A multi-hazard framework for spatial-temporal impact analysis

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ABSTRACT
This paper aims to provide a five-step conceptual framework to analyze the impacts to the built environment from multi-hazard interactions. Our methodology includes a critical literature review and stakeholder workshops. This framework’s five steps are the following: (I) identify hazards and their interactions, (II) multi-hazard modelling, (III) analysis of the hazards’ spatio-temporal evolution of impacts, (IV) identification of impact interactions, (V) a multi-hazard risk or impact assessment. Our approach is based on the systematic analysis of the spatial and temporal evolution of hazards to determine potential impact interactions. In Step IV, we classify the spatial-temporal overlap of hazard impacts into four types: (i) spatial-temporal overlapping, (ii) temporal (but not spatial) overlapping, (iii) spatial overlapping (with residual and subsequent damage), (iv) independent single hazards. Building on current multi-hazard approaches and guidelines, this framework is generally applicable to a broad range of hazards, includes both hazard and impact interactions, and considers residual damage and recovery processes. The framework is applied to a real-world case study in Po Valley, Italy, of a hypothetical damage scenario from an earthquake shock that weakens the levee system, and then combined with intense rain results in a levee collapse and flood. The framework application is supported by a visualization of each step, useful to identify key elements for multi-hazard impact modelling. Practical uses of the framework include the creation of checklists for decision-making, narrowing future research needs in multi-hazard risk, and integrating multi-hazard aspects into international disaster risk management guidelines.

1. Introduction

This paper aims to construct a multi-hazard impact conceptual framework to support practitioners and researchers in analyzing the impact of multiple hazards and their interactions in a given region of interest. This framework was developed from a critical literature review of multi-hazard impacts and stakeholder engagement. In addition to focusing on multi-hazard causal dependencies, this paper evaluates how hazards overlap in space and time, resulting in four types of impact interactions. In this introduction, we will (i) describe the background and rationale of this work, (ii) clarify the main terminology adopted in the context of multi-hazards, and (iii) summarize the overall organization of this paper.

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The number of people affected by natural hazards is increasing in many world regions [1-3] due to population growth and urbanisation (particularly in developing countries) [4]. In addition to single hazards, there are also examples of impacts from interacting natural hazards (e.g., an earthquake blocking a river resulting in a flood) and hazard events that coincide in time and space [5-7]. Many regions of the world are prone to multiple types of natural hazards. Through an analysis of all the relevant threats, an effective risk reduction can be adequately carried out [8].

The current COVID-19 pandemic has dramatically shown the need to develop multi-hazard risk scenarios with the ability to consider the interactions between pandemics and other natural hazards, such as hydrogeological or geomorphological hazards. Indeed, the lack of multi-hazard risk early warning systems has increased the risk of compounding impacts originating from natural hazard events during the COVID-19 pandemic [9-11]. This has included both the natural disaster’s effects being worse than they would otherwise be without COVID-19 and the additional spread of COVID-19 [9].

In contrast to the analysis of single hazard events, examining events involving multiple hazards poses a series of challenges in each

| Term                          | Definition                                                                 | Reference       |
|-------------------------------|---------------------------------------------------------------------------|-----------------|
| Capacity                      | “The combination of all the strengths, attributes and resources available within a community, society or organization that can be used to achieve agreed goals. Capacity may include infrastructure and physical means, institutions, societal coping abilities, as well as human knowledge, skills and collective attributes such as social relationships, leadership and management”. | UNISDR [19], UN [20] |
| Damage                        | Negative impacts i.e., impacts that result in negative effects on assets, people, socioeconomic and environmental systems. | GFDRR [21], Moore and Phillips [22], Groeve et al. [23] |
| Exposure                      | “The situation of people, infrastructure, housing, production capacities and other tangible human assets located in hazard-prone areas”. Exposure is described through a series of characteristics of the exposed elements (or exposed assets), such as material, occupancy, economic value of a building or number of people. | UNISDR [19], UN [20] |
| Hazard                        | “A process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation. Hazards may be natural, anthropogenic or socio-natural in origin. Natural hazards are predominantly associated with natural processes and phenomena [...]. Hazards may be single, sequential or combined in their origin and effects. Each hazard is characterized by its location, intensity or magnitude, frequency and probability.” | UNISDR [19], UN [20] |
| Impact                        | “The total effect, including negative effects (e.g., economic losses) and positive effects (e.g., economic gains), of a hazardous event or a disaster. The term includes economic, human and environmental impacts.” In this paper, we restrict this term only to tangible direct physical damage to assets. Other types of impacts (economic, environmental, social, etc.) both direct and indirect are not currently addressed. | UNISDR [19], UN [20] |
| Loss                          | A measure (usually in monetary terms) of a certain damage.                  | GFDRR [21], Moore and Phillips [22], Groeve et al. [23] |
| Multi-hazard                  | “An approach that considers more than one hazard in a given place (ideally progressing to consider all known hazards) and the interrelations between these hazards, including their simultaneous or cumulative occurrence and their potential interactions.” | Gill and Malamud [5] |
| Multi-hazard risk (or impact) | A risk (or an impact), which is evaluated considering the effects of multiple hazards |                |
| Natural hazard event (or event scenario) | “A specific occurrence of a [natural] hazard [...] often constrained by a spatio-temporal domain.” | Schmidt et al. [24] |
| Risk                          | “The potential loss of life, injury, or destroyed or damaged assets which could occur to a system, society or a community in a specific period of time, determined probabilistically as a function of hazard, exposure, vulnerability and capacity.” | UNISDR [19], UN [20] |
| Territorial system            | “Territorial systems represent functional structures, made of natural, social, economic, psychological components and supporting elements of the man’s activity (the built space). Between these major components interdependence relationships are established, aiming to attain some common purposes established by human communities”. In this paper, we specifically focus on the physical infrastructural elements of a territorial system, i.e. built-up area, transport networks and lifelines. The expression ‘territorial system’ is used in this manuscript to refer to an ensemble (possibly interrelated) of exposed physical assets able to provide one or more functionalities in a given region of interest. | Ianço et al. [25] |
| Vulnerability                 | The totality of “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”. In this paper, we specifically refer to the physical vulnerability, which is the propensity of territorial elements to suffer physical damages from hazardous events. Vulnerability is represented by curves or functions, which measure the expected damage as a function of the hazard magnitude. | UNISDR [19], UN [20] |
As a practical response to this issue, this paper suggests a five-step approach to multi-hazard risk assessment, focusing on multi-hazard interactions, causal dependencies and evaluating multi-hazard impact, i.e., considering the damages caused by hazard interactions. The approach outlined here has been partially motivated by outcomes from a critical literature review and stakeholder workshops in the context of two research projects [17,18] (described in Section 2).

We now discuss the main terminology adopted in this paper in the context of multi-hazards. As an emerging focus of research and interest, multi-hazard risk assessment lacks a standard glossary among different communities [13]. Table 1 clarifies the terminology adopted in this paper, including the definitions for capacity, damage, exposure, hazard, impact, loss, territorial system, natural hazard event, risk, vulnerability, multi-hazard and multi-hazard risk.

In Table 1, we have briefly introduced twelve definitions for risk-related terms, of which nine are adopted from definitions from other authors [5,19,20,24,25] and two (damage, loss) do not refer to a unique specific definition but have been accepted and extensively used inside the disaster loss data community [21–23]. The definition for ‘multi-hazard risk’, which will be explored in more depth in Section 3, is given in our own terms.

The elements of ‘hazard’ in Table 1 are (i) physical process, (ii) location, (iii) frequency and (iv) probability of occurrence of a dangerous phenomenon. A multi-hazard approach considers these elements (and possibly their interactions) for more than one hazard acting upon a single location over a predefined time window. The definition of risk reported in Table 1 includes various combinations of the following elements: hazard, exposure, vulnerability and capacity. These elements are usually combined (e.g., Ref. [26]) to evaluate the risk through the so-called ‘Risk Equation’:

\[
\text{Risk} = \frac{\text{Hazard} \cdot \text{Exposure} \cdot \text{Vulnerability}}{\text{Capacity}}
\]  

(1)

In this representation, hazard, exposure, and vulnerability increase the overall risk, while capacity reduces it. According to these concepts, the term ‘multi-hazard risk’ is not a synonym of ‘multi-hazard’; instead, multi-hazard is a key component for a multi-hazard risk assessment. The term ‘multi-hazard’ refers to a series of approaches where multiple hazards and their interrelations are analyzed and modeled. Multi-hazard risk is defined here as a risk assessment that considers the impact of multiple hazards. A multi-hazard risk approach involves both multi-hazard and multi-vulnerability perspectives [27]. See Section 3 for a more nuanced view of the word multi-hazard, its definitions, and multi-hazard risk concepts.

This paper is organized as follows: first, our methodology is presented (Section 2). Then, a critical review of multi-hazard risk approaches is reported (Section 3). This is followed by a description of the five steps of our multi-hazard conceptual impact framework with an aim to standardize the approach for model damages arising from hazard interactions (Section 4). Then, the application of this multi-hazard impact framework is illustrated in a multi-hazard case study in Po Valley, Italy, consisting of an actual earthquake from 20 May 2012, which weakens a levee, followed by hypothetical intense rain on 29 May 2021, resulting in a levee collapse and riverine flood (Section 5). Finally, the main conclusions and future developments are discussed (Section 6).

2. Methodology

This paper presents a conceptual framework to support practitioners and researchers in analyzing the potential spatial-temporal impact of multiple hazards and their interactions in a given region and time period of interest. The two primary methodologies used in this paper are the following:

i. Critical literature review of multi-hazard risk approaches. A critical approach to reviewing the literature has been adopted to identify the main current issues related to multi-hazard risk and impact assessment to be integrated into our conceptual multi-hazard impact framework.

ii. Engagement with stakeholders via workshops. Stakeholder workshops and expert knowledge, as part of the MERCI [17] and RASOR [18] projects (described below), were iteratively combined with the critical literature review to construct (i) six basic interaction mechanisms between hazards, (ii) the five steps of our multi-hazard impact framework, (iii) the stakeholder choice and then application of a semi-real life case study.

