

Multi-hazard risk assessment at territorial level: proposal of a methodology and related application

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Abstract

The study addresses the complex issue of multi-risk assessment in multi-hazard contexts. A methodological approach has been specifically developed to support Civil Protection planning across wide areas. The methodology includes cascading and compound interactions among natural hazards, including earthquakes, landslides, floods, avalanches, forest fires, and dam-break. Population, built environment, mobility systems, and strategic and relevant facilities for Civil Protection purposes are considered as exposed elements; for each, the presence and specific dimensions are evaluated, and metrics to obtain exposure measures are defined. A semi-quantitative, deterministic approach has been adopted, in a complete procedure, despite the current methodological and data barriers (data availability, dynamic vulnerability, etc.). The entire assessment process has been implemented within a GIS project, providing a flexible tool. At each step of the procedure, the relevant elements' values are assigned and then elaborated, considering the different possible overlays, in minimum cartographic units defined as hexagonal cells. In each cell, the multi-hazard, exposure, and multi-hazard risk levels are measured and collected, enabling further elaborations and/or representations of the elements that respond to specific user needs. Multi-hazard risk assessment is achieved by combining multi-hazard and exposure using a dedicated matrix. The methodology was tested across different areas of the Lombardia region, enabling the identification of its strengths and weaknesses. This study introduces a novel approach that sets the stage for future enhancements through further integrations and improvements.

Keywords: multi-hazard, exposure, multi-hazard risk, GIS, wide areas

1- INTRODUCTION

Many global disasters result from seismic events interacting with other phenomena, either through cascading processes, where one event triggers others, or through independent events occurring simultaneously. Recent examples, such as the 2023 Türkiye earthquake, which caused landslides, liquefaction, and floods, or the 2025 Cebu earthquake, which led to slope failures, ground deformation, and power outages, show that earthquakes should not be considered solely as single events but as potential drivers of complex multi-hazard scenarios, in which natural and technological processes interact across space and time, amplifying disaster impacts [1]. Therefore, it is nowadays necessary to shift toward integrated multi-hazard and multi-risk frameworks that combine hazard characterization with exposure and vulnerability analyses [2, 3, 4]. But, despite international guidelines and policies for Disaster Risk Reduction (DRR) providing a global framework for multi-risk assessment, existing methodologies still reveal limited knowledge of the dynamic interactions among hazards, exposure, and vulnerability, which are crucial for an effective Disaster Risk Management (DRM) [5, 6, 7, 8].

Within this perspective, the present work proposes a methodological approach for multi-hazard risk assessment aimed at supporting Civil Protection planning at a wide scale. The methodology was developed within a collaborative research activity carried out with Lombardia Region, in the context of institutional initiatives aimed at strengthening the knowledge base available for Civil Protection planning and emergency management. The objective of the approach is to provide decision-makers with a spatially explicit framework capable of identifying areas characterized by different levels of multi-hazard risk, taking into account both the potential occurrence of multi-hazardous phenomena and the distribution of exposed elements within the territory. In the present study, the analysis considers several natural hazards that may interact with seismic events and influence territorial risk conditions, including floods, landslides, avalanches, wildfires, and hydraulic hazards associated with potential dam-break scenarios. These hazards were selected based on their

relevance for the regional context as in Lombardia region (northern Italy) [9] and on the availability of spatial datasets suitable for regional-scale analyses. In addition to multi-hazard characterization, the methodology explicitly incorporates exposure analysis, considering the spatial distribution of the population, buildings, infrastructure networks, and strategic facilities relevant to Civil Protection activities. The integration of multi-hazard and exposure layers enables the identification of areas characterized by different levels of potential impact, providing a synthetic representation of territorial multi-hazard risk conditions. The methodological framework is illustrated through application examples in the Lombardia, where the approach has been implemented to support Civil Protection authorities in both planning activities and emergency preparedness strategies. Through these examples, the paper discusses the potential of the proposed methodology to improve the understanding of territorial risk conditions and to provide operational support for multi-risk management, particularly in areas where seismic hazard interacts with other natural processes.

