

From Hazard Co-occurrence to Risk Mechanisms: Climate–Anthropogenic Interactions in Multi-Hazard Risk Formation

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Abstract

Multi-hazard risk is often assessed through the co-occurrence or interaction of hazardous processes. However, the presence of multiple hazards does not, by itself, explain how complex risk forms or why similar hazard combinations can produce different consequences across environmental and human systems. This study examines mechanisms through which climate-related stress, anthropogenic influences and environmental conditions interact in complex multi-hazard risk formation. A comparative analysis of published scientific and institutional evidence was conducted using three Indian evidence portfolios representing contrasting environmental and human-system contexts: the Western Himalaya, Western Ghats of Kerala and Upper Bhima Basin. The selected scientific and institutional evidence was examined using a common analytical approach focused on initiating disturbances, antecedent conditions, hazardous processes, environmental connectivity, temporal stress, anthropogenic influences and consequences. The comparative analysis identified three analytically distinct risk-forming mechanisms represented across the selected evidence portfolios: Type I – Sequential propagation, in which an initiating disturbance contributes to successive process transformations and cascading consequences; Type II – Interaction and connectivity, in which risk emerges through relationships among environmental conditions and connected physical pathways; and Type III – Cumulative stress and changing system condition, in which previous or repeated stress alters the condition from which subsequent risk develops. The findings show that climate-related and anthropogenic influences do not operate as uniform external drivers but enter risk formation through mechanism-specific pathways. The study provides a mechanism-oriented basis for interpreting complex multi-hazard risk and for identifying information relevant to anticipatory risk assessment and governance.

1. Introduction

Multi-hazard risk is increasingly recognised as a defining challenge for disaster risk reduction and climate adaptation because hazardous processes rarely occur in complete isolation. Hazards may occur simultaneously, sequentially, or through interactions in which one process modifies the conditions under which another develops. Such relationships can produce consequences that differ substantially from those associated with individual hazards considered separately. Research on multi-hazard interactions has consequently expanded from hazard-specific assessment towards consideration of cascading processes, compound events and networks of interacting hazards [1–5].

Despite this progress, the presence of multiple hazards does not by itself explain how complex risk forms. A sequence of hazards may represent a genuine cascade in which one process contributes to another, but hazards may also be connected through shared environmental conditions, spatial connectivity, or changes in system condition following previous disturbance. These relationships have different implications for understanding exposure, vulnerability and consequences. Treating all multi-hazard situations as equivalent therefore risks obscuring the mechanisms through which risk develops.

This distinction is particularly important in climate-sensitive systems, where climatic conditions interact with environmental characteristics and human activities across different spatial and temporal scales. Climate-related forcing may contribute to triggering or conditioning hazardous processes, while anthropogenic activities may alter environmental conditions, physical pathways, exposure, resource dependence or adaptive capacity. Anthropogenic processes can therefore influence hazard–risk relationships without necessarily constituting the direct cause of a particular hazardous event [6]. Understanding these relationships requires attention to where climatic and human influences enter the broader risk-forming process.

The challenge is illustrated by contrasting environmental settings in India. In the Western Himalaya, rapid mass movements can transform into downstream processes with consequences extending well beyond the initial source area. The 2021 Chamoli rock–ice avalanche provides a particularly well-documented example of such process propagation [7, 8]. In the Western Ghats of Kerala, extreme rainfall, antecedent conditions, terrain, hydrological behaviour and geomorphic connectivity can interact to influence landslide, debris-flow and flood consequences. In the Upper Bhima Basin, drought and water-resource stress occur within a system in which groundwater availability, agricultural dependence and adaptation can alter the conditions under which subsequent climatic stress is experienced [11–13].

These examples suggest that multi-hazard risk cannot always be adequately represented by a single cascade model. The relationships observed across the three settings differ in their dominant dimensions: rapid transformation between processes in the Western Himalaya, interaction and physical connectivity in the Western Ghats of Kerala, and changing system condition through time in the Upper Bhima Basin. The cases therefore provide an opportunity to examine whether apparently different multi-hazard situations can be compared according to the mechanisms through which their components become connected.

Against this background, this study examines how complex multi-hazard risk becomes connected through different risk-forming relationships rather than through hazard co-occurrence alone. It aims to distinguish analytically different mechanisms of risk formation and to examine how climate-related and anthropogenic influences enter these mechanisms across contrasting environmental and human-system contexts. A comparative evidence-based analysis is conducted using three Indian evidence portfolios—the Western Himalaya, Western Ghats of Kerala and Upper Bhima Basin—using a common analytical structure focused on disturbances or stressors, antecedent conditions, process transformation, connectivity, temporal dependence, anthropogenic influences and consequences. The contribution is an evidence-informed, mechanism-oriented interpretation that distinguishes sequential propagation, interaction and connectivity, and cumulative stress and changing system condition, while linking these distinctions to information relevant to anticipatory risk assessment.

The analysis identifies three analytically distinct risk-forming mechanisms: **Type I—sequential propagation, Type II—interaction and connectivity, and Type III—cumulative stress and changing system condition**. These mechanisms are treated as analytically distinguishable rather than mutually exclusive

categories. Their purpose is to provide a basis for comparing different forms of multi-hazard risk formation while retaining the specific environmental and human-system context of each case.

The contribution of the study is therefore not the proposition that these relationships are entirely new, but their organisation into a common mechanism-based interpretation supported by contrasting evidence from the selected portfolios. By moving from hazard co-occurrence towards the relationships that connect processes, system conditions and consequences, the study seeks to provide a more precise basis for understanding how climate-related and anthropogenic influences shape complex multi-hazard risk and for identifying information relevant to anticipatory risk assessment.

2. Materials and Methods

2.1 Study design and analytical approach

This study adopted a comparative, evidence-based analytical synthesis to examine how complex multi-hazard risk forms through different risk-forming relationships across contrasting Indian environmental and human-system contexts. The analysis draws on selected scientific and institutional evidence from three portfolios representing the Western Himalaya, the Western Ghats of Kerala, and the Upper Bhima Basin. Rather than treating hazards as independent or simply enumerating their co-occurrence, the study examines how processes, environmental conditions and human-system conditions become connected across space and time.

These portfolios were not treated as statistically comparable case studies. Rather, they served as evidence portfolios through which contrasting forms of risk formation could be examined and compared using a common analytical structure.