2.1. Critical literature review

We use a critical literature review [28, 29] approach to initially inform Section 3 (Critical review of multi-hazard approaches) and parts of Section 4 (A five-step multi-hazard impact framework). The literature on multi-hazards and multi-hazard risk has a diverse set of researchers from different disciplines with an extensive set of literature. We wanted a representative and critical view of the
literature (versus a systematic mapping of all relevant literature [30]). The specific protocol that we followed (taking elements from Boaz et al. [31]) includes:

i. Focus on developing and answering specific questions.
ii. Seek to identify a representative sampling of the relevant research on the question(s) while remaining as objective as possible as to the source of information used.
iii. Critically discuss and synthesise the research findings.

Our critical literature review aims to identify the main current issues related to multi-hazard impact assessment to be integrated into the conceptual framework. The following questions have guided this critical literature review:

i. How are the terms ‘multi-hazard’, ‘multi-hazard risk’, and synonyms, defined?
ii. Which approaches for multi-hazard and multi-hazard risk are currently available?
iii. How are current multi-hazard approaches differentiated?
iv. What are the current limitations of these multi-hazard approaches regarding evaluating the impacts generated by multiple hazards?
v. What are the primary interaction mechanisms among hazards, including examples, and how can these mechanisms be defined?

In Google Scholar and Scopus databases, we applied a series of keywords (multi-hazard, multi-risk, hazard interaction, multiple hazards, multi-hazard risk) to identify peer-review literature in English. Throughout the literature review, we attempted to remain objective without considering the number of citations or the authors’ institution name or country. We supplemented these findings using public deliverables and results of European co-funded projects related to multi-hazards. The relevant projects have been selected from the Community Research and Development Information Service (CORDIS) of the European Commission using the same keywords used in Google Scholar and Scopus databases. In addition, for key papers and projects found, we also examined their references and those who cited the source. About 400 papers/documents were returned from these searches, and of these, we used about 100 to inform our results in this paper. Within each research question, we then clustered the papers, finding the following gaps:

i. Multi-hazard studies mainly focus only on hazard interactions, without including other risk or impact assessment elements.
ii. Many multi-hazard studies only focus on one or two families of hazards (e.g., tectonic, hydrogeological).
iii. Available multi-hazard risk or impact approaches usually do not model recovery dynamics and residual damage due to consecutive disasters.

2.2. Stakeholder workshops

Our five-step multi-hazards framework (Section 4) has also been shaped by integrating iteratively the critical literature review outcomes (Section 2.1), with our additional expert knowledge and the outputs of stakeholder engagement. Stakeholders included actors from different stages of the Disaster Risk Management cycle, with engagement via meetings and workshops carried out in the framework of two research projects:

i. RASOR “Rapid analysis and spatialisation of risk” [18]. This 2.5 year 2013–2016 EU-funded research project included six multi-hazard case studies, each with corresponding local stakeholders in Indonesia, Greece, Italy, Haiti, the Netherlands, and Malawi (Table 2). Two dedicated multi-hazard workshops (one day and two days, 40–50 participants each) were held in Italy as

| Case study | Stakeholders | Case study request |
|------------|--------------|--------------------|
| Indonesia (Jakarta, Bandung, Cilacap) | BNBP (Indonesian Civil protection); BPBD (Jakarta sub-national civil protection authority); ITB (Bandung Institute of Technology); Unilever Foundation | Multi-hazard approaches to model impacts from coastal flooding and subsidence in Jakarta, riverine flooding and subsidence in Bandung, storm surge and tsunami in Cilacap. |
| Greece (Santorini Island) | Greek Civil Protection | Cascading earthquake-induced rockfalls and consequent tsunami in the caldera: multi-hazard risk assessment and identification of evacuation response time parameters. |
| Italy (Emilia Romagna) | ADBPO (Po Basin Authority); A IPO (Agenzia Interregionale del Fiume Po); ARPA-SIMC (Agenzia Regionale di Protezione Ambientale); DPC (Italian Civil Protection Department) | Earthquake damage to flood structural protection measures, re-evaluation of flood hazard and flood risk maps, computation of “what if” scenarios, including levee disruption. |
| Haiti (Port-au-Prince, Gonaives) | Haitian Civil Protection; CNIGS (Centre National d’Information Geospatial); CIRMH (Caribbean Institute for Meteorology and Hydrology); UWI (University of West Indies) | Combined loss caused by parallel hazards due to hurricane passage: wind, localised flooding and riverine flooding, storm surge. Earthquake damage assessment. |
| The Netherlands (Rotterdam) | Ministry of Infrastructure (Rijkswaterstaat - WMCN) | Compound coastal and riverine flooding, including monitoring of flood defences through interferometry. |
| Malawi (Salima, Karonga, Mangochi) | DODMA (Department of Disaster Management Affairs); DCCMS (Department of Climate Change Meteorological Services); DWR (Department of Water Research); DoS (Department of Survey) | Impacts due to consecutive drought and flood events. |
part of the RASOR research grant: 9-10 June 2015 and 17 May 2016. The purpose of these workshops was (i) to define user requirements and main functionalities, including pilot sites requests for multi-hazard risk modelling, (ii) to present and get feedback on an initial framework done in the context of the RASOR project for multi-hazard modelling.

ii. **MERCI “Multi-site events response and coordinated intervention”** [17]. This 2 year 2016–2018 EU-funded project was led by the French Red Cross and included five other Red Cross partners (Bulgaria, Spain, Italy, Portugal and the Red Cross EU Office). CIMA Research Foundation (some of the authors of this paper) were involved as an external consultant, and had multiple discussions with the Italian Red Cross to develop further the draft five-step multi-hazard impact framework. Then, at a one day workshop (16 October 2017) which included 1-2 representatives of each partner, this draft of the five-step multi-hazard impact framework was extensively discussed with further stakeholder feedback.

Each RASOR case study (Table 2) was defined and analyzed in close coordination with local end-users that helped to shape the methodology to contribute to existing multi-hazard risk management procedures and operations. In addition to the six local case studies, the project worked with global organizations, specialized institutes and local users on meeting the need for global and national standards in risk management, broken up into the following five user groups:

i. *International organizations or companies working on DRR* (World Bank, United Nations Satellite Centre (UNOSAT), Global Earthquake Model (GEM)).

ii. *Regional disaster management and agencies* (Caribbean Disaster Emergency Management Agency Protection Authorities (CDEMA), Caribbean Institute for Meteorology and Hydrology (CIMHI)).

iii. *National and sub-national disaster management decision-makers* (Dutch Ministry of Environment and Infrastructure, Italian Civil Protection Department, the Greek National Civil Protection, and other local sub-national decision-makers in Greece, Italy and Indonesia).

iv. *Insurance and reinsurance companies* (Munich Re, Risk Management Solutions (RMS)).

v. **Specialized institutes and other data providers** such as PusAir (The Indonesia Flood Research institute), Centre National de l’Information Géo-Spatiale in Haiti, ITHACA (Information Technology for Humanitarian Assistance, Cooperation and Action) and NGOs such as Map Action.

These five sets of users were engaged through the two RASOR stakeholder workshops, where stakeholders and practitioners from the international arena interacted. As a result of the critical literature review and then iteratively working with stakeholders in the context of both the RASOR and MERCI research projects, an initial multi-hazard framework for temporal and spatial analysis was developed. The two stakeholder workshops in RASOR were particularly essential in informing the breadth of spatial-temporal interaction types included in our framework. Different stakeholders identified specific priorities as to what would be included in a broader framework. After the workshops were over, which included an initial draft of our multi-hazard impact framework, the authors refined the framework to arrive at the one seen in this paper, particularly focusing on the synthesis graphics presented in Section 4. Among the case studies investigated by the RASOR project, a real-world multi-hazard impact case study in the Po Valley (Italy) has been selected for this paper to test the applicability of our conceptual framework (Section 5). For this case study, and as part of the RASOR research project, a strong interaction was developed with the following groups, which helped to inform the choice and development of this project in Section 5:

i. The ADBPO (Po Basin Authority) has responsibility for the risk profiling in the Po basin, Italy.

ii. The AIPO (Agenzia Interregionale del Fiume Po) has responsibility for maintaining the active and passive flood defences along the Po Basin main river and tributaries.

iii. The ARPA-SIMC (Agenzia Regionale di Protezione Ambientale) holds the technical knowledge and advises the regional civil protection on the risk conditions also based on forecasts.

iv. The DPC (Italian Civil Protection Department) coordinates actions in case of large disasters.

In this real-world case study from Po Valley, Italy, we selected and developed (in consultation with the above agencies) a hypothetical scenario of damage from an earthquake main shock that weakens the levee system, and then combined with intense rain, results in a levee collapse and flood. This specific case study has been chosen for the following reasons:

i. Based on a stakeholders’ needs assessment, the multi-hazard impact interaction described in this case study is of great interest for the Italian Civil Protection.

ii. This case study includes the most innovative features of our multi-hazard framework, such as interacting hazards belonging to different families (i.e. geophysical and hydrological), and modelling of the residual damage generated by subsequent (non-simultaneous) events.

iii. Seismic and flood risk have been the two most investigated hazards in the RASOR project and for which detailed hazard modelling is available.

iv. According to the INFORM Risk Index [32] from the European Commission Disaster Risk Management Knowledge Centre (DRMKC), the two most significant risks in Italy regarding hazard probability and exposure are earthquakes (and consequent tsunamis) and floods.

### 3. Critical review of multi-hazard risk approaches

This section presents a critical review of multi-hazard risk approaches. We first identify different definitions of ‘multi-hazard’, then
present an overview of the main multi-hazard approaches in the literature, distinguishing two main categories. Finally, as a result of this review, we identify some of the leading open issues in multi-hazard risk assessment. In Section 1, we defined multi-hazard as a series of approaches where multiple hazards and their interrelations are analyzed and modeled. However, different definitions are found in the literature, where the overarching theme is more than one hazard is considered in the assessment. Three definitions are given in Table 3.

