Extended Partnership

Return

multi-Risk sciEnce for resilienT commUnities undeR a changiNg climate

Spoke TS3 – Communities' resilience to risks: social, economic, legal and cultural dimensions

WP 7.2 – Innovative tools to evaluate risk mitigation effectiveness

T 7.2.2 – Problem definition

Deliverable 7.2.2

Tools to evaluate risk-reduction potential of structural and non-structural measures in multi-hazard environments.

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1 Introduction

In the context of the RETURN project (multi-Risk sciEnce for resilienT commUnities undeR a changiNg climate), Work Package (WP) 7.2 – Innovative tools to evaluate risk mitigation effectiveness, under Spoke TS3 – Communities' resilience to risks: social, economic, legal and cultural dimensions, aims to establish national guidelines for evaluating the effectiveness of intervention alternatives in natural risk management.

The most relevant organizations involved in the decision-making process for natural risk management are civil protection, local authorities, and policy makers. Their fundamental role is to ensure the maintenance of the prosperity, security, and identity of communities before, during, and after the occurrence of natural hazard events. Yet, actions for improving the climate resilience of communities are not usually designed from a multi-disciplinary perspective, with an integration of the physical, economic, social, environmental, and cultural dimensions of the problem. Furthermore, to the extent of our knowledge, current practices are typically oriented towards a single risk approach with the different natural risks being addressed by different governmental agencies, each with specific priorities and preferences. For this reason, there is a need for the development of a risk-informed decision support system capable of evaluating, in a consistent and coherent way, the full range of natural hazard impacts on the natural and built environment, as well as the effect of multi-purposes intervention alternatives, through a multi-risk perspective. Accordingly, WP 7.2 focuses on (i) multi-risk contexts for which the knowledge is currently limited, (ii) all the phases of the natural risk management chain in which actions are taken (i.e., mitigation, preparedness, response, and recovery), and (iii) the wide range of both structural and non-structural risk mitigation measures that can be adopted in a specific area.

To achieve our goal, we selected Multi-Criteria Analysis (MCA), among the several existing methodologies (e.g., cost-benefit analysis, cost-effectiveness analysis, life cycle assessment), as a supporting tool for the formulation of policies for natural risk management and climate change adaptation. This is because this type of analysis can enable decision-makers to integrate the multiple and often conflicting objectives of the various stakeholders involved in natural risk management into a structured framework, thus enhancing the effectiveness of group decisions in complex problems.

In the previous Task 7.2.1, we framed a flowchart that illustrates the process leading to the prioritization of risk reduction strategies through MCA. The flowchart points out that for addressing the structural complexity of the problem, it is fundamental to break it down into smaller, and therefore more manageable parts. In particular, the following operational steps can be identified: (i) the identification of intervention alternatives and their characterization in terms of spatial and temporal scale of effectiveness, potential risk reduction (or increase) with respect to the different natural hazards, and secondary effects on the affected communities, (ii) the recognition of stakeholders' objectives and their respective dimensions, (iii) the definition of attributes and indicators according to which alternatives are evaluated, (iv) the selection of the most appropriate MCA tool and definition of the related parameters, and (v) the performance of a sensitivity analysis.

Task 7.2.2 constitutes the physical backbone of the MCA process as it provides tools to evaluate the effectiveness of intervention alternatives towards their main objective of reducing risk in multi-hazard environments. More specifically, Task 2.2.2. focuses on steps (i) and (iii) of the flowchart, limiting the attention on the primary objective of intervention alternatives that is risk reduction. First, the different alternatives were characterized into an "Abacus of Measures", linking each alternative with its potential risk reduction/amplification, considering all hazards that may co-exist in a certain area. In fact, the analysis focused on floods, landslides, drought, earthquakes, and volcanic activity as the most representative and widespread natural hazards in the Italian context. Still, the implemented methodological framework allows extending the analysis also to other natural hazards that are presently not considered, such as wildfires. Second, a matrix was developed (called "Hazards-Impacts matrix") that enables the evaluation of the potential direct and indirect impacts on the elements exposed in case of an event occurrence. The integration of the two tools allows estimating the expected multi-risk reduction linked to a specific alternative.

The remainder of this contribution is organized as follows. Section 2 introduces the Abacus of Measures along with the methodology followed for its definition. In Section 3, the matrix Hazards-Impacts and the different working phases for its development are described. In Section 4, the next steps are delineated and concluding remarks are provided.

2 The Abacus of Measures

The purpose of the abacus of measures is to compile and characterize the most relevant existing structural and non-structural risk reduction measures, particularly in terms of their potential to reduce risk. A multi-risk perspective has been adopted in this approach. However, it is important to note that this focuses solely on the co-existence of different natural hazards—and thus risks—without delving into the possibility of compound or cascading events.

The objective of the abacus is to assess whether a measure, originally designed to mitigate a specific risk, may also have additional impacts—either reducing or increasing other co-existing risks. A clear example of this is the design of resilient buildings: certain solutions that reduce seismic vulnerability may inadvertently increase flood vulnerability, and vice-versa; on the other hand, some solutions aimed at reducing seismic vulnerability might also help reduce volcanic vulnerability. The abacus of measures helps identify which risks should be considered, both before and after implementing a particular measure, in order to assess its overall effectiveness in reducing risks, for moving towards multi-risk-resilient communities.

Moreover, each measure is characterized by its spatial and temporal scale of effectiveness. This enables the identification of the appropriate spatial scale for conducting risk assessments, as well as the ability to decide whether to include (or exclude) long-term impacts in the analysis.

The process leading to the definition of the abacus of measures was based on a scoping review of both scientific and grey literature. The scientific databases consulted included Scopus and Google Scholar, while grey literature was analyzed using Google. The review was conducted in two stages. In the first stage, the most common structural and non-structural risk reduction measures were identified for each individual hazard considered (i.e., floods, landslides, drought, earthquakes, and volcanic activity). These measures were then grouped based on their functional similarities (e.g., reducing peak discharge in the case of floods) and typology (e.g., land use regulation), and classified according to the phase of the natural risk management cycle they correspond to (i.e., mitigation, preparedness, response, and recovery). In the second stage, synergies and trade-offs of each measure in relation to the reduction or increase of other risks were evaluated. This was achieved by cross-referencing each hazard with the corresponding measures identified in the literature review.

The abacus of measures is presented in the form of a table, where the rows refer to measures and the columns provide details to characterize them (Figure 1). More specifically, each row represents a class of measures which supply the same function (e.g. discharge reduction, physical vulnerability reduction). The second column details the spatial scale of effectiveness of the measures, classified into three levels:

- Micro-scale: risk reduction is expected on single elements at risk. For instance: a school, a cultural heritage site, etc.
- Meso-scale: risk reduction is expected at the municipality level or multi-municipality level
- Macro-scale: risk reduction is expected at the regional, or national level

The third column describes the temporal scale of effectiveness of the measures, also categorized into three levels:

- Short-term: the effect of the measure is temporary, lasting for hours or days
- Medium-term: the effect of the measure is temporary, lasting for weeks or months
- Long-term: the measure has a lasting effect, ranging from years to decades

It is worth noting that a single class of measures may be effective across multiple spatial and temporal scales, depending on the level of implementation. Columns 4 through 8 provide information on the measures' impact on the various risks under analysis. Specifically, a green arrow pointing downwards indicates a reduction in risk while a red arrow pointing upwards indicates an increase in risk. The last column lists the reference literature supporting the characterization of each measure.

The rows/measures are grouped according to the risk for which they are designed (i.e. "target hazard") and the phase of the natural risk management cycle they correspond to (i.e., mitigation, preparedness, response, and recovery).

	Target hazard	Measure	Type of measure	Scale of measure's effectiveness		Measure's effect on the natural risk(s)					Reference
				Spatial	Temporal	Earthquake	Flood	Landslide	Drought	Volcano	
Prevention	Flood	Works to increase the conveyable flow (e.g., levees)	Structural	Meso-scale	Long term	↑	↓↑		↑		.....
		...	...	...	...	...	...	...	...	...	
	Earthquake										
	Drought										
	Volcano										
	Landslide										
Response	Flood										
	...										

Figure 1. Exemplification/sketch of the Abacus of Measure

3 The matrix “Hazards-Impacts”

The matrix Hazard-Impacts is the result of an in-depth investigation into the types of elements that are exposed to the natural hazards under study and the potential direct and indirect impacts on these elements in the event of hazard occurrence. This information is crucial for the definition of attributes and indicators according to which the alternatives for risk reduction are evaluated. The objective of the matrix is, in fact, to supply instruments (i.e. attributes and indicators) for estimating the potential risk reduction linked to each alternative within a multi-risk context.

The process leading to the definition of the matrix included the following sub-steps:

1. the classification of the elements exposed;
2. the analysis of the potential direct and indirect impacts of natural hazards on the exposed elements;
3. the identification of possible indicators for the evaluation of natural hazard impacts.

Once drafted, the matrix was shared with other Spokes of the project, and eventually with specific WPs, for comparison purposes. This collaboration was necessary due to the limited expertise of the WP7.2 researchers in certain natural hazards and their potential impacts on exposed elements. Given the complexity of the problem and the wide scope of the analysis required (multi-risk and multi-criteria analysis), the input from other researchers played a crucial role. Several constructive comments and suggestions from other WPs significantly contributed to improving the quality of the matrix, while also strengthening the participatory process within the project.

3.1 Classification of the exposed elements

The adopted classification aimed at including all the various dimensions of the problem under investigation, being the physical, economic, social, environmental, and cultural impacts of disasters on communities. In detail, the exposed elements were classified into seven categories, being individual well-being, built environment, business activities, public services, environmental systems, communities, and financial system (Table 1).

The classification derives from evidence in the literature, highlighting a sort of homogeneity within classes in terms of (i) the related impacts in case of an event occurrence, (ii) the approaches and tools required for their evaluation, and (iii) the related stakeholders for engagement.

The adopted classification sheds light on some categories of elements exposed to natural hazards that are traditionally not taken into consideration in risk assessments, such as the communities and 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 even more negligible.

Table 1. The categories of elements exposed to natural hazards.

Exposed element	Description	Example	References
Individual well-being	Everything that has a direct and indirect impact 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	Doswald et al. 2020 Biagini et al. (2014) IPCC (2014) Zhai (2007)
Built environment	Every physical direct impact on the built environment, from residential, production and	Physical damage, damage to residential buildings, damage to productive buildings, damage to cultural buildings, damage to public	Doswald et al. 2020 Biagini et al. (2014) IPCC (2014)

Exposed element	Description	Example	References
	cultural use, to infrastructure building.	buildings, temporal or permanent damage to infrastructures, physical reduced capacity	
Business activities	Every direct and indirect impact on production factors, including industrial, agricultural, cultural and touristic activities.	Agriculture production, consistency of farms, supply chain interruption, functionality of the food supply chain, production disruption, tourist operator costs, farmers/breeders and industrial costs (energy costs will not be considered here)	Quinn (2023) Doswald et al. 2020 Biagini et al. (2014) IPCC (2014)
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, less employees able to reach the offices), transports availability, water and energy supply, energy production, energy cost, interruption of telecommunications, school closures, administrative service reduction/slow down. General effect of crowding out with respect to business-as-usual activities (crowding out effect of emergency measures)	Quinn (2023) Doswald et al. 2020 Biagini et al. (2014) IPCC (2014) Myaux et al. 1997
Environmental systems	Every direct and indirect impact on ecosystems and natural biodiversity, including reduction of biodiversity.	Disruption of the value of green and natural areas (including protected natural areas and green infrastructure), pollution, biodiversity, quantity and quality of vegetation, ground quality (effects on fires, floods, landslides, avalanches)	Quinn (2023) Hagedoorn et al. 2021 Doswald et al. 2020 Biagini et al. (2014) IPCC (2014) Zhai (2007)
Communities	Every impact on how communities identify themselves and interact with each other and in relation to their local community places.	Social identity, place identity, traditional activities, cultural landscape (international, national, local)	Quinn (2023) Barnett et al. 2021 Clarke et al. 2018
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. Examples include credit rating (Standard & Poor's, Moody's, Spread), stock quotation and pre booking cancellation of touristic activities	Doswald et al. 2020 Biagini et al. (2014) IPCC (2014)

3.2 Analysis of the natural hazards impacts on the exposed elements

For each category of exposed elements, the potential direct and indirect impacts of natural hazards in case of an event occurrence are identified, representing the attributes required for the implementation of the MCA, as far as the risk reduction capacity of the alternative measures is evaluated. The identification of the impacts was subdivided into two phases: the analysis of the impacts in a single natural hazard perspective and the merge/adaptation of the "single" natural hazard matrices to a multi-hazard framework.

In the first phase, the analysis was based on an extensive literature review in which a generalized approach was adopted, looking for international literature in academic search engines and without focusing on the relevance of the impacts in the Italian context. The main objective was to avoid the risk of missing relevant evidence and information.

On the contrary, only impacts that are relevant in the Italian context were maintained in the merge, considering factors such as prevalence and contextual appropriateness. The merge had the main objective of identifying “common patterns” in expected damages to support the standardization of the MCA process (Kappes et al., 2012; Zschau, 2017). Nonetheless, the analysis allowed to highlight specificities of individual hazards. The impacts have been assembled into homogeneous classes, thus classifying them into two main categories: attributes and sub-attributes. This grouping strategy aims to streamline the evaluation process by limiting the number of attributes to be finally included and therefore weighed up by the stakeholders involved.

Figure 2 shows attributes identified for each category of exposed elements. The next sub-section describes them in detail.

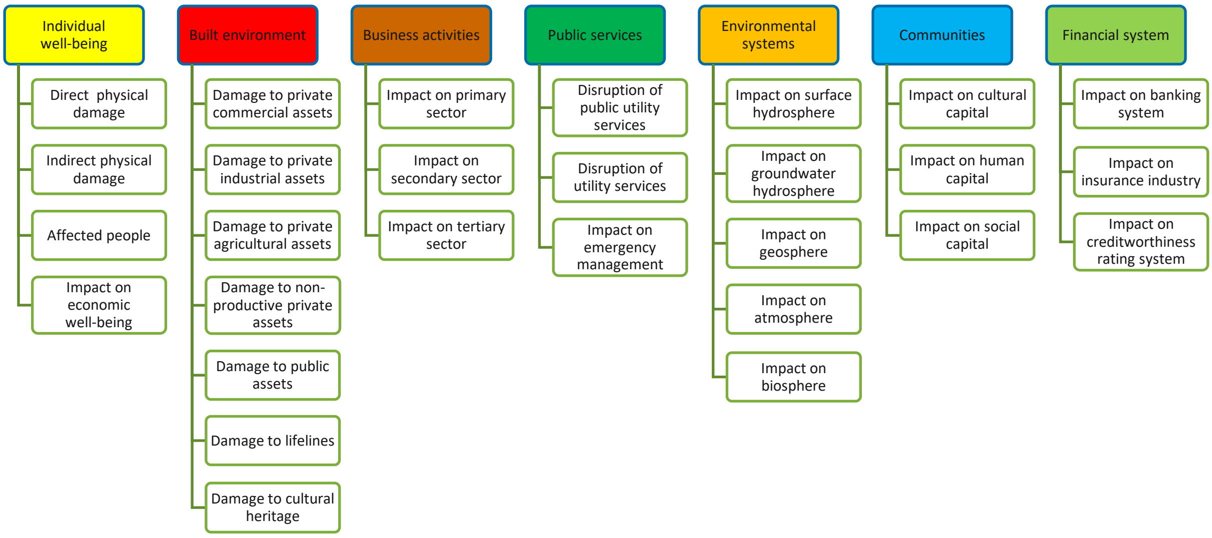

Figure 2. Attributes associated with each exposed categories in the matrix Hazards-Impacts.

3.2.1 Individual well-being

Natural hazard impacts referring to the category “Individual well-being” concern both direct and indirect effects on individuals that may worsen their physical and mental health, as well as their social and economic conditions. The emphasis is particularly on the consequences experienced at the personal level by each affected individual.

Four attributes have been identified, each further described by the related sub-attributes, as illustrated in Figure 3:

- “Direct physical damage” is related to the expected number of deaths, also considering missing people, and injuries resulting from the occurrence of a natural hazard event.
- “Indirect physical damage” is associated with the negative effects of natural hazards on the individuals’ health, including physical harm, such as infectious, respiratory, eye, and skin diseases, along with mental health issues.
- “Affected people” captures the impacts on individuals who experienced social disruptions due to the occurrence of natural hazards, including discomfort caused by the lack of services, essential goods, accommodations, and other basic needs.

- “Impact on economic well-being” refers to the adverse effects on individuals' financial stability, such as increased consumption costs, reduced employment opportunities or personal income, and higher poverty rates.

