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

Christopher J. White[1]; Mohammed Sarfaraz Gani Adnan[2]; Marcello Arosio[3]; Stephanie Buller[4]; YoungHwa Cha[1]; Roxana Ciurean[5]; Julia M. Crummy[6]; Melanie Duncan[6]; Joel Gill[4]; Claire Kennedy[1]; Elisa Nobile[3]; Lara Smale[6] and Philip J. Ward[7,8]

[1] Department of Civil and Environmental Engineering, University of Strathclyde, Glasgow, G1 1XJ, UK
[2] Department of Civil and Environmental Engineering, Brunel University of London, Uxbridge, UB8 3PH, UK
[3] Department of Science, Technology and Society, Istituto Universitario di Studi Superiori di Pavia (IUSS), Pavia, 27100, Italy
[4] School of Earth and Environmental Sciences, Cardiff University, Cardiff, CF10 3AT, UK
[5] British Geological Survey, Nicker Hill, Keyworth, Nottingham, NG12 5GG, UK
[6] British Geological Survey, The Lyell Centre, Research Avenue South, Edinburgh, EH14 4AP, UK
[7] Department of Water and Climate Risk, VU Amsterdam, 1081 HV Amsterdam, The Netherlands
[8] Deltares, Delft, 2629 HV Delft, The Netherlands

Correspondence to: Dr Christopher J. White (chris.white@strath.ac.uk)

Department of Civil and Environmental Engineering, University of Strathclyde, James Weir Building, 75 Montrose Street, Glasgow, G1 1XJ, UK

Abstract

The development of indicators in disaster risk management has only recently started to explicitly include a multi-hazard and multi-risk approach. However, undertaking a natural hazard or risk assessment from a single hazard approach can be considered incomplete where the interactions between, and impacts from, multiple hazards and risks are not considered. Indicators contain observable and measurable characteristics to simplify information to understand the state of a concept or phenomenon, and/or to monitor it over time. To understand how indicators are being used in this context, using a systematic review, we identified 192 publications that mention indicators within either multi-hazard or multi-risk contexts, including hazards, vulnerability, and risk/impact. We found that most studies exploring indicators focused on multi-layer single hazards and risks, where multiple single hazards or risks within a given location were analysed individually and their outcomes presented in an overlaid format. The results also demonstrate a predominance of studies on hazard indicators (88%) versus risk indicators, with a dominance of hydrometeorological indicators. Only 20% of the studies integrated hazard, vulnerability and risk/impact. Based on the findings, we propose a set of actionable recommendations to enable the development and uptake of multi-hazard and multi-risk indicators.

1. Introduction

Natural hazard events have the potential to impact areas over diverse temporal and spatial scales as well as influence each other (Gill and Malamud, 2014). These events also impact environments where there may be overlapping dynamic vulnerabilities and exposure from the socio-economic conditions of affected areas (Johnson et al., 2016). Undertaking a natural hazard or risk assessment using a single hazard approach can be considered incomplete as these approaches do not consider the possible interactions and impacts from multiple hazards on a specific location (Gill and Malamud, 2016; Sekhri et al., 2020). Despite this, natural hazards and their associated risks have largely been investigated from a single hazard perspective. However, in recent years there has been an increased focus on both multi-hazard and multi-risk approaches (e.g., Kappes et al., 2012; Duncan et al., 2016; Ward et al., 2022). Here multi-hazards are defined as "(1) the selection of multiple major hazards that the country faces, and (2) the specific contexts where hazardous events may occur simultaneously, cascadingly, or cumulatively over time, and taking into account the potential interrelated effects" (UNDRR, 2017a).

The international shift from single to multi-hazard and multi-risk thinking began in the 1990s, initially with the United Nations Agenda 21 where pre-disaster planning and settlement planning recommended the inclusion of "…complete multi-hazard research into risk and vulnerability" (United Nations, 1992). This was followed by the specification of "an integrated, multi-hazard, inclusive approach to address vulnerability, risk assessment and disaster management" (United Nations, 2002) from the World Summit on Sustainable Development. In 2005, the Hyogo Framework for Action—with the aim of reducing disaster losses by 2015—was adopted at the World Conference on Disaster Reduction. This framework called for the implementation of a multi-hazard approach to disaster risk reduction (UNISDR, 2005) and its incorporation into policies and planning for sustainable development. The Sendai Framework for Action (successor to the Hyogo Framework) inspires a multi-hazard approach to disaster risk reduction (DRR) practices (United Nations, 2015).

Aligned with the development and expansion of international DRR approaches, many indicators have been introduced to help assess the level of risk, monitor progress, and guide policies and interventions aimed at reducing disaster risk. Indicators are "…observable and measurable characteristics that can be used to simplify information to help understand the state of a concept or phenomenon, and/or to monitor it over time to show changes or progress towards achieving a specific change" (Gill et al., 2022 adapted from; Ivčević et al., 2019); see Box 1. They can be used as a standard, to assist with making decisions and for communications, and are capable of capturing a broad range of physical, social, and economic parameters. Indicators are used as a tool to define a baseline and track changes for monitoring and evaluation, allowing for the simplification of information, a situation, or an event, allowing them to be better understood, replicated, and monitored over time. Indicators have been used in a wide range of ways and applications, including as single variables representing an environmental or climatic parameter. For example, a precipitation indicator such as the Standardized Precipitation Index (SPI) may be used to represent meteorological drought (AghaKouchak et al., 2023), while cumulative rainfall thresholds or intense rainfall events (e.g., daily precipitation exceeding the 90th percentile) may be used as indicators of flood occurrence (Papagiannaki et al., 2022). Other studies use indices that integrate a combination of indicators to account for a relationship between them, such as the Multivariate Standardized Drought Index that uses a combination of precipitation and soil moisture (AghaKouchak et al., 2023).

Box. 1: From single to multi-hazard and multi-risk indicators

Indicators use empirically derived variables to quantify and measure the state, trends and evolution of a system over time. Derived from observational data and modelling, indicators serve as diagnostic tools for detecting, monitoring, and attributing shifts in hazard frequency, intensity, duration, and spatial distribution, forming essential tools for scientists, policymakers, and the public to understand and respond to climate- and hazard-related risks. Within the context of climate change and natural hazard monitoring, adaptation and disaster risk management, indicators provide a reliable basis for tracking the progress of change and evaluating the effectiveness of mitigation and adaptation efforts. Crucially, they support evidence-based decision-making and are instrumental in communicating complex scientific information in accessible formats. Indicators are also fundamental to the development of national risk-informed adaptation strategies and early warning systems, often forming part of national and international climate assessments, such as those produced by the Intergovernmental Panel on Climate Change (IPCC) and national meteorological and hazard agencies, extending across climate services, infrastructure risk assessments, and intergovernmental policy instruments.

To date, indicators are primarily single variate, covering key environmental parameters such as temperature, precipitation, sea level, ocean heat content, and atmospheric composition. The Sendai Framework for Disaster Risk Reduction (2015–2030), however, highlights the necessity of moving from single hazard and risk approaches to multi-hazards and multi-risks, encouraging countries to adopt indicators that account for the interactions between different hazards and risks. A more recent initiative for achieving the goals outlined in the Sendai Framework (specifically, Target G) is Early Warnings for All (EW4All), launched in 2022 and co-led by the WMO and UNDRR towards the development of Multi-Hazard Early Warning Systems (MHEWS) (UNDRR and WMO, 2023). However, the development of multi-hazard and multi-risk indicators—and the indices unpinning them—has not kept pace with these initiatives. Their development is challenging, requiring distinct methods and datasets. As such, to date, examples are limited and those that do exist have not been applied consistently. For example, Vitolo et al. (2019) use the Fire Weather Index (FWI) and the Universal Thermal Climate Index (UTCI) to assess the combination of extreme heat and wildfire, while Páscoa et al. (2022) apply the Standardized Precipitation Evapotranspiration Index (SPEI), Number of Hot Days (NHD), and Number of Hot Nights (NHN). For compounding flood events, Jalili Pirani and Najafi (2022) developed a Compound Hazard Ratio Index to characterise the interactions between different drivers of flooding (i.e., extreme precipitation, river flows and storm tides) and their effects on return level estimates of compound events, while Ganguli and Merz (2019) analysed spatio-temporal trends in compound flood events caused by the co-occurrence of fluvial floods and extreme coastal water levels using a Compound Hazard Ratio Index that links fluvial discharge with coastal water levels to understand historical trends in compound flooding.

