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Cascading Landslide-Flash Flood-Debris-Flow Hazards in Central Vietnam: A Systematic Review of Mechanisms, Controlling Factors, and Research Gaps

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ABSTRACT: Landslide-flash-flood-debris-flow cascades pose a major hazard in Central Vietnam, where steep terrain, intense rainfall, and human disturbance interact to amplify disaster risk. This study systematically reviews the triggering mechanisms, spatial characteristics, rainfall conditions, impacts, and modelling approaches associated with this multi-hazard cascade. Following the PRISMA 2020 framework, 85 documents published during 2000–2025 were selected from Scopus, Web of Science, and Google Scholar and analysed using qualitative synthesis and bibliometric methods. The results show that landslides, flash floods, and debris flows are closely coupled through catchment topographic connectivity, with landslides commonly supplying sediment to drainage networks and extreme rainfall acting as the dominant transient trigger. Steep slopes, geological weakness, vegetation degradation, and anthropogenic disturbance represent major preconditioning factors. Reported rainfall thresholds vary substantially among locations and methods; Reported rainfall thresholds vary substantially among locations and methods and should therefore not be treated as a universal regional threshold. Research has increasingly shifted towards GIS, remote sensing, and artificial intelligence, although data limitations, model interpretability, and cross-hazard integration remain important gaps. An integrated conceptual framework and three research priorities are proposed: physics-informed explainable modelling, dynamic rainfall-based early warning, and standardised long-term multi-hazard databases.

1. INTRODUCTION

Central Vietnam is highly exposed to hydro-geomorphological hazards under a tropical monsoon climate. Its steep and intensely dissected mountainous terrain, dense drainage network, and active tectonic faulting create highly favourable conditions for the occurrence of landslides, flash floods, and debris flows. Under ongoing climate change, changes in the intensity and frequency of extreme rainfall events may further exacerbate slope and catchment instability (Do Quang Thien et al., 2014, 2021; AghaKouchak et al., 2020).

Globally, the concepts of "multi-hazard" and "multi-hazard cascading" have become increasingly prominent in natural-hazard research and disaster-risk science, receiving substantial attention from international research and policy communities (Kappes et al., 2012; Gill & Malamud, 2014; Pescaroli & Alexander, 2015; AghaKouchak et al., 2020; UNDRR, 2022; IPCC, 2023). In Central Vietnam, field evidence indicates that landslides and flash floods-debris flows rarely occur independently; rather, they may interact sequentially to form cascading hazard chains. Landslide debris can accumulate within stream channels and form temporary natural dams. When these dams fail under high-flow conditions, the sudden release of water and sediment can generate debris flows with considerable destructive potential. The 2020-2021 flood season provides a particularly vivid illustration of such cascading processes. The landslide disaster at the Rao Trang 3 hydropower site and the subsequent disaster involving the rescue delegation at Forest Ranger Station No. 67 in Phong Dien District, Thua Thien Hue Province, in October 2020, resulted in 30 fatalities. In the same period, the landslide at Economic-Defence Unit 337 in Huong Hoa, Quang Tri Province, was recorded as the deadliest single landslide event documented in Vietnam (Pham et al., 2021a, 2021b).

In addition to natural drivers, economic development and engineering activities can amplify hazard risks. Deforestation, mountain-road expansion, mineral extraction, and hydropower development can disturb hillslope equilibrium and modify runoff and sediment-transfer processes (Do Quang Thien, 2014; Hoang & Liou, 2024). Concurrently, geohazard research has undergone a methodological transition from conventional statistical and expert-based approaches towards integrated spatial-data, remote-sensing, and artificial-intelligence frameworks. Machine-learning and deep-learning approaches are increasingly applied to hazard susceptibility mapping and forecasting, including Random Forest and explainable XGBoost-SHAP approaches (Bui et al., 2016; Das et al., 2024; Khan et al., 2025).

Despite the growing body of research on landslides and flash floods-debris flows in Central Vietnam, most existing studies continue to adopt a single-hazard perspective or focus on individual localities. Consequently, systematic reviews that examine these processes from an integrated multi-hazard cascading perspective remain relatively scarce. This gap limits a comprehensive understanding of how individual hazard processes are initiated, interact, and propagate across hillslope-channel-catchment systems. Against this background, the present study conducts a PRISMA-guided systematic review with three specific aims: (i) to systematize the triggering mechanisms, spatial-scale characteristics, and rainfall thresholds associated with landslide-flash-flood-debris-flow cascades in Central Vietnam; (ii) to analyse their impacts and identify prevailing trends in hazard-modelling approaches; and (iii) to develop an integrated conceptual model and propose priority research directions, thereby providing a scientific basis for early warning, spatial planning, and disaster risk governance under climate change.

