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# A new multidimensional framework for risk assessment in multi-hazard context: the Hazards-Impacts matrix

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ABSTRACT

Geographic areas are rarely exposed to a single natural hazard; more often, two or more hazards coexist within the same territory. Consequently, a comprehensive analysis, quantification, and comparison of all potential risks affecting a given area are fundamental to fostering sustainable and climate-resilient environments. To this end, this paper introduces a new indicator-based framework for evaluating risk in multi-hazard contexts, referred to as the "Hazards-Impacts Matrix." Developed through a multidisciplinary effort, the matrix integrates several risk dimensions (i.e. those linked to impacts on individual well-being, the built environment, public services, business activities, environmental systems, communities, and the financial system) and can be consistently applied across multiple spatial scales. Furthermore, by employing a coherent set of indicators across different hazards, it ensures the comparability of risk estimates, thereby enabling the analysis of the simplest form of hazard interrelationships (i.e., compound events) and providing a robust foundation for investigating more complex hazard and risk interdependencies. The matrix is applied to the Lomellina area (Northern Italy) as a proof of concept. While originally designed to support decision-makers during the risk mitigation planning

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phase within the Italian context, the framework can also be adapted for post-event assessments and extended to other countries.

## 1. Introduction

This paper introduces a new framework for evaluating risk in multi-hazard contexts. Such a tool is essential for effective risk management as geographic areas are rarely exposed to only one type of hazard; rather, they are often subject to multiple, coexisting natural threats. According to a 2005 World Bank report on natural hazard hotspots [1], approximately 790 million people worldwide face high exposure to at least two hazards, and around 105 million people are exposed to three or more hazards, a situation likely to worsen with climate change [2]. This picture is confirmed by more recent reports at the global [3] and European level [4] and is particularly pronounced in Italy [5], for which the work presented in this paper has been developed.

A comprehensive analysis, quantification, and comparison of all potential risks affecting a territory is fundamental for fostering sustainable, climate-resilient environments, enabling effective land-use planning, and ensuring efficient risk management both before and during catastrophic events [6]. Considering co-existence of and interactions between risks can significantly influence decision-making processes. On one hand, measures aimed at reducing vulnerability to one hazard may inadvertently increase vulnerability to another [7,8]. On the other hand, synergies can emerge, where a single action mitigates multiple risks simultaneously, enhancing overall resilience [8,9]. Accordingly, the adoption of a multi-risk approach has been recognized as a priority in numerous international frameworks. Calls for multi-hazard and multi-risk strategies date back to the early 1990s, with Agenda 21 for sustainable development emphasizing the necessity of multi-hazard research as part of human settlement planning and disaster risk management. This concept was further advanced through initiatives like the Hyogo Framework for Action and the more recent Sendai Framework for Disaster Risk Reduction [10,11]. At the European level, multi-risk approaches have been endorsed in various policy documents, including the European disaster risk reduction strategy (2008), the EU Community framework on disaster prevention (2013) and the Commission Recommendation on Disaster Resilience Goals (2023), as well as technical and policy report [12,13].

The framework presented in this paper is the result of a multidisciplinary effort, bringing together experts from engineering, architectural design and conservation, urban planning, economics, agronomy, sociology, philosophy, geology and environmental protection, working together to catch all the various dimensions of risk. In detail, the framework was developed in the context of the RETURN (multi-Risk sciEnce for resilienT commUnities undeR a changiNg climate) project, within the WP 7.2 – Innovative tools to evaluate risk mitigation effectiveness of the Spoke TS3 – Communities' resilience to risks: social, economic, legal and cultural dimensions. The outcome is a semi-quantitative framework, i.e., the "Hazards-Impacts (H-I) matrix", made of both quantitative and qualitative indicators, for an ex-ante (i.e., before the occurrence of a disastrous event) estimation of risk in multi-hazard contexts, in support of effective risk management.

The remainder of the paper is structured as follows: Section 2 provides a contextual overview of the H-I matrix within the current literature on multi-risk assessment. Section 3 presents the H-I matrix and describes the methodology employed in its developing. In Section 4, the matrix is demonstrated through its application in a case study. Section 5 discusses strengths and limitations of the proposed framework, also with respect to transferability in space and time. Section 6 concludes the paper.

## 2. The H–I matrix within the current body of literature on multi-risk assessment

The lack of a shared and precise terminology has been identified by several authors as one of the main challenges in providing a comprehensive overview of the current state of the art in multi-risk assessment [2,11,14–16]. Nevertheless, there is general agreement that research on multi-risk has evolved along two main approaches [2,11,14,15]: (i) the consideration of multiple hazards co-existing in the same area, without accounting for any interactions among them, an approach also known as "multi-layer single-risk assessment" [11,17]; and (ii) the consideration of hazard "interrelationships", including triggering, amplification, and compound effects (see e.g. [18–20]). More recently, this second approach has been complemented by analyses of vulnerability interrelationships (see [21]), although this aspect remains relatively understudied [15].

Although there is broad consensus that the second approach is better suited to capture the dynamic and systemic nature of multi-risk, approximately 50% of published studies still adopt a multi-layer single-risk assessment approach [11]. This can partly be explained by the limited understanding of complex interaction mechanisms and by the lack of appropriate tools for their modelling. However, we also argue that another reason lies in the lack of a robust, coherent and comprehensive estimation of risks associated with all relevant hazards. A key challenge emerging from the literature review concerns indeed the absence of common standards in natural risks analysis, which hampers the comparability of hazard and risk assessments [13]. Risk analyses associated with different natural hazards often rely on distinct methodologies, operate at different spatial scales, and, as a result, adopt metrics that are difficult to compare directly [17]. This issue also arises when considering different dimensions of risk (e.g. physical, economic, and societal), even when they are associated with the same hazard. Nevertheless, the inclusion of multiple risk dimensions is essential to ensure comprehensive and meaningful risk assessments, particularly when such assessments are intended to provide a robust knowledge base for the design and prioritization of risk mitigation strategies [16].

The range of risk dimensions included in multi-risk analysis represents, however, another limitation of existing studies, which often focus narrowly on a limited set of exposed elements [11]. Most multi-risk assessments address only one or a few risk dimensions, typically the built environment [17,20,22], population [20,23], cultural heritage [24–26] or critical infrastructures [22,27]. By contrast, considerably less attention has been paid to other dimensions, such as environmental, societal, and financial impacts [16,28]. This may be due to a lack of multidisciplinary studies, as highlighted by. [3,29].

Within this context, this paper focuses on risk assessment in the presence of co-existing hazards as a preliminary step toward the analysis of hazard and risk interrelationships. The aim is to propose an estimation framework that overcomes limitations related to the comparability of single-hazard risk evaluation, thereby enabling the assessment of the simplest form of hazard interrelationships, namely the simultaneous occurrence of multiple hazards affecting the same area (i.e., compound events). In doing so, particular attention is given to ensuring a comprehensive estimation of risk, encompassing all its dimensions.

Such an objective requires addressing two additional limitations of existing studies. The first concerns the spatial scale of analysis. Existing risk studies have been conducted at various levels, from global to local, each offering methodologies suited to their specific contexts [2,11,29]. However, few of them give the possibility to transfer the proposed methodology from one level to another [29]. Given that the most appropriate scale of analysis may vary across risk dimensions (for example, physical risk to buildings is best assessed at the building level, whereas social risk to communities may require analysis at the municipal level) the proposed framework must be consistently applicable across multiple spatial scales.

A final key challenge concerns the evaluation of the relative importance of co-existing risks. A wide range of approaches has been proposed, spanning from qualitative to quantitative methods, including stakeholder-based weighting, risk matrices, risk indices, and statistical techniques [2]. The choice among these approaches largely depends on the scale of the assessment and the availability of data.

## 3. The H-I matrix: structure and methods

Among the various qualitative, quantitative, and semi-quantitative approaches developed to date [2,14], the proposed H-I matrix adopts a risk-indicator-based methodology, widely used and well established in the current literature [11,30–34].

