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An extended hazard interaction matrix for exploring multi-hazard complexity in data-scarce regions: An application to Kerala, India

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Abstract. This paper extends the analysis of multi-hazard interrelationships beyond the primary focus on cascading and amplifying mechanisms, through the development of an evidence-based database in a data-scarce context. The methodology is applied to Kerala, India. To support interpretation, an adapted hazard interaction matrix was developed that extends existing frameworks by (i) incorporating a broader range of interaction mechanisms beyond traditional cascading and amplifying effects, and (ii) enabling representation of three-way hazard interactions, advancing beyond conventional pairwise depictions. The matrix was further enhanced to capture seasonal variation in interaction potential throughout the year. Drawing on academic literature, grey literature, and media sources, the database captures evidence for both well-documented and under-reported hazards and their interactions, whether historically observed or theoretically possible. The final database contains evidence of 22 distinct hazard types across six hazard groups and 137 potential hazard interrelationships. Results indicate that, while cascading and disposition-alteration mechanisms dominate the interrelationships observed in Kerala, accounting for additional interaction mechanisms increases the number of identified interrelationships by 36%. This suggests that restricting analyses to a limited subset of interaction types may not fully capture the region's multi-hazard complexity. The matrix was further enhanced to capture seasonal variation in interaction potential throughout the year. Incorporating seasonality reveals distinct temporal windows of elevated interaction potential shaped by monsoon rainfall and temperature variability. When applying seasonal filters, the number of potential interrelationships identified was reduced by approximately 6%. This study demonstrates that interaction-focused, seasonally informed frameworks can reveal multi-hazard dynamics that may otherwise be overlooked when analysing only a subset of hazard types and interaction mechanisms.

1 Introduction

Disasters rarely occur in isolation. Increasingly, societies are confronted with multiple hazards that interact in complex ways (de Ruiter and Van Loon, 2022), occurring simultaneously (Zscheischler et al., 2018), cascadingly (Marzocchi et al., 2009), and through other interaction mechanisms (De Angeli et al., 2022), producing impacts that exceed their individual effects

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(Gill et al., 2022). Recent events, such as the 2024 Noto Peninsula earthquake (Japan), illustrate how a single initiating hazard event can trigger a cascading sequence of events, in this case leading to fires, liquefaction, landslides and a tsunami (Suppasri et al., 2024). Broader global factors, such as climate change (Benevolenza and DeRigne, 2019), rapid urbanisation (Hossain et al., 2017), and socio-economic disparities (Wang et al., 2022), further contribute to this complexity by influencing hazard intensity and frequency (de Ruiter et al., 2020) or through changing the exposure and vulnerability of the population (Lv and Cao, 2024). Traditional single-hazard assessments often fail to capture these spatial and temporal dynamics (Jäger et al., 2025; Kappes et al., 2012; Ward et al., 2022), leading to an underrepresentation of hazard risk (Zscheischler et al., 2018).

Recognising this challenge, the Sendai Framework for Disaster Risk Reduction called for multi-hazard approaches to risk assessments in its midterm review (UNDRR, 2023a). In response, a range of frameworks have been proposed (Gill and Malamud, 2014; De Angeli et al., 2022; Hochrainer-Stigler et al., 2023; Kappes et al., 2012; Liu et al., 2015; Pescaroli and Alexander, 2018; Tilloy et al., 2019) that move away from the prevailing ‘multi-layer single-hazard’ perspective and recognise hazards as interconnected in order to capture hazard interaction complexity (Gill and Malamud, 2014; Ward et al., 2022; White et al., 2025). While such frameworks have significantly advanced the understanding of how hazards may interact, they often still have a limited scope, focusing on a subset of hazards, interaction mechanisms, or data-rich regions, and providing limited insight into the temporal dynamics of hazard interactions. These limitations are discussed in the following section, alongside how this study works towards addressing them.

1.1 Gaps in Multi-Hazard Research

1.1.1 Representation of Hazard Interactions

The terminology used to describe multi-hazard interactions has evolved unevenly over time, with no standardised definitions adopted across the literature. While initiatives, such as the review by the British Geological Survey (Ciurean et al., 2018) and the EU Myriad Project (Gill et al., 2022), have made progress in developing broader terminology, diversity within the literature continues to hinder comparison across studies and the building of cumulative knowledge (Ward et al., 2022; White et al., 2025). For example, a growing body of work on polycrisis examines how multiple shocks, including natural hazards, interact and propagate across interconnected systems. Although this literature overlaps conceptually with multi-hazard research, it has largely developed in parallel to hazard science and rarely uses the language of "multi-hazard" interactions, making it difficult to align concepts and methods across disciplines. Without clear, consistent terminology and methodological approaches, the complex interplay between hazards may be misrepresented, potentially leading to under- or over-estimation of risk that can affect disaster preparedness and response strategies.

There also remains a lack of detailed, holistic case studies that apply multi-hazard frameworks to complex real-world contexts (Ward et al., 2022). Current approaches tend to focus narrowly on a small number of hazard interrelationships or on a limited set of hazards or hazard groups, often overlooking the broader spectrum of possible interactions (Ciurean et al., 2018; De Angeli et al., 2022; Šakić Trogrlić et al., 2024). This narrow focus may be due to data availability constraints or to reduce complexity. For example, although Šakić Trogrlić et al. (2024) examine a wider range of hazards in Nairobi and Istanbul, their analysis focuses on cascading and amplifying interaction mechanisms, omitting parallel, cyclic and coincident triggering, and additional hazard potential mechanisms. This omission also means temporally coincident interactions and feedback processes are often not represented within a single integrated framework (Ward et al., 2022). Collectively, while the above studies make significant foundational contributions and advances to the literature, they remain oversimplified in terms of the multi-hazard environments and cumulative impacts they consider.

1.1.2 Geographical Imbalance

Multi-hazard research continues to focus disproportionately on regions with readily available hazard data, leaving hazard-prone areas with limited data underrepresented, particularly in the Global South (Delforge et al., 2025; UNDRR, 2022). Mahato et al. (2025) reviewed 62 studies addressing multi-hazard risk assessment and found that most were conducted in the Global North, with the UK (20%) and Italy (12%) accounting for a large proportion of cases. In contrast, lower-income countries, such as India and Nepal, each contributed only 4% of the reviewed studies whilst representing 19% of the world's population. Adil et al. (2025) argue that such gaps are rooted in structural inequalities in data generation. Monitoring infrastructure, such as meteorological (Adil et al., 2025), volcanic (Loughlin et al., 2015), and seismic (Ringler et al., 2022; Willemann and Storchak, 2001) stations, are disproportionately concentrated in high-income countries, while it is often in areas lacking warning systems where the greatest number of fatalities occur (Otto, 2023). Systematic impact reporting is also often fragmented across non-governmental organisations and poorly integrated into national systems (Adil et al., 2025; Osuteye et al., 2017). Osuteye et al. (2017) also note that these gaps are not only due to a lack of data, but also to uneven capacity to generate and standardise relevant data. Inconsistent methodologies across countries further distort global risk indices and undermine accurate representation of hazard risk in data-scarce settings (Adil et al., 2025). Recent work on open science emphasises that a limiting factor is often not the existence of data, but the absence of incentives or infrastructure for open sharing of data across systems (Zhang et al., 2024). Taken together, data scarcity often reflects constraints on how information is produced, managed, and shared, rather than a lack of observations. This lack of evidence complicates the capture of multi-hazard interactions using traditional data-driven methods.

Limitations in widely used hazard databases compound these challenges. Well-established databases, such as HANZE for floods (Paprotny et al., 2024) and DesInventar for multiple hazard types (UNDRR, 2024), are often structured around discrete hazard events rather than the interactions between hazards, and provide limited data on how hazards coincide spatially and temporally (Jäger et al., 2025). Notably, Jäger et al. (2025) demonstrated that within the internationally recognised EM-DAT database, approximately 35% of entries recorded as single-hazard events actually corresponded to multi-hazard events. Additionally, EM-DAT primarily records high-impact events, often overlooking smaller, recurrent hazards such as seasonal floods or localised landslides. These 'everyday' disasters occur far more frequently than large-scale events and can generate substantial cumulative impacts, yet they remain systematically underreported (Bull-Kamanga et al., 2003; IFRC, 2021; Osuteye et al., 2017), leaving gaps in our knowledge of how low-magnitude high-probability hazards interact. The omission of such events creates significant blind spots in understanding interacting hazards and hinders the development of robust multi-hazard models and evidence bases needed to inform disaster risk reduction strategies (Thompson et al., 2025; World Bank, 2021), particularly in regions with limited data availability.

1.1.3 Temporal Dynamics of Multi-Hazard Interactions

Temporal dynamics play a critical role in shaping impacts within a multi-hazard environment. When two or more hazards coincide within the same temporal window, whether over short time scales (e.g. hours to weeks) or longer seasonal or annual periods, their combined impacts can differ significantly from those of individual hazards considered in isolation. This characteristic is central to the concept of compound events, which are defined by the joint occurrence or sequencing of multiple drivers or hazards that together influence risk (Zscheischler et al., 2020). In such cases, impacts may be amplified by the overlap of impacts from different hazards and by the limited time between events, which strain recovery processes (De Angeli et al., 2022; Mohammadi et al., 2024).

Interactions that occur simultaneously or within the same event timeframe are comparatively well documented (Hillier and Dixon, 2020), particularly within compound-hazard and climate-risk literature. For example, Catto and Dowdy (2021) examine the co-occurrence of meteorological hazards, such as extreme wind and rainfall, linked to the same weather system across different seasons. To support the consistent analysis of such events, Zscheischler et al. (2020) formalised a typology of compound events, including multivariate, temporally compounding, and preconditioned events, a framework that has since been widely adopted (Bevacqua et al., 2021; Brett et al., 2025). The developments reflect growing methodological standardisation for analysing short-timescale, temporally coincident hazard interactions.

In contrast, longer-term and seasonal multi-hazard interactions remain comparatively understudied, particularly when hazards are linked through shared environmental preconditioning rather than through direct temporal overlap. Environmental preconditioning describes situations in which antecedent conditions created by prior hazards or climatic states, such as prolonged rainfall leading to soil saturation, modify the likelihood or severity of subsequent hazards over days to months without direct triggering (Bevacqua et al., 2021; Zscheischler et al., 2020). Within multi-hazard frameworks, such processes correspond to influential relationships, in which one hazard alters the conditions under which another may occur without initiating it directly (Gill et al., 2022). While this concept is well established theoretically, studies examining lagged interactions between different hazard types, as well as recovery rates between events, remain limited (Hillier and Dixon, 2020). Reviews over these longer time scales tend to focus on pairwise extremes of single variables, such as temperature (Bieli et al., 2015) or precipitation (Ye et al., 2017), rather than on interactions between distinct hazard types. As a result, many multi-hazard assessments rely on temporally static representations that overlook seasonal and lagged dynamics between hazard interactions, potentially underestimating recurrent hazard combinations that drive long-term vulnerability.

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1.2 Aims of the Paper

In response to these challenges, this paper has three specific aims:

1. Develop a single- and multi-hazard database for Kerala, a hazard-prone region with limited data availability, using the methodology of Gill et al. (2020) to document individual hazards and their interactions across evidence sources, capturing both well-documented and underreported hazards
2. Advance the visualisation of multi-hazard interrelationships by adapting the hazard interaction matrix developed by Gill and Malamud (2014) to integrate the six hazard interaction mechanisms outlined by De Angeli et al. (2022), thereby representing a broader range of multi-hazard interactions in Kerala
3. Adapt the hazard matrix to illustrate the temporal dynamics of hazard interactions in Kerala, focusing on how hazard seasonality shapes the region's multi-hazard environment and when multi-hazard interactions have an increased occurrence potential

Overall, this study aims to explore how existing multi-hazard frameworks can be extended to integrate multiple interaction mechanisms and temporal dynamics to represent hazard interaction complexity in a data-scarce environment.

