainment and hillslope erosion (Ding et al., 2022).

Where vegetation is removed, for example, through deforestation or wildfires, flash-flood risk can increase markedly. Extensive deforestation can increase the frequency of large floods by two- to four-fold, and the removal of $>20\%$ of forest area typically increases annual runoff (Affek, 2019). Wildfire-induced hydrophobicity also significantly reduces infiltration: in Colorado's Front Range, runoff posed the greatest flood and debris flow hazard during the first two post-fire years (Gabet and Sternberg, 2008), but risk decreased progressively as vegetation and soil hydraulic conductivity recovered. By 5-7 years post-fire, even 1-in-100-year rainfall produced limited surface runoff (Ebel, 2020). Land degradation from improper management, such as the long-term overgrazing of the Bayinbulak grasslands, reduces pasture productivity while increasing downstream flash-flood risks (Williams, 2010).

Analysis of the Luanhe River Basin suggests that while forest expansion generally reduces peak flows, it does not substantially lessen the frequency of multi-peak events caused by moderate, long-duration storms occurring every 5-10 years (Gao et al., 2024). Under prolonged dry and hot conditions, hydrophobicity in thick litter layers can also suppress infiltration and accelerate early-storm runoff, shortening response times (Douinot et al., 2022). Land-use change can also feed back onto rainfall patterns: in eastern Kentucky's Appalachian region, simulations indicate that mountaintop-removal mining reduces precipitation by replacing high-elevation forest with low bare surfaces, whereas regrowth of grass or forest increases simulated rainfall relative to the post-mining bare-soil state (Rodgers et al., 2018).

In recent years, small suburban watersheds have increasingly experienced coupled "suburban flash-flood" and severe waterlogging events (Leal et al., 2020; Llasat et al., 2025). Urbanisation modifies mountain-front hydrology by increasing impervious cover, accelerating piped drainage and shortening travel times to channels. Along the Mediterranean coast, a 1-in-50-year rainfall event was estimated to produce a natural flood peak of $380 \text{ m}^3\text{s}^{-1}$, compared with $940 \text{ m}^3\text{s}^{-1}$ after

urbanisation (Jodar-Abellan et al., 2019). Other disturbances, including mineral extraction, road construction, canal excavation and dam construction, can further disrupt natural drainage pathways and reduce catchment flood-buffering capacity (Manoj et al., 2024).

3.3 Hydrological and sediment connectivity in mountain flash-flood processes

The surface controls described above primarily regulate how rainfall is partitioned into infiltration, storage and rapid runoff, but the downstream flood response also depends on whether spatially distributed runoff-producing areas become connected to the channel network within a similar time window. Short hillslope-channel pathways, tributary confluences and synchronised tributary responses can accelerate runoff concentration and amplify flood peaks. If runoff-producing areas remain disconnected or tributary peaks arrive at different times, the basin response is distributed over a longer period and the resulting peak is lower (Desilets et al., 2008; Jin et al., 2024; Chu et al., 2024). Hydrological connectivity therefore concerns the event-scale activation and synchronisation of runoff pathways from hillslopes and tributaries to the main channel.

Several of the same surface controls also determine the supply and accessibility of erodible material. Sediment connectivity concerns whether this material can be transferred from source areas through the channel network. Structural connectivity reflects the potential hillslope-channel sediment cascade, whereas functional connectivity captures how effectively that connection is realised during a particular event (Scorpio et al., 2022). Connectivity indices quantify this potential coupling by integrating upslope contributing area and slope, downslope flow-path length and gradient, and surface resistance or barriers such as vegetation, roads and check dams, thereby identifying sediment-source areas with stronger potential coupling to the channel network (Bombino et al., 2020; Koreňová et al., 2024). They therefore provide a spatial basis for comparing where sediment transfer is more or less likely within a catchment. Actual sediment transfer further depends on hydrological forcing, sediment availability and channel transport capacity (Scorpio et al., 2022; Chiari and Rickenmann, 2011).

A source-transfer-sink framework provides a useful way to trace how sediment moves through mountain catchments. Sediment may be supplied from hillslopes, gullies, banks or material already stored within channels, then transferred through the drainage network or retained along the way. The dominant source can differ markedly between catchments and disturbance conditions. In a small UK mountain torrent, channel and bank sources contributed 95% of the 184 t of sediment delivered to the basal alluvial fan over one year, while hillslope processes and rockfall contributed only 5% (Johnson and Warburton, 2002). Following wildfire in south-eastern Australia, substantial sediment was instead supplied from steep hillslopes and subsequently entrained within channels (Nyman et al., 2011). In the southern Atacama Desert, gully and channel erosion dominated the 2015 extreme event, while sediment delivery was also influenced by material stored within the channel network between storms (Aguilar et al., 2020). Once mobilised, the amount of sediment transferred downstream also depends on channel conditions; simulations in six Alpine torrents showed that sediment availability, bed armouring, roughness and flow resistance all affected sediment transport (Chiari and Rickenmann, 2011). Storage can further limit

395 downstream transfer, with check dams and other channel-control works in the European Alps retaining sediment and reducing sediment connectivity (Marchi et al., 2019).

Changes in the balance between discharge, sediment supply and transport capacity can also alter the character of mountain flash floods. Water-dominated floods may become increasingly sediment-rich, including hyperconcentrated and debris-flood conditions, while debris flows are treated here as a related but distinct geomorphic hazard. The available evidence does not support treating these responses as a universal sequence separated by fixed concentration thresholds (Ilinca, 2021; Baggio et al., 2024; Wang et al., 2009). Morphometric analysis in the Southern Carpathians distinguished basins prone to floods, debris floods and debris flows using Melton ratio, relief ratio, basin length and area, while also showing overlap among the resulting classes (Ilinca, 2021). A broader synthesis likewise concluded that debris floods and debris flows are related but require distinct hazard scenarios rather than interchangeable terminology (Baggio et al., 2024). At higher sediment concentrations, sediment becomes an active component of the hydraulics rather than a passive load. Hyperconcentrated floods in Chinese rivers which defined in that study by sediment concentrations exceeding 200 kg m⁻³ showed rapid bed adjustment and hydraulic behaviour distinct from lower-concentration floods (Wang et al., 2009). Coupled hydro-sediment-morphological modelling in Suide County further demonstrated that erosion and deposition during hyperconcentrated flash floods create spatial hazard patterns that cannot be represented by inundation depth alone (Lai et al., 2024).

4 From hazard to disaster risk: exposure, vulnerability, capacity, and impacts

Flash-flood losses in mountain basins are not determined by hazard intensity alone. They arise when rapid flows, sediment and debris interact with exposed populations, assets, infrastructure, livelihoods and ecosystems, while vulnerability and response capacity shape the ability to withstand, respond to and recover from disruption. Section 4.1 therefore examines the spatial concentration of exposure and the factors that differentiate vulnerability and response capacity. Section 4.2 then considers the realised economic, social and ecological impacts of mountain flash floods and the hazard chains through which antecedent disturbance legacies, within-event transformations and downstream failures can increase hazard magnitude, extend its reach and disrupt essential services. These relationships are synthesised in the mountain flash-flood hazard-chain and cascading-impact framework (Fig. 4).

4.1 Uneven exposure, vulnerability, and response capacity

Mountain flash-flood losses are strongly shaped by where people and assets are located and by how well communities can withstand and recover from sudden events. In many mountain regions, flat land is scarce, so settlements, farmland and infrastructure cluster along valley floors, alluvial fans, narrow channel corridors and steep hillslopes. This places homes, livelihoods and infrastructure in the same pathways that carry runoff and sediment. Rapid or poorly regulated development can add to this exposure. In Egypt, urban expansion has occupied natural detention basins and wetlands, while in Petrópolis,

Brazil, more than 1,021 buildings were constructed on hillslopes of 20°–45° with reduced vegetation cover (Helmi and Zohny, 2020; Alcântara et al., 2023).

