RESPONSE TO REVIEWERS (egusphere-2026-2999)

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

Author(s): Anisha Desai et al.

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We would like to thank the reviewers for taking the time to provide constructive and useful feedback. We have carefully addressed each comment and believe that with their help we will be able to improve the manuscript, particularly in strengthening the positioning, clarification and interpretation of the study. Below, we provide responses and clarifications in reply to the comments. The reviewers' comments [RC] are in blue, while our replies [AC] are in black, and proposed changes to be implemented in the manuscript are in *black italics*. Line numbers refer to those in the original version of the manuscript.

[RC1] Anonymous Referee #1

[RC1a] I would like to thank the authors for a very interesting manuscript; I very much enjoyed reading it. I agree with the authors that detailed local case studies such as this one are novel and very valuable, and that they help address the global imbalance in multi-hazard research towards data-rich regions. I also really like the visualizations; in particular Figures 2, 7 and 10 are a very nice way of conveying a lot of information, and I can see the seasonal matrix being a useful communication tool. I do have some general comments that I would like to exchange thoughts on with the authors, mostly around positioning the extended matrix within recent classification work and the interpretation of some of the headline numbers.

[AC1a] Thank you for taking the time to provide constructive feedback. We particularly appreciate your comments on the value of this study and presentation of the results. Your suggestions will help us to strengthen the positioning of the study within recent classification work and clarify the interpretation of the findings.

[RC1b] The authors could reflect on the recently published TST (Type-Space-Time) classification of hazard interrelations by Wenzel et al. (2026, Natural Hazards).

- For example, Figure 2 of the manuscript covers what Wenzel et al. call the type dimension (and the seasonal matrix covers the temporal dimension), but the spatial dimension of interactions is currently absent: the matrix aggregates over all of Kerala. Could the authors reflect on how spatial (non-)overlap within the study region affects which of the interrelationships are actually plausible, similar to how they use seasonal (non-)overlap to filter out interactions?
- It would also help to briefly position the six mechanisms from De Angeli et al. (2022) relative to the TST types also given the authors' own point (Section 1.1.1) that different terminology hinders comparison across studies.

[AC1b] Thank you for drawing attention to the recently published Type-Space-Time (TST) classification. We agree that it provides a valuable structure for positioning the interrelationship types and temporal analysis considered in our study, as well as for identifying an important limitation concerning spatial dynamics. We will therefore incorporate the TST classification into the introduction, methodology and discussion.

The matrix developed in this study represents interaction potential at the state level rather than demonstrating local spatial overlap between individual hazard footprints. Although the locations of documented case-study events were recorded in the multi-hazard database, this information was not incorporated into the assessment of plausible interactions. The available evidence varied considerably in spatial resolution, and comparable quantitative hazard footprint data were not available across all hazard types. Applying a spatial filter comparable to the seasonal filter would risk excluding plausible cross-boundary or widespread interactions. This limitation will be made explicit in section 5.3 when discussing the development of multi-hazard evidence in a data-scarce context. We will also clarify that the identified relationships should be interpreted as a state-level screening of interaction potential and note that future work could use more spatially detailed data to further filter interaction potential at more localised scale.

Please see our initial proposed text as follows:

“Line 43: While initiatives, such as the review by the British Geological Survey (Ciurean et al., 2018), the EU Myriad Project (Gill et al., 2022) and the Type-Space-Time (TST) classification of Wenzel et al. (2026), 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)”.

“Line 101: More recently, Wenzel et al. (2026) incorporated a temporal dimension within their Type-Space-Time (TST) classification distinguishing interrelationships according to both timing intervals, ranging from temporally distant to simultaneous, and onset speed, ranging from gradual to sudden. This provides a broader structure within which both the short-term coincident and longer-term lagged interrelationships discussed below can be considered.”