2- SCIENTIFIC BACKGROUND

According to extensive literature [2, 3, 8, 10-13], the “multi-risk” concept captures the combined effects of multiple hazards and their spatial and temporal interactions. As highlighted by Zschau (2020) [3], analyzing such hazard interactions is inherently more complex than traditional hazard-by-hazard approaches, requiring advanced capacities for modeling and assessment that are not yet fully developed in DRM systems. To address this challenge and support Disaster Risk Management (DRM), several European projects (PARATUS, MYRIAD, MEDIATE, MATRIX, ARMONIA, ENSURE) have implemented multi-risk assessment methodologies, using qualitative, semi-quantitative, or quantitative approaches, employing probabilistic models or cause-effect matrices (“hazard matrices”). Among all, Gill and Malamud (2014) [11] offer a useful starting point for hazard interaction classifications, covering independent events like tropical cyclones and earthquakes, as well as cascading effects such as landslides triggered by floods or fires after earthquakes. Liu et al. (2015) [12] propose a three-level framework for multi-risk assessment, integrating hazard analysis, exposure, and vulnerability, providing a systematic and modular approach that can enhance both risk understanding and management strategies. Moreover, operational tools like multi-risk maps are increasingly in demand as they play a crucial role in visualizing and quantifying the potential impacts of multiple hazards, including loss of life, injuries, and infrastructure damage [14-16].

Comprehensive multi-risk assessments have to consider a range of physical, environmental, social, economic, and cultural factors, including urbanization, climate change, and poverty, which can influence both exposure and vulnerability [17]. However, despite international guidelines and policies for Disaster Risk Reduction (DRR) and Disaster Risk Management (DRM), providing global frameworks for multi-risk assessment, they still reveal limited knowledge of the dynamic interactions among hazards, exposure, and vulnerability, which are crucial for effective DRM [7, 8]. The dynamic nature of exposure and vulnerability in driving damage from multiple hazards remains underexplored, and in many cases, these factors are treated as static. Furthermore, there is a widespread lack of comprehensive data sources and analytical tools, particularly regarding physical, socio-economic, and systemic aspects of vulnerability [3, 18].

3- METHODOLOGY: DESCRIPTION AND APPLICATION

Within the presented research context, a methodology [19] was developed to provide an operational tool responding to a defined frame of assumptions and requirements. A complete elaboration was implemented, from multi-hazard to multi-risk, despite the awareness of current barriers related to data, models, and definitions. The outcomes, in each step, have then clear reliability characteristics in a transparency perspective.

A particularly relevant barrier was related to vulnerability assessment due to the lack of available methodologies and data. For all the exposed elements, a constant and conventional value equal to “1” was assigned to the vulnerability, considering a 0–1 range (continuous scale). A range where “0” means the best vulnerability condition and “1” the worst one; in this way, the approach can be considered as conservative. Consequently, in the proposed methodology, according to the definition by Zschau [3], the multi-risk can be considered as a multi-hazard risk: “Risk in a multi-hazard framework - No interactions on the vulnerability level”.

The main assumptions can be resumed in the following:

- a deterministic and semi-quantitative approach was adopted; no occurrence probability was assigned to the involved parameters in the different steps;
- data derive from existing official studies (e.g. from the Lombardy Geoportal [20], floods: hazardous area of the rivers and secondary water bodies, derived from the Flood Risk Management Plan (PGRA); landslides: derived from the hydrogeological plan (PAI). For the earthquakes: municipalities’ seismic

classification derived from the DGR Lombardia 2129/14 [21]. Built environment characteristics and population from the Lombardy Geoportal [20] and census data ISTAT 2011 [22]);

- 1:10.000 was fixed as reference scale;
- hexagonal cells (side length of 50m) constituted the adopted minimum cartographic units [23]. The original or elaborated data are then assigned to each cell, avoiding possible graphical problems of the source data, and properly representing the “real” elements (e.g. buildings, landslides, etc.);
- the measure of data are classified in three levels: “low”, “medium”, and “high”. The levels are translated in numbers to facilitate their elaboration and representation: “low” in “1”, “medium” in “2” and “high” in “3”;
- all the steps of the procedure were implemented in a GIS project.

The methodology consists of three main phases:

- 1) Multi-hazard assessment;
- 2) Exposure assessment;
- 3) Multi-hazard risk assessment.

3.1 Multi-hazard assessment

The multi-hazard assessment must include the knowledge of all the different hazards possibly occurring in a given area, in terms of hazard maps, and their relations: spatio-temporal and cascading [12, 13, 20]. In the proposed methodology, if there are both spatial and temporal overlays, the number of overlaid hazards is counted. Then, the potential hazard interactions are checked, if present (compound hazards), the number of interactions is counted too. At the end, the multi-hazard result is a score, obtained by the sum of the overlaid hazards number and of the hazards interactions number.