The analysis was guided by three questions: (i) what disturbance, stressor or combination of conditions contributes to the risk pathway; (ii) through what physical, environmental or temporal relationships does it become connected to subsequent consequences; and (iii) what evidence supports interpretation of that relationship as a particular mechanism of multi-hazard risk formation?

2.2 Evidence Portfolios

2.2.1 Western Himalaya

The Western Himalayan portfolio was used to examine sequential propagation. Its principal evidence concerns the 2021 Chamoli rock-ice avalanche, in which a large mass movement underwent rapid transformation and generated destructive downstream consequences [7, 8]. Additional studies addressing extreme rainfall and landslides in Uttarakhand provide environmental context for mountain slope instability [9, 10].

The portfolio was not used to imply that Himalayan hazards generally follow the same cascade sequence. Instead, it was examined for evidence of a relationship in which an initiating disturbance is

followed by successive process transformations and propagation.

2.2.2 Western Ghats of Kerala

The Western Ghats of Kerala portfolio was used to examine interaction and connectivity. Evidence from the 2018 floods in Kerala¹, the Pamba River and the 2024 Wayanad debris-flow event was examined in relation to extreme environmental conditions, slope processes, sediment dynamics, hydrological response and downstream pathways [14–16].

2.2.3 Upper Bhima Basin

The three evidence portfolios were selected purposively to represent contrasting Indian environmental and geomorphological settings and different forms of multi-hazard and climate-related risk. The Western Himalaya represents a high-mountain environment characterised by interconnected mass-movement processes; the Western Ghats of Kerala represents a sensitive mountain–river–settlement system exposed to floods, landslides and debris-flow processes; and the Upper Bhima Basin represents a drought-prone basin in which climatic variability and change interact with land-use dynamics, groundwater dependence, water-resource conditions and human adaptation.

The portfolios are not intended to provide statistically representative samples of Indian multi-hazard systems. Rather, they serve as contrasting evidence settings through which different risk-forming relationships can be examined using a common analytical framework. The comparison therefore focuses on the mechanisms connecting processes, environmental conditions and human-system conditions rather than on direct quantitative comparison of hazard magnitude or frequency across the three regions.

2.3 Evidence identification and selection

Scientific and institutional evidence was assembled through targeted searches of peer-reviewed research literature and publicly available institutional sources, including Web of Science, Google Scholar, OpenAthens-accessed scholarly resources, and relevant government and ministry reports. The evidence collection focused on multi-hazard interactions, cascading hazards, climate-related stress, anthropogenic influences, land-use change, environmental connectivity, drought, floods, landslides and water-resource stress.

The collected evidence was reviewed comparatively and selected based on its relevance to the environmental, climatic, spatial and human-system dimensions of the study. Three evidence portfolios were purposively selected to represent contrasting Indian environmental and geomorphological settings: the Western Himalaya, the Western Ghats of Kerala, and the drought-prone Upper Bhima Basin. Particular attention was given to evidence concerning recurrent or interconnected risks and the repeated exposure and vulnerability of communities and human systems.

The selected evidence was organised into the three portfolios and interpreted qualitatively according to the risk-forming mechanism most strongly represented in the available evidence. A detailed inventory of

the evidence included in the comparative analysis is provided in Supplementary Table S1, which summarises the sources, evidence focus, portfolio assignment and relevance to the comparative analysis.

2.4 Comparative analysis of the evidence

The selected evidence was examined comparatively to determine how disturbances and stresses became connected to subsequent processes and consequences within each portfolio. Particular attention was given to the initiating disturbance or stressor, the environmental and system conditions preceding or accompanying it, and the processes through which impacts developed. Where the evidence indicated a transformation from one process to another, this relationship was considered in assessing sequential propagation. Where the development or transmission of consequences depended on interactions among environmental conditions or on physical and hydrological connections, these relationships were examined as evidence of interaction and connectivity. In the Upper Bhima Basin, attention was instead given to whether previous or repeated climatic stress altered resource availability, buffering conditions, adaptation or other aspects of the system state relevant to subsequent stress.

Climate-related and anthropogenic influences were considered within these relationships rather than treated as separate explanatory categories. Climatic influence was assessed from evidence concerning variability, extreme conditions or persistent stress, while anthropogenic influence was considered where the literature documented effects associated with infrastructure, land-use or environmental modification, exposure, resource dependence, management or adaptation [6, 18, 19].

The analysis was qualitative and comparative. No numerical weights or scores were assigned because the selected studies differed substantially in geographical scale, event characteristics, data sources and methodological approach. Instead, interpretation was based on the strength and specificity of the relationships documented in the underlying studies.

The principal mechanism represented by each portfolio was subsequently determined from the risk-forming relationship most consistently supported by the evidence. This resulted in the identification of sequential propagation for the Western Himalayan portfolio, interaction and connectivity for the Western Ghats of Kerala portfolio, and cumulative stress and changing system condition for the Upper Bhima Basin. These assignments describe the risk-forming mechanism most strongly represented in the selected evidence and do not imply that other mechanisms are absent or that the three mechanisms are universally applicable.

2.5 Evidence interpretation and causal boundaries

A central methodological principle was to distinguish evidence-supported relationships from broader interpretation. Spatial association between hazards was not treated as proof of causal interaction or connectivity. Similarly, a sequence of events was not classified as a cascade without evidence supporting process transformation or a relevant triggering relationship [1–5].

Repeated disturbances were likewise not interpreted automatically as evidence of declining system capacity. For Type III systems, the analysis required evidence that previous stress or associated responses altered a relevant environmental, functional or human-system condition before interpreting subsequent risk as temporally dependent.

Climate-related and anthropogenic influences were also treated conservatively. The study does not undertake formal attribution of individual events to anthropogenic climate change. Climate-related influence was considered where the underlying evidence identified climatic variability, extreme conditions or persistent stress as relevant to the risk-forming relationship. Anthropogenic influence was considered where evidence supported a role for environmental modification, infrastructure, exposure, resource dependence, management or adaptation.

3. Results: Evidence for Constructing Mechanisms of Multi-Hazard Risk Formation

The comparative analysis identified three contrasting ways in which hazards, environmental conditions and consequences become connected across the selected evidence portfolios. The Western Himalayan evidence is characterised primarily by sequential propagation, the Western Ghats of Kerala evidence by interaction and connectivity, and the Upper Bhima Basin evidence by cumulative stress and changing system condition.