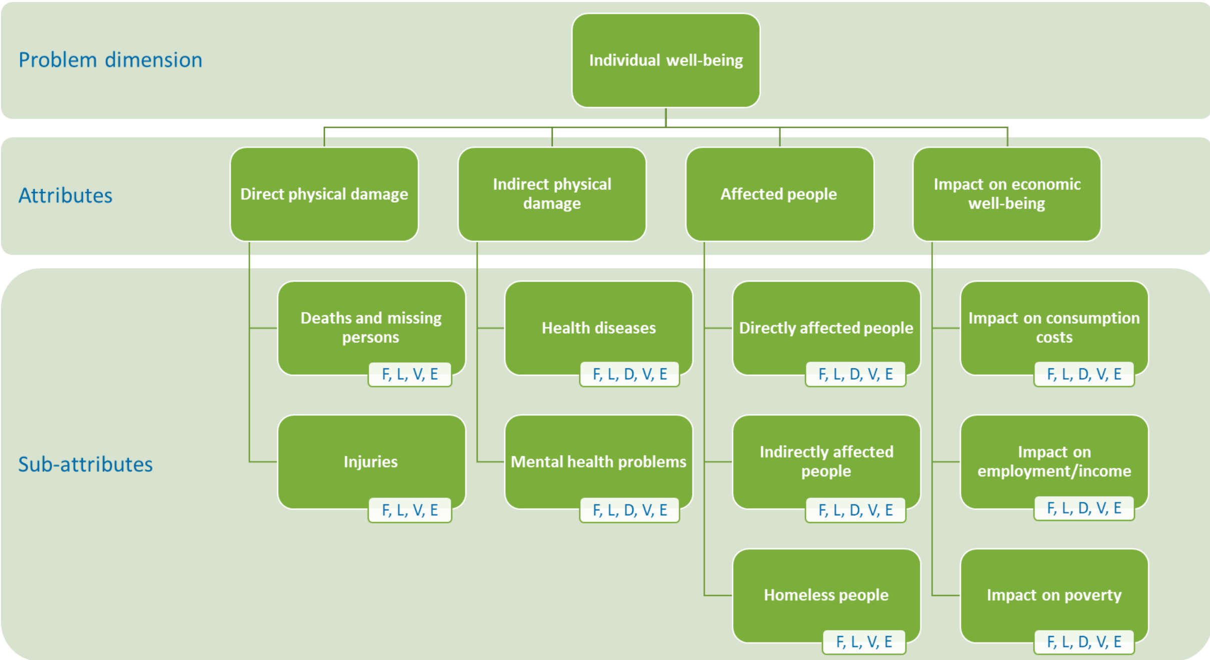

Figure 3. Schematic representation of the attributes and sub-attributes within the “Individual well-being” category. The letters F, L, D, V and E refer to “Floods”, “Landslides”, “Drought”, “Volcanoes” and “Earthquakes”, respectively. The presence of a letter indicates the relevance of the associated attribute to the corresponding natural hazard.

3.2.2 Built environment

Natural hazard impacts referring to the category “Built environment” concerns the direct impact due to the physical damage to the built assets itself, namely the constructed elements ranging from residential, production and cultural buildings, to public sectors and infrastructures.

Seven attributes have been identified, each further described by the associated sub-attributes, as shown in Figure 4:

- “Damage to private commercial assets” refers to the physical damage to the buildings and vehicles of commercial activities.
- “Damage to private industrial assets” is related to the physical damage to the buildings and vehicles of industrial activities.
- “Damage to private agricultural assets” is associated with the physical damage to the buildings, infrastructures, perennial plants and vehicles of agricultural activities.
- “Damage to non-productive private assets”, regards the physical damage to the residential buildings and the vehicles of residents.
- “Damage to public assets” concerns the physical damage to the buildings and vehicles of public sector.
- “Damage to lifelines” is about the physical damage to private and public infrastructures.

- "Damage to cultural heritage[1]" captures the physical damage to cultural heritage assets.

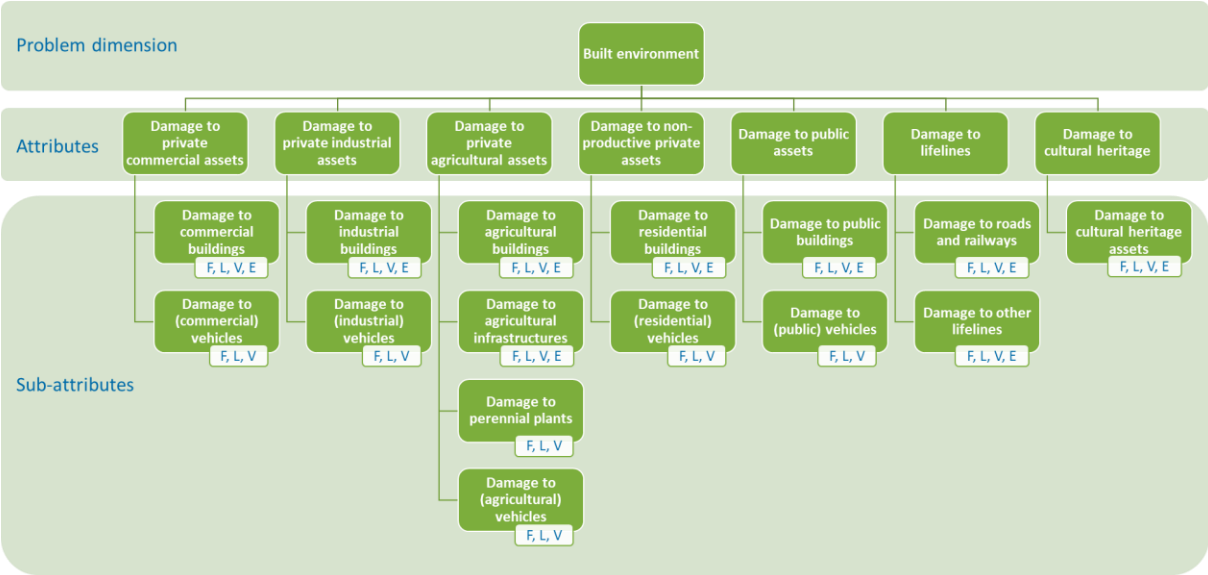

Figure 4. Schematic representation of the attributes and sub-attributes within the "Built environment" category. The letters F, L, D, V and E refer to "Floods", "Landslides", "Drought", "Volcanoes" and "Earthquakes", respectively. The presence of a letter indicates the relevance of the associated attribute to the corresponding natural hazard.

3.2.3 Business activities

Natural hazards represent significant threats to economic systems, particularly by disrupting business activities (Blaikie et al., 2014). These disruptions may manifest in direct damage to physical capital—included in the built environment matrix —as well as in the temporary or permanent cessation of operations and broader repercussions throughout supply chains, on which impacts related to the category "Business activities" refer to.

Business activities have been classified into three categories: primary, secondary, and tertiary sectors of the economy. Accordingly, three attributes have been identified, each further described by the respective sub-attributes (direct and indirect costs and direct and indirect impact), as shown in Figure 3:

- "Impact on primary sector" refers to the increase in incurred costs and the reduction in generated income of agricultural activities, including farming and crop production, fishing, forestry, mining, and oil and gas extraction.
- "Impact on secondary sector" concerns the increase in incurred costs and the reduction in generated income of industrial activities, such as manufacturing, construction, food processing, and the production of steel and chemicals.
- "Impact on tertiary sector" considers the increase in incurred costs and the reduction in generated income of commercial activities, comprising retail and wholesale trade, healthcare, education, banking and finance, tourism, transportation and logistics, and entertainment.

[1] Buildings and complexes recognized as Cultural heritage have been identified through the consultation and application of accessible databases, as follows. On the national level, buildings and complexes are identified following the listing as present in Vincoli in Rete database (Istituto Superiore per la Conservazione ed il Restauro – MiC). For what concerns UNESCO World Heritage Sites, these are identified following the inventory of inscribed Properties on the World Heritage List in Italy. On the regional level information are gathered through Regional Information Systems, when available (e.g., SIRBeC, Sistema Informativo Regionale dei Beni Culturali, Regione Lombardia). On the municipal scale, data are gathered from local urban planning tools. The data obtained were processed to avoid possible duplications.

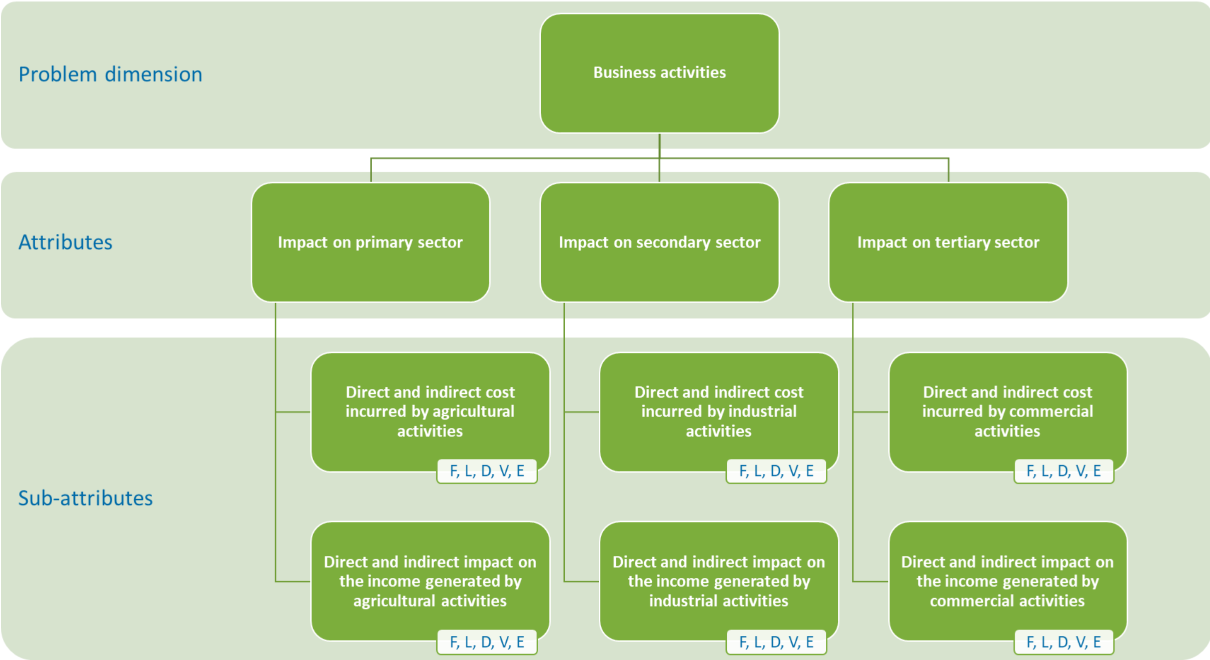

Figure 5. Schematic representation of the attributes and sub-attributes within the "Business activity" category. The letters F, L, D, V and E refer to "Floods", "Landslides", "Drought", "Volcanoes" and "Earthquakes", respectively. The presence of a letter indicates the relevance of the associated attribute to the corresponding natural hazard.

3.2.4 Public services

Natural hazard impacts referring to the category "Public services" concerns any potential impact on the availability of public services to end-users. These impacts do not refer to the physical damage to lifeline assets caused by the natural hazards, as defined in Section 3.2.2, but rather to the loss of service functionality as a cascading effect resulting from the physical damage to assets. In fact, impacts on public services are strongly linked to impacts on the built environment and can be regarded as an indirect consequence of the event. Here, the focus is on the disruption of public services in terms of functionality, including the lack of territorial governance and institutional crowding out.

Public services have been classified into three categories: public utilities, utilities and emergency management organizations. Accordingly, three attributes have been identified, each further detailed through corresponding sub-attributes, as presented in Figure 6:

- "Disruption of public utility services" is associated with the reduced access of people to essential services, such as education, health services, administrative services, and recreational and sport activities.
- "Disruption of utility services" refers to the adverse effects on the proper functioning of critical infrastructures, including reduced customer access to transport services, electric power supply, natural gas supply, water supply, waste treatment and telecommunication services.
- "Impact on emergency cost" regards public expenses required for emergency services during an event. These services are typically operated by police and army forces, fire brigades and disaster response organizations. It also includes the costs incurred by the responsible authorities for managing the emergencies.

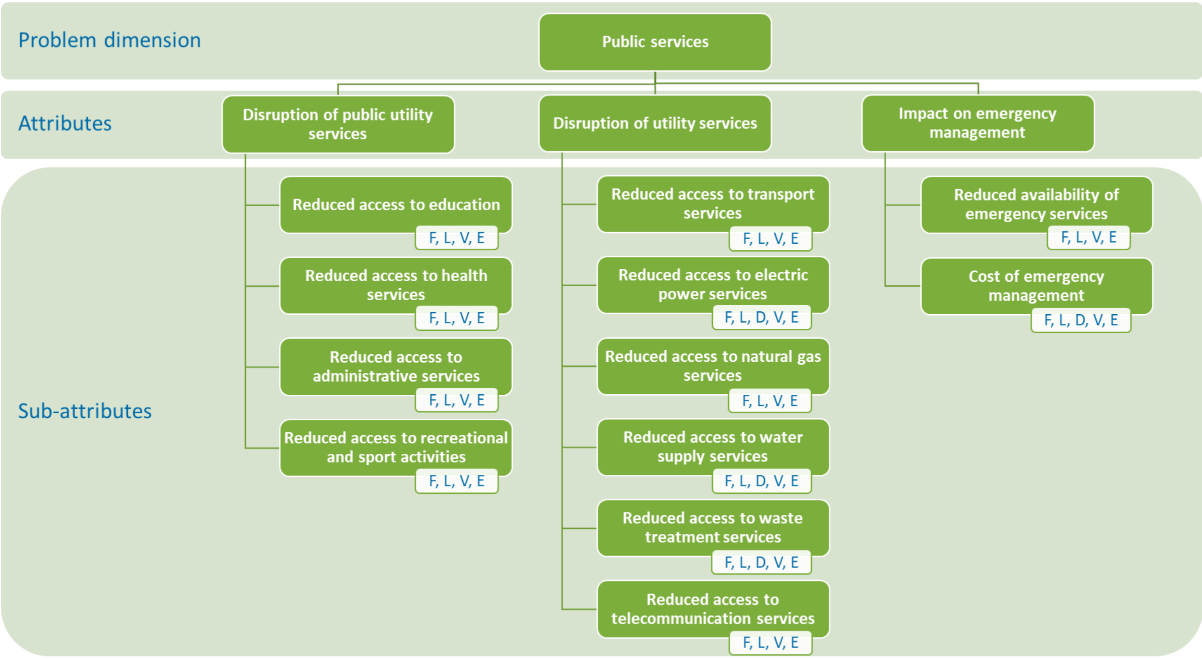

Figure 6. Schematic representation of the attributes and sub-attributes within the "Public services" category. The letters F, L, D, V and E refer to "Floods", "Landslides", "Drought", "Volcanoes" and "Earthquakes", respectively. The presence of a letter indicates the relevance of the associated attribute to the corresponding natural hazard.

3.2.5 Environmental systems

Natural hazard impacts referring to the category "Environmental systems" concerns the expected impacts on ecosystems and biodiversity in case of a natural hazard event occurrence. Specifically, the focus is on the consequences for nature itself, excluding considerations of nature's economic, social or cultural relationship with humans.

Environmental systems have been classified adopting the standard classification of Earth's systems. The Earth's system is typically divided into four main sub-systems based on the elements they encompass: water, air, soil, and living organisms. These sub-systems, known as spheres, include the hydrosphere, atmosphere, lithosphere and biosphere, respectively. Each of these four spheres can be further subdivided into sub-spheres. For example, the hydrosphere is split into the surface hydrosphere and the groundwater hydrosphere, primarily to distinguish between surface water bodies and groundwater bodies.

Accordingly, five attributes were identified, each further described by the corresponding sub-attributes, as illustrated in Figure 7. More specifically:

- "Impact on surface hydrosphere" is related to the negative effects on the quality, quantity and temperature of surface water bodies.
- "Impact on groundwater hydrosphere" regards the harmful effects on the quality, quantity and temperature of groundwater bodies.
- "Impact on lithosphere" refers to the adverse effects on soil, including geomorphology alteration of rivers, soil erosion and reduction of soil quality.
- "Impact on atmosphere" is associated with the detrimental effects on air quality
- "Impact on biosphere" is linked to all the effects on urban, terrestrial and aquatic habitats.

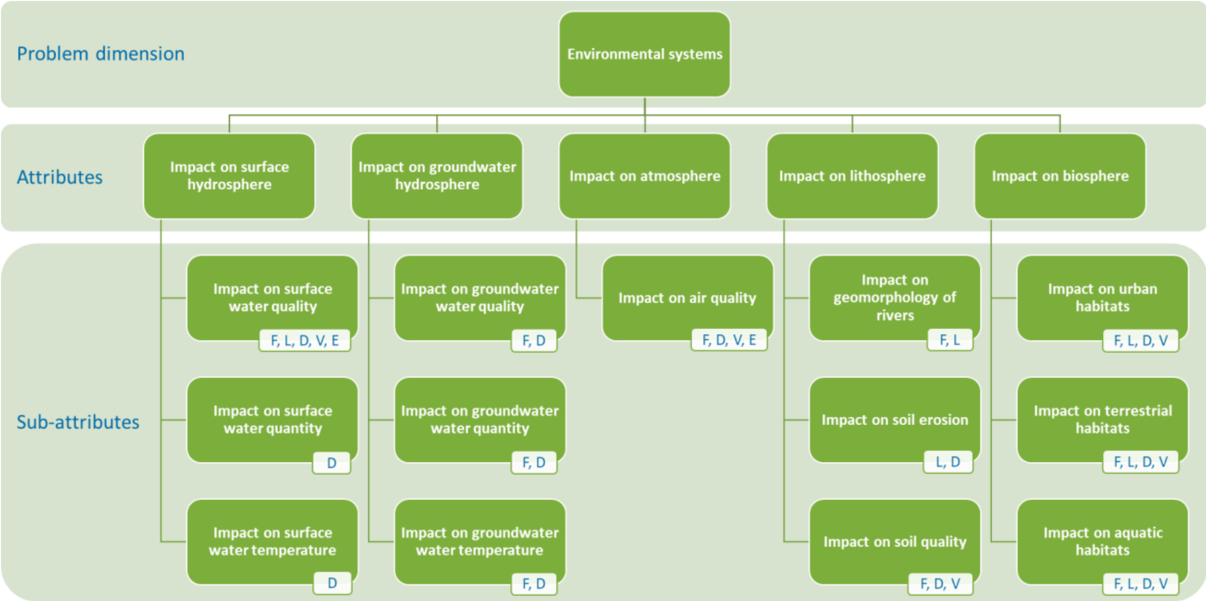

Figure 7. Schematic representation of the attributes and sub-attributes within the "Environmental systems" category. The letters F, L, D, V and E refer to "Floods", "Landslides", "Drought", "Volcanoes" and "Earthquakes", respectively. The presence of a letter indicates the relevance of the associated attribute to the corresponding natural hazard.

3.2.6 Communities

Impacts referring to the category "Communities" focus on the effects that an extreme natural hazard event can have on the interactions among affected community members, as well as between community members and local community places.

