https://doi.org/10.5194/egusphere-2026-3753
Preprint. Discussion started: 29 July 2026

Review article: How hazard-related disruptions become system-wide crises: event-level evidence on failure pathways and continuity functions, 1980–2025

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Abstract. Cascading disasters are increasingly recognized as systemic escalation processes, yet comparative evidence on how initial hazard impacts are transformed into wider crises remains fragmented. Resilience dimensions clarify how system weaknesses interact with triggering hazards and determine whether disruption is absorbed, contained, or transmitted. Drawing on a PRISMA-guided search and targeted supplementary searches, this review synthesizes 43 event-level cascading-disaster cases from 1980 to 2025 to identify failure pathways linking hazards, failure mechanisms, and resilience dimensions. Each event was coded for initiating hazards and transformed hazards, propagation stages, escalation points, failure mechanisms, impacts, and resilience dimensions. Results show that technological and infrastructure failures were the most recurrent transformed hazards, while lifeline failure and secondary hazards formed the main escalation points. Cascade severity depended less on the length of the propagation chain than on which critical functions failed and how disruption propagated through dependent systems. Failure mechanisms clustered around monitoring/control, transport/access, coordination, lifeline services, exposure management, and health-system protection. The resilience crosswalk revealed an interdependence–redundancy gap in which connected systems lacked fallback capacity. These pathways produced persistent recovery burdens. The review proposes a continuity-function framework for cascade-risk reduction, emphasizing monitoring and control, lifeline services, access and logistics, emergency coordination, and equity-sensitive social protection.

1 Introduction

Disaster risk is not created solely by a hazard. Across disaster-risk scholarship, risk is understood as the potential for loss that emerges when hazards interact with exposed and vulnerable people, assets, and systems, and when available capacities are insufficient to prevent disruption or absorb shocks (United Nations General Assembly (UNGA), 2016). Therefore, the severity of a disaster cannot be explained only by the strength of the triggering event. It also depends on where that event strikes, what it strikes, how exposed and dependent the affected systems are, and whether institutions and infrastructures can continue functioning under stress. This is especially important for natural hazards, because their consequences often extend

https://doi.org/10.5194/egusphere-2026-3753
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beyond direct physical damage and may include secondary hazards, infrastructure disruption, service interruptions, and long-term recovery burdens.

Building on this basic risk logic, it is necessary to distinguish between different kinds of complex risk rather than treating them as interchangeable labels. Pescaroli and Alexander (2018) show that compound, interacting, interconnected, and cascading risks overlap, but do not mean the same thing. Compound risk refers to the concurrent or combined occurrence of hazards, especially in climate and environmental contexts. Interacting risk is more closely tied to physical cause-and-effect relations between hazards and environmental processes. Interconnected risk concerns how linked human, environmental, and technological systems transmit disruption through dependency relations. Cascading risk, by contrast, is most directly concerned with the escalation of secondary emergencies through vulnerable social and infrastructure nodes, especially when disruption travels across dependent systems and becomes the main crisis in its own right. Sulfikkar Ahamed et al. (2023) make a similar point from a different angle. Reviewing the literature and examining 40 Asia-Pacific cases, they argued that systemic, cascading, and compound risks are increasingly used in disaster risk management, but their overlap and distinction remain unclear. This makes cascading disasters a particularly important category for this review, because they focus less on the coexistence of hazards and more on the process through which an initial disruption is amplified by system weaknesses and transformed into a wider crisis. While this risk logic is widely accepted, empirical studies still do not consistently show how specific system failures convert initial hazard impacts into cascading disaster processes.

These distinctions are closely linked to changes in the structure of modern society. According to Alexander (2021), modern society is structured by a thick web of interrelationships supported by complex flows of energy, commodities, people, and information, through which cascading disasters can happen frequently. The same chapter emphasizes that escalation points occur when multiple types and dimensions of vulnerability intersect, leading to consequences that can be more severe than the initial hazard itself. In other words, the primary analytical question is no longer only how risks occur, but how interconnected vulnerabilities enable disruption to spread, expand, and persist over time. In this sense, the modern disaster problem is increasingly a problem of interconnectedness, where social life, critical infrastructure, supply systems, communications, health systems, and governance arrangements are all so intertwined that disruption in one can quickly spread to others (Pescaroli and Alexander, 2018; Sulfikkar Ahamed et al., 2023).

Against this background, the literature on cascading disasters has moved toward a more specific definition of what constitutes a cascade. Pescaroli and Alexander (2015) argue that cascading disasters should not be reduced to the familiar metaphor of toppling dominoes. Cascading disasters are defined as extreme events in which cascading effects intensify over time and generate secondary crises that can be as serious as, or even more serious than, the original event. Importantly, Alexander (2021) links these processes to interdependencies, vulnerability, amplification, secondary disasters, and critical infrastructure. Although the conceptual literature has become clearer, the methods used to describe and map cascades remain heterogeneous. One important strand comes from risk assessment and multi-risk research. Gasparini and Garcia-Aristizabal (2014) argue that the shift from single-risk to multi-risk assessment requires moving from a hazard-centered to a territorial-centered perspective, where cascading events become a fundamental concept. This perspective is relevant to natural-hazard

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research because it connects hazard processes, exposed systems, vulnerability, and territorial consequences rather than treating hazards as isolated events. In this regard, many studies recognize cascades as analytically important, yet operationalizing them consistently across cases remains difficult.

A second strand focuses on critical infrastructure and infrastructure interdependencies. Rehak et al. (2018) defined a framework showing the conditions under which cascading, escalating, and common-cause infrastructure failures can occur. They go further by proposing a Cascading Impact Assessment method that quantifies how impacts spread through infrastructure systems by assessing lines of business, resilience, and inter-system links. Although this work makes cascade paths visible and measurable, it remains primarily infrastructure-centered, leaving unanswered how infrastructure failures interact with governance problems, social vulnerability, emergency response bottlenecks, and longer-term recovery burdens.

Beyond infrastructure assessment, the third group of studies has used scenario-building and systems methods to map possible cascade pathways. Pescaroli et al. (2018) proposed a replicable scenario-building process based on a cross-disciplinary understanding of vulnerability and argue that the technological and human components of critical infrastructure can act as primary vectors for the escalation of secondary emergencies. A system methodology for cascading climate-change impacts was also developed using systems thinking, visual aids, interactive discussion, and expert elicitation, and it explicitly notes that there is still little practical guidance and few empirical examples for identifying and evaluating cascades (Lawrence et al., 2020). These contributions moved beyond static lists of impacts and tried to reconstruct transmission pathways; they also show that cascades are often investigated through scenarios, workshops, and systems diagrams rather than through standardized cross-case empirical coding.

The fourth group of studies applies more formal analytical tools to specific hazard families or settings. To model and visualize cause-and-effect relations in a coastal megacity, typhoon cascading-effect scenarios for Shenzhen were developed by combining historical cases, expert judgment, and social network analysis (Tang et al., 2023). Another study infers cascading effects from social media videos using content coding and image analysis to reconstruct relations among failures in natural and built environments (Guo et al., 2024). Researchers also developed a model for cascading-disaster risk using uncertainty theory (Gong et al., 2020). A deterministic, scenario-based assessment of cascading earthquake and tsunami actions for engineering design was developed by Reis et al. (2022), who argued that such approaches can complement probabilistic estimates. Although these studies are methodologically innovative, they remain largely hazard-specific, place-specific, or method-specific. Therefore, a broad comparison across many types of real-world cascading disasters is still needed to better understand and manage cascade events.

This methodological fragmentation is also mirrored by differences in how scholars explain the drivers of cascading disasters. Hazard-centered studies often highlight physical transformations and secondary hazards. For example, Suppasri et al. (2021) review recent tsunami disasters and apply a cascading magnitude scale to identify causes, effects, and escalation points. Their work systematically explained how physical hazard chains and critical-facility failures combine. Yet it remains tied to a specific hazard family. By contrast, governance-oriented and crisis-management studies often emphasize a different part of the picture. Drawing on six crisis case studies, Hagen et al. (2015) identify six categories of triggers of cascading effects. A

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mixed-method approach with local stakeholders was also used to examine awareness of cascading risk and found a gap between awareness and its integration into policy and practice (Pescaroli, 2018). These studies show that cascades often intensify not only because hazards or infrastructures fail, but because coordination, information flow, preparedness, and operational resilience are inadequate. Still, much of these works are based on a limited number of cases, stakeholder perceptions, or city-specific planning settings and cannot support broader event-level comparisons.

A third explanation centers on long-term vulnerability, dependency, and social inequality. Some studies show how historical political-institutional dynamics, unsustainable development, weak local institutions, population mistrust in public authorities, social inequalities, and environmental degradation accumulated over time and amplified the impacts of the 2017 tropical cyclones (Duvat et al., 2021). Kelman (2018) pushes this critique further by arguing that the root causes of disasters are vulnerabilities, that these vulnerabilities are long-term and multi-causal, and that attempts to identify neat causal chains can obscure the deeper social processes through which disasters emerge. These arguments are a necessary correction to narrow hazard-chain thinking. However, when taken alone, they can make it difficult to identify the concrete system failures through which vulnerability becomes operational during a disaster. This issue can be further investigated using the resilience concept and its dimensions. If vulnerability-oriented studies explain why some societies are more exposed to cascading consequences, resilience-oriented studies help identify which system qualities determine whether disruption is absorbed, contained, or transmitted. Comparable applied resilience studies have used resilience attributes to explain differences in post-earthquake urban recovery, to frame management metrics, and to diagnose built-environment weaknesses before disruption occurs (Al-Humaiqani and Al-Ghamdi, 2024; Allan and Bryant, 2014; Kerner and Thomas, 2014). This framing is especially important for cascading disasters, which are rarely explained by a single hazard or a single damaged component. In this study, resilience dimensions are therefore used as an analytical bridge between observable failure mechanisms and the deeper system weaknesses that allowed those failures to propagate. This makes it possible to move beyond merely describing what failed and to examine why those failures cascaded.

Taken together, previous studies have advanced the field by clarifying that cascading disasters are not simple linear hazard chains, but escalation processes shaped by interdependence, vulnerability, infrastructure disruption, and amplification. However, this literature remains methodologically fragmented. What is still missing, however, is a broad event-level synthesis that compares real cascading-disaster cases across hazard types and consistently asks two practical questions: which systems failed, and through what types of weaknesses did those failures cascade. To answer this question, the study systematically reviews empirical cases of cascading disasters from 1980 to 2025. It develops an event-level coded database that compares initiating hazards, transformed hazards, escalation points, failure mechanisms, long-term impacts, and resilience dimensions, along with related system weaknesses. By linking cascade pathways to failure mechanisms and resilience dimensions, the study provides a comparative basis for identifying where cascade prevention should focus: not only on hazards or damaged assets, but on the system functions whose failure allows disruption to spread.