In practice, the H–I matrix takes the form of a table (see the online Supplement for the complete version), in which each row represents a consequence associated with the occurrence of a natural hazard. The matrix considers five natural hazards: earthquakes,

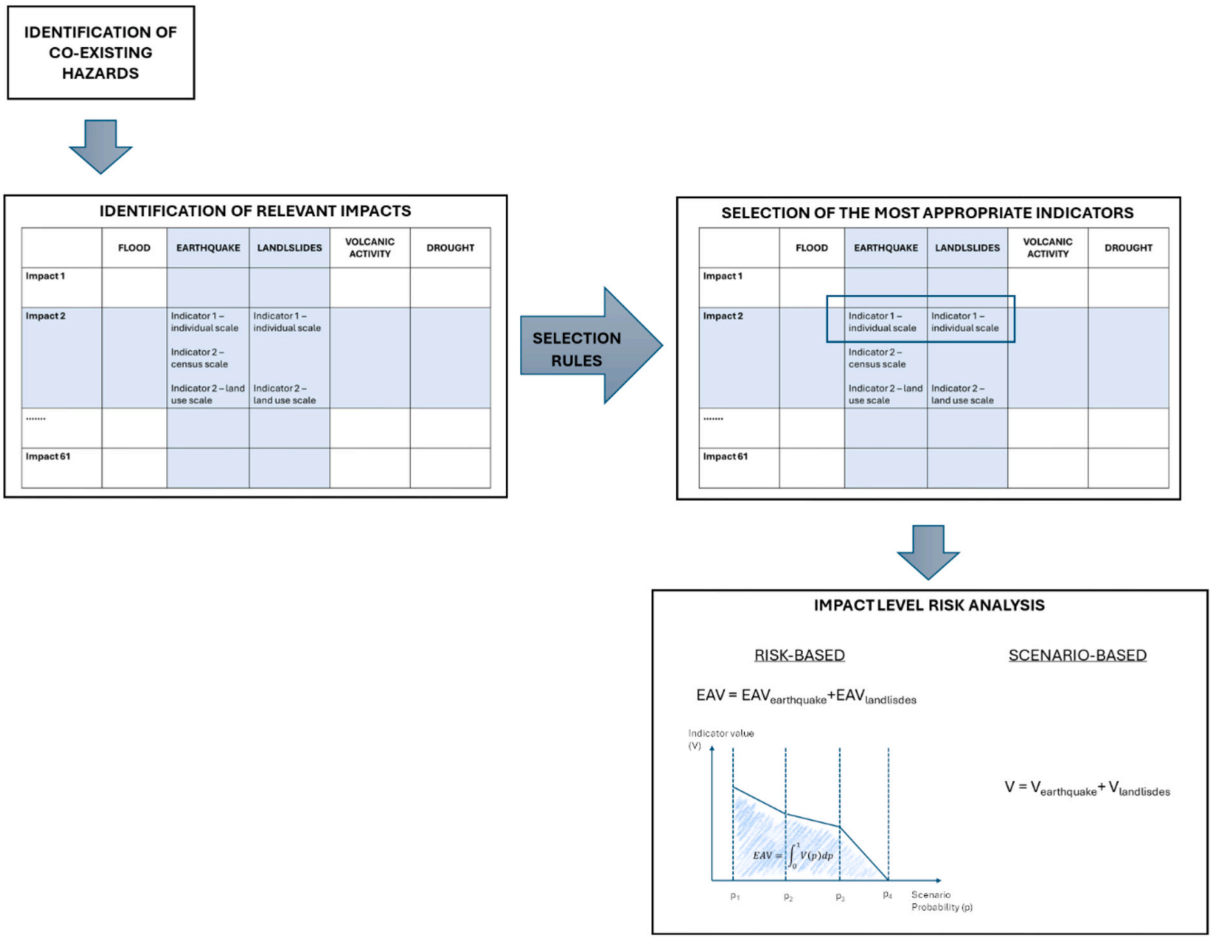


**Fig. 1.** Flowchart for the implementation of the H-I matrix.

floods, landslides, droughts, and volcanic activity. Hazard-related consequences are referred to in the matrix as "impacts" and include direct or indirect, tangible or intangible effects, in accordance with the broader definition of damage provided by [35]. Overall, the H–I matrix includes 61 impacts, organized into sub-tables corresponding to different dimensions of risk (see Fig. 4 in the Appendix and the online Supplement). It is worth noting that not all impacts are relevant for all hazards (e.g., physical damage to buildings is not relevant in the case of drought). This is explicitly reflected in the matrix by associating each impact with the hazards that can trigger it.

For each impact, one or more indicators are defined for its quantification. It is important to emphasize that the H-I matrix was designed to be implemented ex-ante, i.e., to assess risk before the occurrence of a disastrous event. This is a fundamental prerequisite in the definition of potential indicators that, for this reason, cannot be based on specific ex-post measurements/evaluations. As better specified in section 3.2, the selection of indicators was then primarily driven by the availability in the literature of predictive models suitable for their quantification. Still, when quantitative assessments are impractical (e.g., because they require not-available data, their estimation is too expensive or is affected by high uncertainty invalidating reliability), qualitative, expert-based indicators are proposed.

The level of scientific knowledge regarding damage mechanisms and, consequently, the availability of models for the quantification of impacts, varies across hazards. As a result, the same impact may be quantified using multiple indicators for some hazards, or only a single indicator for others. For example, several well-established damage models are available for seismic and flood risk, especially for the built environment, whereas damage associated with landslides is less extensively modelled. Nonetheless, damage models operate at specific spatial scales. In some cases, models are available to compute a given indicator at all spatial scales considered in the matrix, while in other cases they are applicable only at selected scales. Moreover, even when similar modelling approaches are available across multiple scales, the required input data may differ, particularly in terms of spatial resolution.

To account for these aspects and, at the same time, to ensure that the matrix can be applied in a consistent manner across multiple hazards, impacts, and spatial scales, namely through the use of comparable and homogeneous indicators, a set of specific "selection rules" was introduced. These rules identify the appropriate indicator to be applied for each impact, i.e. the indicator that can be consistently evaluated across hazards, depending on the hazards considered, available data and the spatial scale of analysis (various spatial scales are considered in the matrix spanning from the individual exposed elements to regional areas). In particular, the selection rules first indicate whether indicators referring to the same impact are mutually exclusive or should be combined (e.g., summed). Furthermore, they define whether to select damage or exposure indicators, as well as qualitative or quantitative ones, according to the available modelling capabilities and data, at the scale under investigation and for each hazard considered. In doing so, mismatches in data resolution and aggregation bias are avoided. The general criterion underlying the selection rules is to enable the best possible estimate for the analyzed context, while ensuring the use of consistent indicators across all hazards coexisting in the area.

Fig. 1 provides a schematic overview of how the matrix can be implemented in practice.

The implementation process begins with the identification of the co-existing hazards affecting the study area (e.g., earthquakes and landslides in the example shown in Fig. 1). Based on this step, the relevant impacts are identified (e.g., only Impact 2 in Fig. 1 example, for simplicity). For each relevant impact, the matrix proposes one or more indicators, which may operate at the same or at different spatial scales (e.g., indicators 1 and 2 in Fig. 1). The most appropriate indicator for each impact is then selected through the application of the selection rules, which identify indicators that can be consistently evaluated across hazards, given the spatial scale of analysis.The choice of the spatial scale depends, on the one hand, on the objectives and motivations of the assessment and, on the other, on the availability of suitable indicators for the relevant impacts. For instance, in the example shown in Fig. 1, if the required spatial scale is assumed to be the census level, the selection rules would indicate selecting indicator 1, even though it may provide a rougher estimate of the impact than Indicator 2. Indeed, indicator 2 can be consistently calculated across hazards only at a coarser spatial resolution than the one required.

The last step consists in the risk analysis. Based on the available knowledge about the hazard(s) and the objectives of the analysis, the H-I matrix can be implemented using either a "scenario" or a "risk-based" approach [17]. While the scenario approach is more appropriate for emergency planning, the risk-based approach must be preferred when the risk assessment is at the base of long-term risk mitigation strategies. The risk-based approach considers, for each hazard, multiple scenarios, each associated with a probability of occurrence. Indicators are calculated for each individual scenario and then averaged according to their respective probabilities, resulting in annual expected values of indicators (EAV), for each hazard, in accordance with the definition of risk provided in [36].

