Supplement of Nat. Hazards Earth Syst. Sci., 25, 4263–4281, 2025
https://doi.org/10.5194/nhess-25-4263-2025-supplement

Natural Hazards and Earth System Sciences
Open Access

Supplement of

Review article: Towards multi-hazard and multi-risk indicators – a review and recommendations for development and implementation

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Supplementary tables

Table S1. Search terms used in this study to obtain peer-reviewed literature from Scopus, Web of Science and PubMed including multi-hazard/risk (Level 1 search terms) and indicators (Level 2 search terms).

Level 1: Multi-hazard/risk		Level 2: Indicators	
1	multi-hazard*	1	indicator*
2	multihazard*	2	index*
3	multi hazard*	3	indices
4	multi-risk*	4	metric*
5	multirisk*	5	disaster risk indicator*
6	multi risk*		
7	compound* hazard*		
8	compound* event*		
9	compound* risk*		
10	interacting hazard*		
11	interacting event*		
12	interacting risk*		
13	cascading hazard*		
14	cascading event*		
15	cascading risk*		
16	interconnected hazard*		
17	interconnected event*		
18	interconnected risk*		
19	interrelated hazard*		
20	interrelated event*		
21	interrelated risk*		
22	multiple hazard*		

Table S2. Search strings used in Scopus, Web of Science and PubMed.

Scopus	Web of Science	PubMed
TITLE-ABS-KEY-AUTH (“multi-hazard*” OR “multihazard*” OR “multi hazard*” OR “multi-risk*” OR “multirisk*” OR “multi risk*” OR “compound* hazard*” OR “compound* event*” OR “compound* risk*” OR “interacting hazard*” OR “interacting event*” OR “interacting risk” OR “cascading hazard*” OR “cascading event*” OR “cascading risk*” OR “interconnected hazard*” OR “interconnected event*” OR “interconnected risk*” OR “interrelated hazard*” OR “ interrelated event*” OR “interrelated risk*” OR “multiple hazard*”) AND TITLE-ABS-KEY-AUTH(“indicator*” OR “index*” OR “indices” OR “metric*” OR “disaster risk indicator*”) Results = 769 Date Range is 2015 – present (day of search 3/11/2023) = 621 English = 597	(TI=(“multi-hazard*” OR “multihazard*” OR “multi hazard*” OR “multi-risk*” OR “multirisk*” OR “multi risk*” OR “compound* hazard*” OR “compound* event*” OR “compound* risk*” OR “interacting hazard*” OR “interacting event*” OR “interacting risk” OR “cascading hazard*” OR “cascading event*” OR “cascading risk*” OR “interconnected hazard*” OR “interconnected event*” OR “interconnected risk*” OR “interrelated hazard*” OR “ interrelated event*” OR “interrelated risk*” OR “multiple hazard*”) OR AB=(“multi-hazard*” OR “multihazard*” OR “multi hazard*” OR “multi-risk*” OR “multirisk*” OR “multi risk*” OR “compound* hazard*” OR “compound* event*” OR “compound* risk*” OR “interacting hazard*” OR “interacting event*” OR “interacting risk” OR “cascading hazard*” OR “cascading event*” OR “cascading risk*” OR “interconnected hazard*” OR “interconnected event*” OR “interconnected risk*” OR “interrelated hazard*” OR “	(“multi-hazard*”[Title/Abstract] OR “multihazard*”[Title/Abstract] OR “multi hazard*”[Title/Abstract] OR “multi-risk*”[Title/Abstract] OR “multirisk*”[Title/Abstract] OR “multi risk*”[Title/Abstract] OR “compound* hazard*”[Title/Abstract] OR “compound* event*”[Title/Abstract] OR “compound* risk*”[Title/Abstract] OR “interacting hazard*”[Title/Abstract] OR “interacting event*”[Title/Abstract] OR “interacting risk” [Title/Abstract] OR “cascading hazard*”[Title/Abstract] OR “cascading event*”[Title/Abstract] OR “cascading risk*”[Title/Abstract] OR “interconnected hazard*”[Title/Abstract] OR “interconnected event*”[Title/Abstract] OR “interconnected risk*”[Title/Abstract] OR “interrelated hazard*”[Title/Abstract] OR “ interrelated event*”[Title/Abstract] OR