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2 Methods

This study employed a PRISMA-guided systematic review to identify and synthesize empirical studies of cascading disaster events across natural and unintentional technological hazards. The review was designed to support event-level comparison rather than publication-level counting; therefore, the disaster event was treated as the main unit of analysis after study selection. Figure 1 presents the framework that summarizes the study workflow from PRISMA-guided identification and screening to event-level coding, cross-case synthesis, and risk-reduction interpretation.

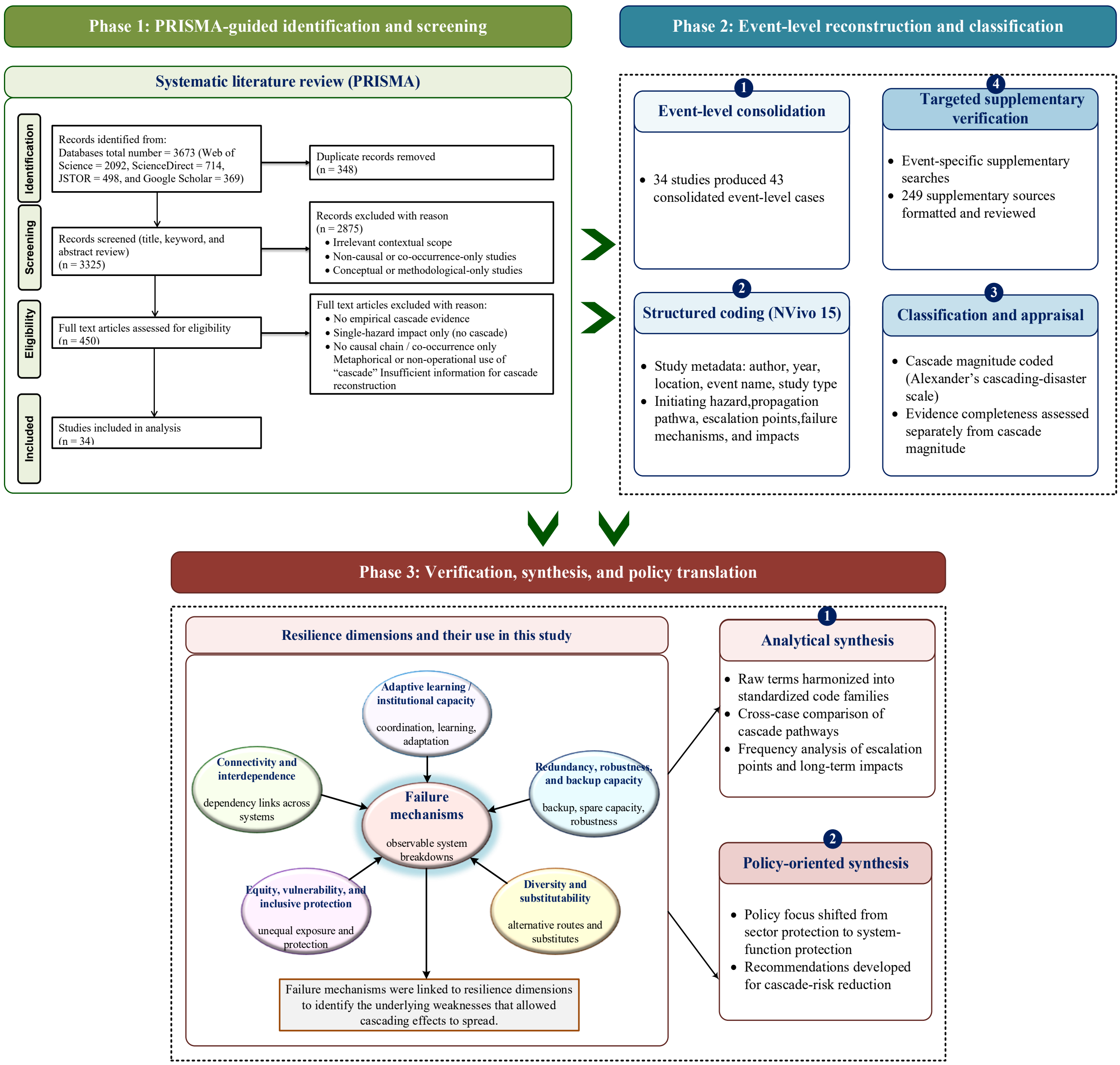

Figure 1: Methodological framework

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a) Identification:

The search strategy followed the identification phase of PRISMA and was designed to capture literature on cascading disasters across multiple disciplinary framings. Searches were conducted on 21 January, 2026, and covered the period 1980–2025. This period was selected to provide a sufficiently broad event window for comparing historical and contemporary mechanisms of cascading disasters while maintaining a manageable, documentable evidence base. Only English-language records were retained. To maximize coverage while preserving conceptual precision, multiple complementary search strings were used across Web of Science, ScienceDirect, JSTOR, and Google Scholar. These searches targeted explicit cascading and domino processes, multi-hazard and secondary-trigger events, and vulnerability- or exposure-related escalation pathways. The database searches identified 3673 records. The full set of database-specific search strings is provided in Appendix A.

b) Screening

After removing 348 duplicate records, the records were screened in Rayyan. Although dual independent screening is commonly recommended in systematic reviews, screening in this study was conducted by a single reviewer because the literature was highly interdisciplinary and conceptually heterogeneous. To reduce inconsistency, the screening criteria were applied through a predefined hierarchical procedure, ambiguous records were revisited before exclusion, and inclusion/exclusion decisions were documented in a screening log. This procedure was used to improve transparency and traceability, but the single-reviewer design is acknowledged as a limitation.

Screening was conducted using a hierarchical three-step procedure: title screening, keyword screening, and abstract screening. In the title-screening step, records were retained only when the title contained at least one system-interaction term, such as cascade, domino, interconnected, compound, chain, complex, interdependent, multi-hazard, or secondary, together with at least one disaster-related term, such as disaster, hazard, failure, event, risk, impact, or effect. Records that passed this step were then screened by keywords using the same lexical logic: at least one system-interaction term and at least one disaster-related term had to be present. In the third step, abstracts were reviewed to confirm substantive relevance to cascading or multi-hazard phenomena. To reduce the risk of excluding relevant studies due to terminology variation, ambiguous records were retained for abstract screening when the title or keywords suggested possible hazard interactions, system propagation, secondary effects, infrastructure interdependence, or multi-sector impact.

Records were excluded when they were unrelated to hazard, disaster, or system-failure contexts; when they lacked any system-interaction component; or when they described simultaneous or independent hazards without evidence of a causal relationship, propagation sequence, or secondary consequence pathway. Studies that were purely theoretical, conceptual, or methodological, and therefore did not provide empirical event grounding, were also excluded from the empirical synthesis. This screening step resulted in the retention of 450 studies for eligibility assessment.

c) Eligibility assessment

A full-text eligibility assessment was conducted for the 450 studies retained after screening. At this stage, each study was examined in more detail, with particular attention to the methods, results, and conclusion sections, to determine whether it documented an empirical cascading-disaster event consistent with the review criteria.

Studies were included when they reported a real-world event initiated by a natural hazard or by a non-intentional technological or system failure, and when the evidence showed a causal, operational, or functional propagation pathway from the initial event into another hazard, system, service, sector, or recovery process. Studies were excluded if they did not report an empirical cascading event, used the term in a general or metaphorical sense, or described single-hazard impacts without evidence of propagation. Studies were also excluded if the event sequence was unclear, if there was insufficient empirical detail to confirm causal escalation, or if the focus was on intentional human-induced events such as war, terrorism, sabotage, or civil unrest. After full-text eligibility assessment, 34 studies (see Appendix B for the list of included refrences and covered cases) met all criteria and were retained for final data extraction and analysis.

d) Data extraction and synthesis

Data extraction was conducted in two stages. First, all studies retained through the PRISMA were coded in NVivo 15. For each study, the author extracted study metadata, including author, year, event name, location, and study type. Using a structured extraction form, primary hazard, transformed hazard, propagation stages, escalation points, and impacts were also coded. Primary hazard refers to the initial triggering event; transformed hazard refers to the secondary hazard; propagation stages refer to the sequence through which disruption spreads; escalation points refer to critical moments or system nodes where the disaster intensifies; and impacts refer to the immediate and long-term consequences recorded for affected systems and populations. Relevant information was recorded as closely as possible to the wording used in the source material.

Failure mechanisms were then coded against five resilience dimensions to identify not only what failed, but also why the failure propagated. In this study, failure mechanisms represent the proximate expressions of system breakdown (for example, a transport system closure, a levee or control failure, or a hospital-service interruption), whereas the resilience dimensions trace the underlying system weaknesses that allowed these disruptions to cascade. This interpretation is compatible with resilience research, which considers redundancy, interdependence, inclusivity/equity, diversity, and adaptive learning as essential features of a system's capacity to absorb and contain disturbance rather than transmit it (Coleman et al., 2024; Rockström et al., 2023). Redundancy, robustness, and backup capacity (RED) refers to the availability of spare capacity, alternative routes, backup systems, structural robustness, and service continuity under stress. Connectivity and interdependence (CON) describe how failures spread across interconnected infrastructure, services, supply chains, information systems, and governance networks. Equity, vulnerability, and inclusive protection (INEQ) refers to unequal exposure, protection gaps, poverty, displacement, marginalization, and disparities in access to support. Diversity and substitutability (DIVA) refers to the availability of alternative systems, varied response options, substitutable services, and non-dependent pathways that can reduce reliance on a single failure-prone system. Adaptive learning/institutional capacity (ADL) refers to an institution's ability to predict, coordinate, learn, regulate, and adapt its decisions as crises evolve.

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Information that was not reported in the source material was coded as "not reported" rather than inferred. Publications describing the same event were consolidated under a single event ID to avoid double-counting. When multiple sources provided complementary information about the same event, they were combined to reconstruct the codes. This consolidation step was important because the objective of the review was to compare event-level cascade processes, not to count how often individual publications mentioned particular disasters.