3.1 Western Himalaya: Sequential propagation

The Western Himalayan portfolio provides the clearest evidence of sequential propagation. The 2021 Chamoli disaster involved a large rock–ice avalanche followed by rapid downstream movement and transformation of the mobilised material. Reconstruction of the event indicates that the initial mass movement developed into a highly mobile flow that travelled through the valley system, producing extensive downstream impacts [7, 8].

The significance of this evidence lies in the connection between successive processes. The consequences were not confined to the initial failure location but developed as the mobilised material moved through and interacted with downstream terrain. The event therefore provides evidence of a process relationship in which an initiating disturbance is followed by transformation and propagation.

The wider Uttarakhand evidence provides additional context for susceptibility to rainfall-related slope failures. Studies of the June 2013 event identify extreme rainfall and landslide activity as important components of the disaster sequence [9, 10]. These studies provide environmental context but are not treated as evidence that rainfall caused the 2021 Chamoli event.

The portfolio therefore demonstrates a distinction between physical propagation of a hazardous process and human modification of exposure or susceptible pathways. The dominant relationship represented by the evidence is sequential propagation.

3.2 Western Ghats of Kerala: Interaction and connectivity

The Western Ghats of Kerala portfolio demonstrates a different configuration in which hazardous consequences emerge through interactions among environmental conditions and connected physical pathways [19, 20]. Evidence from the 2018 floods in Keralam, the Pamba River and the 2024 Wayanad debris-flow event provides complementary information on rainfall, hydrological behaviour, sediment mobilisation, slope processes and downstream transmission [14–16].

The 2024 Wayanad event provides particularly clear evidence of this relationship. The event followed intense rainfall and involved slope failure, mobilisation of debris, movement through the valley system and downstream geomorphic effects. The documented runout and channel-related behaviour demonstrate the importance of physical connectivity in determining how material and impacts were transmitted beyond the initial failure area [16].

Evidence from the Pamba River provides a complementary perspective on flood and sediment dynamics. The 2018 flood was associated with substantial changes in valley and river-bed conditions, illustrating the interaction between high-flow conditions and sediment processes [15]. Institutional work by the National Water Development Agency has additionally addressed flood forecasting and integrated reservoir operations in the Pamba Basin [17].

The 2018 Keralam landslide inventory also illustrates the importance of maintaining causal boundaries. The inventory provides spatial evidence for examining the relationship between landslide occurrence and land-use change, but does not support treating recent land-use change as a universal explanation for landslide occurrence [19, 20].

The evidence therefore demonstrates how environmental conditions can interact with connected landscape and hydrological pathways, while human development and management can influence exposure or pathway conditions in particular settings. The dominant relationship represented by the portfolio is interaction and connectivity.

3.3. Upper Bhima Basin: Cumulative stress and changing system condition

The Upper Bhima Basin provides evidence for a third form of risk-forming relationship in which previous or recurrent climatic stress interacts with resource conditions and human responses, thereby influencing the condition in which subsequent stress is experienced. In this portfolio, the multi-hazard dimension is understood more broadly as the interaction between recurrent climatic stress, water-resource stress and associated functional consequences rather than as a discrete sequence of multiple physical hazards.

The basin experiences substantial spatial and temporal variability in rainfall and water availability. Recent analysis based on 31 years of rainfall data (1991–2021) demonstrates pronounced seasonal and spatial variability, with particularly high variability during dry-season and transition months and

implications for water availability and agricultural planning [21]. The longer-term evidence also indicates recurrent drought conditions within the Upper Bhima Catchment, providing an important context for examining how successive climatic stress interacts with resource conditions [22].

Groundwater constitutes an important buffering resource in the Upper Bhima Catchment. Evidence from a village-level assessment shows that groundwater use expanded in drought-prone areas in association with recurrent drought, limited surface-water availability, improved drilling technology, institutional finance and electrification. The study surveyed 22 villages across different levels of irrigation dependence within the Upper Bhima Catchment and documented substantial differences in water availability between normal and drought years [22].

Importantly, the 2011–2012 drought provides a documented functional transition within this system. The drought that began in 2011 and deteriorated further in 2012 was associated with rapid declines in reservoir storage and groundwater levels, followed by failure of public water-supply systems. Most dug wells and borewells either dried up or yielded substantially less water, while 15 of the 22 surveyed villages reported drinking-water scarcity during the second consecutive drought year [22]. Affected communities increasingly relied on alternative surface-water sources and tanker deliveries [22].

This evidence provides a more specific temporal pathway than a simple drought–impact relationship:

The sequence demonstrates that prolonged or successive climatic stress can alter

environmental resource conditions and, in turn, the functional capacity of water-supply systems. It is therefore consistent with the interpretation of cumulative stress and changing system condition, while not implying a universal recovery deficit or a fixed groundwater threshold for system failure.

This buffering capacity is not independent of human demand and land-use change. Evidence from hydrological modelling of the Upper Bhima River Basin demonstrates substantial land-use change between 1992 and 2009, including an increase in built-up area from 2.6% to 7.3%. At sub-basin scale, increased urbanisation was strongly associated with increased surface runoff and reduced baseflow and percolation. The reported correlations were particularly strong for surface runoff ($R = 0.96$), baseflow ($R = -0.95$) and percolation ($R = -0.99$) [23].

The spatially heterogeneous response is also important for interpreting changing system condition. The same modelling study found that hydrological effects were substantially stronger at sub-basin scale than at the basin outlet, with surface-runoff changes reaching 13.6% and baseflow changes ranging from –29% to 1.7%. This indicates that the environmental condition inherited by subsequent climatic stress may differ considerably across locations within the basin [23].

Complementary modelling evidence indicates that adaptation under consecutive drought conditions can alter vulnerability, supporting the interpretation that responses to one period of stress may influence the condition from which subsequent drought is experienced [13]. However, this evidence is treated as modelled mechanism evidence rather than direct observation of all farmer responses. The analytical

significance of the Upper Bhima portfolio is therefore cumulative stress and changing system condition, rather than a conventional event-scale cascade.

3.4 Comparative Results

The three portfolios demonstrate that complex multi-hazard risk may be organised through different forms of connection. In the Western Himalaya, the evidence is centred on transformation and propagation from an initiating disturbance. In the Western Ghats of Kerala, it is centred on interactions among environmental conditions and connected physical pathways. In the Upper Bhima Basin, it is centred on the influence of previous stress and responses on subsequent system condition.