“Line 206: Due to the diversity in multi-hazard terminology throughout the literature, we aimed to position these mechanisms within broader frameworks to align this study with wider literature. Firstly, these mechanisms can be positioned within the Type-Space-Time (TST) classification proposed by Wenzel et al. (2026), which organises multi-hazard interrelationships along three dimensions: type (how hazards influence one another), space (the spatial relationship between hazard footprints), and time (the temporal relationship between events). The four interrelationship types defined by Wenzel et al. (2026) offer a broader, higher-level structure within which the six De Angeli et al. (2022) types used in this study can be positioned. “Cascading” corresponds directly to the cascading interrelationship type used in this study, where one hazard triggers another. Cyclic triggering can similarly be understood to be a more specific, iterative case of the cascading type, in which a secondary hazard exacerbates the primary hazard that produced it. “Pre-conditioning” aligns with disposition alteration and additional hazard potential, both of which describe the first hazard altering the magnitude or likelihood of the second without directly triggering it. “Trigger-coupled” interrelationships, where a shared external trigger causes two or more hazards, align closely with the parallel interrelationship type used here. Coincident triggering is more complex as two co-occurring hazards jointly contribute to the generation of a subsequent

hazard and can therefore incorporate elements of both "trigger-coupled" and "cascading behaviour". The fourth TST type, "independent", has no direct counterpart within the De Angeli et al. (2022) types applied here, as these, by definition, represent some form of interrelationship between hazards. This comparison illustrates how the Wenzel et al. (2026) TST framework's four broader types and the six De Angeli et al. (2022) interrelationship types align with each other. Secondly, the full set of interrelationship types illustrated in Figure 2 can also be placed within the broader multi-hazard categories outlined by Gill et al. (2022): "Triggering" can refer to cascading and cyclic triggering, "Influential" to disposition alteration, alleviation and additional hazard potential, and "Compound" to simultaneous, parallel, and coincident triggering. ***Figure 2*** *illustrates the key components of the commonly observed interrelationship types and how they fit into these broader frameworks."*

"Line 484: Another challenge was accounting for the spatial relationship of hazard interrelationships. The matrix developed here identifies interrelationship potential at the scale of Kerala but does not explicitly assess whether individual hazard footprints overlap or are otherwise spatially connected. Wenzel et al. (2026) distinguish overlapping interrelationships, where hazard footprints partially or fully coincide; source-to-spread interrelationships, where effects propagate from the hazard source location to another area; and non-overlapping interrelationships, where spatially distinct hazards remain indirectly connected. These relationships may additionally extend across natural or administrative boundaries, classified by Wenzel et al. (2026) as being "cross-boundary". Within Kerala, such boundaries may occur not only at the state level but also between its 14 districts. This distinction demonstrates that spatial plausibility cannot be assessed through spatial overlap alone. Some interrelationship types require spatial coincidence or physical connectivity, whereas others may remain plausible where effects propagate between locations or where hazards arise from a common driver affecting different areas. For example, Wenzel et al. (2026) use the 2018 Kerala event, which was noted in the multi-hazard database, to illustrate how intense rainfall generated the simultaneous occurrence of landslides and flash floods, with landslide sediment combining with rainfall runoff to produce hyperconcentrated flows or debris flows. This demonstrates that modelling the hazards independently may misrepresent the combined intensity produced. Taking this into account, a spatial assessment of plausible interrelationships within Kerala could further refine the hazard matrix. While the locations of documented events were recorded, the spatial resolution of evidence varied between hazard types, and comparable spatial data were therefore unavailable across the hazards considered. Applying a spatial filter under these conditions could incorrectly exclude plausible interrelationships where apparent lack of spatial connectivity reflects incomplete evidence rather than genuine spatial incompatibility. The matrix should therefore be interpreted as a state-level screening of potential interrelationships. Future work incorporating more spatially detailed data could be used to refine the identified interaction potential at finer spatial scales."

[RC1c] Related to this: the manuscript uses "interaction", "interrelationship" and "interaction mechanism" somewhat interchangeably. Given that the introduction (rightly) flags the lack of standardised terminology as a gap, it would be good to define these terms explicitly early on and use them consistently.

[AC1c] Thank you for the suggestion. We agree it would add clarity to the paper to use consistent terminology. We will use the term “interrelationship” throughout as an umbrella term to represent the relationship between hazards, and “interrelationship type” to describe the specific form that relationships takes e.g. cascading. We will revise the manuscript accordingly.