2. METHODOLOGY

2.1. Search Strategy and Document Selection Criteria

This study adopted a systematic review approach for synthesising evidence on multi-hazard processes and disaster-risk modelling (Kappes et al., 2012). Relevant documents were retrieved from three academic databases-Scopus, Web of Science (WoS), and Google Scholar-for the period 2000-2025. The literature search employed combinations of Boolean search strings, including: (“landslide” OR “mass movement”) AND (“flash flood” OR “debris flow”); (“landslide susceptibility” OR “landslide hazard”) AND “Vietnam”; and (“flash flood” OR “debris flow”) AND (“Central Vietnam” OR “tropical mountainous area”).

Documents were considered eligible for inclusion if they met the following criteria: (i) they were directly relevant to Central Vietnam or, for comparative purposes, to tropical mountainous regions with broadly comparable hazard-generating conditions; (ii) they were published through established scholarly or professional outlets, including Scopus- or WoS-indexed journals, international conference proceedings, theses, and technical reports; (iii) they addressed at least one of the following aspects of landslides, flash floods, or debris flows: triggering mechanisms, conditioning factors, susceptibility assessment, predictive modelling, propagation dynamics, or socio-economic impacts; and (iv) they reported quantitative evidence or provided a clearly described physical or process-based mechanism. Comparative studies outside Central Vietnam were used only for methodological, conceptual, or international-contextual comparison and were not treated as direct evidence for Central Vietnam rainfall thresholds. Popular-science publications without peer review, duplicate records, and documents lacking sufficient methodological or empirical information were excluded.

2.2. PRISMA Review Process and Bibliometric Analysis

The systematic review process was conducted in accordance with the PRISMA 2020 guidelines (Page et al., 2021) and comprised four sequential stages: Identification, Screening, Eligibility, and Inclusion. A total of 186 records were initially retrieved from the three databases. After removing 48 duplicate records, the remaining documents underwent title and abstract screening, resulting in the exclusion of a further 36 records that fell outside the scope of the review. Full-text assessment subsequently excluded 17 records that did not satisfy the predefined methodological or data-quality criteria. Consequently, 85 documents were retained for the final synthesis (Figure 1).

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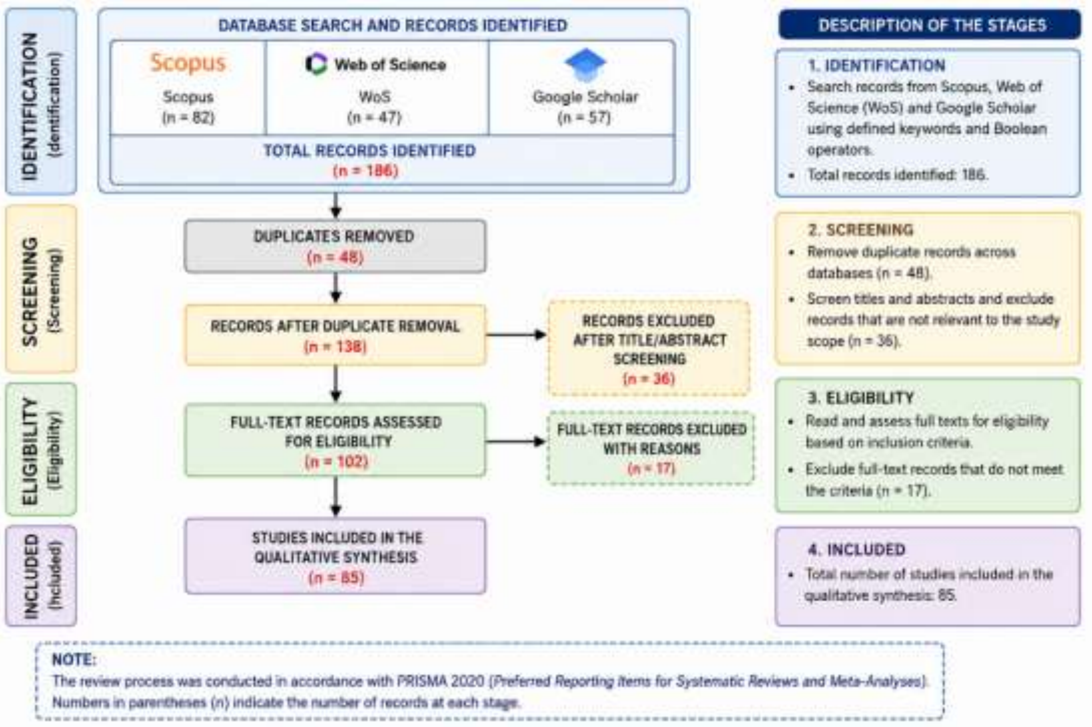

Figure 1. PRISMA flow diagram of the systematic literature selection process

In parallel with the qualitative synthesis, bibliometric analysis was conducted using VOSviewer and Bibliometrix (R) based on the Scopus dataset. The analysis was used to characterise temporal publication trends, the geographic distribution of research output, and keyword co-occurrence networks. These bibliometric results complemented the qualitative synthesis by providing an overview of the development, thematic structure, and prevailing research trends in the literature on landslide-flash-flood-debris-flow cascading hazards.