These steps were then applied in some areas of Lombardia region. In figures 1, 2, 3 the illustration of this procedure, related to a part of the studied area, is presented. In figure 1 it is possible to observe as the basic data about river flood (a) is assigned to the cells (b) and then, the “presence” (value equal to “1”) is assigned to a cell if the overlaid area exceeds a fixed minimum threshold.

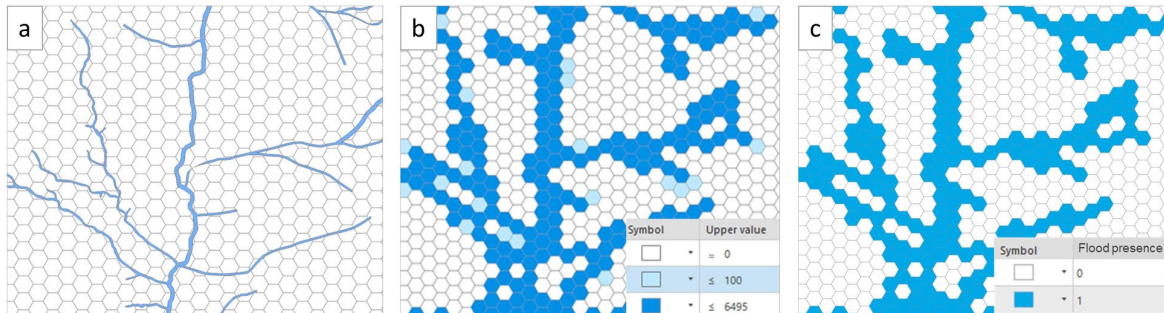


Figure 1- Hazard “presence” assignment to each cell [19]

After the application of the steps in Figure 1 to all the hazard possibly occurring in the area, the spatial overlay score in each hexagonal cell is calculated by the sum of the related “presences”.

The potential hazard interactions are then checked and counted by the application of an interaction matrix (adapted by Liu et al. [12]) shown in Figure 2. It allows identifying, in pairs, the hazards having in theory a cause-effect interaction. In case of influence of the hazard H_i on the hazard H_j (left to right arrows) and/or, vice versa, a value equal to “1” is written in the matrix, otherwise, the value “0” is written. The matrix has to be applied considering all the hazards present in each hexagonal cell, and the hazards interaction score is obtained by the sum of all the interactions.

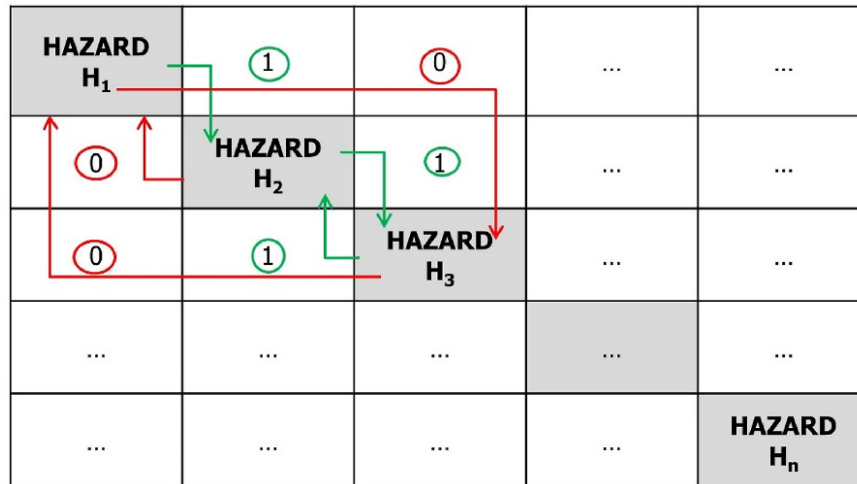


Figure 2- Interaction matrix [19]

In figure 3, then, it is possible to observe the assessment of the multi-hazard score in each hexagonal cell, by the sum of the spatial overlay score and of the interaction score. The multi-hazard map is represented in terms of the three levels (high, medium, low); their numerical levels definitions are fixed adopting a conservatory criterion (small low range and wide high range) and considering the multi-hazard scores obtained in the different case studies. It is important to note that the final multi-hazard score represents the number of hazards in each cell, and does not quantify the severity level of the hazards.