**Table 1**
Descriptive characteristics of the indicators included in the columns of the matrix.

| Column (field) | Possible values/description |
|---|---|
| Measurement unit | qualitative classes or specific metrics |
| Model | e.g. exposure model, parametric model, vulnerability or damage model/fragility function/consequence function, input-output models, qualitative analysis |
| Input data - hazard | e.g. flood inundation area and probability of occurrence, spatial distribution of peak ground acceleration or spectral acceleration and probability of occurrence, landslide susceptibility zone and probability of occurrence |
| Input data - exposure | e.g. spatial distribution of items and their economic value |
| Input data - vulnerability | e.g. vulnerability features of exposed items |
| Spatial scale (applicability) | - Individual item (sub-municipality, municipality, multi-municipality)<br>- census block (municipality, multi-municipality)<br>- land cover/land use area (multi-municipality, national) |
| References | link to papers/reports describing the model and to national or international databases where to retrieve model input data |

Hazard-specific expected values (i.e., risks) can then be summed at the level of individual impact to obtain a multi-hazard risk assessment. It is worth noting that this approach is fully consistent with the foundational assumptions of the matrix—namely, the co-existence of multiple hazards—as it inherently accounts for the relative weight of each hazard through the computation of expected values. Conversely, in the scenario-based approach, the analysis focuses on a specific hazard scenario, evaluating the indicators solely within the context of that scenario. However, as the interaction among hazards is not considered by the matrix, such a scenario must be carefully evaluated and must refer to the simultaneous occurrence of independent hazards on the same area, i.e. compound events, even with different probability of occurrence (e.g. floods and landslides due to intense precipitation). In this case, indicator values no longer refer to annual expected values (since hazard probabilities are not considered) but can be summed across hazards to obtain a multi-hazard impact estimate.

The assessment of the indicators is facilitated by information provided in the matrix. Indeed, for each indicator, the columns of the H-I matrix specify the unit of measurement and the model to be adopted for its calculation together with the hazard, exposure, and vulnerability data required (Table 1). In addition, references to the adopted indicators and models are provided, together with links to databases from which information on hazard, exposure, and vulnerability can be retrieved. Supplied information may change according to the hazard considered and the spatial scale of the analysis, as previously discussed.

Overall, the structure of the matrix makes it an operational and user-friendly tool for risk analysts. In the following sub-sections, the impacts and indicators included in the matrix are described in detail, together with the methodology adopted for their definition.

### 3.1. Natural hazard impacts: definition and classification

The identification of impacts was conducted in two distinct phases. The first phase relied on an extensive literature review (not included here), carried out adopting a generalized approach that encompassed international studies sourced from academic search engines. In this phase, impacts were identified by the entire team of authors, each contributing according to their specific expertise in terms of hazard types and impact dimensions. For instance, earthquake engineers primarily investigated seismic impacts from the perspective of physical damage, while sociologists focused on direct and indirect impacts on communities, without reference to a specific hazard. The interdisciplinary composition of the author team ensured that all considered hazards and a wide range of risk dimensions were addressed.

In the second phase, results from the literature review were integrated and refined to develop a comprehensive multi-hazard framework. The merging process was conducted collaboratively by the interdisciplinary team during an in-person workshop, involving all its members, followed by numerous online interactions. During these meetings, the impacts identified in the previous phase were examined individually. Each impact was then associated with the relevant hazards by comparing the inputs provided by experts across different hazard domains. This process made it possible to identify common patterns of expected impacts across multiple natural hazards, as well as to highlight hazard-specific effects. Then, only impacts relevant to the Italian context were retained, considering factors such as prevalence and contextual appropriateness. For instance, lack of food and migration are not expected in case of disaster in Italy. Finally, identified impacts have been assembled into homogeneous classes and further classified as impacts and sub-impacts. This grouping strategy was designed to streamline the evaluation process by guiding risk analysts through the range of

**Table 2**
Categories of impacts included in the H-I matrix and scientific sources supporting their definition.

| Category | Description of associated impacts | Examples of associated impacts | References |
|---|---|---|---|
| Individual well-being | Direct and indirect impacts on people's health, including the effects on social vulnerability and impacts aggravating the condition of vulnerable people. | Injuries, deaths, psychological unease, spread of pathologies, incidence of respiratory diseases, well-being decrease, poverty increase, usage conflict | [37–41] |
| Built environment | Every physical direct impact on the built environment, from residential, production and cultural use, to infrastructures. | Physical damage to residential buildings, productive buildings, cultural buildings, public buildings, infrastructures | [37–40] |
| Business activities | Every direct and indirect impact on production factors, including industrial, agricultural, cultural and touristic activities. | Agriculture production interruption, supply chain interruption, production disruption, tourist operator costs, farmers/breeders and industrial costs | [37–40,42] |
| Public services | Every impact on public services availability (local authorities, municipal offices, hospitals, institutional planning, infrastructure) that does not have a pure physical component, including territorial governance and institutional and regulatory crowding out. | Reduction of services availability and efficiency (e.g., less hospital places and service for general and specific purposes, school closures), transports availability, water and energy supply, interruption of telecommunications, administrative service reduction/slow down. | [37–40,42,43] |
| Environmental systems | Every direct and indirect impact on ecosystems and natural biodiversity, including the reduction of biodiversity. | Disruption of the value of green and natural areas (including protected natural areas and green infrastructure), pollution, reduction of biodiversity, quantity and quality of vegetation, ground quality | [37–42,44] |
| Communities | Every impact on how communities identify themselves, interact with each other and relate to their local community places. | Loss/decrease of social identity, place identity, traditional activities, cultural landscape | [37,38,42,45,46] |
| Financial system | Every impact on the companies' credit worthiness and/or reputation, commercial and touristic image that might impact on the credit, worthiness of a company, region, household or any other economic agent. | Access to credit and to market, stock market expectations and return, cash and public fund transfers insurance and credit cost. | [37–40] |

impacts and indicators considered in the assessment. It is worth noting, that such an approach is commonly adopted in risk-indicator-based methodologies, including the impact reporting framework of the Sendai Framework for Disaster Risk Reduction [37].

Table 2 summarizes the adopted impact classification. Impacts were grouped into seven categories, each corresponding to a dedicated sub-table in the online Supplement. The primary criterion guiding the classification process was to define categories representing different risk dimensions, ensuring comprehensiveness and avoiding double-counting and overlaps. To this aim, the categories were identified through a mixed approach combining evidence from the literature and the authors' expertise. Evidence from the literature, reported in the last column of Table 2, refers both to studies addressing specific risk dimensions and to comprehensive frameworks dealing with overall natural hazards impacts, such as the Sixth assessment report of IPPC [38] and the Sendai Framework [37]. It is important to note, however, that risk dimensions are not univocally defined in the literature. For this reason, a description of each adopted category is provided in Table 2, together with practical examples of associated impacts.

The authors' expertise was crucial in avoiding overlaps; moreover, it contributed to the definition of categories that are not only mutually exclusive and collectively exhaustive but also characterized by consistency in the approaches and tools required for their quantification (see Section 3.2), as well as by homogeneity in the associated stakeholders.

The full list of categories and associated impacts is depicted in Fig. 4 of the Appendix.

Impacts categorized under "Individual Well-being" focus on the direct and indirect effects of natural hazards on individuals that exacerbate their health, social, and economic conditions, emphasizing the personal consequences for each affected individual. In addition to physical impacts, such as health issues and injuries, the matrix also incorporates additional impacts identified in the literature, like "indirectly affected people" [47,48] and impacts on "economic well-being" [38,47]. The first refers to individuals who do not reside in the affected area but may still experience negative consequences as "users" of the area, such as students or employees, as they rely on the services or infrastructure of the affected region. The second encompasses changes in factors like consumption costs, employment rates, or poverty levels, highlighting the broader economic repercussions on individual well-being.

On the other hand, when impacts on "Communities" are considered, the focus is not on individuals anymore but on the impacts that an extreme/disastrous event could have on the interactions among affected community members and between community members and the local community places. Three kinds of impacts are considered: impacts on cultural capital, impacts on human capital, and impacts on social capital [49–51]. The first is related not only to tangible heritage (i.e., built heritage, landscapes), but also to intangible heritage, assumed as the system of relationships and creative skills that, over time, have generated tangible elements, giving them the value of cultural legacies and local identity [52–54]. Human capital reflects the competence, local knowledge, local entrepreneurship, and creativity of people and expresses the ability of a community to regenerate and innovate. Social capital is identified as the relations associated with individuals and communities under different social organizations and the set of actual or potential assets and resources linked to these relationships [49,55,56]. Social capital and its different manifestations/forms (i.e., bonding networks, social networks, formal and informal ties, etc.) are identified as a fundamental aspect underpinning community resilience [51], that strongly determines both individual and community ability of recovery after an extreme event and builds the coping capacities as well as safety networks that would positively impact disaster preparedness measures.