	interrelated event*" OR "interrelated risk*" OR "multiple hazard*") OR AK=("multi-hazard*" OR "multihazard*" OR "multi hazard*" OR "multi-risk*" OR "multirisk*" OR "multi risk*" OR "compound* hazard*" OR "compound* event*" OR "compound* risk*" OR "interacting hazard*" OR "interacting event*" OR "interacting risk" OR "cascading hazard*" OR "cascading event*" OR "cascading risk*" OR "interconnected hazard*" OR "interconnected event*" OR "interconnected risk*" OR "interrelated hazard*" OR " interrelated event*" OR "interrelated risk*" OR "multiple hazard*")) AND (TI=("indicator*" OR "index*" OR "indices" OR "metric*" OR "disaster risk indicator*") OR AB=("indicator*" OR "index*" OR "indices" OR "metric*" OR "disaster risk indicator*") OR AK=("indicator*" OR "index*" OR "indices" OR "metric*" OR "disaster risk indicator*")) Results = 590 Date Range is 2015 – present (day of search 3/11/2023) = 498 English = 494	"interrelated risk*"[Title/Abstract] OR "multiple hazard*"[Title/Abstract]) AND ("indicator*"[Title/Abstract] OR "index*"[Title/Abstract] OR "indices" [Title/Abstract] OR "metric*"[Title/Abstract] OR "disaster risk indicator*"[Title/Abstract]) Results = 109 Date Range is 2015 – present (day of search 3/11/2023) = 84 English = 83 Free Full Text = 49

Table S3. Broad classification of hazards with corresponding hazard types. The classification is adapted from the UNDRR hazard information profile (HIPs).

Broad classification	Specific hazards
Meteorological and hydrological	Drought Extreme precipitation Extreme temperature Flood - fluvial, pluvial, coastal or flash flood Heatwaves (or cold waves) Storm - tropical cyclone, tornado, wind storm, extra-tropical cyclone, hail, electrical/thunderstorm Tsunami
Geohazards	Earthquake Erosion - coastal erosion and shoreline change Landslide Tsunami - volcanic/earthquake triggering Volcanic eruption
Environmental	Erosion - river bank erosion Erosion - soil erosion Sea level rise Soil salinity Wildfire (Wildfire, forest fire)
Technological	Flood - sewer or reservoir flooding Pollution

Supplementary figures

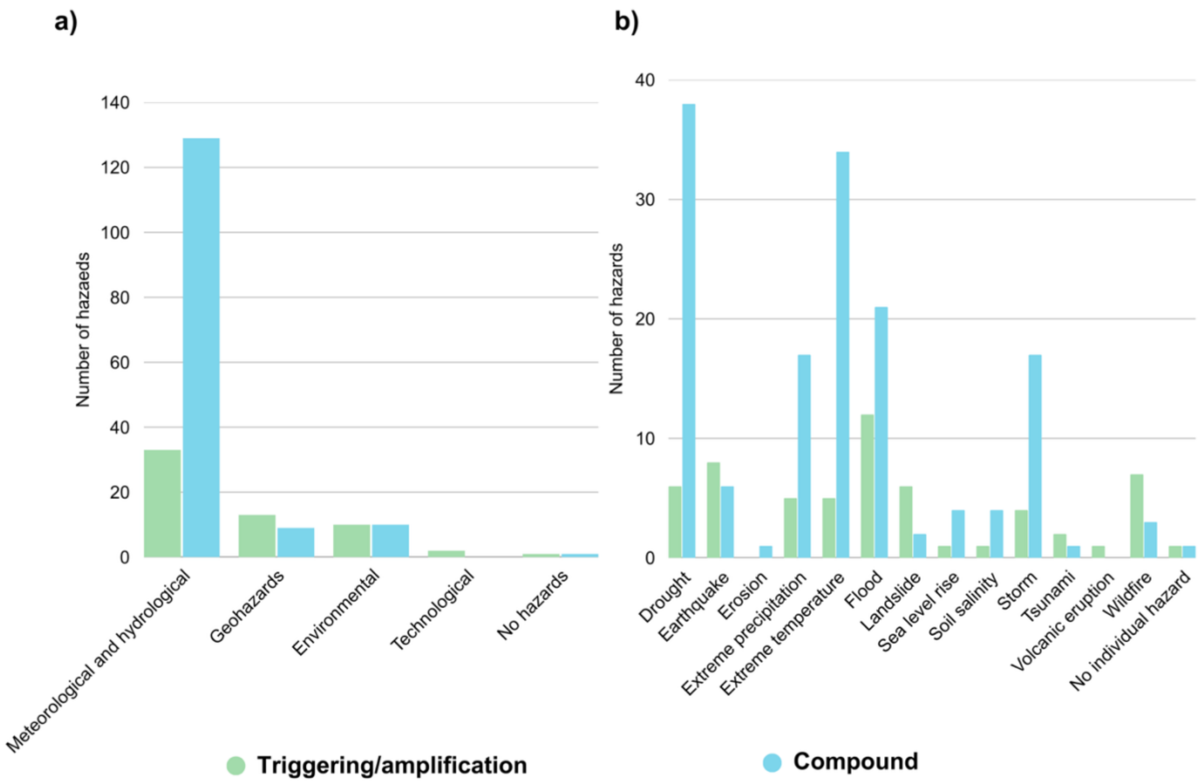

Figure S1. Distribution of hazards addressed in multi-hazard studies involving compound events or triggering/amplification relationships. (a) shows the number of hazards categorized according to the UNDRR's Hazard Information Profiles (HIPs) classification. (b) displays the number of studies based on the primary hazard involved in each multi-hazard sequence.