The matrix adopts the definition of community as described in RETURN Deliverable 4.2 "Disaster Risk Reduction and Climate Change Adaptation: Advancing Community-Based Approaches, Community Trust, and their Effectiveness Evaluation", developed within WP4, Task 4.1 "Common set of methods and guidelines for community based (CB) activities". In this context, community identifies a collective of actors, such as individuals, organizations and businesses, who possess a shared identity (Kruse et al., 2017). We conceive community as a multi-layered concept that is threefold; indeed, a community can be place-based, interest-based or practice-based. Within this definition, we identified the core aspects that, according to literature (Cox and Perry, 2011; Aldrich and Meyer 2015; De Dominicis et al. 2015; Nocca, 2017), build up community dimension as: cultural capital, human capital and social capital. These forms of capital are interconnected and shape community members' identification and recognition as part of a specific community, as well as the creation of emotional bonds that exist between community members and their surrounding environment (including both urban and non-urban landscapes) (Altman and Low 1992; Norris et al. 2008; Khan et al. 2020).

We define these three aspects as follows.

Cultural capital consists of a tangible and an intangible component that are closely interrelated. In this sense, cultural capital refers not only to historical built heritage, but also to the system of relationships (social capital) and the creative skills (human capital) that, over time, have generated it, giving it the value of testimony and cultural identity (Bouchenaki, 2003; Fairclough et al. 2014). The impact on cultural capital can be assessed through the following sub-attributes (Figure 8):

- Impact on community participation in cultural activities; community participation in cultural events is considered a proxy for the safeguarding of a rich and shared cultural capital. A reduction in cultural activities is likely to lead to decreased community participation, which may ultimately to an impoverishment of the community's cultural capital (Jackson, 2008).

- Impact on the transmission of cultural capital in formal education; school and formal education systems are identified as key means for transferring cultural capital and cultural heritage to younger generations (UNESCO, 2022), thus ensuring the transmission and preservation of heritage.
- Impact on the conservation of cultural capital; conservation of cultural capital does not entail only the conservation of physical capital, but it also includes the conservation of technical and traditional knowledge produced at local level, for example traditions, techniques of landscape management, vernacular architecture, etc. (Arefian et al., 2021; UNESCO n.d.). This attribute takes into consideration specifically the cultural capital that encloses or is connected to a specific traditional and technical knowledge.
- Impact on place attachment; according to literature place attachment, seen as an element of sense of place, is a concept that puts in relation emotions, affective bonds and the environment (De Dominicis et al., 2015; Masterson et al., 2017; Khan et al., 2020). Place attachment is developed by individuals over time when interacting with the social and physical environment in association with the cultural identity, background and heritage. Previous research (e.g., De Dominicis et al., 2015 and Bonaiuto et al., 2016) has studied the concept of place attachment in the context of hazards and disasters. Specifically, the research focused on how people's attachment to a place is affected when they are forced to leave their homes due to mandatory relocation or eviction caused by such events. Human capital arises from the connection between social and cultural capital. It reflects the competencies, local knowledge, entrepreneurship and creativity of people (Fusco Girard et al., 2014). Through the support of existing social capital and the valorization of cultural capital, human capital expresses the ability of a community to regenerate and innovate, starting from the existing cultural capital. The impact on human capital can be evaluated by the "loss of local skills", as the loss of knowledge will prevent the community to use it for its own recovery in case of a natural hazard.

Social capital is identified as the relations associated to individuals and communities under different social organizations, as well as the set of actual or potential assets and resources linked to these relationships (Cox and Perry, 2011; Pfefferbaum et al., 2013; Nakagawa and Shaw, 2004). Social capital and its different manifestations/forms (bonding networks, social networks, formal and informal ties, etc.) is identified as a fundamental aspect underpinning community resilience. It strongly determines both individual and community ability of recovery after an extreme event (Patel et al., 2017) and builds the coping capacities as well as safety networks that would positively impact disaster preparedness measures.

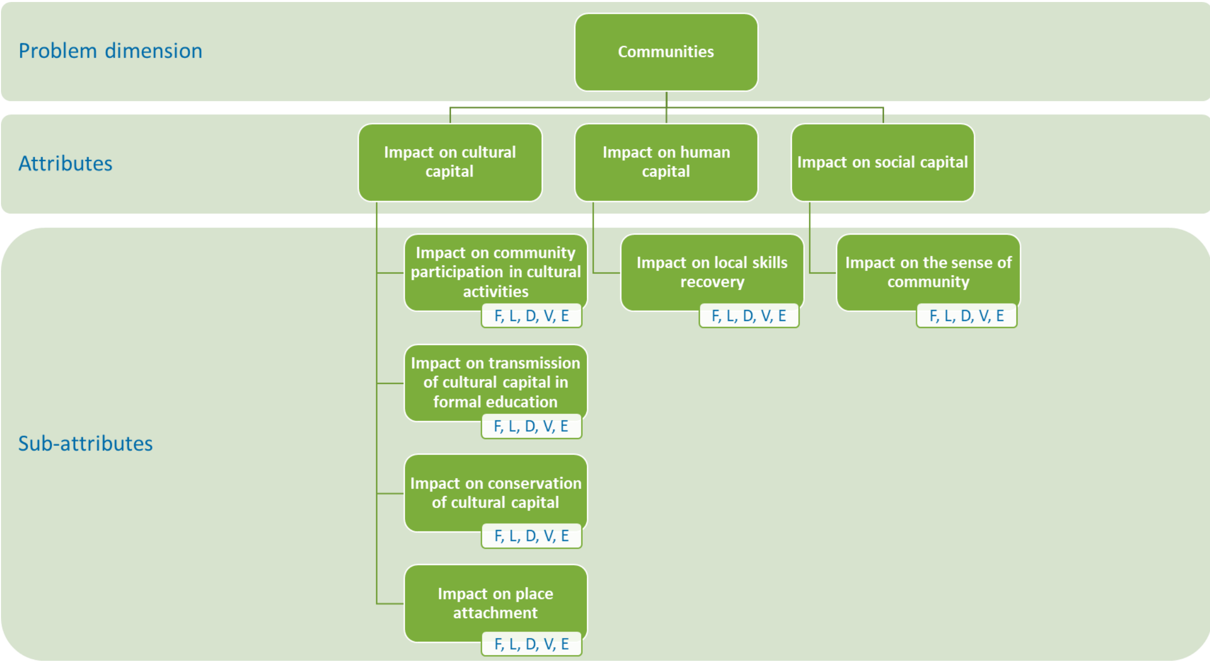

Figure 8. Schematic representation of the attributes and sub-attributes within the "Communities" category. The letters F, L, D, V and E refer to "Floods", "Landslides", "Drought", "Volcanoes" and "Earthquakes", respectively. The presence of a letter indicates the relevance of the associated attribute to the corresponding natural hazard.

3.2.7 Financial system

The "Financial System" category examines how natural events can impact on the smooth functioning of the financial system as a driver of healthy economic life in a regional context.

A financial system is defined as a structured network of financial institutions, markets, instruments, and regulatory frameworks that facilitate the efficient allocation of capital, risk management, and liquidity provision across economic agents (Levine, 2005; Mishkin, 2019). It operates through a set of interconnected mechanisms that channel savings into productive investments, ensure financial intermediation, and sustain economic stability.

Within this definition, we identified the core aspects that build up a financial system for the purpose of assessing the impacts of natural hazards on 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 (Freixas and Rochet, 2008); 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 (Doherty, 2000; Cummins and Venard, 2008); 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 (Cantor and Packer, 1996).

These components collectively determine the financial system's resilience to external shocks, such as asset losses, liquidity stress, and credit market disruptions caused by natural events. Accordingly, impact on the financial system can be assessed by evaluating impact on these three components (Figure 9).

The financial system's ability to absorb, mitigate, and adapt to such shocks is contingent upon the robustness of its institutions, the effectiveness of financial risk-sharing mechanisms, and the degree of completeness of market (Allen and Gale, 2000).

The *banking system* is the cornerstone of financial intermediation, liquidity transformation, and credit allocation in an economy. As the primary financial intermediary, banks channel funds between surplus and deficit economic agents, thereby facilitating the efficient allocation of resources. This sector's pivotal role in the economy is underscored by its ability to create credit and mobilize savings for productive investments (Freixas and Rochet 2008), manage and transform liquidity and convert short-term liabilities into long-term assets (Gertler and Kiyotaki 2010), facilitate payment systems, influence and transmit monetary policy (Bernanke et al., 1999), and enhance financial stability by diversifying risk through loan portfolios (Doherty, 2000; Cummins and Venard, 2008). The banking system provides financing to consumers, businesses, institutions, and other organizations present in a region. Such financing is granted against collateral, often represented by real estate assets that are exposed to the impacts of natural events, susceptible to damage, and loss of economic value. Additionally, the financing concerns businesses and other economic activities potentially subject to damage and interruptions in the provision of services or the production of goods. In the event of significant and recurring natural event damage, the payments expected in return for such financing may be compromised or become partially or entirely uncollectible, contributing to the increase in the value of Non-Performing Loans (NPLs) in the banks' liabilities. Therefore, it is considered that a high portion of financing granted to businesses and other organizations located in a certain territory, in the presence of recurring impacts of natural events, could be jeopardized, increasing the likelihood that such sums become uncollectible and thus generate NPLs.

The *insurance industry* facilitates risk transfer, capital accumulation, and financial protection, playing a crucial role in the financial system. As a financial stabilizer, the insurance sector distributes risks across economic agents, allowing businesses and individuals to hedge against uncertain losses (Cummins and Weiss, 2014). This sector's primary functions include risk transfer and pooling, capital formation, boosting liquidity and investment in support to economic growth (Swiss Re, 2020), loss absorption and indemnification as key factors in financial stabilization (Fackler, 2023) and recovery of businesses and individuals from financial setbacks (The Geneva Association, 2024), market efficiency, confidence and credit enhancement (Kampa, 2010), and efficient risk pricing and incentivization of risk mitigation (Cummins and Weiss, 2014), reducing overall risk exposure. The insurance system provides insurance coverage, which guarantees the payment of a sum of money in the event of verified damage to individuals or property in exchange for the payment of a monetary premium. The insurance industry functions as a financial stabilizer by enabling risk transfer and capital formation, crucial for mitigating the financial impact of natural hazards. When assessing the impact of such events, indicators should assess the sustainability of payouts against the premiums earned, the sector's capacity to expand coverage in response to increasing risks and protect more economic agents. These indicators highlight the insurance industry's pivotal role in maintaining financial resilience against natural disasters.

The *creditworthiness rating system* facilitates risk assessment, capital cost determination, risk-based pricing in debt markets, and market discipline. Credit rating agencies (CRAs) evaluate the credit risk of sovereigns, corporations, and financial institutions, thereby influencing borrowing costs and market confidence. Their core functions include default risk quantification and pricing (Kaur et al., 2023), capital market stability and investor confidence by reducing asymmetric information (Frost, 2007), debt market liquidity and accessibility (White, 2010), regulatory and prudential risk management, affecting capital adequacy requirements under frameworks like Basel III and Solvency II, and macroeconomic and sovereign risk assessment. The credit rating system plays a central role in assigning a credit reliability rating to states and sub-state administrative units. These ratings combine quantitative and qualitative criteria to produce a representative rating of the financial health and future prospects of the entity in question. The main metrics used for such an assessment are financial and evaluate the ability of a territory to finance interest expenses on debt through generated value, which in the case of states or regions can be approximated by GDP value. This capacity largely depends on the economic system's ability to produce output or to service debts through generated product (consider the debt-to-GDP ratio). Essentially, the rating indicates the sustainability of public debt for a state or its administrative unit.

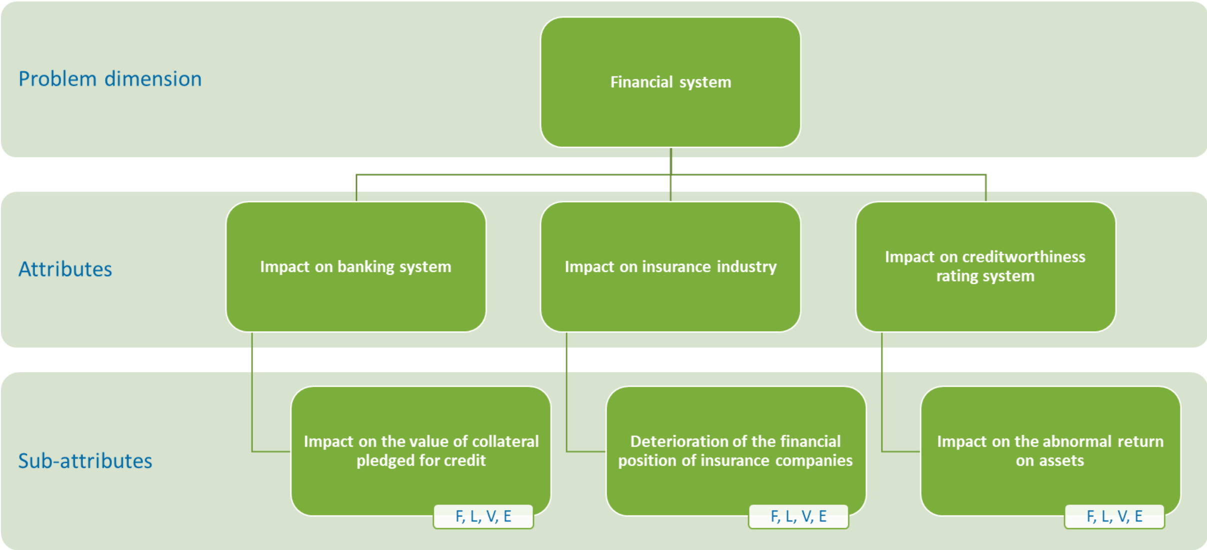

Figure 9. Schematic representation of the attributes and sub-attributes within the "Financial system" category. The letters F, L, D, V and E refer to "Floods", "Landslides", "Drought", "Volcanoes" and "Earthquakes", respectively. The presence of a letter indicates the relevance of the associated attribute to the corresponding natural hazard.

3.3 Definition of the impact indicators

As anticipated, the identified impacts represent the attributes according to which alternative risk reduction strategies are evaluated within the MCA process, particularly in terms of their potential to reduce, or in some cases increase, specific natural risks. For this reason, the impact analysis was also aimed at identifying appropriate indicators for their assessment.

The indicators were selected based on the following criteria, ensuring a comprehensive and contextually relevant set:

i. Data availability: Indicators must be based on data available for the entire Italian territory to guarantee consistent implementation across different contexts; still, if more detailed local datasets are available, it is recommended to carry out the analysis with these refined datasets;

ii. Quantitative/qualitative nature: Indicators must be quantitative wherever possible, including the use of proxy variables when necessary; if quantitative indicators cannot be defined, qualitative ones may be used;

iii. Homogeneity across hazards: Indicators must be, as far as possible, consistent across the different types of natural hazards considered;

iv. Clarity and reproducibility: Indicators must be clearly and univocally defined, with detailed specifications on their calculation methods (i.e., models employed) and the required input data (i.e., relevant databases)

v. Scalability: Indicators must, to the greatest extent possible, be applicable across all spatial scales at which the matrix Hazards-Impacts is implemented: micro-scale (single-element), meso-scale (sub-municipality, municipality, multi-municipality) and macro-scale (regional, national).

It is also important to emphasize that the evaluation process (i.e., the implementation of the matrix) is always carried out ex-ante. This is a fundamental prerequisite for defining potential indicators, which cannot rely on ex-post measurements or evaluations.

Since each indicator serves as a "measure" of a hazard's impact, the model used for its assessment can theoretically be considered as a "damage model", while the input data can be classified into three categories: hazard, exposure and vulnerability. Nevertheless, a notable disparity exists in the level of detail currently achievable when assessing impacts on different exposed elements. Depending on the available knowledge on the underlying "damage mechanisms/phenomena" and the quality of data, it is not always feasible to estimate the "actual" impact ex-ante, particularly in quantitative terms and across all spatial scales. More often, only an estimation of the "maximum" potential impact (i.e. the total exposed value) is possible, even if only in qualitative terms and at aggregated spatial scales. For instance, research on potential impacts on the built environment is significantly more advanced than in other domains, due to numerus validated models and tools available in literature. Depending on the level of knowledge and data availability, it is also possible for multiple indicators to be identified for a single attribute. The following sub-Sections provide a detailed description of the identified indicators

3.3.1 Individual well-being

As introduced in Section 3.2.1, the impacts on individual well-being are assessed through four attributes. These attributes are further detailed into sub-attributes, for each of which one or more indicators have been proposed. Table 2 summarizes the indicators used in the evaluation process, while the scale of analysis, the modelling approach and the necessary data required for their calculation are described in greater detail in the remainder of this section.

Table 2. Attributes, sub-attributes and indicators of the "Individual well-being" category.

Individual well-being		
Attribute	**Sub-attribute**	**Indicators**
Direct physical damage (F, L, V, E)	Deaths and missing persons (F, L, V, E)	Expected (annual) number of casualties
	Injuries (F, L, V, E)	Expected (annual) number of injured people
Indirect physical damage (F, L, D, V, E)	Health diseases (infectious, respiratory, eye, skin) (F, L, D, V, E)	Expected (annual) number of people affected by health diseases
	Mental health problems (F, L, D, V, E)	Expected (annual) number of people showing indications of Post-Traumatic Stess Dissorder (PTSD)
Affected people (F, L, D, V, E)	Directly affected people (F, L, D, V, E)	Expected (annual) number of people living in the affected area
	Indirectly affected people (F, L, D, V, E)	Expected (annual) number of employees in the affected area
		Expected (annual) number of students in the affected area
	Homeless people (F, L, V, E)	Expected (annual) number of displaced people
Impact on economic well-being (F, L, D, V, E)	Impact on consumption costs (F, L, D, V, E)	-
	Impact on employment/income (F, L, D, V, E)	-
	Impact on poverty (F, L, D, V, E)	-

The modelling approaches proposed for the calculation of indicators, based on current knowledge of damage mechanisms and the available input data, are:

1. The use of statistics derived from historical data on past natural hazard events. These data come from two main sources. The first is the EM-DAT Database (https://www.emdat.be), from which percentage values for casualties, injured individuals and displaced persons with respect to the total directly affected population are calculated as weighted averages based on the number of recorded events for all natural hazards considered. The events analyzed were selected both at the national

scale (Italy) and at the broader European level. The second source consists of studies by Di Fiorino et al (2005), Puechlong et al. (2020) and Zenker et al. (2024), which provide percentage values of individuals showing symptoms of Post-Traumatic Stress Disorder (PTSD) relative to the total directly affected population, specifically in the context of flood-related events. As regards health disease, there is no evidence in the literature nor data, supporting the estimation of required statistics. Accordingly, local data must be explored. The results derived from available sources are reported in Table 3.