Table 1

Comparative evidence matrix linking the selected portfolios to dominant mechanisms and climate–anthropogenic pathways

Evidence portfolio	Principal mechanism represented	Principal relationship	Climate-related influence	Anthropogenic / human-system influence
Western Himalaya	Type I – Sequential propagation	Transformation and downstream propagation of processes	Rainfall and environmental conditions	Infrastructure, susceptibility and exposure
Western Ghats of Kerala	Type II – Interaction and connectivity	Interaction among environmental conditions and connected pathways	Extreme rainfall and hydrological forcing	Development, infrastructure, settlement exposure and management
Upper Bhima Basin	Type III - Cumulative stress and changing system condition	Previous stress and responses altering subsequent system condition	Climatic variability and recurrent drought	Groundwater dependence, resource management and adaptation

Table note

The portfolios are comparative evidence portfolios rather than statistically equivalent case studies. Climate-related and anthropogenic influences are reported only where supported by the underlying evidence; the table does not imply formal event attribution or quantitative estimates of causal contribution. The distinction is analytical rather than exclusive. Elements of connectivity may occur within a propagating event, while previous environmental or human-system conditions may influence both propagation and connectivity.

Overall, the results indicate that hazard co-occurrence alone provides an incomplete description of complex risk. The nature of the connection between processes, environmental conditions and consequences provides a more informative basis for distinguishing different forms of multi-hazard risk formation.

4. Climate-Anthropogenic Interactions in Multi-Hazard Risk Formation

Climate-related and anthropogenic influences affect multi-hazard risk through different components of environmental and human systems. Climatic conditions may contribute to triggering, antecedent conditioning, interaction or repeated stress, while human activities may modify environmental conditions, process pathways, exposure, resource dependence or adaptive capacity [6].

4.1 Climate-related influences

The role of climatic conditions differs across the three evidence portfolios. In the Western Himalaya, rainfall and other environmental conditions form part of the setting in which slope and mass-movement processes develop, while the Chamoli evidence primarily demonstrates the subsequent transformation and propagation of the initiating mass movement [7–10].

In the Western Ghats of Kerala, intense rainfall interacts with antecedent environmental, hydrological and geomorphological conditions. The Wayanad evidence demonstrates how rainfall-triggered slope failure developed into a debris-flow process with substantial downstream movement, while evidence from the Pamba Basin illustrates the interaction between high-flow conditions and sediment dynamics [15, 16].

In the Upper Bhima Basin, climatic influence is expressed differently through variability and recurrent drought. The effects of climatic stress depend partly on groundwater availability and agricultural water dependence, making the condition of the resource system important to subsequent responses [11–13].

These differences indicate that climate-related influence can operate through event-scale forcing, environmental conditioning or recurrent stress, depending on the system under consideration. The present study does not undertake formal attribution of individual events to anthropogenic climate change.

4.2 Anthropogenic influences

Anthropogenic influences likewise occur through different pathways. Human activities may modify environmental conditions, alter susceptible process pathways, increase exposure, affect resource availability, or change adaptive responses.

In the Western Himalaya, infrastructure development provides evidence of an anthropogenic influence on susceptibility and exposure. Along the Rishikesh–Joshimath highway, road widening was associated with an increased occurrence of road-blocking landslides after accounting for other explanatory factors [18]. This finding indicates that infrastructure development can influence risk in unstable terrain, but it does not establish that infrastructure development caused the Chamoli avalanche.

In the Western Ghats of Kerala, anthropogenic influence is similarly context-dependent. Analysis of the 2018 landslide inventory found that 50% of damaging landslides originated in forest plantations and 25%

in built-up areas, with many landslides in built-up areas occurring along cut slopes next to buildings. This provides evidence that human-modified terrain and settlement patterns can influence exposure and local slope conditions [19, 20]. However, the same analysis found that recent land-use and land-cover change between 2010 and 2018 was not the main contributing factor for most of the landslides [19, 20], indicating that land-use change should not be treated as a universal explanation for the 2018 disaster.

The Upper Bhima Basin provides more direct evidence of human-system influence on changing resource conditions. Groundwater development and agricultural dependence have increased the importance of groundwater as a buffer during climatic stress, while urbanisation and land-use change can modify hydrological pathways, including runoff, percolation and baseflow. Hydrological modelling shows that increased built-up area was strongly associated with increased surface runoff and reduced baseflow and percolation at sub-basin scale [23]. Under recurrent drought, resource use, management and adaptation therefore become part of the evolving system condition rather than merely external responses to hazard.

Across the three portfolios, anthropogenic influence is consequently better understood in terms of where human activities enter the risk pathway—through susceptibility, environmental or physical pathways, exposure, resource dependence or adaptation—rather than as a single causal category.

4.3 Governance and institutional capacity

Governance provides a further dimension through which climate-related and anthropogenic influences can affect risk. Planning, monitoring, infrastructure management, preparedness, resource allocation, institutional coordination and adaptation can shape the conditions under which hazards develop and consequences are experienced.

The evidence examined here does not support a general claim that governance failure caused any of the selected events. Instead, institutional arrangements are relevant to the management of risk pathways and to the capacity to anticipate and respond to changing conditions. In the Pamba Basin, the National Water Development Agency has addressed flood forecasting and integrated reservoir operations, providing an institutional example of anticipatory management within a connected hydrological system [17].

Governance is particularly relevant where the processes producing risk extend across administrative or sectoral boundaries. These observations indicate that institutional capacity should be considered alongside physical and environmental processes when interpreting multi-hazard risk, while avoiding unsupported attribution of particular disasters to governance failure.

4.4 Climate–anthropogenic interactions across the portfolios

The three portfolios demonstrate that climate-related and anthropogenic influences are neither uniformly additive nor independent. Their significance depends on the mechanism through which risk develops. In the Western Himalaya, climatic and environmental conditions contribute to a setting in which processes

can propagate, while infrastructure influences exposure and, in some contexts, susceptible pathways. In the Western Ghats of Kerala, climatic forcing interacts with environmental conditions and physical connectivity, while human development can influence exposure and pathway conditions in particular locations. In the Upper Bhima Basin, recurrent climatic stress interacts with groundwater dependence, resource management and adaptation, making human responses part of the changing system condition.

The Human–Climate Interface is therefore expressed through context-specific relationships between climatic conditions, environmental processes and human-system conditions.

