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Development of a multi-risk index for Italy: a tool for supporting informed decision making on disaster risk reduction prioritisation

Gabriella Tocchi
PhD student, Department of Structures for Engineering and Architecture, University of Naples Federico II, Naples, Italy

Gemma Cremen
Assistant Professor (Lecturer), Department of Civil, Environmental and Geomatic Engineering, University College London, London, UK

Carmine Galasso
Professor, Department of Civil, Environmental and Geomatic Engineering, University College London, London, UK

Maria Polese
Associate Professor, Department of Structures for Engineering and Architecture, University of Naples Federico II, Naples, Italy

ABSTRACT: Effective disaster-risk management decision making relies on holistic multi-risk quantification approaches. Such approaches should capture the effects of multiple (natural) hazards, facilitating the development and implementation of appropriate preparedness and mitigation strategies. They should also account for social vulnerability factors, which may significantly influence how different communities respond to and cope with hazardous events. We propose a straightforward multi-risk index that integrates both of these crucial considerations. The index appropriately accounts for uncertainties, relying on probabilistic distributions of hazard inputs, physical and social vulnerability indices, and population exposure for each individual risk of interest. The resulting individual risk scores are combined through suitable weights that explicitly reflect variable stakeholder perspectives in related policymaking. We demonstrate the index for earthquake and flood risk across the entire country of Italy (at the resolution of municipalities) using easily accessible data. The proposed metric identifies hotspots across the Italian territory that should be prioritised for actions that promote disaster risk reduction. Sensitivity analyses of metric weights reveal how these hotspots can change as a function of stakeholder preferences and/or variations in the emphasis placed on different types of hazards, ultimately underlining the importance of accounting for accurate stakeholder feedback and adopting a holistic view of risk in disaster-related decision making. A prominent advantage of the proposed index is that it is relatively simple and could be easily adopted for practical multi-risk decision support across any other national or transnational context of interest.

1. INTRODUCTION

Quantifying the potential magnitude of societal consequences resulting from natural-hazard events is a crucial step in the disaster risk management cycle, supporting the design of suitable impact-mitigation strategies (policies). As many regions of the world are exposed to multiple, often interacting, hazards (e.g., Durham, 2003; Marzocchi et al., 2012; Gill and Malamud, 2014; Dabbeek and Silva, 2019), this type of analysis should jointly consider all risks that may affect the same area. A multi-layer single-hazard approach is often used to analyse the risks of two or more (in principle independent) hazards (e.g., Zchau, 2017), which involves spatially superimposing hazard layers to identify areas where hazards overlap. While this type of approach neglects interrelations between hazards (e.g., Iannacone et al., 2023; Otarola et al., 2023), reducing its dependability, it is straightforward, enables many hazards to be considered, and produces results that are easy to understand. Nevertheless, such multi-hazard/multi-risk modelling can be challenging, particularly at large geographic scales, because it is not necessarily clear how the quantification of each underlying individual hazard/risk should be aggregated or combined (e.g., Marzocchi, et al., 2009, Kappes, et al., 2010). This challenge is compounded by the fact that different hazards vary by nature in terms of their local intensities within a prescribed return period and their corresponding effects on exposed elements.

Furthermore, it is well known that the impacts of hazard events are not equally distributed within society (e.g., United Nations Office for Disaster Risk reduction; UNDRR, 2015). Social vulnerability factors (e.g., age, gender, ethnicity, education, employment status and income) can influence how people respond to and cope with hazard events (e.g., Cutter and Finch, 2007). Thus, disaster risk assessments should consider social as well as physical exposure and vulnerability information to ensure that related decision making is as effective as possible. However, conventional risk analyses typically fail to account for diverse socioeconomic and demographic risk drivers.