Supplementary text

Multi-layered single hazard indicators

Approximately 45% of the 192 reviewed articles focused on multi-layer single hazard studies, primarily targeting meteorological, hydrological, and geological hazards. Notably, these studies did not account for interactions between hazards. Indicators in this category were typically applied to individual hazards or aggregated into composite forms. Individually applied indicators often describe a hazard's extent and intensity. Single-variable indicators—frequently used in machine learning (ML) applications—support the identification of areas potentially exposed to specific hazards. This approach is particularly common in flood and landslide susceptibility assessments, where past occurrences and hazard preconditioning factors inform predictions of future hazard potential (Nguyen et al., 2023; Rehman and Azhoni, 2023; Pourghasemi et al., 2020). However, these studies are highly dependent on the quality of input data and often lack consideration of interactions or temporal overlaps between hazards.

In studies using composite indicators, multiple hazard maps are often overlaid for a specific geographic region. For instance, Emrich et al. (2022) developed a Composite Multi-Hazard Index (CHI) map for the United States, integrating 15 natural hazards and classifying them into five groups: (1) severe weather; (2) flooding, hurricanes, and storm surges; (3) winter weather; (4) heat, drought, and wildfires; and (5) earthquakes. These composite indicators are typically standardised or normalised to categorise hazard intensity levels (e.g., "very low" to "very high"). This methodology facilitates the inclusion of a broad array of variables and is widely employed in hazard mapping (e.g., Wang and Sebastian, 2022; Fleming et al., 2023; Ou et al., 2022; Barasa et al., 2022; Murnane et al., 2019).

Another subset of multi-layer single hazard studies involves assigning weights to individual hazard-causing factors, thereby reflecting variations in hazard intensities. Multi-hazard indicators developed using methods such as the Analytical Hierarchy Process (AHP) (Durlević et al., 2021; Guerriero et al., 2022) or ML-based algorithms (Mandal et al., 2022) exemplify this approach. Nonetheless, despite their methodological rigor, these studies still neglect spatiotemporal interactions among hazards, justifying their classification as multi-layer single hazard analyses.

Risk indicators based on multi-layer single hazards

Risk assessment research has increasingly incorporated multi-layer single hazard approaches. Among the 86 studies identified in this category, approximately 41% (n = 35) addressed risk, with the majority (n = 32) focusing on meteorological and hydrological hazards.

These risk assessments span multiple scales, from global to national levels, each employing context-specific methodologies. At the global scale, Marulanda Fraume et al. (2020) introduced a holistic risk assessment framework using data from 216 countries. Their model evaluated physical risk through direct hazard-induced damage and examined underlying risk drivers and amplifiers. At the national scale, Zuzak et al. (2022) developed the National Risk Index (FEMA, US), which integrates diverse geographic datasets and risk factors to generate a county-level risk profile. This index uses a transdisciplinary approach, involving stakeholder participation and composite indicators for comprehensive risk evaluation.

Several studies have also incorporated social vulnerability into multi-hazard risk assessments. Bixler et al. (2021), for example, used a modified Social Vulnerability Index (SoVI) to assess hazard exposure at the census block level. Similarly, Guillard-Gonçalves et al. (2015) applied SoVI in Greater Lisbon to delineate risk zones for six natural hazards—including earthquakes, floods, flash floods, landslides, tsunamis, and coastal erosion—through susceptibility and exposure mapping at the parish level.

Further, the scope of these studies extends to a variety of assets, including cultural heritage, rural communities, agriculture, and infrastructure. Valagussa et al. (2021) proposed the UNESCO Risk Index for assessing multiple hazard risks to cultural heritage sites in Europe. Asare-Kyei et al. (2017) developed the West Sudanian Community Risk Index to quantify drought and flood risks in rural West Africa, validated through a novel Community Impact Score (CIS).

Multi-criteria decision analysis (MCDA) is frequently employed to assess risk across multiple natural hazards. For instance, Arvin et al. (2023) used MCDA to integrate 25 indicators, evaluating flood, earthquake, and landslide exposure, as well as infrastructure resilience in Iran. In another example, Pagliacci (2019) created a risk framework for Italy's agri-food sector, using composite indicators for hazards, exposure, vulnerability, and overall risk across municipalities. Nofal et al. (2023) introduced a method for assessing infrastructure resilience to hurricane-related hazards, considering physical damage, functionality, and demographic factors, and employing composite indicators to quantify structural impacts. Additionally, Anderson et al. (2021) developed ecological and social vulnerability indices for the Mississippi Delta, which were combined into a multi-hazard vulnerability index. Asare-Kyei et al. (2017) also created a community-based socio-ecological systems (SES) indicator and validated it using a CIS framework.

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