



Review article: Flash Floods in Mountainous Regions: Global Research Trends, Process Mechanisms, and Control Measures

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Abstract. Flash floods in mountainous regions are becoming more frequent and destructive under climate warming, yet
15 cross-regional understanding of their triggering mechanisms, cascading impacts, and governance remains fragmented. This
review synthesises 1,967 studies published during 2000–2025 to establish a globally comparable baseline of mountain flash-
flood research. By integrating bibliometric and topic analyses with qualitative synthesis, we reveal pronounced geographical
and thematic imbalances, with research concentrated in Europe and Asia. At the same time, many high-risk mountain regions
in Africa and South America remain overlooked. Across regions, flash-flood initiation and impacts are shown to be strongly
20 state-dependent and coupled, emerging from interactions between storm intensity, duration and spatial concentration,
antecedent hydrological conditions, and hillslope-channel connectivity. This coupling helps explain why fixed rainfall
thresholds are difficult to generalise and highlights the need for dynamic, multi-source early-warning approaches.
Comparing evidence on early warning, structural protection, and Nature-Based Solutions, the review shows that cascading
processes dominate risk management challenges. We therefore propose an adaptive governance framework that links
25 monitoring and forecasting, spatial planning, grey-green integration, and basin-scale risk sharing under non-stationary
climate conditions. Overall, this synthesis consolidates fragmented evidence into a cross-regional knowledge base to support
flash-flood risk reduction in mountainous regions, where data and capacity are limited.

1 Introduction

Flash floods are rapid, short-lived events with high peak discharges, typically occurring within four to six hours of rainfall
30 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



35 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).

40 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., 2019). Physical features such as steep slopes, diverse geological conditions, and orographically-enhanced rainfall render these regions highly susceptible to flash flooding (Stäubli et al., 2017). 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., 45 2019; Wang et al., 2023).

Anthropogenic land-use changes, including deforestation (Deijns et al., 2024), wildfires (Ebel, 2024), and soil compaction (Adnan et al., 2019), negatively affect vegetation interception and soil infiltration. These alterations amplify surface runoff and elevate flood risks. Additionally, floods may be triggered by sudden water releases from dam or levee failures, or the clearance of river blockages (Hong et al., 2013). These pressures are compounded by population growth and urban 50 expansion onto steep slopes due to limited flat land (Shi et al., 2025), which constrains the response capacity of mountain communities. These high-velocity flows frequently transport massive sediment loads, including boulders and woody debris. Consequently, they can destroy infrastructure, damage agricultural land, contaminate water supplies, and trigger secondary hazards such as landslides (Liu et al., 2023; Singh and Kansal, 2024).

Existing research on flash floods in mountainous regions is still dominated by site-specific observations and single-basin 55 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 compound 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). Data-driven and quantitative syntheses remain limited relative to other hazard fields, and advances in 60 monitoring, modelling, and early-warning design have not been consolidated into a coherent, cross-scale understanding for mountains (Ahmed et al., 2018; Bodoque et al., 2015). 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 65 (Adhikari et al., 2023; Lombardi et al., 2021).

To address these gaps, this review makes three contributions:



- (1) To establish the first globally comparable baseline 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.
- 70 (2) To synthesise cross-regional process evidence 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 translate process understanding into governance-relevant insights by comparing early warning, structural, and Nature-Based measures, and proposing an adaptive framework that addresses cascading risks under non-stationary climate
- 75 conditions.

2 Global research trends

This study adopts a structured literature search and screening strategy to identify research on mountainous 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 across disciplines, we applied a structured Boolean query that

80 constrains both the hazard type and the terrain setting (Sect. S1). The core search string used in the Web of Science and Scopus was:

("flash flood" OR "flash-flood" OR "pluvial flash flood*" OR "rapid-onset flood*" OR "cloudburst*" OR "mountain torrent*") AND (mountain* OR alpine OR "hilly area*" OR upland* OR highland* OR plateau* OR "steep slope*" OR wadi* OR arroyo*) **

85 Through strict inclusion and exclusion criteria, 1,967 peer-reviewed papers were selected for this study. Dynamic Topic Modelling (DTM) was applied to identify core research themes over the 25-year period, with deterministic training protocols ensuring reproducibility (Sect. S2).

Figure 1 illustrates the temporal, spatial, and academic landscape of global mountain flash-flood research from 2000 to 2025. The Journal of Hydrology produced the highest volume of literature (Fig. 1c), followed by Natural Hazards and Earth

90 System Sciences. The publication trend (Fig. 1d) exhibits moderate growth between 2000 and 2010, followed by a rapid escalation thereafter, peaking at 181 articles in 2023. This volume of output highlights the status of flash floods as a significant interdisciplinary field, bridging hydrology, geomorphology, and disaster science. Due to the escalating risks associated with global environmental change, this topic has received increasing priority from the international scientific community.

95 The geographic distribution of mountain flash-flood research closely aligns with the actual occurrence of disasters (Fig. 1). This correlation reflects event-driven academic interest and funding priorities, particularly in Europe and Asia, which are regions that lead in both research investment and academic output. Case statistics (Fig. 1b) indicate that flash-flood events are most prevalent in China and India, followed by Egypt and the central-to-eastern Mediterranean countries, including Italy,



100 France, and Spain. Notably, Switzerland and the USA provide substantial research contributions (Fig. 1a). Although they do not have the highest counts of documented cases (Fig. 1b), their high output reflects strong research capacity, sustained investment in monitoring infrastructure, and leadership in methodological innovation.

105 In China, major clusters are situated along the northern mountain fronts, such as the Taihang foothills, and in the Hengduan and Three Parallel Rivers regions (Fig. 3). In South Asia, events are concentrated along the Himalayan and Hindu Kush arcs, spanning Pakistan, Nepal, and the Ganges and Yarlung Zangbo sectors. Arid regions in Egypt, Saudi Arabia, and Oman show persistent wadi-related hot spots along the Eastern Desert and Red Sea margins. Further clusters are identified across the Andes, the Carpathians - Balkans, and parts of the Middle East.

110 While clusters exist in Ethiopia, Morocco, and South Africa, these patterns require careful interpretation. Inconsistent monitoring and reporting, particularly in parts of Africa and South America, likely mask many events. This contributes to a north-south imbalance in research resources and attention, which ultimately hinders the development of locally tailored risk-reduction strategies.