After coding the primary source pool identified through PRISMA, each event was assigned a provisional cascade magnitude using Alexander's cascading-disaster scale (Alexander, 2018). Cascade magnitude referred to the substantive complexity of the event. In this review, lower-magnitude events described localized or limited propagation, while higher-magnitude events involved wider cross-system, cross-sector, spatial, or temporal escalation. Cases classified as M3 were treated as moderate cascades, while M4 and M5 cases were treated as high-complexity cascades. M1 and M2 cases were excluded from the final event pool because they did not exhibit sufficient cascade complexity to meet the objectives of this review. The study also coded evidence completeness, which refers to the amount and clarity of documentation available for coding the case. It assessed whether sufficient event-level information was available to code the initiating event, the cascade sequence, the escalation point(s), and the main impact pathways. Cases were rated as high when all four elements were clearly documented and supported by more than one source type; moderate when the main cascade pathway was clear but one element required supplementary confirmation; low when the case was mentioned as a possible cascade but the sequence or escalation mechanism was weakly documented; and insufficient when the available evidence did not support confident event-level classification.

Targeted supplementary searches were then conducted for all remaining cases to improve evidence completeness and then verify, upgrade, downgrade, or exclude event-level codings. These searches were case-specific and were not used to expand the review beyond the PRISMA-identified evidence base. The supplementary evidence base comprised 249 formatted sources, including governmental, UN-system, humanitarian, development, technical, academic, NGO, and sector-specific sources. The detailed source breakdown is provided in Appendix C. Searching continued until no additional sources changed the coded initiating event, cascade sequence, escalation point(s), failure mechanisms, long-term impacts, or event classification.

After the full extraction was completed, the raw extracted terms were reviewed across all cases and harmonized into standardized analytical groups. To strengthen coding consistency, all code families were defined through operational coding rules, and ambiguous coding decisions were revisited after cross-case comparison. This step was necessary because similar mechanisms were often described using different terms across sources, such as "blackout," "power outage," "grid failure," or "electricity disruption." These terms were therefore consolidated into a common, standardized code only after their meaning and role in the cascade were checked against the event context. The coding rules are presented in Appendix D. The original extracted wording was retained for traceability, while the standardized groups were used for cross-case comparison, frequency analysis, and matrix-based synthesis.

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Quantitative synthesis was then conducted using event-level coding outputs. Frequencies were calculated at the case level to avoid double-counting multiple publications describing the same event. Percentages represent the share of cases in each cascade-magnitude group containing a given escalation-point family, failure-mechanism family, or long-term impact family. Resilience-dimension counts represent coded links between failure mechanisms and resilience dimensions, not the number of cases. These descriptive statistics were used to summarize patterns within the reviewed event database and should not be interpreted as estimates of the global frequency of cascading disasters.

3 Results

3.1 Cascade transformation pathways and long-term impacts

Because the event, rather than the publication, was used as the main unit of analysis, a single study could contribute to multiple disaster events, while multiple publications referring to the same event were consolidated under a single event ID. The 34 retained studies produced 43 consolidated event-level cascading-disaster cases. The reviewed cases show a wide geographic distribution, but the evidence base is unevenly concentrated. Cases were identified across North America, East and Southeast Asia, South Asia, Europe, the Middle East, Africa, Latin America, and Oceania. However, this distribution should be interpreted as the geographic coverage of the reviewed case database, not as the global incidence of cascading disasters. The concentration of cases in countries such as the United States and Japan may partly reflect stronger documentation, data availability, and research visibility.

The comparison of mechanistic cascade types (Figure 2.b) shows that hydro-meteorological and geophysical hazards dominated the initiating stage of the reviewed cases, but their relative importance differed by cascade magnitude. Among moderate cascade cases, hydro-meteorological hazards were the most frequent initiating hazard (11 of 19 cases), followed by geophysical hazards (6 cases). However, the pattern shifted slightly among high-complexity cascade cases: geophysical hazards were the most frequent initiating hazard (12 of 24 cases), followed by hydro-meteorological hazards (10 cases). This difference should not be interpreted as a strict separation between moderate and high-complexity cascades. However, it suggests that the higher-magnitude cases in this dataset were more often associated with geophysical triggers capable of generating severe secondary processes or widespread built-system disruption.

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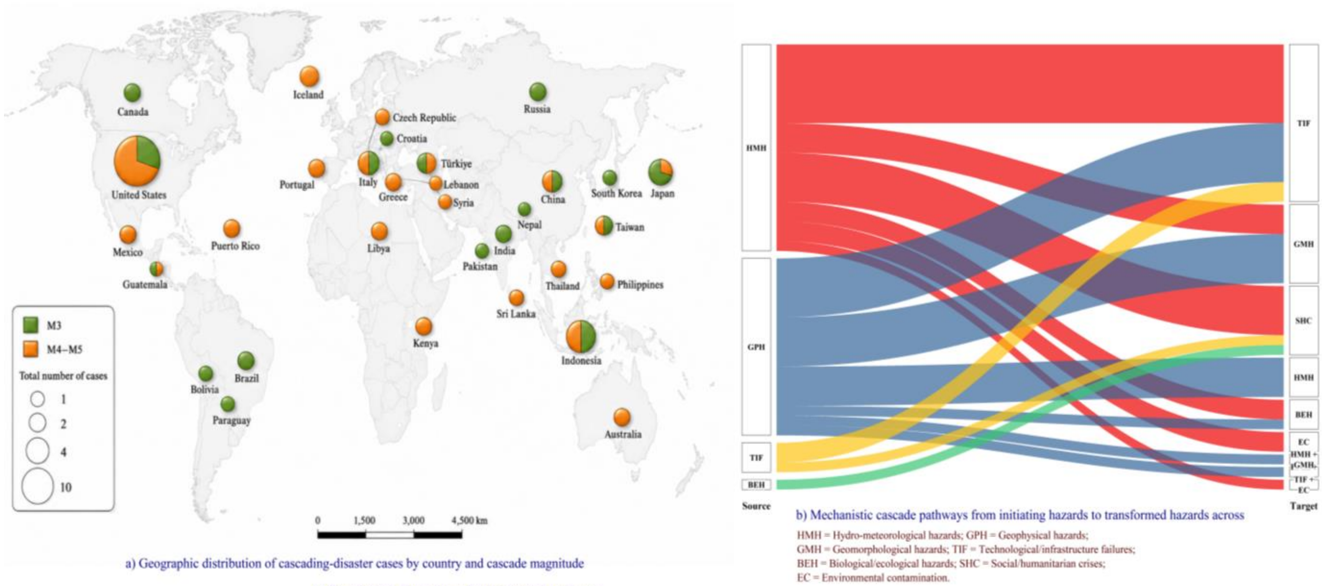

c) Cases included in each mechanistic cascade pathway

Initiating hazard	Transformed hazard	Events'names
HMH	TIF	Uri 2021; Katrina 2005; Lekima 2019; Otis 2023; Sandy 2012; Central Italy snow 2017; China ice storm 2008; Storm Daniel 2023
GPH	TIF	San Fernando 1971; Eyjafjallajökull 2010; Marmara 1999; Gorkha 2015; Hengchun 2006; Sea of Japan 1983
GPH	GMH	Central Italy landslide 2016–17; Unzen/Mayuyama 1792; Alaska 1964; Pinatubo–Yunya 1991; Fuego–Agua 1717
HMH	SHC	Puerto Rico 2016–20; Amphan 2020; TC Harold 2020; Tornado COVID 2020; Makassar 2019
GPH	HMH	Indian Ocean tsunami 2004; Okushiri 1993; Anak Krakatau 2018; Türkiye–Syria 2023
HMH	GMH	Morakot 2009; Agatha–Pacaya 2010; Madeira 2010
HMH	BEH	Kenya floods–cholera 2020; Pantanal wildfires 2020
HMH	EC	Prague flood Natech 2002; Black Summer 2019–20
TIF	TIF	Baltimore tunnel 2001; North America blackout 2003
BEH	SHC	Desert locust Pakistan 2019–20
GPH	BEH	Zagreb earthquake 2020
GPH	HMH + GMH	Palu 2018
GPH	HMH + TIF	Tōhoku 2011
HMH	TIF + EC	Harvey 2017
TIF	SHC	Beirut port 2020

Figure 2: Geographic distribution and mechanistic pathways of cascading-disaster cases

Across both magnitude groups, technological and infrastructure failures were the most common transformed hazards (8 and 10 cases in moderate- and high-complexity cascade cases, respectively). This finding indicates that lifeline and built-system disruption was the most recurrent pathway through which initial hazards developed into broader cascading consequences. However, the second-most-visible transformed hazards differed by magnitude group. In high-complexity cascade cases, geomorphological hazards were more prominent, reflecting the roles of secondary physical processes, including landslides, liquefaction, debris flows, lahars, tsunami-related processes, and slope failures. In moderate cascade cases, social and humanitarian crises were more visible as transformed outcomes, including displacement, shelter disruption, livelihood stress, and humanitarian-response constraints. This pattern should be interpreted cautiously because the dataset is event-based and documentation-sensitive. A supplementary propagation-depth check shows that cascade magnitude should not be treated as a simple proxy for cascade length. High-complexity cascades had a higher average number of propagation steps than moderate cascades, but this difference was not statistically significant. High-complexity cascades had a mean of 7.57 steps and a median of 7 steps (n = 23, SD = 2.39, range = 3–12), while moderate cascades had a mean of 6.47 steps and a median of 6 steps (n = 19, SD = 1.84, range = 4–11). The Kruskal–Wallis test did not indicate a statistically significant difference across