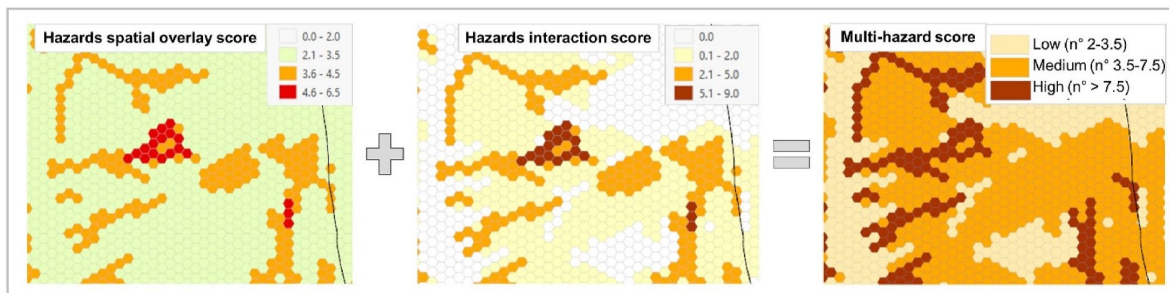


Figure 3- Multi-hazard score calculation in each hexagonal cell. [19]

The hazards contributing to the final score are not directly visible in the multi-hazard map, nevertheless, this information is maintained in the GIS project which layers can be queried, so the “history” of each hexagonal cell can be retrieved.

3.2 Exposure assessment

The exposure assessment consists of a quali-quantitative evaluation of the presence of different territorial elements in the analysed area. The carried study considers a) population, b) built environment, c) mobility system, and d) strategic and relevant facilities for civil protection purposes. The methodology implies a singular evaluation of each type of exposed elements and their classification in “high”, “medium” and “low” levels which are later used to obtain the total exposure level.

Precisely the procedure, according to the available data, entails the following:

- **Population:** the exposure level of the population is measured in terms of number of people potentially present in each cell. For the residents, the number of people in each residential building, real or estimated, obtained from the census or from other demographic databases is considered. By the overlay of residential buildings and the tessellation layers, the estimated number of people in each cell is estimated. For the non-resident population, the number of people in each cell is calculated considering the number of beds available in accommodation facilities, assuming a full occupation of all the facilities. It would be advisable to account in the non-resident population also the number of commuters if the data would be available;
- **Built environment:** it includes the buildings independently of the related urban functions (residential, commercial, industrial, etc.). First, the buildings volumes are calculated and then, overlaying the buildings

and the tessellation layers, the volumes in each cell are summed up. The total volume is then divided by the cell area, obtaining the volumetric density in each hexagonal cell (m^3/m^2);

- Mobility system: roads, railways, and underground networks are separately considered. The exposure measure is evaluated in terms of lines length (m) in each hexagonal cell, independently on their importance or characteristics. Through the overlay of the infrastructure layer and tessellation layer, the sum of the lengths of the line segments in each cell is calculated (Figure 5).
- Strategic and relevant facilities: the presence of buildings considered strategic for their function during the emergency phase and/or relevant for their crowding level is assessed. They are considered singularly, and they are punctually represented in the exposure maps without assigning them to the cells, due to their intrinsic importance in a territory affected by hazards.

The assessment of the exposure levels above described, implemented in the GIS, allows carrying out thematic maps for each category of exposed element, or, for the total exposure (all the elements at the same time).