The first definition in Table 3 [8] is the simplest. It refers to multiple hazards as a series of hazards relevant to a region, without considering any interactions among them. The other two definitions [5,33] introduce mutual interactions and interrelationships among hazards, with [33] slightly more detailed. These two kinds of definitions are representative of the two multi-hazard approaches [5,8]:

i. **Multi-hazard approach I: Independent** multi-hazards (does not consider hazard interactions).

ii. **Multi-hazard approach II: Interacting** multi-hazards (considers hazard interactions).

Multi-hazard approach I, ‘independent multi-hazards’, is directly related to risk-reduction and sustainability international policies; for example, Agenda 21 [34], the Johannesburg plan [35], and the Hyogo Framework for Action [36]. These policies are based on a spatial approach; that is, all relevant hazards in a defined area are considered. This concept, named by Hewitt and Burton [37] as an “all-hazards-at-place-approach” and discussed by Gill and Malamud [5] as a “multilayer single hazard” approach, entails methodologies for the following:

i. The independent analysis of multiple different hazards, e.g., Refs. [38–40].

ii. The superimposition of various hazard layers to identify areas that overlap, e.g., Refs. [41–45].

Both approaches consider which natural hazard types are relevant. Relevance criteria can vary and might consider the hazard’s frequency, intensity, damage potential, or overall risk (including exposure and vulnerability) [8]. Spatial approaches to multi-hazards range in the scale considered, from global to regional to local. For example, at a global scale, the multi-hazard index developed by Dilley et al. [41] is an example of an “all-hazards-at-place-approach” [37]. This index sums category values between 8 and 10 (the highest category values) across six natural hazards. Their approach results in a multi-hazard index reflecting the number of relatively significant hazards in a particular grid cell. A similar but more quantitative approach is in the Global Assessment Report [46] and in the Global Risk Atlas [47]. In their approach, Annual Average Losses (AALs) from different hazards deriving from a probabilistic risk assessment are summed to identify a cumulative AAL that considers all hazards potentially impacting the same region, but does not consider hazard interactions.

At a more regional (e.g., 1000 to 10,000 km²) or local (e.g., 0.1–1000 km²) scale, many spatial approaches focus on the homogenization of the hazard assessment. In other words, attempting to make different hazards and the related risk comparable [48]. Some of these approaches are probabilistic (i.e., by determining the return period of a given intensity for a given hazard) (e.g., Refs. [12,24,39,49–55]). Other approaches provide a qualitative categorization (e.g., high, medium, low, negligible) based on the frequency or intensity of the hazard (e.g., Refs. [56,57]).

The second approach to multi-hazards, ‘interacting multi-hazards’, includes methodologies investigating two or more hazards and considering the hazard interactions (e.g., triggering or cascade effects). This second approach is generally more demanding in computational efforts and data requirements than the first approach, which considers hazards independent. For this reason, there are more models in the literature for the first approach compared to the second approach. To overcome data availability issues, Barrantes [58] proposes a qualitative procedure to model spatial interactions between individual natural hazards in data-poor contexts, such as developing countries. Different authors identify and classify different types of interactions between hazards, as given by six authors in Table 4.

The classifications in Table 4 vary in terms of completeness and focus. However, it is possible to identify commonalities in the six studies compared in Table 4, for the following three main mechanisms of interaction [63]:

i. The trigger (or causation) happens when one hazard directly triggers another, generating what is called a “domino effect” or “triggering mechanism” among hazards.

ii. The influence happens when one hazard can influence the probability or magnitude or spatial distribution of a hazard without acting as a trigger.

iii. The independent coincidence happens when two (or more) hazards impact the same region independently but simultaneously.

Despite many published articles investigating and modeling various natural hazard combinations, they do not systematically cover all possible multi-hazard cases [64]. We believe that all significant hazard interactions and cascade effects should be appropriately

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**Table 3**

| Definition | Reference |
|-----------|-----------|
| “The totality of relevant hazards in a defined area.” | Kappes et al. [8] |
| “The word ‘multi-hazards’ refers to all possible and relevant hazards, and their interactions, in a given spatial region and/or temporal period.” | Gill and Malamud [5] |
| “[Multi-hazard analyses refer to the] implementation of methodologies and approaches aimed at assessing and mapping the potential occurrence of different types of natural hazards in a given area. [The employed methods] have to take into account the characteristics of the single hazardous events [...] as well as their mutual interactions and interrelations.” | Delmonaco et al. [33] |
modelled to estimate the damage of a target exposed to multiple and potentially simultaneous natural hazards. This is because losses from hazard interactions may be larger or smaller than the simple aggregation of single losses considering each hazard as independent and another. Due to the lack of available data, Jaimes et al. [70] introduce two simplifications in their approach: (i) the processes of altering the disposition of another one and thus its disposition towards a possibly occurring trigger event, without direct triggering or simultaneous occurrence of the two hazards (triggering or cascade effects), which means a change of the probability of occurrence of the triggered event; (ii) the change in trigger factors that induce hazard A are independent of those which induce hazard B. Since the occurrence of a certain hazardous event is likely to ‘trigger’ other hazards (triggering or cascade effects), which means a change of the probability of occurrence of the triggered event, the change in trigger factors that induce hazard A are independent of those which induce hazard B. Thus, hazards A and B cannot occur together.

Multi-hazard risk evaluation is a relatively new field, particularly when done quantitatively (including uncertainty). Much research has been conducted on this topic in recent years, but mature methods have not yet been developed [66]. Some basic principles for multi-hazard risk assessment are underlined by Marzocchi et al. [7], together with an explanation on how interactions between hazardous events may influence a final risk estimation, and how these interactions can be included in a multi-hazard risk assessment. The available literature on empirical or deterministic quantitative multi-hazard risk assessment has been developed only for specific couples or groups of hazards by experts from different backgrounds [63]. Examples include earthquakes and wind [67], earthquakes and hurricanes [68], wind and storm surge [69], and earthquakes combined with ash fall and pyroclastic flow from volcanic eruption [65].

A general criterion for the quantitative estimation of losses of a structure exposed to several hazards has been presented by Jaimes et al. [70]. Due to the lack of available data, Jaimes et al. [70] introduce two simplifications in their approach: (i) the processes of damage generation from different hazard sources is considered independent; (ii) the assumption that every time damage or failure occurs, the structure is repaired or rebuilt to its initial conditions without considering any dynamic of recovery between one hazard and another.

From our analysis of available literature on multi-hazard and multi-hazard risk presented in this section, we highlight the following

### Table 4
Classification of hazard interaction types according to six different authors.

| Classification of hazard interactions | Reference |
|--------------------------------------|-----------|
| i. **Alteration of the disposition:** one process changes the general setting of another one and thus its disposition towards a possibly occurring trigger event, without direct triggering or simultaneous occurrence of the two hazards (including cascading hazards) | Kappes et al. [59] |
| ii. **Triggering:** one hazard inducing one or more other threats which may again provoke further ones | Garcia-Aristizabal and Marzocchi [48] |
| iii. **Mutual exclusion (negative dependence):** two natural hazards exhibit negative dependence or can be mutually exclusive | Tilloy et al. [62] |
| vi. **Causation:** hazards generate secondary events, which may occur immediately or shortly after the primary hazard | Duncan et al. [60] |
| vii. **Series relationship:** hazard A induces changes in some trigger factors, and then the changes in these trigger factors induce hazard B | Liu et al. [61] |
| viii. **Independent relationship:** the change in trigger factors that induce hazard A are independent of those which induce hazard B | Tilloy et al. [62] |
| ix. **Mutex relationship:** the changes in trigger factors that induce hazard A and which induce hazard B are mutually exclusive (mutex). Thus, hazards A and B cannot occur together | Liu et al. [61] |
| x. **Parallel relationship:** the changes in one or some trigger factors have the chance to induce more than one hazard, and the change in trigger factors that induce hazard A are independent of those which induce hazard B | Tilloy et al. [62] |
| xi. **Compound hazard (association):** different hazards are the result of the same “primary event”, or large-scale processes which are not necessarily hazards. In this case, there is not a primary and a secondary hazard as the different hazards occur simultaneously | Tilloy et al. [62] |
| xii. **Mutual exclusion (negative dependence):** two natural hazards exhibit negative dependence or can be mutually exclusive | Tilloy et al. [62] |
three main points:

i. Multi-hazard studies that focus on hazard interaction modelling often do not include a quantitative risk or impact assessment.
ii. Many studies only focus on one or two families of hazards (e.g., tectonic, hydrogeological); therefore, a comprehensive multi-hazard approach is often missing.
iii. Available qualitative and quantitative multi-hazard risk or impact approaches usually do not model recovery dynamics and residual damage due to consecutive disasters.

Therefore, we have developed a multi-hazard impact framework that considers these three issues, which are now described in Section 4.

4. A five-step multi-hazard impact framework

This section presents the five steps (from event modelling to damage assessment) of a multi-hazard framework for spatial-temporal impacts resulting from interacting hazards. This framework results from a critical literature review (Section 2.1 and 3), stakeholder engagement (Section 2.2), and our expert judgement. Steps I to V are summarized in Fig. 1 and discussed briefly here with more detail given in Sections 4.1 to 4.5:

Step I. Identification of hazards and their interactions (discussed further in Section 4.1). All possible hazards acting on a specific region are compiled. The interaction mechanisms among these different considered hazards are identified and described, using one or more of the six basic interaction mechanisms identified from a critical literature review (Section 4.1). This step can identify (i) which hazards are involved and (ii) the causal dependence among them to set the basis for a coherent and realistic multi-hazard simulation. This step is fundamental to defining the mechanisms of hazard interaction mechanisms that need to be considered in the following Step II.