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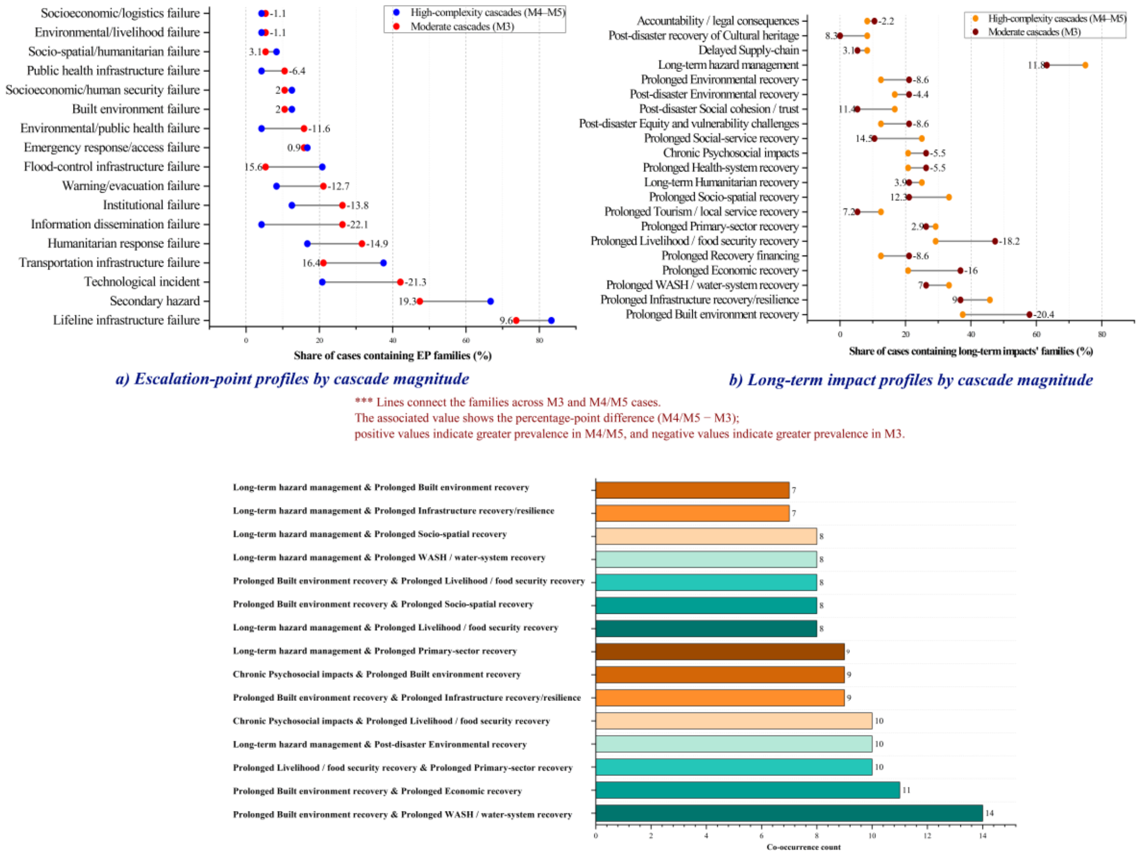
groups (H = 2.53, p = 0.112), indicating that a higher cascade magnitude does not necessarily imply a longer linear propagation chain. Instead, cascade severity may depend on the type of escalation points activated, the system functions affected, and the extent to which secondary hazards or service disruptions spread beyond the initial impact.

The escalation-point results further support this interpretation (Figure 3.a). Lifeline infrastructure failure was the most frequent escalation family in both groups, while secondary hazards were particularly prominent in high-complexity cascade cases. This finding suggests that the transition from an initiating hazard to a larger cascade was commonly mediated by system-critical failures, such as power, water, transport, fuel, and critical-facility disruption, and in higher-magnitude cases, often by additional physical hazard processes.



a) Escalation-point profiles by cascade magnitude

b) Long-term impact profiles by cascade magnitude

*** Lines connect the families across M3 and M4/M5 cases.
The associated value shows the percentage-point difference (M4/M5 − M3);
positive values indicate greater prevalence in M4/M5, and negative values indicate greater prevalence in M3.

c) Top 15 co-occurring pairs of long-term impact categories, ranked by number of events in which both categories appear together

Figure 3: Escalation-point and long-term impact profiles

The long-term impact analysis (Figure 3.b) shows that cascading disasters frequently leave persistent recovery burdens beyond the immediate emergency phase. The most common family in both magnitude groups was long-term hazard management (12 and 18 cases in moderate- and high-complexity cascades, respectively). Long-term hazard management refers to the ongoing management of unresolved or recurring hazard conditions, such as post-disaster slope instability, flood risk, contamination risk, dam or reservoir concerns, recurrent disease risk, and ongoing monitoring and preparedness

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demands. Its high prevalence in both groups suggests that cascading disasters often remain active as risk-management problems even after the main emergency has ended. The co-occurrence structure (Figure 3.v) also suggests that long-term impacts rarely appeared in isolation. Long-term hazard management most frequently co-occurred with prolonged built-environment recovery, prolonged infrastructure recovery, and prolonged socio-spatial recovery, indicating that ongoing hazard exposure, reconstruction, infrastructure restoration, and spatial recovery often combined to form a recovery burden.

These results show that long-term impacts were closely connected to earlier escalation mechanisms. The high-complexity cascades showed a stronger profile of system-scale and spatial recovery burdens. Prolonged infrastructure recovery/resilience was observed in 45.8% of high-complexity cascades, compared with 36.8% in moderate cascades, while prolonged WASH/water-system recovery and prolonged socio-spatial recovery were also more frequent in high-complexity cascades. This pattern is consistent with earlier findings on escalation points, where higher-magnitude cascades more often involved lifeline failure, secondary hazards, flood-control failure, and transportation disruption, which, in turn, led to longer-term infrastructure restoration, water-system recovery, relocation, resettlement, and spatial recovery needs. In contrast, moderate cascades showed a relatively higher prevalence of prolonged built environment recovery, prolonged livelihood/food security recovery, and prolonged economic recovery. Prolonged built-environment recovery occurred in 57.9% of moderate cascades, compared with 37.5% in high-complexity cascades, while livelihood/food security and economic recovery were also more common in the first group. This pattern suggests that several moderate-complexity cascades in the dataset generated long-lasting local recovery burdens concentrated in housing, livelihood systems, business activity, and household economic recovery.

Overall, these findings show that cascading disasters are not only the result of severe triggering hazards but also of how disruption spreads through interconnected social, infrastructural, and institutional systems. Critical infrastructure failures often serve as the primary conduit through which an initial hazard impact becomes a broader emergency. Although high-complexity cascades are more often associated with geophysical triggers and severe secondary hazards, the statistical results suggest that their complexity cannot be explained solely by a longer sequence of events. What matters more is which systems fail, how strongly they are connected to other systems, and how far the disruption spreads once these connections are broken. These failures also create overlapping long-term burdens, especially in hazard management and infrastructure recovery, requiring agencies to continue managing active risks long after the immediate emergency has ended.

3.2 Failure mechanisms and underlying resilience weaknesses

In this study, failure mechanisms capture the functional pathways of failure, such as loss of hazard control, access disruption, and lifeline interruption. Therefore, the analysis first identifies which system functions failed most frequently and then examines which resilience weaknesses enabled those failures to cascade.

The failure-mechanism analysis shows that cascade propagation was concentrated in a limited set of system functions. As shown in Figure 4. a, the largest failure-mechanism family is hazard-monitoring/control mechanism failure, with 136 resilience-dimension links, followed by transportation/access failure (107), compound-crisis institutional failure (67), lifeline

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infrastructure failure (64), spatial planning/exposure failure (51), and health-system failure (50). These six mechanism families alone account for 45.2% of all 1052 coded resilience-dimension links in this database, while the top 10 account for 59.7%. This pattern indicates that a single, isolated sector did not drive cascading disasters, but rather that repeated breakdowns across multiple system functions central to hazard monitoring, access, service continuity, emergency coordination, exposure management, and public health protection did.

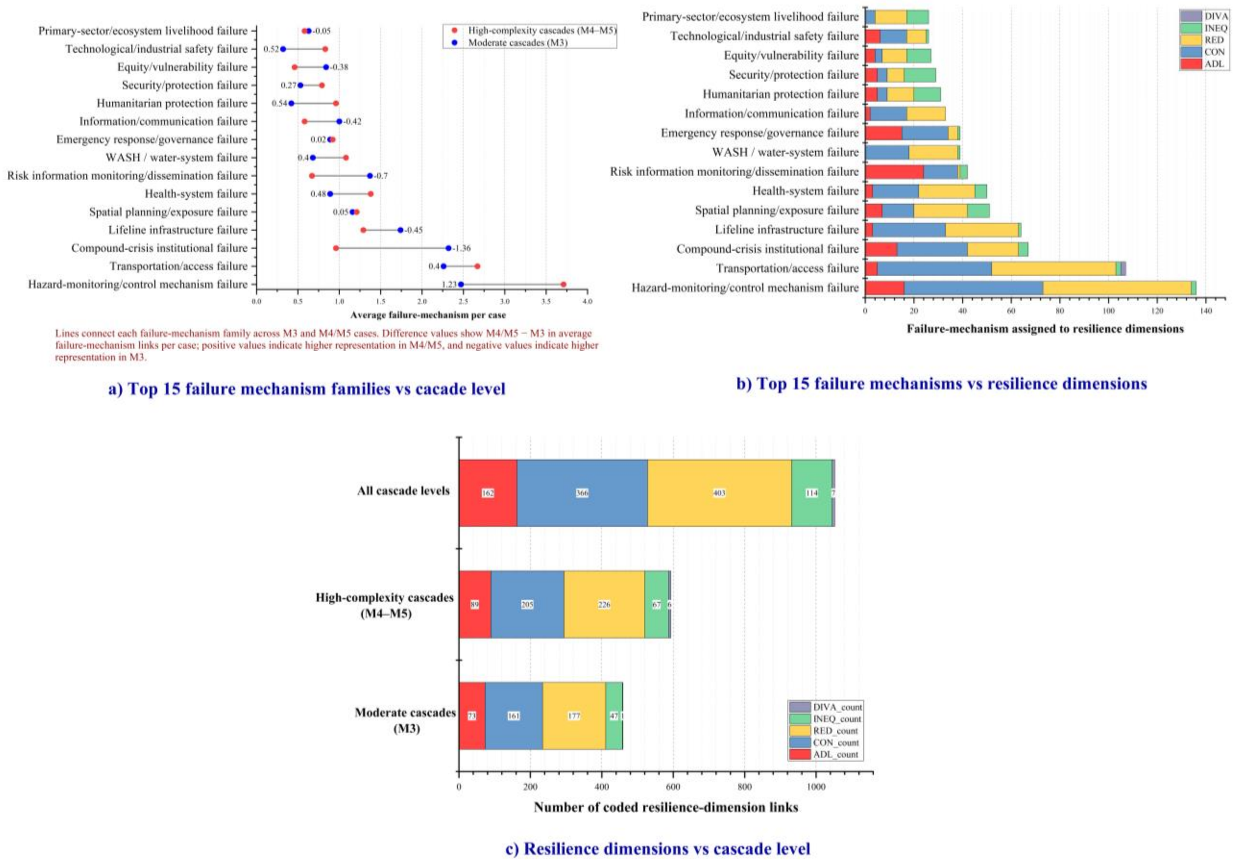

Figure 4: Failure mechanisms and resilience-dimension profiles of cascading disasters

The crosswalk between mechanisms and resilience dimensions shows that the database points to a specific pattern of weakness rather than a generic "low resilience" (see Figure 4.d). Across all cases, redundancy accounts for 403 of 1,052 coded links (38.3%) and connectivity for 366 (34.8%). Together, they make up 72.1% of all resilience-dimension links. By contrast, adaptive learning contributes 162 links (15.4%), inclusivity/equity 114 (10.8%), and diversity only 7 (0.7%). This pattern suggests that the dominant resilience weakness was an interdependence–redundancy imbalance, meaning that systems were tightly coupled but lacked sufficient fallback capacity. The comparison between cascade groups shows that higher-magnitude cascades did not exhibit a distinct resilience profile (Figure 4.c). This suggests that higher-magnitude cascades did not come from a fundamentally different resilience model. Rather, they came from different failure pathways through a similar resilience architecture. Moderate cascade cases showed stronger relative signals in compound-crisis

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institutional failure, risk-information monitoring/dissemination failure, and information/communication failure. In contrast, the high-complexity cascades showed stronger signals in hazard-monitoring/control failure, transportation/access failure, health-system failure, WASH/water-system failure, humanitarian protection failure, and technological/industrial safety failure.

