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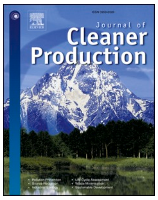

Urban resilience against natural disasters: Mapping the risk with an innovative indicators-based assessment approach

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ABSTRACT

The increase in the frequency and intensity through which natural disasters have hit cities in the last twenty years has created the need to prefigure a model of sustainable urban development not only consistent with the goals promoted by the Agenda 2030, but also efficient in the regulation of the main cause of the natural disasters: consumption of natural soil. Therefore, the aim of the research is to define an indicators-based methodology for determining a synthetic natural risk index, which represents the degree of territorial exposure to multiple natural disasters in the different sub-urban areas within a vulnerable city. The proposed methodology is structured into eight sequential and ordered phases that comply a system of 23 indicators for the three main components of natural risk (hazard, exposure and vulnerability). Their importance is accounted in the final aggregation of the index through the application of the Analytic Hierarchy Process multi-criteria evaluation technique. The validated results achieved by the application of the proposed methodology to the city of Rome (Italy), represented in a georeferenced map of the risk level of natural disasters, allow to immediately identify the most critical sub-urban areas on the west coast of the "Tevere" river. The proposed risk index may be useful for public and private subjects involved in the predisposition of sustainable urban plans and projects, aimed at improving the level of urban resilience connected to natural disasters aggravated by land consumption. In this way the targets of Goals n.13 "Reducing climate change" and n.15 "Life on Earth" of the Agenda 2030 can be applied at the sub-urban scale.

1. Introduction

In the context of sustainable development, the protection of urbanized territories from natural hazards such as floods, cyclones, hurricanes, landslides, droughts and heat waves due to the worsening of climate change, is one of the fundamental points of the strategic actions promoted by the Agenda 2030 with the 17 Sustainable Development Goals (SDGs). All of them, in fact, require an effort of governments for a better regulation of land use in cities, so that the harmful effects generated on the climate and the environment are reduced, to ensure a long period sustainability (European Commission, 2016). The close relation between the unsustainability of the urban structure and the frequency with which natural disasters occur is principally due to the consequences generated by the consumption of natural soil and is confirmed by the economic, social and environmental damages recorded in recent years. According to the Report "The Human Cost of Disasters 2000–2019" (United Nations Office for Disaster Risk Reduction, 2020), in the period between 2000 and 2019, 7348 serious catastrophic events have occurred that caused 1.23 million victims, affecting 4.2 billion people – also on more than one occasion - resulting in global economic losses of approximately 2.97 trillion dollars. This is a significant increase over the previous twenty years. In fact, between 1980 and 1999, 4212 disasters occurred worldwide, about 60% less than the current conditions. Much of the difference is explained by the worsening of climate change and its effects turned into serious natural disasters.

In the current scientific literature (Assumma et al., 2021; Rentschler and Salhab, 2020), the term "natural risk" generally refers to the dependence function on three components: i) the probability that a potentially dangerous natural phenomenon (*hazard*) will occur, ii) the economic value of the damage caused to public and private real estate assets, to human lives and to productive activities (*exposure*), and iii) the susceptibility of the affected area, assumed as the characteristics of the same in coping with a natural catastrophic event *(vulnerability)*. The risk is directly proportional to the expected damage to humans (including

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economic and social properties) and the environment, and inversely proportional to the rate of urbanization and land take. The relationship between natural hazard and human activities defines the level of risk to which the territories are subject. Frequently, inappropriate methods of use and management of the territory are at the origin of an amplification of the current disruptions or the triggering of new ones (Sun et al., 2020). A precise identification and characterization of areas subject to natural risk is functional both to the protection of existing urban areas (through risk mitigation actions), and to the correct definition of future uses. In this field, the multidimensionality is an essential element. The urban resilience to natural disaster's is a complex concept that involves both the socio-economic and environmental sphere. Moreover, it is important to highlight that the urban resilience pertains to all the type of natural hazards that could affect a territory. It cannot be reduced to a partial/one hazard analysis to be efficient. For efficiently manage the natural disaster's related issues, the growing field of research based on synthetic indexes and synthetic indexes turned out to be a point of reference. The indexes/composite indicators have the advantages of reducing the complexity of the examined issue to an individual and synthetic value that represents all the performed analyzes. In the urban resilience context, the synthetic risk indexes are widely spread and often developed with the application of multi-criteria decision making models (MCDM). The main parameters on which the assessment of the natural risk level within an urban context must be carried out is the possibility to take into account at least a partial compensation among the factors, both quantitative and qualitative ones, affecting the risk, and its capacity to be users friendly for the Public Administration. This last characteristic is essential for a real improvement of the sustainable development and planning process. The Public Administration (PA) together with the Private Entrepreneurs (PE) involved in the urban transformation projects, are the main subject that set the urban tissue of a city, and therefore its capacity to resist or not to a natural hazards. It is possible to identify three principal reasons for developing indicators-based systems: i) possibility of relative performance ranking among the territorial units' sample or in absolute terms at the global scale, according to the aim of the analysis; ii) improving the awareness of policy-makers about the decisions they are expected to make; iii) monitoring the effects of the policies adopted over the years. A wide consideration of how synthetic indexes are constructed and the variables that are used could support both the technicians involved in the development, by identifying common practices or gaps, and the policy-makers, by critically choose an index that is appropriate for their aims (Roy et al., 2021).