[RC1d] I would be curious to read a slightly more in-depth reflection on the intended use of the matrix in practice. Section 5.4 positions it as an exploratory tool for scenario development and stakeholder engagement, and engagement with KSDMA is mentioned as future work; can the authors say a bit more about how they envisage a practitioner actually using Figures 7, 10 and 11 (which are rich but also dense, see also below minor comment), and whether for example an interactive/digital version of the matrix is foreseen?

[AC1d] We agree with this comment, and the following initial proposed changes will be made to section 5.4 to add more detail on how the matrix could be used in practice. We also agree that a digital version would improve usability, particularly given the density of Figure 7. Although developing such a tool is beyond the scope of the present study, we will identify it as a useful direction for future work.

“Previous applications of the hazard interaction matrix demonstrate that it can be used to support discussion and stakeholder engagement. In Guatemala, Gill et al. (2020) ran a workshop with civil-protection professionals to complete an empty hazard interaction matrix to document practitioner knowledge of relevant hazard interactions. In Nairobi and Istanbul (Šakić Trogrlić et al., 2024) and Kathmandu Valley (Thompson et al., 2025), workshops were used to supplement the hazard interaction matrix and facilitate discussion on locally relevant multi-hazard scenarios. These applications suggest that the hazard matrix is useful as an exploratory tool to elicit knowledge and discussion of the implications of locally relevant multi-hazards, as well as support scenario development.

In this study, Figure 7 could first be used to identify interrelationships present in the case study location and potentially relevant hazard pathways to help stimulate discussion on the local multi-hazard environment. Figure 10 could be used to highlight periods of the year when individual hazards are more likely to occur to help understand seasonal patterns, and Figure 11 combines the interrelationship and seasonal information to help prioritise plausible and locally relevant multi-hazard scenarios. Together, these visualisations therefore provide a structured basis for selecting and discussing locally relevant scenarios. A limitation to using these figures in a practical manner is that they are still quite complex and dense. An interactive implementation of the hazard matrix could increase its practical usability. Although development of such an interface is beyond the scope of the present study, this would be a useful direction for future work.”

[RC1e] How are mechanisms without temporal ordering (parallel, coincident triggering, cyclic triggering) placed in the asymmetric hazard-one/hazard-two matrix, and how are they counted in the link counts of Figure 6? Are these counted once or twice (i.e. in both the upper and lower triangle)? This matters for the interpretation of the stated percentages (32% and 50% of all links).

[AC1e] Thank you for highlighting this. In the original analysis, interrelationships without a temporal ordering could be represented in both orientations of the matrix and have therefore been counted twice in summary statistics. We agree that this should not be interpreted as two independent interrelationships. We will therefore revise the analysis so that each unique interrelationship is only considered once, and revise the figures, caption, and associated results accordingly. An explicit description to explain how these numbers should be interpreted will also be added.

[RC1f] Abstract: the sentence "The matrix was further enhanced to capture seasonal variation in interaction potential throughout the year" appears twice (around L. 6–7 and L. 13–14).

[AC1f] Thank you for identifying this duplication. The repeated sentence at line 13-14 will be removed from the abstract.

[RC1g] 176: the sentence "More broadly, Kerala provides a useful case study for exploring how interaction-focused" is incomplete.

[AC1g] Thank you for identifying this omission. The following completed sentence will be added.

"More broadly, Kerala provides a useful case study for exploring how interrelationship-focused approaches can be applied to identify and characterise multi-hazard complexity in data-scarce settings"

[RC1h] 175: "structure inference": maybe "structured inference"?

[AC1h] This sentence has been rewritten to add clarity, as per **[AC2l]**

[RC1i] 145: the formatting of the population density (860 persons km-2) appears to be negative; please check the superscript.

[AC1i] Thank you for flagging this. The intended notation is "860 persons km^{-2}" using standard scientific notation to represent per square km. We will check the formatting in the revised manuscript to ensure the superscript is displayed correctly.

[RC1j] There are several confusing cross-references left in the text: "Table 3.1" (L. 223 and the caption of Figure 3) presumably should be "Table 1", and "Figure 6.1" (L. 463) and "Table 6.1" (L. 466) presumably should be Figure 3 and Table 1?