Location alone does not determine the severity of loss. Mountain roads, bridges, drainage networks and utility systems often have few alternative routes or backup systems, so the failure of a small number of critical structures can isolate communities and delay evacuation and emergency access. During the 2009 Jeddah flood, embankment breaches, a restricted urban road network and insufficient drainage capacity jointly contributed to severe flooding, with water depths reaching up to 2 m (El-Hames and Al-Wagdany, 2012). At Vajont in 1963, a massive landslide entered the reservoir and generated a displacement wave that overtopped the dam and devastated downstream settlements, causing approximately 2,000–2,600 fatalities even though the dam structure itself remained intact (Stoffel et al., 2016). The event shows that severe losses can also arise when hazard recognition, monitoring and emergency response are inadequate.

Recovery is also uneven because households differ in their livelihood options and access to support. Families dependent on exposed farmland, livestock or local infrastructure may continue to lose income long after the floodwater has receded. In high-altitude areas of South Asia, flood-driven erosion combined with poor farming practices has removed fertile topsoil and reduced cereal yields to around one-third of their potential (Ashraf and Ahmad, 2024). In rural Cameroon, only 5% of affected households had fully restored their livelihoods six weeks after a severe flash flood (Buchenrieder et al., 2021). A rapid assessment following the broader 2022 Pakistan floods found that 77% of surveyed women had limited access to sexual and reproductive health services, while 69% of surveyed adolescent girls had stopped attending school (Ashraf et al., 2024). In northern India, many survivors of the 2013 flash floods preferred rebuilding in place with stronger protection because permanent relocation would disrupt their livelihoods and community ties (Arlikatti et al., 2018). Livelihood dependence and limited access to support can therefore prolong and unevenly distribute post-flood recovery.

Cultural assets also require consideration within vulnerability and capacity analysis. Historic settlements, sections of the Great Wall of China and ancient Himalayan temples are exposed to flash-flood damage (Prince et al., 2024; Zhao et al., 2023). Their vulnerability cannot be assessed only through replacement cost, because cultural loss may involve irreplaceable heritage, place identity and long-term social value. Cultural protection should therefore be considered in exposure reduction and recovery planning in mountain regions.

4.2 Flash-flood impacts and hazard chains

4.2.1 Economic, social, and ecological impacts

Once mountain flash-flood hazards interact with exposed elements, their realised impacts can be grouped into three interrelated domains. Economic impacts include losses to agriculture, buildings, industrial assets and infrastructure; social impacts include mortality, displacement and livelihood disruption; and ecological impacts include slope erosion, sediment redistribution, channel adjustment, habitat disturbance and pollutant transport.

The abrupt onset, high velocity and substantial sediment loads of flash floods can cause severe agricultural losses (Lara et al., 2018). In the Babessi region of Cameroon, a 30-minute event destroyed approximately 160 ha of crops (Buchenrieder et al.,

2021). In Xingyang City, China, a catastrophic flood affected 21,745 ha of farmland, of which 8,239 ha experienced total
460 crop loss (Hao et al., 2023). In Camposalone, Italy, coarse debris covered 63 ha of farmland and impaired soil moisture and
nutrient retention (Santo et al., 2017). Livestock mortality can further intensify livelihood losses among households
dependent on farming and pastoralism (Arlkatti et al., 2018).

Buildings and infrastructure are similarly vulnerable to high-velocity water, sediment and debris. Common impacts include
building collapse, burial by sediment, foundation undermining and damage to roads, bridges, railways and culverts (Gan et
465 al., 2018; Hao et al., 2022; Roy et al., 2024). In Liulin Town, China, flooding damaged 11.3 km of roads and 63 bridges
(Hao et al., 2022). Specialised equipment and inventories in industrial areas may also sustain substantial losses, depending
on asset density, preparedness and regional economic structure (He et al., 2024; Singh et al., 2023).

Loss of life is the most direct social impact. In Petrópolis, Brazil, a 258 mm rainfall event on 15 February 2022 triggered
flash floods and landslides that caused at least 231 deaths (Alcântara et al., 2023). In Uttarakhand, India, the 2013 cloudburst
470 and associated flash floods and landslides affected approximately 80,000 people and damaged about 10% of the upper
Mandakini catchment (Mishra, 2015). Beyond immediate casualties, damage to housing, transport and public services can
cause displacement, livelihood disruption and prolonged recovery burdens that persist after floodwaters recede.

Flash floods can also rapidly reshape hillslopes and channels. In the Braunsbach catchment, Germany, an extreme
debris-laden flash flood substantially reworked the valley floor (Bronstert et al., 2018). Along the southern margin of Chile's
475 Atacama Desert, a 2015 flash flood produced approximately 1.3 mm of surface erosion, comparable to about one thousand
years of background erosion (Aguilar et al., 2020). Flash floods may also transport pollutants and toxic chemicals into rivers
and lakes, degrading water quality and habitats (Al-Rawas et al., 2024a). Their ecological consequences therefore include
both immediate geomorphic change and longer-lasting deterioration of aquatic and riparian environments.

4.2.2 Hazard chains and risk amplification

480 Causal interactions in mountain flash-flood cascades can occur between successive events or unfold within a single event.
Cross-event cascades occur when the persistent effects of earlier disturbances or longer-term environmental changes alter the
hydrological or sedimentary response to a subsequent event. Within-event cascades unfold over a short period, as an initial
hazard triggers a rapid sequence of processes that generates a mountain flash flood; the resulting flood may then be further
amplified as it propagates downstream. Intense rainfall remains the primary trigger of mountain flash floods, although
485 snowmelt and sudden releases from natural or engineered storage can also contribute to flood generation.

Cross-event cascades arise when disturbance legacies persist and alter the conditions of subsequent floods. In high-mountain
regions, climate change is altering the contribution of snow and glacier systems to flood regimes. In snow-dominated
mountain basins, snowmelt remains an important component of seasonal runoff, while shifts in melt timing alter the seasonal
distribution of high flows (Chai et al., 2022). Glacier retreat and glacial-lake evolution can also increase the potential for
490 sudden water release and associated flood hazards in high-mountain regions (Rijal et al., 2024). During the 2023 South
Lhonak event, a large landslide entered the glacial lake and caused a rapid rise in lake level, followed by moraine-dam

breach and a glacial lake outburst flood (GLOF) that propagated downstream through the Teesta River system (Singh et al., 2025).