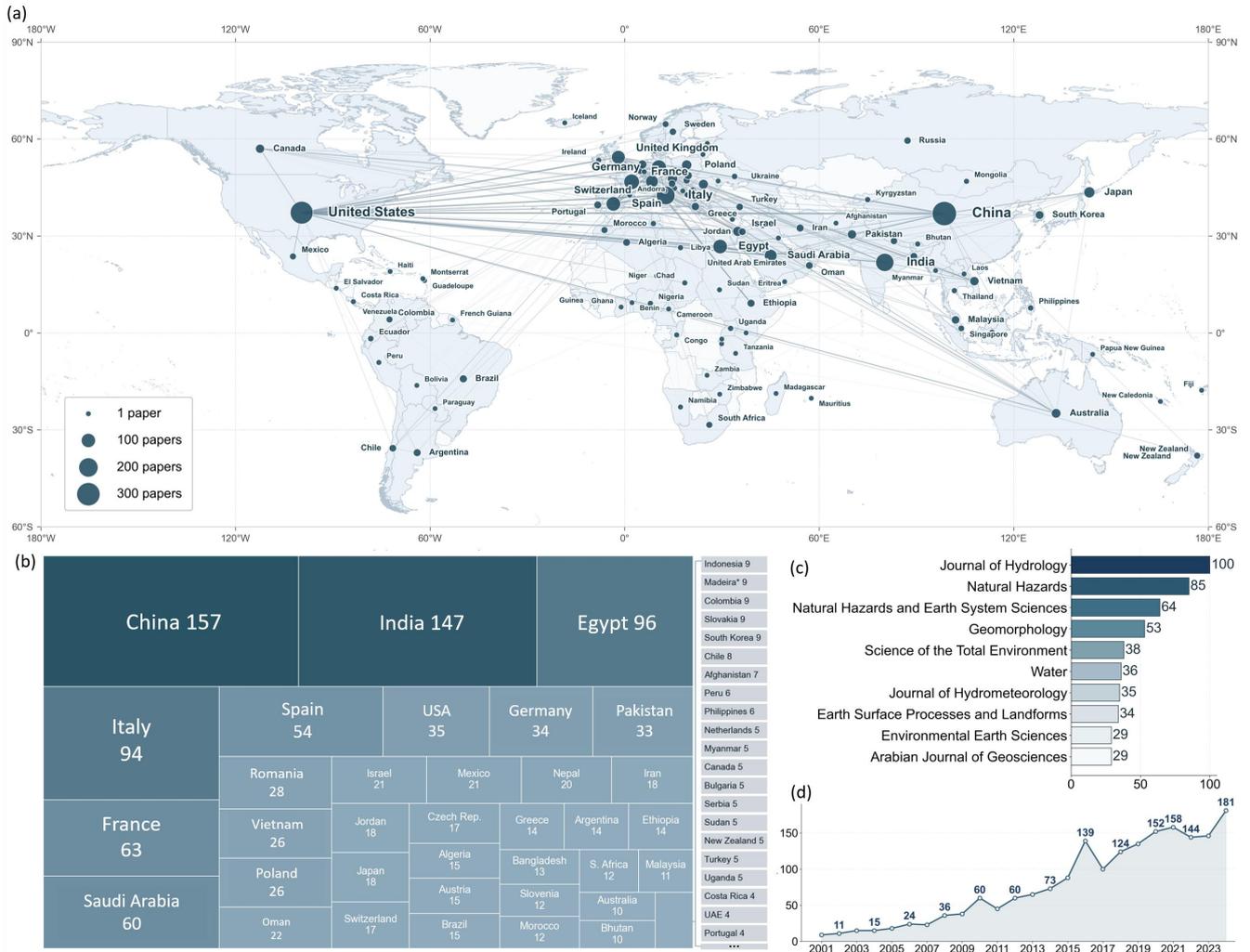
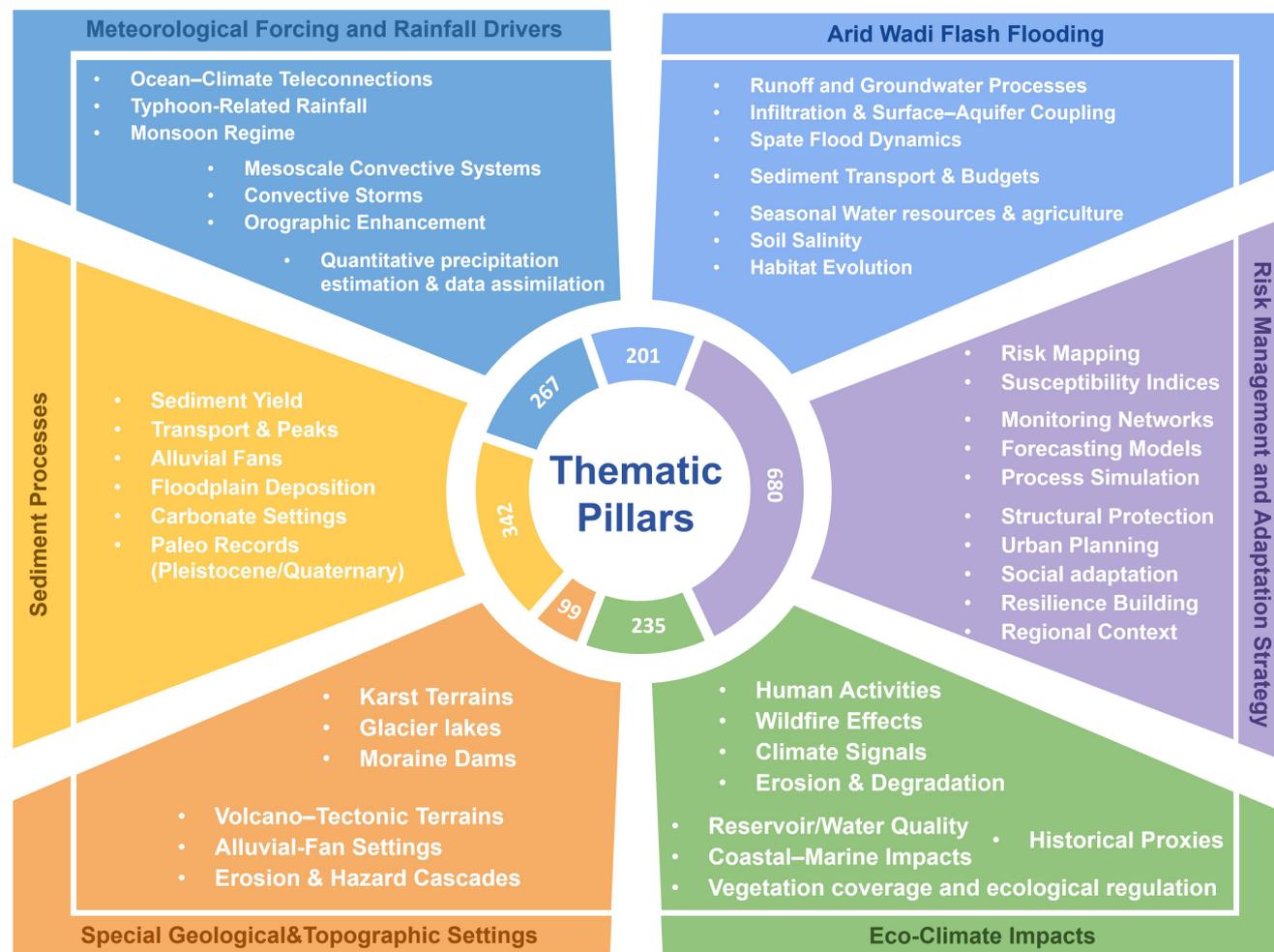


Figure 1: Spatial distribution and temporal trends in global flash-flood research in mountainous regions. (a) Global distribution of research outputs on mountainous flash floods (2000–2025) and associated cross-border collaborations. Node size represents the total number of publications for each country, 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.