2. The use of an exposure model. This approach allows the estimation of the population exposed to different natural hazards based on their spatial distribution within the affected area. When the analysis is implemented for the single exposed element, then the intersection of natural hazard affected area with the assets inside the affected area is done. On the other hand, when the analysis is implemented for each census block then the exposure of individuals is determined by intersecting the perimeter of the flood area with the census block layer, which contains population data. Once the affected blocks or portions are identified, the total resident population is calculated at the block level. Assuming uniform population distribution, the number of residents is reduced proportionally to the flooded area of the block.
3. The use of human loss consequence functions. These functions are derived from fragility curves representing the structural response of buildings to seismic risk (Borzi et al., 2021) and the structural response of roofs and non-structural elements to volcanic activity (Spence et al., 2004; Spence et al., 2005; Spence et al., 2007; Zuccaro et al., 2008). In particular, they correlates physical damage to percentage of fatalities based on the number of floors, and the type and size of openings.

Direct physical damage

Direct physical damage (attribute) is further divided into deaths and missing people, and injuries (sub-attributes).

One indicator has been proposed to estimate the deaths and missing people:

1. Expected (annual) number of casualties

One indicator has been proposed to estimate the injuries:

1. Expected (annual) number of injured people

Indirect physical damage

Indirect physical damage (attribute) is further divided into health diseases and mental health problems (sub-attributes).

One indicator has been proposed to estimate the mental health problems:

1. Expected (annual) number of people showing indication of health diseases

One indicator has been proposed to estimate the mental health problems:

2. Expected (annual) number of people showing indication of Post-Traumatic Stress Disorder (PTSD)

Affected people

Affected people (attribute) is further divided into the directly affected people, indirectly affected people and homeless people (sub-attributes).

One indicator has been proposed to estimate the directly affected people:

1. Expected (annual) number of people living in the affected area

Two indicators has been proposed to estimate the indirectly affected people:

1. Expected (annual) number of employees in the affected area
2. Expected (annual) number of enrolled students in the affected area

One indicator has been proposed to estimate the homeless people:

1. Expected (annual) number of displaced people

Impact on economic well-being

Impact on economic well-being (attribute) is further divided into the impact on consumption, impact on employment/income and impact on poverty (sub-attributes).

No indicators have been proposed to estimate the impact on economic well-being, as no evidence has been found in the literature.

Table 3. Percentage values to be applied to "directly affected people" to estimate impact on individual well-being.

Indicators	Flood	Landslide	Earthquake	Volcanic activity	Drought
Expected (annual) number of casualties	- 0.02% (Eur) - 0.20% (Ita)	- 1.32% (Eur) - 2.84% (Ita)	- 0.10% (Eur) - 0.54% (Ita)	- 8.54% (Eur) - No data (Ita)	
Expected (annual) number of injured people	- 0.31% (Eur) - 0.30% (Ita)	- 0.82% (Eur) - 3.41% (Ita)	- 0.59% (Eur) - 1.56% (Ita)	- No data (Eur) - No data (Ita)	
Expected (annual) number of people showing indications of Post-Traumatic Stress Disorder (PTSD)	- 6.6÷30% (Eur) - 45.90% (Ita)				
Expected (annual) number of displaced people	- 1.93% (Eur) - 7.70% (Ita)	- No data (Eur) - No data (Ita)	- 19.61% (Eur) - 62.96% (Ita)	- No data (Eur) - No data (Ita)	

As above mentioned, for each indicator, the evaluation process follows the traditional steps of risk assessment: hazard, exposure and vulnerability.

For what concerns the hazard component, the main objective is to identify the affected area and the spatial distribution of the event's intensity. In this regard, the following indications are provided:

- The flood hazard can be evaluated referring to the hazard maps developed for the Flood Risk Management Plans (PGRA), which serve as the reference operational tools for the District Basin Authorities in Italy. These maps identify the geographical areas that could be affected by flooding, considering at least three scenarios: low, medium and high probability of occurrence. For each scenario, the flood extent and the water depth must be represented on the maps. The delineation of the flooded area is essential when the exposure model has been defined and proposed as modelling strategy for a specific indicator calculation.
- Landslide hazard can be evaluated using the maps available from the national geoportal IdroGEO. These maps refer to those produced by the District Basin Authorities in Italy as part of their Hydrogeological Plans (PAI). The landslide hazard zones defined in the PAI encompass not only areas affected by past landslides but also zones with potential for the reactivation or expansion of existing landslides, as well as areas susceptible to the initiation of new landslide events. A national mosaic was created by harmonizing the PAI legends into five classes: very high (P4), high (P3), medium (P2), moderate (P1), and areas of attention (AA). The landslide susceptibility zones here

considered for the calculation of indicators are the very high (P4) and high (P3) susceptibility levels.

- Drought affected area can be derived from Copernicus and the Italian Environmental Agency (ISRA). The intensity variable to be considered depends on the specific indicator (SPEI-6/12, SMA-6, growing season).
- Volcanic activity hazard can currently be assessed using the Volcanic Impact Simulation Model, a tool developed at the PLINIVS Center. This will be integrated with the new hazard maps produced by Spoke 3 (WP3.3) of the RETURN project. The new maps will provide data on load (tephra fall) and dynamic pressure (pyroclastic flow and lahar) at both municipal and regional scales. Moreover, the LAVAFLOW model developed by INGV can be used to estimate the extent of the lava flow, as well as its thickness and temperature.
- The seismic hazard can be evaluated using seismic hazard maps, for which different sources are available:
  - The National Italian seismic hazard map (Stucchi et al., 2004),which displays two shaking parameters; horizontal Peak Ground Acceleration (PGA) and Spectral Acceleration (SA);
  - The 2020 European Seismic Hazard Model (ESHM20) (Danciu et al., 2021);
  - Local microzonation studies.

For the analysis of the exposure the following layers are suggested:

- Population distribution. In general, in Italy, the information provided by the National institute of Statistics (ISTAT) is adopted as reference (referred to as "Census" in the following), referring to the census tracts level. However, for the development of population exposure layers different datasets are available as, the Facebook global dataset, Global Human Settlement Layer (GHSL), WorldPop (University of Southampton).
- Employed distribution. Also in this case, the information derived from the Census can be used. It provides the number of employees for NACE classes (which identifies the economic sectors) at the census tract level.
- Educational facilities distribution. This information is derived mainly from the corresponding OpenStreet Map layer and thematic national layer like national geoportal, regional open data, ministerial data.
- To apply the modelling strategy 3, related to the consequence functions, it is necessary to introduce a built-up layer to which associate the fragility curves. The curves are function of different types of buildings materials, age of construction and number of stories. This information can be extracted from the Census database.

3.3.2 Built environment

As introduced in §3.2.2, the impacts on built environment are assessed through seven attributes. These attributes are further detailed in sub-attributes, for each of which indicators have been proposed. Table 4 summarizes the indicators used in the evaluation process, while the scale of analysis, modelling approach and the necessary data required for their calculation are described in greater detail in the remained of this section.

Table 4. Attributes, sub-attributes and indicators of the "Built environment" category.

Built environment		
Attribute	**Sub-attribute**	**Indicators**

Damage to private commercial assets (F, L, V, E)	Damage to commercial buildings: structure, equipment and stock (F, L, V, E)	Expected (annual) number of exposed commercial activities (structure, equipment and stock)
		Expected (annual) value of exposed commercial activities (structure, equipment and stock)
		Expected (annual) physical damage to commercial buildings
		Expected (annual) economic damage to commercial buildings
	Damage to (commercial) vehicles (F, L, V)	Expected (annual) number of exposed commercial vehicles
		Expected (annual) economic damage to commercial vehicles
Damage to private industrial assets (F, L, V, E)	Damage to industrial buildings: structure, equipment and stock (F, L, V, E)	Expected (annual) number of exposed industrial activities (structure, equipment and stock)
		Expected (annual) value of exposed industrial activities (structure, equipment and stock)
		Expected (annual) physical damage to industrial buildings
		Expected (annual) economic damage to industrial buildings
	Damage to (industrial) vehicles (F, L, V)	Expected (annual) number of exposed industrial vehicles
		Expected (annual) economic damage to industrial vehicles
Damage to private agricultural assets (F, L, V, E)	Damage to agricultural buildings: structure, equipment and stock (F, L, V, E)	Expected (annual) number of exposed agricultural activities
		Expected (annual) physical damage to agricultural buildings
		Expected (annual) economic damage to agricultural buildings
	Damage to agricultural infrastructures (F, L, V, E)	Expected (annual) exposed irrigated areas
	Damage to perennial plants (F, L, V)	Expected (annual) exposed permanent crops area
		Expected (annual) value of exposed perrential plants
	Damage to (agricultural) vehicles (F, L, V)	Expected (annual) number of exposed agricultural vehicles
		Expected (annual) economic damage to agricultural vehicles
Damage to other non-productive private assets (F, L, V, E)	Damage to residential buildings: structure and contents (F, L, V, E)	Expected (annual) number of exposed residential buildings
		Expected (annual) value of exposed residential buildings
		Expected (annual) physical damage to residential buildings
		Expected (annual) economic damage to residential buildings
	Damage to (residential) vehicles (F, L, V)	Expected (annual) number of exposed residents' vehicles
		Expected (annual) economic damage to residents' vehicles
Damage to public assets (F, L, V, E)	Damage to public buildings (F, L, V, E)	Expected (annual) number of exposed buildings
		Expected (annual) physical damage to public buildings
		Expected (annual) economic damage to public buildings
	Damage to (public) vehicles (F, L, V)	Expected (annual) number of exposed public vehicles

		Expected (annual) economic damage to public vehicles
	Damage to roads and railways (F, L, V, E)	Expected (annual) length of exposed roads
		Expected (annual) number of exposed road elements
		Expected (annual) physical damage to road elements
		Expected (annua) value of exposed roads
		Expected (annual) value of exposed road elements
		Expected (annual) length of exposed railways
		Expected (annual) number of exposed railway stations
		Expected (annual) number of exposed railway elements
		Expected (annual) physical damage to railway assets
		Expected (annual) value of exposed railways
		Expected (annual) value of exposed railway stations
		Expected (annual) value of exposed railway elements
	Damage to other lifelines: electric power, natural gas, water supply, waste and wastewater, telecommunication, ports and airports (F, L, V, E)	Expected (annual) impact on electric power network
		Expected (annual) impact on natural gas network
		Expected (annual) impact on water supply network
		Expected (annual) impact on wastewater network
		Expected (annual) impact on waste network
		Expected (annual) impact on telecommunication network
		Expected (annual) impact on ports
		Expected (annual) impact on airports
Damage to cultural heritage (F, L, V, E)	Damage to cultural heritage: assets (F, L, V, E)	Expected (annual) number of exposed cultural heritages sites
		Expected (annual) physical damage to cultural heritage sites

For each sub-attribute, four types of indicators have been proposed, which are then declined for each natural hazard, and that may be totally or partially present according to available knowledge on damage mechanisms and available data for their evaluation. They are:

1. Expected (annual) number of exposed assets (measured in number);
2. Expected (annual) value of exposed assets (measures in €);
3. Expected (annual) physical damage (measured in %)
4. Expected (annual) economic damage (measured in €);

Where the assets can be buildings, lifelines, equipment, vehicles, stock, industrial or agricultural infrastructures, perennial plants.

The evaluation of these indicators is related to two modelling strategies, based on the adoption of:

a. An exposure model for the estimation of the indicators 1 and 2. This model allows to evaluate the assets placed in a hazard prone area;
b. Damage, vulnerability and fragility models for the estimation of the economic indicator, 3.

While the former is a common approach to all hazards and attributes, the second is specific for each of them. In the following the modelling strategies adopted for each hazard and indicator are described in detail along with hazard, exposure and vulnerability data required for their implementation. It is worth noting that drought is not expected to affect the built environment.

3.3.2.1 Flood

Floods affect all exposed assets included in the built-environment category (i.e., all sub-attributes are relevant).

As introduced in the §3.3.1, the main reference for flood hazard assessment in Italy are the Flood Risk Management Plans including information on the extension of the flooded area and the spatial distribution of water depth for different flood scenarios. This dataset is common for all the attributes. Differently, the damage models, the vulnerability analysis and the identification of the elements at risk (dataset of reference, cost, …) are different for each attribute or group of attributes.

Non-productive private assets

For impacts to residential buildings, at micro and meso scale (from single assets to multi-municipality), it is suggested to use available local damage models. For example, in the Po River District, it is suggested to use the models implemented into the MOVIDA project (i.e., Carisi et al. 2018, Arrighi et al. 2013, Galliani et al., 2020;

Exposure and vulnerability data for their implementation (mainly related to the characteristics of buildings) come mainly from the Census, regional geoportals, the Corine Land Cover database and CRESME. Whether local data are available, their implementation is encouraged.

The damage to private vehicles can be described through the function proposed in HAZUS (USACE, 2009) and in Notaro et al., (2014). Exposure and vulnerability data for their implementation come from the Census and the private market.

Private commercial and industrial assets

Impact to commercial and industrial buildings can be evaluated in terms of exposure. Indeed, no models are presently available for the national context for these assets. Moreover, the estimation can be carried out only at the micro and meso scales as neither input data nor models have been found for the macro scale. Exposure and vulnerability information come mainly from the Census.

As for private vehicles, damage to industrial and commercial vehicles can be described through the function proposed in HAZUS (USACE, 2009) and in Notaro et al., 2014. Exposure and vulnerability data for their implementation come from the Census and the private market.

Private agricultural assets

Impacts to agricultural buildings can be evaluated in terms of exposure. Indeed, no damage models are presently available for the national context for these assets. Moreover, the estimation can be carried out only at the micro and meso scales as neither input data nor models have been found for the macro scale. Exposure data come from the national cadastral database.

Perennial crops can be also considered as an agricultural asset, as they represent an investment forming part of the landholding. These are multi-year investments, such as olive groves and vineyards. In analysing the tree planting as a structural part of the farm, the income part derivable from the annual production of the stand is not considered, while this loss will be included in impacts on business activities.

Flood-affected perennial tree plantations may lose their productive capacity because they are either dislodged from the soil, which could occur in the case of a young plantation, or due to the potential phytosanitary issues, which may subsequently need for felling and replanting. Accordingly, impacts on perennial plants can be quantified as the value of the replanting cost and of the related initial cultivation care. At micro and meso scale, exposure and vulnerability data for their estimation come from farm declarations for CAP subsidies, which make it possible to identify the crops on the different farm parcels, and the regional price list to derive the costs for replanting work, expressed in euros per hectare. At the national scale, Census data can be used.

Floods can also compromise irrigation infrastructures, which are critical for water supply. Impacts to them is evaluated in terms of “expected (annual) exposed irrigated areas”. Exposure and vulnerability data for their estimation is included in the mapping of the national irrigation system (SIGRIAN). This dataset provides information on areas occupied by infrastructure managed by irrigation authorities, as well as areas designated for irrigated crops. The indicator can therefore be expressed as the surface area where vulnerable irrigation infrastructure is exposed to risk, assessed at the municipal, sub-municipal, multi-municipal levels through the intersection with flooded area (PGRA).

Damage to agricultural vehicles can be described through the function proposed in HAZUS (USACE, 2009) and in Notaro et al., 2014. Exposure and vulnerability data for their implementation come from the Census and the private market.

Public assets

Impacts on public buildings can be evaluated in terms of exposure. Indeed, no damage models are presently available for the national context for these assets. Moreover, the estimation can be carried out only at the micro and meso scales as neither input data nor models have been found for the macro scale. Exposure and vulnerability information is derived mainly from Open Street Map and thematic national layer national geoportal, regional open data, ministerial data, etc.

Damage to public vehicles can be described through the function proposed in HAZUS (USACE, 2009) and in Notaro et al., 2014. Exposure and vulnerability data for their implementation come from the Census and the private market.

Lifelines infrastructures

Impact on roads and railways can be evaluated in terms of exposure. Indeed, no models are presently available for the national context for these assets. Exposure and vulnerability information come mainly from Open Street Maps and Corine Land Cover database.

Impact on other infrastructure have not been included in the hazard as even information on exposure is lacking.

Cultural Heritage

Impacts on cultural heritage can be evaluated in terms of exposure. Indeed, no damage models are presently available for the national context for these assets. Exposure and vulnerability information is derived mainly from national thematic databases (i.e., Vincoli in rete – GIS). At the micro scale, local thematic information like those included in urban plans can also be exploited.

3.3.2.2 Earthquake

Earthquakes affect almost all the elements constituting the built environment, in particular structures and plants, producing potentially relevant damage.

Following the assumptions used in the entire matrix, the indicators identified for each earthquake impact express mainly the concept of risk in terms of expected damage, as expected annual structural damage or expected annual economic losses.

As introduced in the §3.3.1, the main references for seismic hazard assessment in Italy are:

- National Italian seismic hazard map (Stucchi et al. 2004). The maps display two shaking parameters, PGA (horizontal peak ground acceleration) and SA (spectral acceleration);
- 2020 European Seismic Hazard Model (ESHM20) (Danciu et al. 2021);
- Microzonation studies.

These datasets are common for all the attributes.

Buildings

A peculiar aspect of the earthquake hazard, well recognizable in the matrix, is that the physical effects of the earthquakes (on the same site and hazard property) on a structure do not depend on its use or functions but depend on its construction characteristics. This means, for example, that for one type of building, the assumed damage model is the same, independently of the fact that this building is used as a residence or public office.

At the meso and macro scales, the assumed models are typological, relying on fragility curves for different types of structures. For individual elements (micro scale), however, specific models are suggested to provide a sufficiently detailed structural assessment.