We propose a straightforward multi-risk index that addresses the aforementioned challenges and limitations across large spatial areas, identifying "multi-risk hotspots" that should be prioritised in terms of disaster risk reduction actions. The proposed Risk Index (RI) combines individual standardised indicators for multiple hazards, as well as physical and social exposure and vulnerability inputs. The combination of individual risk scores integrates suitable weights that explicitly reflect stakeholder risk priorities related to policy (or more general) decision making. The RI also appropriately accounts for uncertainties, relying on probabilistic distributions of hazard information, physical and social vulnerability indices, and population exposure for each individual risk of interest. We demonstrate the index through an application to earthquake and flood risk across the entire country of Italy at a municipal level, illustrating the importance of incorporating stakeholder perspectives and a holistic view of risk in disaster-related decision making.

2. RISK INDEX CALCULATION

2.1. Background

Index-based approaches are particularly suitable for modelling multidimensional concepts (e.g., De Groeve et al., 2015). They have been adopted in various practical applications, including to measure the development level of a country (United Nations Development Programme; UNDP, 2020), community resilience (e.g., Bruneau et al., 2003; Marin Ferrer et al., 2017), and social vulnerability (e.g., Cutter, et al., 2003).

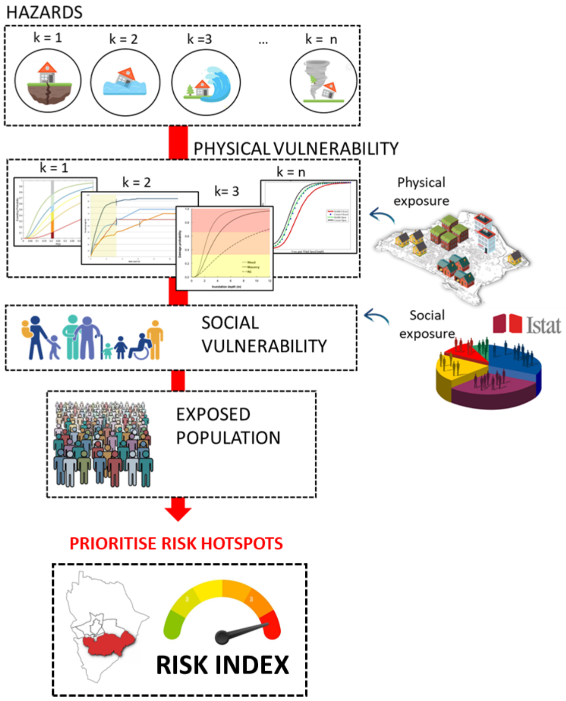


Figure 1: Integrating physical, social and multi-hazard dimensions in a risk index, to identify areas most in need of disaster risk reduction actions.

Accordingly, we propose an index-based approach for capturing multi-hazard risk in a region, which combines information on different hazards with region-specific physical and socioeconomic exposure and vulnerability data (see Figure 1). The exact number of hazards and types of physical and social information considered is 3ustomizable by the user, depending on their objectives.

The proposed RI for the jth sub-region within a broader area of interest and considering N_h hazards is calculated according to:

$$RI = \prod_{k=1}^{N_h} [F_H^{e_k}(h_j) \cdot F_{P_v}^{e_k}\left(p_{v_j}\right)]^{w_{e_k}} \cdot F_{S_v}(s_{v_j})^{w_{s_v}} \cdot F_p\left(p_j\right)^{w_p} \tag{1}$$

Where H denotes hazard information (e.g., the value of a hazard-specific intensity measure associated with a prescribed return period), P_v indicates physical vulnerability information (such as the damage probability outputs of hazard-specific, building-level fragility curves), S_v denotes social vulnerability information (such as the values of a social vulnerability index, including various sub-indicators; e.g., Cutter et al., 2003; Yoon, 2012), and P incorporates information on the population exposed to the hazards. $F_X(x_j)$ is the empirical cumulative distribution function (ECDF) for X (i.e., the considered indicator – H, P_v, S_v or P) across all examined sub-regions. It is, therefore, a relative measure of how the value x_j compares to other values of X within the area. w_{e_k}, w_{s_v} and w_p are the weights adopted for each dimension of the index, representing the relative importance of individual dimensions to relevant stakeholders, which could be defined using participatory methods such as the Budget Allocation Process (e.g., Jesinghaus, 1997). These weights vary between 0 and 1 and sum to 1. This means that RI also ranges from 0 and 1, with larger values indicating riskier sub-regions. Note that the RI is based on a geometric aggregation, so it can be considered a partially compensatory approach (e.g., Mazziotta and Pareto, 2013). In other words, compared to a linear aggregation, a high value of the ECDF for one indicator does not compensate as much as for a low value of the ECDF for another type of indicator (e.g., Nardo et al., 2008). Thus, areas where only one hazard dominates are de-emphasised, allowing a better representation of the multi-risk concept.