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.



125 **Figure 2: Literature-based hotspots of global mountain flash-flood research (2001–2025) and their thematic intensity.** Studies
 130 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
 135 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.



140 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 680 publications or 35% of the entire corpus. This domain has experienced a particularly robust and consistent
145 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
150 characterize the current state of the literature.

First, process-centric research is substantial but fragmented: Sediment Processes represents 342 studies, reflecting sustained
attention to sediment yield, transport and peak-flow metrics, and fan-floodplain deposition; however, these insights are not
proportionally mirrored in governance-oriented work, where design standards and decision thresholds are often needed, with
only 86 Risk Management and Adaptation Strategy studies explicitly addressing sediment-related factors.

155 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
is smaller than might be expected given rainfall’s role as the primary trigger; its sub-topics (teleconnections,
monsoon/typhoon regimes, mesoscale convective systems and convective storms, and orographic enhancement), together
160 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
165 historical proxies of flood frequency—thereby providing an emerging bridge between event-scale hydrology and longer-term
environmental change.



3 Flash floods in mountain basins: mechanisms and cascading impacts

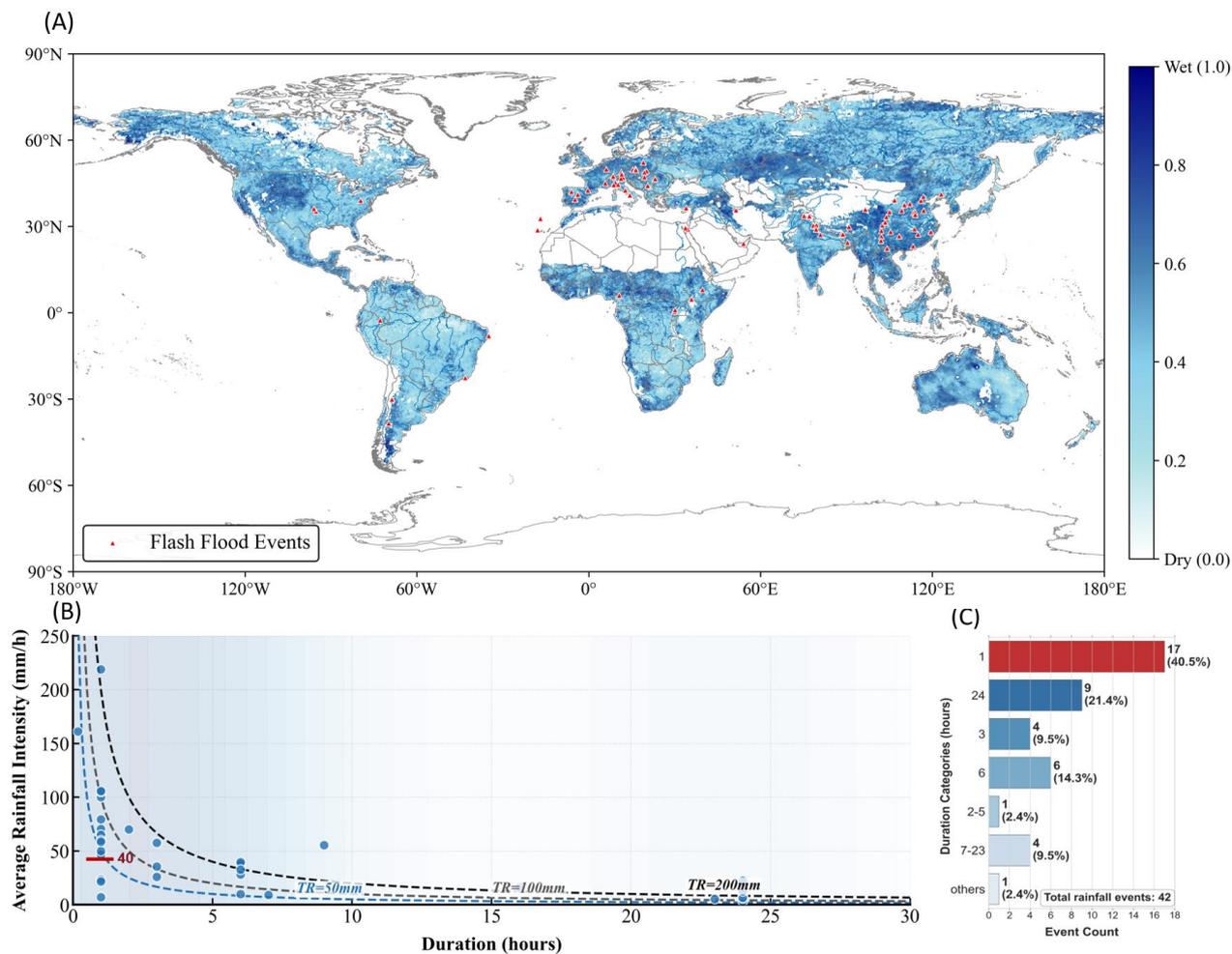
3.1 Drivers and mechanisms of flash floods in mountain basins

3.1.1 Climate–topography interactions and flood initiation

170 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 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 1.57×10^7 m³ (Attwa et al., 2021).

180 The spatial-temporal concentration of rainfall further exerts a major control on hydrological responses. In the Luanhe River 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.

185 Approximately 70% of flash-flood events occurred between June and August and were associated with moderate to high values of the Microwave Integrated Drought Index (MIDI) (Zhao et al., 2025) (typically 0.4-0.6). Rainfall characteristics extracted from 42 flash flood cases fall into two categories: hourly peak rainfall at the time of flood initiation, and the other reports the cumulative rainfall total. Reported cumulative rainfall ranged from 43 to 1,631 mm, with a 25th percentile of 150 mm and only one event registering < 100 mm (43 mm) (Fig. 3d). 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 findings are broadly consistent with Di et al. (2021), who proposed a dynamic precipitation-threshold warning model that couples short-term (1-24 h) rainfall with antecedent catchment conditions. Representative hourly thresholds were approximately 35 mm h⁻¹ in humid southeast China and 10 mm h⁻¹ in its northern regions. For south-eastern China specifically, the corresponding dynamic thresholds for 12-, 6-, 3-, and 1-hour periods were approximately 100, 80, 60, and 35 mm, respectively. These values are broadly applicable given the region’s humid subtropical monsoon climate, complex relief, and high exposure of populations and infrastructure (Di et al., 2021).



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Figure 3: Background moisture and rainfall characteristics associated with documented flash flood events. (a) Global distribution map of the Microwave Integrated Drought Index (MIDI) derived from FY-3 products (2022–2024 summer mean); red triangles indicate the geographic distribution of the 42 typical flash flood events analysed in this study. (b) Relationship between peak rainfall intensity and corresponding duration for the 42 cases. Grey dashed lines represent iso-surfaces of different Total Rainfall (TR) levels (e.g. 50, 100, and 200 mm); the red horizontal line marks a high-intensity reference of 40 mm/h. The scatter positions reflect the key rainfall process characteristics leading to flood initiation. (c) Distribution of event-duration categories and corresponding event counts associated with flood initiation. Together, the data in these panels reveal the diverse threshold relationships between rainfall intensity and duration required to trigger flash floods.