2.3. Data extraction and evidence synthesis

For each eligible document, information was extracted on study location, hazard type, triggering rainfall characteristics, rainfall duration, antecedent rainfall, reported rainfall thresholds, topographic and geological conditions, modelling approach, and key findings. Rainfall thresholds were recorded using the original units and definitions reported in each study and subsequently harmonised only where the metrics were sufficiently comparable.

Because the reviewed studies differed substantially in rainfall duration, temporal resolution, event definitions, spatial scale, data sources, and threshold-estimation methods, threshold values were synthesised primarily using ranges and representative values rather than pooled into a single statistical estimate. A regional range was considered indicative only when comparable values were reported across multiple independent studies. Accordingly, rainfall ranges reported for selected Central Vietnam locations are interpreted as evidence-based ranges rather than universal deterministic thresholds.

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3. RESULTS AND DISCUSSION

3.1. Characteristics of the Study Area

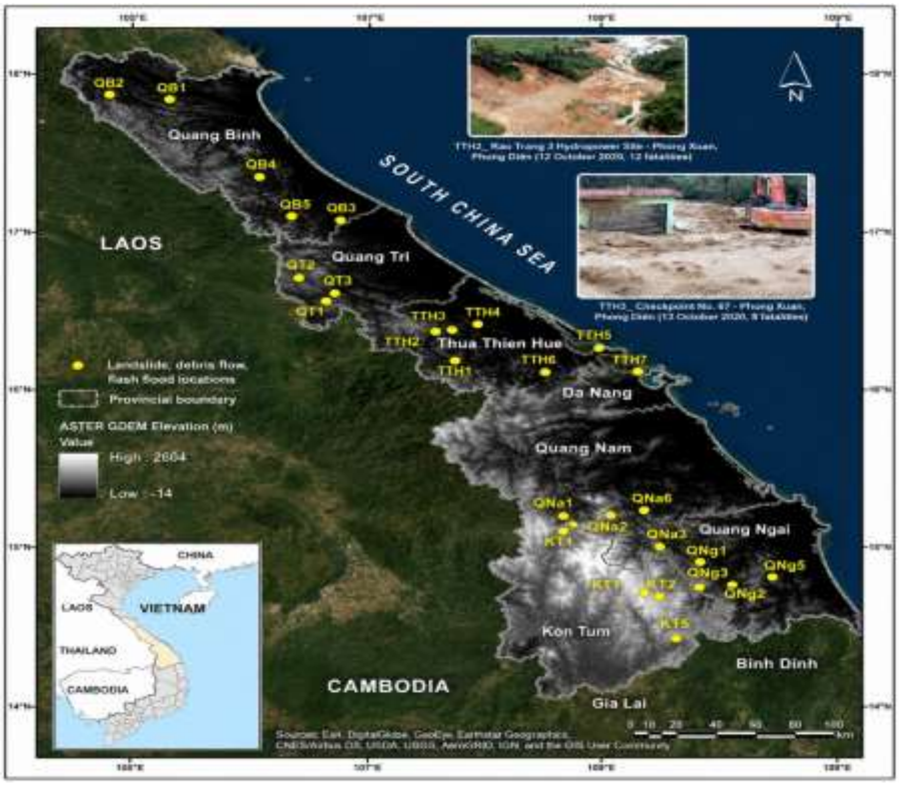

Figure 2. Map of the Central Vietnam study area showing the spatial distribution of representative landslide, flash-flood and debris-flow sites

Central Vietnam extends predominantly along a northwest–southeast axis, encompassing the Truong Son (Annamite) Mountain Range in the west and a narrow coastal plain in the east. This pronounced topographic transition creates short and steep river catchments with rapid runoff concentration, substantially increasing the potential for flash-flood generation during the rainy season (Do Quang Thien et al., 2013, 2023). The regional geological framework consists of interbedded magmatic, metamorphic, and sedimentary formations that have undergone intense weathering under a humid tropical climate. This weathering has produced a relatively thick weathered mantle characterised by weak geotechnical properties. In addition, tectonic fault systems oriented predominantly northwest–southeast and along sub-meridional trends can further reduce the mechanical strength and structural integrity of the rock mass.

From a climatic and hydrological perspective, Central Vietnam is strongly influenced by circulation systems associated with the western Pacific and the South China Sea. Mean annual rainfall typically ranges from 2,000 to 3,500 mm, although its spatial and temporal distribution is highly uneven, with a substantial proportion of annual precipitation concentrated in extreme rainfall events associated with typhoons and tropical depressions. Orographic uplift over the Truong Son Mountain Range further enhances rainfall on windward slopes, while the region's short and steep river networks contribute to a rapid hydrological response to extreme precipitation (Do Quang Thien & Nguyen Duc Ly, 2013). These combined topographic, geological, climatic, and hydrological characteristics provide favourable conditions for the initiation and propagation of landslides, flash floods, and debris flows.