Step II. Multi-hazard modelling (discussed further in Section 4.2). Once the interaction mechanisms have been identified and the causal dependencies investigated and described, complete multi-hazard modelling can be implemented. Modelling multi-hazard scenarios is not a standardized procedure due to the variety and heterogeneity of interaction types and hazards involved in the analysis. Nevertheless, an overview of the different approaches is summarized in Section 4.2.

Step III. Analysis of spatial and temporal evolution of the impacts from the hazards (discussed further in Section 4.3). The analysis of spatial and temporal evolution of the hazards obtained from the hazard modelling is performed in the domain of interest. Areas of spatial and temporal overlap of hazards can then be identified.

Step IV. Identification of the impact interaction types (discussed further in Section 4.4). The identified spatial and temporal hazard overlap scenario can generate different types of impact interactions in specific areas of the domain, according to the classification of impact interactions typologies presented in Fig. 3.

Fig. 1. A five-step multi-hazard impact framework. The arrows indicate that the five steps are consecutive. Steps I and II (blue box) refer to multi-hazard assessment and focus on causal dependencies among hazards. Steps III to V (orange box) allow researchers to perform a multi-hazard impact (or risk) assessment and focus on the spatial and temporal evolution of the impacts from the hazards. Each step is discussed in more detail in the section given in the corresponding box.
Step V. The multi-hazard risk or impact assessment (discussed further in Section 4.5). Identifying the type of impact interaction allows the assessment of the resulting multi-hazard impact considering all significant aspects in the modelling, either in qualitative or quantitative ways. Aspects to consider for assessing these impact interactions are identified in Section 4.5.

As illustrated in Fig. 1, the five steps can be grouped into two distinct assessment phases, characterized by a significantly different multi-hazard approach. Phase 1 includes Steps I to II: identification of hazards and their interactions; multi-hazard modelling. Phase 1 exclusively focuses on the hazard assessment. In other words, it does not yet consider the potentially exposed elements and how the hazards could act on and their vulnerability. In phase 1, the focus on the multi-hazard dimension is related to identifying and quantifying potential causal dependencies and interaction mechanisms among hazards.

Phase 2 includes Steps III to V: analysis of spatial and temporal evolution of the impacts from the hazards; identification of the type of impact interaction; multi-hazard risk or impact assessment. Phase 2 focuses on the impact (or risk) assessment, evaluating the impact of multiple hazards on the exposed elements characterized by a specific vulnerability. Phase 2 investigates the spatial and temporal overlapping of hazards, which determine interaction at the impact level independently from their causal dependencies. In Phase 2, the exposed elements and their vulnerability are the sole connections among the different hazards considered. This distinct separation is crucial as it allows a more practical and effective quantification of the different hazards interacting at these two different levels by simplifying the overall modelling approach.

We now discuss each step and then, in Section 5, will apply these five steps to a case study. The five steps presented in this paper exclusively refer to natural hazards. Nevertheless, the hazard list can include not only natural but also biological hazards (such as pandemics), technological hazards and anthropogenic processes (e.g., Ref. [71]).

| MECHANISM                      | DEFINITION                                                                 | EXAMPLE                                                                 |
|-------------------------------|---------------------------------------------------------------------------|-------------------------------------------------------------------------|
| PARALLEL HAZARDS              | A series of hazards are generated by the same trigger                      |                                                                                   |
| (a) TRIGGER                   |                                                                           | INTENSE RAIN                                                             |
|                               | H1                                                                         | LANDSLIDE                                                               |
|                               | H2                                                                         | FLOOD                                                                   |
| CASCADING HAZARDS             | A hazard acts as a trigger for one or more sequential events              |                                                                                   |
| (b) TRIGGER                   |                                                                           | TECTONIC STRESS                                                        |
|                               | H1                                                                         | EARTHQUAKE                                                              |
|                               | TRIGGERING                                                                 | TSUNAMI                                                                 |
| DISPOSITION ALTERATION        | The occurrence of a first hazard is able to influence the frequency and/or the magnitude of a second hazard |                                                                                   |
| (c) TRIGGER                   |                                                                           | RAPID SNOW ACCUMULATION                                                |
|                               | H1                                                                         | ROCK EROSION                                                           |
|                               | TRIGGERING                                                                 | ROCK FALL                                                              |
|                               | Alteration of the disposition                                              |                                                                                   |
| ADDITIONAL HAZARD POTENTIAL   | The damage caused by the first hazard is able to influence the magnitude of the second one |                                                                                   |
| (d) TRIGGER                   |                                                                           | TECTONIC STRESS                                                        |
|                               | H1                                                                         | EARTHQUAKE                                                              |
|                               | TRIGGER                                                                   | INTENSE RAIN                                                           |
|                               | H2                                                                         | FLOOD                                                                   |
|                               | ADDITIONAL HAZARD POTENTIAL                                               | DISRUPTION OF FLOOD PROTECTION MEASURES                                 |
| COINCIDENT TRIGGERING         | The simultaneous occurrence of two hazards is a trigger for a third one   |                                                                                   |
| (e) TRIGGER                   |                                                                           | ELECTRIC UMBALANCE                                                    |
|                               | H1                                                                         | WATER SCARCITY                                                        |
|                               | TRIGGER                                                                   | LIGHTNING                                                              |
|                               | H2                                                                         | DROUGHT                                                                 |
|                               | TRIGGERING                                                                 | WILDFIRE                                                                |
| CYCLIC TRIGGERING             | The triggering of the second hazard exacerbates the first hazard, therefore triggering further episodes of the second hazard, creating a sort of positive feedback |                                                                                   |
| (f) TRIGGER                   |                                                                           | STRONG RIVER CURRENTS                                                 |
|                               | H1                                                                         | SLOPE UNDERCUTTING                                                    |
|                               | TRIGGERING                                                                 | TRIGGERING                                                             |
|                               | H2                                                                         | CHANNEL AGGRAVATION                                                   |
4.1. Identification of hazards and their interactions (multi-hazard impact framework step I)

To implement a multi-hazard risk assessment, Step I identifies all hazards that might significantly affect a specific region. These include hazards in that region that have already occurred or might occur, and those in other regions that might also impact the region of interest. Ideally, a hazard list should include those that may occur unexpectedly and at very short notice (e.g., earthquakes, flash floods), and longer-term hazards (e.g., drought, subsidence). An extensive hazard classification according to temporal development is introduced in Section 4.3.

Once a hazard list is compiled, all possible interaction mechanisms among these hazards should be identified and described. This section uses the definitions and classifications given previously (Section 3) and a range of examples to identify six basic interaction mechanisms between hazards. Our final summary of the six interaction mechanisms is given in Fig. 2, along with the examples (right column) used to help inform the mechanisms.

These interaction mechanisms help identify and explain the main causal dependencies between two or more hazards, with more complex interaction mechanisms resulting from combining two or more of these categories. Therefore, they can be used as a reference guide to identify multi-hazard interactions systematically and exhaustively.

We now discuss each of the six identified hazard interaction mechanisms in Fig. 2 along with evidence (e.g., literature) we used to classify and define a specific category.

(a) **Parallel hazards.** This mechanism inherits its name from Liu et al. [61]. It refers to a series of hazards generated by the same trigger, named “primary event” [62], such as a volcanic eruption which triggers lava flow and ash fall (or a pyroclastic flow) [65,72] or an intense rain which triggers a flood and landslides [59]. The resulting hazards are named “compound hazards” [62,73]. As underlined by Tilloy et al. [62], the primary event might not be necessarily a hazard, but it can just be a be large scale process. For example, river flooding and sea surge co-occurrence could result from the same tropical cyclone [74,75], or a convective storm which generate compound precipitation and wind extremes [73].

(b) **Cascading hazards.** This mechanism, named by Marzocchi et al. [53] as “coupled events” and by Tilloy et al. [62] as “triggering”, is the case in which “an adverse event triggers one or more sequential events” [53]. For example, an earthquake that triggers either a tsunami [76–78] or a mass movement [79–83].

(c) **Disposition alteration.** This mechanism name is from the definition of “alteration of the disposition” introduced by Kappes et al. [59]. Here one hazard can change “the general setting of another one and thus its disposition towards a possibly occurring trigger event”. In other words, there is no direct triggering of one hazard by another or any simultaneous temporal occurrence. Still, the occurrence of the first hazard can influence the frequency or the magnitude of the second one. A typical example is removing the protective forest by a winter snow avalanche, leading to higher frequency and magnitude of rockfalls in summer [8]. This mechanism also works in the case of a negative influence [62], such as heavy rainfall, which can reduce a region’s wildfire probability.

![Fig. 3. Identification of impact resulting from two different overlapping hazards H1 and H2 (uppermost grey oval) for four spatial-temporal overlap types: (i) spatial-temporal overlap impact (yellow oval), (ii) temporal (but not spatial) overlap impact (green oval), (iii) spatial overlap impact (with residual and subsequent damage) (orange oval), (iv) independent single hazards impacts (blue oval). Diamonds A, B1, B2 and C represent Boolean decisions (‘yes’ or ‘no’).](image-url)
4.2. Multi-hazard modelling (multi-hazard impact framework step II)

Step I of our multi-hazard impact framework systematically identifies hazard interaction types and investigates causal dependencies. Step II implements a full multi-hazard model that considers the modelling of every single hazard identified in Step I, and hazard interactions. The relationships between these hazards and other components of the risk equation (vulnerability, exposure, impact assessment) will be part of Step III. Step II does not detail the type of modelling required, as the variety of approaches is large. Instead, Step II categorizes the different types of approaches, which are linked to the final application of the risk assessment. However, a clear idea of the modelling framework to be used is fundamental for applying the complete five-step approach and with reference to a specific problem, which we will do in a case study in Section 5.

Choosing the most suitable modelling approach depends on the hazards’ typology. Floods, droughts, earthquakes and volcanic eruptions have different temporal and spatial scales and require different types of input data and models [88]. Therefore, each possible hazard interaction previously identified must be analyzed separately. If resources are limited, or there are specific interests, only a subset of the possible cases may be further investigated in step II (and subsequent steps).