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Differences in the rainfall volumes and intensities that trigger flash floods indicate that effective early-warning systems cannot rely on a single rainfall intensity threshold. Instead, integrated approaches that combine IDF relationships, rainfall duration, and antecedent soil moisture conditions are required to produce multi-levelled warnings that reflect regional climatic and topographic variability. For example, the Chinese government adopts an orange threshold of 100 mm h⁻¹ in the rugged mountainous areas of Chongqing, but only 20 mm h⁻¹ in the arid areas of Ningxia (Chongqing Municipal People's

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Government, 2024).



Early-warning design is further complicated by uncertainties related to future climatic drivers of extreme rainfall. In Basilicata, southern Italy, station records (2001–2024) show significant increases in 1- and 3-hour rainfall extremes, particularly in summer and autumn (Piccarreta et al., 2026). Similarly, abnormally heavy dry-season rainfall has been
215 recorded in arid areas of West Asia (Terry et al., 2023), and heavy rainfall is projected to become more frequent during the latter half of the 21st century (Hasan et al., 2018). Elsewhere, however, long-term records remain heterogeneous (Krishnaveni and Arunya, 2024). In the Genoa Metropolitan Area, for instance, annual rainfall totals exhibit no significant trend, although the number of rainy days has declined (Abuzied and Mansour, 2019).

Ocean-atmosphere interactions at global to regional scales modulate moisture transport, storm tracks, and convective
220 instability, thereby creating seasonal-to-interannual windows of elevated extreme-rainfall and flash-flood potential. Evidence linking flash-flood-rich periods to phase changes in major climate modes (e.g., ENSO transitions (Cheng et al., 2018), negative IOD (Terry et al., 2023)/NAO phases (Ballesteros-Cánovas et al., 2015)) and persistently warm–humid monsoonal backgrounds suggests that incorporating such climate-mode diagnostics into forecasting and preparedness can help identify periods when flash-flood risk is rising (Adnan et al., 2019; Kumar et al., 2017).

At local to regional scales, mountain extreme rainfall is often produced by terrain-modulated convection (Chen et al., 2023; Li et al., 2024), where moist inflow and synoptic forcing interact with orography to organise and anchor convective cells on
225 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
230 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).

Flash-flood risk is elevated by non-rainfall triggers. Snowmelt contributes strongly to seasonal flooding in temperate and
235 high-latitude mountain regions (Chai et al., 2022). Warming-driven glacier melt, calving, and lake expansion increase the likelihood of debris flows (Rijal et al., 2024; Verma et al., 2022) and raise flash-flood potential. In Tibet, for instance, moraine-dammed lakes at South Longka and Sedongpu are expanding, heightening the risk of glacial lake outburst floods (GLOFs) (Singh et al., 2025; Zhang et al., 2022). Sediment-rich meltwater can also aggrade channels and worsen
240 downstream flooding (Verma et al., 2022). Dam-failure floods may occur through overtopping during extreme storms (Santos-González et al., 2021) or as a result of human factors such as insufficient design capacity, poor maintenance, or operational errors (Singh et al., 2025). Because such triggers are often sudden and difficult to anticipate, delicate risk assessment and preparedness measures are essential. Although early warning for non-rainfall triggers remains challenging, systematic hazard evaluation and contingency planning can mitigate the impacts of unexpected flooding.



245 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
250 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 should include consideration of large-scale
climate–weather diagnostics to identify hazard windows (e.g. teleconnections, monsoon/typhoon regimes, convective
systems, and moisture transport), mesoscale high-resolution precipitation observation and nowcasting to constrain storm
location and concentration under complex terrain, basin-scale tracking of susceptibility states (e.g. wetness, cryosphere,
255 disturbance, and connectivity proxies) so conditional thresholds can be updated in real time.

Advancements in channel scale sensing remain essential, particularly regarding the integration of stage and velocity data
with indicators of sediment and woody debris. Such developments are crucial for the rapid triggering and verification of
flash-flood events. Furthermore, incorporating deformation and stability monitoring tools, such as InSAR, GNSS, and pore-
pressure sensors, can significantly augment existing systems. These technologies facilitate the detection of hazard pathways
260 that are not primarily triggered by rainfall, including slope failures, landslide dams, glacial lake outbursts, and reservoir or
dam breaches. 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.

3.1.2 Surface controls on flash-flood flow

A catchment's retention potential is governed by an integration of soil characteristics, vegetative density, topographic slopes,
265 and the underlying geological framework. Together, these factors define the thresholds for infiltration and subsurface storage.
When storm intensity or volume surpasses these critical capacities, overland flow is triggered, often resulting in the rapid
onset of flash flooding. 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
270 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
275 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).

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Geological disturbances further alter hydrological response. Landslides in the Rwenzori Mountains of Uganda (Jacobs et al., 2016) 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).

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Soil characteristics have a major role to play in the, "Infiltration Rate, Storage of Water, Drainage Processes, and Delivery of Sediment" all of which are essential aspects to how rain water becomes surface runoff. Soil types with high permeability, such as sand or gravel allow for a great deal of rainfall to infiltrate the soil. On the contrary, types of soil containing clay will not only become saturated quickly but will also produce significant surface runoff. 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).

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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°) (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). Urban areas are made up of mainly impervious surfaces like paved roads, rooftops, and other forms of hard-surface construction that result in significantly reduced infiltration of rainfall. Additionally, urban piped drainage methods convey water from urbanized land areas into surface channels of rivers, increasing the runoff coefficient and reducing the timeframe for water to reach a particular outlet. Similarly, urbanization along the Mediterranean coast has caused a dramatic increase in natural flood peak flows. For example, a 1-in-50-year natural flood peak flow from a rainfall event was estimated to be $380 \text{ m}^3 \text{ s}^{-1}$, while the same event after urbanization produced an urban flood peak of $940 \text{ m}^3 \text{ s}^{-1}$ (Jodar-Abellan et al., 2019). There are many other activities undertaken by humans that impact natural waterways, namely through excessive mineral extraction, construction (building roads, digging canals, and constructing dams), interfering with natural watersheds and thus reducing flood control capabilities throughout the region (Manoj et al., 2024).

3.2 Cascading impacts and potential challenges of flash floods

The destructive forces associated with flash floods cause significant multi-faceted stresses upon mountain river basins, developing a series of complicated interrelated and progressive effects that go far beyond just the immediate physical destruction caused by flooding. The primary impacts of flash floods can be grouped into three types of interdependent



domains (fig. 4): economic, social, and environmental – each representing unique challenges for regional stabilization and
 345 resilience to disasters.