The successful development of multi-hazard and multi-risk indicators will require consistency and the adoption of inherently interdisciplinary approaches and datasets involving a range of hazard types, their interactions, as well information on exposure, vulnerability, and risk/impact.

The International Decade for Natural Disaster Risk Reduction (IDNDR), which was declared by the United Nations between 1990 and 1999 (United Nations Department of Humanitarian Affairs, 1994), saw the growth and use of single hazard and single risk indicators. Today, the use of single hazard and single risk indicators are commonplace (see Box 1). The development of multi-hazard and multi-risk indicators for disaster risk assessment and management has, however, not kept pace with the development of multi-hazard DRR approaches and the use of indicators more generally. While indicator-based methods are commonly used to assess hazards and the vulnerability of elements at risk, these approaches are limited as they do not integrate analyses of different hazards or the interaction between them (Julià and Ferreira, 2021). Adopting multi-hazard and multi-risk approaches with indicators would allow for the identification of interactions and the subsequent impacts of various hazards that could be used to improve the understanding of both hazards and risk (Depietri et al., 2018). However, existing approaches largely remain insufficient to support a multi-hazard analysis that take account of the complex interactions between hazards (Lou et al., 2023a) and it remains a challenge to represent the dynamic nature of hazards, exposure, vulnerability, and multiple risks. Cardona (2005) is one of the earlier works in this field, presenting a framework for assessing and managing disaster risks by using indicators that account for various hazards and vulnerabilities in Latin America and the Caribbean—a region particularly prone to several natural hazards. However, the development of multi-hazard and multi-risk approaches was in its infancy at that time, limiting the adoption and uptake of the concepts presented. More recent approaches advocating for the development and use of multi-hazard and multi-risk indicators have been seen across a range of climate change adaptation and disaster risk-related studies focusing on hazards, vulnerability, or exposure, but also impact, coping capacity, and resilience. AghaKouchak et al. (2023) for example calls for drought monitoring and research to "move beyond individual drivers and indicators to include the evaluation of various potential cascading hazards" and to develop indicators that establish links between different hazards and the impact. In an assessment of coastal resilience frameworks that also investigated the use of resilience indicators, Almutairi et al. (2020) note that most of the frameworks evaluated consider single hazard types only, and that future frameworks should address the interrelationships between multiple hazards. Sebesvari et al. (2016) similarly calls for a multi-hazard assessment of vulnerability with the development of new indicators that would be able to capture the complexity and exposure of multi-hazards, particularly in delta socio-ecological systems and regions. There remains, however, a gap in knowledge as to what multi-hazard and multi-risk indicators have been developed or a clear demonstration of what their potential is.

Terminology is a particular issue that has affected the development and uptake of multi-hazard and multi-risk indicators up to now. For example, there are different ways of describing the interaction between hazards. These include triggering or cascading relationships, where a primary hazard may cause an associated hazard; compound relationships, where multivariate events and unrelated hazards may overlap spatially and/or temporally; and (de-)amplification, where one decreases or increases the probability of occurrence or the magnitude of another hazard (Ciurean et al., 2018; Gill et al., 2022). There are also alternative terms for what an indicator is, including index and metric. In some instances, these terms are used interchangeably even though there is a distinction between their definitions, i.e., an indicator is a single measurable variable or metric that provides information about a specific aspect of a system, condition, or outcome; whereas an index is a composite measure that combines multiple indicators into a single numerical value or score (OECD, 2008). To establish consistency, a set of definitions are provided in Table 1.

Table 1. List of terms and definitions used in this study.

Terminology	Definitions	Source
Multi-hazard	"1) the selection of multiple major hazards that the country faces, and 2) the specific contexts where hazardous events may occur simultaneously, cascadingly or cumulatively over time, and taking into account the potential interrelated effects."	UNDRR (2017a)
Multi-risk	Risk generated from multiple hazards and the interrelationships between these hazards (and considering interrelationships on the vulnerability level).	Zschau (2017)
Compound hazards	"Compound weather and climate events are defined as a combination of multiple drivers and/or hazards that contribute to risk."	Zscheischler et al. (2020)
Triggering/ cascades	"One hazard causes another hazard to occur, which can result in hazard chains, networks, or cascades."	Ciurean et al. (2018)
Amplifying	"The occurrence of one hazard can increase the likelihood and/or magnitude of additional hazards in the future."	Ciurean et al. (2018)
Indicator	"Observable and measurable characteristics that can be used to simplify information to help understand the state of a concept or phenomenon, and/or to monitor it over time to show changes or progress towards achieving a specific change."	Gill et al. (2022) adapted from Ivčević et al. (2019)
Vulnerability	"The conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards."	Sendai Framework Terminology on Disaster Risk Reduction (UNDRR, 2015)
Impact	The realised, or potential consequences on natural and human systems, where consequences result from the interactions of hazards, exposure, and vulnerability. Impacts generally refer to effects on lives, livelihoods, health and well-being, ecosystems and species, economic, social and cultural assets, services (including ecosystem services), and infrastructure. Impacts may be referred to as consequences or outcomes.	IPCC (2018)
Qualitative method approach	"Qualitative research methods aim to address societies' scien-tific and practical issues and involve naturalistic and in-terpretative approaches to different subject matters. These	Taherdoost (2022)

	methods utilize various empirical materials such as case studies, life experiences, and stories that show the routines and problems that individuals are struggling with in their lives through focusing on their in-depth meaning and mo-tivations which cannot be defined by numbers. Qualitative research aims to collect primary, first-hand, textual data and analyse it using specific interpretive methods.”	
Quantitative method approach	“Quantitative research methods aim to define a particular phenomenon by collecting numerical data to address specific questions such as how many and what percentage in different fields. It is the method of employing nu-merical values derived from observations to explain and describe the phenomena that the observations can reflect on them. This method employs both empirical statements, as descriptive statements about the meaning of the cases in real words not about the ought of the cases, and methods. It also applies the empirical evaluations intending to determine to which degree a norm or standard is fulfilled in a particular policy or program. Finally, the collected numerical data is analysed using mathematical methods.”	Taherdoost (2022)
Mixed-method approach	“Mixed-method methods simply employ a combination of both qualitative and quantitative approaches based on the purpose of the study and the nature of the research question aiming to provide a better understanding of the subject.”	Taherdoost (2022)

To date, there has been no concerted effort to collate and review existing multi-hazard and multi-risk indicators or attempt to unify these approaches, demonstrate their potential value in DRR activities or offer guidance for their development. This paper uses a systematic review process to document and explore the use of indicators within the multi-hazard and multi-risk contexts for the first time and sets out recommendations for their future development and use. The review paper is structured as follows: section 2 lays out the methodology for the systematic literature review and the analysis of the findings; section 33 provides a detailed overview of the use of indicators in hazard and risk assessments; section 4 provides a wider discussion and a suggested recommendations for the development of multi-hazard and multi-risk indicators; and section 5 provides some concluding remarks.