When considering multi-hazard modelling, one element is the probabilistic risk, which is quantified from a series of historical or synthetic events spanning a time period long enough to be statistically representative of all possible disastrous events that can occur in a territory [89]. Risk is calculated as the convolution of the damage caused by all events, considering their associated likelihood. Each event (historical or synthetic) can be seen as one of the possible realizations of the risk and represents a particular ‘scenario’ [90,91]. Each damage scenario, considered as an independent random variable, is described by its mean value and its standard deviation. Therefore, the overall damage probability distribution is the statistical convolution of the individual damage scenario distributions.

Different modelling approaches for probabilistic multi-hazard assessment have been implemented in different parts of the world: HAZUS (USA) for hurricanes, earthquakes and floods [92]; RiskScape (New Zealand) for ash fall, floods, tsunamis, landslides, storms and earthquakes [93]; and CAPRA (Central America), for hurricanes, extreme rainfall, landslides, floods, earthquakes, tsunamis and volcanic hazards [55]. These approaches may underestimate the overall multi-hazard risk, as they do not consider the spatial and temporal overlap of hazards and their interactions [58].

An alternative modelling approach to take into account these interactions has been proposed by Marzocchi et al. [53]. In this approach, a scenario technique is combined with event trees, and possible scenarios following an initial event are identified and their probabilities quantified. This probabilistic approach requires an up-to-date and sufficiently long record to evaluate the probability of a specific multi-hazard scenario occurrence ([7,58]). Consequently, this method’s application is challenging due to the lack of historical data on multi-hazard triggering or cascading scenarios.

As a workaround to limited multi-hazard data, it may be sufficient to perform a ‘multi-hazard scenario’ risk assessment, in which the impacts caused by one or more specific multi-hazard scenarios are evaluated. This approach is less time consuming and mathematically simpler than a comprehensive probabilistic risk assessment as it does not necessarily require evaluating the associated probability of occurrence. Usually, this multi-hazard scenario approach is performed in the insurance and reinsurance fields to evaluate the consequences of a ‘worst case’ scenario or the ‘most probable’ scenario, or by the scientific community to model and study significant historical events. In both cases, the approach is not a single or multi-hazard risk assessment, as they do not fully account for the probability. Thus we define these approaches as ‘single or multi-hazard damage or impact assessments’.

4.3. Analysis of spatial and temporal evolution of the impacts from the hazards (multi-hazard impact framework step III)

Step III of our multi-hazard impact framework considers the hazards’ spatial and temporal evolution and their impact. In particular, Step III focuses on the interactions between the hazards and the other components of the risk equation: vulnerability, exposure, and impact resulting from their interaction with the hazard component.

Space and time play an essential role in multi-hazard impact assessment [5,65]. When two or more hazards co-occur in the same location (or successively in a short time window), physical infrastructure and population may be placed under more significant stress than if the hazards had occurred in different locations or at different times [5,73]. The occurrence of two or more hazard events may result in changes to the exposed elements’ vulnerability [66]. For example, damage generated by the first event could increase the vulnerability of the exposed elements when the second hazard occurs, therefore potentially amplifying the resulting damage. A real-world example of this was earthquake damage to a dyke resulting in increased flooding in Karonga, Malawi [94,95]. Consequently, the spatial and temporal overlap of hazards should be further investigated to understand how the impact from multiple
hazards can interact. The spatial and temporal overlapping of hazards can occur both dependent and independent of each hazard’s drivers. For example, when there are triggering mechanisms among hazards (e.g., earthquake and landslide driven by the same phenomenon) or when independent hazards occur “within a relevant time frame and with appropriate spatial overlap” [94,95].

Focusing on time, three different temporal dimensions can be identified:

i. **The hazard time**: the time interval in which the natural hazard evolves and potentially impacts exposed elements.

ii. **The exposure time**: the time interval in which the direct and indirect effects of the hazard act on exposed elements.

iii. **The resulting damage time**: the time interval in which the territorial system remains damaged.

These three temporal dimensions do not necessarily coincide. Their extent can vary significantly from one hazard to another; for example, drought slowly depleting water resources has a timescale of months versus an earthquake instantaneously damaging water infrastructure.

The hazard time and the exposure time can differ as indirect impacts may follow immediate physical impacts. An example of this difference is represented by a territorial system affected by a strong earthquake. The physical damage due to the ground shaking on the exposed elements has a usual duration of a few seconds. However, other indirect physical and direct or indirect social, economic, environmental impacts (e.g., fires) can start and continue when the hazard (ground shaking) has already temporally evolved. The exposure time differs from the resulting damage time because even after the end of the exposure between the hazard and the environment, damages remain until recovery and restoration processes are completed. The time difference between exposure and damage is strongly related to social, economic and political factors resulting in a more or less resilient system [96]. This time discrepancy is essential for modelling multi-hazard impact, specifically for multiple subsequent hazards. Indeed, suppose there is a time lag between two impacts (generated by two hazards). The territorial system may be stressed from the first hazard when exposure to the second hazard occurs, making response and recovery more challenging.

When analyzing the temporal evolution of a hazard in a given location in detail, three instances of time can be identified as significant in terms of impact:

i. **The initial time** ($t_i$).

ii. **The peak time** ($t_p$), i.e., the instant in which the hazard reaches its maximum intensity in the considered location.

iii. **The final time** ($t_f$).

$\text{With } t_i \leq t_p \leq t_f$

The duration of the event is determined by the final and initial times, $t_f - t_i$. When the peak time comes significantly later than the initial time ($t_i \neq t_p \text{ or } t_p \gg t_i$) the hazard is considered ‘slow onset’. A ‘rapid-onset’ hazard is when the two times are almost coincident, or the difference is lower than a certain threshold ($t_i \approx t_p$). We define an ‘instantaneous hazard’ as an event where the initial, peak and final times are coincident. Examples of rapid-onset events are hurricanes, flash floods and earthquakes, while slow-onset hazards include global temperature variations, sea-level rise, drought, disease, and famine [96]. The terms ‘slow’ and ‘fast’ here are used to consider impact with no definitive delineation between what one might consider ‘slow’ versus ‘fast’ in actual units of time.

Slow-onset events allow a territorial system “the opportunity to change or modify existing behaviours and practices to reduce the impact of a hazard while the event is unfolding” [96], determining dynamic changes in exposure and vulnerability that are challenging to quantify, but should be considered in the modelling framework.

The analysis of the evolution in time of each of the considered hazards allows us to (i) identify if there is a temporal overlapping among them or (ii) to evaluate the time frame between the end of one hazard and the beginning of another. These elements play a significant role in identifying the type of hazard interaction at the impact level, as is detailed in Section 4.4. For example, droughts and pandemics represent slow-onset hazards, each characterized by a long duration and, for a given region, often a series of events (e.g., successive droughts over a hundred-year period). These slow-onset hazards contrast with rapid-onset ones of much shorter duration (e.g., earthquakes, flash floods). To evaluate the combined effect of a pandemic (slow-onset) and flood (rapid-onset), one needs to understand the spatial dynamics of both, and to identify if the concurrent natural event is going to occur before or after a peak in the pandemic spread (measured by the infection rate in time). Indeed, a concurrent event occurring before reaching the peak of the infection rate curve increases the new infection rate more in the aftermath of a concurrent event than if it were to occur at a post-peak time [9].

To have a significant impact interaction, different hazards must occur close in time, but they also have to totally or partially overlap in space. An aspect that influences the impact assessment is the “areal or spatial extent of the hazard” [97]. Some hazards can be considered localized as they cover an area ranging from a few square meters to a few square kilometres (e.g., a landslide or an urban flood). Other hazards are classified as extended as their coverage is more extensive and may extend beyond international boundaries (e.g., riverine flood, earthquake, hurricane, drought). The spatial extent of the hazard directly influences the spatial scale of the direct impacts, which can range from municipal to intercontinental levels. Nevertheless, in some cases, even a very localized hazard can generate indirect consequences at a much larger scale. For example, a landslide blocking a road may immediately damage a few square meters of road surface, resulting in regional traffic delays. The spatial scale of direct and indirect impacts determines which stakeholder types would potentially be involved in disaster management.

The aspects mentioned above should consider relating the spatial and temporal evolution of the hazard(s) to determine possible areas and time windows of overlap. By investigating spatially and temporally overlapping hazards, it is possible to understand if there is any interaction at the impact level independently from the causal dependencies among hazards. Section 4.4 further discusses the different kinds of impact interactions arising from overlapping temporal and spatial hazards.
4.4. Identification of type of impact interaction (multi-hazard impact framework step IV)

While Step II focuses on hazard-to-hazard interaction and Step III focuses on the hazard to exposure interactions, Step IV focuses on the type of impact interaction. We outline four different cases of impact interactions considering different scenarios of temporal and spatial overlapping of the hazards, as given in Fig. 3:

i. **Spatial-temporal overlapping impact** (yellow oval).
ii. **Temporal (but not spatial) overlapping impact** (green oval).
iii. **Spatial overlapping impact (with residual and subsequent damage)** (orange oval).
iv. **Independent single hazards impacts** (blue oval).

Fig. 3 is a flow-chart where ovals represent initial and final states, and diamonds represent a condition for which a Boolean decision can be made (“Yes” or “No”). We start from a specific spatial and temporal evolution scenario of two hazards H1 and H2 (grey oval at the top of Fig. 3). According to the verification or not of the spatial and temporal overlapping conditions, the four different cases of impact interactions given in the coloured ovals can be obtained.

This flow diagram (Fig. 3) provides the core of our multi-hazard impact framework. A hazard or risk manager from a range of organizations and institutions (e.g., civil protection emergency planners, urban planners) can use this diagram in the ‘preparedness’ phase of disaster risk management.

Fig. 3 will help the user identify which potential scenarios they might face and prioritise which cases to investigate further to better implement an effective disaster risk reduction strategy.