Impacts referring to the category "Built environment" concerns the physical direct impact on built assets, from residential, production and cultural buildings, to infrastructures [37]. Specifically, this category includes physical damage to building structures as well as to their contents (in the case of industrial and commercial buildings, damage to equipment and stock is considered), physical damage to linear and point infrastructure elements (such as roads, railways, and other lifelines), and physical damage to cultural assets. Damage to perennial plants is also included, with specific reference to material losses rather than productivity losses. Finally, damage to public and private vehicles is considered.

Impacts to "Business activities" refer to indirect impacts on costs and income of the primary, secondary and tertiary sector. This enables a comprehensive understanding of the consequences of natural events on production systems, market linkages, and regional economic dynamics [37,57].

Impacts under the category "Public services" concerns any potential impact on the availability of public services to end-users. Then, these impacts do not refer to the physical damage to lifeline assets caused by the hazards (included in impacts on the built environment) but to the loss of services functionality as a cascading effect that arises due to the physical damage to assets. To implement a comprehensive impact assessment, public services have been classified into public utilities, utilities and emergency management organizations [37].

Impacts under the category "Environmental Systems" pertain to the expected effects on ecosystems and biodiversity arising from natural hazard events [58]. This category specifically focuses on consequences for nature itself, excluding its economic, social, or cultural connections to human activities. To organize the wide range of potential environmental impacts, the common classification of Earth's systems is employed. These systems are divided into four primary subsystems—water, air, soil, and living beings—known as "spheres." These spheres correspond to the hydrosphere, atmosphere, lithosphere, and biosphere, respectively. Each of these spheres can be furter broken down into sub-spheres. For instance, the hydrosphere is subdivided into the surface hydrosphere and groundwater hydrosphere, enabling a clear distinction between surface water and groundwater bodies.

Finally, impacts on "financial systems" concerns effects on the core aspects that build up a financial system and guarantee financial stability, comprising: the banking sector, which serves as the primary conduit for credit allocation, liquidity transformation, and monetary policy transmission, being responsible for providing financing to households, firms, and governments while managing credit and systemic risks [59]; the insurance industry, which enables risk transfer, loss absorption, and capital formation by pooling and pricing uncertainties, thereby mitigating the financial consequences of adverse shocks [60,61]; and the creditworthiness assessment system, which evaluates the financial soundness of sovereigns, corporations, and financial institutions, influencing capital costs, market confidence, and debt market liquidity through standardized credit risk assessments [62].

It is worth noting that the adopted classification sheds light on some categories of impacts that are traditionally not taken into consideration in risk assessments, such as those on environment, communities and the financial system, but whose neglection might cause an underestimation of the risk. For example, the impact of natural hazards on the financial system related to the negative effects on the reputation and credit worthiness of companies probably tends to be zero in case of a risk assessment at the micro-scale or meso-scale. However, when the macro-scale of analysis is adopted, these potential impacts are not negligible.

### 3.2. Impact indicators

The proposed indicators were primarily selected from the existing literature, with specific references for each indicator reported in the matrix (i.e., the online Supplement). The selection was carried out collaboratively by the entire expert team, with each member focusing on their specific domain of expertise, following criteria designed to ensure applicability at the national level and consistency within a multi-hazard context. Nonetheless, it is important to remember that the H-I matrix was designed to be implemented ex-ante; for this reason, indicators cannot be based on specific ex-post measurements/evaluations.

The primary criteria guiding the selection of indicators are consistency and reproducibility. With regard to consistency, preference is given to indicators that are as homogeneous as possible across hazards and spatial scales. However, as anticipated, full consistency cannot always be guaranteed. For this reason, specific selection rules were defined to identify the most appropriate indicators based on the hazard considered and the spatial scale of analysis. Regarding reproducibility, wherever feasible, indicators are quantitative, in some cases relying on proxy variables. When quantitative assessments are impractical (e.g., because they require not-available data, their estimation is too expensive or is affected by high uncertainty invalidating reliability), qualitative, expert-based indicators are proposed. In both cases, reproducibility is supported by clearly and unambiguously defining each indicators, with detailed guidance on calculation or estimate methods (e.g., models or criteria to be used) and the input data sources (e.g., specific databases) on which they rely on, as previously described. Importantly, the selected indicators are based on data and models that are available across the entire Italian territory, thereby ensuring applicability and consistency in nationwide applications. Nevertheless, when more detailed local data or model are available and cross-location comparisons are not required, the use of local datasets and tools is recommended to enhance the precision of the analysis.

The H-I matrix includes a total of 130 indicators. Their full description, including associated models, is supplied in the online Supplement. The indicator selection process highlighted a substantial disparity in the level of detail that can currently be achieved when assessing impacts on different exposed elements and of different nature (e.g. direct/indirect, tangible/intangible). Depending on the available knowledge on the damage mechanisms and phenomena and available data, it is not always possible to estimate ex-ante the actual impact, in quantitative terms and at all the spatial scales. More often, only an estimate of the maximum potential impact (i.e. exposed value) can be provided as proxy, often in qualitative terms and at aggregated spatial scales. Moreover, no models or data were identified in the literature or in available data repositories for defining indicators related to impacts on individual economic well-being (within the "individual well-being" category) and on social capital (within the "communities" category). For this reason, these impacts are not included in the online Supplement.

In general, impacts on the individual well-being, are primarily assessed using parametric models derived from statistical analyses of historical data. For example, the indicators "expected numbers of casualties" and "expect number of injuries" are estimated by applying hazard-specific ratios to the total affected population. These ratios were derived from historical records of fatalities and injuries caused by natural hazards in Italy, obtained from the international EM-DAT database (https://www.emdat.be/). Alternatively, simple exposure models are considered, as in the case of indirectly affected people. Exposure models estimate the total amount of exposed elements by overlaying the potentially affected area (derived from national and institutional hazard assessments) with the spatial distribution of exposed items. For instance, the potentially affected area is combined with information on commuters provided by the National Institute of Statistics (ISTAT) to estimate the indicators "Expected number of employees in the affected area" and "Expected number of students in the affected area". In these cases, the minimum spatial resolution of the analysis strongly depends on the spatial scale of the available input data (e.g., ISTAT data are provided at the census block level).

Impacts on the built environment are mostly evaluated by damage models, fragility models and consequence functions, available for the Italian context. These models link hazard, exposure and vulnerability variables with the expected damage and are available at different spatial scales, from individual assets to meso (sub-municipal, municipal) and macro (national) scale aggregation. For example, the indicator "expected economic damage to residential buildings" is estimated using different hazard-specific models: the flood damage model developed within the MOVIDA project, for the Po River District, for flood risk [63]; the fragility models proposed by [64] for volcanic risk; and the fragility models adopted by national regulations for seismic risk [65]. Still, exposure models are used for those built assets (e.g., cultural heritage) or hazards (e.g., landslide) for which available knowledge on damage mechanisms is insufficient.

Impacts on business activities are evaluated by proxy variables of economic indicators and parametric models coming from available national input-output tables. For example, the direct and indirect impacts on the three economic sectors (i.e., primary, secondary, and tertiary) are estimated by summing the "expected effects on sales" with the "impacts on the sources and destinations of intermediate goods". These indicators are quantified by multiplying the revenues of exposed activities (derived from the ORBIS and AIDA databases) by the outputs of a national input–output model for natural disasters developed by [66]. In this case, the minimum spatial resolution of the analysis depends on the spatial scale for which the implemented models are developed, which is typically the municipal level.

As regards public services, three main assessment approaches are taken. Most of time exposure models are used (e.g., to estimate "the expected number of exposed education/health service assets") but there are also services (like power, gas and water supply) for which damage models are available, like fragility curves and restoration curves for component failure. This is the case, for example, of electric network components, or gas networks components, for which fragility curves are supplied by the U.S. Federal Emergency Management Agency (FEMA), at the individual level. At last, parametric costs coming from historical data are used to assess impact on emergency services. For example, "assistance costs per affected person" are supplied by the national Red Cross or the national Civil Protection.