The models and data indicated in the matrix have to be considered as possible references; if territory- or case-specific models and data are available, these should ideally replace the suggested ones. It is important to note that data availability, granularity and suitability vary significantly across regions. While potential data sources are indicated in the matrix, these are not universally applicable or adequate, and new surveys may be required in some cases. Conversely, in some territories, the available data may surpass the referenced options due to more in-depth regional studies.

In detail, exposure and vulnerability data suggested in the matrix are:

- Census data for residential, industrial and agricultural buildings
- Data from regional geoportal
- Construction costs from "Libro bianco dell'Aquila"
- Open Street Map and thematic national layer like the Earthquake Microzonation and Emergency Limit Condition (for schools), Vincoli in rete -GIS (for cultural heritage buildings)

Lifelines infrastructures

For the lifelines attributes, roads and railway systems are considered separately. Still, in both cases the identified models refer mostly to the punctual fragile elements of these systems that can be directly damaged by earthquakes, as bridges, indicating fragility functions that can be used for the assessment of the corresponding damage. Exposure and vulnerability data for their implementation can be mostly found in Open Street Map.

When physical damage to roads and railways track is taken into account, it must be considered that geological phenomena triggered by earthquakes like landslides, displacement, liquefaction (rarer), etc., are among the most important causes of damages to transport infrastructures and cannot be ignored. For this reason, it is important to estimate the extension of roads and railways exposed to instabilities within the seismic area. To this aim information coming from Open Street Map and the landslide hazard mapping supplied by ISPRA within the IdroGEO portal can be used.

3.3.2.3 Volcano

Volcanoes affect almost all the elements constituting the built environment, in particular structures and plants, producing potentially relevant damage.

Following the assumptions used in the entire matrix, the indicators identified for each volcano impact express mainly the concept of risk in term of expected damage, as expected annual structural damage or expected annual economic losses.

Many hazards can be linked to the presence of a volcano including tephra fall, pyroclastic flow, lava flow, and lahar. As introduced in the §3.3.1, the main reference for volcanic hazard assessment in Italy is the Volcanic Impact Simulation Model, providing map load (tephra fall) and dynamic pressure (pyroclastic flow and lahar) data at municipal and regional scales. Moreover, the LAVAFLOW model can be used for an estimation of the extension of the lava area, its thickness, and temperature. These tools are common to all attributes in the matrix.

Buildings

As for earthquakes, the physical effects of a specific volcanic hazard on a structure do not depend on its use or functions but depend on its construction characteristics. Therefore, the damage models will be the same, for example, for public buildings and residential buildings. Several vulnerability curves have been developed in the Speed project (Hazard and Damage Scenarios for Campania Region Volcanoes 2007–2009, Zuccaro and Leone, 2014) for different roofing, walls, and infill panel typologies, and can be used as reference for estimation at the meso scale (i.e., census block level), which is the typical scale at which volcanic risk is estimated. It is important to specify that the damages to the buildings are caused not only by the vulnerability of structural elements but also by the resistance of nonstructural elements, such as doors and openings and infill panels.

Private agricultural assets

Perennial crops in areas at risk of volcanic eruptions may become completely and irreversibly unproductive. For the areas directly affected by such events, it is necessary to consider both the replanting costs and the costs of restoring the damaged agricultural land, similarly to what described in § 3.3.2.1

3.3.2.4 Landslide

Landslides affect all exposed assets included in the built-environment category (i.e., all sub-attributes are relevant). However, no specific damage/impact models have been so far developed for the Italian context. Accordingly, impacts are evaluated in terms of exposure, for all sub-attributes; when possible, a monetary evaluation is also supplied.

As introduced in the §3.3.1, the main reference for landslide hazard assessment is the national geoportal IDROgeo, supplying the perimeter of the areas prone to landslides. Still, for impact assessment at the microscale, information coming from landslide propagation models can be used, if available.

Non-productive private assets

Exposure and vulnerability data for the assessment of exposure of residential buildings (mainly related to the characteristics of buildings) come mainly from the Census, regional geoportals (at the micro-scale), the Corine Land Cover database and CRESME. Whether local data are available, their implementation is encouraged.

The exposure of private vehicles can be assessed with data from the Census and the private market.

Private commercial and industrial assets

Exposure and vulnerability information for the exposure assessment of buildings come mainly from the Census.

The exposure of industrial and commercial vehicles can be assessed with data from the Census and the private market.

Private agricultural assets

Exposure data on agricultural buildings come from the national cadastral database.

As for the other hazards, impacts on perennial plants can be assessed in terms of replanting costs for farms located in areas affected by landslides risk (§ 3.3.2.1). Similarly, zones where irrigation infrastructure overlaps with landslide risk areas are considered vulnerable and exposed (§ 3.3.2.1).

The exposure of agricultural vehicles can be assessed with data from the Census and the private market.

Public assets

Exposure and vulnerability information for the exposure assessment of buildings is derived mainly from Open Street Map and thematic national layer like the Earthquake Microzonation and Emergency Limit Condition (for schools), mapping portal, regional open data, ministerial data, etc.

The exposure of public vehicles can be assessed with data from the Census and the private market.

Lifelines infrastructures

Exposure and vulnerability information come mainly from Open Street Maps and Corine Land Cover database.

Cultural Heritage

Exposure and vulnerability information is derived mainly from national thematic databases (i.e., Vincoli in rete – GIS). At the micro scale, local thematic information like those included in urban plans can also be exploited.

3.3.3 Business activities

As introduced in §3.2.3, the impacts on business activities are assessed through three attributes. These attributes are further detailed into sub-attributes, for each of which indicators have been proposed. Table 5 summarizes the indicators used in the evaluation process, while the scale of analysis, modelling approach and the necessary data required for their calculation are described in greater detail in the remainder of this section. It is worth noting that the sub-attributes remain consistent across all main attributes, although they pertain to different business sectors. Consequently, the selected indicators are also the same. Nonetheless, both sub-attributes and indicators are consistent among hazards as impacts here considered can be assessed independently from the physical event that originate the business disruption.

Table 5. Attributes, sub-attributes and indicators of the “Business activities” category

Business activities		
Attribute	**Sub-attribute**	**Indicators**
Impact on primary sector (F, L, D, V, E)	Direct and indirect cost incurred by agricultural activities (F, L, D, V, E)	Expected (annual) impact on sales per agricultural firm
		Expected (annual) impact on the destination of final goods as intermediates from agricultural firms
		Expected (annual) impact on the sources of intermediate inputs for agricultural firms

	Direct and indirect impact on the income generated by agricultural activities (F, L, V, D, E)	Expected (annual) impact on Gross Domestric Product (GDP)
Impact on secondary sector (F, L, D, V, E)	Direct and indirect cost incurred by industrial activities (F, L, D, V, E)	Expected (annual) impact on sales per industrial firm
		Expected (annual) impact on the destination of final goods as intermediates from industrial firms
		Expected (annual) impact on the sources of intermediate inputs for industrial firms
	Direct and indirect impact on the income generated by industrial activities (F, L, V, D, E)	Expected (annual) impact on Gross Domestric Product (GDP)
Impact on tertiary sector (F, L, D, V, E)	Direct and indirect cost incurred by commercial activities (F, L, D, V, E)	Expected (annual) impact on sales per commercial firm
		Expected (annual) impact on the destination of final goods as intermediates from commercial firms
		Expected (annual) impact on the sources of intermediate inputs for commercial firms
	Direct and indirect impact on the income generated by commercial activities (F, L, V, D, E)	Expected (annual) impact on Gross Domestric Product (GDP)

In particular, to systematically analyze the effects of natural hazards on economic activities, two sub-attributes are proposed:

1. **Direct and Indirect Cost Incurred by Economic Activities**

This attribute encompasses the expenditures borne by firms as a consequence of natural hazards. These costs include direct losses, such as inventory depletion, and indirect losses, such as operational downtime or diminished market demand. The indirect loss category is particularly broad and difficult to define. Even when focusing solely on business interruption, the loss of production and turnover affects not only the firm itself but also propagates through local and global supply chains. For example, suppliers of intermediate goods may face decreased demand, reducing their turnover, while customers may encounter input shortages, forcing them to seek alternatives that increase costs and possibly reduce output (Van Der Veen and Logtmeijer, 2005).

2. **Direct and Indirect Impact on the Income Generated by Economic Activities**

This second attribute includes the impact of natural hazards on the income streams of firms and their associated stakeholders. It includes immediate revenue losses and long-term effects on income generation due to disrupted supply chains, altered market structures, or reallocation of productive inputs. The reduction in wages resulting from business interruptions also affects regional GDP through decreased consumption. If the disruption is prolonged, producers may permanently lose their customers, impeding economic recovery even after operations resume. These indirect effects necessitate the use of general equilibrium models for accurate assessment (Okuyama, 2007).

The direct components of exposure relate to those producing losses directly due to a disaster (i.e., direct economic exposure). Indirect components refer to the losses caused by disruptions in local and global production and supply chains (i.e., indirect socio-economic exposure). However, quantifying these effects remains a challenging task due to the inherent unpredictability of natural events (Hallegatte and Przylusky, 2010) and the lack of detailed economic data at small geographic scales. The measures proposed here draw upon established literature to introduce practical methodologies capable of mapping economic exposure at fine spatial resolution, thus offering valuable insight into the potential vulnerabilities of economic activities to natural hazards.

Building on the reviews of existing literature on economic assessments of natural disasters (Modica and Reggiani, 2015; Modica et al., 2017), this study focuses on cost and income measures that serve as proxies for direct local losses. To address indirect exposure, we examine local economic linkages and the diffusion of damage via intersectoral input-output relationships across municipalities, as defined by Marin and Modica (2017).

Detailed Description of the First Measure: Cost Incurred by Economic Activities

The first evaluation measure—Direct and Indirect Cost Incurred by Economic Activities—is further detailed through three indicators derived from empirical research:

1. **Impact on Sales per Firm [€]**

This indicator captures the revenue generated per firm. It reflects both supply-side constraints (e.g., reduced output capacity) and demand-side shocks (e.g., client loss). This metric is a proxi that provides a granular understanding of the direct economic turnover experienced by firms by analyzing sales data prior to the hazard event.

As highlighted in the literature (Cardona et al., 2012; Modica and Reggiani, 2015), turnover data serve as suitable proxies for direct local economic losses from disasters. However, actual turnover data are typically unavailable for most firms at the municipal level; data are often limited to turnover bands or larger companies. Employment data, on the other hand, are more readily accessible via registries and censuses. Therefore, sales estimates are generated by leveraging employment data and statistical models using databases such as AIDA (Bureau van Dijk). The resulting sales estimates are then normalized per square kilometer to reflect spatial variations in risk exposure, acknowledging that natural hazards impact specific land areas rather than entire municipalities.

The indicator enables the formulation of damage scenarios. Assuming uniform distribution of economic activity within a municipality, the indicator can estimate potential losses. For instance, if all production ceases for one year in a square kilometer, the turnover loss for that area corresponds to its annual turnover. For partial disruptions (e.g., one week), the loss is proportionally scaled (e.g., 1.9% of annual turnover for a 7-day interruption).

2. **Impact on Destination of Final Goods as Intermediates**

This indicator assesses the extent to which final goods produced by firms in a municipality are used as intermediate inputs by other firms in neighboring areas. Disruption of these flows due to natural hazards reveals downstream vulnerabilities, as reduced availability or delays in key inputs affect other production processes.

The methodology involves:

i) Estimating total turnover in neighboring municipalities (within specified radius);
ii) ii) Applying sectoral input-output technical coefficients to determine potential intermediate demand;
iii) iii) Calculating the share of this demand met by the output from the municipality of interest.

A turnover-weighted sectoral average is then computed, reflecting the reliance of neighboring areas on the municipality's output. A decline in this metric indicates diminished intersectoral linkages, exacerbating the systemic impact of natural hazards.

3. **Impact on Sources of Intermediate Inputs**

This third indicator evaluates how natural hazards disrupt the procurement of intermediate goods necessary for production. Such disruptions may stem from damaged infrastructure, supplier outages, or price volatility. This metric identifies potential vulnerabilities in the supply chain, focusing on the accessibility of inputs.

The procedure entails:

i) Using the turnover vector of the focal municipality to compute its intermediate input demand via the input-output coefficient matrix.
ii) Comparing this demand with sectoral turnover in neighbouring municipalities;
iii) Calculating a weighted average (by turnover) to estimate the share of inputs potentially sourced locally.

This indicator illustrates the upstream implications of local disruptions. If a municipality suffers a production halt, its decreased demand for inputs translates into economic strain on nearby suppliers. The analysis presumes that all national-level inputs could be locally sourced, a strong assumption necessitated by the absence of granular trade flow data. To assess spatial sensitivity, results are provided for different geographic thresholds (e.g., 20 km and 50 km).

Collectively, these three indicators offer a robust framework for quantifying the impact borne by economic activities in the wake of natural hazards. They address both the localized and interconnected nature of modern production systems, thereby providing essential insights for resilience planning and risk mitigation.

Detailed Description of the Second Measure: Income generated by Economic Activities

The risk associated with natural hazards is determined not only by the intensity or magnitude of the hazard event itself, but also significantly by the level of economic exposure.

One alternative is to use macroeconomic indicators that are more readily available and consistently compiled across countries. One such indicator is Gross Domestic Product (GDP), provided by national and international statistical offices. These data are often available at the national level and increasingly provided in digital formats, including GIS-compatible databases.

Exposure and population

Population density and economic exposure are closely correlated (World Bank, 1995). Specifically, GDP data at the national or regional level can be spatially redistributed based on population distribution to approximate economic exposure per unit area:

$$GDP\ per\ unit\ area = \frac{Regional\ GDP \times Population\ in\ unit\ area}{Total\ regional\ population}$$

This method of estimating exposure is particularly valuable in the context of various natural hazards—such as floods, hurricanes, wildfires, landslides, or tsunamis—where the spatial extent and intensity of impact vary greatly, and direct inventory data may not be available.

In this framework, *social wealth* serves as a proxy for exposure, with GDP representing the cumulative value of economic activity and thus approximating the density of income generating activities in the area considered. The underlying assumption of this holistic approach is that the number and value of man-made facilities and infrastructure are directly proportional to a region's economic productivity, as measured by its GDP.

By mapping GDP data to finer spatial units based on population density and economic activity patterns, analysts can derive estimates of exposure that account for the built environment and its vulnerability to natural events. This methodology is especially valuable in global or national risk modeling for a wide range of hazards, including but not limited to earthquakes, hurricanes, floods, and wildfires. It facilitates consistent and scalable exposure assessments that can inform risk reduction strategies, emergency planning, and resilience investments across diverse geographies.

Local shock diffusion area measured by Labour Market Areas. Labour Market Areas define groups of municipalities characterized by substantial within-area commuting patterns and limited commuting patterns with municipalities in other Labour Market Areas. Labour Market Areas are defined by the Italian Institute of Statistics every 10 years, using data on commuting patterns from the decennial general census of population.

3.3.4 Public services

As previously discussed, with impacts on public services we mean impacts on their functioning instead of the direct physical impacts on public infrastructures and buildings. Obviously, the impact on the built environment (e.g. a school, a railway) is strictly connected with the impacts produced on the functioning of the public service. However, the functioning of the public service is also influenced by other factors, such as the possibility to run the service by remote and the presence of alternative solutions (e.g. an alternative hospital close to my home). Therefore, a careful assessment of each public service functioning and of the socio-economic context where the service is placed is essential to properly assess the possible impact of a natural hazard.

As discussed before, the impacts on public services are evaluated by three main attributes, divided into 12 sub-attributes:

- Disruption of public utilities services (e.g. impacts on the education services, on health services)
- i. Disruption of utilities services (e.g. impacts on the transport services, on the waste treatment service)
- ii. Impacts on the emergency services (e.g. impacts on the availability of emergency services, or impacts on the costs of emergency management)

For their evaluation, several indicators have been defined that are not distinguished among hazards as mainly referring to indirect impacts. Consequently, the cause of the physical/direct impact does not influence the extent of the impact itself.

To assess the different hazards, as indicated for the previous categories, we suggested the following datasets and maps:

- Extension of the flooded area (from PGRA maps)

- Extension of landslide hazard zones (from IdroGeo/PAI maps)

- Extension of volcanic activity affected areas (tephra, lahar, lava, pyroclastic flow) (from related maps), see built environment table

- Italian Seismic hazard map, European hazard map produced by GEM

- Extension of drought affected areas (from ISPRA or Copernicus maps)

However, it must be noted that, in absence of specific findings from scientific literature, drought has been considered a relevant hazard only for certain impacts: i.e., the reduced access to electric power services and to water supply services and the costs of emergency management.

As regards exposure and vulnerability, datasets have been identified for an assessment at both the micro and higher scales. As regards the individual level (micro-scale) we focused on different sources of dataset: a) data from national institutions, such as the Ministry of education database (Scuola in Chiaro, Portale Unico dei Dati della Scuola); b) data from local public administrations or technical agencies (waste dataset by ARPA); c) data from national organizations representing a specific infrastructure/service (such as Assoporti and Assoaeroporti); c) open data as OpenStreet Map. These datasets have been considered in order to better characterize the importance of each individual item and of the related public service. For example, through these datasets we can identify the number of students attending lessons in a specific school, the number of goods or passengers served by a specific harbor or airport or the amount of wastewater treated by a wastewater treatment facility. At the meso-scale, the main source of data is the National Institute of statistics (ISTAT) where available and identified data are aggregated and organized over different administrative levels (such as census block or the municipal level).

Table 6. Attributes, sub-attributes and indicators of the "Public services" category.