5. Mechanism-Based Typology of Complex Multi-Hazard Risk Formation

The comparative evidence indicates that complex multi-hazard risk does not arise through a single form of relationship. Although the selected portfolios contain different hazards, the more important distinction concerns how one process, condition or system state becomes connected to another. On this basis, the selected evidence can be interpreted through three analytically distinct risk-forming mechanisms.

5.1 Type I – Sequential propagation

Sequential propagation occurs when an initiating disturbance is followed by successive physical processes through which the disturbance is transformed and its consequences extend beyond the initial source area. The defining characteristic is therefore a supported relationship between an initial process and subsequent process development.

The Western Himalayan evidence provides the principal example. At Chamoli, the initial rock–ice avalanche underwent rapid transformation as the mobilised material travelled downstream, producing a destructive flow and impacts well beyond the original failure location [7, 8]. The importance of the case lies in the documented physical sequence connecting the initiating mass movement with subsequent downstream processes.

Sequential propagation can therefore increase the spatial extent of consequences and create exposure in locations that are not necessarily close to the initiating disturbance. Its identification requires evidence of process transformation or propagation; temporal succession alone is insufficient.

5.2 Type II–Interaction and connectivity

Interaction and connectivity describe situations in which consequences depend on relationships among environmental conditions and the physical pathways through which processes, materials or impacts are transmitted. The defining feature is not necessarily a discrete process-to-process sequence, but the interaction of conditions within a connected system.

The Western Ghats of Kerala evidence illustrates this mechanism. Intense rainfall can act within a landscape characterised by particular terrain, hydrological and geomorphological conditions, while slope failures and debris mobilisation can transmit material through connected valleys and drainage pathways [15, 16].

The mechanism therefore draws attention to the spatial organisation of risk. The location of an initiating process alone may not indicate where consequences will occur if material or floodwaters can move through connected pathways.

5.3 Type III–Cumulative stress and changing system condition

Cumulative stress and changing system condition occur when previous or repeated stress alters the condition from which a subsequent disturbance is experienced. The defining feature is not simply recurrence, but evidence that earlier stress, resource depletion, environmental change or human response has influenced the subsequent system state.

The Upper Bhima Basin provides the principal evidence for this mechanism. Groundwater can buffer agricultural production against climatic variability, while groundwater use and management influence the availability of that buffering resource [11, 12]. Under repeated drought conditions, agricultural responses may also change as households adapt to earlier stress. Modelling of consecutive droughts in the Bhima Basin indicates that adaptation can produce different vulnerability outcomes across successive droughts [13].

The significance of this evidence is that subsequent drought does not necessarily occur against an unchanged baseline. Previous stress and responses may alter resource conditions, adaptive behaviour or system functioning. This does not imply that vulnerability must increase with every successive disturbance. The mechanism instead captures the condition in which the state of the system at one point in time influences its response to subsequent stress.

5.4 Distinguishing the mechanisms

The three mechanisms differ primarily in the relationship through which risk becomes connected. Sequential propagation is centred on transformation between successive processes; interaction and connectivity on relationships among conditions and connected pathways; and cumulative stress and changing system condition on changes in system condition between successive periods of stress. These distinctions are analytical rather than mutually exclusive, and a single environmental system may exhibit more than one mechanism.

Sequential propagation is identified where evidence supports a relationship in which an initiating disturbance is transformed into subsequent processes and its consequences extend beyond the initial source area. Interaction and connectivity is identified where risk depends on interactions among environmental conditions and on physical, hydrological or geomorphological pathways through which

processes, materials or impacts are transmitted. Cumulative stress and changing system condition is identified where previous or repeated stress, together with associated resource conditions or human responses, alters the system state from which subsequent stress is experienced.

The three mechanisms therefore provide different analytical perspectives on how multi-hazard risk becomes connected across processes, space and time. Their identification in the selected portfolios reflects the mechanism most strongly represented by the available evidence and should not be interpreted as a universal classification or as evidence that other mechanisms are absent.

6. Cross-Typology Synthesis

The comparison of the three evidence portfolios indicates that the typology identifies the risk-forming relationship most strongly represented by the evidence examined, rather than establishing mutually exclusive categories for environmental systems. The Western Himalayan evidence is dominated by transformation and propagation from an initiating disturbance, the Western Ghats of Kerala evidence by interactions among environmental conditions and connected pathways, and the Upper Bhima evidence by changes in system condition associated with previous or repeated stress.

The principal distinction is therefore not the number or type of hazards involved, but the relationship through which risk develops. In Type I systems, the connection is expressed through transformation from one process into subsequent processes. In Type II systems, the connection depends on interactions among conditions and the physical pathways through which materials or impacts are transmitted. In Type III systems, the connection extends through time, with previous stress and associated responses influencing the condition in which subsequent stress is experienced.

These dimensions may overlap within the same environmental system. A process may propagate through a connected landscape, while the susceptibility of that landscape may reflect conditions established before the event. Similarly, a system subjected to repeated stress may contain spatial pathways through which impacts are transmitted. The typology therefore identifies the dominant relationship represented by the evidence examined.

The comparison also demonstrates that climate-related and anthropogenic influences enter these mechanisms in different ways. In sequential propagation, climatic and environmental conditions may contribute to the setting in which an initiating process develops, while human infrastructure and settlement can determine where propagated consequences intersect with exposed elements. In interaction and connectivity, climatic forcing operates together with antecedent environmental conditions, while development and infrastructure can influence exposure and pathway conditions. In temporally dependent systems, recurrent climatic stress interacts with resource availability, human dependence and adaptation, potentially changing the condition from which subsequent stress is experienced.

This pathway-dependent interpretation provides a more cautious basis for discussing the Human–Climate Interface. Climate-related conditions cannot be assumed to have the same role across different multi-hazard systems, just as anthropogenic activity cannot be reduced to a single category of hazard causation.

7. Mechanism-Specific Anticipatory Risk Interpretation

The comparative analysis indicates that anticipating multi-hazard risk requires attention not only to the likelihood of individual hazards but also to the relationships through which risk develops. Because these relationships differ among the three mechanisms, the information needed to anticipate changing risk also differs.

For **Type I – Sequential propagation**, anticipation depends on recognising when an initiating disturbance may develop into subsequent processes and extend beyond its source area. In the Western Himalaya, the Chamoli evidence demonstrates how a large mass movement can transform into a rapidly propagating downstream flow [7, 8]. Anticipatory assessment in such settings therefore needs to consider the potential transformation of an observed disturbance and the pathways through which subsequent processes may travel.