2. Methods

A systematic literature review approach was employed to identify peer-reviewed literature that either use indicators, or analyse the use of indicators, in multi-hazard and multi-risk studies, guided by the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) protocol (Page et al., 2021). The methodology followed six steps: 1) definition of key search terms, 2) identification of records, 3) screening of results based on inclusion and exclusion criteria, 4) categorising the research papers into two broad categories of multi-hazard and multi-risk studies, 5) selecting key works from each category that are the most significant and provide good examples of multi-hazard and multi-risk indicator use, 6) assessing the suitability of each record in more detail.

The Scopus, Web of Science and PubMed databases were used to extract literature related to indicators in multi-hazard and multi-risk studies, due to their comprehensive coverage of peer-reviewed articles. The search terms (Table S1) were stratified into two levels. The first level encompassed terminology associated with multi-hazard and multi-risk studies, including alternative spellings and descriptors such as "compound", "interacting", "cascading", and "interconnected" hazards and/or risks. A total of 22 Level 1 search terms were employed. The alternative terminologies were combined using an "OR" Boolean operator and then paired with Level 2 search terms using an "AND" Boolean operator. Level 2 comprised five search terms related to indicators and alternative or related terminology for indicators (i.e., "index", "indices", "metric", "disaster risk indicator"). The search terms were applied across title, abstract, and keywords. To ensure methodological rigor and minimise the omission of relevant studies, keywords were carefully selected to maximize coverage of pertinent literature while limiting the retrieval of irrelevant results, following best practices for systematic reviews (Pullin and Stewart, 2006). Although not exhaustive, this set of search terms effectively narrowed the research scope to multi-hazard and multi-risk studies, excluding single hazard or risk papers that fall outside the scope of this study. The search strings used across all three databases, together with relevant keywords and Boolean operators, are provided in Table S2.

The initial search returned 1,468 articles that met the search criteria. A date restriction was applied to include only papers published post-2015, aligning with the publication year of the Sendai Framework for Disaster Risk Reduction and its emphasis for the adoption of a multi-hazard approach. A duplicate removal process, executed using R, was applied to the 1,140 articles, identifying and excluding 515 duplicates. Figure 1 provides a flowchart detailing the screening process, including the number of articles at each stage of the review.

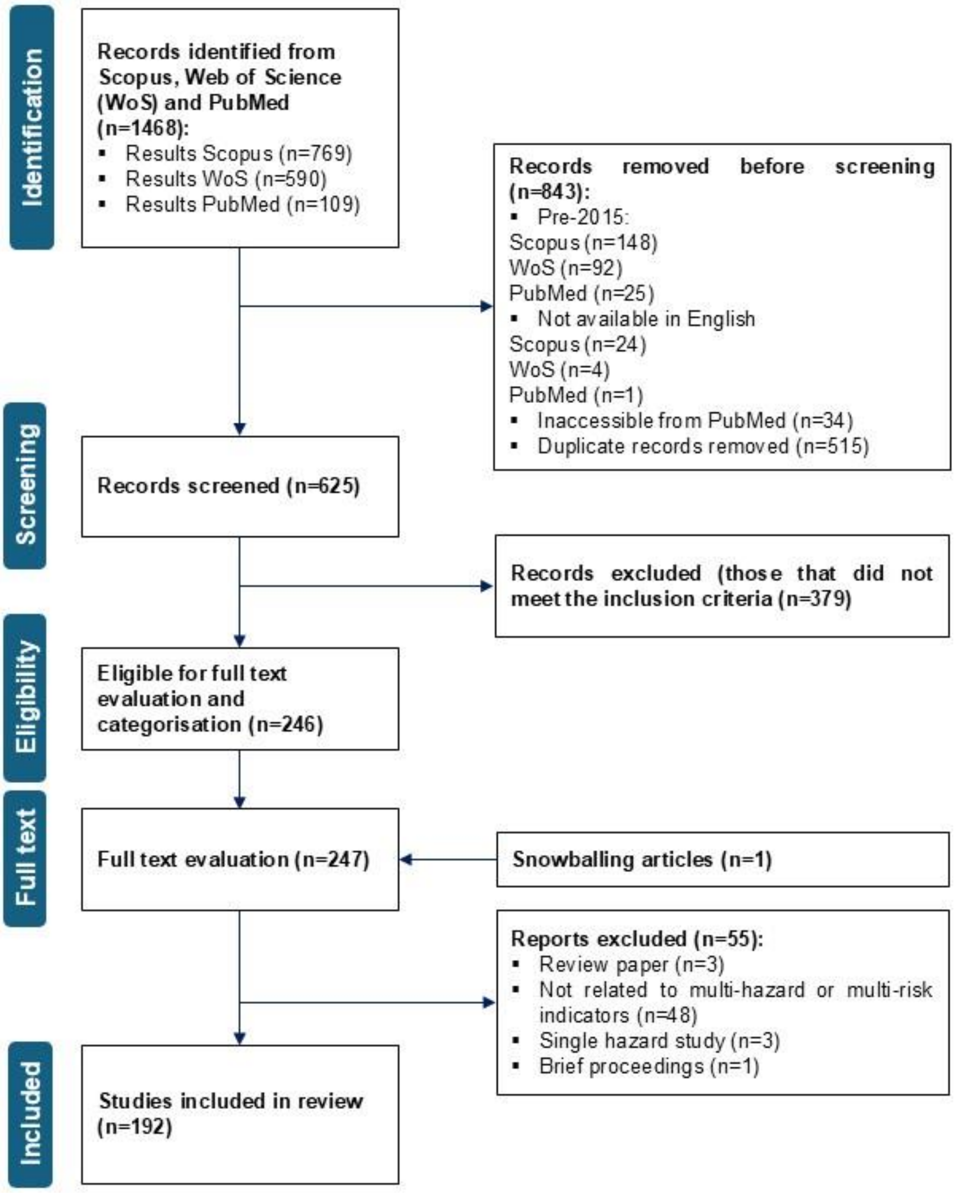

Figure 1. Flowchart of the systematic literature review used in this study, showing the identification, screening and inclusion process together with the numbers of articles at each stage.

After removing duplicates, a two-part screening process was applied to the remaining unique 625 articles. Initially, all articles were screened based on their titles and abstracts to create a database comprising papers considered relevant for further review, while irrelevant papers were excluded. Relevance was primarily assessed manually based on the use of multi-hazard and multi-risk indicators in evaluating natural hazards across diverse research domains. The first phase of the screening excluded 379 papers, leaving 246 that were relevant for further investigation. In the second screening phase, the full text of these 246 articles were evaluated. An additional reference (i.e., snowballing article) was identified and included during the full text evaluation (n=247) stage. A database was established to collect the retrieved information (Pickering and Byrne, 2014) and to minimize the risk of bias in the selection process. A total of 53 articles were excluded at the full-text evaluation stage. The following exclusion criteria were applied during both screening phases:

- Articles that did not align with the study's objectives, as determined by the title, abstract, or keywords.
- Review articles.
- Studies focusing on risks related to animal, bird, plant species, marine habitats, human health, pollution, unmanned vehicles, workplace safety, finance and insurance, and nuclear risks.
- Studies investigating structures, electrical grids, infrastructure resilience, and transport networks in terms of robustness, functionality, or performance based on structural integrity or design.
- Articles that did not address or utilise multi-hazard or multi-risk indicators.
- Brief conference proceedings.

Following the screening process (i.e., full text evaluation), 192 papers were retained for analysis and critical assessment. These studies were used to extract information on single hazard types and their classification according to the UNDRR hazard information profiles (HIPs) (Murray et al., 2021). A total of 19 hazard types were identified, falling into four broad classes defined by HIPs: (1) meteorological and hydrological, (2) geohazards, (3) environmental, and (4) technological. Studies that did not address any specific hazard were categorised as ‘no hazards’. Supplementary Table S3 presents these four classes alongside their corresponding specific hazards.