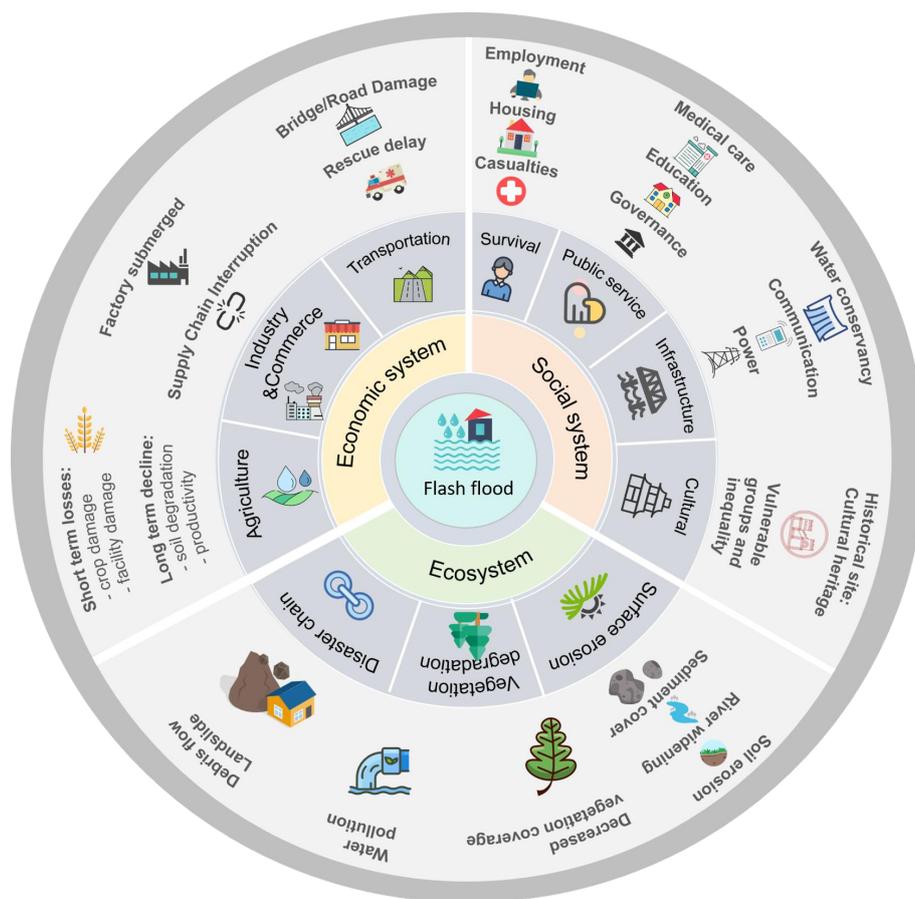


Figure 4: Schematic overview of the multi-dimensional cascading impacts and potential challenges of flash floods on mountain river basins. Highlight cascading impacts on economic, social, and ecosystem components.

3.2.1 Economic losses and land use planning

350 Flash floods are characterized by their abrupt onset, high velocities, and substantial sediment transport, all of which present
 severe threats to food security by devastating crops, degrading soil quality, and dismantling agricultural infrastructure (Lara
 et al., 2018). Specific incidents underscore this volatility: in Cameroon’s Babesi region, a single 30-minute event decimated
 approximately 160 hectares of crops (Buchenrieder et al., 2021). Similarly, a catastrophic flood in Xingyang City, Henan,
 impacted 21,745 hectares, resulting in the total loss of 8,239 hectares (Hao et al., 2023). Beyond direct destruction, intense
 355 precipitation compacts surface soils and triggers overland flow when rainfall exceeds infiltration capacity. This process
 amplifies runoff and accelerates the erosion of steep slopes (Villinger et al., 2022).



The long-term agricultural consequences are equally profound. In the high-altitude regions of South Asia, the combination of flood-driven erosion and substandard farming practices has stripped away fertile topsoil, suppressing cereal yields to a mere
360 third of their potential (Ashraf and Ahmad, 2024). In Camposalone, Italy, the deposition of coarse debris across 63 hectares of farmland significantly impaired the soil's ability to retain essential moisture and nutrients (Santo et al., 2017). Furthermore, livestock sectors face extreme vulnerability, evidenced by the 2018 flash flood in Uttarakhand, India, which resulted in over 11,000 animal fatalities (Arlikatti et al., 2018). While some Himalayan farmers have attempted to adapt through crop diversification and shifting planting schedules, the efficacy of these strategies is often undermined. In many mountainous
365 regions, the lack of robust early-warning systems, technological constraints, and insufficient financial resources continue to obstruct successful adaptation (Dilshad et al., 2021).

The structural integrity of buildings is severely compromised by flash floods, which can lead to total collapses, burial under mud, or the undermining of foundations (Gan et al., 2018; Hao et al., 2022). A poignant example is the 2023 Derna flood in
370 Libya, where the failure of upstream dams unleashed dual peak flows that decimated the city, leveling 737 homes and inflicting partial damage on another 2,859 structures (Ashoor and Eladawy, 2024). In low-lying industrial zones, floodwaters frequently ruin specialized equipment and inventory. However, the magnitude of these losses is contingent upon the region's economic framework, asset density, and preexisting disaster preparedness (He et al., 2024; Singh et al., 2023). Transportation and utility networks are similarly susceptible to these high-energy events. Rapid surges can wash out roadways, sweep away vehicles, and destroy bridges, while accumulated debris often obstructs railways and culverts (Roy et
375 al., 2024). Such destruction was documented in Liulin Town, China, where floods incapacitated 11.3 km of roads and 63 bridges (Hao et al., 2022). Furthermore, the impact on critical facilities such as power plants and water treatment centers often triggers a cascade of failures, disrupting potable water supplies, wastewater management, and communication networks. These service interruptions not only impede emergency rescue operations but can also incite widespread social panic (Brázdil et al., 2024; Jin et al., 2024).

In designing critical infrastructure, redundancy and resilience must be incorporated. As noted in the event of a flash flood that occurred in Jeddah, Saudi Arabia during 2009, when breaches in embankments for flood control combined with narrow urban roadways to exceed the design capacity of flood control features, floodwaters reached up to 2 m deep (El-Hames and Al-Wagdany, 2012). Thus, critical infrastructure build within these mountains should have multiple routes for emergency supply chain services and resilient communication networks, as well as connections between regions. Flash flood damage
385 tends to be compounded because of previous land use decisions, such as rapid and unplanned urban growth, which often put buildings and infrastructure into flood plains, dry detention basins, and steeply sloped hillslopes, etc. For example, in Egypt, new districts were constructed over naturally dry detention basins and wetlands that resulted in reactivating routes for flood accumulation after storms (Helmi and Zohny 2020).