Considering the top 15 failure mechanisms and their corresponding resilience dimensions (Figure 4.b), three patterns emerge from this comparison: First, the largest failure-mechanism families are associated with failures of societal functioning, not only asset damage. Hazard control, transport access, water systems, hospitals, and lifelines are services that connect many sectors and determine whether disruption remains localized or spreads across systems. Second, the failure mechanisms with the strongest adaptive-learning signature are primarily risk information and emergency governance, rather than heavy infrastructure. It indicates that some cascades deepened not because society lacked sensors or plans on paper, but because decision-makers could not update the operational picture, interpret changing conditions, align messages, or convert warnings into timely action. Third, inclusivity/equity is not the dominant share overall, but it becomes far more visible in humanitarian protection, security/protection, equity/vulnerability, primary-sector livelihood, and spatial planning/exposure. In short, inequality is not only a background condition but a channel through which service failures become socially distributed crises.

Overall, these findings show that cascading disasters do not result solely from isolated sector failures, but from fragile system conditions in which critical services are closely connected while backup capacity remains limited. Disasters expand when essential functions such as transportation, water management, hazard monitoring, and emergency coordination are disrupted, because these functions connect many other parts of society. The similarity between moderate and high-complexity cascades suggests that the same underlying vulnerability structure shapes both. Their final severity depends less on a fundamentally different type of weakness and more on the specific pathway by which failure propagates across systems. The results also show that cascading impacts become more severe when emergency management systems cannot translate warnings and situational information into timely action, allowing infrastructure failures to reach vulnerable communities more directly.

4 Discussion

Analytically, the findings indicate that cascading disasters were associated not only with weak assets but also with weak continuity arrangements across connected systems. The most significant failure patterns were linked to infrastructure, transport, monitoring, water, health, communication, and emergency response systems. These systems are deeply interdependent, but many lacked sufficient backup capacity, redundancy, or operational flexibility when disrupted. This result is consistent with resilience theory, which warns that connectivity is beneficial only when it is balanced with redundancy and managed so that shocks do not propagate unchecked (Coleman et al., 2024).

In line with findings by Mühlhofer et al. (2024), who found that failure cascades accounted for 64–89% of service disruptions and often spread beyond the hazard footprint, this study confirms that cascading disasters become catastrophic

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not only because of the magnitude of the triggering hazard, but because the initial disruption interacts with dependent system components and produces further escalation. This system interaction can occur through different escalation routes. In some cases, it is driven by secondary hazards directly generated by the triggering event, such as tsunamis, landslides, flooding, fires, contamination, or technological accidents. The 2011 Tōhoku earthquake–tsunami–Fukushima disaster is the clearest example: the earthquake generated a tsunami, the tsunami disabled nuclear safety systems, and the disaster then expanded into radioactive contamination, evacuation, infrastructure disruption, supply-chain interruption, and long-term social and environmental recovery. However, this study's findings suggest that escalation is often enabled not only by the secondary hazard itself, but also by failures in the systems responsible for monitoring, controlling, or containing evolving risk conditions. Hazard-monitoring and control failure emerged as one of the most prominent failure mechanisms in the dataset and was strongly associated with connectivity/interdependence and redundancy/backup-capacity deficiencies. This pattern suggests that many systems remain highly connected to evolving hazard conditions while lacking sufficient monitoring capability, operational flexibility, or backup mechanisms to detect deterioration and prevent escalation. Consequently, hazards that might otherwise remain localized can propagate through interconnected infrastructure, environmental, and institutional systems, developing into wider cascading crises.

The findings also show that lifeline infrastructure failure is one of the most critical escalation points because it keeps the cascade active across multiple sectors. Once power, water, and sanitation, fuel, communication, health facilities, or other critical service systems fail, the cascade often extends beyond the original hazard-impact area. It becomes a chain of service disruptions, emergency response delays, shelter pressure, public health stress, livelihood interruptions, and humanitarian needs. This finding aligns with infrastructure interdependency research, which shows that service disruption risk is often driven by second-order and cross-sector propagation rather than by direct physical damage alone (Lewis and Petit, n.d.). Winter Storm Uri in the USA in 2021 illustrates this clearly. The storm became catastrophic not simply because of extreme cold, but because electricity failure exposed the dependence of heating, water systems, healthcare, fuel supply, transport, shelters, and household safety on uninterrupted power. The 2003 North American blackout demonstrates the same mechanism in a more technical form: a power-grid disturbance spreading through interconnected infrastructure and disrupting urban services beyond the original technical failure.

Closely related to lifeline failure, road and transportation network failure was another major stage at which disaster cases cascaded. In many cases, the disaster cascaded not only because infrastructure was physically damaged, but also because damaged roads, airports, ports, communication systems, and logistics channels prevented response systems from functioning at the required speed and scale. The dataset repeatedly links transport and mobility disruption with access isolation, emergency response delays, supply chain and logistics disruption, humanitarian aid system strain, health system disruption, shelter disruption, and prolonged repair operations. Communication and information systems also shape whether access disruption becomes a wider cascade. Recent review work on social media in disasters triggered by natural hazards shows that disaster-management information increasingly depends on data collection, actionable information extraction, relevance filtering, and decision-support capacity (Gopal et al., 2026). This supports the present study's finding that communication

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failure should not be treated as a secondary inconvenience but as part of the operational backbone of emergency response and cascade containment. This pattern was visible in the 2004 Indian Ocean tsunami, where damaged transport and communication systems isolated affected communities and delayed aid delivery; in Hurricane Katrina, United States, 2005, where flooded transport corridors, communication breakdown, shelter failure, and emergency-management strain converted a storm event into a prolonged humanitarian crisis; and in Hurricane Otis, Mexico, 2023, and the Türkiye–Syria earthquake, 2023, where access-route and communication-network failure weakened the operational backbone of emergency response and allowed secondary impacts to spread into health, shelter, food security, public order, and recovery systems.

These escalation points also help explain why prolonged infrastructure recovery and resilience challenges appeared as one of the important long-term impact patterns. Because critical infrastructure systems provide the main lines of service immediately after disasters, they are continuously required during response and early recovery. When these systems are damaged or overloaded, their own restoration can be delayed. At the same time, the recovery of other dependent sectors is also postponed, which creates a weak-cycle effect: delayed infrastructure restoration slows emergency response, shelter support, health services, water and sanitation, fuel supply, communication, livelihood recovery, and repair operations; these delays can further weaken already stressed systems and prolong the cascade across sectors. Cases such as the 2021 Winter Storm Uri in the USA, Hurricane Katrina in the USA, and the 2011 Tōhoku–Fukushima disaster in Japan demonstrate how the disruption of critical infrastructure can propagate through interconnected systems, creating persistent recovery bottlenecks. The resilience-dimension analysis suggests that this pattern is partly rooted in high levels of interdependence and low backup capacity in critical facilities and service networks.

Apart from causing extensive destruction of the built environment and creating substantial reconstruction burdens, cascading disasters may also expose affected populations to prolonged hazards that persist long after the triggering event has ended. In many cases, recovery does not occur in a stable post-disaster environment. Instead, communities remain exposed to secondary hazards, environmental contamination, unstable terrain, damaged protective infrastructure, and disrupted essential services. A representative example is the 2011 Tōhoku–Fukushima disaster in Japan, where radioactive contamination and evacuation restrictions continued to shape recovery for years after the earthquake and tsunami. Similar patterns can be observed in Hurricane Katrina (United States, 2005), where contaminated floodwaters, environmental pollution, and prolonged displacement extended vulnerability well beyond the hurricane itself, and in the 2015 Gorkha earthquake (Nepal), where landslides and unstable slopes continued to threaten settlements and infrastructure after the initial seismic event. This interpretation is further supported by the co-occurrence structure of long-term impacts: hazard management, infrastructure recovery, built-environment recovery, livelihood recovery, and psychosocial impacts tended to cluster rather than appear in isolation. This finding reinforces the argument that cascading disasters create bundled recovery burdens, where physical reconstruction, service restoration, livelihood support, and social recovery must be planned together rather than through separate sectoral programs.

Finally, the contrast between moderate and high-complexity cascades in this dataset does not show markedly different resilience-dimension profiles; rather, both are dominated by redundancy and connectivity. What differs is where those weaknesses are expressed. Moderate cascades are often shaped by coordination overload, uncertain operating pictures, and communication friction, while the most complex cascades are more likely when system-critical protection and service-continuity functions fail together. This difference highlights systemic-risk governance literature, which repeatedly finds that institutions remain siloed, that single-hazard planning struggles with interdependent risks, and that information systems are often not designed for fast-changing, cross-sector crises (United Nations Office for Disaster Risk Reduction, 2022). Therefore, the magnitude of cascading events is explained less by the initiating hazard alone than by whether disruption reaches and overloads the core functional interfaces that sustain societal continuity (United Nations Office for Disaster Risk Reduction, 2022).

Taken together, these findings suggest that cascade-risk governance should focus less on sector-by-sector protection alone and more on the continuity functions that prevent disruption from spreading across systems. This provides the basis for the following policy recommendations.

5 Conclusions and policy recommendations

The findings support previous arguments that, although multi-hazard and multi-risk indicators are increasingly used, they often remain insufficient for capturing interactions between hazards and risks (White et al., 2025) and the wider system pathways through which impacts propagate (Brett et al., 2025). The present study extends this discussion by showing that cascading disasters require attention not only to interacting hazards but also to the continuity failures that allow disruption to move through infrastructure, response, health, access, and recovery systems. The central policy recommendation of this review is that cascade-risk reduction should not be organized solely around sectors, but around the system functions that prevent disruption from spreading across sectors. Disaster risk reduction, therefore, cannot focus solely on the triggering hazard or on protecting individual assets. It must also identify which failures in lifeline services, access networks, monitoring systems, emergency coordination, and social protection are likely to convert a hazard into a public-health, humanitarian, logistical, or long-term recovery crisis. Figure 5 summarizes this in policy logic by showing how a hazard-related disruption can cascade when it reaches critical escalation points and spreads through dependent systems, and how this process can be reduced by protecting continuity functions rather than sectors alone. It conveys the message that the cascade-risk reduction should not focus solely on sectors, but on continuity functions, including monitoring and control, lifeline services, access and logistics, emergency coordination, and equity-sensitive social protection. On this basis, the framework identifies five practical policy priorities to reduce the likelihood that hazard-related disruption will escalate into a wider, cascading crisis.