We now detail the four Boolean Decision cases (diamond) outlined in Fig. 3, discussing examples and issues associated with modelling in each case. Specifically, we will discuss each of the cases arising from the confirmation (“Yes”) or the rejection (“No”) of the sentences reported in each of the four diamonds. The four Boolean decision cases are labelled with letters (A, B1, B2, C).

(A) “Hazard spatial overlap” = “Yes”.

**Overview:** There will be one or more areas that are subject within a specific time to the effect of more than one hazard.

(A) “Hazard spatial overlap” = “Yes” + (B1) “Hazard temporal overlap” = “Yes” leads to (i) “Spatial-temporal overlap impact” (yellow oval).

**Overview:** The hazards are now spatially and temporally overlapping. In this case, the resulting multi-hazard impact on the territorial system is a combination of simultaneous impacts from different hazards acting in the same location.

**Impact interaction:** spatial-temporal overlapping impact (yellow oval in Fig. 3).

**Example:** a building hit simultaneously by an earthquake and ashfall due to a volcanic eruption [65]. In this case, the impact on the building is a combination of the single loads due to the two separate events, which can generate more significant damage than the simple sum of the two damages caused by the two hazards considered separately. Another example is the impact caused by the combined effects of wind and storm surge on a building acting simultaneously due to the same meteorological event [68,98].

**Challenges:** The methodological challenge, in this case, is to understand the overall amplification of the damage due to the coincidence of the loads from different sources.

(A) “Hazard spatial overlap” = “Yes” + (B1) “Hazard temporal overlap” = “No”.

**Overview:** If the spatially overlapping hazards do not temporally overlap, we would like to understand if the territorial systems have recovered in the time window between the final time of the first hazard and the start time of the second hazard: (i) $t_f[H_1]$ is the initial time (starting time) of a generic hazard $H_i$; (ii) $t_f[H_2]$ is the final time of a generic hazard $H_i$. We start observing a given territorial system at time $t_0$. For any generic time $t$: $t_0 \leq t < t_f[H_1]$, the system does not suffer any physical (and consequently economic) loss. At time $t_f[H_1]$ a natural hazard event $H_1$ starts and the system’s cumulative direct damage increases until time $t_f[H_1]$, when $H_1$ ceases its impact. After $t_f[H_1]$, the system can hypothetically start to restore the loss. Over time, the system’s residual damage decreases until reaching the initial condition (restoration phase). When a second event $H_2$ occurs at time $t_f[H_2]$, the system again starts to experience damage.

**Sub-cases:** We define $\Delta t[H_1-H_2] = t_f[H_2] - t_f[H_1]$ as the time window between the end of the first hazard $H_1$ and the start of the second hazard $H_2$ and $t_{REC}[H_1]$ as the time required by the territorial system to completely recover from damage caused by $H_1$. Two different scenarios may arise: (i) spatial overlap of impact (with residual and subsequent damage) if $\Delta t[H_1-H_2] < t_{REC}[H_1]$, or (ii) independent single hazards impacts, if $\Delta t[H_1-H_2] > t_{REC}[H_1]$.

(A) “Hazard spatial overlap” = “Yes” + (B1) “Hazard temporal overlap” = “No” + (C) “Second hazard starts when the territorial system has not completely recovered from the damage caused by the first hazard” = “Yes” leads to (iii) “Spatial overlapping impact (with residual and subsequent damage)” (orange oval).

**Overview:** If $\Delta t[H_1-H_2] < t_{REC}[H_1]$, the territorial system does not have enough time to completely recover from damage when the second event occurs. In this case, it is necessary to quantify the level of residual damage at time $t_f[H_2]$. This condition is the initial damage state of the system to assess the impact caused by the second event.

**Impact interaction:** overlapping spatial impact (with residual and subsequent damage) (orange oval, left of Fig. 3).

**Example:** A structure subjected to earthquake ground motion that is successively subjected to one or more aftershocks within a short period following the occurrence of the principal earthquake shock [99] or a structure subjected to an earthquake and then a
pyroclastic flow [65]. In these cases, the combined damage assessment, as suggested by Zuccaro et al. [65], can be treated as a “progressive deterioration of the building’s resistance characteristics that is essentially represented by the damage level”. Another example of this spatial overlap impact with residual and subsequent damage is illustrated by the effect of an earthquake followed by a flood when the physical mechanisms for flood reduction are damaged (described in Section 4.1). This example has been studied in detail for the Po Valley levee system as one of the case studies of the RASOR project [18,100].

**Challenges:** In this case, the methodological issue is understanding how this residual damage can influence the vulnerability to the second hazard, particularly for a quantitative assessment, which uses vulnerability and fragility curves to assess damages.

(A) “Hazard spatial overlap” = “Yes” + (B1) “Hazard temporal overlap” = “No” + (C) “Second hazard starts when the territorial system has not completely recovered from the damage caused by the first hazard” = “No” leads to (iv) “Independent single hazards impacts” (blue oval).

**Overview:** If Δt[H1-H2] > tREC[H1], the time between the end of the first event and the start of the second event is more than the time required to restore the territorial system. There are no effective interactions between the two events in terms of impact, and we can treat the impact assessment as a series of independent single hazards impact assessments.

**Impact interaction:** independent single hazards impacts (blue oval, right of Fig. 3).

**Challenges:** The system’s vulnerability could be reduced due to the recovery process through changes to building methods (i.e., ‘built back better’ [101,102]). Therefore, the system at time \(t_s[H2]\) may not be precisely the same that was at \(t_0\) and the physical vulnerability may be different. Consequently, a second event with the same characteristics as the first event would generate more (minor) damage. Therefore, updating the system’s exposure and vulnerability changes is essential at the end of the recovery process to ensure the damage calculated for subsequent hazards is correct.

(A) “Hazard spatial overlap” = “No”.

**Overview:** No area will be subject to the effects of more than one hazard. Although this case does not pose any challenge in impact interactions, it may still be significant in terms of risk and emergency management, as two hazards can still overlap temporally even if they do not overlap in space.

(A) “Hazard spatial overlap” = “No” + (B2) “Hazard temporal overlap” = “Yes” leads to (ii) “Temporal (but not spatial) overlapping impact” (green oval).

**Overview:** In this case, two different areas will be subject to the simultaneous effect of two different hazards without generating any impact interactions at the same location.

**Impact interaction:** temporal (but not spatial) overlap impact (green oval, right of Fig. 3).

**Example:** For example, snowstorms (and triggered avalanches) [103,104] and wildfires [105] co-occurred in Italy in 2017. All these events had relevance at the national level and required the management and the resources from the same institution: the Italian Civil Protection Agency.

![Fig. 4](image-url). Four types of impact interactions are classified with spatial scale on the y-axis (local, regional, national) given as a function of temporal scale on the x-axis (hours, months, years).
**Challenges:** Although there are no impact interactions, the event may still be significant in terms of risk and emergency management. Indeed, the temporal overlap of two or more hazards in different locations can be challenging in managing and distributing resources for a territory.

(A) "Spatial overlap" = "No" + (B2) "Hazard temporal overlap" = "No" leads to (iv) "Independent single hazards impacts" (blue oval).

**Overview:** If hazards do not overlap in time or space, there are no interactions between the two events, neither in terms of impact assessment nor emergency management. Therefore, impact assessment can be treated as a series of independent single hazard impact assessments.

**Impact interaction:** independent single hazards impacts (blue oval, right of Fig. 3).

**Challenges:** there are no significant challenges to be addressed in this case.

The four different types of damage interactions given in Fig. 3 usually occur at different spatial scales and involve different time horizons, which we show in Fig. 4. Hazards that overlap spatially and temporally typically occur over short time horizons (hours to months) at a subnational spatial scale. Over a slightly longer time horizon (several months to a year), we may observe a sequence of hazards with a time window of varying sizes between each event. Recovery may have commenced in the time window following each successive hazard and should be considered when modelling the impact from subsequent hazards. When the time horizon is expanded (i.e., more than one year), the time window between successive events may mean the impact interactions are negligible and can thus be assumed to be independent. When we examine a broader spatial scale (returning to a short time horizon), we may observe simultaneous impacts distributed across the region of interest.

4.5. **Multi-hazard risk or impact assessment (multi-hazard impact framework step V)**

Finally, in Step V of our multi-hazard impact framework, assessing the multi-hazard risk or impact is performed. As an example of impact types, the classification used by the DesInventar database of the UNDRR [106] includes different types of impacts to a broad range of assets, including the impact (e.g., destroyed, partially destroyed) to houses, crops and woods, livestock, educational centres, hospitals, roads, agriculture, water supply, sewerage, power/energy, industry and emergency networks. This paper will consider impact as the tangible direct physical damage to assets (see Table 1). We will not address other impact types (e.g., economic, environmental, social), both direct and indirect. Nevertheless, our proposed approach could be adapted to include other impact categories.