Although this review primarily focused on multi-hazard and multi-risk studies that address interactions between hazards or risks, a number of included articles were found to adopt a multi-layer single hazard or risk approach. To distinguish between these different approaches, the 192 reviewed articles were classified into two broad categories:

Category 1: Multi-layer single hazard and risk—These studies individually analysed multiple single hazards or risks occurring within a given location, with outcomes presented in an overlaid format. Although often referred to by the authors as multi-hazard or multi-risk, these assessments did not consider interactions between hazards and thus do not meet the definition of multi-hazard as used in this review.

Category 2: Multi-hazard and multi-risk—these studies explicitly addressed interactions between hazards. They were further categorised into two broad classes based on the nature of these interactions: compound; and triggering and amplification relationships. Definitions of these interaction types are provided in Table 1.

The review also examined aspects of vulnerability, impact and risk assessment approaches, including quantitative, qualitative and mixed-method studies. The terms "risk" and "impact" were used to encompass both studies focusing on potential future consequences, typical of risk assessments, and those analysing past events. Exposure was not evaluated separately, as it was implicitly incorporated through the vulnerability typologies and the consequences evaluated within risk/impact assessments. Definitions of the various assessment approaches are also provided in Table 1.

Finally, the multi-hazard and multi-risk studies were further reviewed to extract information on the indicators used. Through an inductive analysis of the reviewed literature, indicators were grouped into four main categories based on their primary roles in the studies: (1) (UNDRR, 2017a) indicators used to describe hazard characteristics, (2) indicators representing exposure, vulnerability (sensitivity, or susceptibility), and adaptive capacity (or resilience), (3) indicators describing risk/impacts, and (4) composite indicators. Hazard indicators were further subdivided into three types following the UNDRR (2017a) classification: intensity, frequency, and probability. Studies that did not include any form of indicator were grouped under a separate ‘no indicator’ category. Table 2 provides a summary of each indicator category along with corresponding definitions and representative examples.

Table 2. Classification of indicators in multi-hazard and multi-risk studies.

Indicator category	Types	Description
Hazard	Intensity	Indicators measuring the strength or magnitude of a hazard event, such as flood extent, earthquake peak ground acceleration, wind speed, etc. (e.g., Paulik et al. (2023); Depietri et al. (2018)).
	Frequency	Indicators reflecting how often a hazard occurs over a given period. Examples include flood frequency, number of landslide events, etc. (e.g., Ramli et al. (2021); Rehman et al. (2022)).
	Probability	Indicators expressing the likelihood of a hazard event occurring, such as return period of extreme water level, probability of landslide occurrence (e.g., Mahendra et al. (2021); Bernal et al. (2017)).
Exposure/ Vulnerability/ Resilience	Exposure	Indicators capturing the presence of people, assets, or systems in hazard-prone areas (e.g., Viavattene et al. (2018)).
	Vulnerability, sensitivity or susceptibility	Indicators reflecting the degree to which exposed elements are likely to be affected, such as vulnerable population number (e.g., Depietri et al. (2018); Cremin et al. (2023).
	Adaptive capacity or resilience	Indicators reflecting the ability of a system or community to adjust and recover from hazards (e.g., Pal et al. (2023); Bernal et al. (2017)).
Risk/impact	N/A	Indicators quantifying observed or potential consequences of hazard events. Examples include, economic losses, number of fatalities, damaged infrastructure (e.g., Bernal et al. (2017)).
Composite indicator	N/A	Aggregated indicators combining multiple dimensions, such as storm severity index and flood severity index (e.g., Bloomfield et al. (2023)).
No indicator	N/A	Studies that did not employ explicit indicators in their methodology.

3. Results

3.1 Overview of the articles reviewed

3.1.1 Distribution of articles with respect to risk components

This review analysed the use of multi-hazard and multi-risk indicators, focusing on four main categories: hazard, vulnerability, risk/impact, and composite indicators (see Table 2). Figure 2 provides an overview of how the reviewed articles are distributed across the hazard, vulnerability, and risk/impact components. Among the 192 studies included in the review, the components of hazard, vulnerability, and risk/impact were addressed a total of 338 times, as many articles discussed more than one component. This reflects the overlapping and interconnected nature of these elements in multi-hazard and multi-risk studies.

Hazard was the most frequently discussed component, appearing in 174 articles, followed by vulnerability (96 articles) and risk/impact (68 articles) (Figure 2a). Figure 2b illustrates how these components overlap within the literature. For example, only the 44% of the studies(n=84) focused solely on hazard, while the remaining 56% (n=108) also included discussions of vulnerability and/or risk/impact. In contrast, most articles addressing vulnerability or risk/impact were associated with overlapping concepts. Notably, only 54 articles (28%) examined all components.

To better understand how hazard was conceptualised, the 174 hazard-related articles were further analysed to determine whether they considered interactive multi-hazard events. The results show that 51% (n=89) of these articles accounted for interactions between hazards, while 49% (n=85) analysed multiple single hazards separately, with outcomes presented in an overlaid format. These were classified as multi-layer single hazard studies (Figure 2c).

For the articles related to vulnerability and risk/impact, the review also examined the methodological approach—qualitative, quantitative, or mixed methods. As shown in Figure 2c, mixed methods were most commonly employed, whereas qualitative-only approaches were least frequent. This trend suggests that integrating multiple methodologies is considered important for capturing the complexity and potential consequences in risk/impact assessments.

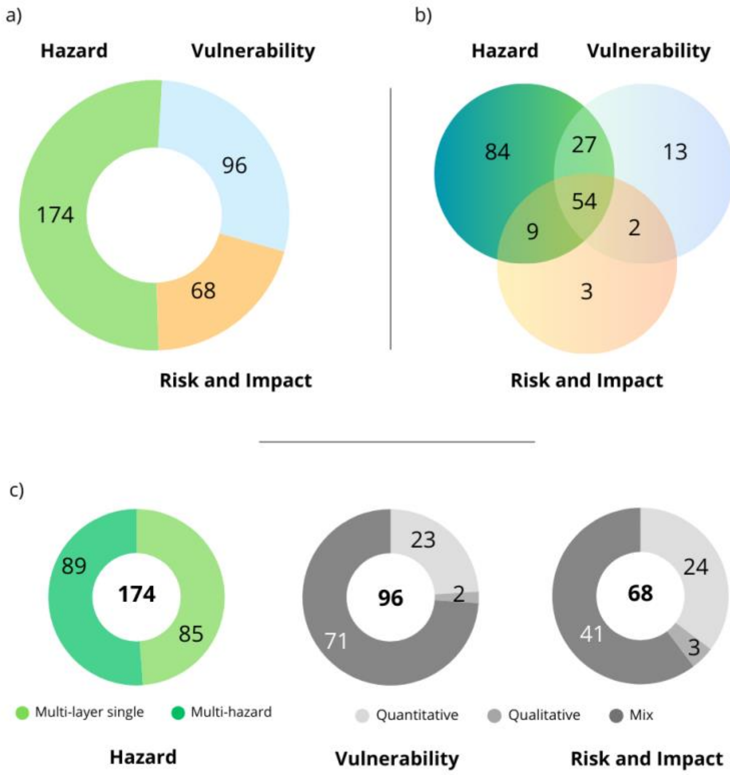

Figure 2. Distribution of articles reviewed in this study: a) Number of articles addressing hazard, vulnerability, and risk/impact components, b) Venn diagram illustrating the overlap between articles that considered different combinations of these components, and c) Number of articles categorized by assessment approaches: for hazards—multi-hazard vs. multi-layer single hazard; for vulnerability—quantitative, qualitative, or mixed methods; and for risk/impact—quantitative, qualitative, or mixed methods.