This paper is organised as follows. **Section 2** introduces the case-study region of Kerala, India. **Section 3** outlines the methodology used to develop a multi-hazard profile for Kerala and assess hazard interactions and seasonality. **Section 4** presents the results for single hazards, multi-hazard interrelationships, and their temporal dynamics. **Section 5** discusses the implications of building a multi-hazard profile, including interaction mechanisms to consider and the role of seasonality. Concluding remarks are provided in **Section 6**.

2 Kerala

Kerala is situated in southwest India, bordered by the Arabian Sea to the west and the mountainous Western Ghats to the east (KSDMA, 2016), as shown in **Figure 1**. The state has a total estimated population of 35 million and one of the highest population densities in India, at 860 persons km^{-2}. It can be divided into three topographic zones: highlands (>600 m), midlands (20 – 600 m), and coastal plains (<20 m) (Kumar and Jayalakshmi, 2016). Forests cover approximately 29% of the state (KSDMA, 2016). Kerala has a humid climate and is subject to two annual monsoons: the Southwest Monsoon season (June – September) and the Northeast Monsoon season (October – November). This results in higher inter- and intra-annual variability in rainfall (Mohapatra et al., 2025), with approximately 120-140 rainy days per year (Singh et al., 2025). In contrast, rainfall is less frequent during the winter months (December – February) and pre-monsoon summer period (March – May) (Mini et al., 2016). These climatic and topographic conditions shape the range of hazards observed across Kerala (KSDMA, 2016) and, in

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turn, the interactions that may occur between them.

Figure 1. *Map showing the location of Kerala, India, displaying boundaries for 14 districts (grey lines), selected major rivers (blue lines), and relief (green shading). Administrative boundaries are derived from the Database of Global Administrative Areas v4.1 (GADM, n.d.); elevation data from the USGS Shuttle Radar Topography Mission 1 Arc-Second Global dataset (Earth Resources Observation and Science Center, 2019); Waterways: © OpenStreetMap contributors via HOTSOM India Waterways export (Humanitarian OpenStreetMap Team, 2024)*

India frequently ranks among the most affected countries in the Global Climate Risk Index, recording over 400 events between 1993 and 2022, resulting in estimated losses of approximately USD 180 billion and at least 80,000 fatalities (Adil et al., 2025). Prominent recent events affecting Kerala include the 2004 Indian Ocean tsunami (Chadha et al., 2005), the 2018 floods and landslides (Wadhawan et al., 2020), and Cyclone Tauktae in 2021 (Ratnakaran and Abish, 2023). Although often characterised as single hazards, these events are better understood as multi-hazard events. For example, intense seasonal monsoon rainfall in 2018 triggered simultaneous flooding and landslides (Parthasarathy et al., 2021), while Cyclone Tauktae also triggered extensive coastal flooding (Ramakrishnan et al., 2022). These examples underscore Kerala's exposure to multiple interacting hazards and the importance of understanding how such interactions shape the state's multi-hazard environment.

Despite this high level of hazard exposure, documentation of interacting hazards in Kerala remains limited, particularly for smaller-scale events that are rarely captured in official disaster databases. National datasets, such as the National Database for Emergency Management (NRSC, 2019), provide only partial coverage, primarily capturing high-impact events in actively monitored areas, while smaller or unmonitored hazards, such as fog, are often absent. Kerala also exemplifies broader inequities in hazard-monitoring capacity. During the 2018 floods, meteorological observation infrastructure in the state was limited; KSDMA reports that the Indian Meteorological Department (IMD) operated only 15 automated weather stations in Kerala in 2019, of which only six were functional, while the Bureau of Indian Standards (BIS) indicated that 256 weather stations were required for adequate disaster management coverage in the state (KSDMA, 2025).

Overall, Kerala exemplifies a high-hazard environment in which diverse hazard types interact in complex ways, yet where formal hazard data remain limited. These constraints support the use of a blended-evidence approach that draws not only on conventional datasets but also on supplementary evidence and structure inference to identify hazard interactions. More broadly, Kerala provides a useful case study for exploring how interaction-focused

3 Methodology

This paper aims to enhance understanding of the full spectrum of potential hazard interrelationships in Kerala. To achieve this, the study builds on an established global matrix of possible hazard interactions (**Section 3.1**) and compiles a database of evidence assessing whether these interactions can occur (**Section 3.2**). Hazards are classified by season of occurrence (**Section 3.3**), and identified interactions are assigned to their respective interaction mechanisms. The hazard interaction matrix is then modified to reflect both the identified interrelationships and their temporal dynamics (**Section 3.4**), thereby helping to explore the complexity of hazard interaction in Kerala.

3.1 Single-Hazard and Multi-Hazard Interrelationships Included

The primary objective of this phase was to identify and compile evidence for both individual hazard events and interactions between hazards, focusing on those that have occurred in Kerala, have been observed regionally, or are theoretically possible but have not been evidenced locally. This includes both historical records and plausible modelled or hypothetical scenarios.

The focus is primarily on natural hazards, as defined by the 2025 UNDRR Hazard Information Profiles (HIPs) (UNDRR and ISC, 2025), excluding technological, environmental, and biological hazards unless they are directly linked to natural processes. The hazards initially included in the search were drawn from the Gill and Malamud (2014) hazard classification framework, which categorises hazards into six major groups: geophysical, hydrological, shallow Earth processes, atmospheric, biophysical, and space hazards. The inclusion of fog and urban fires, following Šakić Trogrlić et al. (2024), was deemed relevant for Kerala. For example, fog hampered rescue efforts during the 2024 Wayanad landslide event (Varma, 2024), and over 150 urban fires were recorded in 2025 between April and May (Bureau, 2025). Coastal erosion is included as an additional hazard in this study, given its significance in Kerala, as recognised by the Kerala State Disaster Management Authority (KSDMA); for example, recent tropical cyclone events have been associated with coastal erosion impacts (Pradeep et al., 2022). Snow avalanches and snowstorms were not found to be a plausible risk in Kerala due to the region's topographic and climatic conditions and were therefore excluded, leaving 22 hazards considered relevant to Kerala.

Building on the identification of single hazards affecting Kerala, the global hazard interaction matrix developed by Gill and Malamud (2014) was used to consider all potential interactions between hazards. These interrelationships were assessed using both direct evidence and inferred or modelled linkages where data were limited. Given the absence of standardised terminology within the multi-hazard literature, this study adopts the classification system developed by De Angeli et al. (2022), which identifies six mechanisms of hazard interaction: parallel, cascading, disposition alteration, additional hazard potential, coincident triggering, and cyclic triggering, as shown in **Figure 2**. Given the exploratory nature of the framework and the limited evidence base in Kerala, the study focused on mechanisms that help explain how hazards may intensify, propagate, or compound adverse consequences. Consequently, simultaneous (hazards occurring at the same time but with unrelated processes) and alleviation (one hazard reduces the intensity of another) mechanisms, as noted in the EU MYRIAD project (Gill et al., 2022), are included in **Figure 2**, but are excluded from this study. These exclusions reflect a scoping choice rather than indicating that simultaneous or alleviation mechanisms are absent in Kerala.

3.2 Evidence Search

The search strategy was built upon the foundational work by Gill et al. (2020) in Guatemala and incorporated recent advancements by Šakić Trogrlić et al. (2024) and Thompson et al. (2025), who applied similar approaches to multi-hazard database development in data-scarce urban contexts such as Nairobi, Istanbul, and the Kathmandu Valley. The methodology of using blended sources of evidence was adapted to suit data availability in Kerala, including adjustments to evidence sources, publication dates, and keywords searched. The evidence sources included academic literature, grey literature, media sources such as online newspapers, and social media. These are presented in **Table 1** in order of priority, reflecting their relative reliability and level of detail. Academic databases such as Web of Science and Google Scholar were searched first, as they provide high-quality, peer-reviewed evidence. Media and social media sources were examined last, as they are typically less detailed and less reliable than other sources, but they can capture small-scale events that may be overlooked elsewhere (Taylor et al., 2015).

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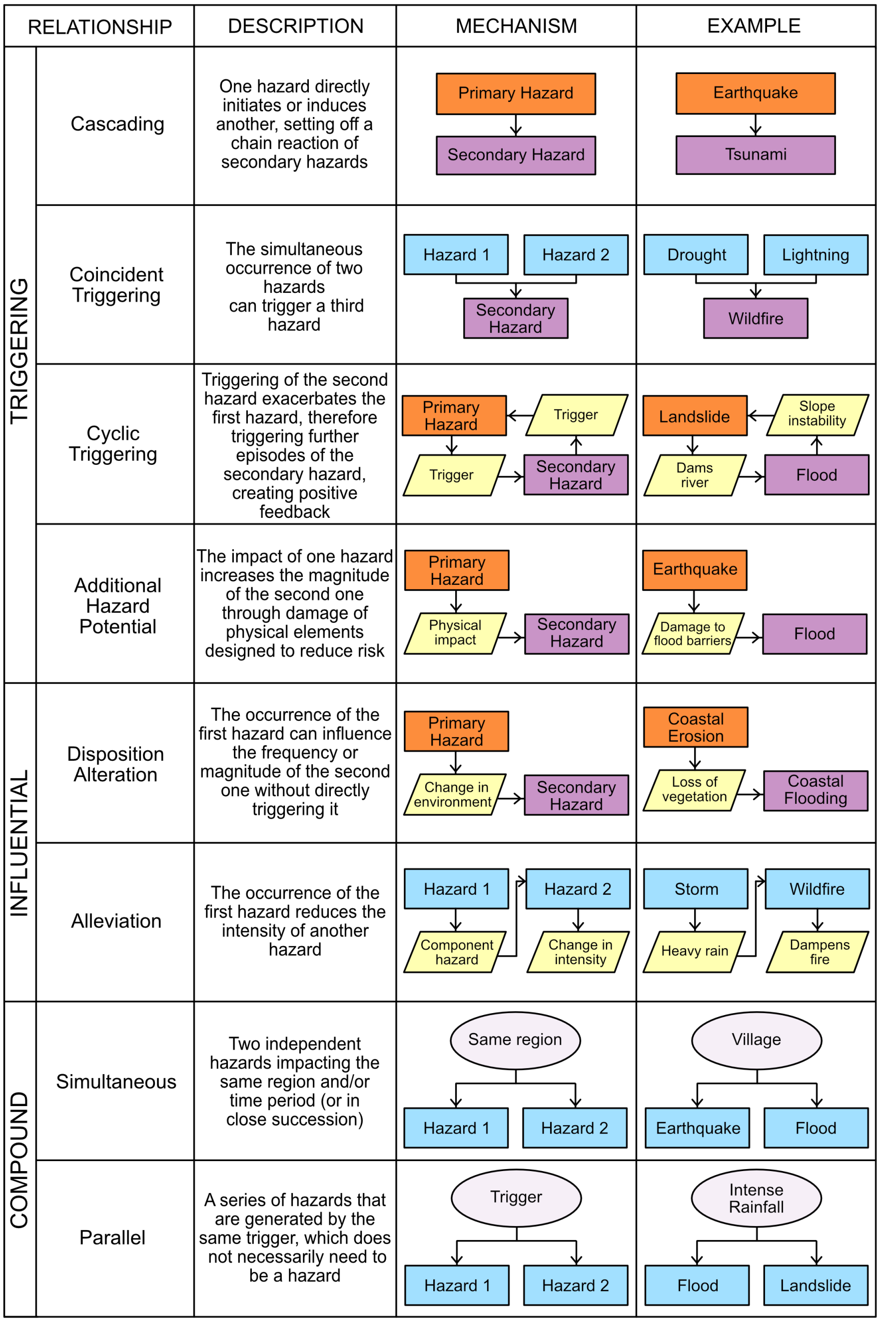