Fig. 5. Visualization of Phase 1, Steps I and II of the multi-hazard impact framework (see also Fig. 1): application to a Po Valley (Italy) case study where (i) an actual 20 May 2012 6.1 MW earthquake weakens and damages parts of the levee system, (ii) nine days later there is intense rain which when combined with the weakened levee results in a hypothetical levee collapse and a flood. Step I is a schema of the relevant hazards and interaction mechanisms considered. Step II is a simplified flow of the adopted modelling chain and main outputs.
The quantification of impacts arising from overlapping hazards is a complex issue. The approaches identified in the literature (discussed in Section 3) introduce a series of simplifications (e.g., Ref. [70]), or only consider a certain family of hazards (e.g., Ref. [65]). Although the development of a generalized quantitative procedure to model multi-hazard impacts is beyond this paper’s scope, a series of aspects to consider for modelling impact interactions are discussed here. Identifying these four aspects constitutes the basis for future development of generalized semi-qualitative or quantitative mathematical modelling. These aspects have been identified by analyzing the different impact interactions described in Fig. 3, together with the literature review presented in Section 3. The four aspects, and our comments on each, are given as follows:

i. **Hazard sequence.** The order in which the hazards impact the exposed elements can influence the final damage. An earthquake event followed by a flood is not the same as a flood followed by an earthquake, as the sequence in which the physical damages occur can influence the overall damage. For this reason, we model the correct time evolution of the hazards.

ii. **Time window between hazards and recovery rate of the assets.** Understanding the temporal evolution of particular hazards allows us to understand if they partially overlap in time or occur in sequence. If hazards occur in sequence, it is possible to identify time windows between the hazards in which the territorial system can potentially recover. The combination of length of the time window between the hazards and the ‘recovery rate’ of the assets (i.e., the function describing the asset’s residual damage versus the time from the event) determines the residual damage from the previous hazard when the subsequent hazard occurs.

iii. **Type of physical interaction between hazards and the exposed elements.** The damage caused by the combined effect of multiple hazards can be higher than the sum of the damages caused by the single hazards acting independently. The amplification depends on the physical process of the hazard interacting with the exposed elements (e.g., the building, the road). For this reason, we want to understand the range of physical mechanisms generated by each hazard and how they can potentially interact. For example, a building damaged by a windstorm (or cracked by an earthquake) might be more greatly affected by the hydrostatic and hydrodynamic pressure of a flood. This type of evaluation usually requires laboratory testing to reproduce the impact dynamics on a sample building or dedicated mathematical modelling on topical infrastructures (e.g., finite element modelling [107]).

iv. **Impact targets (structure or content or both).** Some hazards mainly affect either the building’s structure or content (e.g., furniture, door and window frames, electrical and plumbing systems), while other hazards impact both the structure and contents equally. This aspect can significantly influence how interacting or consequent impacts are combined. For this reason, we recommend the separate assessment of damage to content and structure using separate vulnerability curves.

5. **Application of the multi-hazard impact framework to the Po valley, Italy**

We now present an application of our five-step multi-hazard conceptual impact framework (Fig. 1) to a case study, including the descriptive potential of each step’s visualization. As our real-world case study, we use a scenario of damage from an actual 20 May 2012 earthquake that weakened parts of the Po Valley, Italy levee system. We then put together a hypothetical scenario where on 29 May 2012, there is intense rain, which combined with the weakened levee results in the levee collapse and flood. We first introduce the case study (Section 5.1) and then apply our five-part multi-hazard impact framework (Section 5.2).

5.1. **Case study description**

The Po river valley is one of Italy’s largest economic regions, with industries and agricultural production sites accounting for 40% of Italy’s gross domestic product [108]. The valley, in northern Italy, is named for the Po river, which runs 652 km from west to east, crossing four Italian regions (Piemonte, Lombardia, Veneto, Emilia Romagna) [109]. In May 2012, the Emilia Romagna Region in northern Italy experienced two main earthquake shocks (20 May 2012 Mw = 6.1; 29 May 2012 Mw = 6.0), each followed by aftershocks lasting into June 2012 [110,111]. Primarily industrial assets were damaged, with scattered damage in residential buildings [112]. Despite the low earthquake magnitudes, there were significant losses due to the high concentration of exposed elements in the Po alluvial plain [113].

The Po valley is a natural flood plain for the Po river and some of its major tributaries. A complex combination of passive (e.g., levees) and active (e.g., expansion areas, pumping stations) flood counter measures are in place in the Po valley [114]. During the first of the two earthquake shocks, on 20 May 2012, several flood defences were partially or wholly damaged [115,116]. The Po valley’s flood control system includes an active part composed of diversion channels that can be activated remotely [114]. The diversion channels drain the water from the flood plain back into the river system when a flood occurs [114]. Because of the earthquake shocks, the remote-control system of the gates that control the use of diverting channels was unusable. As a result, several institutions responsible for the flood protection structures later asked for an assessment of the flood risk, given that the flood defence system was only partially operational [117,118].

AIPO, the Interregional Agency of the Po river, responsible for the levee maintenance, surveyed the levee status and identified several that were partially damaged, particularly on the tributary sections [119]. The water irrigation authorities (Consorzii di Bonifica), who managed the diversion channels, gates, and pumping stations, estimated more than one year to repair all damages suffered [120]. In these conditions, the regional agency for environmental protection (ARPA-SIMC) was asked to perform a multi-hazard risk assessment starting from the precondition of earthquake damage on potential flooding [117,118]. In this case, the winter rainfall was lower than anticipated, and therefore the damaged levees did not collapse, and thus flooding did not occur. Still, this example raised the awareness of a need for a standardized protocol for multi-hazard damages in the Po valley if an earthquake causes damage to the levees, resulting in flooding.

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Using this real-world case, we developed a hypothetical scenario of damage from the (actual) 20 May 2012 earthquake mainshock, which weakened the levees in Po Valley. In our hypothetical scenario, on 29 May 2012, there is a significant increase in the river’s water levels (along the flood defence line) due to heavy rains. The increased river water acts on the levee system already significantly damaged by the earthquake shock, such that the levee completely collapses and there is a flood. Although this scenario did not occur in May 2012, both authorities and local people were concerned that it was plausible. We applied the five steps of our multi-hazard impact framework (Fig. 1), as illustrated in Section 5.2.

5.2. Application of the framework

The application of our multi-hazard impact framework (Fig. 1), is now discussed, supported by a visualization of each step.

5.2.1. Phase 1. Step I. Identification of hazards and their interactions (Fig. 5)

Visualization: A schema of the hazards considered and their interactions, to be selected among the mechanisms discussed in Section 4.1 and reported in Fig. 2.

Case study application: In this real-world case scenario, two hazards are considered: a 20 May 2012 earthquake main shock (which...
damages parts of the levee system) which, when combined with hypothetical intense rain on 29 May 2012, results in a levee collapse and riverine flood. In actuality, there was an aftershock sequence after the 20 May 2012 earthquake mainshock and another main shock (and subsequent aftershocks) on 29 May 2012. For the simplicity of the visualization reported in Figs. 5–7, we will not consider these aftershocks in our hypothetical multi-hazard example. Nevertheless, additional seismic shocks acting on assets previously damaged would be able to increase their damage level and to further decrease their structural performances, as deeply investigated in seismic literature (e.g. Refs. [121–123]). The type of interaction mechanisms between the earthquake mainshock and flood is an ‘Additional hazard potential’ (mechanism (d) in Fig. 2). In this case, the impact caused by the first hazard (earthquake main shock on 20 May 2012) increases the intensity of the second hazard (riverine flood on 29 May 2012) as the physical damage caused by the earthquake on a specific class of elements (i.e., the levee system) changes the flood hazard scenario and consequently increases the overall level of risk (Step I, Fig. 5).

5.2.2. Phase 1. Step I. Identification of hazards and their interactions (Fig. 5)

**Visualization:** A simplified flow of the adopted modelling chain and main outputs.

**Case study application:** The hazard modelling of both the 20 May 2012 earthquake main shock (resulting in a weakened levee system) and the hypothetical 29 May 2012 consequent intense rain, levee collapse and flood, has been developed in the RASOR project framework [100]. RASOR modelled the multi-hazard scenario according to the workflow described in Fig. 5 Step 2. They employed a model based on Ground Motion Prediction Equations (GMPEs), with the spatial variations of ground motion due to a seismic wave

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**Fig. 7.** Visualization of Phase 2, Steps IV and V of the multi-hazard impact framework (see also Fig. 1): application to the Po Valley (Italy) case study (20 May 2012 earthquake plus hypothetical 29 May to 8 June 2012 flood). Step IV shows a map with A, B, C as three points along the river-plain. Also indicated are the corresponding impact interaction mechanisms (see Fig. 3). Step V illustrates damages over time (in orange) in locations A, B and C.
radiating from an earthquake source calculated and a Ground Motion Map produced. They used the distribution of the ground shaking as an input to evaluate the levees failure probability. They also used a probabilistic riverine levee breach model to transform the water level time series at a specific location of the flood defence line (given by a meteorological-hydrologic model) into a time series of failure probabilities and – in case of a failure – into a breach development over time. The transformation of water levels into a time series of failure probability was done by using fragility curves to consider the damage caused by the earthquake. Finally, the RASOR project implemented a two-dimensional hydrodynamic model [86,124] to evaluate the resulting flooding and produce the water depth’s evolution in time and space.

5.2.3. Phase 2. Step III. Analysis of spatial and temporal evolution of the impacts from the hazards (Fig. 6)

**Visualization**: Step III is composed of three different elements:

- **III.a** A representation of the spatial and temporal evolution of the hazards through a series of hazard maps captured at different time steps.
- **III.b** A series of timelines – one for each hazard – reporting the duration of each hazard from initial time to final time and an indication of the magnitude.
- **III.c** A timeline showing the area impacted by each hypothetical hazard over time. This allows the comparison of each hazard’s extension and its spreading velocity, i.e. the velocity of spatial progress of the hazard.

To evaluate the number of significant time steps to include, we consider that ‘instantaneous hazards’ (see Section 4.3) need only one map to be described. In contrast, the other hazards usually require at least three maps (one at the initial time or slightly later, one at the peak and one at a final time or slightly earlier).

**Case study application**: In our real-world scenario, we outline the impacts at three representative locations along the river (Step III.a of Fig. 6) using the letters A, B, C:

- (A) A polygon in the built-up area on the river plain encompassing several residential assets outside the flooded area.
- (B) A point location representing the collapsed levee on the river plain.
- (C) A polygon in the built-up area on the river plain encompassing several residential assets inside the flooded area.