Figure 2 presents the spatial distribution of representative landslide, flash-flood, and debris-flow sites compiled across the provinces of Quang Binh, Quang Tri, Thua Thien Hue, Da Nang, Quang Nam, Quang Ngai, and Kon Tum.

3.2. Triggering Mechanism and Preconditioning-Triggering Factors

The synthesis indicates that the occurrence of landslides, flash floods, and debris flows in Central Vietnam results from interactions between preconditioning factors and extreme triggering factors. Steep topography, complex geological structures, a thick weathered mantle, and degraded vegetation cover establish a predisposed state of hillslope instability, whereas prolonged heavy rainfall and short-duration extreme rainfall events act as dominant triggering agents (Iverson, 2000; Guzzetti et al., 2007, 2008). These factors do not operate independently; rather, their combined effects influence the initiation, development, and subsequent propagation of cascading hydro-geomorphological hazards.

Table 1. Summary of preconditioning and triggering factors for landslides, flash floods, and debris flows in Central Vietnam

No.	Factor group	Key components	Role
1	Topography-geology	Steep slopes, deep dissection, intense weathering, and faults	Creates hillslope instability
2	Climate	Prolonged heavy rainfall and short-duration extreme rainfall	Triggers landslides and flash floods
3	Hydrology	Small catchments and rapid flow concentration	Enhances hazard propagation
4	Ecology	Degraded vegetation cover	Reduces surface stability and increases erosion
5	Economic-engineering	Deforestation, road building, hydropower development, and mining	Amplifies hazard likelihood and magnitude

A salient characteristic of the hazard system in Central Vietnam is the strong coupling among landslides, flash floods, and debris flows through a cascading mechanism. Landslides can act as an initiating process by supplying loose soil and rock material that accumulates within stream channels and, in some settings, contributes to temporary channel blockage. Failure or erosion of such blockages under high-flow conditions can mobilise water and sediment and contribute to downstream debris-flow processes. The subsequent transformation and propagation of mobilised material depend on the volume and availability of sediment, channel gradient, flow conditions, and the degree of topographic connectivity within the catchment (Jakob & Hungr, 2005; Wieczorek & Glade, 2005; Gill & Malamud, 2014). Consequently, cascade impacts are not necessarily confined to the landslide source area but can propagate downstream through connected hillslope–channel systems.

3.3. Scale, Spatial Distribution, and Rainfall Thresholds

Landslide events reported across Central Vietnam exhibit substantial variability in scale, ranging from shallow failures involving tens to several hundred cubic metres to deep-seated failures exceeding tens of thousands of cubic metres. The reported volume distribution is strongly skewed, with small failures representing the majority of documented events, whereas a relatively small number of large failures can account for a disproportionate share of mobilised material and may constitute critical initiating components of the landslide-flash-flood-debris-flow cascade.

Spatially, hazard occurrence is concentrated in areas characterised by steep slopes, intensely weathered geological materials, proximity to tectonic fault zones, and mountain-road corridors affected by cut-slope excavation. These conditions increase hillslope susceptibility, while extreme rainfall provides the principal transient forcing responsible for triggering slope failure and subsequent runoff and sediment mobilisation (Do Quang Thien & Nguyen Duc Ly, 2013; Das et al., 2024).

Rainfall thresholds reported in the reviewed literature show considerable spatial and methodological variability. The threshold values depend on rainfall duration, antecedent precipitation, topographic setting, lithology, vegetation condition, regolith properties, and the initial hydrological state of the slope. For selected areas of Central Vietnam, reported cumulative rainfall thresholds vary substantially among locations and methods. These values should not be interpreted as a fitted regional probability curve, a universal critical threshold, or a deterministic probability model. Differences among studies also reflect variations in rainfall datasets, temporal resolution, event inventories, and threshold-definition methods (Guzzetti et al., 2007, 2008; Iverson, 2000).