Impacts on environment and communities are evaluated by exposure models or qualitative indicators. These are, in fact, the categories of impacts for which less data and knowledge is available for an ex-ante estimation. Nevertheless, it is important to emphasize that qualitative indicators are grounded in objective data and well-defined evaluation criteria. For example, the impact of a natural disaster on surface water ecological status is assessed using three qualitative classes (null, not significant, and significant), based on the proportion of surface water bodies affected by the event and their pre-existing ecological status, as defined within the framework of the European Water Framework Directive.

Finally, impacts on the financial system are assessed using sector-specific indicators, adapted to the availability of ex-ante data in the Italian context. For example, impacts on the insurance sector are evaluated using the proxy indicator "expected impact on the loss ratio for natural hazards", calculated as the ratio between total claims paid and total premiums earned by the insurance sector in the affected area, based on historical data provided by the national Insurance Supervisory Authority (IVASS), at the regional level.

## 4. Case study

As a first proof of concept the H-I matrix has been implemented to assess risk in the Lomellina region (Lombardy region, North of Italy). Lomellina is made up of 57 municipalities (mostly with agricultural vocation) with around 190000 inhabitants. It is bounded by the Sesia River to the west, the Po River to the west and south, the Ticino River to the east, and the Lower Novarese area (Piedmont) to the north. Consequently, flood risk is significant in the area. On the other hand, other risks co-exist in the region. The most significant is the industrial one, as seven "Major accident hazard establishments" are located in the area. Finally, the area is exposed to seismic and drought hazard.

The H-I matrix was implemented only on 12 municipalities of the region, located on the side of the Po River and characterized by high value of integrated risk according to the PRIM regional study on integrated risk [67]. As an illustrative case, the analysis was limited to flood and seismic risks.

The remaining features of the analysis were defined following the flowchart presented in Fig. 1. With regard to impacts relevance, most of the impacts included in the matrix are associated to the hazards considered, as detailed in the online Supplement, and were therefore included in the assessment. The only exception concerns impacts on the financial system, which were not considered meaningful given the limited spatial extent of the study area. The exclusion of this category, however, does not affect the significance of the results as a basis for risk management, as all relevant risk dimensions for the area are evaluated. Selection rules were then applied to identify the most appropriate indicators for the analysis from those included in the matrix. In this context, only indicators compatible with an analysis at the municipal or sub-municipal scale were considered, as this represents the most appropriate scale for the study area, balancing its spatial extent, computational effort, and the required level of precision. For example, physical damage to residential buildings was assessed in terms of "expected economic damage", since both flood damage models and seismic consequence and fragility functions are available for the study area, at the individual or census block level. In contrast, physical damage to industrial and commercial buildings was evaluated in terms of "expected annual value of exposed buildings", as consequence and fragility

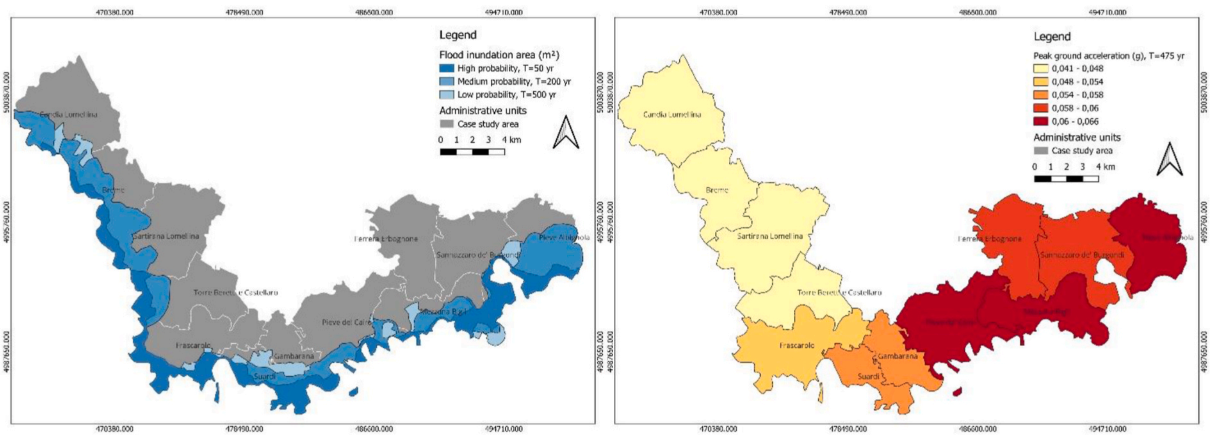


Fig. 2. Flood and seismic hazard in the Lomellina area. On the left, the flood hazard maps provided by the Flood Risk Management Plans of the Po River District are shown. The maps illustrate the extent of flooded areas for three different return periods (Tr), corresponding to a flood with high probability (Tr = 50 years), medium probability (Tr = 200 years), and low probability (Tr = 500 years). On the right, the peak ground acceleration with 10% probability of exceedance in 50 years, corresponding to a return period of 475 years, for the 12 municipalities is displayed, as derived from the Italian seismic hazard (MPS04 [68]).

functions are available for seismic risk, whereas flood damage models for these building categories are not currently available in Italy.

Once the context had been identified and the aforementioned assumptions defined, the matrix was implemented following a risk-based approach (see Section 3).

As a first step, the reference hazard analyses were identified. Flood hazard maps were derived from the Flood Risk Management Plans of the Po River District, while the Italian seismic hazard model MPS04 [68] was adopted for seismic risk assessment. The adopted flood maps represent both the spatial extent of inundated areas (as shown in Fig. 2) and the spatial distribution of water depth for several return periods, associated with different probabilities of occurrence. With regard to seismic hazard, peak ground acceleration values were implemented at the municipal scale for different return periods; an example corresponding to a 475-year return period is reported in Fig. 2.

Following hazard characterization, the selected indicators were estimated for each impact, each hazard, and each return period using the models specified in the matrix as well as corresponding exposure and vulnerability data. Table 3 provides illustrative examples of the datasets and models used to estimate selected indicators within the "Individual well-being" and "Built environment" categories, while Appendix A lists the corresponding datasets and models for the remaining categories. It is worth noting that the table is not intended as a re-proposition of the H–I matrix but rather aims to clarify the evaluation chain required for the calculation of the indicators. For simplification purposes, impact types based on the same data and modeling approaches are grouped together in the "Example of assets and impacts" column.

**Table 3**
Datasets and models adopted in the case study, as defined in the H-I matrix (the complete table is reported in Appendix A).

| Category | Example of assets and impacts | Exposure and vulnerability Data | Impact Models |
|---|---|---|---|
| Individual well-being | Residential population<br>- Direct physical damage<br>- Indirect physical damage<br>- Affected people | Census 2011 (population and buildings), available at census tracts but aggregating at municipality level | Seismic risk:<br>1 Damage: fragility models from the literature [69], based on the age of construction, number of floors and materials<br>2 People affected obtained with a damage threshold on residential buildings (damage state equal or higher than "moderate damage")<br>3 Consequence: Literature model [70] for deaths, injuries and homeless or parametric model, based on statistical analysis of historical events [EM-DAT] related to the people affected (conforming to flood risk and adopted in the multi-hazard evaluation) |
| | | Census 2021 (population and buildings), available at census tracts | Flood risk:<br>1 Exposure model for the definition of people affected, based on the product of resident population in a census tract and the percentage of intersection between the census tract area and the flood inundation area<br>2 Parametric model, based on statistical analysis of historical events [EM-DAT] related to the people affected |
| | Students<br>- Indirectly affected people | National Repository (Scuola in Chiaro), single school data combined with more data on vulnerability characteristics from previous work on the area analyzed | Seismic risk:<br>1 Damage: fragility models from the literature [71] based on the age of construction, number of floors and materials<br>2 Students affected obtained with a damage threshold on school buildings (damage state equal or higher than "moderate damage")<br>Flood risk:<br>1 Exposure model, based on the intersection between the spatial distribution of schools with the corresponding enrolled students and the flood inundation area |
| Built environment | Damage to residential buildings | Census 2011 (buildings), available at census tracts but aggregating at municipality level | Seismic risk:<br>1 Damage: fragility models from literature [69]<br>2 Consequence: Literature model [70] for economic impact |
| | | Census 2011 (buildings), available at census tracts | Flood risk:<br>1 Damage model from literature [72], based on the number of floors, building type, building structure, level of maintenance and reconstruction cost |
| | Damage to commercial buildings | Regional Geoportal, single building data aggregating at municipal level | Seismic risk:<br>1 Damage: fragility models from literature [69] for commercial ordinary buildings and Damage Probability Matrix approach for commercial warehouses [73]<br>2 Buildings exposed obtained with a damage threshold on commercial buildings (damage state equal or higher than "moderate damage") |
| | | Census 2011 (industries and services), available at census tracts | Flood risk:<br>1 Exposure model, based on the intersection between the spatial distribution of commercial activities with the corresponding added value and gross capital value, and the flood inundation area |