Public services		
Attribute	**Sub-attribute**	**Indicators**
Disruption of public utility services (F, L, V, E)	Reduced access to education (F, L, V, E)	Expected (annual) number of exposed education assets
		Expected (annual) number of exposed enrolled students
	Reduced access to health services (F, L, V, E)	Expected (annual) number of exposed health service assets
		Expected (annual) number of exposed available beds
	Reduced access to administrative services (F, L, V, E)	Expected (annual) number of exposed administrative service assets
	Reduced access to recreational and sport activities (F, L, V, E)	Expected (annual) number of exposed recreational and sport activity assets
Disruption of utility services (F, L, D, V, E)	Reduced access to transport services (F, L, V, E)	Expected (annual) length of exposed roads
		Expected (annual) length of exposed railways
		Expected (annual) number of exposed railway stations
		Expected (annual) number of exposed airports
		Expected (annual) number of exposed ports
		Expected (annual) number of passengers affected
		Expected (annual) amount of goods affected
	Reduced access to electric power services (F, L, D, V, E)	Expected (annual) number of exposed electric power network assets
		Expected (annual) number of failed electric power network assets
		Expected (annual) exposed service area
	Reduced access to natural gas services (F, L, V, E)	Expected (annual) number of exposed natural gas network assets
		Expected (annual) number of failed natural gas network assets
	Reduced access to water supply services (F, L, D, V, E)	Expected (annual) number of exposed water supply assets
		Expected (annual) number of failed water supply assets
		Expected (annual) customer disruption days
	Reduced access to waste treatment services (F, L, V, E)	Expected (annual) number of exposed wastewater treatment assets
		Expected (annual) number of failed wastewater treatment assets
		Expected (annual) number of inhabitants missing the wastewater treatment service
		Expected (annual) number of exposed waste treatment assets
		Expected (annual) amount of waste not treated
		Expected (annual) amount of energy not recovered
	Reduced access to telecommunication services (F, L, V, E)	Expected (annual) number of exposed telecommunication assets

Impact on emergency services (F, L, D, V, E)	Reduced availability of emergency services (F, L, V, E)	Expected (annual) number of exposed emergency services
	Cost of emergency management (F, L, D, V, E)	Expected (annual) emergency cost based on hazard
		Expected (annual) assistance cost for one person

3.3.5 Environmental systems

The matrix related to impacts on "Environmental systems" is organized in fundamental compartments, which provide the main ecosystem services and shape biodiversity on Earth. The impact on each compartment corresponds to an attribute in the matrix, as introduced in Section 3.2.5:

- Impact on surface hydrosphere
- Impact on groundwater hydrosphere
- Impact on lithosphere
- Impact on atmosphere
- Impact on biosphere

These attributes have been further described in sub-attributes to facilitate the evaluation process within the MCA for a total of 27 indicators, as summarized in Table 7. For each individual sub-attribute, quantitative or qualitative indicators are defined based on the existence of validated damage models and the availability of data for calculation. In detail, where standard modelling approaches that supports an ex-ante impact assessment are available, quantitative indicators can be developed. In cases where the necessary datasets for calculation are not available, or the required modelling approach is able to assess the impacts only ex-post, qualitative indicators are employed. When neither quantitative nor qualitative indicators can be selected, the extent of exposed areas to the different natural hazards is considered in the Hazard-Exposure-Vulnerability risk assessment. Eventually, based on the existence of damage models and the availability of data, indicators were defined resulting from the implementation of two different modelling approaches:

- Exposure analysis: it allows the identification of those vulnerable elements that are situated in a natural hazard prone area.
- Qualitative analysis; in this case, impacts are assessed using qualitative rating scales that integrate various categorical parameters, synthesizing the impact status into a specific qualitative scale.

This involves the use of specific hazard maps (e.g., PGRA maps, SPI maps, volcanic activity maps) and a comprehensive evaluation of the areas, determining whether they can be classified as vulnerable due to the presence or absence of protected species, habitats, or a general state of environmental vulnerability. In detail, to assess the different hazards datasets and maps discussed in previous subsections can be implemented.

Table 7. Attributes, sub-attributes and indicators of the "Environmental systems" category.

Environmental systems		
Attribute	**Sub-attribute**	**Indicators**
Impact on surface hydrosphere (F, L, D, V, E)	Impact on surface water quality (F, L, D, V, E)	Expected (annual) exposed surface water protected area
		Expected (annual) number of exposed water polluting sources
		Expected (annual) impact on surface water ecological status, including salinity
		Expected (annual) impact on surface water chemical status
	Impact on surface water quantity (D)	Expected (annual) impact on river discharge
		Expected (annual) impact on lake water level

	Impact on surface water temperature (D)	Expected (annual) impact on lake surface water temperature
Impact on groundwater hydrosphere (F, D)	Impact on groundwater quality (F, D)	Expected (annual) exposed groundwater protected area
		Expected (annual) impact on groundwater chemical status
	Impact on groundwater quantity (F, D)	Expected (annual) impact on groundwater quantitative status
	Impact on groundwater temperature (F, D)	Expected (annual) impact on groundwater temperature
Impact on atmosphere (F, D, V, E)	Impact on air quality (F, D, V, E)	Expected (annual) number of exposed air polluting sources
		Expected (annual) air pollutants concentration
Impact on lithosphere (F, L, D, V)	Impact on geomorphology of rivers (F, L)	Expected (annual) impact on Morphological Quality Index (MQI)
	Impact on soil erosion (L, D)	Expected (annual) impact on soil susceptibility to erosion
	Impact on soil quality (F, D, V)	Expected (annual) number of exposed soil polluting sources
		Expected (annual) exposed soil biomass productivity
Impact on biosphere (F, L, D, V)	Impact on urban habitats (F, L, D, V)	Expected (annual) exposed urban protected area
		Expected (annual) number of exposed urban species
	Impact terrestrial habitats (F, L, D, V)	Expected (annual) exposed terrestrial protected area
		Expected (annual) number of exposed terrestrial species
	Impact on aquatic habitats (F, L, D, V)	Expected (annual) exposed aquatic protected area
		Expected (annual) number of exposed aquatic species

Surface hydrosphere

The impacts on surface hydrosphere (attribute) are further divided into the impact on the quality of surface water, the impact on the quantity of surface water, and the impact on the temperature of surface (sub-attributes), as previously mentioned in Section 3.2.5.

Four indicators have been proposed to estimate the impact on surface water quality:

1. Expected (annual) exposed surface water protected area
2. Expected (annual) number of exposed water polluting sources
3. Expected (annual) impact on surface water ecological status
4. Expected (annual) impact on surface water chemical status

The first two indicators are evaluated in terms of exposure considering:

(i) the spatial distribution of surface water bodies (rivers, lakes, transitional waters, coastal waters) and protected areas (nitrates vulnerable zones, designated areas such as fish protected areas and shellfish protected areas, urban wastewater sensitive areas, drinking water protected areas, bathing water protected areas), as identified within the context of the Water Framework Directive (WFD) 2000/60/EC

(ii) the spatial distribution of polluting sources and the type of polluting sources, with specific reference to those that can affect water, as identified by the European environmental agency

The ecological status expresses the quality of the structure and functioning of the aquatic ecosystem and can be evaluated in five classes: high, good, sufficient, poor, bad. According to the WFD, the evaluation of ecological status is implemented using a set of biological, chemical, chemical-physical, and hydro-morphological indicators, representing the different conditions of the river or lake ecosystem. However, these indicators can be estimated only in the aftermath of an event occurrence, following an ex-post assessment, with the sample of monitoring data from point extractions. Accordingly, a qualitative indicator is proposed that classifies impact on the ecological status of the surface waters in three classes (null, significant and not significant), according to the ex-ante ecological status of the exposed water, as identified within the context of the WFD.

The same "qualitative" approach has been adopted foe estimating the impact on the chemical status of the surface waters, that can be quantitatively assessed only ex-post. The latter is classified, within the context of the WFD, in two classes: failing to achieve good and good, according to the presence of priority chemical substances identified by the legislation (heavy metals, pesticides, industrial pollutants, etc.) in concentrations exceeding environmental quality standards. The qualitative indicator classifies impact on the chemical status of the surface waters in three classes (null, significant and not significant), according to the ex-ante chemical status of the exposed water, as identified within the context of the WFD.

Two types of indicators have been proposed to estimate the impact on surface water quantity:

1. Expected (annual) impact on river discharge
2. Expected (annual) impact on lake water level

Both indicators are qualitative, classifying impact in three classes (null, significant and not significant) according to the type of affected river or lake (natural, artificial, heavily modified), as identified within the context of the WFD. The same approach is adopted for the only indicator proposed to estimate the impact on surface water temperature: the expected (annual) impact on lake surface water temperature.

Groundwater hydrosphere

The impacts on groundwater hydrosphere (attribute) are further divided into the impact on the quality of groundwater, the impact on the quantity of groundwater, and the impact on the temperature of groundwater (sub-attributes), as mentioned in Section 3.2.5.

Two types of indicators have been proposed to estimate the impact on groundwater quality:

1. Expected (annual) exposed groundwater protected area
2. Expected (annual) impact on groundwater chemical status

In the same way as for surface water, the first is estimated in terms of exposure considering the spatial distribution of groundwater bodies and protected areas (nitrates vulnerable zones, designated areas such as fish protected areas and shellfish protected areas, urban wastewater sensitive areas, drinking water protected areas, bathing water protected areas), as identified within the context of the WFD. The second is assessed qualitative based on the ex-ante chemical status of the exposed bodies, as identified within the context of the WFD.

One indicator has been proposed to estimate, respectively, the impact on groundwater quantity (the Expected (annual) impact on quantitative status) and the impact on groundwater temperature (Expected (annual) impact on groundwater temperature). Both are evaluated qualitatively, based on the quantitative status of the exposed aquifers and their depth, as evaluated within the context of the WFD.

Atmosphere

The impact on atmosphere is evaluated in terms of impact on air quality, through two indicators:

1. Expected (annual) number of exposed air polluting sources
2. Expected (annual) impact on air pollutants concentration

The first is estimated in terms of exposure considering the spatial distribution of polluting sources and the type of polluting sources, with specific reference to those that can affect air, as identified by the European environmental agency. For the second, a qualitative indicator is proposed that classifies impact on air pollutants concentration in three classes (null, significant and not significant), according to the ex-ante air quality category, as identified by the European Environmental Agency and the National Environmental Agency (ISPRA).

Lithosphere

The impacts on lithosphere are further divided into impacts on geomorphology of rivers, impacts on soil erosion and impacts on soil quality.

One indicator has been proposed to estimate the impacts on geomorphology of rivers: the expected (annual) impact on Morphological Quality Index (MQI). The indicator is evaluated qualitatively, on the basis of the ex-ante value of MQI in the exposed area.

Impacts on soil erosion are estimated in terms of the expected (annual) impact on soil susceptibility to erosion. The indicator is quantitative and considers the spatial distribution of agricultural areas, forest and seminatural areas, and areas with high soil susceptibility to erosion, according to land use maps and national classification.

Two indicators have been proposed to estimate the impact on soil quality:

1. Expected (annual) number of exposed polluting sources;
2. Expected (annual) exposed soil biomass productivity

Both indicators are estimated in terms of exposure. The first considers the spatial distribution of polluting sources and the type of polluting sources, with specific reference to those that can affect soil, as identified by the European environmental agency. The second the spatial distribution of of gross dry matter productivity.

Biosphere

Impacts on biosphere are further divided in impact on urban habitats, impact on terrestrial habitats and impacts on aquatic habitats. For the three of them, two quantitative indicators are proposed

1. Expected (annual) exposed protected area;
2. Expected (annual) number of exposed species

Both indicators are based on the spatial exposure of the considered item. In particular, in order to identify vulnerable areas regarding species and habitats, the mapping provided by the World Database on Protected Areas (WDPA) is utilized. This database is derived from periodic global habitat reports, including the UN List of Protected Areas, the CBD Global Biodiversity Outlook, the UN Environment Global, and the Protected Planet Reports. The latter is updated on a biennial basis to monitor progress towards the CBD targets and the Sustainable Development Goals (SDGs). It encompasses both global protected areas and those defined at the regional level, including the European Habitat and Birds Directives, which are defined by the Natura 2000 Network. The data are presented as points and, where feasible, as polygons, thereby facilitating the extraction of habitat extent or location at municipal, sub-municipal, and regional levels. The WDPA dataset allows for the referencing of different levels, which correspond to the subdivisions made within the biosphere matrix. The number of protected species and the main compartments, such as forest areas and grassland located within the risk zones, can be considered using the Corine Land Cover maps with a spatial resolution of 100m. The WDPA protected areas include the areas assigned as protected on the Natura 2000 Directive, the CDDA/EUAP areas, and the RAMSAR wetlands. The Natura 2000 Directive includes the Birds Directive (ZPS) and the Habitats Directive (SIC). In Italy there are already considered 57 RAMSAR zones and 9 more are towards consideration. Protected species can be classified as terrestrial and aquatic species. Both categories can be found in urban environments, further classified as urban species.

3.3.6 Communities

As discussed before, the category "community" focuses on the impacts that an extreme / disastrous event could have on the interactions among community members and between community members and the local community places.

The impacts on communities are evaluated by three main attributes, divided into 5 sub-attributes, that are not distinguished among hazards as mainly referring to indirect impacts. Consequently, the cause of the physical/direct impacts does not influence the extent of the impact itself.

To assess the different hazards, as indicated for the previous categories, we suggested the following datasets and maps:

- Extension of the flooded area (from PGRA maps)

- Extension of landslide hazard zones (from idroGEO/PAI maps)

- Extension of volcanic activity affected areas (tephra, lahar, lava, pyroclastic flow) (from related maps), see built environment table

- Italian Seismic hazard map, European hazard map produced by GEM

- Extension of drought affected areas (from local models/studies)

Cultural Capital

The impact on cultural capital is evaluated by 4 sub-attributes for which a specific indicator has been defined.

The impact on *community participation in cultural events* is evaluated by the number of cultural events exposed to natural hazards that would be cancelled / relocated in case of an event. With cultural events we mean "recurring and official events that have cultural relevance for the community under consideration (e.g. religious events, traditional events, recurrent cultural and gastronomical events)". However, as we are aware that the community of reference may be composed by multiple sub-groups, we would like to keep the definition and mapping of cultural events as wide as possible to include all the relevant events.

As there is not "institutional/official" and standardized information on cultural events, their exposure must be evaluated case by case, by the identification and following mapping of the events that characterize the community of reference. Accordingly, the evaluation can be carried out only at the micro or meso scale (municipality / multi- municipality)

The impact on *the transmission of cultural capital in formal education* is evaluated by the percentage of educational infrastructure affected by a natural hazard (whose service is disrupted). For sure, a paucity of critical infrastructures is per se a critical situation, that can be worsen by the occurrence of an extreme event. To evaluate the indicator, we can rely on the datasets used in the category "public services" to identify "out of service" schools, both at the micro and meso scale.

The impact on the *conservation of cultural capital* is evaluated by considering the exposed number of cultural sites. This indicator is a composite indicator as it takes into consideration the exposure of different types of cultural capital. The indicator is defined as

I = ECHR + RL +LP + MAB

where:

ECHR=Endowment of cultural heritage resources. This type of heritage includes landscapes and built heritage that are included in the Cultural Heritage and Landscape Code D.lgs 42/2004 and UNESCO World Heritage Sites.

RL= rural landscape. This type of heritage considers historic rural landscape. Historic landscapes are enrolled and defined by the National Register of Historic Rural Landscapes (Rete Rurale Nazionale, MASAF) and by identification as Globally Important Agricultural Heritage Site (GIAHS - FAO).

LP = Landscape protection. Specifically, we consider those areas/landscapes that are identified as particularly important for biodiversity (e.g. Aree Prioritarie per la Biodiverstà - APB) and local communities by rural development plans (Piani di Sviluppo Rurale – PSR).

MAB= Unesco MAB reserves

Exposure and vulnerability data for the calculation of the indicator include:

- ECHR maps ("Carta del Rischio" - risk map of Istituto Centrale del Restauro, Direzione Generale per la Sicurezza del Patrimonio Culturale - Ministero della Cultura / Ministry of Culture)
- RL maps (GIS) maps of rural historical landscapes (Rete Rurale Nazionale, ISMEA, MASAF; GIAHS, FAO)
- LP regional maps of landscapes considered for landscape protection at regional level (e.g. APB, Lombardy Region)
- Geosites identified in MAB (UNESCO)

The indicator for the impact on *place attachment* takes as proxy buildings / services that would be relocated in case of a natural hazards, assuming as theoretical foundation that higher is the number of relocated activities higher would be the negative impact on place attachment and sense of place, reducing the shared experience among community members and consequently on community resilience.

Human Capital

The impact on human capital can be evaluated by changes in the share of " local skills" that are at risk of being lost due to a natural hazard over the total local skills endowed by a given community**.** The indicator assumes that loss of local skills will cause loss of human capital, as the loss of knowledge will prevent the community to use it for its own recovery in case of a natural hazard. The indicator will map the "owners" of local knowledge (local artisan, cluster of local production / local products) and the places where local knowledge is endowed (i.e. vernacular architecture or traditional landscape management techniques) to map the level of risk of losing human capital in case of hazards. In this regards, local skills are intended as local crafts, local building techniques, local landscape / environmental management technique formally recognized/and or listed by national and international bodies and agencies (e.g., UNESCO, FAI, Slow Food, P.D.O. etc.).

As there is not "institutional/official" and standardized information on local skills, their exposure must be evaluated case by case, by the identification and following mapping of the local skills that characterize the community of reference. Accordingly, the evaluation can be carried out only at the micro or meso scale (municipality / multi- municipality)

Social Capital

The quantification of the contribution of social capital, social networks and community relationships in the overall recovery it is an extremely challenging aspect (Imperiale and Vanclay, 2021). Even more challenging is identifying a priori how the social capital could be affected by a certain extreme event or by specific mitigation measures. Indeed, research and literature investigated the relationship between social capital and disasters mainly focusing on how social networks and social capital are functional to post-disaster recovery (Aldrich, 2015).

Further than paucity of references and literature, we have faced a lack of data availability at Italian level to define and estimate proxy variables for measuring social capital, especially at local level. Considering the current state of the art, despite we recognize as extremely important assessing how disasters could impact different dimensions of social capital, we faced several limitations in defining suitable proxy as well as assessment methodologies. Thus, we did not provide any indicator for measuring change in social capital due to extreme events.