In Petrópolis, Brazil, disorganised urban expansion resulted in over 1,700 buildings on hillslopes with gradients of 20°–45°
390 and reduced vegetation cover. A 258 mm rainfall event on 15 February 2022 triggered flash floods and landslides, resulting in at least 231 fatalities (Alcântara et al., 2023). In Uttarakhand, India, nearly three-quarters of the state lies in high to severe



395 landslide risk zones. The 2013 cloudburst and associated flash floods and landslides destroyed approximately 10% of the upper Mandakini catchment, affecting roughly 80,000 people (Mishra, 2015). Therefore, land use planning, settlement, and infrastructure development in mountain regions should be integrated into comprehensive flash-flood risk management frameworks

3.2.2 Human costs and social vulnerability of flash floods

Flash floods pose a significant threat to human safety, particularly in densely populated areas with inadequate early-warning systems. They can cause devastating losses of life and long-term welfare disruption (He et al., 2024). Flash floods and debris flows in the Indian Himalayas cause mass casualties and disappearances almost every year (Prince et al., 2024). In Derna, 400 Libya, a flash flood caused by Storm Daniel in September 2023 led to the sequential failure of two upstream dams, creating a flood wave that swept through the city and left up to more than 4,000 deaths and thousands reported missing (Ashoor and Eladawy, 2024). The 1963 Vajont disaster in Italy illustrates how mountain floods can be generated by slope failure–reservoir interaction: a massive landslide from Mt. Toc rapidly entered the Vajont reservoir, producing a displacement wave that overtopped the dam and devastated Longarone and neighbouring settlements, causing on the order of 2,000–2,600 405 fatalities. A key lesson is that even when the dam structure survives, catastrophic losses can still arise from insufficient geological risk recognition, underestimated worst-case scenarios, and delayed precautionary actions (monitoring, reservoir operation, evacuation) in unstable mountain settings (Stoffel et al., 2016).

Besides immediately causing the death of individuals, flash floods routinely create the conditions for mass population displacement and create long-term disruptions to the ability of populations to maintain their livelihoods. These weaken 410 peoples' capacity for socio-economic resilience. For instance, following the 2022 flood disaster in Pakistan, more than 8 million people were displaced and more than 2 million homes were damaged. Although the government subsequently set up many further relief camps, 600,000 displaced people remained living in temporary shelters for the foreseeable future (Ashraf et al., 2024). Approximately 48,000 people were rapidly evacuated away from their homes during the debris flow created by the 2019 flash flood disaster in Wenchuan, China (Jin et al., 2024).

415 Large-scale relocation creates a heavy burden on governance and can leave affected households without stable housing and income for years. A survey of survivors of the 2013 flash floods in northern India found that most respondents were unwilling to permanently relocate due to severed community ties and disrupted livelihoods, instead opting for in situ reconstruction with strengthened local protection (Arlikatti et al., 2018). A similar survey in rural Cameroon, conducted six weeks after a severe flash flood, showed that only 5% of affected households had fully restored their livelihoods, even when 420 they remained within their communities, highlighting the slow and uneven recovery processes (Buchenrieder et al., 2021). Such conditions may foster social instability, including the growth of informal settlements and shantytowns due to poverty and housing shortages.

Vulnerable groups, such as women, children, the elderly, low-income households, marginalised communities, and culturally significant sites, are particularly impacted. A rapid assessment of the impact of the 2022 flooding in Pakistan found that 84



425 percent of women were unhappy with the relief and medical assistance provided to them, that 77 percent of women had
limited access to family planning and reproductive health services, that 69 percent of girls aged 5 to 13 years had left school,
and that approximately 30 percent of families were now living in poverty and relying on charity (Ashraf et al., 2024). The
results of a survey conducted in Babassi, a rural community located in Cameroon, suggest that community members'
perceived risk of flash floods varies greatly based on community location and settlement pattern. For example, Christian
430 communities located at the base of the hills compounded their vulnerability to flash flooding compared to Muslim
communities located further up the hills, and therefore they rate their level of concern regarding flash flooding higher than
the Muslim community members (Buchenrieder et al., 2021). Many historic settlements and cultural assets in mountain
regions, such as parts of the Great Wall of China and ancient Himalayan temples, are damaged or threatened by flash floods
(Prince et al., 2024; Zhao et al., 2023).

435 3.2.3 Ecological risks of flash floods

Flash floods can quickly change hillslopes and river channels by transporting significant quantities of sediment and debris, as
well as causing landslides and changing future water flow paths and habitats (Ali, 2024; Scorpio et al., 2022). An extreme
flash flood in the Braunsbach catchment of Baden-Württemberg, Germany, surpassed regional design discharges, and debris-
laden flows destroyed buildings and reshaped the town's valley floor (Bronstert et al., 2018). Such events are often part of
440 cascading hazard chains, with approximately 39% of the Kashmir–Karakoram region simultaneously exposed to landslides,
avalanches, and flash floods (Akbar et al., 2023). In the Hindu Kush Mountains of north-western Pakistan, interacting
hazards, such as landslides, flash floods, glacial lake outbursts, and debris flows, frequently reshape landscapes and cause
widespread damage (Ahmad et al., 2025).

Flash floods and other similar secondary hazards greatly impact the ecosystem for an extended period of time. Flash floods
445 regularly occur with sediment-rich water that removes some of the soil (top soil) and vegetation from the landscape and
deposits coarse material on the valley bottoms and hill sides. An example is a flash flood that happened in 2015 along the
southern margin of Atacama Desert in Chile, which resulted in approximately 1.3 mm of erosion at the surface level, which
is nearly identical to what would be expected over one thousand years (Aguilar et al., 2020). During the 1959 Vega de Tera
dam-failure flood in north-west Spain, over 2×10^6 m³ of coarse sediment was deposited in the Tera valley, along with a 10
450 cm sandy-silt layer in Lake Sanabria (Santos-González et al., 2021). Without timely ecological recovery, degraded slopes
and channels become more sensitive to subsequent rainfall, heightening the risk of renewed floods and debris flows (Rijal et
al., 2024; Yu et al., 2023).

Flash floods can also transport pollutants and toxic chemicals into rivers and lakes, degrading water quality (Al-Rawas et al.,
2024a). As climate change is likely to increase both extreme rainfall and flash flood frequency in many regions (Arnell et al.,
455 2023), disaster prevention should be paired with ecological conservation and restoration efforts. Integrating ecological
restoration, land-use planning, and flash flood risk-reduction strategies is essential for strengthening resilience in high-risk
mountain areas (Ashraf and Ahmad, 2024).



4 Flash floods: synergistic measures and evidence

Existing studies highlight that effective flash-flood management must integrate non-engineering, engineering, and Nature-
460 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
465 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.

4.1 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
470 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
475 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).

To address these limitations, machine-learning techniques have been used to regionalise parameters in small mountainous
catchments in southwest China, yielding more accurate hydrographs than manual calibration (Ragetti et al., 2017). Recent
480 global experiments demonstrate that deep-learning forecasting models trained on thousands of gauged catchments can
skilfully predict extreme events in ungauged watersheds with several days of lead time, forming a robust basis for regional to
national warning systems (Nearing et al., 2024). Nevertheless, purely black-box models face challenges of interpretability
and extrapolation (Nearing et al., 2021). Hybrid modelling that embeds hydrological processes with data-driven frameworks
is emerging.

485 For example, 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).



One of the biggest difficulties is that many mountain regions have very few, and low frequency, hydrometeorological
490 networks. Therefore, they are unable to properly identify short-lived or very localized 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
495 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).

500 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
505 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., 2021; Maqtan et al., 2025).

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
510 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).

515 These findings highlight that it is necessary to design risk governance that copes with the local conditions and addresses 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
520 emergency response capacity by directly involving residents in mapping and preparedness (Zang et al., 2025). A notable
example of operational integration is in the Illgraben watershed in the Swiss Alps, which combines community organisation
and planning, event detection, automatic alarms, watershed monitoring, and applied weather forecasting. It can issue sound



and light warnings 5-15 minutes before events at major river intersections, with only one false alarm in its first year (Badoux et al., 2009).