Other antecedent disturbances can leave hydrological and sedimentary legacies that persist into later storms. Fire-induced
495 vegetation loss and soil water repellency reduce infiltration and increase runoff and sediment mobilisation, leaving burned
catchments susceptible to flash floods and runoff-generated debris flows until vegetation and soil hydraulic properties
recover (Gabet and Sternberg, 2008; Nyman et al., 2011; Ebel, 2020). On Montserrat, vegetation damage caused by volcanic
acid rain in the preceding weeks, together with volcanic debris and synchronous tephra deposition, altered runoff behaviour
and contributed to unusually sediment-rich flash floods during intense rainfall (Alexander et al., 2010). In the Wenchuan
500 earthquake zone, earthquake-derived sediment remained available for remobilisation 15 years after the earthquake; during a
severe rainstorm in 2023, flash-flood erosion of material stored within the channel network contributed to a catastrophic
debris flow, by which time the dominant sediment source had shifted from hillslope landslides to channel deposits (Ran et al.,
2015; Chen et al., 2024). Multiple disturbance legacies can also converge. In the Rwenzori Mountains, intense rainfall
affected a catchment in which wildfire had burned 18% of the area and 29 landslides had supplied debris to the river system,
505 producing a destructive debris-rich flash flood whose severity could not be explained by rainfall alone (Jacobs et al., 2016b).
Within-event cascades unfold over a short period, as an initial disturbance initiates a rapid sequence of processes that
generates a mountain flash flood. Following the 2015 Gorkha earthquake in Nepal, a landslide blocked the Kali Gandaki
River, and overtopping of the resulting landslide dam generated a downstream flash flood (Bricker et al., 2017). The 2018
Sedongpu rock-ice avalanches developed into debris flows, blocked the Yarlung Zangbo River and subsequently produced
510 flooding, while the 2021 Rishiganga rock-ice avalanche evolved into a debris-rich flood that damaged downstream
hydropower infrastructure (Zhang et al., 2022; Singh et al., 2023). The 2023 South Lhonak event involved a longer sequence:
a landslide entered the glacial lake and displaced water, the resulting wave overtopped and breached the moraine dam, and
the GLOF propagated downstream and contributed to failure of the Chungthang Dam (Singh et al., 2025).

Once the resulting flood or debris flow enters the channel network, unstable material, channel constrictions and existing
515 barriers can generate further amplification. In Zhouqu, upstream flows successively breached landslide dams and increased
downstream debris-flow magnitude (Cui et al., 2013; Zhou et al., 2013). In Shimen Valley, flood-mobilised large wood and
boulders blocked a channel constriction and impounded water and debris; failure of the temporary blockage subsequently
generated a destructive flood wave (Hou et al., 2020). Engineered structures can introduce additional links into the same
chain. In Derna, extreme flooding caused the sequential failure of two upstream dams and produced successive destructive
520 flood waves through the city (Ashoor and Eladawy, 2024). In the Longda watershed, a mine debris flow breached a tailings
dam, blocked the Fu River and generated an outburst flood that transported heavy-metal contamination downstream (Ge et
al., 2013). Dam-failure floods can likewise follow overtopping under extreme inflows or failure of structures already stressed
by upstream hazards (Santos-González et al., 2021; Ashoor and Eladawy, 2024). Across these events, successive
transformations and failures increased the magnitude and downstream reach of the hazard. Failure of roads, bridges, power

525 systems, water-treatment facilities and communication networks may not generate another flood wave, but can intensify the continuing disaster by restricting evacuation, emergency access and essential services (Brázdil et al., 2024; Jin et al., 2024). These coupled pathways require monitoring beyond rainfall thresholds. Real-time observations of water level, velocity and discharge can support rapid flood detection, while operational systems integrating catchment monitoring, event detection and automatic alarms can issue warnings within the short lead times available in rapidly responding mountain basins (Al-mamari et al., 2019; Badoux et al., 2009). Continuous monitoring of sediment and large wood throughout the channel network is unlikely to be practical. Where large-wood mobilisation is plausible, risk assessments should instead identify bridges and channel constrictions susceptible to blockage (Ruiz-Villanueva et al., 2014). In high-mountain settings, targeted monitoring of unstable slopes, glacial-lake levels and natural or engineered barriers can help identify failures capable of generating new downstream flood waves (Bricker et al., 2017; Singh et al., 2025). Such observations can help document hazard transitions, but spatial co-occurrence alone does not establish causal cascading. Causal attribution requires evidence that one process changes the likelihood, magnitude, pathway or consequences of another. Multi-hazard susceptibility mapping may identify areas jointly susceptible to landslides, snow avalanches and flash floods without demonstrating causal transitions among them (Akbar et al., 2023). Most evidence still comes from individual event reconstructions and site-specific modelling, leaving transition and the amplification between successive hazards poorly quantified.

540 Figure 4 synthesises these relationships in a mountain flash-flood hazard-chain and cascading-impact framework, linking cross-event disturbance legacies, within-event flood generation and transformation, downstream hazard amplification, and realised economic, social and ecological impacts.

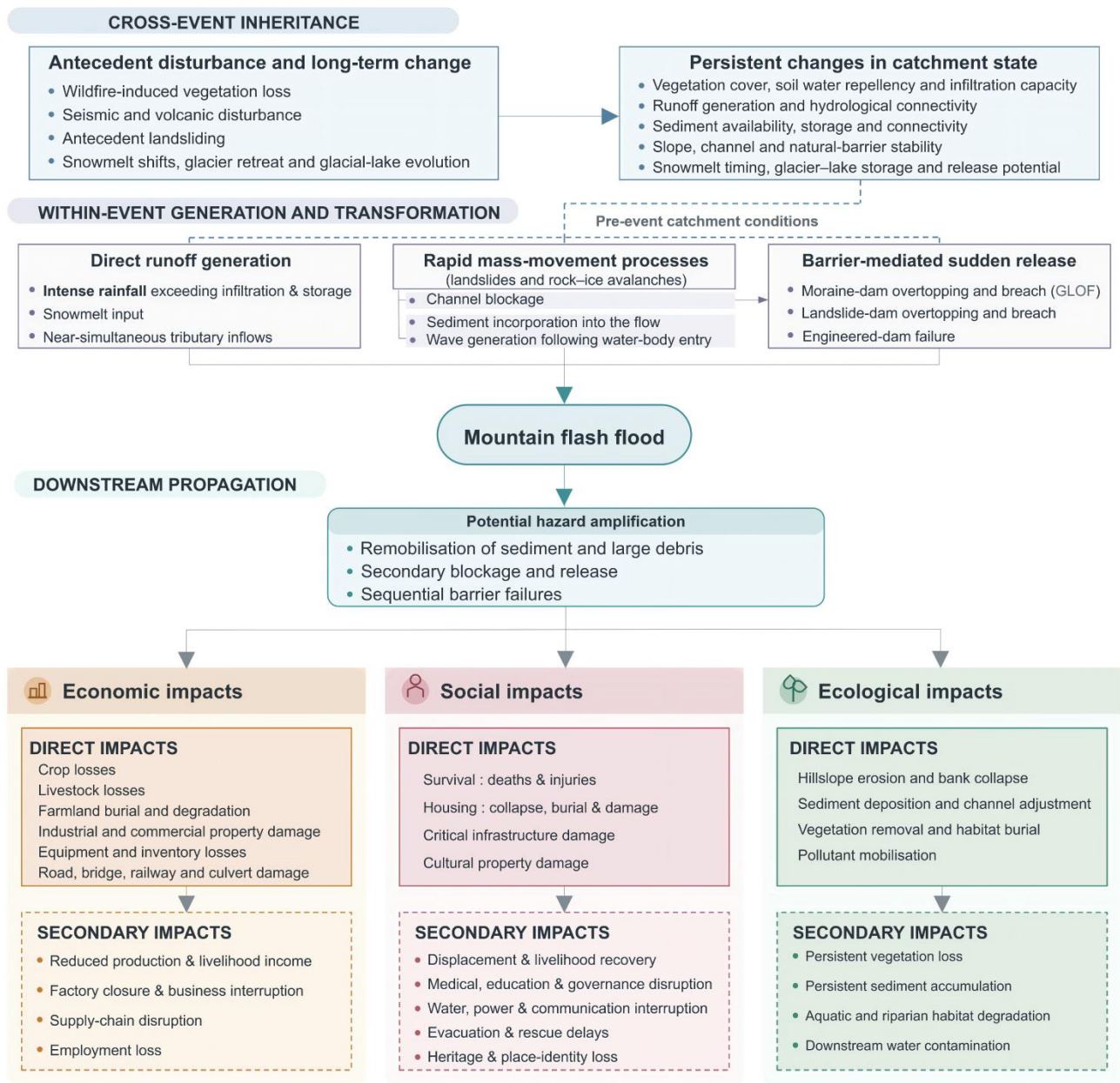


Figure 4. Mountain flash-flood hazard-chain and cascading-impact framework showing cross-event disturbance legacies, within-event flood generation and transformation, downstream hazard amplification, and realised economic, social and ecological impacts.