Table 2. Evidence synthesis for interpreting rainfall thresholds in Central Vietnam

Evidence category	Synthesis from reviewed literature	Interpretation	Representative sources
24-h rainfall thresholds	Substantial variation among locations, event inventories, and threshold definitions	Do not pool into a single regional threshold	Guzzetti et al., 2007, 2008; Iverson, 2000
72-h cumulative rainfall	Reported values vary among locations and event types; no single regional value was retained in this review.	Do not treat as a universal threshold.	Guzzetti et al., 2007, 2008; Iverson, 2000
Antecedent rainfall and wetness	Influence slope response and rainfall-triggering conditions	Should be retained in dynamic threshold models	Iverson, 2000; Guzzetti et al., 2008
Methodological variability	Differences in temporal resolution, rainfall products, event inventories, and threshold methods	Limits direct comparison among studies	Guzzetti et al., 2007, 2008

At relatively low cumulative rainfall, landslide occurrence is generally less likely, whereas the likelihood tends to increase as cumulative rainfall and antecedent wetness increase. Across selected Central Vietnam studies, cumulative rainfall thresholds vary with rainfall duration, antecedent wetness, local terrain, geology, and the threshold-definition method. These values should not be interpreted as a fitted regional probability curve, a universal critical threshold, or a deterministic probability model. Rather, the evidence supports a conceptual nonlinear relationship between cumulative rainfall and landslide occurrence likelihood, consistent with the influence of rainfall infiltration and pore-water-pressure development on slope stability (Iverson, 2000; Guzzetti et al., 2008). Figure 4 therefore presents a conceptual relationship rather than a statistically fitted regional probability function.

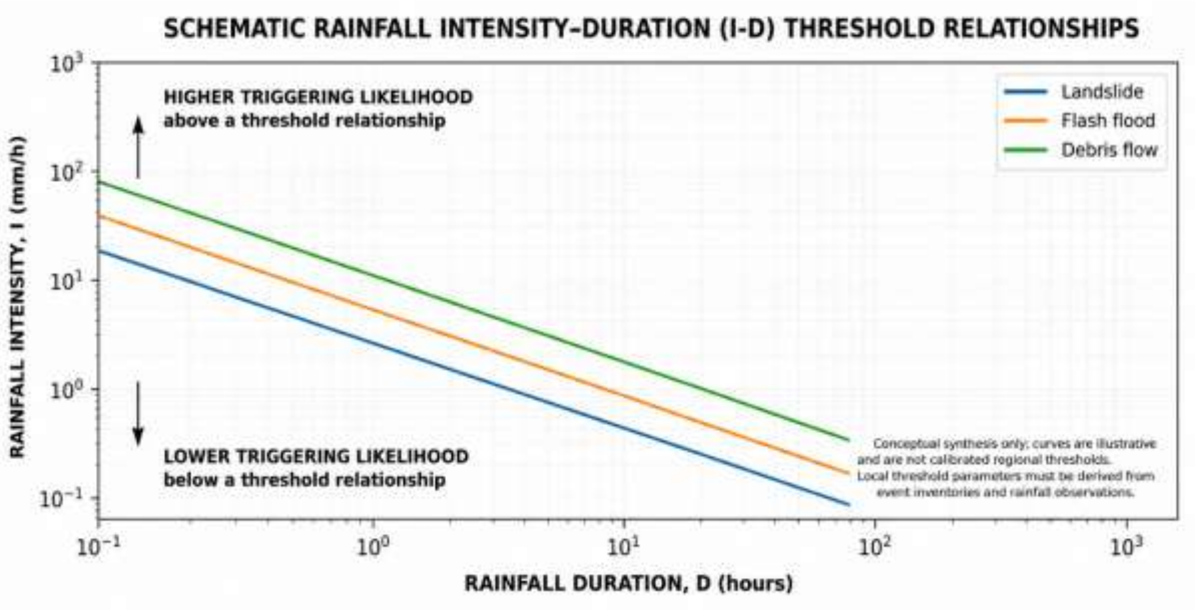

Figure 3. Schematic rainfall intensity-duration (I-D) threshold relationships illustrating relative triggering conditions for landslides, flash floods, and debris flows. The curves are conceptual and are not calibrated regional thresholds.

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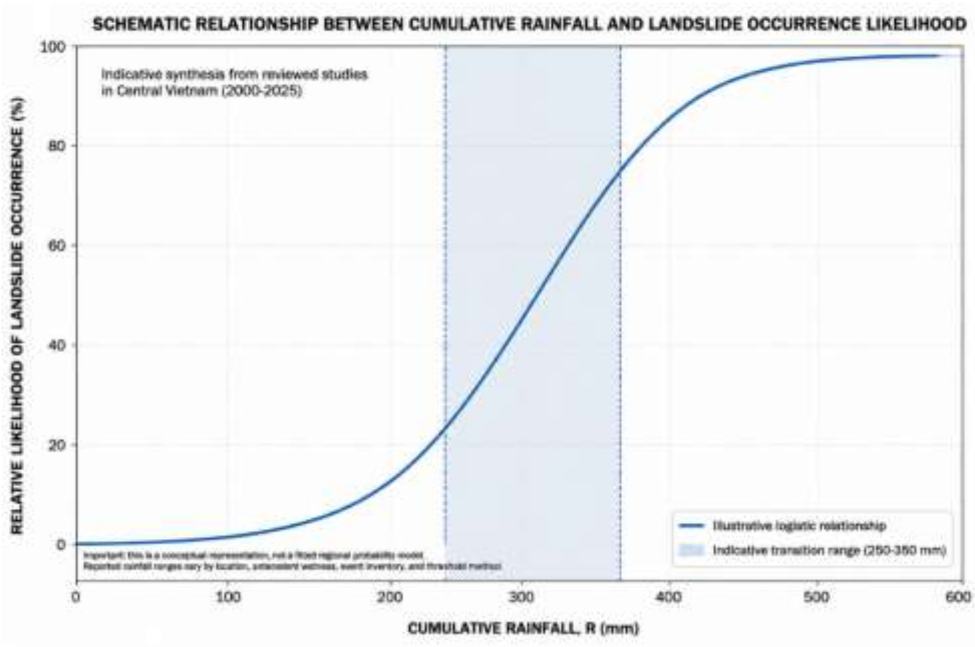