For **Type II–interaction and connectivity**, anticipation requires greater attention to the combination of environmental conditions and the connections through which processes or impacts can be transmitted. The Wayanad evidence illustrates how intense rainfall, slope instability, debris mobilisation and valley connectivity contributed to downstream consequences [16]. Similarly, the Pamba evidence demonstrates the relevance of flood forecasting and integrated reservoir operations to the management of a connected hydrological system [17].

For **Type III–Cumulative stress and changing system condition**, anticipation requires information about the condition inherited from previous stress. In the Upper Bhima Basin, groundwater availability can provide buffering against climatic variability, while groundwater dependence, resource management and adaptation influence the conditions under which subsequent drought is experienced [11–13]. Anticipatory assessment therefore needs to consider not only the characteristics of an incoming drought but also the condition of the resource and human system before that drought occurs.

These differences suggest that anticipatory risk assessment should be **mechanism-sensitive**. For sequential propagation, information on process initiation, transformation and downstream pathways is particularly relevant. For interaction and connectivity, antecedent environmental conditions and physical or hydrological connections require greater attention. For Cumulative stress and changing system condition, previous stress, current system condition, resource buffering and adaptive responses become more important.

The governance implications follow from these differences. Sequential propagation places importance on monitoring, warning and preparedness along potential propagation pathways. Interaction and

connectivity require coordination across connected landscapes, catchments and infrastructure networks. Temporal dependence requires longer-term resource management and adaptive planning because decisions made during one period of stress may influence the condition of the system during subsequent periods.

The evidence therefore suggests that mechanism-specific anticipation can complement conventional early-warning and hazard-monitoring approaches. The relevant question is not simply whether a hazard threshold has been reached, but whether the conditions indicate that a risk-forming relationship is developing, propagating, interacting or changing through time.

Table 2
Analytical distinctions and information priorities associated with the three mechanisms

Mechanism	Defining relationship	Principal analytical emphasis	Representative portfolio	Information particularly relevant to anticipation
Type I – Sequential propagation	An initiating disturbance develops through successive processes	Process transformation and propagation	Western Himalaya	Initiation, transformation and downstream pathways
Type II – Interaction and connectivity	Interacting conditions influence processes within connected pathways	Spatial and system connectivity	Western Ghats of Kerala	Antecedent conditions, interacting processes and physical/hydrological connectivity
Type III – Cumulative stress and changing system condition	Previous or repeated stress alters subsequent system condition	System condition through time	Upper Bhima Basin	Previous stress, current system condition, resource buffering and adaptive responses

Table note

The mechanisms are analytical distinctions and may coexist within the same environmental system. The information requirements indicate priorities suggested by the comparative evidence rather than a universal monitoring protocol.

8. Discussion

8.1 What the typology adds

The comparative analysis indicates that hazard co-occurrence alone provides an incomplete account of complex multi-hazard risk formation. Although the selected portfolios contain different hazards, the more important distinction concerns how one process, condition or system state becomes connected to another. The selected evidence can therefore be interpreted through three analytically distinct risk-forming mechanisms: sequential propagation, interaction and connectivity, and cumulative stress and changing system condition. These mechanisms are analytically distinguishable but not mutually exclusive.

The analytical value of the comparison therefore lies in distinguishing the relationship through which risk develops rather than simply enumerating the hazards involved. A documented sequence of process transformation supports interpretation as sequential propagation, whereas jointly interacting environmental conditions and connected pathways indicate interaction and connectivity. Repeated stress may instead be better understood through temporal dependence, where previous stress and associated responses influence subsequent system condition. These mechanisms are analytically distinguishable but may coexist within the same environmental system.

8.2 Climate–anthropogenic interaction is mechanism-dependent

The comparative evidence indicates that climate-related and anthropogenic influences do not enter multi-hazard risk formation through a uniform pathway. Climatic conditions may contribute to triggering, antecedent conditioning, interaction among environmental processes or recurrent stress, whereas anthropogenic influences may modify environmental conditions, susceptibility, exposure, resource dependence or adaptive capacity. Their significance therefore depends on the particular risk-forming relationship within which they operate.

The selected portfolios illustrate this pathway dependence. In the Western Himalaya, climatic and cryospheric conditions form part of the environmental setting in which mass-movement processes develop, while infrastructure development can influence susceptibility and exposure in unstable terrain [18]. In the Western Ghats of Kerala, rainfall operates within particular geomorphological and hydrological conditions, while human-modified terrain and settlement patterns can influence exposure and local slope conditions. Evidence from the 2018 landslide inventory shows that built-up areas accounted for 25% of damaging landslides, while recent land-use change was not the main contributing factor for most landslide locations [19]. The 2024 Wayanad evidence further illustrates the importance of maintaining causal boundaries when interpreting individual events, because event occurrence and runout characteristics alone do not establish anthropogenic causation [16].

In the Upper Bhima Basin, recurrent climatic stress interacts with groundwater dependence, agricultural systems, resource management and adaptation, making resource conditions and human responses part of the changing system state [11–13].

This interpretation avoids treating climate change as a universal explanation for changing hazard risk or anthropogenic activity as a generic cause of environmental hazards. Instead, climate-related and anthropogenic influences are interpreted according to the specific component of the risk pathway they affect and the evidence available for that relationship.

8.3 Implications for anticipatory risk assessment

The contrasting mechanisms imply different information requirements for anticipatory risk assessment. A system characterised by sequential propagation requires attention to process initiation, transformation and downstream pathways. A system characterised by interaction and connectivity requires information on antecedent conditions and the physical or hydrological connections through which material, water or impacts may be transmitted. A temporally dependent system requires information on previous stress, current system condition, resource buffering and adaptive responses in addition to the characteristics of an incoming disturbance.

These distinctions do not imply that separate assessment systems are required for each mechanism. Rather, conventional hazard monitoring can be complemented by mechanism-sensitive information capable of identifying whether risk is developing through process transformation, interacting conditions and connectivity, or changes in system condition through time. This provides a more targeted basis for early interpretation and pre-event decision-making.

8.4 Governance, adaptation and anticipatory intelligence

Governance and adaptation influence risk not only through post-event response but also through the conditions under which risk pathways develop. Planning, infrastructure management, monitoring, preparedness, resource allocation, institutional coordination and adaptation can modify exposure, resource availability and response capacity. The evidence examined here does not support a general attribution of the selected disasters to governance failure. Rather, it indicates that institutional arrangements form part of the broader human-system context within which risk pathways develop and are managed.