3. SPECIFIC APPLICATION TO ITALY

We apply the RI to the country of Italy at a municipality scale of analysis (i.e., a jth sub-region corresponds to a municipality) for the specific context of earthquake (e_1) and flood risk (e_2; such that $N_h = 2$) and considering residential physical vulnerability only.

3.1. Hazard indicators

The considered seismic hazard information (e_1) is the peak ground acceleration (PGA) value with a 10% probability of exceedance in 50 years (i.e., corresponding to a mean return period of 475 years) measured at the centroid of each municipality, according to the official reference for seismic hazard values of Italy, i.e., the map of seismic hazard also known as MPS04 ("Modello di pericolosità sismica" in Italian, proposed by Stucchi et al., 2004; 2011). This map is derived from a probabilistic seismic hazard analysis, adopting a logic-tree approach to model the epistemic uncertainty in the completeness of the earthquake catalogue, the assessment of the seismicity rates and the ground-motion models. The map reports the seismic hazard over a grid of more than 16,000 points for the median values of the branches in the logic tree.

The flood hazard information (e_2) is equivalent to the percentage of a municipal area expected to be inundated in a medium probability scenario (with a mean return period between 100 and 200 years), based on reference flood hazard maps for Italy provided by ISPRA ("Istituto Superiore per la Protezione e la Ricerca Ambientale", in Italian), a public research institute that provides services for the Italian Ministry for Environment, Land and Sea Protection. These hazard maps are derived from regional ones developed by eight District Basin

Authorities based on specific hydrological and hydraulic modelling and historical data.

3.2. Physical vulnerability indicators

We represent earthquake physical vulnerability information using the Risk-UE index- (score-) based approach (Lagomarsino & Giovinazzi, 2006), which facilitates aggregation with other terms of the RI. The Risk-UE vulnerability indicator ranges between 0 and 1, with values close to 1 indicating the most vulnerable buildings and close to 0 indicating buildings with superior seismic performance. Basic information on construction material and structural system (masonry type: e.g., simple stone, massive stone; reinforced concrete – RC: frame or walls; etc.) are used to define an initial value of the indicator. This value can then be modified (through secondary modifiers) if additional information on the asset's vulnerability, such as the structure's height, the horizontal structure type (for masonry buildings) and the earthquake-resistant design (in the case of RC), is available. For example, a value of 0.87 is assigned to masonry buildings with an irregular layout, and this value could increase if vaults (+0.08) or flexible slabs (+0.02) characterise the horizontal structure. Information on construction materials is found in Italian census data (ISTAT, 2011), so we only focus on residential buildings. The other required data are derived by adopting a suitable exposure/vulnerability model that defines rules to assign census building typologies (e.g., classified based on construction material and age of construction only) to building classes (or types), as detailed in Tocchi et al. (2022). The Risk-UE indicator is first evaluated at the building class level, i.e., for each building type with the same structural features. Then, the final municipal-level indicator is obtained as a weighted average based on building type presence in the municipality.