However, we strongly invite decision makers / planners / risk managers to investigate which type of social networks characterize a specific area and how relevant / strong these networks are. It is strongly proven that the presence of different kind of networks / subnetworks enhance community resilience by reducing the effects of extreme events, supporting recovery efforts and

Furthermore, in the aftermath of an extreme event it would be advisable to collect data on how a specific event has impact relations among community members, to investigate which aspects of social capital have been affected and in which way, to better design policies that would foster local action though civic activity and strengthening the existing social infrastructure (Aldrich, 2015).

Table 8. Attributes, sub-attributes and indicators of the "Communities" category.

Communities		
Attribute	**Sub-attribute**	**Indicators**
Impact on cultural capital (F, L, D, V, E)	Impact on community participation in cultural activities (F, L, D, V, E)	Expected (annual) number of exposed cultural events that will be cancelled or relocated in case of a natural hazard event
	Impact on the transmission of cultural capital in formal education (F, L, D, V, E)	Expected (annual) percentage of exposed education assets to a natural hazard event whose service will be disrupted
	Impact on the conservation of cultural capital (F, L, D, V, E)	Expected (annual) number of exposed cultural heritage assets to a natural hazard event
		Expected (annual) intangible damage to cultural heritage assets
	Impact on place attachment (F, L, D, V, E)	Expected (annual) number of buildings inaccessible to people requiring relocation in case of a natural hazard event
Impact on human capital (F, L, D, V, E)	Impact on local skills recovery (F, L, D, V, E)	Expected (annual) percentage of exposed "local skills" that will be lost due to a natural hazard event
Impact on social capital (F, L, D, V, E)	Impact on the sense of community (F, L, D, V, E)	-

3.3.7 Financial system

As discussed before, the category "financial system" focuses on the impacts that an extreme / disastrous event could have on the three main components/domains of financial systems being the bank system, the insurance system and the creditworthiness rating system

For each of them, we provide more indicators to offer either a more thorough information basis for the assessment (if data can be easily retrieved), or some alternative metrics to measure variables being relevant to each domain (if some data cannot be easily retrieved). We also provide some references to likely sources and databases where data are typically stored or to the institutions held responsible for data collection.

However, for the purposes of Multi-Criteria Analysis (MCA) we highlight one *key indicator* for each dimension (indicated by a * in the title) that can be estimated ex-ante and that is more directly related to physical impacts or damages attributable to natural hazards. These primary indicators are chosen to facilitate an immediate assessment of how natural events affect the financial system through direct damage pathways. For them only we provide a more detailed calculation methodology.

Table 9. Attributes, sub-attributes and indicators of the "Financial system" category.

Financial system		
Attribute	**Sub-attribute**	**Indicators**
Impact on banking system (F, L, V, E)	Impact on the value of collateral pledged for credit (F, L, V, E)	Expected (annual) collateral value depreciation rate
		Expected (annual) impact on the Collateral Coverage Ratio (CCR)
Impact on insurance industry (F, L, V, E)	Deterioration of the financial position of insurance companies (F, L, V, E)	Expected (annual) impact on the loss ratio for natural hazards
Impact on creditworthiness rating system (F, L, V, E)	Impact on the abnormal return on assets (F, L, V, E)	Expected (annual) impact on the ratio of natural hazard losses to Gross Domestic Product (GDP)

Banking System

The ratio between the total NPLs (Non-Performing Loans) and the total outstanding loans over a specific period indicates the proportion of loans or credits issued by a bank, where borrowers have defaulted on payments due to financial distress (typically: repayment delays exceeding 90 days) (Basel II, EBA Guidelines).

The extent of NPLs may demonstrate a proportional relationship to the magnitude of damage to the collateral assets of the loans, which causes their depreciation and reduces the recoverable value of these assets in the event of default. Additionally, loans issued in sectors particularly exposed to damaging natural events may be at higher risk of default. Moreover, cascading effects related to regional contexts, originating from damages caused by natural events, can compromise the overall regional economic climate, thus increasing the incidence of NPLs on the total financing within the relevant territory.

Banks may exhibit greater risk aversion and reduce credit supply to consumers and businesses. However, the increase in the "NPL ratio" also has macroeconomic effects on the stability of the entire financial system, through the increase in stress (distress) within the banking system, which may lead to subsequent increases in the capital guarantees required by credit institutions in addition to the mandatory guarantees defined by central banks. A significant increase in these guarantees could generate known effects of credit supply reduction (and possibly money supply reduction), with potential impacts on market interest rates and the possibility of creating *credit crunch* situations at the regional level.

In the indicators that follow we use collateral value as a variable. Collateral may refer to any asset pledged by a borrower to secure a loan or financial instrument. Typically, collaterals used to secure a loan include real estate, cash and bank deposits, and financial securities (including stocks, bonds, and mutual funds). In case no other information is available the real estate value can be used as a proxy.

*Collateral Value Depreciation Rate (CVDR)**

A useful indicator for assessing the impact of natural disaster damage on the banking system is the Collateral Value Depreciation Rate (CVDR). This is measured by the ratio between the loss in the value of collateral and the total value of the collateral itself. If this ratio increases, it becomes more difficult for banks to recover credit; if it remains constant or decreases, the risk does not significantly change (Basel Committee on Banking Supervision, 2004).

$$CVDR = \frac{Estimated\ Collateral\ Value\ Loss\ due\ to\ NH}{Total\ Collateral\ Value} \cdot 100$$

Natural hazards and the damage they cause to assets used as collateral for a loan can reduce their market value, especially in the case of real estate. This phenomenon can be translated into an estimate of collateral value depreciation. An increase in the calculated index indicates a higher credit risk for banks (Allen & Gale, 2000).

The absolute value of the numerator (Estimated Collateral Value Loss due to NH) is also significant, as it indicates the total economic value of the damage suffered proportionate to the share of the value of the assets given as collateral to the banking system against mortgages and loans.

The calculation procedure can be structured in specific steps, as indicated below:

1. Identify the Real Estate Market Observatory - Agenzia delle Entrate (OMI) zones of the municipalities considered (e.g.: historic center, suburbs, industrial areas).
2. For each OMI zone and each building category (e.g., residential, industrial):
    a. Calculate the average market value of real estate properties per m² (from OMI).
    b. Calculate the total market value of properties knowing
    b1. The total surface area of properties (from regional geoportals or ISTAT, considering footprint area and number of floors): Total zone value: OMI Value per m²× total surface area, or
    b2. The average surface area of properties (from OMI) and the number of properties: Total zone value: OMI Value per m²× average surface area × Number of properties
3. Add the values of all the zones to obtain the total real estate value of the municipalities: Total value
4. Apply the percentage of properties secured by a mortgage (PMI) and the percentage of the value of the property that the bank finances with a mortgage (LTV mortgage) to calculate the total value of the collateral: Total collateral value = Total value ×PIM ×LTV mortgage.
5. For each OMI zones, return period (TR) and building category:
    a. Calculate the surface of damaged properties:
    a1. Floods: surface of flooded floors
    a2. Landslide: surface of properties in landslide area
    a3. Volcanoes: surface of properties in buildings with a physical damage exceeding X%
    a4. Earthquakes: surface of properties in buildings with a physical damage exceeding X%
    b. Calculated the total market value of damaged properties: OMI Value per m²× damaged surface
6. Add the values of all the zones to obtain the total real estate value of damaged properties in the municipalities for each return period: Total value loss, $_{TRi}$
7. Apply the percentage of properties secured by a mortgage (PMI) and the percentage of the value of the property that the bank finances with a mortgage (LTV mortgage) to calculate the total value loss of the collateral for each return period: Estimated Collateral Value Loss due to NH, $_{TRi}$= Total value loss, $_{TRi}$× PIM × ×LTV mortgage.
8. Calculate the Estimated (annual) Collateral Value Loss due to NH, considering the probability of occurrence of each scenario (p=1/TR)
9. Calculate the Collateral Value Depreciation Rate (CVDR)

Data availability and sources:

To accurately calculate the Collateral Value Depreciation Rate (CVDR), data from several key sources are essential. The Agenzia delle Entrate's Osservatorio del Mercato Immobiliare (OMI) provides periodic evaluations of property values across various geographical areas and property types, which are critical for assessing the depreciation of assets used as collateral. Additionally, the Istituto per la Vigilanza sulle Assicurazioni (IVASS) offers valuable information on insurance policies and risk exposures. Data from these policies can help evaluate the insurance coverage of the collaterals and their possible depreciation, thereby providing a comprehensive understanding necessary for accurate CVDR computation.

Reference values for North-West Italy are:

- Average surface area of residential properties: 106.4 m^2/property
- Average market value per residential property: 173,698€/property
- PIM: percentage of residential properties for sale secured by a mortgage in the OMI area (North West: 38.5%, 2023)
- Financial capital disbursed per housing unit: €143,000: (OMI-ABI, 2023: Lombardy)

Collateral coverage ratio (CCR)

Another indicator critical for evaluating the adequacy of collateral to cover outstanding loans involves the proportion of collateral relative to the total loans outstanding in a given period over a certain territory: it is known as the "collateral coverage ratio" (CCR).

$$CCR = \frac{Market\,Value\,of\,Collateral}{Outs\tan d\,ing\,Loan\,Amount} \cdot 100$$

The Collateral Coverage Ratio (CCR) expresses the relationship between the market value of the collateral used to secure loans in a specific territory and the total amount of loans disbursed in the same context. It indicates how much coverage the collateral provides relative to the loan.

A higher CCR suggests greater security for the lender in case of default. A reduction in the value of the index can indicate that the collaterals are insufficient to cover the already disbursed loans, increasing the credit risk associated with the granted financing. The CCR helps in understanding the risk exposure of financial institutions in the event of collateral value depreciation. Used in capital adequacy assessments to measure a bank's ability to absorb losses.

The incidence of natural events on the market value of collaterals could create distress for credit institutions primarily involved in providing financing in a territory affected by particularly damaging natural events.

Data availability and sources

Accurately calculating the Collateral Coverage Ratio (CCR) requires robust data from authoritative sources. The Banca d'Italia provides crucial data through its Base Dati Statistica (BDS), detailing credit distribution across economic sectors and regions. ISTAT offers information on the value added by these sectors, aiding in comparing credit exposure with economic significance. Additionally, the Associazione Bancaria Italiana (ABI) supplies reports on Italian banks' credit policies. Together, these datasets enable a precise assessment of the CCR, enhancing the understanding of credit risk for mortgage-backed loans. The Agenzia delle Entrate's Osservatorio del Mercato Immobiliare (OMI) offers critical data on property market values, which is necessary for determining the market value of a large share of collateral.

Insurance System

The selected indicators essentially refer to the level of damages recorded following natural events in a specific geographical area, the degree of diffusion and incidence of insurance coverage on different natural hazards, and the variation in insurance premiums following the occurrence of disastrous natural events.

*Loss ratio for natural hazards (LR_{NH})**

A significant increase in recorded damages in a given area, all other conditions being equal, generates a variation in the relationship between premium collection and payments made by the insurance company, classically expressed by the "loss ratio," i.e., the ratio between total claims paid and total premiums collected by an insurance company. It represents the portion of premiums that an insurance company spends on indemnities. In the case of damages attributable to natural events, the "loss ratio" measures the economic sustainability of policies for natural events. A value exceeding 100% indicates that insurance companies are paying out more than they are collecting, which may lead to an increase in premiums or a reduction in coverage (Cummins & Weiss, 2014).

$$LR_{NH} = \frac{Total\ Claims\ Paid}{Total\ \mathrm{Pr}\, e\, miums\ Earned} \cdot 100$$

In the face of increasing damages, an insurance company can respond by raising premiums to compensate; reducing coverage by including restrictions for certain natural hazards; or exiting the market altogether. Overall, the resulting economic and social effect is the restriction of the availability of insurance contracts, causing greater exposure of assets to financial losses in the event of new natural events. The inability to insure certain assets could also compromise the granting of mortgages by banks, which require borrowers to provide guarantees that may include an insurance obligation (Swiss Re, 2019).

To estimate the insurance premiums earned for coverage related to natural risks in the area of interest, it is possible to follow the steps below:

1. Identify the Real Estate Market Observatory - Agenzia delle Entrate (OMI) areas of the municipalities considered (e.g.: historic center, suburbs, industrial areas).
2. For each OMI zone and each building category:
    a. Calculate the average market value of real estate properties per m^2 (from OMI).
    b. Calculate the total market value of properties knowing
       b1. The total surface area of properties (from regional geoportal or ISTAT, considering footprint area and number of floors): Total zone value: OMI Value per $m^2 \times$ total surface area, or
       b2. The average surface area of properties (from OMI) and the number of properties: Total zone value: OMI Value per $m^2 \times$ average surface areas × Number of properties
3. Add the values of all the zones to obtain the total real estate value of the municipalities: Total value
4. Identify the insurance rate in the municipalities considered (TA): i.e. the percentage of properties insured against natural hazards
5. Identify the average annual premium per property (PMAI): Average amount paid for policies against natural hazards (e.g.: 0.5% of real estate value).
6. Estimated the total premiums earned by zone (PIT_z): PIT_z = Total zone Value × TA × PMAI
7. Add the values of all the zones to obtain the total premiums earned in the municipalities (PIT_{tot})

To quantify the compensation paid (Total claims paid) for damage from natural events in the area of interest, the expected (annual) direct damage estimated in the built environment matrix can be used, multiplied by the insurance rate in the municipalities considered (TA)

Data availability and sources

The available data sources for calculating the discussed indicator include ANIA, IVASS, and the Banca d'Italia. ANIA (Associazione Nazionale fra le Imprese Assicuratrici) provides detailed data on insurance policies, including collected premiums and paid indemnities, which are essential for calculating the loss ratio and the incidence of policies on various categories of natural risks. IVASS (Istituto per la Vigilanza sulle Assicurazioni) offers reports on the insurance market, analyzing the solvency and financial stability of companies, and information on insurance premium trends. The Banca d'Italia contributes with reports on financial stability and studies on the economic impact of natural events, helping to assess the sustainability of the insurance sector and its coverage capacities in case of natural disasters.

NH insurance penetration rate (NHIP)

Another indicator that can be considered at a systemic level concerns the insurance system's capacity to cover the risk of natural events. This can be defined as the natural hazard insurance penetration rate and indicates the actual risk coverage provided by the insurance system. If the rate is low, many assets remain uncovered, increasing systemic risk.

$$NHIP = \frac{Total\ Insured\ Asset\ Value\ for\ NH\ Risk}{Total\ Exposed\ Asset\ Value\ for\ NH\ Risk} \cdot 100$$

Data availability and sources

The data sources needed to calculate the indicator include ANIA, IVASS, and the Banca d’Italia. ANIA provides data on insurance policies, including premiums and indemnities, essential for determining loss ratios and policy impacts on natural risks. IVASS offers detailed reports on the insurance market, including company solvency and premium trends. Banca d’Italia supplies insights into financial stability and the economic effects of natural events. ISTAT provides estimates on the value of real estate and economic activities.

Annual Change NH Insurance Premiums (CNHIP)

A third useful indicator to assess the perception of an increased risk of natural event impacts studies the variation in premiums for natural hazard insurance policies (NHIP) over a standard period (e.g., one year).

$$CNHIP = \frac{NHIPyear_t - NHIPyear_{t-1}}{NHIPyear_{t-1}}$$

If premiums increase significantly after catastrophic events, it can be a signal of heightened risk perception by the companies or financial difficulties in covering the damages.

Data availability and sources

The calculation of the natural hazard insurance penetration rate (NHIP) requires data from several key sources. At a national level, ANIA provides comprehensive data on insurance policies, including premiums and indemnities, which are crucial for assessing loss ratios and the impact of policies on natural risks. IVASS offers detailed reports on the overall insurance market, covering aspects such as company solvency and premium trends, essential for understanding systemic risk coverage. Banca d’Italia supplies valuable insights into financial stability (report sulla stabilità finanziaria) and the broader economic impacts of natural events, while ISTAT provides estimates on the value of real estate and economic activities, which are fundamental for evaluating exposed asset values.

At the regional and municipal levels, the differentiation in datasets aligns primarily with the granularity and specificity of data. Regional data sources may include localized reports on insurance uptake and policy details specific to regional insurers, often segmented by types of natural hazards prevalent in the area. Municipal datasets are typically more focused on the asset values and insurance coverage within the municipality, provided by local insurance entities and municipal records. These datasets are crucial for a precise assessment of NHIP at a granular level, ensuring that localized risks and coverage gaps are accurately identified.

Creditworthiness rating system

In this regard, it is suggested to refer to indices widely used in financial practice.

*Ratio of natural hazard losses to GDP (DLGDP)**

The ratio of natural hazard losses to GDP measures annual economic losses from natural hazards (which derive from physical damage and disruptions) relative to the overall economic output (annual GDP) of the region or country, indicating financial vulnerability and potential downgrade risk for the territory involved (Allen & Gale, 2000).

$$DLGDP = \frac{Regional\ Annual\ Loss\ from\ NH}{RegionalGDP} \cdot 100$$

This indicator offers a direct view of the magnitude of physical damage and disruption relative to the size of the regional economy, thereby serving as a key signal for credit rating agencies when assessing fiscal vulnerability and overall financial stability. It connects physical damage and disruption directly to economic performance, addressing a central aspect in credit risk evaluations (Cantor & Packer, 1996).

Since this indicator could lead to strategic or behavioral changes of firms in the financial system only beyond a certain quantitative threshold, it will only be considered if the following conditions occur separately or at the same time:

- Substantial economic impact: Losses above an absolute threshold (e.g.: € 1 billion) or relative (e.g.: >1% of regional GDP).
- Territorial extension of natural events, or damage recorded to more than 50% of the regional territory

The regional annual loss is equal to the total expected (annual) damage calculated in the built environment and business matrices. National statistics supply regional GDP values.

<u>Data availability and sources</u>

At the national level, the Ministry of Economy and Finance (MEF) and the Italian Civil Protection provide comprehensive data essential for calculating financial indicators. The MEF publishes national debt and fiscal revenue figures in documents like the Medium-Term Budget Structural Plan Italy 2025-2029 and the 2024 Economic and Financial Document (DEF), while ISTAT offers national GDP figures in reports such as the PIL E INDEBITAMENTO AP. The Civil Protection agency regularly reports on the impacts of national disasters.