RELATIONSHIP		DESCRIPTION	MECHANISM	EXAMPLE
TRIGGERING	Cascading	One hazard directly initiates or induces another, setting off a chain reaction of secondary hazards	Primary Hazard Secondary Hazard	Earthquake Tsunami
	Coincident Triggering	The simultaneous occurrence of two hazards can trigger a third hazard	Hazard 1 Hazard 2 Secondary Hazard	Drought Lightning Wildfire
	Cyclic Triggering	Triggering of the second hazard exacerbates the first hazard, therefore triggering further episodes of the secondary hazard, creating positive feedback	Primary Hazard Trigger Trigger Secondary Hazard	Landslide Slope instability Dams river Flood
	Additional Hazard Potential	The impact of one hazard increases the magnitude of the second one through damage of physical elements designed to reduce risk	Primary Hazard Physical impact Secondary Hazard	Earthquake Damage to flood barriers Flood
INFLUENTIAL	Disposition Alteration	The occurrence of the first hazard can influence the frequency or magnitude of the second one without directly triggering it	Primary Hazard Change in environment Secondary Hazard	Coastal Erosion Loss of vegetation Coastal Flooding
	Alleviation	The occurrence of the first hazard reduces the intensity of another hazard	Hazard 1 Hazard 2 Component hazard Change in intensity	Storm Wildfire Heavy rain Dampens fire
COMPOUND	Simultaneous	Two independent hazards impacting the same region and/or time period (or in close succession)	Same region Hazard 1 Hazard 2	Village Earthquake Flood
	Parallel	A series of hazards that are generated by the same trigger, which does not necessarily need to be a hazard	Trigger Hazard 1 Hazard 2	Intense Rainfall Flood Landslide

Figure 2. *Conceptual classification of hazard interaction mechanisms drawing on the framework developed by De Angeli et al. (2022) and Gill et al. (2022) The figure illustrates the key components of eight commonly observed interaction mechanisms, which are subtypes of the three main interaction categories: Triggering, Influential and Compound. This conceptual diagram is accompanied by illustrative examples for each mechanism. Hazard labels and colours are used to distinguish between mechanisms with temporal ordering (primary (orange) and secondary (purple)) and those without (hazard 1 and hazard 2 (blue)). This figure has been modified from (De Angeli et al., 2022)*

Table 1. *Evidence categories used to compile the multi-hazard database for Kerala, including definitions and example sources. Categories are ordered by priority based on their reliability and level of detail for documenting hazard events.*

Evidence Category	**Definition**	**Examples**
Academic literature	Peer-reviewed research publications	Journal articles found on Web of Science or Google Scholar
Grey literature	Non-peer-reviewed material, including reports from government bodies, intergovernmental NGOs, hazard databases, and presentations	Kerala State Disaster Management Authority, Kerala Museum, UNDRR Prevention Web, National Disaster Management Authority (India), EM-DAT
Media	Content published in online newspapers, as well as other digital sources such as television broadcaster websites and blogs	The Hindustan Times, Onmanorama, The Times of India, New Indian Express, The Hindu, Down to Earth, Kerala Kaumudi, Asia Times, Economic Times, Live Mint
Social Media	Websites and applications that enable users to create and share content	YouTube, Instagram

Boolean strings were developed to locate specific hazards and multi-hazard interactions across evidence sources listed in Table 3.1. For single hazards, initial searches used strings such as “Landslide” AND “Kerala”. For multi-hazard interrelationships, both hazards were included in the search query, for example, “Flood” AND “Landslide” AND “Kerala”. If no relevant results were returned, the search was expanded to include proxy indicators, such as “temperature rise” for heatwaves or “unusually cold weather” for cold waves. Proxy indicators were based on plain-language terminology commonly used to describe natural hazards.

Keyword specificity was adjusted based on initial search results; for example, the term “waterspout” was used instead of “tornado”, reflecting the terminology and phenomena observed in Kerala. For hazards with no documented history of occurrence in Kerala but with theoretical potential to occur, such as geomagnetic storms, the search strategy was adapted to include global literature to assess possible regional implications. Unlike single-hazard searches, locating evidence of multi-hazard interactions presented additional challenges. Conventional keyword searches often yielded few relevant results. To address this, more technical terms, such as “soil piping” for ground collapse, and event-specific queries were incorporated to broaden the scope and improve search precision. The compiled hazard database (see **Supplementary Material A**) contains a complete list of search terms, along with the corresponding evidence sources for each individual hazard and potential interaction.

To maintain feasibility and balanced coverage across hazards, in line with the exploratory focus of the study in a data-scarce setting, the number of sources reviewed for each hazard was limited. Queries that yielded more than 10 documents were screened for spatial and temporal relevance using titles and abstracts. Up to five of the most relevant sources were selected for

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each hazard to identify documented instances of single-hazard occurrence, based on their representativeness and relevance to Kerala, and their usefulness for assessing interaction potential. Priority was given to documents published between 2000 and 2025 to reflect current hazard dynamics.

3.3 Hazard Seasonality Filtering

Sources selected as evidence for each individual hazard were also scanned for information on the season or months during which the hazard was likely to occur or had occurred before. If no such information was provided in the selected documents, an additional evidence search was undertaken using Boolean strings, such as “Landslide” AND “Kerala” AND “Season”. Up to three sources of evidence were selected for each hazard, where relevant, to obtain a general understanding of when these hazards are most likely to occur within a year.

Hazards were then assigned a broad seasonal occurrence window based on the available evidence, using either specific months or broader seasonal periods when month-level information was unavailable. Where sources provided inconsistent or broad timing estimates, the widest possible window was retained to avoid excluding valid interactions on the basis of limited evidence. Hazards that may occur throughout the year were excluded from the seasonality search; for example, earthquakes have no direct or indirect link to atmospheric processes. This resulted in 16 hazards classified as seasonal. Seasonal classifications were subsequently used to identify periods of temporal overlap between hazards, allowing potential seasonal multi-hazard interactions to be inferred.

3.4 Multi-Hazard Database and Matrix Visualisation

The compiled evidence is organised in the Kerala Multi-Hazard Interrelationship Database (see **Supplementary Material A**). Each entry represents a documented or theoretical potential for a single hazard or a multi-hazard interaction, along with associated metadata. Where evidence permitted, entries in the database also record relevant anthropogenic drivers, such as land-use change or infrastructure characteristics, as contextual metadata to reflect human influences on hazard occurrence and interaction potential.

The compiled interactions are organised into an updated hazard interaction matrix, adapted from the original 21 x 21 grid proposed by Gill and Malamud (2014). For this study, a 24 x 24 grid is used to account for the additional hazards of fog, urban fires, and coastal erosion. The original matrix developed by Gill and Malamud (2014) represented only cascading and amplifying hazard interactions. In this study, the matrix is further modified to represent six interaction mechanisms (De Angeli et al., 2022) by subdividing each grid cell into sections for each interaction type. Visual symbols are used to distinguish between hazard interactions supported by case-study evidence and those that are theoretical or inferred, thereby allowing uncertainty to be communicated within the visualisation. The updated matrix also extends beyond pairwise relationships by allowing a third hazard code to be entered within a grid cell, representing three-way interactions, such as drought and lightning coinciding to trigger a wildfire.

To represent hazard seasonality, the matrix is rearranged again into a 24 x 12 grid, with rows corresponding to individual hazard types and columns representing calendar months. The matrix begins in June, reflecting the onset of the southwest monsoon. Colour gradients represent uncertainty in seasonal timing, based on variability in reported occurrences and limitations in available evidence, with darker shading indicating greater confidence in reported seasonality. Patterned cells indicate hazards that have no seasonal variation.

4 Results

4.1 Kerala Single Hazards and Multi-Hazard Interactions

Drawing on 48 sources of evidence, 22 distinct hazard types were identified as occurring in, or having the potential to occur in, Kerala. Of these sources, around 60% were comprised of direct case-study evidence, as summarised in **Figure 3a**. These findings demonstrate the breadth of natural hazards affecting Kerala, spanning all six hazard groups defined in the Gill and Malamud (2014) classification framework. Around two-thirds of the evidence for these 22 hazard types derives from academic literature published between 2010 and 2025. Older sources were used for rare events such as tsunamis (Chadha et al., 2005) and for global-scale hazards that may indirectly affect Kerala, such as volcanic eruptions (e.g. Mount Pinatubo; (Jeyaseelan and Thiruvengadachari, 1993)).

Hazards with frequent recurrence, particularly floods and landslides linked to the southwest monsoon, were consistently documented and described in greater detail. Similarly, large-scale events of global significance, such as the 2004 Indian Ocean tsunami, received substantial coverage. In contrast, evidence for less frequent or lower impact hazards was limited, with some hazards identified only as theoretically possible (e.g. impact events). Other hazards, such as urban fires and tornadoes, were primarily documented in local sources, including newspaper articles and social media posts, as shown in **Figure 3b**. These hazards tended to be small-scale events that were underrepresented in academic literature.

Drawing on single-hazard evidence and incorporating additional sources where required, 137 potential multi-hazard interrelationships were identified for Kerala. Of these, 59 were supported by direct case-study evidence, highlighting the relative difficulty of identifying observed evidence for multi-hazard interactions compared with single-hazards. The remaining interactions were supported by inferred or model-based evidence, reflecting data limitations rather than the absence of interaction potential. **Figure 4** also indicates a more blended evidence base for multi-hazard interrelationships, with media sources contributing approximately one-third of the evidence, compared with a much smaller contribution for single-hazard types.

Figure 5 illustrates the distribution of interrelationships across all six interaction mechanisms. While disposition alteration and cascading mechanisms were the most commonly occurring in Kerala, the remaining mechanisms together accounted for

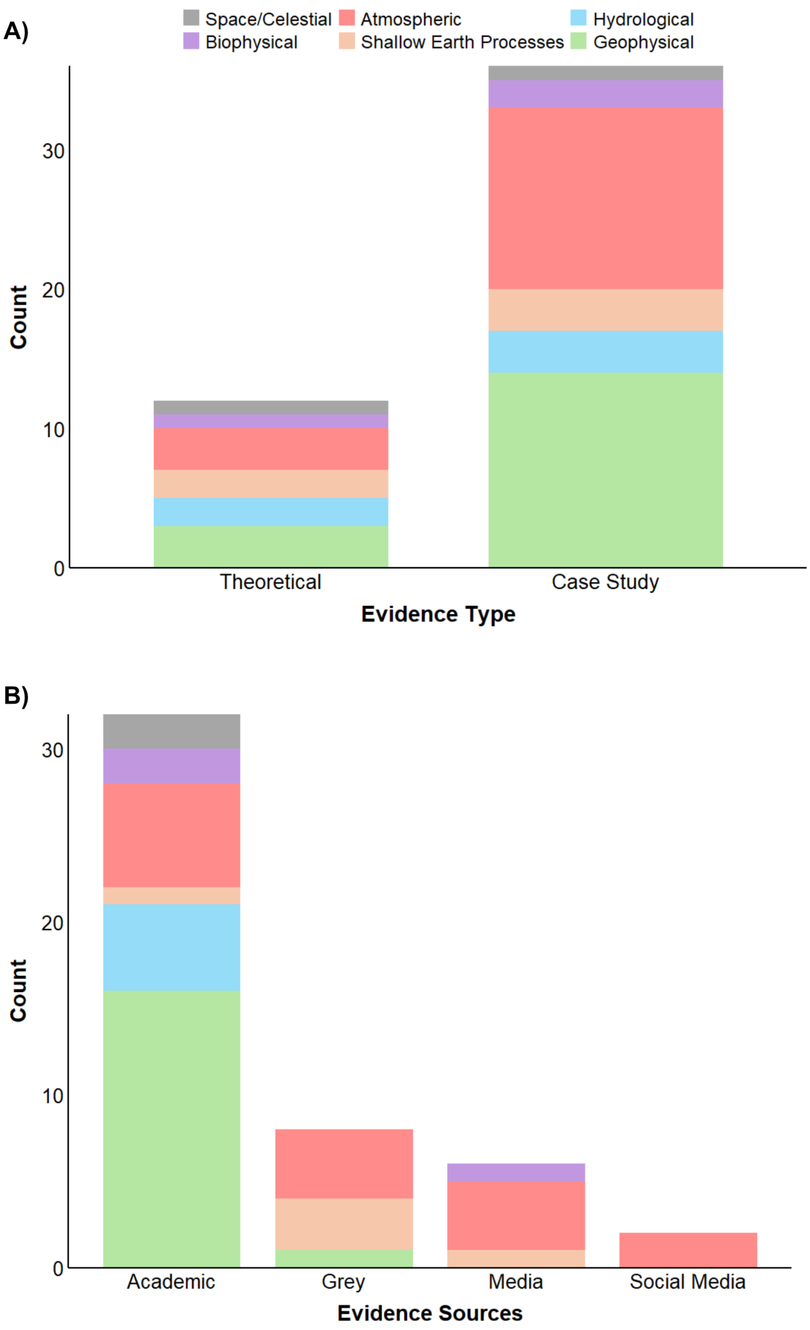

Figure 3. *Distribution of single hazards identified for Kerala, characterised by hazard classifications from Gill and Malamud (2014) Graph A compares single-hazards documented through direct case-study evidence with those identified as theoretical, showing that the majority of evidence for single-hazards is attributable to historical occurrences. Graph B presents the contribution of different evidence sources outlined in Table 3.1 to the identification of single hazards in Kerala. Counts are based on evidence-source entries rather than unique hazards; therefore, when a single hazard was supported by multiple source types, it was counted once within each relevant source category.*