[AC1j] Thank you for identifying these cross-reference errors. Line 223 and 466, and the Figure 3 caption will be corrected to Table 1, and Line 463 will be corrected to Figure 3.

[RC1k] Abstract L. 15: "reduced by approximately 6%": in the text this is 9 of 137 interrelationships (≈6.6%) showing no seasonal overlap; it would help to state in the abstract

what the 6% refers to (interactions ruled out for temporally coincident mechanisms only, not removed altogether).

[AC1k] We agree that this should be made clearer. Please find below the proposed changes to Line 15:

"When applying seasonal filters, approximately X% of the potential interrelationships were ruled out as they did not coincide in time, although some may remain plausible through temporally lagged interrelationships like cascading or disposition-alteration types"

[RC1l] Similarly, for the 36% in the abstract, it would help to state the baseline explicitly (i.e. relative to the 101 cascading + disposition-alteration interrelationships).

[AC1l] We agree that the baseline should be stated explicitly. Please find below the proposed changes to Line 10:

"including four additional interaction mechanisms increased the identified interrelationships from 101 to X, representing a X% increase relative to the baseline that considers only cascading and disposition-alteration interrelationships.

[RC1m] Figure 7 is impressive but very dense; maybe check legibility

[AC1m] We agree that the density of information in Figure 7 makes legibility quite important. We will increase the visual distinction between evidence categories and interrelationship types, revise label orientation and sizing, and check that the figure remains legible at the final manuscript size.

[RC1n] Please check reference Bureau, 2025 (?)

[AC1n] Thank you for identifying the incomplete reference. The reference will be updated to the following:

"The Hindu Bureau: Fire safety measures ignored despite frequent warnings, The Hindu, https://www.thehindu.com/news/national/kerala/fire-safety-measures-remain-ignored-despite-frequent-warnings/article69250993.ece, 1 May, 2025"

[RC2] Anonymous Referee #2

[RC2a] This is a very nice piece of work, with an extensive and well-documented evidence base that has clearly been developed with great care. I think the framework has considerable potential for application not only in data-scarce regions but also in areas where more extensive data are available, providing a useful tool to assess the multi-hazard profile of a region. I also appreciate the quality of the figures, which greatly support the reader in navigating the complex methodology.

My main suggestions concern the clarity and presentation of the manuscript. The study adapts and combines a large number of existing frameworks, definitions, and

methodologies, which at times makes it difficult for the reader to follow the narrative, especially early in the paper. I believe these revisions would improve the readability and accessibility of an otherwise strong and valuable contribution.

[AC2a] Thank you for taking the time to provide constructive feedback. We particularly appreciate your comments on the potential wider applicability of the framework and the quality of the figures. We agree that a clearer introduction and organisation of the different frameworks used in the study will improve the readability of the manuscript, and we will revise the introduction and methodology.

[RC2b] Some references do not seem to fully support the statements they accompany. For example, de Ruiter and Van Loon (2022), cited right at the start of the paper, focuses primarily on dynamic vulnerability and how vulnerability changes in multi-hazard contexts, rather than providing evidence for the frequency or increasing occurrence of multi-hazard events experienced by societies. Moreover, Gill et al. (2022) provides a handbook of definitions and does not support the statement that multi-hazard events produce impacts that exceed the sum of their individual effects. I would therefore recommend critically reviewing the use of references throughout the manuscript.

[AC2b] Thank you for your suggestion. References will be checked against statements made throughout the manuscript. The following changes will be made:

- Remove de Ruiter and van Loon, 2022 from the opening sentence.
- Revise phrasing to *"producing impacts that can exceed those of any single hazard alone occurring (Li et al. (2012)"*

[RC2c] In line 32, the manuscript states that several frameworks were proposed in response to the Sendai Framework (2023), whereas most of the cited frameworks actually predate 2023.

[AC2c] Thank you for highlighting this. We intended to indicate that the emphasis on multi-hazard approaches has remained relevant since 2015, and we agree that this point is unclear in this section. We will revise this paragraph to the original Sendai Framework 2015 date and recognise that many frameworks were developed at a similar time.