These three locations experience different hazards at different times and, therefore, different impacts. The two hazards considered (Step III.b of Fig. 6) are an earthquake on 20 May 2012 of magnitude MW = 6.1 on the Richter scale and a hypothetical riverine flood on 29 May 2012 with a return period of 200 years. The evolution of the hazards in these locations is graphically shown in Step III.a of Fig. 6, with a series of hazard maps captured at four different time steps (all dates in 2012 and local time):

- \( t_1 = 20 \text{ May 04:00 LT} \): the main earthquake shock of MW = 6.1 occurs (Points A, B, C all affected), which weakens the levee system (damaging parts of it).
- \( t_2 = 29 \text{ May 00:00} \): intense rain combined with the weakened levee system results in the levee collapsing and the flood starting (flood at Point B).
- \( t_3 = 29 \text{ May 03:00} \): the flood has started spreading across the region at a given speed and has increased the affected area (flood at Points B and C).
- \( t_4 = 29 \text{ May 2012 08:00} \): the flooded area reaches its maximum extent covering an area along the river plain, which primarily includes points B and C.
- \( t_5 = 8 \text{ June 2012 10:00} \): withdrawal of the flood event (almost concluded) with a significant reduction of the flooded area extent (flood at Point B).

On 20 May 2012, the earthquake occurs and is experienced by all three of the considered locations (A), (B) and (C). On 29 May 2012 at 00:00 LT, a flood begins due to the levee collapse, impacting location (B). For simplicity, we assume that the levee breach occurs when the river reaches its highest flow (peak discharge) in the corresponding cross-section. The time window between the earthquake and flood differs from location (B) to location (C), as the flood does not instantaneously affect the entire region but instead spreads across the region in time at a given speed (Step III.c of Fig. 6). Therefore, location (C) is reached by the flood a few hours later than location (B). The flood does not impact location (A). The two hazards are characterized by very different temporal and spatial evolution. Step III.b of Fig. 6 reports two timelines — one for each considered hazard (earthquake and riverine flood) — reporting the duration from the initial to final time and indicating the magnitude. According to this representation, we highlight the following:

i. The two hazards (earthquake 20 May 2012 and flood 29 May to 8 June 2012) are not temporally overlapping, with a time window of at least nine days between the end of the earthquake and the starting of the flood.

ii. The main earthquake shock occurs over a very short time period (almost instantaneous), while the flood has a duration of days.

Step III.c of Fig. 6 reports a timeline showing the area impacted by the two hazards over time. According to this timeline, we find for this case study:

i. The main earthquake shock on 20 May 2012 impacts a spatial footprint many times larger than the one affected by the flood 29 May to 8 June 2012.

ii. The main earthquake shock impacts almost instantaneously the entire region. At the same time, the flood spreads across the region in time at a given speed, reaching a maximum extension, and then (after a few days) it withdraws. To simplify the visualization,
after reaching the maximum extent, it is assumed that the flooded area extent remains almost the same for a few days before starting to withdraw. Small changes due to infiltration and evapotranspiration are neglected.

5.2.4. Phase 2. Step IV. Identification of type of impact interaction (Fig. 7)

**Visualization:** Step IV includes a map reporting in each point of the spatial domains chosen, the resulting mechanism of impact interaction, according to the classification introduced in Section 4.4.

**Case study application:** In Fig. 7, Step IV are three locations, A, B, C (see also Fig. 6, Step IIIa), with a spatial map giving the following: the area impacted only by the earthquake (in blue); the area impacted by both earthquake and flood (in orange), with the maximum flood extent reached on 29 May at 08:00 LT. At location (A), only one hazard (i.e. the earthquake) occurs. Therefore, an “independent single hazard impact assessment” can be performed, as shown in the blue oval (Fig. 3) and explained in detail in Section 4.4. In locations (B) and (C), the occurrence of the earthquake is followed by a flood after a particular time window. This is the case of a “spatial overlap impact (with residual and subsequent damage)”, as shown in the orange oval (Fig. 3) and explained in detail in Section 4.4 (Step IV, Fig. 7).

5.2.5. Phase 2. Step V. Multi-hazard impact assessment (Fig. 7)

**Visualization:** A series of timelines describe the evolution in time of the damage in a series of selected domain locations. These timelines enable the identification of whether there are time windows in which: (i) one or more hazards is causing impact, (ii) there are no hazards. The damage levels change in time according to the intensity and presence of the hazards and the territorial system’s recovery dynamics. The damage level usually increases once a new hazard arrives, while it decreases or remains constant in the time windows in which hazards are not acting on the system. The damage depends on the exposure element considered, and therefore, to draw the graph, a specific asset or a group of assets needs to be specified.

**Case study application:** When the 20 May 2012 earthquake mainshock occurs (Fig. 7, Step V), the infrastructures at locations (A), (B) and (C) hypothetically suffer a certain level of damage. After the earthquake, the territorial system starts to recover from the disaster, and a decrease in damage is observed in all three locations. From 29 May to 8 June 2012, the flood occurs, and only locations (B) and (C) experienced additional damage. The time window between the earthquake and flood start differs from location (B) (29 May 2012, 00:00) to location (C) (29 May 2012, 03:00), as the flood does not instantaneously affect the entire region. Still, it spreads across the region in time at a given speed. Location (B) represents the collapsed levee site, and thus, the damage reaches 100% (i.e. the levee is completely destroyed). In the case of the built-up area in location (C), it is difficult to estimate the final cumulative damage due to the effects of a flood on assets previously damaged by an earthquake. A question mark has been left on the graph (Step V, Fig. 7) as the quantitative estimation of the combination of multiple damages is still an open issue.

The analysis framework helps a consistent choice of the step-by-step modelling, from the most appropriate hazard models to the aspects that need to be taken into account in the vulnerability and exposure assessment to determine the evolution of damage in time. The visualization of each step (Figs. 5–7) facilitates the summary of all interconnected aspects so that no one component is overlooked in the final assessment.

6. Discussion and conclusions

This study presents a five-step multi-hazard impact framework to evaluate the damages resulting from hazard interactions. The need for a standardized approach that practitioners and researchers can implement to evaluate multi-hazard impacts has arisen from a critical review of existing multi-hazard risk approaches (Section 3) and stakeholder workshops. We have identified gaps and highlighted the need for a standardized procedure (i) which considers both hazard interactions and impact interactions, (ii) takes into account residual damages and recovery dynamics and (iii) is not focused on a specific category or family of natural hazards.

The approach consists of five steps: (Step I) the identification of the hazard interaction mechanism (Section 4.1), (Step II) the modelling of the multi-hazard scenarios (Section 4.2) (Step III) the analysis of spatial and temporal evolution of the hazards and their impact in the domain of interest (Section 4.3), (Step IV) the identification of the type of impact interaction generated by the specific scenario of spatial and temporal hazard overlapping (Section 4.4), (Step V) the multi-hazard impact assessment (Section 4.5). The application of this framework supports a hazard (or risk) manager to:

i. Identify the mechanism of hazard interactions and implement it in the development and modelling of a specific hazard scenario.
ii. Analyze how these hazard interactions can result in a series of different patterns of hazard overlaps in space and time and how these overlaps can generate different types of impact interactions.
iii. Identify a series of aspects that need to be considered in the impact assessment, according to the type of impact interaction identified.
iv. Use a synthetic visualization for hazard and impact interactions.

A series of factors and limitations contribute to uncertainty within this conceptual framework’s development. These limitations can also influence the utility of the results. These are the following:

i. **The so-called “knowledge bias” [5].** The approach proposed in this paper is strongly engineering in nature, which leads to a focus on physical damages on the built environment, without considering other impact types (e.g., social, economic, environmental).
ii. **The limitation in the number of multi-hazard cases analysed**
   This is due to (i) the limited use of grey literature in the analysis, which in some cases can be a significant source of information, (ii) the exclusion of specific hazards or hazard groups from the analysis, such as anthropogenic and technological hazards.
iii. The detailed analysis of only three of the five framework steps (Fig. 1). The event scenario modelling (Step II) is not discussed in detail since the variety and heterogeneity of different interaction types and the different hazards involved in the analysis, makes it challenging to define a standardized procedure. However, the framework classifications guide the user towards the most appropriate approaches, helping in clearly identifying the type of hazard interactions to model.

This paper aims to set a conceptual framework to address multi-hazard impact scenarios. However, the quantification of impacts, i.e., the quantitative impact assessment (Step V), has not been addressed. The development of a standardized way to calculate multi-hazard impacts is not found in the grey- or peer-review literature due to the variety and heterogeneity of different interaction types. Even if each hazard interaction case has to be modelled separately, this paper has tried to identify and discuss significant aspects that we believe should be included in the modelling, such as reconstructing the hazard sequence and the dynamic modelling of recovery between recovery hazards.

Future work may formalize the framework’s quantitative aspect by parameterizing the full range of aspects in a generalized mathematical formulation when possible and appropriate. The final aim is to quantitatively calculate the multi-hazard impact on a series of exposed elements, given the hazards’ typology and their spatial and temporal evolution. In moving towards a more quantitative framework, uncertainty should be appropriately integrated and treated in all its aspects. Uncertainty is widely addressed in the literature, referring to hazard and risk assessment in a single hazard perspective both in its aleatory and epistemic component [125]. However, uncertainty growth will require additional research when taken in a multi-hazard context.

Despite the limitations and challenges previously introduced, this paper’s main contribution resides in developing a multi-hazard conceptual framework that (i) is standardized and applicable for a wide range of natural hazards and (ii) brings in both hazard and impact. This framework, which can be appropriately expanded, and customized, represents a tool to facilitate a multi-hazard impact assessment by those working on natural hazard risk management and reduction. Examples of this conceptual framework’s practical use include: (i) to define checklists and standards operating procedures for decision-makers, which can be used as a guide to performing a comprehensive and complete multi-hazard risk impact assessment, (ii) to narrow future research priorities for funding and time allocation in evaluating multi-hazard risk, (iii) to integrate multi-hazard aspects into disaster risk management international guidelines.

Author contributions

SDA conceived and designed the analysis and collected the data. LR, RR and ET contributed data, specifically case study data, including flood maps and vulnerability data. SDA performed the analysis, supported by all other authors. SDA, supported by ET and FET, developed the visualization of the framework. SDA led on all parts of the paper writing, except the case study description led by RR. BDM and FET reviewed and revised the paper. BDM supervised the work. RR acquired funds for the research project and this paper’s publication. All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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