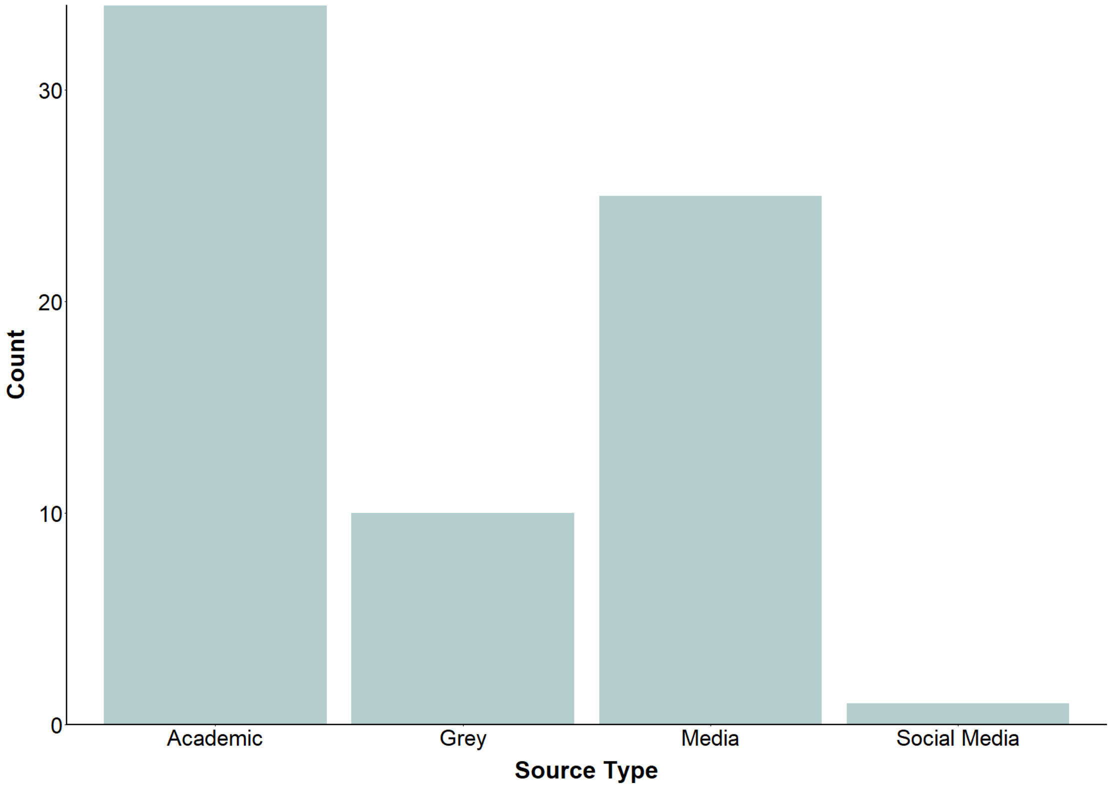

Figure 4. *Distribution of evidence sources used to identify multi-hazard interrelationships in Kerala. The graph shows the number of documented interactions by academic literature, grey literature, media sources, and social media, highlighting the relative contributions of different evidence sources. This figure demonstrates the reliance on media sources for evidence, compared with considering single-hazards, and the use of a more blended evidence source that reflects data limitations when searching for multi-hazard interrelationships.*

26% of all interrelationships. **Figure 6a** shows the distribution of connections from hazard 1 to hazard 2 across the identified interrelationships. Floods (16 links), storms (14 links), and earthquakes (13 links) are the most highly connected hazards, together accounting for 32% of all identified links. In contrast, the hazards most frequently identified as hazard two outcomes (**Figure 6b**) are landslides (26 links), floods (23 links), and urban fires (18 links), which together account for 50% of all links. This highlights the relative sensitivity of different hazards in Kerala in terms of their potential to interact with other hazards. It also shows that restricting analyses to cascading and disposition alteration mechanisms significantly changes the apparent role of certain hazards. For example, tornadoes would exhibit no primary connections, as their interactions are predominantly characterised by parallel mechanisms. On the other hand, storms are primarily characterised by cascading and disposition alteration mechanisms, showing their role in influencing hazard potential within the region.

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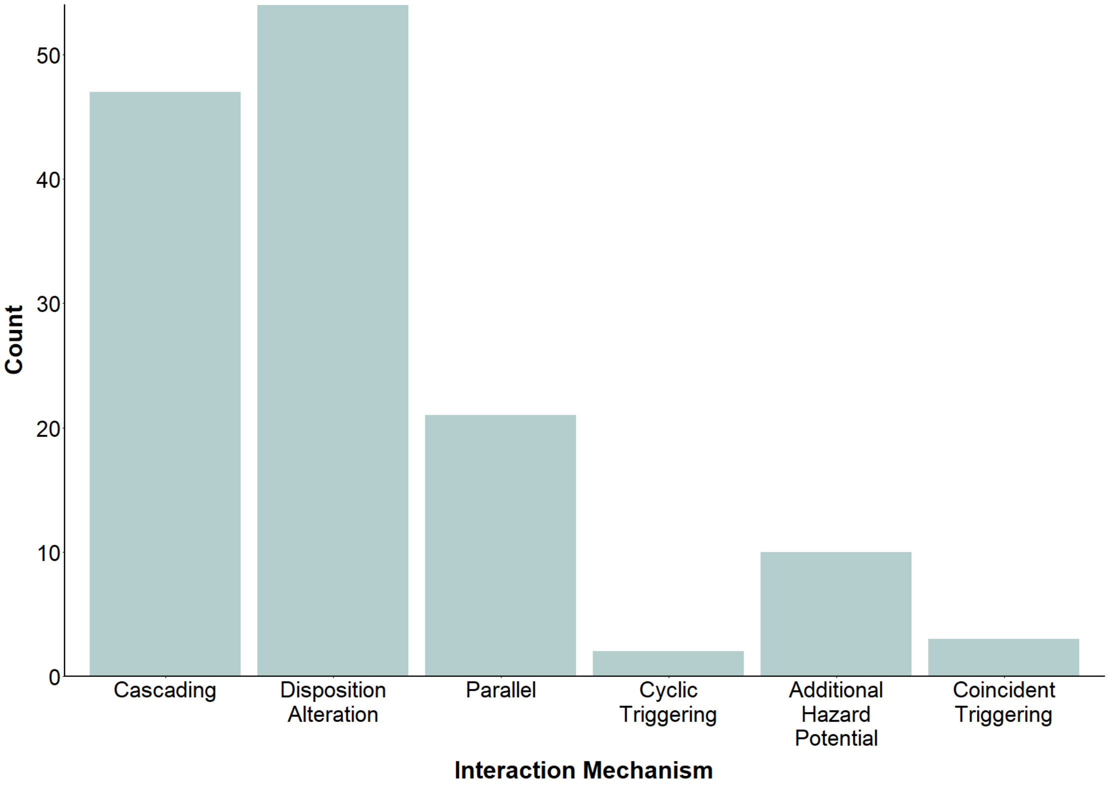

Figure 5. *Distribution of identified interrelationships across interaction mechanisms classified by De Angeli et al. (2022) Although cascading and disposition-alteration mechanisms are the most commonly observed interaction mechanisms contributing to Kerala's multi-hazard environment, other interaction mechanisms were prevalent in Kerala, with Parallel being the third most commonly observed mechanism.*

4.2 Hazard Interaction Matrix and Scenarios

Building on the identified interactions, the final hazard interaction matrix, presented in **Figure 7**, displays all multi-hazard interrelationships for Kerala. Primary hazards, or hazard one, are shown along the vertical axis, with secondary hazards, or hazard two, along the horizontal axis. Whether the hazard is considered primary/secondary or not depends on whether the mechanism represented has a temporal ordering or not, as shown in **Figure 2**. In addition to representing well-documented two-way hazard interactions, such as a landslide triggering a flood during the 2024 Wayanad landslide and flood events (Roy et al., 2025), the matrix can also be used to explore less commonly reported interrelationships in Kerala. These include:

1. Three-way interactions, such as drought and lightning coinciding to trigger a wildfire (coincident triggering mechanism)
2. Positive feedback loops between hazards, such as landslides and floods
3. Parallel occurrence of hazards sharing a common trigger, such as landslides and fog during the 2024 monsoon season, both driven by heavy rainfall (Varma, 2024)