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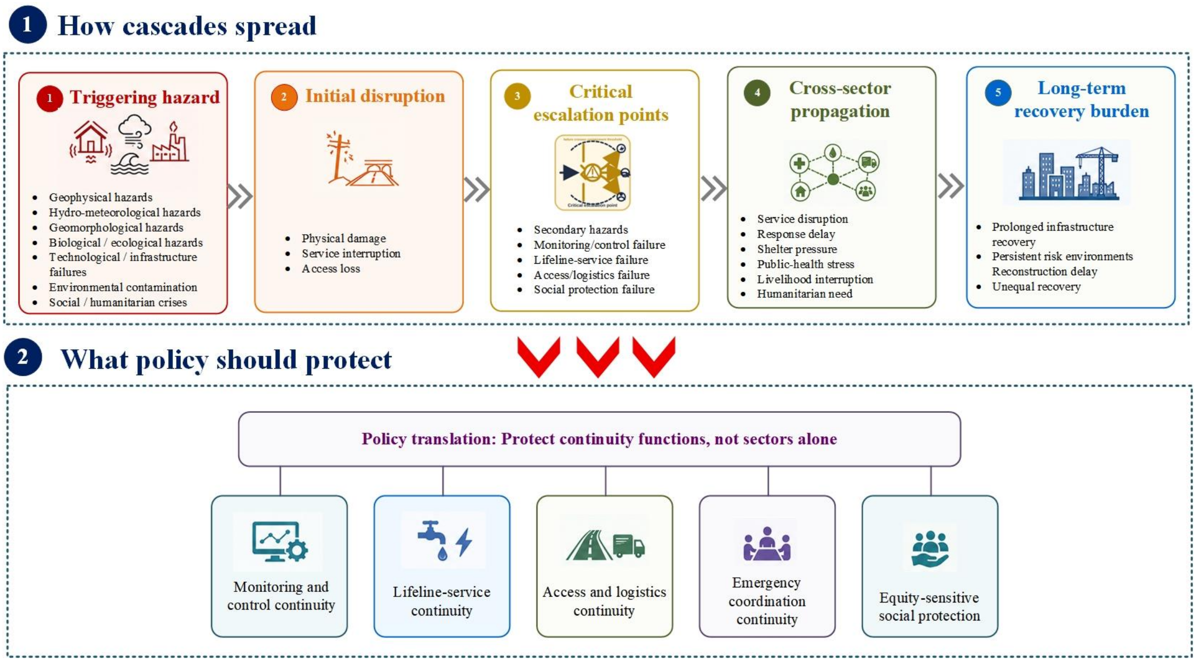

Figure 5: From sector protection to continuity-function governance: a conceptual framework for cascade-risk reduction

First, protecting lifeline continuity should be treated as a core priority in cascade prevention. Power, water, and sanitation, fuel, communication, health facilities, and other essential service systems should be planned as cascade-control systems, not only as infrastructure assets to be repaired after a disaster. Protecting their continuity can shorten the destructive pathway, reduce emergency response overload, and prevent temporary service disruptions from becoming prolonged humanitarian and recovery burdens. This requires stress-testing interdependencies between lifeline infrastructures, identifying dependency bottlenecks, designing backup systems for essential services, and expanding decentralized service provision where centralized systems are likely to fail.

Second, access continuity should be treated as a central part of disaster-risk reduction, not a secondary recovery issue. Even when supplies, responders, medical care, or shelter capacity exist, they cannot reduce cascading impacts if people, relief goods, fuel, and emergency teams cannot move. Therefore, governments and emergency agencies should pre-position supplies in locations likely to become isolated, protect alternative transport and communication routes, maintain rapid debris-clearance capacity, and prepare logistics plans for cases where roads, airports, ports, or communication networks fail.

Third, monitoring, warning, and control systems must be designed to remain functional during cascading disasters. The findings show that escalation is often enabled when risk conditions evolve faster than institutions can detect, interpret, or communicate them. For this reason, cascade prevention requires monitoring systems that can track secondary hazards, infrastructure degradation, public health risks, and access disruptions together rather than separately. Warning systems should also be able to update messages quickly as conditions change, without fragmenting public trust or creating contradictory instructions.

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Fourth, recovery planning should not assume that risk disappears once the triggering hazard has ended. Cascading disasters often transform short-term emergency conditions into persistent risk environments, where communities remain exposed to secondary hazards, environmental contamination, unstable terrain, damaged protective infrastructure, disrupted services, and delayed reconstruction. Recovery plans should therefore include residual-hazard monitoring, environmental and public health surveillance, long-term support for displaced communities, and reconstruction strategies that address both physical rebuilding and ongoing exposure.

Finally, cascade-risk governance must be equity-sensitive. Housing, livelihood, humanitarian protection, and security failures show that vulnerable groups often experience longer and more severe recovery burdens. Emergency planning should therefore identify who is most likely to lose access to lifeline services, who cannot evacuate easily, who depends on powered medical equipment, who lacks savings or insurance, and who is likely to remain displaced after the immediate emergency. In practical terms, cascade prevention requires governments to identify where a single system failure can disable several others, and to treat those points as priority intervention targets before disaster strikes.

These recommendations should be read as a functional orientation for cascade-risk governance rather than a universal implementation template. The review identifies recurring continuity functions whose failure allowed cascades to spread, but the practical feasibility of protecting them will vary by governance capacity, fiscal resources, legal mandates, infrastructure age, data-sharing arrangements, and public trust. Some recommendations, such as redundant lifeline systems or integrated monitoring, may be difficult in low-resource or politically fragmented settings, and may require phased implementation, prioritization of critical nodes, and explicit trade-off decisions. The evidence base also reflects documentable, largely English-language cases, so informal coping systems, local knowledge, psychosocial recovery, and slow-onset vulnerability pathways may be less visible than infrastructure and emergency management failures. In addition, screening and coding were conducted by a single reviewer. Although predefined criteria, screening logs, repeated checks of ambiguous records, and event-level cross-case harmonization were used to improve consistency and traceability, the absence of dual, independent screening remains a methodological limitation. Therefore, the framework should be used as a diagnostic and prioritization tool to guide context-specific planning, not as a predictive model or fixed checklist applicable in the same way across all hazards and countries.

Appendices

Appendix A. Database-specific search strings

In ScienceDirect, searches were conducted using the Title-Abstr-Key field tag (tak(), which restricts the search to the title, abstract, and keywords. The Boolean operators were applied inside this field restriction. Because cascading disasters are inconsistently framed across disciplines, a single search string risked omitting relevant studies. We therefore employed multiple complementary search queries targeting distinct but theoretically related framings, including explicit cascading or domino processes, multi-hazard and secondary-trigger events, and vulnerability- and exposure-driven escalation pathways.

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Overlap between queries was expected and addressed through systematic deduplication, consistent with PRISMA guidance for complex and interdisciplinary reviews.

Searches were restricted to subject areas and research categories most relevant to hazard processes and socio-technical impacts, including Environmental Science, Social Sciences, Engineering, Business and Management, and Psychology, while biomedical-focused fields were excluded. Only peer-reviewed research articles and review papers were included. Review papers were retained only when they documented or synthesized identifiable real-world cascading-disaster events; where they referred to events also covered by primary studies, evidence was consolidated at the event level to avoid double-counting. JSTOR was selected to complement more technical databases by providing access to broader social science, policy, and environmental perspectives. This approach ensured that the review captured not only technical analyses but also societal, organizational, and governance dimensions of cascading disaster research. This stage yielded 3673 papers.

Table A1: Search strings used in the selected databases

Database	Search string
ScienceDirect	tak((cascading OR domino OR "chain reaction" OR compound) AND (disaster OR hazard) AND (impact OR consequence)) tak((interdependency OR interconnected OR "system failure") AND (disaster OR hazard) AND (impact OR consequence)) tak(("multi-hazard" OR secondary OR triggering) AND (disaster OR hazard) AND (impact OR consequence)) tak((cascading OR compound) AND (disaster OR hazard) AND (vulnerability OR exposure))
Web of Science	TI=(cascad* OR domino OR compound OR "chain reaction") AND AB=(disaster* OR hazard* OR event OR risk) AND AB=(impact OR effect OR consequence OR "systemic vulnerab*")
JSTOR	((((cascade) OR (compound)) OR (secondary)) AND (disaster)) OR (hazard)) AND (impact)) AND (effect))
Google Scholar	"cascading disasters" OR "cascading hazards" OR "compound disasters" OR "compound hazards" ("cascading effects" OR "domino effects") AND ("natural disaster" OR "natural hazard")

Appendix B. Retained studies list

Table B1: Retained 34-study table

No.	Author(s), year	Standardized disaster case(s) covered
1	(Mühlhofer et al., 2024)	2021 Winter Storm Uri, USA
2	(Alexander, 2018)	1971 San Fernando / Sylmar Earthquake Cascade, California, USA; 2005 Hurricane Katrina, USA; 2010 Eyjafjallajökull Volcanic Ash Aviation Cascade, Iceland–Europe; 2011 Tōhoku Earthquake–Tsunami–Fukushima Triple Disaster, Japan; 2004 Indian Ocean Earthquake and Tsunami Cascade
3	(Thomas et al., 2020)	2020 Flooding–COVID-19–Cholera Cascade, Kenya; 2016–2020,