5 Flash floods: synergistic measures and evidence

Having established how mountain flash-flood hazards are transformed into realised disaster impacts, this section synthesises the measures identified in the literature. It clarifies the main intervention families and the available evidence on their roles in modifying hazard processes, reducing exposure, addressing vulnerability, strengthening capacity and managing residual losses. Existing studies highlight that effective flash-flood management must integrate non-structural, structural and nature-based measures within a coherent and adaptive system. Non-engineering measures strengthen early warning and response capacity through risk mapping, vulnerability assessment, emergency planning, and public education (Bai et al., 2022; Fortugno et al., 2017). Engineering and Nature-Based measures reduce flood energy, sediment transport, and exposure via check dams, diversion dikes, vegetation restoration, slope stabilisation, and wetland detention areas. A complementary pillar concerns risk transfer and sharing within watershed communities, through insurance schemes, optimised land-use planning, and cross-border cooperation to address residual risks. Under accelerating climate change, governance is shifting toward integrated models that combine technical early warning, engineering protection, ecological regulation, and social governance, guided by whole-watershed perspectives that balance rigid protection with flexible resilience.

5.1 Non-structural measures: early warning and response

The key to minimizing fatalities caused by flash flooding is putting in place efficient early warning systems. Early warning systems for flash floods utilize radar, satellite, and numerical weather prediction data with hydrologic models for on-line rainfall monitoring and forecasting of flash floods (Gourley et al., 2017) in well-instrumented areas. Where observation networks are sparse, critical-rainfall threshold methods remain the primary operational tool, providing rapid alarms and site-specific estimates of rainfall needed to initiate flood peaks (Zhao et al., 2025). The strong nonlinearity of flash-flood processes, combined with spatial heterogeneity and limited observations, constrains the calibration and performance of traditional physics-based models in poorly gauged basins. For example, a distributed HEC-HMS model applied in an Andean alpine basin achieved a Nash-Sutcliffe efficiency of only 0.26-0.78 and poorly reproduced peak flows (Mejía-Veintimilla et al., 2019).

Machine-learning methods provide useful tools for parameter regionalisation, susceptibility mapping and forecasting in data-limited mountain catchments. Decision-tree regionalisation, for example, improved hydrograph simulation in ungauged mountainous catchments in southwest China (Ragetti et al., 2017), while global deep-learning models trained on large gauged-catchment datasets have shown skill in predicting extreme floods in ungauged watersheds (Nearing et al., 2024). These approaches have also been widely used for flash-flood prediction and susceptibility mapping (El-Magd et al., 2021; Arabameri et al., 2020; Chu et al., 2024; Al-Rawas et al., 2024b). However, high predictive scores do not necessarily demonstrate transferability. Models trained on small, imbalanced or spatially clustered event datasets are particularly

vulnerable to overfitting, and performance under random train–test partitioning may partly reflect shared spatial or event characteristics between the training and test data. In data-poor mountain regions, model evaluation is further constrained by sparse observations, incomplete event inventories and uncertain post-event records (Amponsah et al., 2022; Kaiser et al., 2020). Black-box forecasting models also remain difficult to interpret and may extrapolate poorly under changing climate, land-use and catchment conditions (Nearing et al., 2021). Model robustness should therefore be tested using spatial and temporal cross-validation, independent flood events and catchments, together with checks against hydrological process understanding.

One response to these limitations is to combine data-driven models with physical constraints and real-time observations. A physics-guided, real-time system that trained deep learning models on synthetic outputs from high-resolution hydrodynamic models achieved root-mean-square flow errors of 0.36–0.49 m³ s⁻¹, while reducing computation time by two to three orders of magnitude (An and Ouyang, 2025). Non-contact flow-monitoring techniques, such as LSPIV and STIV, also provide crucial real-time discharge information for model calibration and early warning verification (Al-mamari et al., 2019). These hybrid and observation-supported approaches can improve operational feasibility, but they still depend on the quality of rainfall, flow and post-event information used for calibration and validation.

This dependence on observations exposes a broader limitation of flash-flood warning in mountain regions. Many mountain basins have sparse and low-frequency hydrometeorological networks, which limits the detection of short-lived or highly localised storms (Amponsah et al., 2022; Dietze et al., 2022). While weather radar and satellite measurements can assist in filling these gaps, considerable uncertainty (Barros and Arulraj, 2020) can still exist in mountainous regions due to a combination of beam blockage, ground clutter, and multi-layered clouds. The TRMM satellite often underestimates extreme events, and although its successor, GPM (IMERG), better captures short-duration intense rainfall, it still tends to underestimate peaks and requires local calibration (Benkirane et al., 2022). C-band radar in the Italian Alps underestimated rainfall totals by 50–70% (Anagnostou et al., 2018). Relying only on satellite or long-range radar is therefore insufficient for reliable flash flood forecasting. Multi-source data fusion and assimilation have become essential. For example, a cellular-automata algorithm of rain-gauge data with IMERG estimates markedly improved hydrological model performance in three severe Tanaro River floods (Lombardi et al., 2024). Novel approaches include using seismic sensors as auxiliary indicators of flow surges in narrow valleys (Dietze et al., 2022).

Very few systematic, long-term event databases exist for flash floods within small mountain topographic catchments. Results of a global review of flash flood catalogues indicated that only a very small number of these long-term catalogues have been developed and are documented. The catalogues developed to date exhibit great differences in their spatial coverage, definitions, and usability (Kaiser et al., 2020). At the regional level, the development of databases, such as a geo-historical impact database for Alpine catchments and new flash flood inventories for Peninsular Malaysia, demonstrate that there is a need to develop comprehensive databases to facilitate the assessment of relative risk and the development of reliable indicators that can support the systematic assessment of flash floods (Boisson et al., 2022; Maqtan et al., 2025).

610 These observational and modelling limitations propagate through the warning, modelling and risk-assessment chain. In complex mountain terrain, uncertainty arises from sparse hydrometeorological networks, short-duration rainfall estimation, radar beam blockage, satellite precipitation bias and gauge representativeness (Amponsah et al., 2022; Dietze et al., 2022; Barros and Arulraj, 2020). C-band radar applications in the Italian Alps, for example, underestimated rainfall totals by 50–70%, while satellite products such as TRMM and GPM IMERG can underestimate short-duration rainfall peaks and require local calibration (Anagnostou et al., 2018; Benkirane et al., 2022). These uncertainties propagate through rainfall-threshold estimation, flood simulation, inundation mapping and loss assessment, particularly where observations are sparse and catchment conditions are poorly constrained (Amponsah et al., 2022; Kaiser et al., 2020). The problem is particularly acute in ungauged or poorly monitored mountain basins, where calibration often depends on short event records, post-event traces or transferred parameters. Evidence from data-scarce and complex-terrain basins shows that hydrological modelling and flood simulation can support flash-flood risk assessment, but results remain sensitive to rainfall forcing, antecedent catchment conditions, topography and parameter assumptions (Mejía-Veintimilla et al., 2019; Lombardi et al., 2024). Model outputs should therefore be reported with uncertainty ranges, sensitivity tests and, where possible, validation against independent flood events.