3.1.2 Distribution of articles according to hazard interactions

The hazard-related articles found in this study (see Section 3.1.1) addressed a total of 502 individual hazards. As detailed in the methods section, these hazards were grouped into 19 distinct types and classified into four broad categories based on the UNDRR's HIPs: meteorological and hydrological, geohazards, environmental, and technological hazards. Figure 3 illustrates the frequency of different hazards and their classification according to the type of interaction considered. Findings show that meteorological and hydrological hazards were the most frequently studied, accounting for 64% (n=319) of all hazards, followed by geohazards (21%), environmental hazards (10%), and technological hazards (2%). In 3% cases (n=15), no specific hazard was identified.

As highlighted in Section 3.1.1, 49% of the 174 hazard-related articles did not analyse interactions between hazards. These were classified as multi-layer single hazard studies, where multiple hazards were assessed individually but without accounting for their interactions in time or space. This category includes 51% (n=257) of all 502 hazards analysed. Geohazards are very often represented as multi-layer single hazards, suggesting that they were often studied as isolated or recurring events rather than as part of a complex multi-hazard system. Similarly, all technological hazards fell under this category, indicating a consistent treatment of these hazards as isolated incidents, with minimal consideration of their potential interactions with other hazard types. Further details on multi-layer single hazard studies are provided in the supplementary document.

Compound interactions were the second most common, representing 30% (n=149) of all hazards. These interactions involve hazards that occur simultaneously or in close succession. Most compound events stemmed from meteorological and hydrological hazards—particularly drought, extreme temperatures, floods, storms, and extreme precipitation—highlighting their tendency to co-occur and interact in complex ways. A smaller portion of compound hazards originated from geohazards (e.g., earthquakes) and environmental hazards (e.g., wildfires) (Figure S1, Supplementary document).

Triggering and amplification interactions accounted for 12% (n=59) of the hazards, where one hazard triggers or amplifies the effects of another. These were predominantly associated with meteorological and hydrological hazards (e.g., flooding), followed by geohazards (e.g., earthquakes) and environmental hazards (e.g., wildfires). Finally, 7% (n = 37) of the hazards did not fall into any of the above categories. These were labelled as 'no interaction' cases, either due to limited information or because they did not meet the criteria for multi-layer single hazard, compound, or triggering/amplification relationships (Figure S1, Supplementary document).

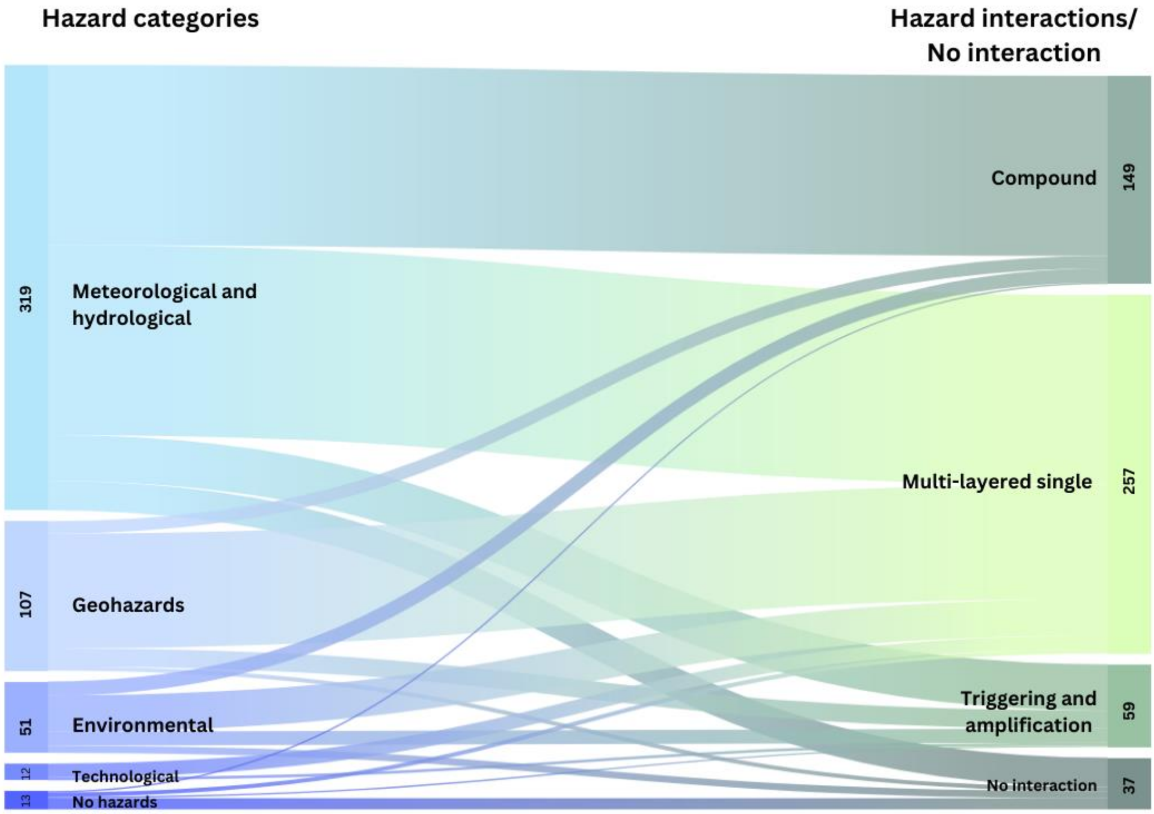

Figure 3. Sankey diagram illustrating the distribution categories and interactions of 502hazards analysed across 174 research papers that discussed hazards. The numbers indicate the number of hazards associated with each node in the diagram, and the flow dimensions are proportional to the number of hazards transitioning between nodes.

3.2 Multi-hazard and multi-risk indicators

3.2.1 Compound hazard indicators

Among the 174 hazard-related articles identified (Figure 2a), 89 addressed multi-hazard events, including compound events and those involving triggering and amplification relationships, for a total of 208 hazards. In particular, 149 compound multi-hazard events were found, constituting the 30% of the 502 hazards identified in this study(Figure S1, Supplementary document)

Various indicators were used to characterise these compound events. Figure a provides a breakdown of the different types of indicators applied to compound multi-hazard events in relation to primary hazards. Overall, composite indicators were the most commonly used, associated with about 47% followed by probability (19%), frequency (15%), and intensity (4%). Notably, 14% of indicators adopted were not associated with any specific hazard indicators (Figure 4a).