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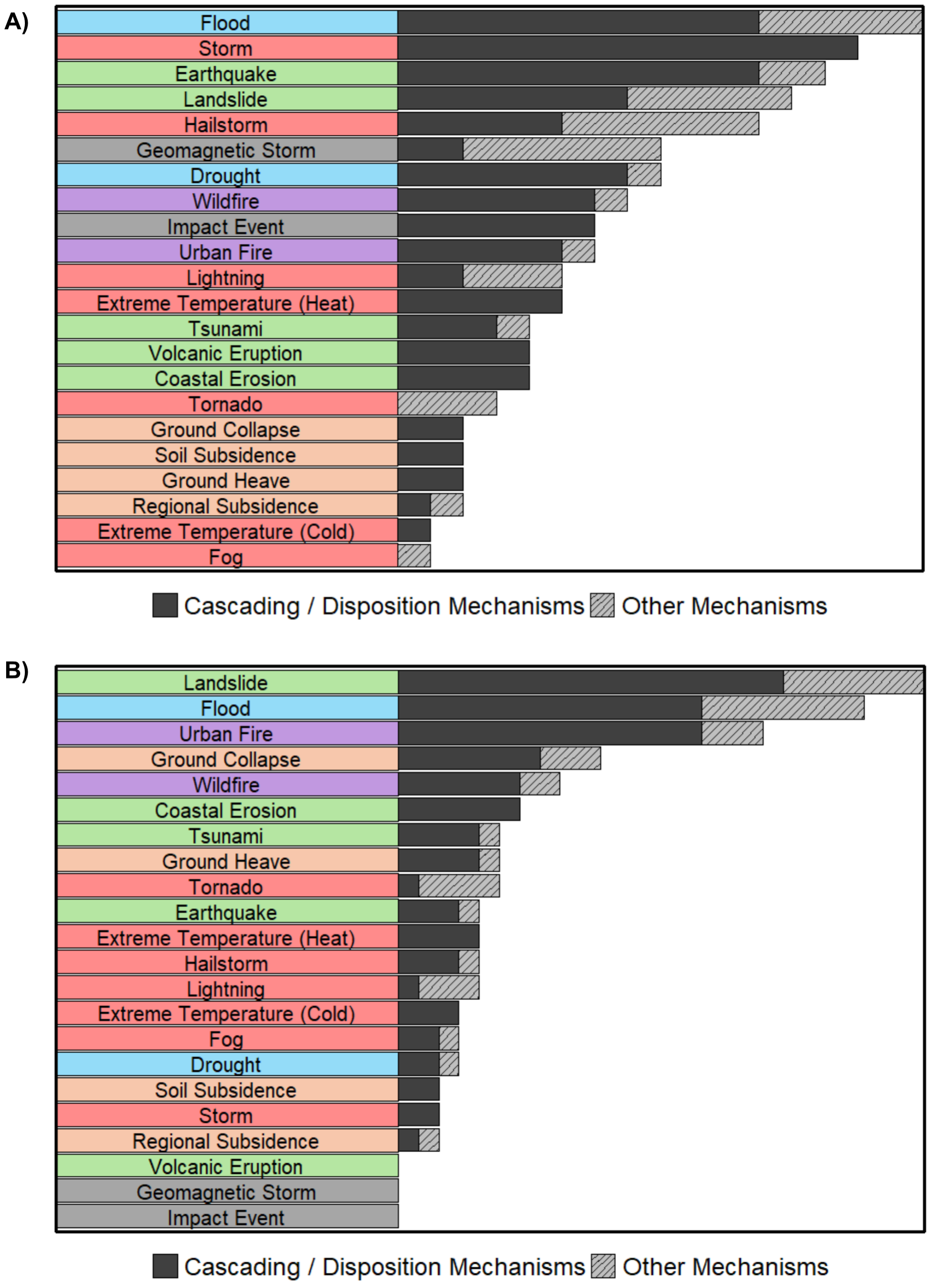

Figure 6. *These two graphs highlight the relative sensitivity of hazards in Kerala to potentially interact with another hazard. Graph A shows the number of connections that hazard one (y-axis in the hazard interaction matrix) has to hazard two (x-axis in the hazard interaction matrix), while graph B shows the opposite (hazard two to hazard one). The bars are subdivided by interaction mechanism, highlighting the contributions of cascading and disposition-alteration mechanisms relative to other mechanisms.*

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4. Interactions where one hazard compromises the natural or built protection of another, for example, during the 2004 Indian Ocean tsunami, wave forces destroyed seawalls that protect the coastal villages from storm-related coastal flooding (Rasheed et al., 2006)

The matrix also highlights theoretical linkages that have not been widely considered locally in Kerala. These include floods compromising electrical infrastructure, increasing the risk of urban fires, or the influence of global-scale hazards, such as volcanic eruptions, on regional extreme temperature events. Together, these examples illustrate how representing multiple interaction mechanisms reveals patterns that pairwise or cascade- and amplification-only frameworks might not fully capture.

In addition, the hazard matrix provides a basis for exploring cascading, multi-step hazard chains. **Figure 8** illustrates such a sequence, in which an earthquake generates a tsunami that can subsequently cause coastal flooding and ultimately coastal erosion. The matrix can also be used to identify more complex networks of hazard interactions involving multiple mechanisms. For example, **Figure 9** shows that a tsunami may trigger coastal flooding and coastal erosion, which can in turn alter coastal morphology in ways that can potentially amplify the severity of subsequent tsunami and coastal flooding events. These links between different grid cells highlight areas that may warrant targeted research, particularly where interactions remain theoretical. The practical application of such scenarios is discussed further in **Section 5.4**.

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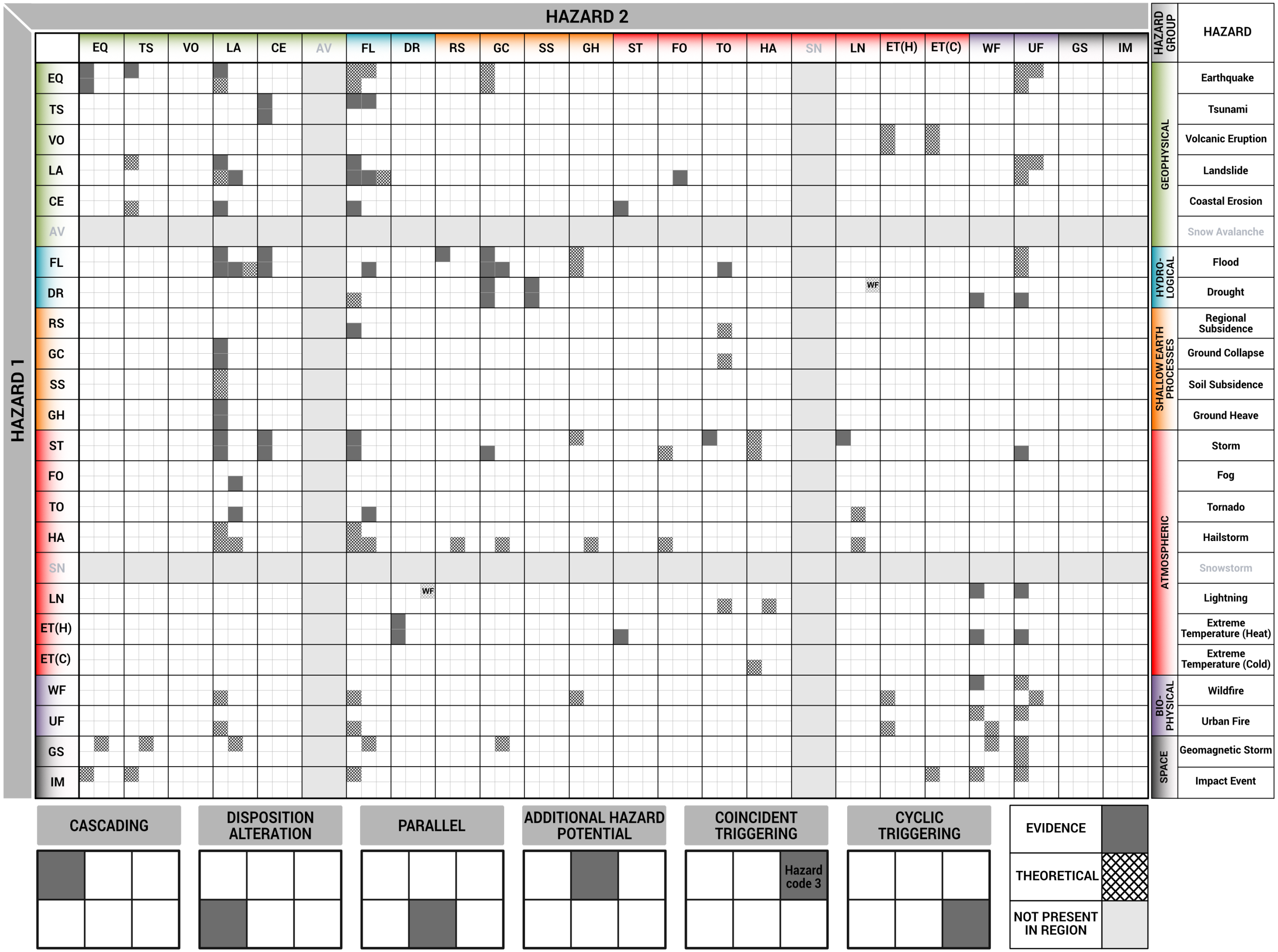

Figure 7. *The hazard interaction matrix, modified from Gill and Malamud (2014), shows the identified multi-hazard interrelationships for Kerala. Shaded cells indicate interactions for which case-study evidence was found, whereas patterned cells represent theoretical or inferred interactions between hazard pairs. The matrix captures multiple interaction mechanisms, with each cell subdivided into six squares to represent each interaction type of cascading (top left), disposition alteration (bottom left), parallel (bottom middle), additional hazard potential (top middle), coincident triggering (top right), and cyclic triggering (bottom right). Filled cells indicate the relationship occurring for that hazard row and column. For coincident triggering, an additional hazard code has been included in the grid cell to illustrate a three-way hazard interaction; for example, drought and lightning together can trigger a wildfire.*

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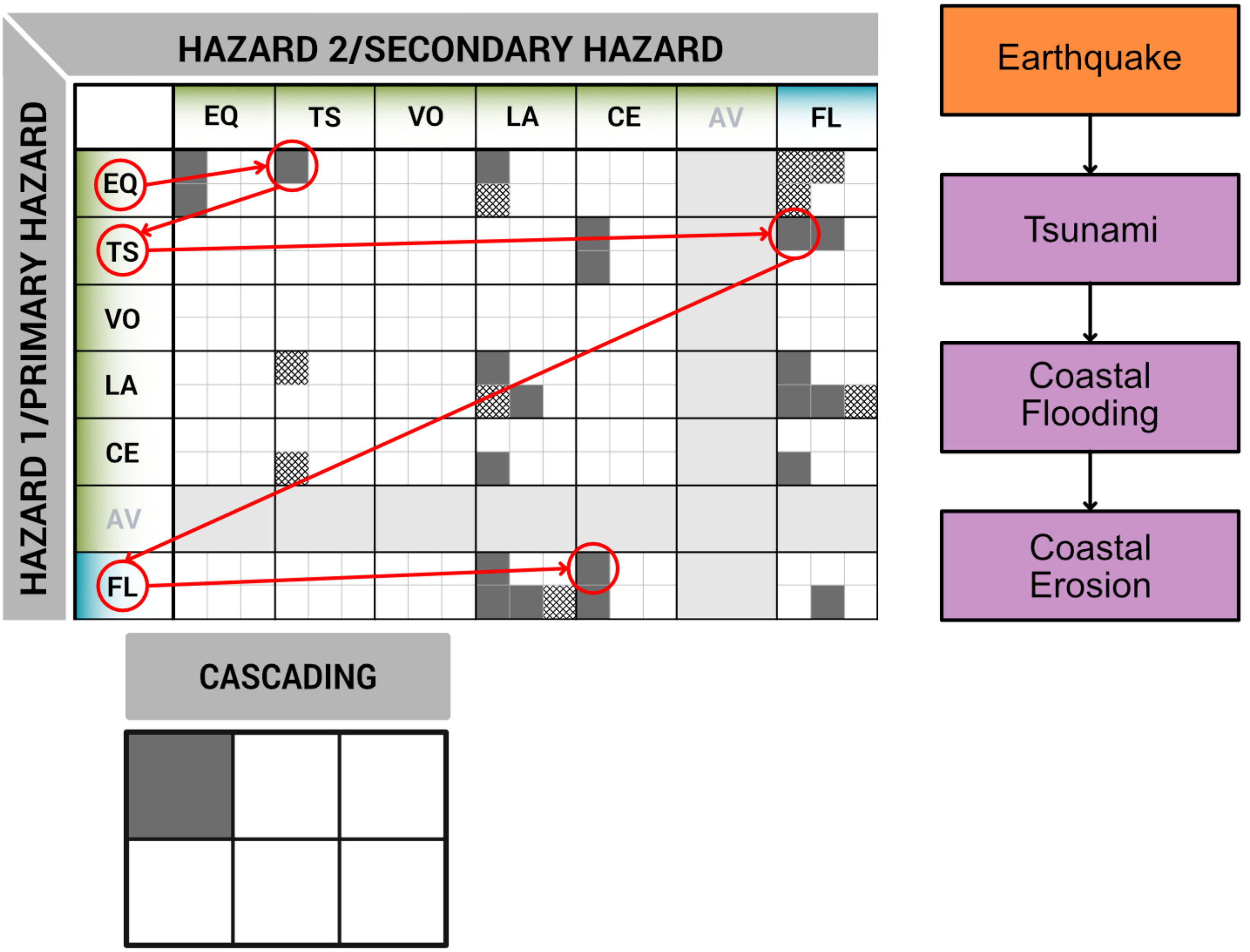