[RC2d] I also think it would help the reader if the overall purpose of the paper were introduced before Section 1.1. After reading the introduction, the objective of the study still is somewhat unclear.

[AC2d] We agree with this suggestion and will add the paper's purpose from Line 134-135 to the beginning of the paper.

[RC2e] The statement that there are "no standardized definitions adopted" is a bit strong. Consider only leaving the following statement that multiple definitions have developed in parallel across different research communities, which is more nuanced.

[AC2e] We agree that the wording is quite strong and will remove the “no standardised definitions adopted” wording.

[RC2f] The second paragraph of Section 1.1.2 focuses primarily on reporting bias and the representation of multi-hazards in disaster databases, which seems conceptually distinct from geographical imbalance. It may therefore be worth considering this as a separate subsection. More generally, the subsection headings could perhaps be revised to reflect the specific research gap discussed in each section, although the current headings are also adequate.

[AC2f] Thank you for your comment. We agree that the original headings do not capture the full scope of the subsections. The titles of the subsections will be amended as follows to better reflect the research gaps being discussed:

“1.1.1. Terminology and Representation of Multi-Hazard Interrelationships”

“1.1.2. Geographical Imbalances and Gaps in Multi-Hazard Data”

“1.1.3. Temporal dynamics of Multi-Hazard Interrelationships”

[RC2g] The transition from Section 1.1 is somewhat abrupt. Consider moving up the introduction of the overall aim and making the link between the aims and the discussed research gaps more explicit.

[AC2g] Thank you for your suggestion. The overall aim will be moved to the beginning of the introduction as per the response to comment **[RC2d]**. The sections for each research gap will be added to the aims as per response **[AC2i]**

[RC2h] As someone not familiar with the region, I would find it helpful to know immediately that Kerala is located in India when the case study region is first introduced.

[AC2h] We agree with this suggestion. Kerala will be identified as a state on the southwestern coast of India at its first mention in the Introduction, as per response **[AC2i].**

[RC2i] The aims themselves are quite specific and rely heavily on references to existing methodologies and frameworks, making them difficult to follow without prior familiarity with the cited studies. I believe it might be clearer to focus the aims more strongly on the intended outcomes of the study, while introducing the specific frameworks later in the methodology. Alternatively, a brief line explaining what the frameworks entail would be already more helpful than only naming them. For example, the wording in lines 201–202 ("Building on the identification of single hazards...") provide the reader with more information than referring only to the “use of the methodology of Gill et al.” (aim 1).

[AC2i] We agree that the aims should focus on the intended outcomes of the study rather than require prior familiarity with methodological frameworks. References to the specific frameworks will be moved to the methodology. The aims (section 1.2) will be revised as follows to focus more on the outcomes of the study:

1. *To address the geographical and data gaps identified in 1.1.2. by developing a single- and multi-hazard database for Kerala, a hazard-prone region on the southwestern coast of India with limited data availability, documenting individual hazards and their interrelationships across a range of evidence sources, capturing both well-documented and underreported hazards*
2. *To address the multi-hazard representation gap identified in 1.1.1. by extending the hazard interaction matrix to represent a broader range of multi-hazard interrelationship types and thereby better capture Kerala's multi-hazard environment*
3. *To address the temporal gap identified in 1.1.3. by adapting the hazard interaction matrix to represent hazard seasonality and explore how temporal variation shapes the potential for multi-hazard interrelationships in Kerala*

[RC2j] For completeness, consider adding a legend explaining the green shading in Figure 1.

[AC2j] We agree, and a legend will be added to Figure 1 to identify the green shading as topographic elevation.

[RC2k] In line 155, I would consider explicitly referring to disasters (e.g., "most disaster-affected countries" or "recording over 400 disaster events...") for clarity.

[AC2k] Thank you for your suggestion. We will revise the statement to explicitly refer to disasters, so that it is clear what the reported number represents.

[RC2l] In line 175, it was not entirely clear to me what is meant by "conventional datasets," "supplementary evidence," or "structure inference." A brief clarification would be helpful.

[AC2l] Thank you for highlighting this lack of clarity. We agree that these terms are ambiguous and will revise the sentence to define them more clearly.