This has particular relevance where risk-forming processes extend across administrative, physical or sectoral boundaries. Connected hydrological systems require coordination across catchments and infrastructure networks, while resource-dependent systems require longer-term management of resource availability and adaptive capacity. Governance and adaptation may therefore benefit from being aligned with the mechanism through which risk develops, supported by anticipatory intelligence that is appropriate to the relevant environmental and human-system context.

8.5 Limitations and scope

This study has several limitations. First, it is based on comparative evidence synthesis rather than a harmonised primary dataset, and the three portfolios differ in spatial scale, evidence availability and methodological approach. Second, the selected portfolios are illustrative rather than statistically representative of all multi-hazard systems. Third, the proposed mechanisms are analytically

distinguishable but not mutually exclusive, and individual systems may exhibit more than one mechanism. Fourth, the study does not undertake formal attribution of individual events to anthropogenic climate change or to specific human activities. Finally, the mechanisms have not been statistically validated as a predictive classification system.

Future research could test their transferability using harmonised event datasets, process-based modelling, remote-sensing observations and longitudinal information on system condition across additional environmental and hazard contexts.

8.6 Overall contribution

Taken together, the findings support a shift from asking which hazards occur together towards examining how risk becomes connected across processes, places and time. The three mechanisms provide a concise analytical language for distinguishing different forms of risk formation while retaining the environmental and human-system context of each evidence portfolio.

The framework also provides a more differentiated interpretation of climate–anthropogenic relationships by locating their significance within the pathways through which environmental processes, exposure, resource conditions and adaptive responses interact. It should therefore be understood as an evidence-informed comparative interpretation rather than a predictive model or universally validated classification. Its principal contribution is to connect the identification of risk-forming mechanisms with the information required for anticipatory assessment and risk-informed governance. By linking the mechanisms through which risk develops with the intelligence required to anticipate their consequences, this framework provides a basis for more context-sensitive and proactive multi-hazard risk governance.

9. Conclusion

This study examined complex multi-hazard risk through a comparative, evidence-based analysis of three contrasting Indian environmental and human-system contexts: the Western Himalaya, the Western Ghats of Kerala and the Upper Bhima Basin. Rather than treating the co-occurrence of hazards as sufficient to explain complex risk, the analysis focused on the relationships through which disturbances, environmental conditions and human-system conditions become connected.

Three analytically distinct risk-forming mechanisms were identified across the selected evidence portfolios. Type I—sequential propagation describes situations in which an initiating disturbance contributes to successive process transformations and cascading consequences. Type II—interaction and connectivity describes risk formation through interactions among environmental conditions and connected physical or hydrological pathways. Type III—cumulative stress and changing system condition describes situations in which previous or repeated stress and associated responses influence the system condition from which subsequent risk develops. These mechanisms are not mutually exclusive, and their identification reflects the mechanism most strongly represented in the selected evidence rather than a universally validated classification.

The comparison further indicates that climate-related and anthropogenic influences enter these risk-forming relationships through different pathways. Climatic variability, extreme conditions and persistent stress may contribute to triggering or conditioning processes, while human-system conditions may modify environmental settings, exposure, resource dependence, management and adaptive capacity. Their significance therefore depends on the mechanism and system context through which they influence risk rather than on a uniform climate or anthropogenic effect.

The principal contribution of the study is therefore an evidence-informed, mechanism-oriented framework that connects the interpretation of risk formation with the information required for anticipatory assessment and risk-informed governance. By distinguishing whether risk develops through process transformation, interaction and connectivity, or cumulative stress and changing system condition, the framework provides a basis for more context-sensitive interpretation of complex multi-hazard risk. It is intended as a comparative analytical framework rather than a predictive model or universally validated classification, and its transferability should be evaluated through future research using broader and more harmonised evidence.

Declarations

Ethics Approval

Not applicable.

Consent to Participate

Not applicable.

Consent for Publication

Not applicable.

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Competing Interests

The authors declare that they have no competing interests.

Author Contribution

N.T. contributed to conceptualisation, methodology, investigation, formal analysis, evidence synthesis, and writing of the original draft and editing. S.V. contributed technical methodological input, technical interpretation of the evidence, and manuscript review and editing. Both authors approved the final manuscript.

Data availability

No primary field data were collected for this study. The research uses published scientific literature and publicly available institutional information. All sources forming the evidence base are cited in the manuscript, and the analytical approach is described in the Methods section. Supplementary Table S1 provides the evidence inventory used in the comparative analysis.

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Footnotes

1. "In this manuscript, 'Keralam' is used for the state in accordance with the official renaming; 'Kerala' is retained where it forms part of the established title or terminology of cited sources, including references to the Western Ghats."