525 Spatial Planning Tools continue to show their strength in application. Susceptibility mapping using GIS data along with machine learning techniques or coupled hydrological models are very commonly shown to work well in areas where there is limited long-term data (Arabameri et al., 2020). The Dahab Watershed in Egypt has successfully identified hazardous zones through mapping and reporting, which gave insights into vulnerable infrastructure and settlements (Abuzied and Mansour, 2019). In addition, the data from a multi-hazard study in the Himalayas showed that the losses were strongly associated with
530 construction quality and unregulated development, so the researchers recommend socioeconomic dimensions must be included with the assessment (Chouhan and Mukherjee, 2023).

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
535 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
540 (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).

4.2 Structural and Nature-Based measures

4.2.1 Structural (grey) measure

Engineering interventions directly regulate flood flow through artificially constructed structures. Check dams are common
545 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
550 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 watershed, two 12m high detention dams with 110,000 m³ storage capacity reduced a 1-in-100-year flood peak by 72%



555 (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
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,
560 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
and raising dikes provides only limited improvement in flood safety. In such settings, the construction of flood-control dams
565 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).

In steep mountain catchments, structural flood mitigation measures are generally most effective when they employ
570 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,
sand-retaining weirs, and slope-stabilisation works in flash-flood-prone mountain catchments, especially across the Loess
575 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 (Cánovas et al.,
2016).

580 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
structures that were designed based on unfavourable historical climatic conditions and possess low active-storage ratios
585 (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).



590 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).

595 4.2.2 Nature-based solutions (NBS)

Compared with conventional engineering methods, Nature-Based solutions tend to offer greater environmental compatibility, a favourable benefit—cost ratio, simpler maintenance and multiple ecological services. These advantages have received increasing attention under the broader paradigm of "green development" (Esraz-Ul-Zannat et al., 2024; Rehman et al., 2023). In the mountainous areas of the Great Rift Valley in northern Ethiopia, watershed reforestation and vegetation restoration
600 substantially reduced flood peaks and sediment risks (Asfaha et al., 2015). On China's Loess Plateau, large-scale conversion of cropland to forest and grassland, combined with coordinated operation of check-dam systems, has decreased hillslope erosion, lowered flood volumes, and therefore diminished downstream flash-flood and sediment risks (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, 2017).

605 These findings collectively emphasise the importance of conserving natural forests and vegetation in watersheds as a cost-effective disaster prevention strategy. 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
610 reduce peak discharge (Bohorquez et al., 2023).

Natural wetlands and floodplains also act as hydrological "sponges", storing and detaining flood water, improving water quality and supporting biodiversity. Their water storage can significantly reduce flood peaks. Small wetlands (such as ponds, ditches, and low-lying farmland) can absorb 50–70% of rainfall, reduce surface runoff by 15–30%, and lower peak flood levels by 10–25%, although such effects are highly dependent on rainfall characteristics and environmental contexts (Yang
615 et al., 2024). While such spaces for wetlands are often available in rural areas, urban areas face greater challenges in spatial constraints. Even so, artificial wetlands have been embedded into parks and integrated into urban flood-control projects. China's "sponge city" project initiative promotes blue-green infrastructure such as green roofs, rain gardens, and sunken green spaces to enhance urban resilience (Liu et al., 2025a).

620 Nature-Based measures have limitations. Plant growth and soil restoration take time, and vegetation alone often has limited capacity in moderating moderate-intensity floods, offering less immediate protection than engineered facilities (Gao et al.,



2024). Passive urban blue-green infrastructure also provides insufficient storage capacity to mitigate peak flows during extreme rainfall events. Consequently, there is a recognition that NBS must be integrated with grey infrastructure to form a "grey-green" hybrid approach to flash flood prevention and control (Çelik et al., 2020). Increasingly, research and practice advocate for such hybrid systems, combining engineered structures for reliable protection with blue-green approaches that improve system resilience and reduce pressure on grey infrastructure. Ultimately, a multi-layered, diversified and integrated flood-risk-management strategy is essential to ensure safe and sustainable mitigation under extreme rainfall.

5 Prospects for a comprehensive governance framework of flash-flood risk

This review synthesises research on mountainous flash floods from a cross-regional and interdisciplinary perspective, extending previous reviews that focused on individual regions or single technical approaches (El-Magd et al., 2021; Maqan et al., 2022). Drawing on global multidisciplinary evidence, climate emerges as the core driver of flash-flood hazards, with climate warming expected to intensify extreme rainfall and accelerate snow- and ice-melting processes, thereby increasing the overall frequency and magnitude of mountainous flash flood risks. As risk escalates, research focus is shifting from purely technical interventions towards risk governance, societal vulnerability and climate adaptation — an evolution consistent with the Sendai Framework’s emphasis on preparedness and resilience building, and with the global consensus on enhancing early-warning capabilities (Abegaz et al., 2024; Khodayar et al., 2025).

We propose a governance framework structured around four interconnected pillars — monitoring-forecasting-response, spatial planning and control, grey-green collaboration, and basin-scale risk sharing—guided by a comprehensive logic chain of immediate emergency response, source avoidance, process prevention and long-term protection. The framework comprises:

a monitoring–forecasting–response feedback loop, integrating real-time environmental monitoring, forecasting models, and community response protocols to ensure timely warnings and rapid emergency action;

spatial planning and development control, reducing exposure by restricting or carefully managing development in high-hazard zones such as flash-flood plains and unstable slopes;

grey-green infrastructure coordination, combining engineered defences (e.g. check dams, levees, drainage systems) with Nature-Based solutions (e.g. reforestation, wetland restoration, permeable “sponge” landscapes) to synergistically attenuate floods; and

basin-scale risk sharing and adaptation, including insurance schemes, emergency funds, community capacity-building, and transboundary cooperation to distribute residual risks and enhance long-term resilience.

5.1 Addressing uncertainty and design limitations

Governance has to deal with the growing uncertainty of what the model-based warning thresholds are going to be, along with the design limitations of engineered structures. As extreme events happen with greater frequency, having "absolute safety,"



655 which is based on fixed design standards, has become impossible to achieve. Therefore, planning must change to become more flexible in nature and be risk-informed while factoring in that the possibility of exceeding the design threshold is real. The goal is to keep the flood impacts that occur from an exceedance of a design limit to a socially and economically recoverable level by including redundancy in critical infrastructure and building robust rapid-recovery and contingency plans. This will include engineering-the-exception-oriented plans for emergency response to exceptional events; community-level exercises to help people with learning how to avoid hazards or communicate risks and enhance their ability to recover quickly after disasters.

5.2 Toward integrated governance: interdisciplinary collaboration and local knowledge

660 To address the data, modeling, and coordination deficiencies identified by this systematic review, interdisciplinary collaboration will be critical. Advances in remote sensing, Big Data, and artificial intelligence hold promise for improving flood monitoring and early warning through enhanced detection of localized extreme rainfall events and support the development of dynamic, data-driven warning thresholds (Zhao et al., 2022a). Coordinated ecological restoration efforts in conjunction with engineered interventions can enable structural protection to be implemented in a manner that is consistent with long-term watershed regulation while preventing the isolation of "gray" and "green" solutions. The integration of intelligent control technology with green stormwater management facilities at the urban-mountain interface can enhance urban resilience to extreme precipitation events while also promoting the development of smart, sustainable disaster mitigation.