The last step consisted in the estimation of risk. For each hazard, indicators calculated for each scenario (i.e. return period) were averaged according to their respective probabilities, resulting in annual expected values of indicators. Hazard-specific expected values were then summed at the level of individual impact to obtain a multi-hazard risk assessment. Fig. 3 presents the results of the H–I matrix implementation for the study area, for the impacts specified in Table 3, while the results for the remaining categories are included in the online Supplement. In particular, the expected annual value of the related indicators is reported separately for flood and seismic risk, as well as for the combined multi-risk assessment. The use of consistent indicators across different hazards, together with the explicit consideration of hazard probabilities, enables the aggregation of indicators referring to multiple hazards, thereby providing an estimate of the overall risk in the investigated area. Accordingly, the implementation of the H–I matrix offers a comprehensive overview of risk in the Lomellina area across all its dimensions.

Although the study area is characterized by low seismic hazard, the analysis yielded considerable loss estimates due to the underlying assumptions and the spatial scale adopted. In particular, the assessment was conducted at the municipal level rather than at a point-based scale, which may have led to higher estimated seismic impacts compared to those derived from a more spatially detailed approach. It is also important to acknowledge that the approximations inherent in the data and models used to compute certain indicators introduce uncertainty into the results. Nevertheless, these assumptions enable a preliminary, broad-scale risk assessment, which can be further refined and enhanced through more detailed analyses in future research.

## 5. Discussion

The proposed framework introduces several advancements compared to existing state-of-the-art methodologies, especially those based on multi-layer, single-risk analysis. One of its main strengths lies in ensuring a consistent evaluation across all hazards, thereby enabling comparability. This is achieved through the definition of specific selection rules, which identify the most appropriate indicators to be applied according to the hazard considered, the available data and the spatial scale of analysis. This approach makes it possible to analyse the simplest form of hazard interrelationships (i.e., compound events) and provides a solid foundation for the investigation of more complex hazard and risk interrelationships.

Another key strength of the proposed H–I matrix is the inclusion of many relevant dimensions of risk. In particular, the framework explicitly accounts for environmental, community, and financial dimensions, which are often acknowledged at a conceptual or policy level but remain largely overlooked in operational risk assessment practices. This enables a comprehensive description of the affected areas both in terms of exposure and impacts. Finally, the H–I matrix provides a scale-aware operational framework that can be

| **Individual well-being** | | | | | |
|---|---|---|---|---|---|
| **Impact** | **Sub-impact** | **Indicator** | **Flood** | **Earthquake** | **Multi-risk** |
| **Direct physical damage** | Deaths and missing persons | Expected annual number of casualties | < 1 person | < 1 person | < 1 person |
| | Injuries | Expected annual number of injured people | < 1 person | < 1 person | < 1 person |
| **Affected people** | Directly affected people | Expected annual number of people living in the affected area | 11 persons | 31 persons | 42 persons |
| | Indirectly affected people | Expected annual number of employees and students in the affected area | 4 persons | 22 persons | 26 persons |
| | Homeless people | Expected annual number of displaced people | 1 person | 13 persons | 14 persons |
| **Built environment** | | | | | |
| **Impact** | **Sub-impact** | **Indicator** | **Flood** | **Earthquake** | **Multi-risk** |
| **Damage to non-productive private residential assets** | Damage to residential buildings: structure and contents | Expected annual economic damage to residential buildings | 148,000 € | 219,400 € | 367,400 € |
| **Damage to private commercial assets** | Damage to commercial buildings: structure, equipment and stock | Expected annual value of exposed commercial buildings | 99,000 € | 193,050 € | 292,050 € |

**Fig. 3.** Results of the implementation of the H-I matrix in the Lomellina area (North of Italy) where flood and seismic risk co-exist.

consistently applied across multiple spatial levels, ranging from individual exposed elements to sub-municipal, municipal, multi-municipal, and even national scales.

Taken together, these features make the proposed framework a valuable tool for enhancing multi-risk knowledge and for better tailoring risk mitigation strategies to the most relevant hazards and risk dimensions. The matrix enables the construction of compound event impact scenarios for emergency planning and can be used to provide evidence of risk reduction associated with specific mitigation strategies, considering the effect of the strategy on all co-existing risks. Notably, the matrix allows for distinguishing both common and unique effects across different hazards. For instance, while all analyzed hazards are expected to affect individuals' well-being, drought is unlikely to disrupt public services such as education or administrative functions. Conversely, drought is the only hazard that influences the availability of surface water. Such insights are essential for tailoring risk mitigation strategies to the specific characteristics of each context.

Given the ambition of the proposed approach, the H–I matrix comprises a total of 130 indicators, covering five hazards, seven risk dimensions, and several spatial scales. Nevertheless, the structured design of the matrix, together with clear references to the required models and data sources, ensures its operability, as demonstrated by its application to the Lomellina case study.

The H–I matrix integrates multiple models and methodological approaches (e.g., parametric models, exposure models, fragility functions, damage models, input-output models), which is considered essential for achieving a comprehensive understanding of the potential consequences of risk [8]. This level of integration was made possible by the multidisciplinary composition of the author team.

A direct consequence of this integration is that the matrix currently includes both qualitative and quantitative indicators, as well as indicators representing either actual or maximum damage. This diversity persists despite efforts to ensure indicator homogeneity across hazards, at least for the same impact. As a result, a straightforward aggregation of indicators across all risk dimensions is not feasible. Although several approaches exist (most notably the monetization of all impacts), the authors deliberately avoided forcing homogenization, as it could obscure the substantive meaning of the indicators and the effects they represent, and would entail normative choices that should not be made by technical experts alone. The combination of indicators is inherently context-specific, as the relevance of different impacts depends on local conditions, the stakeholders involved, and the objectives of the risk assessment [74]. Consequently, a one-size-fits-all aggregation approach cannot be defined.

To address these challenges, the implementation of a Multi-Criteria Analysis (MCA) involving local stakeholders and decision-makers is recommended. Assessing the relative significance of hazard impacts is, in fact, inherently a social process that requires stakeholder engagement. MCA provides a structured framework to accommodate indicators with different meanings and metrics, while integrating diverse stakeholder perspectives on impact relevance and associated uncertainty. This step is beyond the scope of the present paper and will be addressed in a forthcoming, related publication.

It is worth noting that the structure of the H–I matrix, in terms of the impacts considered, is also applicable to ex post risk assessments, such as the analysis of the negative consequences of specific events. In this case, indicators need to be adapted to incorporate measured or monitored variables. The framework is also potentially transferable to other international contexts; however, in such cases, both the indicators and the set of relevant impacts should be carefully reviewed to incorporate context-specific elements and to remove those that are not meaningful.

## 6. Conclusions

This paper introduces the Hazard-Impacts (H-I) Matrix, a new framework for risk evaluation in multi-hazard contexts. The matrix enables a comprehensive assessment of the potential impacts of multiple hazards on diverse exposed elements, made possible through a multidisciplinary approach capable of addressing the complexity of problem at stake.

The implementation of the matrix supports effective risk management in multi-hazard contexts by enabling the construction of compound event impact scenarios for emergency planning and the evaluation of mitigation strategy effectiveness across co-existing risks. By distinguishing between common and hazard-specific impacts, the matrix offers insights into how different hazards affect risk dimensions in distinct ways. This capability is essential for tailoring risk mitigation strategies to the specific characteristics of each territorial context.