Figures

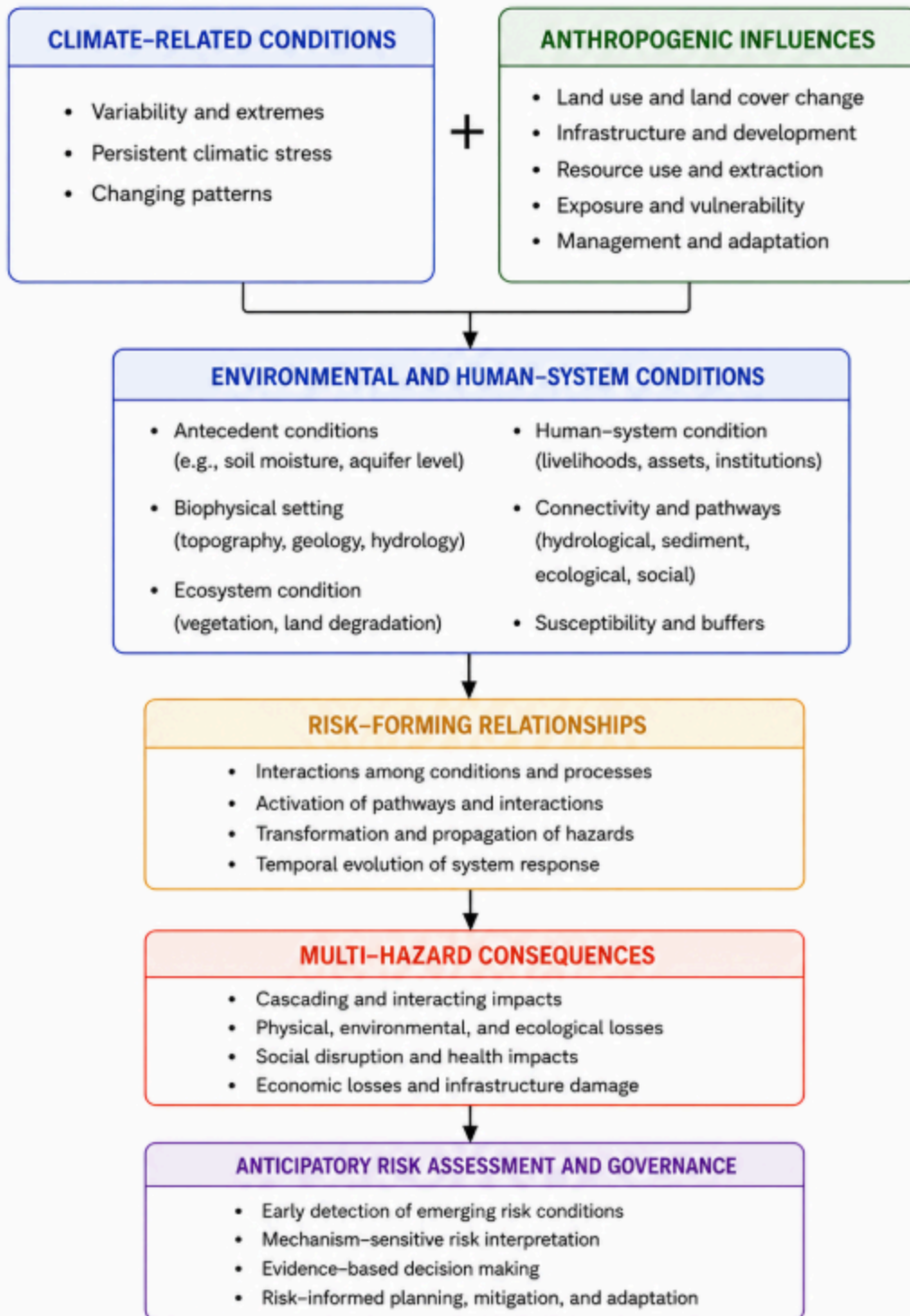


Figure 1

Climate–anthropogenic influences within multi-hazard risk formation

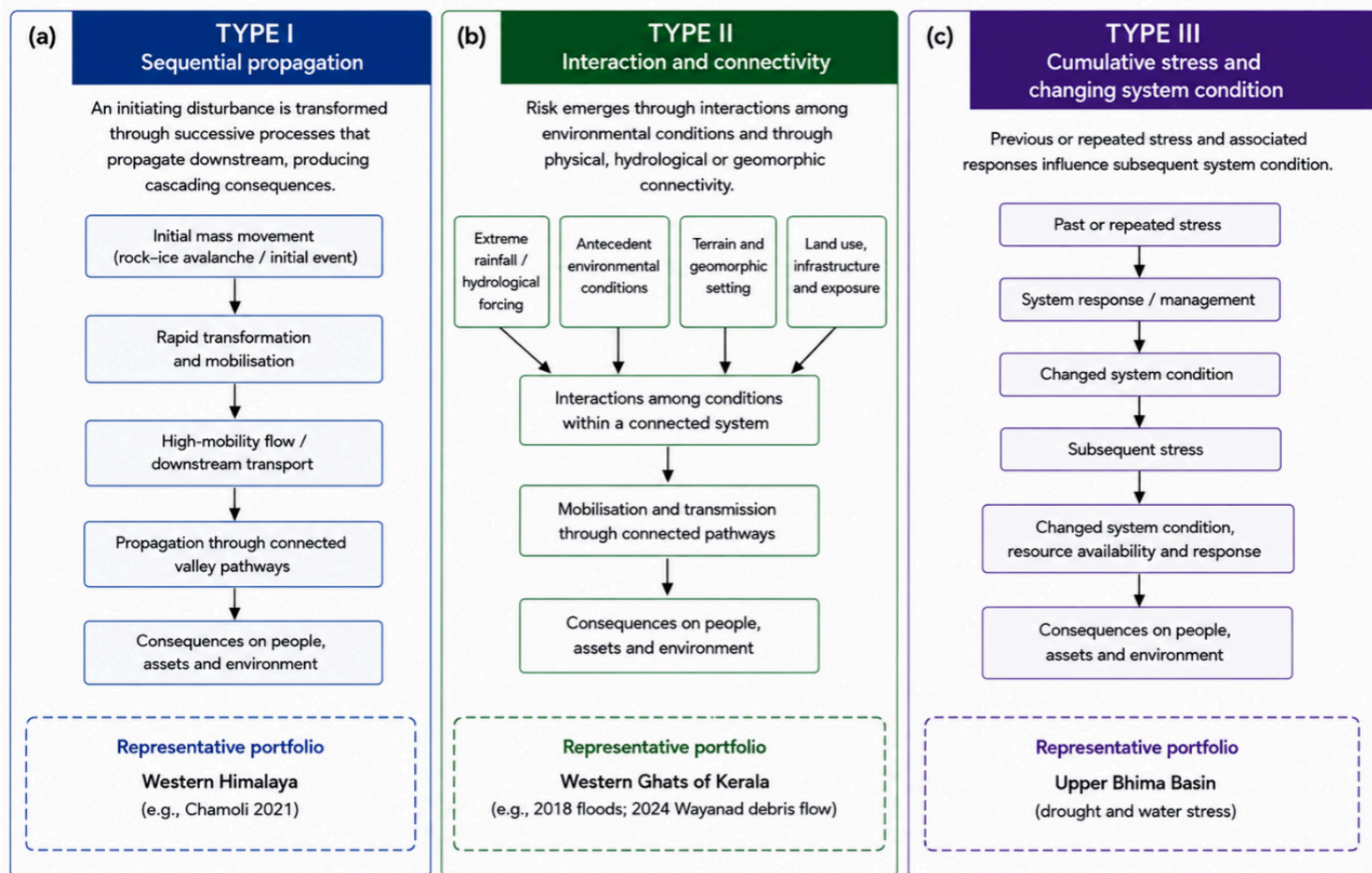


Figure 2

Three analytically distinct mechanisms of complex multi-hazard risk formation represented in the selected evidence portfolios.

Supplementary Files

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- [SupplementaryTableS1.xlsx](#)