670 Over the past decade, intelligent technologies for flash-flood warning and susceptibility assessment have increased significantly, with AI and machine-learning approaches now accounting for more than 64% of studies and achieving high predictive accuracy (Al-Rawas et al., 2024b). China's "River Basin Digital Twin Platform", which integrates meteorological, water conservancy, and urban construction data into climate-scenario extrapolation for real-time simulation and refined early warning (Aziz et al., 2024), provides a concrete example of this monitoring-forecasting-response strengthening.

675 There are significant opportunities to better recognise community practices and indigenous knowledge in flash-flood research and mitigation. Social vulnerability limited local capacity, and poor uptake of warnings often determines actual losses, even where substantial technical systems exist. Effective governance in mountain regions must therefore combine top-down scientific and technical approaches with bottom-up, culturally informed practices. Residents' experiential knowledge of flood patterns, warning signs and coping strategies can be integrated through participatory hazard mapping, co-designed evacuation plans and community-led monitoring, improving the effectiveness of flash flood measures.

680 5.3 Individual risk transfer and risk sharing in river basin communities

Compulsory disaster insurance in high-risk areas can pre-fund losses and reduce pressure on public finances by linking premiums directly to risk. In the United States, however, many households remain uninsured and rely instead on post-disaster assistance, which typically covers less than 20% of losses, while about 46% of disaster-relief loan applications are



rejected (Begley et al., 2024). Insurance pricing is also frequently misaligned with actual risk levels: the National Flood
685 Insurance Program in the USA continues to rely on outdated or low-resolution floodplain maps, and in 2020, only around 4
million of roughly 14 million high-risk properties held flood-insurance coverage (Bhattacharyya and Hastak, 2024;
Ratnadiwakara and Venugopal, 2023). To complement insurance, some states such as New York have introduced buyout
programmes that compensate residents in repeatedly flooded areas, enabling relocation and converting acquired land into
ecological buffers such as wetlands, water bodies and green stormwater infrastructure (Hashida and Dundas, 2023;
690 Kihslinger, 2017).

In some regions, effective flash-flood management also requires cross-border collaborations. India and Bangladesh, for
example, share 54 international rivers and experience recurrent transboundary flooding, highlighting the need for joint river
regulation, ecological restoration and coordinated disaster-prevention systems (Sujon, 2022). Along the Rhine, the
“Rheinland 2020 Plan” integrates flood conveyance and storage by restoring transnational natural flood detention areas
695 (Schulte-Wülwer-Leidig et al., 2018). In Southeast Asia, the Lancang–Mekong Cooperation framework links legal, technical
and policy collaborations among the six riparian states, promoting joint water-resources development, cross-border
hydrological data sharing, real-time river monitoring and coordinated flood-control infrastructure (“Lancang–Mekong
Cooperation Five-Year Action Plan (2023–2027)”).

5.4 Addressing spatial inequalities and context-specific needs

700 Marked inequalities in natural capital, environmental vulnerability, development levels and governance capacity drive
significant differences in flash-flood risk and losses across mountain regions (Zhao et al., 2022b). Documented mountainous
flash-flood events are heavily concentrated in Asia (notably China and India) and North Africa (Egypt), while many high-
risk areas in South America, Sub-Saharan Africa, and smaller states remain comparatively understudied and under-
monitored (Fig. 1b). These regions experience higher mortality and more severe public-health crises during major events.
705 These regions experience higher mortality and more severe public-health crises during major events (Al-Rawas et al., 2024a),
in contrast to many developed countries where mature warning, engineering and response systems have reduced casualties.
This risk gap underscores the need for contextualised governance pathways. An analysis of 37,332 flash-flood events across
China shows that contrasting hazard-forming environments and socio-economic conditions require differentiated portfolios
of ecological restoration, basic monitoring, advanced forecasting and engineering measures (Zhai et al., 2025).
710 In high-risk but low-resource regions, priority should be given to cost-effective early warning systems and community-led
interventions such as rain-gauge networks, radio-based alerts, locally calibrated rainfall thresholds and simple evacuation
plans (Buchenrieder et al., 2021; Greenbaum et al., 2020). In rapidly urbanising mountain regions, strict land-use control,
protection of upstream forests and the construction of key detention facilities are essential to avoid locking new development
into flood channels. In better-resourced regions, governance should focus on upgrading advanced warning technologies,
715 integrating the operation of existing engineering defences, investing in blue-green infrastructure and mainstreaming climate
adaptation.



Internal disparities and poverty-disaster feedback require attention. Resource scarcity often drives cultivation, grazing and settlement in high-risk zones, degrading ecosystems and deepening vulnerability (Asfaha et al., 2015). Targeted subsidies, relocation from the most hazardous sites, systematic infrastructure maintenance and ecological restoration, as implemented in parts of China, illustrate how well-designed interventions can help low-income groups escape disaster traps and should be more widely promoted through inclusive international cooperation (Chen et al., 2020).

6 Conclusion

Flash floods in mountainous regions are intensifying under climate warming and growing human pressure, yet the global post-2000 literature remains geographically uneven and thematically fragmented. By synthesising 1,967 studies, this review establishes the first globally comparable baseline of mountain flash-flood research, showing that research output and collaboration are concentrated in parts of Europe and Asia, while many high-risk mountain regions in Africa and South America remain under-documented. The evidence base is dominated by risk management and application-oriented studies, with a substantial share of empirical cases drawn from arid and semi-arid wadi systems.

Across regions and settings, flash-flood initiation and impacts cannot be represented by single, fixed rainfall thresholds. Instead, they reflect a state-dependent and coupled process in which storm characteristics interact with antecedent hydrological conditions and hillslope–channel connectivity to govern peak formation and cascading impacts. This explains the limited transferability of empirical thresholds and supports the shift toward dynamic, multi-source early-warning systems. From a governance perspective, the synthesis shows that cascading processes — rather than flood magnitude alone — dominate management challenges. Structural measures can effectively regulate peaks and sediment but require life-cycle governance, while Nature-Based solutions provide long-term regulation and co-benefits but are most robust when embedded in grey-green hybrid portfolios. On this basis, the proposed adaptive governance framework links monitoring and forecasting, spatial planning, grey-green integration, and basin-scale risk sharing to manage flash-flood risk under non-stationary climate conditions.

Future progress depends on reducing spatial inequalities in evidence and capacity, particularly through open event inventories, long-term observatories in under-monitored mountain regions, and comparable performance metrics that jointly assess hydrological, sedimentary, social, and ecological outcomes. Together, these steps will move the field from fragmented, site-specific insights toward transferable and operationally useful flash-flood risk reduction in mountainous regions.

Code availability.

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



745 **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 corresponding author upon reasonable request.

Author contribution

750 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 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.

755 **Competing interests.**

The authors declare that they have no conflict of interest.

Disclaimer.

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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