The matrix was developed using models and data available for the entire Italian territory but can be easily adapted to international contexts. However, its practical implementation in risk management depends not only on technical factors but also on the existence of multi-risk governance policies at national and local levels - policies which, to date, are largely absent both in Italy and internationally. One reason may be that disaster risk reduction stakeholders struggle to perceive the added value of a multi-risk approach compared to traditional single-risk frameworks [7]. Therefore, future research efforts should aim to produce clear evidence of the benefits of adopting multi-risk strategies. To this aim, the development of further proofs of concepts can be useful, together with the definition of a clear methodology on how to use information supplied by the matrix within the decision problem on risk mitigation. This is just the next objective of this research.

Further research should also focus on improving the current version of the matrix. One key area for development is addressing the current assumption of risk source independence, which limits the matrix's ability to capture interactions or cascading effects among hazards, beyond compound occurrence. Another area involves refining the assessment of certain damage mechanisms - particularly intangible and long-term impacts - for which only qualitative or proxy evaluations are currently feasible. Lastly, a comprehensive characterization of the uncertainties involved in the assessment process is needed. Given that risk assessments rely on hazard identification, exposure, and vulnerability models, each based on assumptions and methodological choices, these uncertainties must be explicitly incorporated into the final analysis to ensure robustness and transparency.

## CRediT authorship contribution statement

**Daniela Molinari:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Conceptualization. **Francesco Airoldi:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Panagiotis Asaridis:** Writing – review & editing, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Anna Rita Balingit:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Tommaso Bastiani:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Marco Bindi:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Maria Pia Boni:** Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Martina Bosone:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Diana Caporale:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Fabio Castelli:** Writing – review & editing, Project administration, Methodology, Investigation, Conceptualization. **Luca Cetara:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Emilia Corradi:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Cassandra Cozza:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Pasquale De Toro:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Pisa Paola Fontanella:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Camillo Frattari:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Filippo Fraschini:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Daniela Mele:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Simona Muratori:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Malvina Ongaro:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Daria Ottonelli:** Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gloria Padovan:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Lorenza Petrini:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Federica Romagnoli:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Alessandro Rubino:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Francesca Vigotti:** Writing – review & editing, Methodology, Investigation, Conceptualization.

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## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Daniela Molinari reports financial support was provided by Italy's National Recovery and Resilience Plan. If there are other authors, they 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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## Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijdrr.2026.106131.

## Appendix A

## Appendix A

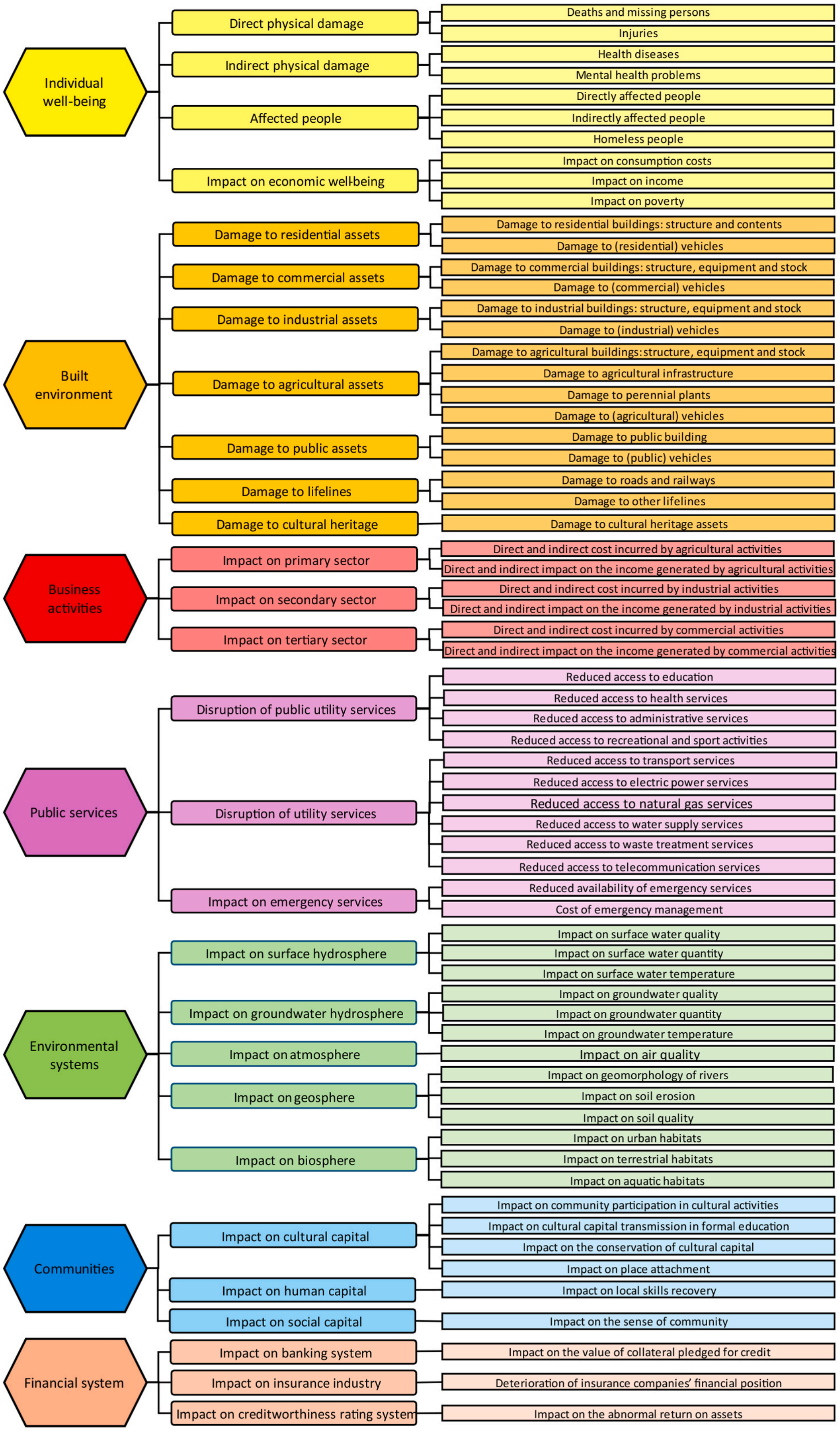


**Fig. 4.** Categories, impacts and sub-impacts considered in the Hazards-Impacts matrix.

**Table 4**
Datasets and models adopted in the case study, as defined in the H-I matrix.

| Category | Example of assets and impacts | Exposure and vulnerability Data | Impact Models |
|---|---|---|---|
| Individual well-being | Residential population<br>- Direct physical damage<br>- Indirect physical damage<br>- Affected people | Census 2011 (population and buildings), available at census tracts but aggregating at municipality level | Seismic risk:<br>1 Damage: fragility models of literature [69], based on the age of construction, number of floors and materials<br>2 People affected obtained with a damage threshold on residential buildings (damage state equal or higher than "moderate damage")<br>3 Consequence: Literature model [70] for deaths, injuries and homeless or parametric model, based on statistical analysis of historical events [EM-DAT] related to the people affected (conforming to flood risk and adopted in the multi-hazard evaluation). |
| | | Census 2021 (population and buildings), available at census tracts | Flood risk:<br>1 Exposure model for the definition of people affected, based on the product of resident population in a census tract and the percentage of intersection between the census tract area and the flood inundation area<br>2 Parametric model, based on statistical analysis of historical events [EM-DAT] related to the people affected |
| | Students<br>- Indirectly affected people | National Repository (Scuola in Chiaro), single school data, more data on vulnerability characteristics from previous work on the area analyzed | Seismic risk:<br>1 Damage: fragility models of literature [71] based on the age of construction, number of floors and materials<br>2 Students affected obtained with a damage threshold on school buildings (damage state equal or higher than "moderate damage")<br>Flood risk:<br>1 Exposure model, based on the intersection between the spatial distribution of schools with the corresponding enrolled students and the flood inundation area |
| | Employees<br>- Indirectly affected people | Regional Geoportal, single building data aggregating at municipal level; Census 2011 (industries and services), available at census tracts but aggregating at municipality level | Seismic risk:<br>1 Damage: fragility models of literature [69] for commercial/industrial ordinary buildings and Damage Probability Matrix approach for commercial/industrial warehouses [73]<br>2 Buildings exposed with the corresponding employees obtained with a damage threshold on buildings (damage state equal or higher than "moderate damage") |
| | | Census 2011 (industries and services), available at census tracts | Flood risk:<br>1 Exposure model, based on the intersection between the spatial distribution of economic activities with the corresponding employees and the flood inundation area |
| Built environment | Damage to residential buildings | Census 2011 (buildings), available at census tracts but aggregating at municipality level | Seismic risk:<br>1 Damage: fragility models of literature [69] as step 1 of resident population, introducing also the reconstruction cost<br>2 Literature model [70] for economic impact |
| | | Census 2011 (buildings), available at census tracts | Flood risk:<br>1 Damage model of literature [72], based on the number of floors, building type, building structure, level of maintenance and reconstruction cost |
| | Damage to commercial or industrial buildings | Regional Geoportal, single building data aggregating at municipal level | Seismic risk:<br>1 Damage: fragility models of literature [69] for commercial ordinary buildings, as residential ones, and Damage Probability Matrix approach for commercial, agricultural and industrial warehouses [73]<br>2 Buildings exposed obtained with a damage threshold (damage state equal or higher than "moderate damage") |
| | | Census 2011 (industries and services), available at census tracts | Flood risk:<br>1 Exposure model, based on the intersection between the spatial distribution of commercial or industrial activities with the corresponding added value and gross capital value, and the flood inundation area |
| | Damage to agricultural buildings | Regional Geoportal, single building data aggregating at municipal level | Seismic risk:<br>1 Damage: fragility models of literature [69] for agricultural ordinary buildings, as residential ones, and Damage Probability Matrix approach for commercial, agricultural and industrial warehouses [73] |