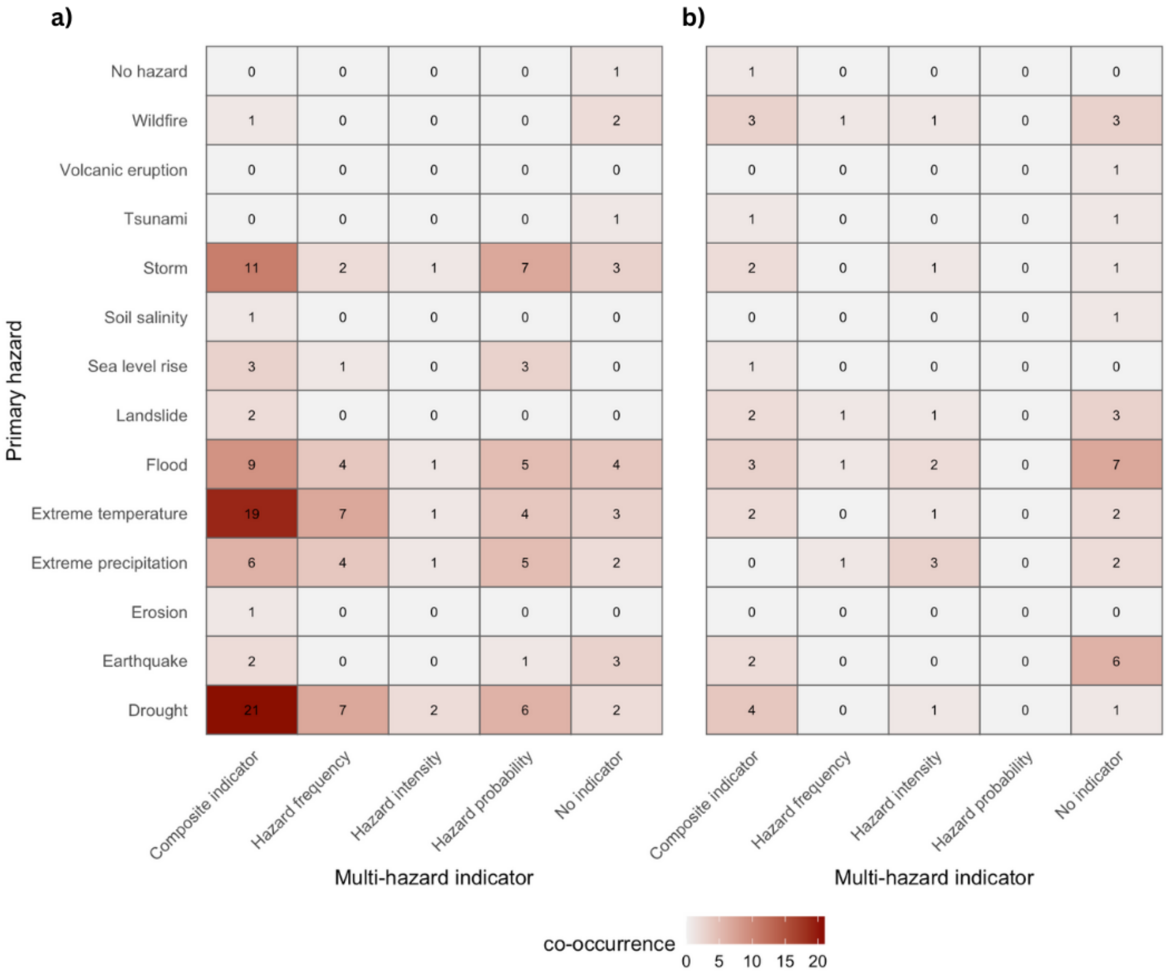

Figure 4. Matrix showing the relationships between primary hazards in multi-hazard sequences and multi-hazard indicators for (a) compound multi-hazard and (b) triggering and amplification events.

A wide variety of indicators were used across different types of compound hazards. In studies focused on meteorological hazards, such as droughts and extreme temperatures, composite indicators were most frequently used. However, the design and application of these indicators varied. For example, Feng et al. (2021) evaluated compound dry and hot events (CDHEs) in global maize-producing regions using a combination of drought indices—self-calibrating Palmer Drought Severity Index (scPDSI), SPI, and Standardized Precipitation-Evapotranspiration Index (SPEI), and Standardized Temperature Index (STI) as "hot" indicators. Bonekamp et al. (2021) used seven indicators, including five single-hazard indicators and two multi-hazard indicators, to analyse extreme temperature and precipitation events under current and future climate scenarios.

Some studies developed specific compound multi-hazard indicators. For instance, Bian et al. (2022) introduced the Compound Drought Heatwave Magnitude Index (CDHMI) based on the non-stationary SPEI (NSPEI) and daily maximum temperature (Tmax), to quantify the probability and intensity of CDH events in easter China. Qian et al. (2023) used an alternative version of CDHMI, replacing Tmax and SPEI with a heatwave magnitude index and a drought magnitude index. Wu et al. (2019) proposed the Dry-Hot Magnitude Index (DHMI) to measure the severity of hot and dry using monthly precipitation and Tmax. Hao et al. (2019) developed the Standardized Compound Event Indicator (SCEI), combining SPI and STI to represent the severity of hot-dry events and predict them in conjunction with the El Niño–Southern Oscillation (ENSO).

Regarding storms and floods, composite and probabilistic indicators were more prevalent. For instance, Jalili Pirani and Najafi (2022) applied copula theory to assess the statistical dependencies between flood drivers—extreme precipitation, river overflows, and storm tides—and developed a Compound Hazard Ratio (CHR) index to evaluate their interactions and influence on return level estimates. Ganguli and Merz (2019) analysed historical trends of compound flooding in northwestern Europe (1901–2014), linking fluvial discharge and coastal water levels through the CHR index. Mitu et al. (2023) developed a topographic D-Index to identify areas dominated by surge, flow, and compound flooding. Alberico and Petrosino (2015) proposed two indices based on hazard recurrence intervals, capturing the temporal dimensions of multi-hazard and multi-risk through time-window-based or probabilistic approaches.

3.2.2 Triggering and amplification hazard indicators

Of the 502 hazards identified in this study (including multi-layer single hazards and multi-hazard events), 12% (n=59) were classified as triggering and amplification types (Figure 3). Nearly half (n=11) were not associated with any specific hazard indicators. Among those with indicators, composite indicators were the most frequently used (n=8), followed by frequency and intensity measures. Notably, probability indicators were not applied to this category (Figure 4b).

Triggering and amplification events occurred across meteorological, hydrological, and geohazards. Various approaches were used to develop composite indicators for these events. Regarding meteorological hazards, Khorshidi et al. (2020) analysed wildfire size to identify the occurrence of 'megafires' triggered by the co-occurrence of several drivers, rather than focusing on the magnitude of individual hazards. Their study examined correlations between eight meteorological drivers and fire sizes, using data from southern California. Piao et al. (2022) developed a spatial fire risk map by identifying regions where drought and wildfire overlapped. They combined existing indicators such as the SPI and Enhanced Vegetation Index (EVI) with machine learning techniques to generate composite hazard indicators.

In studies involving geohazards, Bernal et al. (2017) performed a probabilistic risk assessment of multi-hazard interactions in Manizales, Colombia. Their approach incorporated earthquakes, volcanic (lahar), and landslide hazards. Landslide susceptibility was estimated using an artificial neural network, with earthquakes and extreme rainfall as triggers. Risk was quantified through probabilistic relationships between hazard intensities and mean damage ratios. In the context of hydrological hazards, Rocha et al. (2021) proposed a flood risk management framework for the western Portuguese coast. This study treated coastal flooding as a precursor to coastal erosion, using hazard data and vulnerability indicators to assess overall coastal risk.

Regarding the combination of geo and hydrological hazards, Coscarelli et al. (2021) explored the relationship between climate indices and the frequency of landslides, floods, and forest fires in Italy. They used historical hazard data and weather-derived indices to develop predictive models, revealing that landslides correlated with moderate rainfall, floods with extreme rainfall, and wildfires with low moisture content. Argyroudis et al. (2019) examined consecutive earthquake and flood events to create a multi-hazard resilience index, using "damage state to bridge" as a key indicator. Ramli et al. (2021) developed an Integrated Disaster Risk Assessment Framework (IDRAF), an evolution of the EU MOVE project. This framework encompassed eight meteorological, hydrological, and geohazards types and associated multi-hazard scenarios through two key components: frequency of occurrence and spatial interaction. A semi-quantitative approach was used to develop multi-hazard and multi-vulnerability indicators. The framework was implemented at the local scale in Malaysia and evaluated by 64 disaster risk management experts from both governmental and non-governmental sectors.

3.2.3 Multi-risk indicators

Among the 89 studies related to multi-hazards—including compound, triggering, and amplification hazards—28 (31%) analysed risks or impacts. Of these, 18 studies applied multi-risk indicators that combined various metrics such as exposure/vulnerability indicators, impact indicators, and composite indicators. The remaining 10 studies did not use any specific multi-risk indicators. Table 3 summarises different types of indicators used to explain risks and their components.