Please see our initial proposed text:

"These constraints support the use of a blended-evidence approach that draws not only on formal sources of hazard information, such as national and state government databases and reports, but also on supplementary evidence from media sources and academic literature, as well as already established hazard interrelationships where direct local evidence is unavailable, to identify relevant multi-hazard interrelationships in Kerala".

[RC2m] The sentence in line 176 appears to be incomplete.

[AC2m] The incomplete sentence will be amended as per **[AC1g]**

[RC2n] It is somewhat difficult to link the more general terminology used at the start of this section to the specific frameworks as they are currently introduced in the aims, so the relationship between the aims and the methodological approach is not immediately

apparent. The methodology would be a more natural place than the aims to explicitly introduce these frameworks.

Similarly to my comments on the introduction, it may be worth reconsidering the subsection headings so that they more closely reflect the structure introduced at the beginning of Section 3. This could help guide the reader through the different methodological steps.

Because the manuscript draws on several existing frameworks, I think it would help the reader if each framework would be introduced more comprehensively at first mention and referred to more consistently throughout the manuscript. For example, in line 191 the "Gill and Malamud (2014) hazard classification framework" is introduced, whereas later (lines 265–266) the manuscript refers to the "hazard interaction matrix of Gill and Malamud (2014)."

[AC2n] We agree with these comments. The introduction and methodology sections will be revised to introduce the frameworks in a clearer manner and make sure there is consistent terminology used throughout. To do this, we will add a subsection at the start of the methodology to briefly introduce each framework, its purpose and how it is used in the present analysis before the methodological steps are described in detail.

Please see our initial proposed subtitle changes to better reflect the methodological steps taken:

3.1. Methodological Frameworks Used in this Study
3.2. Identification of Single-Hazard and Multi-Hazard Interrelationships Used to Build Hazard Matrix
3.3. Evidence Search for Multi-Hazard Interrelationships Occurring in Kerala
3.4. Hazard Seasonality Filtering
3.5. Construction of Final Multi-Hazard Database and Hazard Interaction Matrix Visualisation

[RC2o] Overall, I think the results section is clearly presented and the figures are generally of a high quality

In Figure 7 I found the "theoretical" gridded fill somewhat difficult to distinguish from the other categories. Increasing the contrast between these may improve readability. I would also consider rotating any labels that are completely upside down.

Similarly, for Figure 11, rotating the headers that are fully upside down would make the figure easier to read.

[AC2o] Thank you for your suggestions. We will revise the figures accordingly to make them easier to read by increasing the line size of patterned cells and revising the orientation of labels. This label change will also be made to Figure 11.

[RC2p] Lines 377–378: The cited reference (de Ruiter and van Loon, 2022) does not support the statement that disasters evolve through interactions among hazards, as it focuses on dynamic vulnerability and exposure.

[AC2p] We agree and will revise the statement and supporting reference as follows:

"This is consistent with established multi-hazard frameworks that conceptualise hazards as interconnected and capable of interacting through multiple interrelationship types (Gill and Malamud, 2014; De Angeli et al., 2022)."

References cited in our reply (*** and bold = new reference**)

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The Hindu Bureau: Fire safety measures ignored despite frequent warnings, The Hindu, https://www.thehindu.com/news/national/kerala/fire-safety-measures-remain-ignored-despite-frequent-warnings/article69250993.ece, 1 May, 2025

Thompson, H.E., Gill, J.C., Šakić Trogrlić, R., Taylor, F.E. and Malamud, B.D. (2025) A methodology to compile multi-hazard interrelationships in a data-scarce setting: an application to the Kathmandu Valley, Nepal. Natural Hazards and Earth System Sciences, 25, pp. 353–381. Doi: https://doi.org/10.5194/nhess-25-353-2025

***Wenzel, T., van Westen, C., Sunil, M., Reluy, N.P., Marr, P., Glade, T. and Bell, R. (2026) Towards a practical multi-hazard interrelation classification: implications for assessing their impacts. Nat Hazards 122, 82. Doi: https://doi.org/10.1007/s11069-025-07901-0**