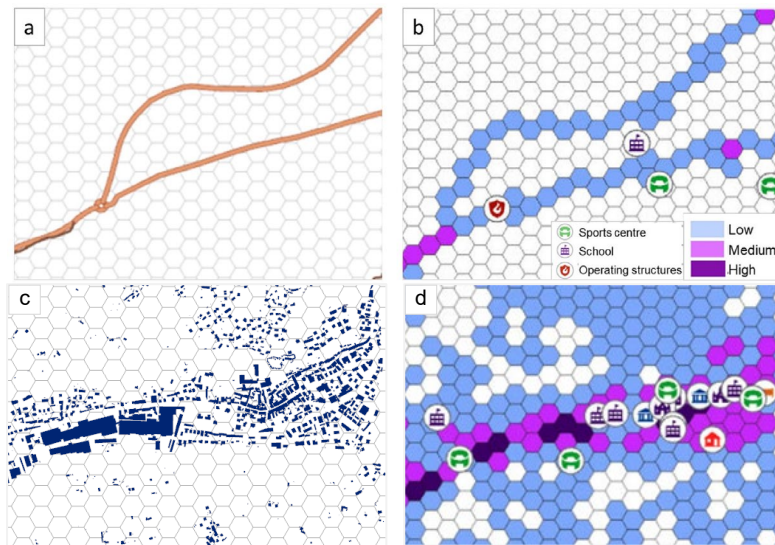


Figure 4 - Example of construction of mobility system (a, b) and built environment (c, d) exposure maps [19]

3.3 Multi-hazard risk assessment

The third phase of the methodology consists of the multi-hazard risk assessment for each hexagonal cell. The approach is based on the application of a specifically designed matrix allowing the combination of the previously calculated multi-hazard and exposure levels (Figure 5). The matrix has a non-symmetric structure, adopting a precaution-oriented criterion in each combination. For instance, the “low” value is assigned only for the low-low case; the “high” value is assigned for the high-medium cases too.

The final outcome is classified as “low”, “medium”, “high”, but, in this case, being the result of a logic combination, there are no numeric ranges defining the levels. This combination, however, leads to an increased knowledge of the territory, compared to consider hazards and exposure singularly or just overlaid.

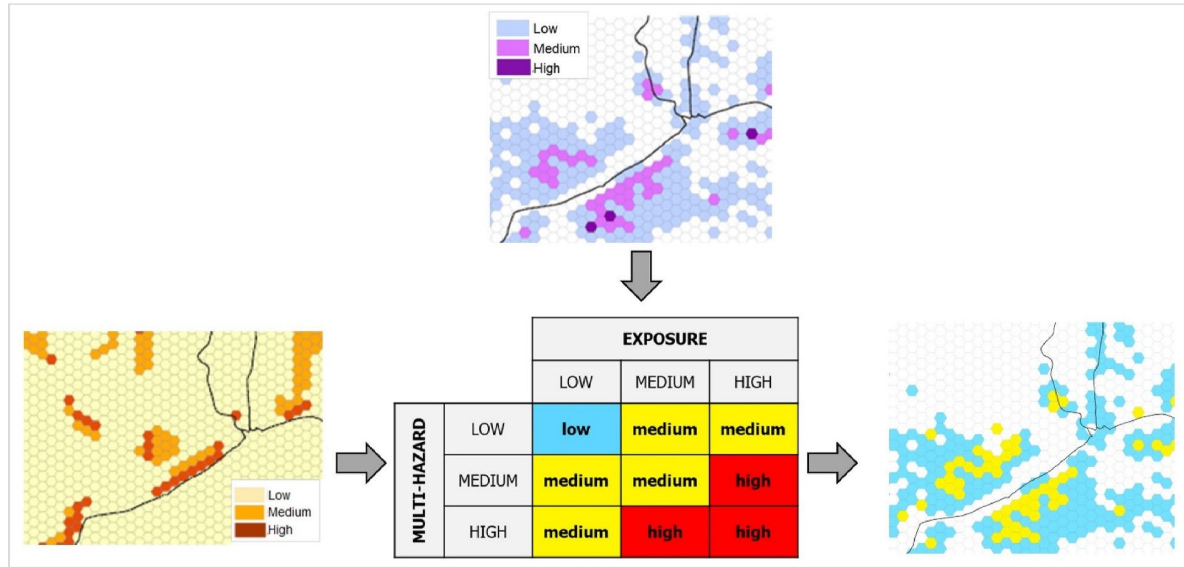


Figure 5- Multi-hazard risk assessment [19]

In the GIS project, in addition to the cartographic visualization, it is possible to query each hexagonal cell, obtaining the entire set of information at the base of the final result: levels of exposure, multi-hazard and multi-hazard risk (Figure 6).