Even when technical forecasts improve, early warning only reduces loss when warnings are received, understood and acted upon in time. Although early-warning technologies continue to advance, warnings alone are insufficient. Their effectiveness depends on whether exposed communities can understand and execute them quickly. Evidence from Mauritius shows that public participation and risk perception directly affect adaptation and response efficiency (Nowbuth et al., 2025) and that messages highlighting concrete personal and property threats are more effective than references to global climate change (Rienow et al., 2022). In fragile Himalayan regions such as Chitral, Pakistan, women's groups and community organisations are central to bottom-up risk governance to compound hazards, including snowstorms, landslides, flash floods, and glacial lake outbursts (Ehsan-ul-Haq, 2007). Surveys in Afghanistan indicate that weakening resilience is linked to limited scientific information, loss of indigenous knowledge, gendered livelihood transitions, and low adaptive capacity (Mohanty et al., 2019).

These findings highlight that risk governance needs to respond to local conditions and address root causes of vulnerability, while incorporating community perspectives in planning to strengthen self-rescue and mutual aid (Nowbuth et al., 2025). Participatory rural appraisal in Turtuk, Ladakh, India, enabled a community-generated risk map consistent with geological assessments, demonstrating the value of local knowledge (Ahmed et al., 2019). Japan's community-based "disaster prevention living circle" model similarly enhances risk awareness, planning accuracy and emergency response capacity by directly involving residents in mapping and preparedness (Zang et al., 2025). The Illgraben watershed in the Swiss Alps provides an operational example of this warning-to-action chain. Watershed monitoring, event detection, automatic alarms, applied weather forecasting and local organisation are linked so that, once debris-flow movement is detected upstream, exposed downstream locations can receive audible and visual warnings about 5–15 min before arrival (Badoux et al., 2009).

This example shows that early warning should be assessed by detection skill, usable lead time, communication effectiveness and connection to predefined local response actions.

645 Community-centred warning and response also need to be supported by spatial planning, because long-term risk depends on where settlements, infrastructure and services are allowed to develop. Spatial planning tools therefore remain central to exposure reduction. Susceptibility mapping using GIS data, machine-learning techniques or coupled hydrological models has been widely applied in areas where long-term data are limited (Arabameri et al., 2020). The Dahab Watershed in Egypt has successfully identified hazardous zones through mapping and reporting, providing information on vulnerable infrastructure and settlements. In addition, evidence from a multi-hazard study in the Himalayas showed that losses were strongly associated with construction quality and unregulated development, indicating that socioeconomic dimensions should be included in risk assessment (Chouhan and Mukherjee, 2023).

655 Complementing these technical approaches, regulatory frameworks are also being strengthened. For example, at the institutional level, China's 2025 water resources industry standard Technical Specification for Delimitation of River and Lake Management Scope stipulates that, in mountain flash-flood prevention areas, the river management scope shall be defined by law and planning to secure flood storage capacity and flood protection, with stricter criteria where riparian communities, downstream areas and debris-laden floods increase risk (Ministry of Water Resources, 2025). Under administrative leadership, governance deviations, unreasonable spatial planning and rushed post-disaster reconstruction can amplify flood risk (Acharjee, 2015; Arlikatti et al., 2018), leading to the expansion of industrial, commercial and residential areas into high-risk flood-prone zones (He et al., 2024) and to a false sense of security created by river regulation projects (Liu et al., 2022). Detailed post-event investigations and lesson learning are therefore essential to raise public awareness and to refine engineering standards as well as land-use and spatial planning controls (Cislaghi and Bischetti, 2022).

5.2 Structural and Nature-Based measures

5.2.1 Structural (grey) measures

665 Engineering interventions directly regulate flood flow through artificially constructed structures. Check dams are common features that retain water and sediment, reducing downstream peak flow and sediment hazards (Abbasi et al., 2019). Simulations in mountainous regions show that different dam types can reduce downstream peak flows by 60–69%, extend flood duration by 0.4–4 times, and reduce channel erosive power by 63–85% (Ke et al., 2025). Their effectiveness, however, strongly depends on design, maintenance, and sedimentation rates that rapidly reduce storage capacity. For example, in Ethiopia's sub-humid highlands, gully erosion rapidly silted up 32 newly built check dams in the early rainy season, with 95% sustained structural damage by season's end (Addisie and Wassie, 2021). Similar ageing and siltation issues arise in China's Loess Plateau (Gao et al., 2023).

Regulation and storage measures—including reservoirs, ponds, flood detention ponds, flood storage dams, and flood buffer zones—delay flood waves and provide time for warnings and intervention (Acheampong et al., 2023). In Machico's Madeira

675 watershed, two 12m high detention dams with 110,000 m³ storage capacity reduced a 1-in-100-year flood peak by 72% (Vieira et al., 2018). Large reservoirs, though effective, involve large investments, long construction periods, and large ecological impacts. Small, decentralised systems are more feasible in hilly areas (Kolosov and Selezneva, 2020). Terraces and horizontal ditches in traditional agriculture slow runoff and extend water residence times. For example, in Petra, Jordan, a restored cascade dam-terrace system delayed flood peaks by up to 25 minutes and reduced discharge by 13.5%, whereas a
680 single large dam reduced peak flow by 30.5% but with a lag time of only 14 minutes (Abdelal et al., 2021). Such multi-stage, small-scale detention and storage systems provide scalable, cost-effective flood mitigation (Abd-el-Kader et al., 2023; Helmi and Zohny, 2020).

Bank-protection projects typically employ engineered interventions along riverbanks and beds, including embankments, revetments, groynes and channel training works. In steep mountain rivers, however, simply cleaning or widening the channel
685 and raising dikes provides only limited improvement in flood safety. In such settings, the construction of flood-control dams on tributaries within flood formation zones is recommended to detain floodwaters and reduce pressure on the main channel (Kolosov and Selezneva, 2020). Within vulnerable reaches, spur dikes are often used to deflect the main flow away from erodible banks and to reduce near-bank velocities. Recent studies, inspired by the Eğri Bridge, indicate that asymmetrical spur-dike layouts can dissipate 50-65% of flow energy, thereby lessening local erosive forces (Aydogdu, 2025).

690 In steep mountain catchments, structural flood mitigation measures are generally most effective when they employ distributed, multi-level, small-scale detention and storage systems that attenuate flood peaks, delay flood waves and temporarily store water. These systems are typically supplemented by targeted control at key nodes and scenario-based operating rules to maximise the efficiency of limited storage during critical periods (Abdelal et al., 2021; Kolosov and Selezneva, 2020). In China, similar strategies have been implemented through extensive programmes of small check dams,
695 sand-retaining weirs, and slope-stabilisation works in flash-flood-prone mountain catchments, especially across the Loess Plateau (Yang et al., 2020). However, the performance of such engineered systems depends strongly on life-cycle management: in the managed Wartschenbach torrent in Austria, the existing system of check dams and debris-flow works can reduce expected losses by about 89%, but sustaining this level of protection under projected increases in debris-flow activity would require a 57–63% rise in maintenance budgets and roughly 50% higher intervention costs (Ballesteros
700 Cánovas et al., 2016).