Figure 4. Schematic relationship between cumulative rainfall and the relative likelihood of landslide occurrence in Central Vietnam. The figure illustrates the indicative transition range reported in the reviewed literature and is not a fitted regional probability model.

3.4. Multi-hazard impacts and damage

Landslides, flash floods, and debris flows in Central Vietnam rarely occur as isolated hazards; rather, they can form a cascading multi-hazard impact chain. Direct losses, including loss of life and damage to housing, bridges, roads, and irrigation infrastructure, are often accompanied by indirect consequences that persist for longer periods and extend over broader areas. These consequences include disruption of transportation networks, interruption of agricultural production, burial of agricultural land, soil degradation, and loss of headwater forest (AghaKouchak et al., 2020). The landslide disasters at the Rao Trang 3 hydropower site and Forest Ranger Station No. 7 in Sub-area 67 in Phong Dien District, Thua Thien Hue Province, in October 2020, as well as the landslide at Economic-Defence Unit 337 in Quang Tri Province, illustrate the severe consequences of rainfall-triggered landslides in Central Vietnam (Pham et al., 2021a, 2021b).

The impacts of such cascading hazards therefore extend beyond the immediate source areas of individual events. The interaction between slope failure, rapid runoff concentration, channel blockage, sediment mobilisation, and downstream flow propagation can increase both the spatial extent and the severity of damage. This interconnected impact structure highlights the importance of assessing landslides, flash floods, and debris flows as components of a coupled hazard system rather than as independent processes.

3.5. Trends in Hazard-Modelling Methods and Knowledge Development

Methods for assessing and modelling landslides, flash floods, and debris flows have undergone a marked methodological transition, from qualitative expert-based approaches and conventional statistical methods towards integrated GIS and remote-sensing frameworks and, more recently, artificial-intelligence-based approaches (Figure 5). Earlier approaches commonly relied on expert judgement, multi-criteria decision analysis such as the Analytical Hierarchy Process (AHP), and bivariate statistical methods such as Frequency Ratio. These approaches have subsequently been complemented by increasingly sophisticated spatial-data frameworks incorporating digital elevation models (DEMs), Landsat and Sentinel imagery, unmanned aerial vehicles (UAVs), and interferometric synthetic aperture radar (InSAR). More recently, machine-learning and deep-learning algorithms, including Random Forest, support vector machines (SVM), convolutional neural networks (CNN), graph convolutional networks (GCN), and Transformer architectures, have been increasingly applied to hazard susceptibility assessment, prediction, and early-warning applications. Recent studies in Central Vietnam and elsewhere demonstrate the growing use of machine learning and explainable AI for landslide and flood susceptibility assessment (Das et al., 2024; Hoang & Liou, 2024; Khan et al., 2025).

AI and machine-learning models can effectively capture complex nonlinear relationships among conditioning and triggering variables. However, their application remains constrained by several challenges, including black-box behaviour, sensitivity to the quality and representativeness of training data, and the potential for overfitting when datasets are highly imbalanced. Consequently, recent research has increasingly focused on physics-informed and hybrid modelling frameworks, together with explainable artificial intelligence (XAI), to improve the balance among predictive performance, physical consistency, and scientific interpretability.

Bibliometric analysis using VOSviewer indicates a continuous increase in publications addressing the landslide-flash-flood-debris-flow cascade during 2000–2025, with the most pronounced growth occurring after 2020. This increasing research activity coincides with major disaster events in Central Vietnam and growing scientific interest in AI-based forecasting and early-warning systems. The keyword co-occurrence network further reveals four principal thematic clusters: (1) landslide mechanisms, slope stability, and rainfall thresholds; (2) flash floods, debris flows, and sediment transport; (3) GIS, remote sensing, and hazard mapping; and (4) machine learning, deep learning, and early warning. Collectively, these clusters indicate a broader transition from predominantly single-hazard assessment towards increasingly integrated approaches to multi-hazard interaction, cascading processes, and early warning.