Italy, due to its particular geodynamic location and in consideration of its high demographic density and territorial fragility, is almost entirely affected by situations of natural risk mainly due to clayey rocks, violent rainfall intensity and seismic and volcanic activity of the subsoil (Spizzichino, 2014). According to the Environmental European Agency analysis (European Environmental Agency, 2021) Italy is the third Country in the world for deaths (about 20,735) due to extreme weather and climate related events that occurred between 1980 and 2019, while it is the tenth for economic damages caused by floods in the same period (about 72,534 million euros). The Italian territory is exposed to two main categories of natural risk: tectonic-volcanic and hydro-geological. At the current state of knowledge, the regions with the greatest seismic hazard are identified in the Eastern Alps, along the entire Apennine chain, Calabria and eastern Sicily. No less important is the risk associated with volcanic eruptions, concentrated however in a significantly smaller area than the one subjected to seismic risk (ISPRA, 2022). The deforestation of many natural areas has contributed to favoring hydro-geological instability, in fact in 1877 the first Italian forest law was promulgated but it did not improve the situation, with about 30, 000 ha per year deforested between 1874 and 1906 (Crupi, 2019). The hydro-geological risk generated by particularly intense atmospheric events that cause landslides and floods, is also frequent. Landslides can be activated even in the absence of heavy rain phenomena, for example following seismic phenomena or human interventions on the territory (from simple excavations to dams). Italy is the European Country most affected by landslides, with about 2/3 of them recorded in Europe. Avalanches and floods can put people's safety at risk and cause significant damage to urban settlements and cultural heritage, infrastructures and industrial, commercial or agricultural activities. The economic and construction develop, often abusive, of the second post World War period aggravated the demographic pressure on already fragile territories, triggering situations of natural risk scattered throughout the territory (Miceli et al., 2008; Frigerio and De Amicis, 2016; Trigila et al., 2015).

In this context, the limitations of the existent studies can be clearly deductible: most of the assessment resilience models are computationally complex (major details on section 3), developed for aggregated territorial scale that does not consider the sub-urban one – especially for the Italian context – and analyzes only one natural disaster individually. Moreover, the models are often not set for being clearly reproducible by the Public Administrations or similar subjects that have the role of planning the transformation projects of the city in a sustainable manner. In most cases the lack of a standardized methodology is detected, therefore the present research gives an innovative contribution on the Italian scientific panorama through the definition of an assessment model based on a protocol of simple and consequential phases, able to create a synthetic risk index that represents the risk levels among the 155 sub-urban units of the city of Rome.

By considering the existent studies on the similar topic and the same city (Rome) there are not researches that investigate how the main socio-economic and environmental factors determine the level of the sub-urban resilience to multiple natural disasters. In Table 1, the main limitations of the most recent studies (from 2017 to 2022) carried out for the city of Rome are reported.

Actually, studies that assess the spatial distribution of the natural risk level that can occur in the city of Rome, and that take into account simultaneously all the main socio-economic and environmental variables pertaining to the three disaster to which the city is exposed (seismic, floods and landslides), are missing. Moreover, if they exist, they consider individual areas characterized by some particular point of interest such as cultural heritage, historical site, etc. Furthermore, existing models provide aggregate-scale analyzes that do not examine the sub-urban distribution of risk levels. Through the implementation of the multicriteria technique of the Analytic Hierarchy Process (AHP) the proposed research also fills the gap of the current computationally very difficult models for the management of urban resilience.

Table 1
Limitations of the main existent studies on natural disaster for the city of Rome (2017–2022).