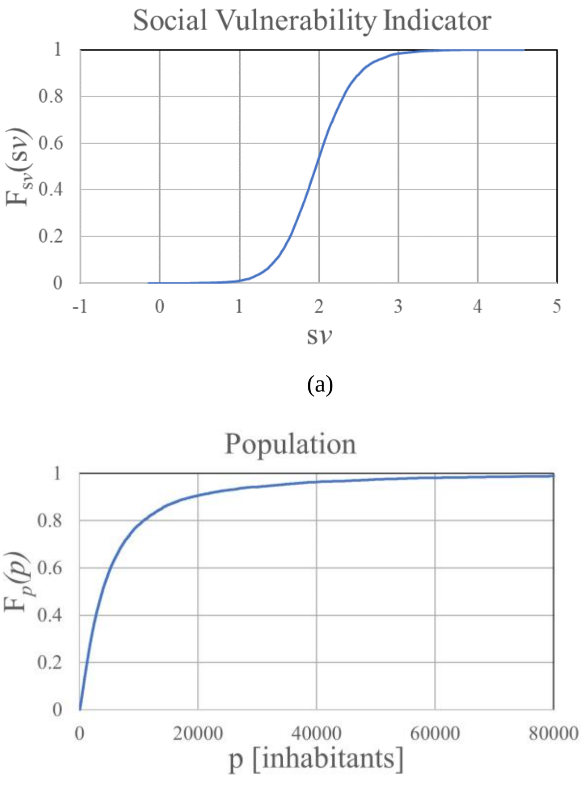
The considered flood physical vulnerability information for a given municipality is simply the percentage of residential buildings with only one story, given that: (1) all considered buildings are residential, so do not vary in flood vulnerability through their occupancy type; (2) construction material does not appreciably affect flood vulnerability, at least in urban contexts (e.g., Maiti, 2007); and (3) flood depth-damage curves available in the literature (e.g., Huizinga et al., 2017; Gentile et al., 2022; FEMA, 2022) indicate that buildings with only one story tend to be notably more vulnerable than those of two or three stories. The percentage of residential buildings with only one story is derived from census data (ISTAT, 2011) at the municipal scale.

3.3. Social vulnerability and population indicators

Social vulnerability information is represented through the social vulnerability indicator (SoVI), derived using the approach proposed by Frigerio et al. (2018). The SoVI is composed of sub-indicators that capture municipality-level information on population age (e.g., rate of elderly older than 65 years), family structure (e.g., family with more than five members), employment (e.g., unemployment rate), socioeconomic status (e.g., commuting rate), ethnicity (i.e., foreign resident), education level and population density, which are obtained from the latest census. The SoVI indicator is not restricted to values between 0 and 1; it could also assume values less than 0 (for municipalities with low social vulnerability) and greater than 1 (for municipalities with high social vulnerability), since it is the sum of normalised variables, each of which has either a positive (increasing) or negative (decreasing) effect on social vulnerability.

The considered exposed population information is the total residential population of a given municipality, derived from the most recent census. 70% of municipalities in Italy have less than 5000 inhabitants (86% of which with less than 3500) while only the 3% have more than 50000 inhabitants.

Figure 2 provides $F_{S_v}(s_{v_j})$ and $F_P(p_j)$ for the case study application.



(a)

(b)

Figure 2: (a) ECDF of the social vulnerability indicator (S_v); and (b) residential population (P) for the case-study application of RI to Italy.

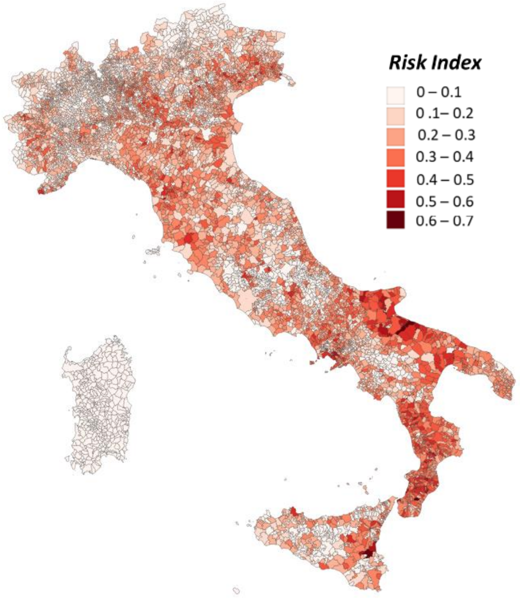


Figure 3:Map of RI for the Italian territory, assuming all weights are equal.