Libya's Derna disaster illustrates that design elements meant to account for historical climatic conditions could fail when faced with unprecedented flooding. There are dam break simulation studies that demonstrate that without the existent dam infrastructure, the same storm would have resulted in lower maximum flood depths, velocities and total flood inundated areas within the city of Derna. These results illustrate the need to review, upgrade or in some cases decommission older dam
705 structures that were designed based on unfavourable historical climatic conditions and possess low active-storage ratios (Ashoor and Eladawy, 2024). Additionally, studies indicate that through strategies to upgrade embankments within urban cores, the risk within core urban areas can be minimised, but the residual hazard remains shifted to downstream and peri-urban locations impacting vulnerable and unprotected groups (Kumar et al., 2025).

Detention and check-dam systems inevitably reshape river ecosystems. In Mediterranean mountain torrents in southern Italy, check-dam-induced changes in channel geometry, hydraulics and bed material explain about 60% of the variance in riparian vegetation structure (Bombino et al., 2019). In small semi-arid catchments in Spain and southern Italy, sediment wedges upstream of check dams accumulate in fine sediment, organic matter and nutrients, supporting higher species richness than downstream reaches with lowered water levels and contracted riparian zones (Bombino et al., 2014; González-Romero et al., 2019). Other work shows that cumulative check-dam construction simplifies bed morphology by including upstream aggradation and localised downstream scour, which disrupt pool-riffle sequences and barform habitats (Galia et al., 2019).

5.2.2 Nature-based solutions (NBS)

Nature-Based Solutions are increasingly examined as complements to structural protection because they can regulate runoff, sediment and slope stability while providing ecological co-benefits (Esraz-Ul-Zannat et al., 2024; Rehman et al., 2023). Vegetation restoration, alone or combined with catchment measures such as check dams, can reduce peak runoff and sediment delivery in mountain catchments (Asfaha et al., 2015; Bai et al., 2022; Gao et al., 2023). In steep terrain in India, Vetiver plantation along the roadside significantly improved soil shear strength and alleviated road collapse after heavy rains (Ghosh and Bhattacharya, 2018).

Together, these studies show that vegetation-based NbS are particularly relevant where hillslope runoff, sediment mobilisation, and shallow slope instability are important contributors to flash-flood processes. For example, the introduction of native plants such as willows and reeds into the Cheonggyecheon Stream restoration project in South Korea enhanced the bank stability using root-reinforced soil-binding (Seo and Kwon, 2018). In steep olive-orchard in southern Spain, small Nature-Based detention features were placed between fields, such as micro-ponds and vegetated strips, have been shown to enhance infiltration, break runoff connectivity, and reduce peak discharge (Bohorquez et al., 2023).

The magnitude of flood attenuation can also depend on implementation extent. In Belo Horizonte, Brazil, simulations of 2-, 10-, 50- and 100-year rainfall events and two observed events showed that green infrastructure implemented in 100%, 50% and 10% of suitable areas reduced outlet peak flow by approximately 60%, 30% and 5%, respectively (Rosa et al., 2020). Wetlands and floodplains provide additional temporary storage: small wetlands, including ponds, ditches and low-lying farmland, have been reported to retain 50 – 70% of rainfall and, at small-catchment scales, reduce surface runoff by approximately 15–30% and peak water levels by 10–25% (Yang et al., 2024). In urban settings, sponge-city measures can provide additional runoff reduction where implementation space is available (Liu et al., 2025a). These studies show that catchment-scale attenuation varies with implementation extent and available storage.

Time to establishment is an additional constraint. Plant growth and soil recovery are gradual, and forest expansion does not eliminate all flood responses: in the Luanhe River Basin, forest expansion reduced peak flows but did not substantially lessen the frequency of multi-peak floods associated with moderate, long-duration storms (Gao et al., 2024). Newly implemented vegetation should therefore not be assumed to provide the hydrological function of mature cover immediately; during the establishment period, warning, emergency response and existing protection remain important. Passive urban blue–

green infrastructure may also provide insufficient storage during extreme rainfall, limiting its effectiveness during high-magnitude events. Quantitative evidence on the decadal performance and maintenance costs of NbS remains limited. Structural measures can provide more immediate and design-specific protection, although they also require life-cycle maintenance (Ballesteros Cánovas et al., 2016). NbS provide more distributed regulation of runoff and sediment, but their effectiveness develops over time and varies with implementation extent and event conditions. These differences support the integration of Nature-Based and grey infrastructure, combining immediate structural protection with longer-term ecological regulation of runoff, sediment connectivity and drainage pressure (Çelik et al., 2020).

6 Toward adaptive governance of mountain flash-flood risk

Mountain flash-flood research has traditionally emphasised hazard mapping, numerical modelling, forecasting and structural control, often within individual regions or technical domains (El-Magd et al., 2021; Maqtan et al., 2022). More recent work has broadened this focus as climate change alters extreme rainfall, snowmelt and glacier-related flood processes and as the consequences of rapid development and uneven social vulnerability become more apparent. This shift has brought risk governance, preparedness and climate adaptation more clearly into mountain flash-flood research, consistent with the priorities of the Sendai Framework and the growing emphasis on early-warning capacity and resilience (Abegaz et al., 2024; Khodayar et al., 2025).

The distinctions among these measures can be organised using the three disaster risk reduction functions defined by UNDRR: preventing new risk, reducing existing risk and managing residual risk (UNDRR, 2017). Risk mapping provides an evidence base for all three by identifying hazards and the people and assets potentially exposed. Preventing new risk concerns decisions made before development takes place. Spatial planning, risk zoning, development control, infrastructure siting and ecological buffer protection can avoid creating new exposure and vulnerability in high-hazard areas. Reducing existing risk applies where people, assets and infrastructure are already exposed. Monitoring, forecasting and warning improve hazard detection and extend the time available for action. Structural protection, integrated grey and green infrastructure and Nature-Based Solutions can moderate runoff, sediment movement and related hazard processes. Community preparedness strengthens response capacity, while facility maintenance reduces the likelihood of failure in protective and lifeline systems. Where repeated exposure cannot be reduced to an acceptable level, relocation or property buyouts may be required. Managing residual risk addresses losses that remain when extreme events exceed design standards or warning and response capacity. Emergency response and temporary shelter can limit immediate consequences, while recovery planning, risk financing and insurance support recovery. Loss recording and post-event learning provide evidence for improving subsequent planning, protection and preparedness.

Three governance problems recur across these interventions. First, thresholds, models and protective structures are inevitably designed under uncertainty and may be exceeded. Second, improved detection and forecasting do not reduce losses unless warnings lead to feasible local action. Third, risk-reduction portfolios must remain affordable, maintainable and socially acceptable over time.

775 6.1 Governing exceedance under uncertainty

Warning thresholds, model outputs and structural designs all depend on assumptions that may not hold during rare or compound events. Rainfall thresholds are sensitive to antecedent soil moisture and rainfall pattern, while estimates of drainage capacity, sediment transport, blockage probability and structural performance depend on incomplete observations and simplified representations of catchment conditions. These uncertainties are particularly pronounced in poorly monitored mountain basins (Zhai et al., 2018; Amponsah et al., 2022; Zhao et al., 2025). Climate, geomorphic conditions and land use are also changing, so historical observations may not fully represent future combinations of rainfall, sediment supply and channel response. Fixed standards remain necessary, but their performance should be treated as conditional rather than assumed to provide complete protection.