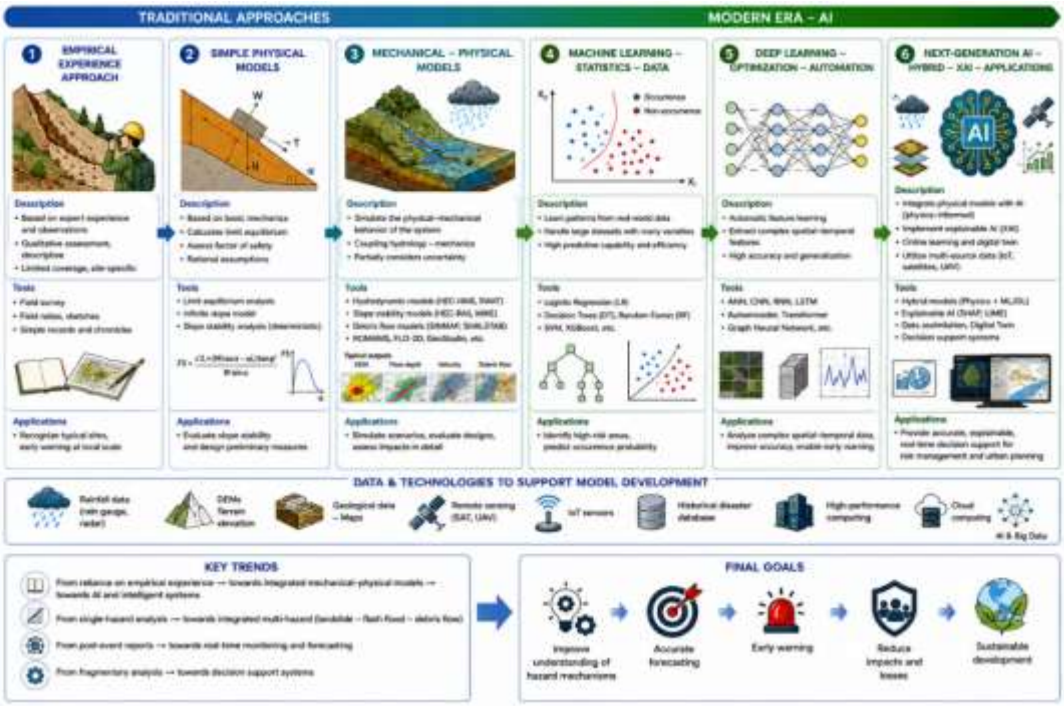

Figure 5. Evolution of hazard-modelling methods from traditional expert-based approaches to artificial intelligence

3.6. International comparison, current limitations, and an integrated conceptual model

Compared with other humid mountainous regions worldwide, including Japan, Taiwan, and the Himalaya, where rainfall-triggered landslides and debris flows are well documented, Central Vietnam exhibits a distinctive hazard regime. The region is characterised predominantly by rainfall-driven triggering associated with typhoons and tropical depressions interacting with the steep and strongly dissected terrain of the Truong Son (Annamite) Range. Japan also experiences rainfall-triggered landslides and debris flows, while Taiwan is strongly affected by typhoon and intense-rainfall-related slope and debris-flow hazards (Suwa, 2020; Chen & Chen, 2022). In the Himalaya, rainfall interacts with additional drivers such as earthquakes and, in some settings, glacial and cryospheric processes (Fan et al., 2023). Compared with Japan and Taiwan, where operational rainfall- and slope-related monitoring and warning systems are more extensively documented, monitoring and real-time early-warning capacities in Central Vietnam remain comparatively fragmented.

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Table 3. Comparison of triggering agents and typical multi-hazard cascades between Central Vietnam and other mountainous regions worldwide

No.	Region	Main driver	Typical hazard cascade	Representative reference(s)
1	Japan	Heavy rainfall and typhoons	Landslide → debris flow	Suwa (2020)
2	Taiwan	Typhoons and intense rainfall	Landslide → debris flow / flood	Chen & Chen (2022)
3	Himalaya	Monsoon rainfall, earthquakes, and cryospheric processes	Landslide → debris flow	Fan et al. (2023)
4	Central Vietnam	Typhoons and tropical depressions	Landslide → flash flood → debris flow	Do Quang Thien et al., (2013, 2021, 2023); Pham et al. (2021a, 2021b)

Despite substantial progress in hazard assessment and modelling, several persistent limitations are evident across the existing literature. First, long-term and consistent monitoring datasets for rainfall, slope deformation, and hazard occurrence remain limited. Second, spatial data coverage is uneven, while DEM resolutions and rainfall data sources vary considerably among studies, limiting the comparability and transferability of modelling results. Third, the interpretability of many artificial-intelligence models remains limited because of their black-box characteristics. Fourth, relatively few studies have integrated the landslide–flash-flood–debris-flow sequence within a single analytical framework capable of representing the interactions and transitions among individual hazard processes. Fifth, a standardised protocol for model evaluation and validation is still lacking, making it difficult to systematically compare model performance across different studies and geographical settings (Reichenbach et al., 2018).