3.4. Results

RI calculations are carried out for the case of equal weights ($w_{e_1} = w_{e_2} = w_{s_v} = w_p = 0.25$). Figure 3 shows the values obtained for each municipality in Italy. It can be observed that RI is particularly high for towns in the southern part of the country, where relatively high values of social vulnerability are combined with relatively high seismic and/or flood hazard/physical vulnerability. The high RI values associated with many municipalities in the Calabria region (the southernmost part of the mainland) are due to relatively high underlying values across all indicators, underlining the multi-hazard-prone nature of the area. In the northern part of the country, high RI values are mainly observed in municipalities with a large number of inhabitants (i.e., population indicator) and characterised by relatively high social vulnerability and flood hazard/physical vulnerability. It is worth noting that despite relatively high social vulnerability across Sardinia's municipalities, final RI values for the island are quite low, mainly due to the absence of seismic hazard. The municipality with the highest RI value (0.7) is Barletta, in the southeastern Apulia region.

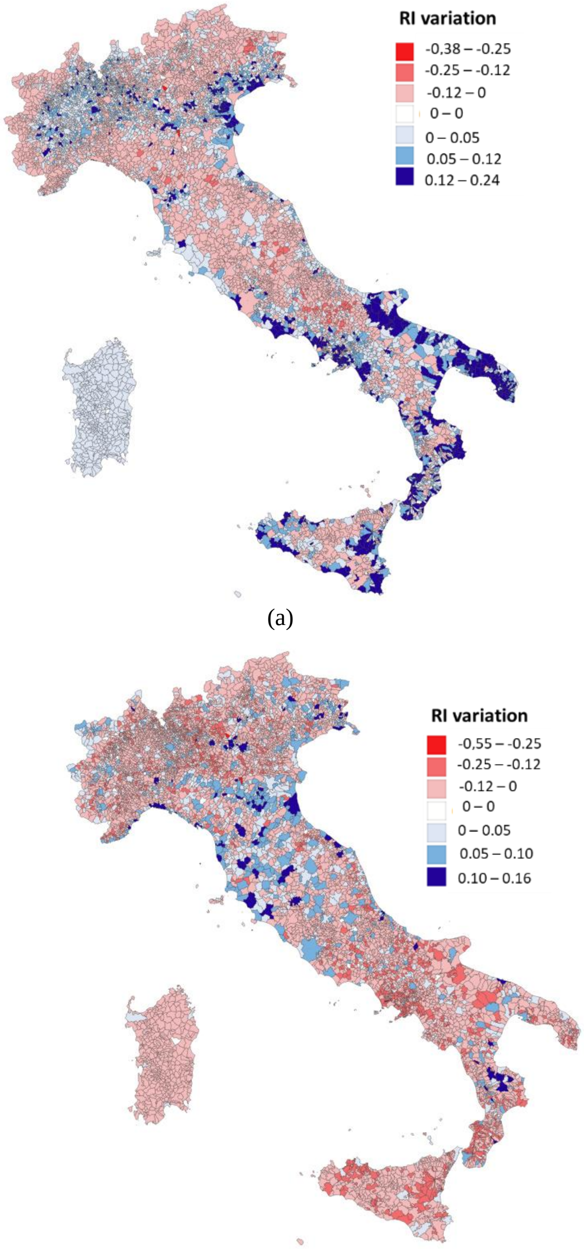
3.5. Sensitivity analysis

We perform a sensitivity analysis, in which each variable (e.g., social vulnerability) is weighted three times more than the other three (e.g., $w_{sv} = 0.5$, $w_{e_1} = w_{e_2} = w_p = 0.166$).

When w_{e_1} is larger than the other weights, the trend in RI closely mirrors that of the seismic hazard map used, with slight deviations due to variations in physical vulnerability. These deviations can be noted, for instance, in many municipalities of the Emilia-Romagna region (towards the northernmost end of the mainland; e.g., Faenza), where although the seismic hazard is relatively high (e.g., PGA = 0.204 g, corresponding to a $F_H^{e_1}(h_j)$ value of 0.85), the seismic vulnerability of residential buildings is relatively low (e.g., Risk-UE indicator of 0.61, corresponding to a $F_{P_v}^{e_1}(p_{v_j})$ value of 0.19). This is because most of masonry buildings were built after 1945, and so (according to the adopted exposure/vulnerability model) they are considered constructed according to more recent construction techniques (e.g., adopting bricks for vertical structures and rigid slabs for horizontal ones). Most RC buildings were instead built after the main seismic regulations were introduced in 1981.