The practical question is therefore how to contain the consequences when thresholds or design capacities are exceeded. Safe overflow routes, redundant access and communication systems, routine inspection, evacuation planning and contingency arrangements can prevent local failure from disrupting the wider response. Check dams and torrent-control structures can reduce flood and sediment hazards, but their performance changes as sediment accumulates, structures deteriorate and event magnitude increases (Addisie and Wassie, 2021; Ballesteros Cánovas et al., 2016; Yang et al., 2020). The Derna disaster illustrates the consequences of overlooking these dependencies: when inflow and storage conditions exceeded the capacity of two upstream dams, protective infrastructure became an additional source of catastrophic flooding (Ashoor and Eladawy, 2024).

Planning for exceedance also requires arrangements for action and recovery after protective capacity has been surpassed. Community exercises and clear emergency protocols can support rapid decisions where lead times are short, while post-event investigations can reveal why warnings, structures or evacuation arrangements failed and inform revisions to engineering standards and land-use controls (Cislaghi and Bischetti, 2022). Adaptive governance therefore involves repeated assessment and revision rather than reliance on a fixed threshold or design standard.

6.2 From technical warning to actionable response

Remote sensing, high-resolution rainfall observations, numerical models, artificial intelligence and machine learning have improved event detection, susceptibility assessment and the estimation of dynamic warning thresholds, especially where ground observations are sparse (Zhao et al., 2022a; Al-Rawas et al., 2024b). Their practical value, however, depends on the time and information available after a warning is issued. A technically accurate forecast has limited protective value if it arrives too late, is not communicated clearly or cannot be linked to a safe evacuation route and an organised local response.

Public understanding and participation influence whether warnings produce action. Evidence from Mauritius indicates that risk perception affects response and that messages describing concrete threats to people and property are more actionable than abstract information about climate change (Nowbuth et al., 2025; Rienow et al., 2022). In Chitral, Pakistan, women's groups and community organisations have contributed to local governance of interacting landslide, flash-flood and

glacial-lake hazards (Ehsan-ul-Haq, 2007). Conversely, evidence from Afghanistan shows that limited scientific information, erosion of indigenous knowledge and low adaptive capacity can weaken local response even where hazards are recognised (Mohanty et al., 2019).

810 Local knowledge can complement technical monitoring by identifying flood pathways, warning signs, safe routes and locations damaged in previous events. Participatory assessment in Turtuk, Ladakh, produced a community risk map broadly consistent with geological analysis (Ahmed et al., 2019). Japan's community-based "disaster prevention living circle" approach similarly involves residents in local mapping and preparedness planning (Zang et al., 2025). In the Illgraben watershed in the Swiss Alps, upstream monitoring, event detection, automatic alarms, weather forecasting and local response
815 arrangements operate as a connected system. Once debris-flow movement is detected, downstream locations can receive audible and visual warnings approximately 5–15 min before arrival (Badoux et al., 2009). Warning systems should therefore be evaluated not only by forecast or detection performance, but also by usable lead time, communication coverage and whether predefined actions can be completed before the hazard arrives.

6.3 Costs and trade-offs

820 The long-term viability of structural protection depends on the recurrent expenditure required to preserve its performance. This is particularly important in sediment-rich mountain torrents, where sediment accumulation increases the need for inspection, clearance, repair and upgrading. In Austria's Wartschenbach torrent, check dams and debris-flow control works were estimated to reduce expected losses by approximately 89%. Under projected increases in debris-flow activity, maintaining this level of protection would require maintenance budgets to rise by between 57% and 63%, together with an
825 increase of approximately 50% in intervention costs (Ballesteros Cánovas et al., 2016). An assessment of detention basins in Madeira also considered implementation and maintenance costs alongside hydraulic performance (Vieira et al., 2018). Economic evidence is even more limited for Nature-Based Solutions. Broader reviews indicate that including ecological and social co-benefits can increase their estimated economic value, but empirical evidence on cost-effectiveness remains sparse. Flood-reduction performance also varies with spatial scale, and robustness under extreme events remains uncertain
830 (Esraz-UI-Zannat et al., 2024). Establishment and maintenance costs over longer periods are rarely quantified for mountain flash-flood applications. Available evidence is therefore insufficient to compare the long-term cost-effectiveness of Nature-Based Solutions, structural protection and combined portfolios.

Land-use regulation and financial instruments involve trade-offs among risk reduction, development and social acceptance. Zoning can limit further development in flood-prone areas, but enforcement is difficult where land is scarce and local
835 economies depend on construction, tourism or farming. Relocation reduce exposure more directly, yet households may be reluctant to move when compensation is uncertain or relocation threatens their livelihoods and community ties. Such programmes also require stable long-term funding. Insurance and risk-financing mechanisms can support recovery, but only where coverage is affordable and risk information is reliable. In the United States, many households remain uninsured and rely on post-disaster assistance that typically covers less than 20% of their losses, while approximately 46% of applications

840 for disaster-relief loans are rejected (Begley et al., 2024). Access to these loans is also uneven, with denial rates higher in areas containing larger shares of minority residents and subprime borrowers and greater income inequality (Begley et al., 2024). Flood-insurance prices may poorly represent actual risk where floodplain maps are outdated or too coarse. In 2020, only about 4 million of an estimated 14 million high-risk properties in the United States had flood-insurance coverage (Bhattacharyya and Hastak, 2024; Ratnadiwakara and Venugopal, 2023). Coverage may also be difficult to sustain, as
845 unexpected premium increases are more likely to prompt policy termination among homeowners who perceive climate change as a limited risk (Ratnadiwakara and Venugopal, 2023). In New York, buyout programmes have enabled repeatedly flooded properties to be acquired and converted into ecological buffers, although their implementation depends on continued funding, household consent and subsequent land management (Hashida and Dundas, 2023; Kihlslinger et al., 2017). These sites can provide wider ecological benefits, but their restoration and long-term management create continuing responsibilities
850 for local governments (Kihlslinger et al., 2017). Risk sharing also extends across administrative and national boundaries. India and Bangladesh share 54 international rivers and experience recurrent transboundary flooding, requiring data exchange and coordinated river and flood management (Sujon, 2022). In the Rhine basin, transnational restoration of natural detention areas has been used to address flood conveyance and storage across borders (Schulte-Wülwer-Leidig et al., 2018).
The appropriate combination of measures nevertheless differs among mountain regions. In under-monitored or
855 resource-constrained basins, sparse hydrometeorological observations can constrain the calibration and operation of complex forecasting systems. Locally maintained gauges, radio warnings, simple evacuation plans and routine maintenance may therefore provide greater immediate benefit than technically complex forecasting systems. In rapidly urbanising valleys, early control of land development and targeted drainage or detention may be more effective than attempting to remove exposure after settlements and infrastructure have become established. No portfolio eliminates mountain flash-flood risk.
860 Governance should therefore combine prevention of new risk, reduction of existing risk and preparation for residual losses, while revising measures as environmental conditions, development patterns and evidence change. The objective is not simply to reduce aggregate losses, but to avoid transferring risk downstream, across administrative boundaries or towards populations with fewer resources to anticipate, respond and recover.

7 Conclusion

865 Mountain flash floods pose growing risks under climate and environmental change, yet the global post-2000 literature remains geographically uneven and thematically fragmented. By synthesising 1,967 studies, this review establishes a structured evidence baseline across climatic, geomorphic and development contexts, showing that research remains concentrated in parts of Europe and Asia, while many mountain regions in Africa and South America are under-documented. Regional differences also extend to the types of evidence available, affecting the transferability of process relationships,
870 models and management approaches.

Mountain flash-flood response is strongly state-dependent. Storm intensity, duration and spatial concentration interact with antecedent hydrological conditions, surface controls and hillslope – channel connectivity to govern runoff concentration and peak formation, while sediment supply and connectivity influence sediment-rich flood conditions. These interactions limit the transferability of fixed rainfall thresholds and support dynamic, multi-source early-warning approaches.