Figure 8. *Example of a cascading multi-hazard scenario derived from the hazard interaction matrix. The figure illustrates a cascading sequence in which an earthquake triggers a tsunami, leading to coastal flooding and subsequent coastal erosion. Circled cells indicate the relevant cascading interactions within the matrix.*

4.3 Temporal Dynamics of Hazard Interactions

The hazard matrix was also used to examine how the likelihood of individual hazards and their potential interactions varies annually in Kerala. The seasonal matrix shown in **Figure 10** indicates that hazards do not occur uniformly over time. The number of concurrent hazards varies substantially across the year, indicating that the opportunity for multi-hazard interactions

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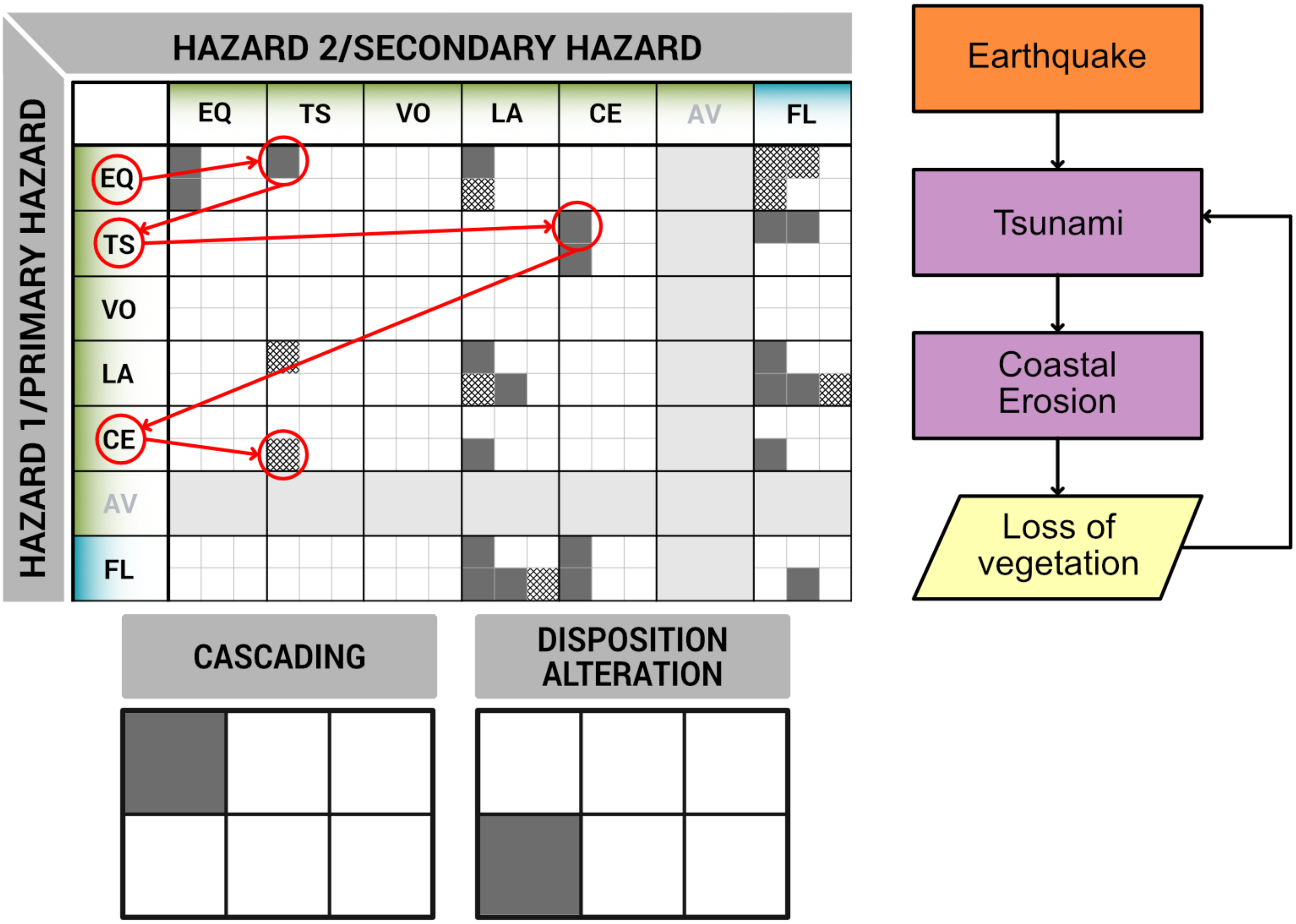


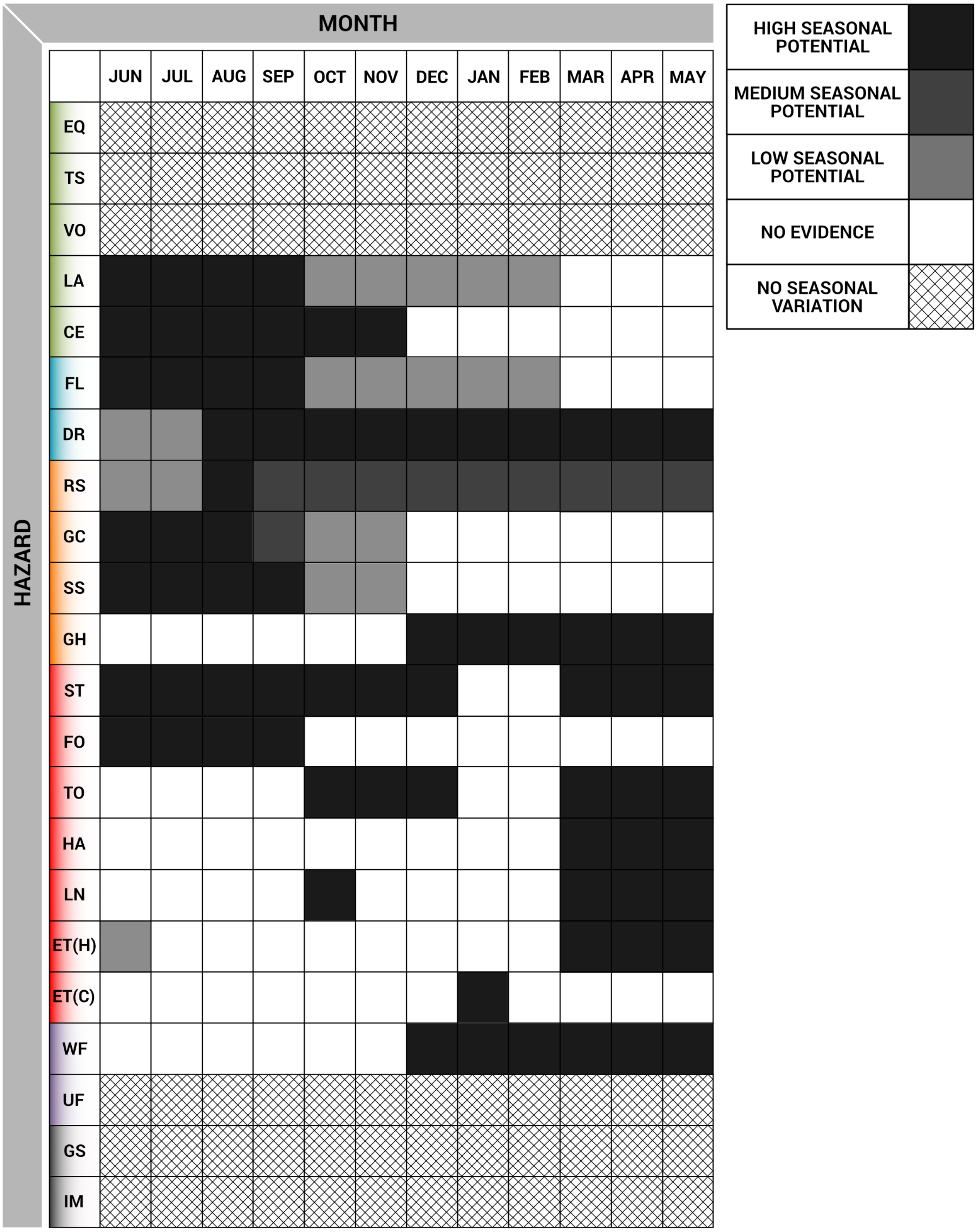
Figure 9. *Example of a multi-interaction hazard scenario derived from the hazard interaction matrix. The figure illustrates how a tsunami may trigger coastal flooding and coastal erosion through cascading mechanisms, while also incorporating disposition alteration processes that modify coastal morphology and influence the severity of subsequent tsunami impacts. Circled cells indicate interactions across multiple mechanism types.*

is unevenly distributed in time. Shading within the matrix represents seasonal potential and associated uncertainty, reflecting variability in reported seasonal timing and limitations in the available evidence

Hazards influenced by heavy rainfall, such as floods, landslides, and ground collapse, are more likely to occur during the Southwest Monsoon period (June–September), with a secondary peak during the Northeast Monsoon season (October–November). In contrast, the likelihood of these hazards decreases during the winter (December–February) and pre-monsoon summer months (March–May), when rainfall is less frequent. Hazards associated with dry conditions, such as wildfires and extreme heat, exhibit opposing seasonal patterns. These hazards are more likely during the pre-monsoon period, when rainfall deficits prevail. During this period, higher temperatures also increase the likelihood of storms and associated hazards such as lightning and tornadoes. This concentration of hazards across these seasons indicates a heightened potential for cascading, parallel, and cyclic triggering interactions driven by shared meteorological triggers, such as intense or prolonged rainfall or elevated temperatures.

Although some hazards are not seasonally constrained, their impacts may still be seasonally preconditioned by environmental conditions. Geophysical hazards, including earthquakes, tsunamis, and volcanic eruptions, exhibit no seasonal variability, reflecting their independence from atmospheric conditions and their potential to occur year-round. Consequently, their potential for coinciding with seasonal hazards varies across seasons. Combining the seasonal likelihood matrix with the hazard interaction matrix further constrains the plausibility of specific interaction mechanisms (**Figure 11**). Of the 137 interrelationships identified, 9 show no seasonal overlap between the primary and secondary hazard. These interactions are therefore unlikely to occur through parallel mechanisms, which require temporal coincidence, but remain possible for cascading and disposition alteration interactions due to their potential for temporal lag.