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		Compound Disaster and Migration Cascade, Puerto Rico
4	(Guo et al., 2024)	2019 Typhoon Lekima, Eastern China
5	(McDermott et al., 2022)	1999 Marmara / İzmit Earthquake, Türkiye; 2015 Gorkha Earthquake, Kathmandu, Nepal
6	(Ramírez-Herrera et al., 2025)	2023 Hurricane Otis, Mexico
7	(Wen et al., 2025)	2004 Indian Ocean Earthquake and Tsunami Cascade
8	(Alexander and Pescaroli, 2019)	2011 Tōhoku Earthquake–Tsunami–Fukushima Triple Disaster, Japan; 2010 Eyjafjallajökull Volcanic Ash Aviation Cascade, Iceland–Europe; 2002 Flood Natech and Water-Contamination Cascade, Central Europe / Prague; 2017 Hurricane Harvey Industrial Natech Cascade, Texas, USA
9	(Lorenz et al., 2023)	2020 Pantanal Wildfires, Brazil
10	(DuttaGupta et al., 2021)	2020 Cyclone Amphan, Indian Sundarbans
11	(Quigley et al., 2020)	2020 Zagreb Earthquake and COVID-19 Emergency-Response Cascade, Croatia; 2020 Tropical Cyclone Harold, Pacific Islands; 2018 Mount Anak Krakatau Volcanic Flank-Collapse Tsunami Cascade, Indonesia; 2020 Tornado Outbreak, USA
12	(Pescaroli and Alexander, 2015)	2001 Baltimore Howard Street Tunnel Freight Rail Crash, USA; 2002 Flood Natech and Water-Contamination Cascade, Central Europe / Prague; 2003 North America Blackout, USA–Canada; 2006 Hengchun Earthquake, Taiwan / East and Southeast Asia; 2010 Eyjafjallajökull Volcanic Ash Aviation Cascade, Iceland–Europe; 2011 Tōhoku Earthquake–Tsunami–Fukushima Triple Disaster, Japan
13	(Shieh ChjengLun et al., 2010)	2009 Typhoon Morakot Flood–Landslide–Water-System Cascade, Taiwan
14	(Bagulayan et al., 2012)	2011 Tōhoku Earthquake–Tsunami–Fukushima Triple Disaster, Japan
15	(Boni et al., 2021)	2016–2017 Earthquake-Triggered Landslide, Central Italy; 2017 Snowstorm and Power-Outage Cascade, Central Italy
16	(Suppasri et al., 2021b)	1983 Sea Earthquake and Tsunami Lifeline Cascade, Japan; 1993 Okushiri Earthquake and Tsunami Warning/Evacuation Cascade, Japan; 2004 Indian Ocean Earthquake and Tsunami Cascade; 2011 Tōhoku Earthquake–Tsunami–Fukushima Triple Disaster, Japan; 2018 Sulawesi / Palu Earthquake–Tsunami–Liquefaction Cascade, Indonesia; 2018 Mount Anak Krakatau Volcanic Flank-Collapse Tsunami Cascade, Indonesia
17	(Pescaroli and Kelman, 2017)	2002 Flood Natech and Water-Contamination Cascade, Central Europe / Prague; 2005 Hurricane Katrina, USA; 2011 Tōhoku Earthquake–Tsunami–Fukushima Triple Disaster, Japan
18	(Clark-Ginsberg et al., 2021)	2021 Winter Storm Uri, USA
19	(Kemter et al., 2021)	2019–2020 Black Summer, Australia
20	(Kincey et al., 2023)	2015 Gorkha Earthquake, Kathmandu, Nepal
21	(Gill and Malamud, 2014)	1792 Mount Unzen / Mount Mayuyama Landslide-Tsunami Cascade, Japan; 1964 Alaska Earthquake Landslide–Tsunami–, USA; 1991 Mount Pinatubo–Typhoon Yunya Lahar Cascade, Philippines; 2010 Tropical Storm Agatha–Pacaya Eruption Multi- Cascade, Guatemala

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22	(Hutchison et al., 2016)	1717 Volcán de Fuego–Volcán de Agua Volcanic–Seismic–Mudflow Cascade, Guatemala
23	(Arto et al., n.d.)	2011 Tōhoku Earthquake–Tsunami–Fukushima Triple Disaster, Japan
24	(Wolff and Ramírez-Lovering, 2022)	2019 Makassar Compound Flooding, Indonesia
25	(NASSAR and NASTACĂ, 2021)	2020 Beirut Port Explosion, Lebanon
26	(Sugg et al., 2023)	2021 Winter Storm Uri, USA
27	(Pervaz, 2021)	2019–2020 Desert Locust, Pakistan
28	(Spraktes and McEntire, 2024)	2021 Winter Storm Uri, USA
29	(Nguyen et al., 2013)	2010 Madeira Extreme Rainfall–Landslide–Debris-Flow Cascade, Portugal
30	(Xie et al., 2014)	2008 Great Chinese Ice Storm, China
31	(Gulbaz et al., 2026)	2023 Türkiye–Syria Earthquake, Türkiye–Syria
32	(Görüm et al., 2025)	2023 Türkiye–Syria Earthquake and Post-Seismic Cascades, Türkiye–Syria
33	(Diakakis et al., 2025)	2023 Storm Daniel / Thessaly Flood Cascade, Greece and Libya
34	(Aranda et al., 2022)	2016–2020, Compound Disaster and Migration Cascade, Puerto Rico

Appendix C. Supplementary evidence source categories

Supplementary searches were event-specific. Supplementary evidence was used only to triangulate and complete event-level coding where database-indexed studies did not provide sufficient detail. The supplementary evidence base comprised 249 formatted sources. Most sources came from major public, humanitarian, development, or technical organizations: national or subnational government and public technical agencies (n = 65, 26.1%), UN-system agencies and UN information platforms (n = 64, 25.7%), World Bank/GFDRR assessments (n = 18, 7.2%), Red Cross/Red Crescent/IFRC sources (n = 18, 7.2%), and international or regional development and technical institutions (n = 12, 4.8%). Together, these institutional sources accounted for approximately 71% of the supplementary evidence base. Academic or peer-reviewed sources accounted for a further 12.9% (n = 32), while NGO/civil-society sources, contextual repositories, sector reports, and manually checked mixed-origin sources made up the remainder.

Appendix D. Coding rules

Table D1: Coding rules, escalation points

Escalation-point keyword	Coding rule	Toral observation
Power system failure	Use when power loss becomes the central event that causes multiple downstream system failures.	34
Infrastructure interdependency feedback loop	Use when failure in one infrastructure system reinforces failure in another.	34
Fuel and gas supply disruption	Use when fuel/gas loss blocks generation, heating,	34

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	transport, hospital generators, or logistics.	
Water and sanitation system disruption	Use when water/sanitation failure opens health, contamination, shelter or hospital pathways.	34
Flood-protection / drainage failure	Use when levee, drainage, flood-control or pumping failure transforms hazard exposure into wider inundation.	6
Dam/reservoir failure or failure-risk pathway	Use when dam/reservoir instability creates a new emergency or threatens downstream populations.	6
Tsunami generation and coastal inundation	Use when earthquake/landslide/volcanic failure generates a tsunami that becomes a larger damage source.	25
Landslide / slope-failure propagation	Use when slope failure after earthquake/rain/volcanic activity becomes a new impact source.	25
Liquefaction and ground-failure propagation	Use when ground failure creates major building, transport, displacement or service disruption.	25
Debris-flow / lahar / mudflow propagation	Use when lahars/debris flows remobilize material and create new destructive paths.	25
Volcanic ash / tephra disruption	Use when ashfall/tephra causes roof, aviation, environment, or transport disruption.	25
Aviation-system closure	Use when airspace/airport closure becomes the main spread mechanism of economic/logistics impacts.	13
Transport and mobility disruption	Use when road/rail/port/airport disruption blocks rescue, logistics, commerce or evacuation.	13
Access isolation and emergency-response delay	Use when blocked access directly delays rescue, relief or healthcare and amplifies impacts.	7
Communication and information-system disruption	Use when communication collapse affects warning, coordination, finance, transport or relief.	6
Warning and evacuation-communication failure	Use when failure/absence of warning or evacuation communication increases exposure or mortality.	6
Shelter and evacuation disruption	Use when evacuation/shelter failure transforms physical damage into mass humanitarian or health risk.	6
Humanitarian relief and aid-system strain	Use when relief logistics/governance become overwhelmed and amplify suffering or delay recovery.	10
Pandemic-response constraint	Use when COVID restrictions, infection control, health-system pressure, or lockdowns reshape response and exposure.	10
Disease transmission / outbreak pathway	Use when cholera, COVID exposure, vector-borne disease, or outbreak becomes a new damage pathway.	4
Health-system disruption	Use when hospital/medical disruption itself amplifies mortality, evacuation, treatment delay, or public health response.	3
Critical facility / public-building failure	Use when hospitals, schools, shelters, public buildings, or critical facilities fail and drive new impacts.	5
Industrial / chemical facility disruption	Use when industrial facility damage/release creates a Natech or technological cascade.	13
Nuclear accident / radiological	Use when nuclear/radiological release becomes a	13

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contamination	major independent disaster pathway.	
Fire / explosion / hazardous-material ignition	Use when ignition/explosion/hazmat release becomes a major secondary damaging event.	13
Environmental contamination / pollution pathway	Use when contamination, debris, pollution, smoke, ash or radiological spread creates new health/ecosystem/livelihood impacts.	4
Food-security and livelihood disruption	Use when livelihood/food loss becomes a major secondary crisis or prolongs recovery.	5
Supply-chain and logistics disruption	Use when logistics failure spreads impacts across sectors or regions.	2
Social vulnerability / inequality amplification	Do not code as an escalation point in this round; keep it for vulnerability/resilience analysis instead.	5
Governance and coordination breakdown	Do not code as an escalation point in this round; keep it for institutional vulnerability/resilience analysis instead.	8
Monitoring / control-system failure	Do not code as an escalation point in this round; keep it for warning/control-system vulnerability analysis instead.	8
Housing and building damage	Use only when mass building collapse/loss becomes an escalation point producing displacement, shelter, health or social crisis.	5
Displacement and migration pathway	Use when displacement/migration becomes a major secondary pathway affecting health, education, economy, or recovery.	3
Security / public-order disruption	Use when public-order breakdown or security problems worsen relief, livelihoods or safety.	5
Agricultural / ecosystem damage pathway	Use when ecosystem/agricultural damage becomes a continuing pathway to livelihood, food, health or economic disruption.	1

Table D2: Coding rules, long-term impacts

Long-term impact keyword	Coding rule	Toral observation
Housing and built-environment reconstruction	Persistent housing loss, reconstruction, structural repair, or rebuilding delay.	29
Lifeline and critical-infrastructure restoration/resilience	Prolonged restoration or resilience needs in power, transport, communication, critical facilities, or lifelines.	38
Water, sanitation and drainage recovery	Continuing WASH, drainage, sewage, water-quality, or water-system restoration burden.	16
Economic loss and business recovery	Lasting business interruption, local economic loss, or commercial recovery burden.	15
Recovery financing, insurance and debt burden	Debt, compensation, insurance, recovery-finance, or funding constraints.	10
Livelihood and food-security recovery	Prolonged livelihood, employment, food access, or food-security recovery needs.	24
Agriculture, fisheries and primary-sector recovery	Recovery of farming, fisheries, livestock, aquaculture, forestry, or primary-sector systems.	15