(*continued on next page*)

**Table 4** (*continued*)

| Category | Example of assets and impacts | Exposure and vulnerability Data | Impact Models |
|---|---|---|---|
| | | | 2 Buildings exposed obtained with a damage threshold (damage state equal or higher than "moderate damage") |
| | | Regional Geoportal, single building data | Flood risk:<br>1 Exposure model, based on the intersection between the spatial distribution of agricultural buildings and the flood inundation area |
| | Public assets | OpenStreetMap (OSM) and Regional Geoportal, single building data | Seismic risk:<br>1 Damage: fragility models of literature [69] as the residential buildings<br>2 Buildings exposed obtained with a damage threshold (damage state equal or higher than "moderate damage") |
| | | OpenStreetMap (OSM) and Regional Geoportal, single building data | Flood risk:<br>1 Exposure model, based on the intersection between the spatial distribution of public buildings and the flood inundation area |
| | Lifelines<br>- Roads<br>- Railways | OpenStreetMap (OSM), single transportation asset data aggregated at municipality level | Seismic risk:<br>1 Assessment of the percentage of road length adjacent to buildings higher than two storeys;<br>2 Percentage of damaged buildings obtained with a damage threshold (damage state equal or higher than "heavy damage");<br>3 Evaluation of roads potentially affected by these damaged buildings. |
| | | OpenStreetMap (OSM), single transportation asset data | Flood risk:<br>1 Exposure model, based on the intersection between the spatial distribution of roads and railways, and the flood inundation area |
| | Cultural heritage assets | National Repository (Vincoli in Rete), single cultural heritage asset data | Seismic risk:<br>1 Damage: Damage Probability Matrix based on vulnerability model proposed in [75]<br>2 Assets exposed obtained with a damage threshold (damage state damage state equal or higher than "moderate damage ")<br>Flood risk:<br>1 Exposure model, based on the intersection between the spatial distribution of cultural heritage assets and the flood inundation area |
| Business activities | Sectors:<br>- primary<br>- secondary<br>- tertiary | National Repository (AIDA), single agricultural/industrial/commercial firms data aggregating at municipal level | Seismic risk:<br>1 Damage of residential buildings: fragility models of literature [69]<br>2 Ratio of the area of buildings exposed obtained with a damage threshold (damage state or higher than "moderate damage") over the total area of the buildings in the municipality<br>3 Input-Output model, based on the product of impact on agricultural/industrial/commercial sales and the percentage of supply and absorption share [66]<br>Flood risk:<br>1 Exposure model, based on the product of the total sales revenue of agricultural, industrial or commercial firms in a municipality and the percentage of intersection between the municipality area and the flood inundation area<br>2 Input-Output model, based on the product of impact on agricultural/industrial/commercial sales and the percentage of supply and absorption share [66] |
| | Gross Domestic Product (GDP) | IstatData 2025 (Regional counts), available at regions | Seismic and flood risk:<br>1 Proxy variable, based on the product of regionally estimated GDP per capita and the number of people affected by flood or earthquake (see Individual well-being section) |
| Public services | Public utilities | National Repository (Scuola in Chiaro), single education asset data; National Repository (Ministero della Salute), single health asset data; Regional Geoportal (Regione Lombardia), single administrative asset data; OpenStreetMap (OSM), single sport and recreational asset data | Seismic risk:<br>1 See Individual Well-Being section/Students affected for education assets with the corresponding enrolled students<br>2 Damage: fragility models of literature [69] for health and administrative assets |

(*continued on next page*)

**Table 4** (*continued*)

| Category | Example of assets and impacts | Exposure and vulnerability Data | Impact Models |
|---|---|---|---|
| | | | 3 Assets exposed with the corresponding beds obtained with a damage threshold on buildings (damage state equal or higher than "moderate damage")<br>Flood risk:<br>1 Exposure model, based on the intersection between the spatial distribution of education assets with the corresponding enrolled students, health assets with corresponding available beds, administrative assets, and sport and recreational assets, and the flood inundation area |
| | Utilities | OpenStreetMap (OSM), single transportation asset data | Seismic risk:<br>1 See Built environment section/Lifelines<br>Flood risk:<br>1 Exposure model, based on the intersection between the spatial distribution of roads and railways, and the flood inundation area |
| Environmental systems | Surface water bodies | Po River District Basin Authority (ADBPO), single bodies data | Flood risk:<br>1 Exposure model |
| | Groundwater bodies | Po River District Basin Authority (ADBPO), single bodies data | Flood risk:<br>1 Exposure model |
| | Polluting sources | European Environmental Agency (EEA), single polluting source data | Seismic risk:<br>1 Damage: Damage Probability Matrix for industrial warehouses [73]<br>2 Buildings exposed obtained with a damage threshold (damage state equal or higher than "moderate damage")<br>Flood risk:<br>1 Exposure model, based on the intersection between the spatial distribution of polluting sources and the flood inundation |
| | Land Cover Land use (LCLU) areas | Copernicus, single Land Cover Land Use area data | Flood risk:<br>1 Exposure model |
| | Protected areas | Po River District Basin Authority (ADBPO), single protected area data including CDDA EUAP, drinking water protected areas | Flood risk:<br>1 Exposure model |
| Communities | Cultural events | Local Repository (EcoMuseo), single cultural event data | Flood risk:<br>1 Exposure model, based on the intersection between the spatial distribution of cultural events and the flood inundation area |
| | Educational assets | National Repository (Scuola in Chiaro), single school data | Seismic risk:<br>1 see Individual Well-Being section/Students affected<br>Flood risk:<br>1 see Public services section/Education assets affected |
| | Cultural heritage assets | National Repository (Vincoli in Rete), single cultural heritage resource data; Regional Geoportal (Regione Lombardia), single landscape considered for landscape protection data | Seismic risk:<br>1 see Built Environment section/Cultural heritage assets<br>Flood risk:<br>1 Exposure model, based on the intersection between the spatial distribution of cultural heritage resources and landscapes considered for landscape protection, and the flood inundation area |
| | Local skills | Local Repository (Cipolla Rossa di Breme), single cluster of local production data; Regional Geoportal (Regione Lombardia), single vernacular architecture data | Flood risk:<br>1 Exposure model, based on the intersection between the spatial distribution of local production clusters and vernacular architectures, and the flood inundation area |
| | Residential buildings | Regional Geoportal (Regione Lombardia), single building data | Seismic risk:<br>1 see Built Environment section/Residential assets<br>Flood risk:<br>1 Relative damage thresholds, based on water depth values to affected buildings that become inaccessible to people |

## Data availability

Data will be made available on request.

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