Figure 6. Integrated conceptual model of the landslide–flash-flood–debris-flow multi-hazard cascade based on catchment topographic connectivity in Central Vietnam

Drawing on the synthesis of domestic and international studies, together with the authors' long-term field investigations along the Ho Chi Minh Highway, across the Binh-Tri-Thien region, and within Phong Nha–Ke Bang National Park (Do Quang Thien & Nguyen Duc Ly, 2013), this study proposes an integrated conceptual model for the initiation, propagation, and amplification of the multi-hazard cascade through catchment-scale topographic connectivity (Figure 6).

The proposed conceptual model describes a sequential but dynamically coupled process. Extreme rainfall acts on a set of preconditioning factors-including steep terrain, intensely weathered rock, tectonic faulting, degraded vegetation cover, and anthropogenic disturbances-thereby progressively reducing hillslope stability. Landslides can then generate loose soil and rock debris, which may be transferred from hillslopes into the drainage network through catchment-scale topographic connectivity. The interaction between concentrated runoff and mobilised sediment can initiate or intensify flash-flood processes. Where the concentration and availability of solid material reach sufficiently high levels, flow transformation into debris flow may occur, resulting in greater flow density, mobility, and destructive potential. The cascade ultimately produces compounded risks to people, infrastructure, ecosystems, and local livelihoods.

The integrated framework therefore conceptualises the hazard sequence as:

Extreme rainfall → Preconditioning factors → Landslide initiation → Sediment mobilisation → Hillslope–channel connectivity → Flash flood → Debris-flow transformation → Downstream impact amplification → Multi-hazard risk

This framework highlights topographic connectivity as the critical linkage between hazard initiation and downstream propagation, providing a conceptual basis for moving from conventional single-hazard susceptibility assessment towards integrated multi-hazard cascade modelling and early-warning systems.

4. CONCLUSION AND RESEARCH DIRECTIONS

The findings of this PRISMA-guided systematic review of 85 documents demonstrate that landslides, flash floods, and debris flows in Central Vietnam rarely occur as isolated hazard processes. Rather, they are closely coupled within a multi-hazard cascade, in which landslides constitute common initiating processes by supplying loose material, whereas flash floods and debris flows represent subsequent propagation and damage-amplification processes facilitated by catchment-scale topographic connectivity. Extreme rainfall is the dominant transient forcing of the cascade, with rainfall thresholds varying substantially across locations, event inventories, and estimation methods; this variability prevents the definition of a single universal regional threshold.

From a methodological perspective, hazard research has undergone a marked transition from traditional expert-based and statistical approaches towards integrated frameworks combining GIS, remote sensing, machine learning, and deep learning. Nevertheless, models that simultaneously represent the initiation, propagation, and transformation of landslides, flash floods, and debris flows within a unified spatio-temporal analytical framework remain limited in Vietnam. This represents a major research gap for improving the understanding, prediction, and early warning of cascading hazards.

Based on the identified knowledge and methodological gaps, three priority research directions are proposed for Central Vietnam:

1) Development of physics-informed and explainable hybrid AI models. Future studies should develop hybrid frameworks that combine physical process understanding with machine-learning and deep-learning techniques, thereby improving predictive accuracy while retaining physical consistency and scientific interpretability.

2) Development of dynamic, multi-source early-warning systems. Early-warning frameworks should incorporate dynamic rainfall thresholds together with real-time rainfall observations, multi-temporal remote sensing, and slope-deformation monitoring technologies, including UAV and InSAR, to support near-real-time detection and prediction of cascading hazard development.

3) Establishment of a standardised long-term, cross-disciplinary database. A regional database integrating rainfall, topography, geology, land use, and historical hazard records should be developed to support consistent model calibration, validation, comparison, and multi-hazard risk assessment. Such a database would also provide a scientific basis for incorporating cascading hazard risk into land-use planning and mountain infrastructure development.

Implementation of these research directions will require sustained interdisciplinary collaboration across geology, geomorphology, hydrology, data science, remote sensing, and disaster-risk management. Such integration can strengthen the scientific basis for multi-hazard assessment and early-warning systems while improving the resilience of mountain communities and infrastructure in Central Vietnam under a changing climate.

AUTHOR CONTRIBUTIONS

Nguyen Thi Thu Hien: Methodology, Conceptualization, Investigation, Writing-Review & Editing.

Do Quang Thien: Data Curation, Formal Analysis, Supervision, Laboratory Analysis.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

ETHICS STATEMENT

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Ethical approval was not required for this study.

DATA AVAILABILITY STATEMENT

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Data supporting the findings of this study are available from the corresponding author upon reasonable request.

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