Flash-flood losses emerge when rapid flows, sediment and debris intersect with exposed settlements, infrastructure, livelihoods and ecosystems under different vulnerability and capacity conditions. Hazard chains can further amplify impacts as interacting hazards propagate through mountain catchments. Effective risk reduction therefore depends on coordinated portfolios of non-structural, structural and Nature-Based measures adapted to local hazard processes, exposure patterns, monitoring capacity and available resources. The adaptive governance framework developed here integrates prevention of new risk, reduction of existing risk and management of residual risk while addressing exceedance uncertainty, warning-to-action effectiveness, and long-term costs and trade-offs.

Future progress depends on reducing spatial inequalities in evidence and capacity. High-resolution rainfall and discharge monitoring, longer-term observatories and open event inventories are particularly needed in under-monitored mountain regions. Machine-learning warning systems require stronger uncertainty quantification, spatial and temporal validation, and testing beyond their training data, while closer integration of artificial intelligence with physical models and real-time observations could improve operational performance and interpretability. Comparative studies should also quantitatively evaluate intervention performance, life-cycle costs and implementation conditions to establish where risk-reduction approaches are transferable and where local adaptation is required.

Appendix A Regional evidence profiles

Table A1. Regional evidence profiles across selected GMBA major mountain systems.

GMBA major mountain system	<i>n</i>	A1 Ground observation and monitoring	A2 Remote sensing and spatial analysis	A3 Modelling and data-driven analysis	A4 Historical event reconstruction	A5 Experimental evidence	B1 Exposure, vulnerability and disaster impacts	B2 Risk-reduction measures
Himalaya	168	15 (8.9 %) LQ = 0.62	55 (32.7 %) LQ = 1.14	39 (23.2 %) LQ = 0.83	7 (4.2 %) LQ = 0.43	0 (0.0 %) LQ = 0.00	96 (57.1 %) LQ = 1.50	52 (31.0 %) LQ = 1.31
Tibetan Plateau	28	3 (10.7 %) LQ = 0.74	9 (32.1 %) LQ = 1.12	9 (32.1 %) LQ = 1.15	3 (10.7 %) LQ = 1.11	0 (0.0 %) LQ = 0.00	9 (32.1 %) LQ = 0.84	8 (28.6 %) LQ = 1.20
Central China Mountains	16	1 (6.2 %) LQ = 0.43	2 (12.5 %) LQ = 0.44	5 (31.2 %) LQ = 1.12	0 (0.0 %) LQ = 0.00	1 (6.2 %) LQ = 7.91	3 (18.8 %) LQ = 0.49	6 (37.5 %) LQ = 1.58
European Alps	43	14 (32.6 %) LQ = 2.26	7 (16.3 %) LQ = 0.57	11 (25.6 %) LQ = 0.92	6 (14.0 %) LQ = 1.44	2 (4.7 %) LQ = 5.88	9 (20.9 %) LQ = 0.55	8 (18.6 %) LQ = 0.78
Carpathian Mountains	37	3 (8.1 %) LQ = 0.56	6 (16.2 %) LQ = 0.57	8 (21.6 %) LQ = 0.78	8 (21.6 %) LQ = 2.23	0 (0.0 %) LQ = 0.00	4 (10.8 %) LQ = 0.28	3 (8.1 %) LQ = 0.34
American Cordillera (North America)	28	4 (14.3 %) LQ = 0.99	3 (10.7 %) LQ = 0.37	7 (25.0 %) LQ = 0.90	1 (3.6 %) LQ = 0.37	0 (0.0 %) LQ = 0.00	2 (7.1 %) LQ = 0.19	2 (7.1 %) LQ = 0.30
Appalachian Mountains	12	5 (41.7 %) LQ = 2.89	1 (8.3 %) LQ = 0.29	3 (25.0 %) LQ = 0.90	2 (16.7 %) LQ = 1.72	0 (0.0 %) LQ = 0.00	1 (8.3 %) LQ = 0.22	0 (0.0 %) LQ = 0.00

GMBA major mountain system	<i>n</i>	A1 Ground observation and monitoring	A2 Remote sensing and spatial analysis	A3 Modelling and data-driven analysis	A4 Historical event reconstruction	A5 Experimental evidence	B1 Exposure, vulnerability and disaster impacts	B2 Risk-reduction measures
East Sahara Mountains	40	5 (12.5 %) LQ = 0.87	31 (77.5 %) LQ = 2.70	15 (37.5 %) LQ = 1.35	2 (5.0 %) LQ = 0.52	0 (0.0 %) LQ = 0.00	16 (40.0 %) LQ = 1.05	10 (25.0 %) LQ = 1.05
Atlas Mountains	7	2 (28.6 %) LQ = 1.98	4 (57.1 %) LQ = 1.99	3 (42.9 %) LQ = 1.54	0 (0.0 %) LQ = 0.00	0 (0.0 %) LQ = 0.00	4 (57.1 %) LQ = 1.50	2 (28.6 %) LQ = 1.20
Madeira	10	2 (20.0 %) LQ = 1.39	2 (20.0 %) LQ = 0.70	4 (40.0 %) LQ = 1.44	0 (0.0 %) LQ = 0.00	0 (0.0 %) LQ = 0.00	5 (50.0 %) LQ = 1.31	2 (20.0 %) LQ = 0.84
Andes	16	2 (12.5 %) LQ = 0.87	4 (25.0 %) LQ = 0.87	5 (31.2 %) LQ = 1.12	3 (18.8 %) LQ = 1.94	0 (0.0 %) LQ = 0.00	7 (43.8 %) LQ = 1.15	3 (18.8 %) LQ = 0.79
East African Highlands	7	1 (14.3 %) LQ = 0.99	1 (14.3 %) LQ = 0.50	2 (28.6 %) LQ = 1.03	1 (14.3 %) LQ = 1.48	0 (0.0 %) LQ = 0.00	5 (71.4 %) LQ = 1.87	4 (57.1 %) LQ = 2.41

Notes: Each cell gives the number of publications and within-system percentage, followed by the location quotient (LQ). Labels are non-exclusive, so percentages do not sum to 100 %. LQ is the within-system proportion divided by the corresponding proportion across the 506 system-resolved publications. Categories discussed as regional concentrations in the text meet all three criteria: system $n \geq 10$, category count ≥ 3 , and $LQ \geq 1.25$; systems with $n < 10$ are interpreted descriptively. Major-system labels may overlap.

895 **Code availability.**

The code used in this study is available from the corresponding author upon reasonable request.

Data availability

The bibliometric database of 1,967 peer-reviewed articles and the event-level dataset of 95 documented mountainous flash-flood cases compiled in this study are provided in the Supplement. Additional derived data are available from the
900 corresponding author upon reasonable request.

Author contribution

ZC and MF designed the study and developed the overall review concept. ZC carried out the bibliometric analysis and dynamic topic modelling. FKC and MF led the synthesis of global case studies and governance frameworks. MFJ and NW contributed to the sections on hydrological and geomorphological processes and provided critical revisions. YW contributed
905 to data curation and visualisation and assisted with manuscript revision. FW contributed to the sections on Chinese case studies and policy implications. All authors contributed to the writing, discussion, and revision of the manuscript.

Competing interests.

The authors declare that they have no conflict of interest.

Disclaimer.

910 Portions of the manuscript were translated using DeepL and Google Translate and language-polished with GPT-based tools. These tools were used for language editing only and did not affect the study design, analysis, results, or conclusions.

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