When w_{s_v} is largest, municipalities in the south of Italy tend to experience an increase in RI relative to the equally weighted case, whereas many municipalities in the north of the country experience a decrease. This is mostly due to the greater economic well-being characterising northern regions (i.e., greater gross domestic product and lower unemployment rate with respect to southern regions). When w_{e_2} is highest, the biggest increases in RI relative to the equally weighted case are primarily concentrated in municipalities of the Emilia-Romagna and Calabria regions. This is explained by the fact that both regions are associated with relatively significant flood hazard. (Emilia-Romagna is the region with the highest flood hazard in the country, where the area per municipality expected to be inundated in the examined flood scenario is 40% on average). In addition, Calabria is characterised by relatively high flood physical vulnerability, i.e., the percentage of residential buildings with only one story at the municipal level is particularly high, which is greater than 15% (the average for all Italian municipalities) in 77% of municipalities in the Calabria region. Finally, if w_p is larger, the bigger variation of the index can be observed for the most populous places (e.g., for the towns of Turin and Rome RI increase of 0.16 and 0.15). Figure 4 plots the difference between RI values obtained for the equally weighted case and those obtained by placing larger importance on both seismic hazard/physical vulnerability and social vulnerability.

When w_{e_1} is highest, the RI value associated with the riskiest municipality for the equally weighted case (Barletta) decreases to 0.63, and the riskiest municipality is Palmi, in the Calabria region, where seismic hazard input is notably higher (PGA=0.261 g against PGA=0.155 g for Barletta).



(a)

(b)

Figure 4: Differences in RI values when (a) seismic hazard/physical vulnerability; (b) and social vulnerability information is most weighted. Red and blue values respectively indicate increases and decreases in the RI value for the revised weighting schemes.

In case of w_{e_2} is highest, the municipality with the largest RI value is Catania (RI=0.75), in

Sicily region, where the area potentially flooded is considerable (50% of the municipal area corresponding to a $F_H^{e_k}\left(h_j\right)$ value of 0.96) and the city of Barletta follows immediately after (RI=0.71). In contrast, if w_{s_v} or w_p assumes the largest weight, Barletta still is the riskiest municipalities, with a RI=0.82 and RI=0.80 in the two cases respectively. As a matter of fact, social vulnerability is particularly high for this town (SoVI=2.6, corresponding to a $F_{S_v}(s_{v_j})$ value of 0.92), and it is also a significantly populous town (about 93000 inhabitants, corresponding to a$F_P(p_j)$ value of 0.99). These results reveal that risk hotspots identified through the RI are sensitive to the emphasis placed on the underlying components of the index.

4. CONCLUSIONS

We proposed a novel holistic risk index that simultaneously captures physical and social impacts from multiple hazards within a probabilistic framing to identify hotspot areas most needing disaster risk reduction (DRR) strategies. The index incorporates subjective stakeholder weightings on various input data components, facilitating a participatory approach to risk assessment that is strongly recommended in disaster management. Furthermore, the proposed index is a relatively simple tool that can be easily applied across any regional, national, or transnational context of interest, using only publicly accessible data.

The case study application of the index to Italy for earthquake and flood hazards revealed that risk hotspots are largely concentrated in the south of the country if all underlying components of the index (encapsulating information on multi-hazard/physical vulnerability, social vulnerability, and population exposed) are treated equally. However, risk hotspots can change if different index components are weighted higher or lower (reflecting varying stakeholder preferences and varying degrees to which both hazards are considered), emphasising the importance of capturing accurate stakeholder feedback and adopting a holistic (multi-risk) perspective in DRR prioritisation efforts.

The proposed tool is intended to be used as a high-level guide only. More detailed risk assessments that incorporate high-resolution impact calculations (e.g., Tocchi et al., 2022) are required in areas it highlights to identify appropriate DRR preparedness actions to be implemented more accurately.

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