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Tourism and local-service economy recovery	Longer-term damage to tourism, hospitality, retail, and local services.	4
Displacement, resettlement and migration pressure	Continuing displacement, relocation, resettlement, migration pressure, or spatial recovery burden.	18
Humanitarian needs and aid-dependence continuity	Humanitarian needs, aid reliance, relief operations, or protection needs continuing beyond immediate response.	13
Public-health and health-system recovery	Health-system restoration, health service recovery, disease control, or medical-access burden.	10
Mental-health and psychosocial burden	Trauma, grief, stress, anxiety, psychosocial needs, or mental-health impacts after the event.	10
Education and social-service recovery	Restoration of education, child services, social services, or public service continuity.	11
Social inequality and vulnerable-group recovery gap	Unequal recovery, vulnerable-group recovery gaps, poverty-related burden, or exclusion from assistance.	11
Community cohesion and trust erosion	Loss of community cohesion, trust, social capital, or community identity.	7
Environmental/ecological degradation and biodiversity loss	Persistent ecosystem degradation, biodiversity loss, land degradation, or ecological recovery needs.	18
Contamination cleanup and environmental remediation	Cleanup/remediation of pollution, toxic contamination, hazardous materials, debris, or radiological contamination.	11
Hazard persistence and recurrent-risk management	Continued management of recurrent or unresolved hazards such as slope instability, flood risk, dam risk, disease risk, contamination, or recurring exposure.	53
Supply-chain and logistics resilience learning	Delayed logistics restoration, supply-chain disruption, or long-term supply-chain resilience needs.	3
Cultural heritage restoration	Restoration of cultural heritage, historic buildings, monuments, or cultural assets.	2
Legal/accountability and institutional scrutiny	Legal proceedings, accountability pressure, institutional scrutiny, liability, or investigation consequences.	4

Table D3: Coding rules, failure mechanism

Failure mechanism	Coding rule	Toral observation
Pest surveillance and vector-control failure	Use when locust, vector, pest, or biological hazard monitoring/control capacity fails.	75
Built-environment fragility and code/enforcement failure	Use when weak buildings, construction defects, poor code enforcement, seismic/fire/structural fragility, or building regulation failure turns hazard into larger loss.	13
Coastal-defense and tsunami-protection failure	Use when seawalls, coastal barriers, tsunami protection, coastal defenses, or shoreline defenses fail against inundation.	75
Pandemic and compound-crisis operating constraint	Use when COVID-19, concurrent disease, lockdowns, distancing, or compound-crisis operating rules constrain response, sheltering, health care, or recovery.	33
Critical-facility and public-building continuity failure	Use when public buildings, schools, hospitals, government offices, emergency centers, fire stations, or other critical facilities are damaged or lose function.	2
Cultural heritage protection and restoration failure	Use when heritage buildings, museums, historic urban fabric, monuments, or cultural assets are not protected/restored.	7

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Economic and business continuity failure	Use when firms, commerce, markets, insurance, finance, SMEs, local economies, or business operations lack continuity or reserves.	12
Access isolation and rescue-delay failure	Use when blocked access directly isolates communities or delays rescue, healthcare, reconnaissance, relief, evacuation, or repair.	6
Emergency management, command and coordination failure	Use when fragmented command, unclear authority, weak coordination, delayed mobilization, EOCs, emergency governance, or response operation failure worsens outcomes.	19
Responder workforce and operational-capacity failure	Use when staffing, responder fatigue, surge demand, emergency workforce safety, training, or operational capacity is insufficient.	3
Ecological degradation and land-cover resilience failure	Use when ecosystem degradation, forest/land cover, biodiversity loss, wildfire ecology, erosion, slope/soil fragility, or natural buffers reduce resilience.	11
Environmental contamination and remediation-control failure	Use when pollution, toxic releases, debris, waste, oil, chemicals, sewage, smoke, sediment, or contamination management creates long-term/public-health damage.	11
Social equity and vulnerable-group protection failure	Use when poverty, race, age, disability, gender, migration status, informal work, medical dependence, inequality, or low resources shape exposure and recovery.	16
Wildfire suppression and fire-regime management failure	Use when fire regime, drought/fire weather, suppression capacity, smoke management, or wildfire prevention is insufficient.	75
Dam, reservoir and water-retention safety failure	Use when dam, reservoir, embankment, retention structure, tailings, or water-control failure or failure-risk creates downstream danger.	75
Flood-protection, levee and drainage-control failure	Use when levees, flood defenses, drainage systems, pumps, culverts, stormwater infrastructure, or flood-control design fails.	75
Institutional accountability and public-legitimacy failure	Use when negligence, accountability, legitimacy, corruption, public anger, or institutional scrutiny becomes a mechanism weakening response or recovery.	6
Regulatory standards, enforcement and learning failure	Use when codes, standards, regulatory enforcement, safety rules, inspections, formal lessons, or reform/implementation failure causes or prolongs vulnerability.	7
Health-care service continuity and surge-capacity failure	Use when hospitals, clinics, nursing homes, patient evacuation, medical equipment, supplies, personnel, or health-facility continuity fail.	23
Household backup and unsafe-coping failure	Use when lack of safe backup heating/power/water/cooking or unsafe coping behavior causes fire, CO poisoning, injury, or exposure.	2
Housing quality and household-exposure failure	Use when housing quality, insulation, settlement materials, household plumbing, thermal safety, home protection, or household exposure increases risk.	11
Humanitarian logistics and aid-coordination failure	Use when relief supply chains, aid distribution, international assistance, relief coordination, transparency, or accountability problems amplify suffering.	7

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Shelter, evacuation and temporary-protection failure	Use when evacuation, shelter, warming centers, temporary accommodation, camps, population protection, or evacuee management lacks capacity or safety.	15
Communication, ICT and information-flow failure	Use when telecommunications, internet, emergency communication, ICT, cable, data, device charging, or information flow fails.	17
Infrastructure interdependency and cascading-dependency failure	Use when dependence among power, water, gas, transport, ICT, health, or other systems transmits or amplifies failures.	9
Fuel and gas supply dependency failure	Use when gas, fuel, refinery, pump, generator-fuel, or energy-fuel interdependence limits response, heating, transport, power generation, or logistics.	32
Power and energy-service continuity failure	Use when electricity generation, grid operations, load shedding, power restoration, or energy-system reliability failure drives wider disruption.	32
Livelihood and food-security system failure	Use when household income, food access, food systems, employment, livelihood dependence, or food security deteriorates.	6
Cross-border and multi-jurisdictional coordination failure	Use when impacts cross jurisdictions, countries, sectors, or administrative levels and coordination mechanisms are insufficient.	6
Nuclear/radiological safety and contamination-management failure	Use when nuclear plants, radiation release, exclusion zones, decontamination, radioactive waste, or radiological monitoring becomes a failure pathway.	14
Hazard-process amplification and physical-susceptibility failure	Use when geomorphic, seismic, volcanic, hydro-meteorological, wildfire, liquefaction, tsunami or other physical processes amplify because exposed natural/terrain systems are susceptible or insufficiently managed.	75
Preparedness and compound-hazard scenario-planning failure	Use when single-hazard planning fails to account for compound, concurrent, recurrent, or multi-hazard scenarios.	6
Agriculture, fisheries and ecosystem-livelihood failure	Use when agriculture, fisheries, livestock, aquaculture, farming inputs, primary sector livelihoods, or ecosystem services fail.	13
Mental-health and psychosocial support failure	Use when trauma, stress, anxiety, suicidal ideation, grief, crisis demand, or mental-health support capacity becomes a failure mechanism.	13
Public-health surveillance and disease-control failure	Use when infectious disease control, vaccination, quarantine, cholera/vector surveillance, public-health operations, COVID constraints, or sanitation health risk becomes a failure pathway.	2
Financial, insurance and recovery-resource access failure	Use when lack of insurance, debt, recovery finance, compensation, rebuilding funds, or uneven resource access delays recovery.	2
Data, reconnaissance and damage-assessment failure	Use when damage assessment, rapid reconnaissance, data systems, monitoring controls, or situational awareness needed for response/recovery is insufficient.	25
Risk perception, social memory and relocation-decision failure	Use when risk perception, historical memory, fear, trust, or relocation decision-making becomes a failure mechanism.	2
Security, protection and public-order failure	Use when looting, violence, public order breakdown, crime, unsafe shelter, gender/child protection, or security operations fail.	15

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Community cohesion, trust and social-capital failure	Use when loss of community networks, displaced community identity, social fragmentation, mistrust, or degraded legitimacy worsens recovery.	3
Education and social-service continuity failure	Use when schools, child services, social services, education continuity, or public-service access are disrupted.	8
Land-use, settlement exposure and spatial-planning failure	Use when exposed settlement locations, low-lying/coastal/sloping land, informal settlement, floodplain occupation, or poor land-use planning increases impact.	27
Supply-chain, logistics and just-in-time dependency failure	Use when supply chains, logistics, inventory, production networks, just-in-time systems, port/freight/warehouse systems, or cross-border flows transmit disruption.	5
Industrial, chemical and Natech safety-control failure	Use when industrial facilities, chemical plants, refineries, ports, hazardous materials, explosions, fire, toxic release, or Natech risk creates new damage.	14
Tourism and local-service economy dependency failure	Use when tourism, hospitality, local service economy, destination perception, or local visitor-dependent economy collapses or lacks diversification.	3
Transport, mobility and physical-access failure	Use when roads, bridges, rail, airports, ports, ferries, traffic systems, evacuation routes, or physical access fail and delay evacuation, logistics, rescue, commerce, or recovery.	56
Water, sanitation and drainage-service failure	Use when drinking water, wastewater, sanitation, drainage, sewerage, pumping, treatment, or WASH services fail or create public-health risk.	20
Warning, monitoring and risk-communication failure	Use when warning, hazard monitoring, detection, risk communication, advisory, forecast uncertainty, sirens, alerts, or public interpretation fails.	25

Code and data availability

All data used in this review were derived from published literature and publicly available supplementary sources cited in the manuscript and appendices. The search strings, retained-study list, event-level case list, supplementary source categories, and coding rules are provided in the Appendices. No confidential, personal, or non-public data was used.

Author contributions

HB conceptualized and designed the study, developed the search and screening strategy, conducted the literature screening, eligibility assessment, data extraction, coding, synthesis, figure preparation, interpretation of results, and manuscript writing.

Competing interests

The author declares no competing interests.

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Acknowledgements

The author used OpenAI ChatGPT as an assistive tool during manuscript preparation to support English-language editing, improve readability, and ensure consistent terminology. The tool was not used to conduct the literature search, determine study eligibility, extract or code data, generate empirical findings, or make scientific interpretations.

Financial support

This research received no external funding.

Review statement

The review statement will be added by Copernicus Publications listing the handling editor as well as all contributing referees according to their status anonymous or identified.

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