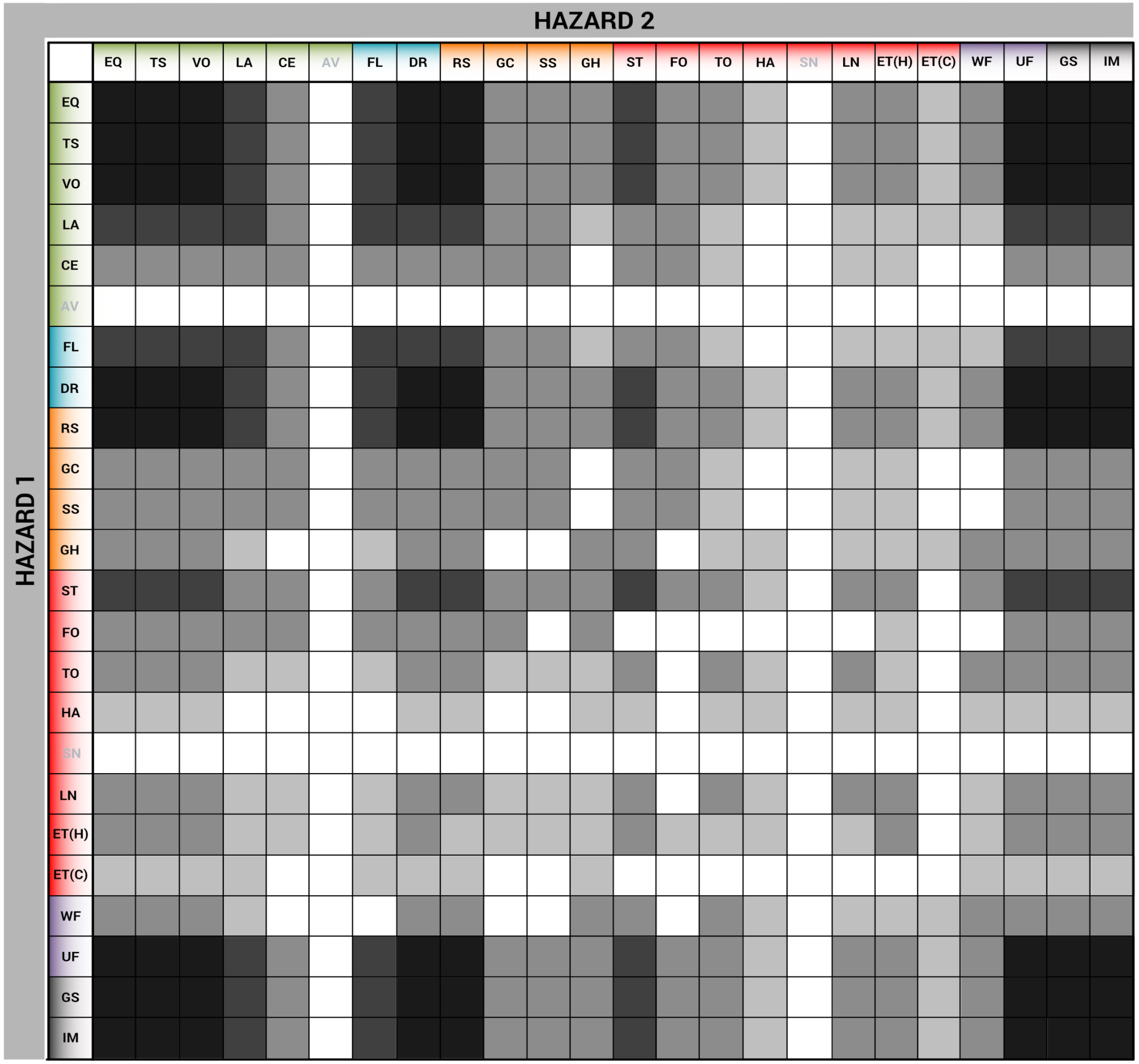
Overall, the seasonal matrix indicates that multi-hazard potential in Kerala varies throughout the year, driven primarily by atmospheric processes and their effects on environmental conditions. The seasonal matrix identifies periods during which multiple hazards are likely to coincide and periods during which interactions are less likely. Incorporating seasonality also indicates that the lack of seasonal overlap limits the possibility of certain interactions, such as those associated with parallel mechanisms. This temporal patterning illustrates how hazard interactions emerge and evolve in Kerala, providing a basis for exploring the temporal dynamics within a multi-hazard environment.



HAZARD	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY
EQ	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
TS	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
VO	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
LA	█	█	█	█	▒	▒	▒	▒	▒	□	□	□
CE	█	█	█	█	█	█	□	□	□	□	□	□
FL	█	█	█	█	▒	▒	▒	▒	▒	□	□	□
DR	▒	▒	█	█	█	█	█	█	█	█	█	█
RS	▒	▒	█	▓	▓	▓	▓	▓	▓	▓	▓	▓
GC	█	█	█	▓	▒	▒	□	□	□	□	□	□
SS	█	█	█	█	▒	▒	□	□	□	□	□	□
GH	□	□	□	□	□	□	█	█	█	█	█	█
ST	█	█	█	█	█	█	█	□	□	█	█	█
FO	█	█	█	█	□	□	□	□	□	□	□	□
TO	□	□	□	□	█	█	█	□	□	█	█	█
HA	□	□	□	□	□	□	□	□	□	█	█	█
LN	□	□	□	□	█	□	□	□	□	█	█	█
ET(H)	▒	□	□	□	□	□	□	□	□	█	█	█
ET(C)	□	□	□	□	□	□	□	█	□	□	□	□
WF	□	□	□	□	□	□	█	█	█	█	█	█
UF	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
GS	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
IM	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨

HIGH SEASONAL POTENTIAL	█
MEDIUM SEASONAL POTENTIAL	▓
LOW SEASONAL POTENTIAL	▒
NO EVIDENCE	□
NO SEASONAL VARIATION	▨

Figure 10. *Seasonal representation of hazard occurrence and interaction potential in Kerala. The matrix illustrates month-by-month variation in the seasonal potential of individual hazards, highlighting periods of increased concurrent hazard occurrence. The matrix starts in June, as this is the beginning of the Southwest monsoon season. Colour gradients indicate uncertainty in seasonal timing due to inconsistencies across evidence sources. The patterned cells indicate hazards that are not influenced by the season, like earthquakes.*



	EQ	TS	VO	LA	CE	AV	FL	DR	RS	GC	SS	GH	ST	FO	TO	HA	SN	LN	ET(H)	ET(C)	WF	UF	GS	IM
EQ	12	12	12	8-11	4-7	0	8-11	12	12	4-7	4-7	4-7	8-11	4-7	4-7	1-3	0	4-7	4-7	1-3	4-7	12	12	12
TS	12	12	12	8-11	4-7	0	8-11	12	12	4-7	4-7	4-7	8-11	4-7	4-7	1-3	0	4-7	4-7	1-3	4-7	12	12	12
VO	12	12	12	8-11	4-7	0	8-11	12	12	4-7	4-7	4-7	8-11	4-7	4-7	1-3	0	4-7	4-7	1-3	4-7	12	12	12
LA	8-11	8-11	8-11	8-11	4-7	0	8-11	8-11	8-11	4-7	4-7	1-3	4-7	4-7	1-3	0	0	1-3	1-3	1-3	1-3	8-11	8-11	8-11
CE	4-7	4-7	4-7	4-7	4-7	0	4-7	4-7	4-7	4-7	4-7	0	4-7	4-7	1-3	0	0	1-3	1-3	0	0	4-7	4-7	4-7
AV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FL	8-11	8-11	8-11	8-11	4-7	0	8-11	8-11	8-11	4-7	4-7	1-3	4-7	4-7	1-3	0	0	1-3	1-3	1-3	1-3	8-11	8-11	8-11
DR	12	12	12	8-11	4-7	0	8-11	12	12	4-7	4-7	4-7	8-11	4-7	4-7	1-3	0	4-7	4-7	1-3	4-7	12	12	12
RS	12	12	12	8-11	4-7	0	8-11	12	12	4-7	4-7	4-7	8-11	4-7	4-7	1-3	0	4-7	4-7	1-3	4-7	12	12	12
GC	4-7	4-7	4-7	4-7	4-7	0	4-7	4-7	4-7	4-7	4-7	0	4-7	4-7	1-3	0	0	1-3	1-3	0	0	4-7	4-7	4-7
SS	4-7	4-7	4-7	4-7	4-7	0	4-7	4-7	4-7	4-7	4-7	0	4-7	4-7	1-3	0	0	1-3	1-3	0	0	4-7	4-7	4-7
GH	4-7	4-7	4-7	1-3	0	0	1-3	4-7	4-7	0	0	4-7	4-7	0	1-3	1-3	0	1-3	1-3	1-3	4-7	4-7	4-7	4-7
ST	8-11	8-11	8-11	4-7	4-7	0	4-7	8-11	8-11	4-7	4-7	4-7	8-11	4-7	4-7	1-3	0	4-7	4-7	0	4-7	8-11	8-11	8-11
FO	4-7	4-7	4-7	4-7	4-7	0	4-7	4-7	4-7	4-7	0	4-7	0	0	0	0	0	0	1-3	0	0	4-7	4-7	4-7
TO	4-7	4-7	4-7	1-3	1-3	0	1-3	4-7	4-7	1-3	1-3	1-3	4-7	0	4-7	1-3	0	4-7	1-3	0	4-7	4-7	4-7	4-7
HA	1-3	1-3	1-3	0	0	0	0	1-3	1-3	0	0	1-3	1-3	0	1-3	1-3	0	1-3	1-3	0	1-3	1-3	1-3	1-3
SN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LN	4-7	4-7	4-7	1-3	1-3	0	1-3	4-7	4-7	1-3	1-3	1-3	4-7	0	4-7	1-3	0	4-7	4-7	0	1-3	4-7	4-7	4-7
ET(H)	4-7	4-7	4-7	1-3	1-3	0	1-3	4-7	1-3	1-3	1-3	1-3	4-7	1-3	1-3	1-3	0	1-3	4-7	0	1-3	4-7	4-7	4-7
ET(C)	1-3	1-3	1-3	1-3	0	0	1-3	1-3	1-3	0	0	1-3	0	0	0	0	0	0	0	0	1-3	1-3	1-3	1-3
WF	4-7	4-7	4-7	1-3	0	0	0	4-7	4-7	0	0	4-7	4-7	0	4-7	1-3	0	1-3	1-3	1-3	4-7	4-7	4-7	4-7
UF	12	12	12	8-11	4-7	0	8-11	12	12	4-7	4-7	4-7	8-11	4-7	4-7	1-3	0	4-7	4-7	1-3	4-7	12	12	12
GS	12	12	12	8-11	4-7	0	8-11	12	12	4-7	4-7	4-7	8-11	4-7	4-7	1-3	0	4-7	4-7	1-3	4-7	12	12	12
IM	12	12	12	8-11	4-7	0	8-11	12	12	4-7	4-7	4-7	8-11	4-7	4-7	1-3	0	4-7	4-7	1-3	4-7	12	12	12

HAZARD GROUP	HAZARD
GEOPHYSICAL	Earthquake
	Tsunami
	Volcanic Eruption
	Landslide
	Coastal Erosion
	Snow Avalanche
HYDRO-LOGICAL	Flood
	Drought
SHALLOW EARTH PROCESSES	Regional Subsidence
	Ground Collapse
	Soil Subsidence
	Ground Heave
ATMOSPHERIC	Storm
	Fog
	Tornado
	Hailstorm
	Snowstorm
	Lightning
	Extreme Temperature (Heat)
	Extreme Temperature (Cold)
BIO-PHYSICAL	Wildfire
	Urban Fire
SPACE	Geomagnetic Storm
	Impact Event

12 Months	■
8-11 Months	▓
4-7 Months	▒
1-3 Months	░
0 Months	□

Figure 11. *Combines the hazard interaction matrix with their seasonal potential, highlighting the number of months per year during which each hazard overlaps temporally with another. White cells indicate interactions without seasonal overlap, limiting the type of interactions that may occur between hazards to those that can have a temporal lag, like disposition alteration and cascading mechanisms. This figure is primarily for assessing seasonal hazards rather than year-round hazards.*

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5 Discussion

5.1 Interpreting Kerala's Multi-Hazard Environment

The results demonstrate that multi-hazard risk in Kerala emerges through a dense network of interactions connecting a wide range of natural hazards, rather than arising from isolated events. This supports earlier statements that argue that disasters do not occur in isolation but instead evolve through interactions among hazards (de Ruiter and Van Loon, 2022). The findings demonstrate this dynamic in a data-scarce context.