Table 3. Examples of indicators used in multi-risk studies.

Category	Types	Number of studies	Description	Sources
Exposure/Vulnerability indicators	Exposure index	2	• Coastal exposure index, an example of vulnerability indicator, is used to assess the exposure of coastal areas to various hazards. • Exposure is defined using variables such as population density, land use, infrastructure, and utilities.	Mahendra et al. (2021); Viavattene et al. (2018)
	Vulnerability index	4	• Vulnerability index is typically calculated as a function of hazard, exposure, sensitivity or susceptibility, and adaptive capacity or resilience. • Social vulnerability indices are commonly used metric, which generally includes different combinations of factors related to exposure (e.g., built environment factors), sensitivity or susceptibility (e.g., demographic characteristics of population, education level, income group), and adaptive capacity or resilience. • Physical coastal vulnerability indices are also used, which focus on	Thakur and Mohanty (2023); Sekhri et al. (2020); Song et al. (2020); Sahoo and Bhaskaran (2018)

			environmental and structural attributes.	
Risk/impact indicators	Impact metrics	7	• Impact metrics include indicators of physical (e.g., building damage, infrastructure disruption), economic (e.g., business losses, household financial impacts), social (e.g., casualties), and environmental (e.g., ecosystem disruption) impacts.	Bernal et al. (2017); Cremen et al. (2023); Viavattene et al. (2018); Ramli et al. (2021); Lou et al. (2023b); Oliveira et al. (2018); Hillier and Dixon (2020)
Composite indicators	Composite hazard indicator	1	• Example: Physical Services Index, a composite indicator used to represent cumulative impacts of hazards on services.	Gotangco and Josol (2022)
	Composite risk indicator	4	• Examples: Global Delta Risk Index (GDRI), multi-risk score, and risk index. • These composite risk indices combine indicators hazard, exposure, and vulnerability, providing an integrated risk assessment framework.	Hagenlocher et al. (2018); Gallina et al. (2016); Depietri et al. (2018); Zhang et al. (2023)

Most studies defined risk by overlaying multiple dimensions, including vulnerability, exposure, and coping capacity to produce composite vulnerability or risk indices (Beltramino et al., 2022). Among the different categories of multi-risk indicators, impact indicators were the most commonly used. Seven studies employed various impact metrics to assess physical impacts (e.g., building damage and infrastructure disruption), economic impacts (e.g., business losses and household income reduction), social impacts (e.g., casualties), and environmental impacts (e.g., ecosystem degradation). Vulnerability indicators followed in usage, often presented in the form of exposure indices or composite vulnerability indices. For example, the Vulnerability Index integrates hazard exposure, sensitivity, and adaptive capacity indicators into a single metric (Sekhri et al., 2020). Similarly, Thakur and Mohanty (2023) estimated a coastal vulnerability index by combining parameters such as physical coastal characteristics, environmental variables, and socio-economic factors.

A commonly used approach in multi-risk studies is the Social Vulnerability Index (SoVI), which combines various socioeconomic and built environment indicators to quantify vulnerability (Cutter et al., 2003). Although SoVI is frequently applied in multi-risk analysis (Song et al., 2020), it is generally hazard-agnostic and can be used across different hazard types. For instance, Yang et al. (2015) employed SoVI to map social vulnerability across regions in China without reference to a specific hazard or hazard impact. This hazard-agnostic approach is also evident in other composite vulnerability assessments, which aim to simplify complex systems by consolidating multiple variables into a single index (Marulanda-Fraume et al., 2022).

Composite risk indicators were also widely adopted across multi-risk studies. For instance, Gotangco and Josol (2022) developed the Physical Service Index (PSI) framework to evaluate the combined effects of urban development, flooding hazards, and chronic deprivation in Manila, Philippines. Several other studies used the Global Delta Risk Index (GDRI), a composite indicator for assessing risks from multiple hazards—such as cyclones, floods, storm surges, and droughts—in vulnerable delta regions (Hagenlocher et al., 2018; Gallina et al., 2016; Depietri et al., 2018; Zhang et al., 2023).

In addition to developing new multi-risk indicators, some researchers created libraries of multi-risk indicators, offering customizable options for practitioners and stakeholders. These databases typically include indicators related to social, ecological, and economic dimensions across various hazards and contexts (Shah et al., 2020; Sebesvari et al., 2016). For instance, Hagenlocher et al. (2018) developed a repository of hazard-dependent and hazard-independent vulnerability indicators, specifically designed for application in delta regions.

Despite the benefits of integrated risk assessments, combining multiple indicators can introduce uncertainties, particularly when equal weights are assigned to different risk components without considering their relative importance. To address this issue, several recent studies have introduced methods for assigning indicator weights more systematically. A common approach involves expert judgment, which is used to estimate the significance of different risk parameters (Mafi-Gholami et al., 2019; Arvin et al., 2023; Cotti et al., 2022). For example, Gallina et al. (2016) used weighted scores within a hazard matrix to evaluate multi-risk scenarios. However, while expert judgment-based weighting improves flexibility, it can also introduce systematic bias if not carefully managed (Jacome Polit et al., 2019).

4. Discussion and recommendations for indicator development

4.1 Key findings

Our review has highlighted the broad use of indicators for risk assessment and management (i.e., Bernal et al., 2017; Sekhri et al., 2020), to identify interactions between hazards (i.e., Jalili Pirani and Najafi, 2022), and as stand-alone indicators for establishing warning thresholds (i.e., Vitolo et al., 2019; Li et al., 2021). However, this study finds that there are few studies that explicitly develop indicators for multi-hazards and/or multi-risks, even when this is presented as the context. Through our review and analysis of these indicators, we note the following:

- While there are many useful examples of indicators being developed and used in layered single hazard studies, there are few studies that explicitly develop indicators for multi-hazards and/or multi-risks, highlighting a notable gap in the literature. However, the global hazard and risk literature analysed recognises that interrelationships exist between hazards and that multi-hazard and multi-risks should be incorporated in indicators, confirming the need and want for their development.
- Current work on indicators supporting multi-hazard and/or multi-risk management is dominated by a focus on compound event types, with less work on indicators for triggering and amplification effects.

- Research on hazard indicators was found to be more common than studies on other components of risk (e.g., vulnerability) or broader characterisation of risk itself. There are limited examples of multi-risk indicators that embed understanding of multi-hazard relationships.

- The selection and use of different terminology and definitions by different groups affects the development and use of indicators and remains a challenge for the advancement of multi-hazard and multi-risk work (e.g., vulnerability indicators developed following the IPCC (2007) versus the UNDRR (2017b) definitions).

- The findings of this study also reveal a lack of stakeholder engagement and prioritisation in developing multi-hazard multi-risk indicators; the extent to which these can therefore translate effectively into supporting multi-hazard disaster risk management is ambiguous.

Aspects of these findings align with similar studies on the increase in the literature. For example, with respect to the impact of terminology and varying interpretations of multi-hazard concepts, Kappes et al. (2012) noted the diversity of terms used for hazard relationships, Gill and Malamud (2014) reflect on the impacts of different interpretations of the multi-hazard concept (the multi-layer single hazard perspective vs. a more holistic multi-hazard approach), and Ciurean et al. (2018) reviewed different classifications of hazards before synthesising these into a proposed taxonomy (subsequently adopted in Gill et al. (2022)). The impact of variations in terminology is evident in the development and application of indicators. Risk management would be strengthened by the creation of and adherence to guidance for the development and use of indicators in multi-hazard, multi-risk contexts, building on existing good practices and drawing on established and agreed terminology and definitions. The broader multi-hazard literature also demonstrates a wide array of new and developing methods for characterising hazard dependencies (e.g., Gill and Malamud, 2014; Tilloy et al., 2019; Zscheischler et al., 2020; De Angeli et al., 2022; Hochrainer-Stigler et al., 2023; Claassen et al., 2023; Lee et al., 2024) and dynamics of other components of risk (e.g., De Ruiter and Van Loon, 2022). A breadth of approaches is likely necessary to support risk characterisation in different contexts (e.g., data poor vs. data rich), but variation in the approaches used to characterise multi-hazard relationships may make it challenging to develop generic indicators for monitoring the management of multiple hazards and multi-risks.