Regionally, data collection involves collaboration between regional administrations and the Civil Protection to document natural hazard losses. The MEF's Finance Department supplies regional fiscal statistics, including tax revenue figures, and ISTAT releases regional GDP data through territorial economic publications.

At the municipal level, local administrations, sometimes in partnership with regional authorities and Civil Protection, gather and publish data on local natural hazard losses. This multi-tiered data collection system allows for the precise calculation of indicators like the ratio of natural hazard losses to GDP and total fiscal revenues, elucidating the financial vulnerability and sustainability of different regions.

Interest Coverage Ratio (ICR)

The ratio of current revenues to interest expenses measures the ability of a public entity to cover interest expenses with regular revenues (Interest Coverage Ratio or ICR). Specifically, an interest coverage index based on current revenues (CR) is proposed. For assessing NH impacts, the ICR needs to be calculated for the affected area rather than using aggregated national data, since natural hazards often have localized effects (e.g. a decline in local economic activity or an increase in borrowing for reconstruction). Using data from the specific region (or municipality) ensures that the indicator reflects the real impact on the area's fiscal capacity. The CR and the interest expenses on public debt therefore refer to the impacted area.

$$ICR_{IA} = \frac{Current\ Revenues\ (from\ impacted\ area)}{Interest\ Expenses\ on\ Debt\ (for\ impacted\ area)} \cdot 100$$

This indicator measures the ability of a regional public entity to cover its interest expenses using its regular (current) revenues, serving as a proxy for operating income in public finance. A natural hazard can lead to a reduction in operating income (i.e., current revenues) due to disrupted economic activities, while simultaneously prompting the affected area to incur additional debt to finance recovery. Both effects would drive the ICR down, indicating reduced fiscal resilience and higher vulnerability to debt service difficulties.

Data availability and sources

For the calculation of the discussed indicator, data is sourced from various levels. At the national level, the "Simplified State Budget" provides an overview of state revenues and expenses, including current revenues and financial charges, accessible at rgs.mef.gov.it. Moving to the regional level, Italian regions publish their budgets, offering detailed information on current revenues and interest expenses, which are available on the official websites of the individual regions. At the municipal level, Italian municipalities also offer their budgets, containing data on current revenues and financial charges, accessible on their respective official websites. Additional sources include the Public Administrations Database (BDAP), managed by the Ministry of Economy and Finance. BDAP grants access to budget data of territorial entities, including regions and municipalities. Through the OpenBDAP portal (openbdap.rgs.mef.gov.it), users can analyze and compare financial data of these entities. Furthermore, the National Institute of Statistics (ISTAT) publishes reports on public finance, including data on revenues and expenses of local entities.

Public Debt-to-GDP Ratio in NH-Affected Regions / Disaster-Adjusted Debt-to-GDP Ratio (DADDGR)

We propose two alternative indicators where the second one is to be preferred to the first one, when data are available and updated. Both can be calculated by referring to the same data sources.

Public Debt-to-GDP ratio (PDGDP) in NH-affected regions

Debt-to-GDP ratio relates a country's total public debt to the value of its Gross Domestic Product (GDP). It provides a measure of the debt's size relative to the productive capacity of the economy. We propose here the Public Debt-to-GDP Ratio in NH-Affected Regions (%).

$$PDGDP_{NH} = \frac{Total\ Public\ Debt\ in\ NH - Affected\ Regions}{Regional\ GDP} \cdot 100$$

A high value of the index indicates that the debt is large in relation to the economy, which might suggest greater difficulty for the country in sustaining debt service (interest payments and principal repayment) without compromising economic growth.

Disaster-Adjusted Debt-to-GDP Ratio (DADDGRNH)

Integrates the debt-to-GDP ratio with estimated costs of natural hazard damages, illustrating better debt sustainability amid environmental shocks. This index reflects the additional debt burden due to reconstruction and fiscal support costs, potentially necessitating a downgrade if significantly increased. The required data for calculation are readily accessible, but estimating damage costs at various administrative levels is essential.

$$DADDGR_{NH} = \frac{Total\ Regional\ Public\ Debt + Total\ reg.\ econ.\ losses\ from\ NH}{Regional\ GDP} \cdot 100$$

Both the ICR_{CR} index and all the Debt-to-GDP ratios are sensitive to variations in economic production levels connected to the impacts of natural events. These values are regularly monitored by rating agencies, which allow them to modify their assessments regarding the economic prospects of a country or territory, influencing the assigned rating (upgrade, downgrade).

Data availability and sources

At the national level, the Ministry of Economy and Finance (MEF) publishes national debt data in the Medium-Term Budget Structural Plan Italy 2025-2029 and the 2024 Economic and Financial Document (DEF). ISTAT regularly provides national GDP figures, particularly in the PIL E INDEBITAMENTO AP report. The Italian Civil Protection collects and publishes data on national disaster impacts.
Regionally, data on natural hazard losses is available through regional administrations in collaboration with Civil Protection. ISTAT offers regional GDP data in its territorial economic publications, while the MEF's Finance Department provides regional fiscal statistics, including tax revenue data.
At the municipal level, local administrations, often working with regional authorities and Civil Protection, gather data on local natural hazard losses.

Non-financial indicators

Non-financial indicators that contribute to the rating definition include evaluations of the management capacity of local and national governments and the availability of high-quality development plans, civil protection, or crisis response strategies. Several studies have investigated the impact of natural disasters on regional ratings, placing pressure on key assets and infrastructure, which can lead to a downgrade, resulting in higher interest on public debt (Haiti, 2010). In other cases, the slow recovery to pre-crisis production levels and increased fiscal pressure to finance reconstruction have caused a country's downgrade. Similar effects are observed in cases of events causing numerous casualties and severe damage to critical infrastructure (Myanmar, 2008). On the other hand, the presence of adequate plans and policies has accelerated recovery and protected ratings from downgrades following natural hazards.

Generally, local and national impacts differ in response to the same natural hazards, with sometimes intense effects on the local economic fabric but insignificant at the national level. This can lead to a systematic underestimation of local impacts in the rating expressed for a state.

Several indicators can link the impact of natural hazards to rating adjustments:

Ratio of natural hazard losses to total fiscal revenues

The ratio of natural hazard losses to total fiscal revenues measures the impact of natural hazard losses on fiscal capacities, influencing financial sustainability and investment and public spending capabilities.

$$DLTFR = \frac{Regional\ Annual\ Loss\ from\ NH}{Regional\ Revenues\ from\ Taxes} \cdot 100$$

Data availability and sources

To accurately calculate financial indicators related to natural hazard losses, data is meticulously gathered from various administrative levels in Italy. At the national level, the Ministry of Economy and Finance (MEF) provides essential financial data such as national debt, fiscal revenues, and comprehensive national GDP figures sourced from documents like the Medium-Term Budget Structural Plan Italy 2025-2029 and the 2024 Economic and Financial Document (DEF). Additionally, the Italian Civil Protection agency is instrumental in reporting the impacts of national disasters, contributing critical data for these calculations.

Regionally, collaboration between regional administrations and the Civil Protection agency ensures the comprehensive documentation of natural hazard losses. The MEF Finance Department supplies regional fiscal statistics, including tax revenue figures, while ISTAT releases regional GDP data through its territorial economic publications. This regional data is vital for understanding the fiscal impact of natural hazards within specific territories.

At the municipal level, local administrations, often in partnership with regional authorities and Civil Protection, collect and publish data on local natural hazard losses.

Change in regional rating by Credit Rating Agencies (CRR)

Credit Rating Agencies (CRAs) use regional credit ratings to gauge the financial impact of natural hazards. These ratings reflect economic fundamentals, fiscal health, and risk exposure. Natural hazards can lower economic growth, decrease fiscal revenues, increase public debt, and create uncertainty, which CRAs consider in their assessments. This indicator directly captures revisions by CRAs due to altered fiscal and economic conditions after NH events.

Credit ratings are typically expressed in qualitative terms (e.g., AAA, AA+, etc.), so for quantitative analysis you can convert these ratings into numerical values (using a conversion table—for instance, assigning AAA = 1, AA+ = 2, …, with higher numbers indicating a lower rating). CR_{pre} refers to the numeric rating value before the natural hazard event, CR_{post} to the numeric rating after the natural hazard event. M represents a normalization constant representing the maximum possible downgrade (or the span of the rating scale, e.g. for scores from 1 to 10, M=9). Then, the change in rating due to an NH event is defined as follows:

$$\Delta CR = \frac{CR_{post} - CR_{pre}}{M}$$

The limit of the indicator rests in the common inability of CRAs to fully consider the impact of NHs and natural disaster on the financial fundamentals of a country or a region after localized events.

Data availability and sources

Regional ratings by credit rating agencies can be retrieved from major agencies (Moody's, Fitch Ratings, and S&P Global Ratings) that routinely publish reports, press releases, and rating updates for both national and subnational entities. The Ministry of Economy and Finance (MEF) and related public agencies, including at the regional level, sometimes publish aggregated analyses or reports that include subnational credit assessments.

Datasets and sources for Italy

The table below lists key variables for calculating indicators that measure natural hazards' impact on the financial system. It includes variable names, recommended data sources (municipal, regional, or national), and URLs to the databases. For municipal-level data, proxies such as local income data or budget reports can be used if direct variables like GDP are unavailable. When multiple sources are listed, choose based on the specific indicator and required granularity. When the same variables are used for different indicators, we use *italic*.

Indicator Category	Variable Name	Data Source (Level)	URL
Banking System (CVDR – Collateral Value Depreciation Rate)	*Estimated value reduction in real estate assets due to NH risk*	Agenzia delle Entrate – Osservatorio del Mercato Immobiliare (OMI) (National, Regional, Municipal – where available)	Agenzia delle Entrate OMI
Banking System (CVDR)	*Total real estate market value in the area*	Agenzia delle Entrate – OMI (National, Regional, Municipal)	Agenzia delle Entrate OMI
Banking System (CCR – Collateral Coverage Ratio)	Outstanding loan amount in NH-exposed sectors	Banca d'Italia – Supervisory Statistics (National and Regional)	Banca d'Italia Statistics
Banking System (CCR)	Collateral value (e.g., real estate used as security)	Agenzia delle Entrate – OMI (National, Regional, Municipal)	Agenzia delle Entrate OMI
Insurance System (LRNH – Loss Ratio for Natural Hazards)	Total claims paid for natural hazard damage	IVASS (Istituto per la Vigilanza sulle Assicurazioni) or ANIA (National; Regional data may be available through local reports)	IVASS ANIA
Insurance System (LRNH)	*Annual NH insurance premiums*	ANIA (National, with some regional breakdowns)	ANIA
Insurance System (NHIP – NH Insurance Penetration Rate)	Value of insured assets against NH risks	ANIA (National and Regional)	ANIA
Insurance System (NHIP)	Total value of assets exposed to NH risks	ISTAT – Economic and Asset Data (National, Regional)	ISTAT
Insurance System (CNHIP – Annual Change in NH Insurance Premiums)	*Annual NH insurance premiums*	ANIA or IVASS (National; regional details available in specific reports)	ANIA IVASS

Rating System (ICR – Interest Coverage Ratio in Public Finance)	*Current revenues or Total Fiscal revenues*	MEF (Ministero dell'Economia e delle Finanze) for national data; BDAP (Banca Dati delle Amministrazioni Pubbliche) for regional/municipal budgets	MEF Open BDAP
Rating System (ICR)	Interest expenses (annual interest payments on debt)	MEF and local budget documents (National, Regional, Municipal)	MEF
Rating System (DGR – Public Debt-to-GDP Ratio in NH-Affected Regions)	*Total public debt*	MEF and Banca d'Italia – Public Debt Publications (National; regional details available)	MEF Banca d'Italia – Finanza Pubblica
Rating System (DGR)	*GDP*	ISTAT – National and Regional GDP Data (National, Regional)	ISTAT
Rating System (DADDGR – Disaster-Adjusted Debt-to-GDP Ratio)	*Total economic losses from natural hazards*	Protezione Civile (National; regional data may be available from local emergency management reports)	Protezione Civile
Rating System (DADDGR)	*Total public debt*	MEF/Banca d'Italia (as above)	MEF Banca d'Italia – Finanza Pubblica
Rating System (DADDGR)	*GDP*	ISTAT (as above)	ISTAT
Rating System (DLGDP – Ratio of Natural Hazard Losses to GDP)	*Total economic losses from natural hazards*	Protezione Civile (aggregated loss data) (National; regional loss data available through regional reports)	Protezione Civile
Rating System (DLGDP)	*GDP*	ISTAT (as above)	ISTAT
Rating System (DLTFR – Ratio of Natural Hazard Losses to Total Fiscal Revenues)	*Total economic losses from natural hazards*	Protezione Civile (National; some regional data may be provided in local reports)	Protezione Civile
Rating System (DLTFR)	*Current revenues or Total Fiscal revenues*	MEF – Fiscal data (National; regional/municipal fiscal data available via BDAP or local budget documents)	MEF
Rating System (ΔCR)	*Regional and country assessments for Italian credit ratings*	MEF – Fiscal data (National); Regional/municipal fiscal data, Rating agencies websites and reports	MEF Moody's Fitch Ratings S&P Global Ratings

3.3.8 Selection Rules

Overall, 65 impacts and 130 indicators are included in the H-I matrix covering different dimensions of risk. For each impact, one or more indicators are defined for its quantification.

For each indicator, the H-I matrix specifies (i) the unit of measurement; (ii) the model to be adopted for its calculation together with the hazard, exposure, and vulnerability data required; (iii) the spatial scale at which the model operates and, consequently, at which the indicator is calculated, (iv) the hazard for which the model has been developed and is applicable. 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.

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); consequently, indicators are not defined for hazard–impact combinations that are not meaningful. In addition, the level of scientific knowledge regarding damage mechanisms and, consequently, the availability of models 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. Finally, 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.

These limitations hinder the objective of the matrix to support applications across multiple hazards, impacts, and spatial scales in a consistent manner, namely through the use of comparable and homogeneous indicators. To address these limitations and ensure consistency, specific "selection rules" were defined and reported in the last column of the matrix. These rules identify the appropriate indicator to be applied for each impact, depending on the hazard considered and the spatial scale of analysis. For example, in case of co-existence of flood and seismic risk, physical damage to residential buildings can be assessed in terms of "expected economic damage", since both flood damage models and seismic consequence and fragility functions are available in Italy, at the individual or census block level. In contrast, physical damage to industrial and commercial buildings can only be evaluated in terms of "expected annual value of exposed buildings", as consequence and fragility functions are available for seismic risk, whereas flood damage models for these building categories are not currently available in Italy.

4 Conclusion remarks

The tools developed in Task 7.2.2 provide a robust foundation for evaluating the risk reduction potential of mitigation measures within a multi-hazard context, forming the core of the MCA. Specifically, the Abacus of Measures offers guidance on the appropriate spatial and temporal scales for risk analysis and identifies which hazards must be considered for each mitigation measure. In parallel, the Hazards-Impacts Matrix supports a comprehensive estimation of expected impacts, both before and after the implementation of each measure (Figure 10). Notably, the matrix incorporates dimensions that are often overlooked in previous studies, including direct and indirect, tangible and intangible damage affecting communities, the environment, and financial systems. Such a result has been achieved thanks to interdisciplinary research efforts.

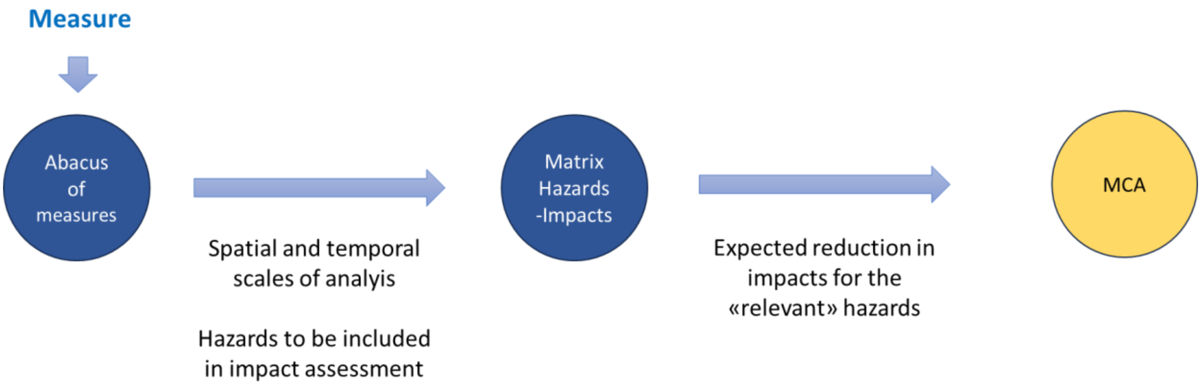

Figure 10. Schematic representation of the steps leading to the definition of risk reduction associated with a reduction measure.

However, in the current context of climate change and constrained investment resources, these tools can only address part of the complex challenge at hand. Today, effective risk mitigation requires the adoption of integrated strategies that simultaneously reduce risks across multiple hazards while promoting economic, social, and environmental sustainability. As a result, decision-making processes must extend beyond the evaluation of direct impacts on risk levels. They must also consider the broader range of benefits and trade-offs that proposed measures may bring to the affected communities.

Moreover, as emphasized in the introduction, additional operational steps must be carefully designed to enable a sound prioritization of risk reduction strategies through MCA. These include the identification and incorporation of stakeholders' objectives, values, and dimensions into the MCA framework, as well as the calibration of the tool's parameters accordingly. A thorough assessment of the uncertainties characterizing the various elements of the MCA, accompanied by a targeted sensitivity analysis, is also essential.

These aspects, together with the identification of additional attributes not directly related to risk reduction but nonetheless considered relevant by decision-makers, will be addressed in Task 7.2.3.

The usability and applicability of the whole MCA process will be demonstrated through their implementation in a case study as part of Task 7.2.4.

5 Links

The following links, which are hosted on the Zenodo repository, provide access to the Excel files for i) the matrix hazards-impacts and ii) the abacus of measures:

i) https://doi.org/10.5281/zenodo.18385185
ii) https://doi.org/10.5281/zenodo.18378884

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