The 101 cascading and disposition-alteration interrelationships identified in Kerala are broadly consistent with the substantial number of potential interactions identified in previous studies using similar in-depth, blended evidence approaches. Comparable studies include 83 cascading and disposition-alteration interrelationships in Nepal (Thompson et al., 2025), 88 in Nairobi (Šakić Trogrlić et al., 2024), and 105 in Istanbul (Šakić Trogrlić et al., 2024). While aligning with these studies, this research also demonstrates that focusing solely on cascading and disposition-alteration mechanisms would under-represent the broader range of interactions present in Kerala. When parallel, coincident triggering, additional hazard potential, and cyclic triggering mechanisms were included, the number of identified interrelationships increased by 36%. By explicitly integrating six interaction mechanisms into a single hazard interaction matrix, this study demonstrates that restricting the analysis to cascading and disposition-alteration mechanisms alone can underestimate the full complexity of a region's multi-hazard environment.

The results also reveal an asymmetry in the functional roles played by different hazards within a multi-hazard environment. Certain hazards, such as storms, floods, and earthquakes, often serve as initiating events that contribute to a range of secondary hazards. In contrast, other hazards, such as landslides and urban fires, more commonly emerge as secondary outcomes. This primary-secondary asymmetry is consistent with previous work on cascading relationships, such as the Gill and Malamud (2014) study, which found that volcanic eruptions, earthquakes, and storms had the most primary-to-secondary hazard links (9), and landslides had the most secondary-to-primary hazard links (13). Even though the number of connections in our study is greater due to the wider range of interaction mechanisms considered, the pattern of a relatively small number of hazards shaping interaction networks is consistent with these previous studies.

Importantly, the multi-hazard complexity observed in Kerala should not be interpreted as unique to the region, but rather as illustrative of conditions common in other regions with monsoon-dominated climates. Strong intra-annual climate variability (IMD, 2021) and close coupling between atmospheric and surface processes are known to promote compound hazards (Zscheischler et al., 2018), such as heavy rainfall that can trigger both floods and landslides simultaneously (Wadhawan et al., 2020). Similar interaction-rich multi-hazard environments have been documented in data-scarce Global South contexts, including Kathmandu Valley, Nepal and Nairobi, Kenya, where blended evidence approaches reveal diverse hazard types and extensive interrelationships that can underpin scenario development Gill et al. (2020); Šakić Trogrlić et al. (2024); Thompson et al. (2025). In this context, Kerala provides an additional case study to demonstrate how interaction-focused frameworks can be applied to reveal multi-hazard complexity that may otherwise remain hidden.

Taken together, these findings suggest that understanding multi-hazard risk requires moving beyond examining a subset of hazards or interaction mechanisms and toward examining all possible multi-hazard interactions. The results reinforce calls for interaction-aware approaches to disaster risk assessment (UNDRR, 2023a) and further illustrate how such approaches could be utilised in regions where detailed hazard data are limited.

5.2 Temporal Dynamics

The results highlight that multi-hazard interactions in Kerala are temporally dynamic, with clear seasonal patterns driven primarily by monsoon rainfall. While individual hazards may occur throughout the year, the seasonal matrix shows that interaction potential is concentrated within distinct temporal windows, particularly during the Southwest Monsoon and pre-monsoon periods. The analysis distinguishes between coincident interactions, which arise through shared environmental triggers within the same season, and lagged interactions, which are mediated by environmental preconditioning across seasons.

A key insight from this analysis is the importance of coincident triggering and parallel hazard interactions during periods of intense or prolonged rainfall. During the monsoon season, hazards such as floods, landslides, and ground collapse cluster in time due to a shared meteorological driver, increasing the potential for compounding impacts. Similarly, during the pre-monsoon period, the co-occurrence of drought and lightning may trigger wildfires. This pattern is consistent with the compound event typology of Zscheischler et al. (2020), encompassing both temporally compounding events, where a sequence of hazards contributes to impacts, and multivariate events, where multiple co-occurring drivers or hazards act simultaneously.

Beyond coincident timing, the results also illustrate how environmental preconditioning shapes lagged multi-hazard interactions and is closely linked to the disposition-alteration mechanism. Conditions established during one season can influence the severity or likelihood of hazards in subsequent periods, for example, when prolonged monsoon rainfall increases slope instability and heightens landslide susceptibility during a seismic event (Premlet, 2019). A similar form of temporal conditioning is evidence for drought, which, although not confined to a single season, is most likely to peak in the post-monsoon period depending on the cumulative rainfall received (Surendran et al., 2019). This aligns with broader literature emphasising the role of preconditioning in compound hazard events, whereby moisture, temperature, or surface conditions modify hazard responses over weeks to months (Hillier and Dixon, 2020; Zscheischler et al., 2020).

The seasonal analysis also reveals contrasting temporal behaviour between hazards that are meteorologically driven and those largely independent of atmospheric processes. While rainfall- and temperature-related hazards exhibit strong seasonal clustering, geophysical hazards such as earthquakes and tsunamis show no inherent seasonality. Their interactions with other hazards are nevertheless temporally conditioned, as the likelihood or severity of secondary impacts depends on the time of year. For example, a tsunami occurring during the monsoon season, when coastal erosion is more likely, may compound impacts more

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severely than a similar event occurring during the pre-monsoon period. Combining the seasonal likelihood with the interaction matrix demonstrates when these interaction windows occur.

At the same time, combining seasonal likelihood with the interaction matrix shows that seasonality can constrain the occurrence of certain interactions. A small subset of hazards shows no seasonal overlap; therefore, these interactions are limited to cascading and disposition-altering mechanisms, which can exhibit time lags, compared to parallel mechanisms. Filtering these mechanisms using temporal analysis reduces the risk of over-representing implausible interaction pathways and highlights how temporal dynamics can shape not only when hazards interact, but also how those interactions occur.

5.3 Developing Multi-Hazard Evidence in a Data-Scarce Context

One of the principal challenges encountered in developing a multi-hazard interaction database for Kerala was the scarcity of direct evidence documenting hazard interactions. Most available sources predominantly describe single-hazard events, with only brief or incidental references to additional hazard types. This pattern mirrors findings by Jäger et al. (2025), who showed that a substantial proportion of events classified as single hazards in the EM-DAT database are, in fact, multi-hazard events. The results presented here indicate that this limitation extends beyond global disaster databases to other forms of evidence, including academic and media sources, and is consistent with observations from studies in Nairobi and Istanbul (Šakić Trogrlić et al., 2024).

Madruga de Brito et al. (2025) further highlight that global multi-hazard datasets remain disproportionately focused on the Global North, resulting in substantial data gaps in the Global South. Their analysis of reports from the International Federation of Red Cross and Red Crescent Societies (IFRC, 2021) showed that hazard impacts in the Global South are considerably more diverse than is typically reflected in global databases. This observation aligns with the diversity of hazards and interactions identified in Kerala, which span 22 distinct hazard types (**Figure 6.1**), despite the relatively limited availability of formal documentation.

Although a wide range of evidence sources was used in this study (**Table 6.1**), the evidence base could be further strengthened through engagement with local practitioners, such as the Kerala State Disaster Management Authority, and through field-based observations, as adopted in previous multi-hazard studies (Gill et al., 2022; Šakić Trogrlić et al., 2024; Thompson et al., 2025). Thompson et al. (2025) emphasise that the low proportion of direct evidence for multi-hazard interrelationships often reflects limitations in documentation rather than an absence of interaction. In this study, approximately 43% of identified interrelationships were supported by direct evidence, a proportion consistent with this interpretation. The reliance on inferred interactions, therefore, reflects data limitations rather than a lack of interaction potential, a distinction widely recognised in multi-hazard research.

Similar challenges have been reported in earlier efforts to compile multi-hazard event datasets. Claassen et al. (2023), for example, found that the construction of a global multi-hazard event set was constrained by uneven data coverage and the inability to capture small-scale events, such as flash floods, due to limited national-level reporting. In this context, the present study contributes an illustrative, regionally focused database that documents both potential hazards and their interactions in Kerala. In doing so, it adds to a growing body of multi-hazard databases (Claassen et al., 2023; Jäger et al., 2025; Lee et al., 2024; Stalhandske et al., 2024; Tilloy et al., 2019) that collectively advance understanding of how diverse hazards interact, even as challenges related to data consistency and coverage persist. By incorporating evidence for hazards that have received limited attention in Kerala, such as fog, the database also helps counter the overrepresentation of more frequently studied hazard groups—particularly floods and landslides—within the multi-hazard literature (Gill and Malamud, 2014; Owolabi and Sajjad, 2023).

5.4 Multi-Hazard Scenarios

The development of multi-hazard scenarios enables exploration of how hazards dynamically interact and provides narrative tools for examining uncertainty across alternative pathways (Dessai et al., 2007; Šakić Trogrlić et al., 2024), particularly when incorporating broader drivers such as climate change, population growth, and urbanisation (Cremen et al., 2022). The hazard interaction matrix developed in this study provides a foundation for generating such scenarios and offers a structured way to explore hazard dynamics in Kerala and to support discussion and stakeholder engagement, as demonstrated in comparable applications in Nepal (Thompson et al., 2025). The matrix is not intended as a predictive or operational tool, but as an exploratory framework to support learning, discussion, and scenario development.

Beyond hazard interactions themselves, disaster risk also evolves through changes in exposure and vulnerability, presenting an additional challenge for multi-hazard risk assessment (Cui et al., 2021; Ward et al., 2022). Gill and Malamud (2017) identified 18 types of anthropogenic drivers capable of triggering or modifying hazard interactions, and evidence compiled for Kerala highlights the influence of such processes on the magnitude, frequency, and spatial distribution of hazard events. For example, deforestation in the Western Ghats has been linked to increased flood (Mishra and Shah, 2018) and landslide risk (Kuriakose et al., 2009), while poor construction practices have amplified seismic damage even during moderate-magnitude events (Rastogi, 2001). Where possible, these drivers were recorded within the Kerala multi-hazard database to reflect human contributions to hazard dynamics, and future research could more explicitly integrate them into scenario development.

Vulnerability and social context can also be incorporated into hazard matrices and scenario analyses, as demonstrated by (Matanó et al., 2022) in Kenya, who examined how social variables such as poverty, governance, and political disruption influence hazard interactions. This perspective aligns with broader conceptual frameworks of systemic and cascading risk, in which human, technological, and environmental factors interact to produce complex chains of consequence (Pescaroli and Alexander, 2018; UNDRR, 2023b). While exposure and vulnerability lie beyond the primary scope of this hazard-focused analysis, scenario-based approaches provide a clear pathway for their future integration into multi-hazard risk assessments in Kerala.

6 Conclusions

This study demonstrates how multi-hazard interactions and their temporal dynamics can be systematically compiled and visualised in a low-data availability, highly hazard-prone region, using Kerala, India, as a case study. By combining a blended-evidence database with an adapted hazard interaction matrix, the research reveals a complex multi-hazard environment characterised by diverse hazard types, multiple interaction mechanisms, and pronounced seasonal structuring.

The findings show that multi-hazard complexity in Kerala is not solely driven by cascading and disposition alteration mechanisms, but instead emerges through a broad range of interaction mechanisms, including parallel, coinciding triggering, additional hazard potential and cyclic triggering mechanisms. Restricting analyses to a limited subset of interaction types risks overlooking certain interactions between hazards that can contribute to cumulative risks. Incorporating seasonality further highlights that interaction potential varies throughout the year, with distinct temporal windows of elevated multi-hazard risk shaped by monsoon rainfall, temperature variability, and environmental preconditioning.

Methodologically, this study illustrates that meaningful insights into multi-hazard environments can be generated even when formal hazard data are limited. While the framework is not intended as a predictive tool, it offers a flexible and transferable approach for examining when and how hazards interact, supporting exploratory scenario development and advancing interaction-focused approaches to multi-hazard risk assessment.

Data availability. The Kerala Single- and Multi-Hazard Database developed for this study using the methodology described in this paper is provided as supplementary material accompanying the manuscript.

Author contributions. AD, MB and FET conceptualised the research and developed the methodology. AD compiled and analysed the data, produced the figures, and wrote the manuscript draft. MB, FJ and FET supervised the research. MB and FET reviewed and edited the manuscript.

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