Many of the papers reviewed (e.g., Li et al., 2021; Lou et al., 2023b; Pal et al., 2023) imply that their results and the use of indicators may be of potential use to stakeholders who are responsible for disaster risk management or climate change adaptation. However, the extent to which stakeholders have been engaged in the process of creating and/or testing indicators to support decision-making in multi-hazard or multi-risk contexts is generally not clear. Stakeholder engagement and prioritisation varies from consulting with expert groups (e.g., Damian et al., 2023) to interactive co-development (e.g., Fleming et al., 2023). Understanding the priorities, interests, ambitions, and challenges of stakeholders is essential to developing and undertaking effective DRR research (Gill et al., 2021). Of the 192 papers reviewed, however, only 15 studies include some element of stakeholder engagement, of which 6 studies are within the multi-hazard category (i.e., Cremen et al., 2023; Gallina et al., 2020; Hagenlocher et al., 2018; Sekhri et al., 2020; Viavattene et al., 2018; Vitolo et al., 2019). The remaining 9 studies are either layered single hazard (n=8) or include no specific hazard (n=1). Of the 15 studies that include stakeholder engagement, 14 focus on multi-hazard risk assessment, which requires consideration of socio-economic vulnerabilities and impacts from multi-hazard events. When developing multi-hazard and multi-risk indicators for disaster risk management and climate change adaptation, it is crucial to consider how and where to use multi-hazard information with stakeholders. For example, interactive stakeholder engagement in setting weighting, prioritisation and thresholds plays a critical role, as it guides sensitivity to certain impact areas, such as applying physical drought models to early warning systems for food security (Boult et al., 2022). This approach also enables stakeholders to issue early and timely warnings (Li et al., 2021). These results show that collaborative environments which integrate interdisciplinary expertise with relevant stakeholder engagement are essential for multi-hazard and multi-risk indicator development and implementation.

With the United Nations increasingly advocating for multi-hazard and multi-risk approaches, data, and governance (United Nations, 2023), this review provides evidence of a notable gap in the literature but also—crucially—growing demand and activity for the development and use of multi-hazard and multi-risk indicators that support the Sendai Framework. The increase in research activity demonstrated through the literature reviewed in this study has been supported by a succession of European Union-funded research projects focused on multi-hazards and multi-risks that are, in-part, addressing this policy demand. These and other ongoing projects have been established to investigate the challenges posed by multi-hazards and multi-risks, highlighting a clear momentum towards a shift from single to multi-hazard analysis and multi-risk assessment and management.

4.2 Recommendations for multi-hazard and multi-risk indicator development

Based on the insights gained on multi-hazard and multi-risk indicators from this review, and building on previously-established challenges associated with multi-hazard and multi-risk research, we suggest the following eight recommendations that are designed to (i) advance research and methodologies that allow robust indicators for multi-hazard and multi-risk contexts, (ii) improve uptake and use of indicators by providing actionable recommendations for their development, and (iii) create and strengthen an enabling and interdisciplinary collaborative environment for their development:

1. Indicator development should not solely focus on hazard characteristics but should also integrate risk-based dimensions (e.g., vulnerability, exposure, sensitivity, adaptive capacity) and impacts (physical, economic, environmental), reflecting the complexity of multi-hazards and multi-risks. This development can be extended beyond hazard and risk assessment to establish real-time monitoring systems and early warning mechanisms that provide up-to-date information on the emergence and propagation of multi-hazard events.

2. Given the current predominance of indicators for compound multi-hazard events evidenced in the literature, there is a need to develop indicators that capture triggering, amplification, and cascading relationships between hazards to represent the dynamic and interconnected nature of multi-hazard systems.

3. Composite indicators designed to capture multi-hazard and multi-risk dimensions should be adaptable to diverse regional contexts, account for socio-economic disparities, and align with the specific priorities of relevant stakeholders, including policymakers, emergency planners, and affected communities.

4. Where feasible, mixed-method approaches are essential for developing robust multi-hazards and multi-risks indicators, integrating quantitative data (e.g., historical hazard frequencies, exposure metrics), qualitative insights (e.g., community perceptions), and expert judgement to comprehensively reflect the complexity and interdependencies of risk drivers.

5. Multi-hazard and multi-risk indicators should be co-developed through interactive and participatory processes involving relevant stakeholders, ensuring that they are meaningful, practical, and tailored to decision-making needs in disaster risk management and climate adaptation.

6. While not specific to indicators, the adoption of clear and consistent terminology in the definition and usage of terms such as ‘multi-hazard’, ‘multi-risk’, ‘indicator’ and ‘index’ is crucial as ambiguities in terminology currently hinder the comparability and integration of different approaches.

7. Indicators should be designed considering the availability, resolution, and quality of underlying datasets, especially where data are scarce or uneven across hazards and/or risks. This can be supported through the use of online open-access collaborative repositories and libraries for sharing good practices and data (e.g., the open-access MYRIAD-EU Disaster Risk Gateway https://disasterriskgateway.net/) together with the use of advanced visualisation tools (e.g., the DRMKC Risk Data Hub https://drmkc.jrc.ec.europa.eu/risk-data-hub#/atlas).

8. Finally, the development of new multi-hazard and multi-risk indicators should align with international frameworks, such as the Sendai Framework for Disaster Risk Reduction, the UN SDGs, MHEWS and EW4All, to ensure these indicators support the measurement, reporting, and achievement of globally recognised targets and contribute effectively to international disaster risk reduction and resilience-building efforts.

5. Conclusions

In this study we systematically reviewed existing multi-hazard and multi-risk indicators and present recommendations for their future development and use. While there is broad use of indicators for risk assessment and management, and for identifying interactions between hazards and warning thresholds, this study finds that there are few studies that explicitly develop indicators for either multi-hazard or multi-risk contexts, highlighting a notable gap in the literature. The majority of the studies described as multi-hazard or multi-risk were, on inspection, multi-layer single hazard and risk; in other words, these did not include the interactions between hazards. The results also demonstrated a predominance of studies on hazard assessment (88% of publications), and a dominance of meteorological and hydrological hazards, particularly in the context of compounding hazards. Only 20% of the papers included in the review integrated hazard, vulnerability and risk/impact—a reflection of the complexity of multi-hazard risk. The methodologies used in the reviewed studies included quantitative, qualitative and mixed methods approaches, with a predominance of mixed methods applied in risk assessment, highlighting the interdisciplinarity and role of methods such as expert judgment in multi-hazard risk assessment. The ongoing challenge related to the selection and use of different multi-hazard risk terminology within the literature was echoed in our findings. Based on the findings of the review, we set out eight actionable recommendations to progress the development and enable the uptake of multi-hazard and multi-risk indicators. This review is limited to the peer-reviewed literature; future work should build upon this review through the exploration of grey literature and direct engagement with stakeholders involved in indicator relevant applications of disaster risk reduction (e.g., through interviews).

Author contribution

Conceptualization: CW; Data curation: CK; Formal analysis and visualization: MSGA, MA, EN, CK; Methodology and writing – original draft preparation: all authors.

Competing interests

At least one of the (co-)authors is a member of the editorial board of Natural Hazards and Earth System Sciences.

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