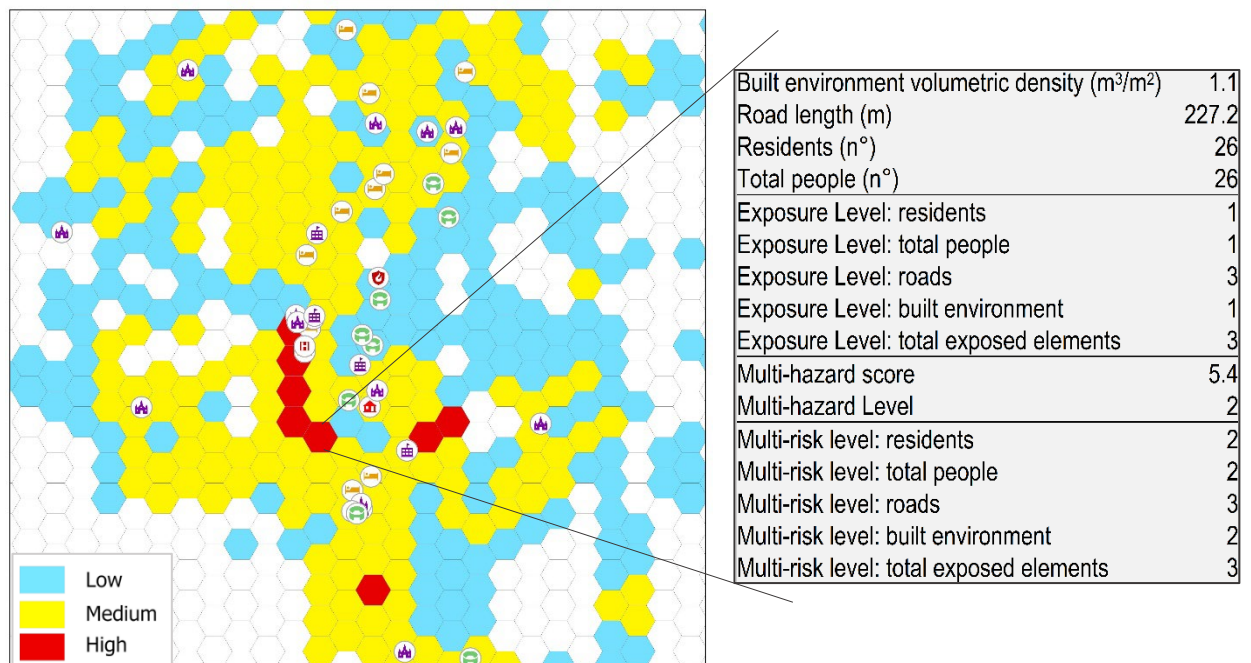


Figure 6- Example of multi-hazard risk map and related GIS information in a cell [19]

4- DISCUSSION AND CONCLUSIONS

The presented methodology allows determining a multi-hazard risk measure considering also the possible interactions among different hazards.

The objective and context of the study bring to a semi-quantitative measure of multi-hazard risk, in a minimum cartographic unit, as combinations of multi-hazard levels considering the hazards “presence” (the severity levels of the hazards are not quantified) and exposure levels.

This methodology and its applications present strengths, limitations, and possible improvements. In the following, the main aspects are resumed:

- the present research has its initial purpose in the field of Civil protection planning in wide areas, the results enhance the knowledge, although as initial approximation, of the multi-hazard and multi-risk of an area. This allow the stakeholders to be aware of the complexities of the different territories and take more suitable decisions in the planning phase;
- the proposed approach has the advantage of allowing the combined use of data derived from different hazard measures (e.g.: hazard maps related to flood and earthquakes) and exposure measures (e.g.: roads, people, buildings) to obtain a significant final result;
- data quality, reliability, granularity and availability, influence the level of applicability of the procedure and the type and usability of the outcome;
- the procedure structure and GIS implementation make it flexible and adaptable to different context in terms of hazards, territories, scales, etc., and in terms of possibilities to upgrade each single step of the procedure;
- the introduction of a complete vulnerability model in this framework, could be a possible future development;
- the inclusion in the process of the hazards severity quantification could improve the completeness of the outcomes.

A multi-hazard risk approach becomes relevant in seismic studies for both pre- and post-event strategies, earthquakes rarely occur in isolation and pre-existing conditions might amplify the impact of the seismic hazard. Adopting a multi-hazard approach is essential for achieving a more realistic, comprehensive picture of risks. Following the growing need for tools and methods to assess risk from different phenomena, the proposed methodology becomes an operative and easily adaptable toolkit for determining more appropriate assessments of areas that might present multi-hazard and multi-risk complexities.

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