Reference	Limitations
Recanatesi and Petroselli (2020)	• Only flood risk examined • Land cover changes are the main parameters • Restricted period of analysis: land cover transformations in 1954, 1967 and 2018 • Absence of spatial analysis
Ciullo et al. (2017)	• Only flood risk is examined • The risk is determined by considering only the hazard and loss components • Only the social aspects are considered • Absence of spatial analysis
Mancini et al. (2020)	• Only flood risk is examined • Only a southern part of the city is analized • Hydraulic modelling
Coletti et al. (2020)	• Only flood and seismic risk is assessed • Only two areas of the city are examined • Risk mini-model related to specific POI • Absence of contemporary assessment of social, environmental and economic aspects
Segoni and Caleca (2021)	• Only landslide risk is addressed • Only environmental indicators are considered • Aggregated scale of analysis

The paper is structured as follows: Section 2 states the aim of the research; Section 3 provides an overview on multi-criteria decision models for building composite indicator/synthetic index and the main weighting system; Section 4 describes the general methodology proposed and its protocol of phases; Section 5 consists of the application of the methodology to the case study of Rome; Section 6 contains the discussion of the obtained results; Section 7 deals with the conclusion and the future insights of the research.

2. Aim

The aim of the work is to give the possibility to the PA and the PE to identify the most critical sub-urban areas within a city exposed to multiple natural hazards through a synthetic index (I_{NR}). In this way, the research intends to give a contribution on the outlined framework by representing a decision support system to be adopted by the PA and the PE for improving the resilience level of the most critical sub-urban areas during the sustainable planning processes. For carrying out this, the proposed methodology consists of an *ex ante* evaluation tool through which scoring, ranking or monitoring and managing the urban dynamics and interventions that contribute to reducing ecological resilience.

3. Background

3.1. Multicriteria decision models for building synthetic indexes

The urban resilience for natural disaster's mitigation is often treated under its multiple aspects, both quantitative and qualitative ones. Due to these characteristics, the MCDM have been widely applied for explaining the significance of each factor and identifying the trade-off among the various issues related to natural hazard's urban resilience. Moreover, due to the absence of stated and fixed standards for resilience indicators given by the heterogeneity of the territorial contexts exposed to the risks, since 1995 different MCDM have been developed to determine synthetic indexes that can address the natural hazard's resilience. By referring to the classification proposed by El Gibari et al. (2019) the MCDM implemented for aggregating single indicators into composite ones (index) can be of 5 types:

1. *Elementary*, such as the Simple Additive Weighting (SAW) and the Weighted Product (WP). The first one means a total compensation among the different indicators whereas in the WP a partial compensation is carried out. Ramkar and Yadav (2021) develop a flood index combining the AHP, questionnaire survey and GIS tool into a SAW tool for detecting the final distribution of the flood risk map;
2. *Value and utility based*, that consists of associating a real number with each alternative and producing a preference order of them according to the decision-makers' value judgments. This typology involves i) the Multi-Attribute Utility Theory (MAUT) that provides for the determination of partial utility functions to calculate a global utility function, ii) the Multi-Attribute Value Theory (MAVT) that determines partial value functions to establish weights for each criterion and to calculate a global value function. Among the several applications, Bottero et al. (2015) use the MAVT for the definition of synthetic index for evaluating sustainable urban projects, plans and programs;
3. *Outranking relation approach* based on comparisons between pairs of options to determine if one of them is "*at least as good as*" the other one. The AHP, the Elimination and Choice Expressing Reality (ELECTRE) and Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) methods pertain to this typology. The former is able to analyze concordance, discordance and threshold values. The latter performs a pairwise comparison of alternatives to rank them with respect to some criteria. Their application to construct synthetic indexes implies that the decision-maker must relate the corresponding thresholds to each indicator, in addition to the weights. The value obtained by their application represents the final synthetic index's value. The normalization is not required, and the original data are used for the comparisons. In particular, Stanković et al. (2021) create a synthetic index as a measure of the development of the circular economy at the national level using an integrated approach with the Principal Component Analysis (PCA) and the PROMETHEE;
4. *Data Envelopment Analysis based methods,* that is a non-parametric approach that adopts linear programming for a full compensation among the criteria. It can be used into two different ways: the first one considers the indicators as input or output variables, depending on whether they have positive or negative proportionality; the second one consists of establishing a dummy output (or input) and then seeing all the indicators as inputs (or outputs). This is also known as the Benefit of Doubt (BoD) model, an increasingly recognized method for constructing synthetic indexes defined as the ratio of an indicator's actual performance over its benchmark, with normalization through linear scaling in the min-max range. The BoD approach endogenously determines the weight of the indicators. Morano et al. (2021) use the BoD model to create a synthetic index for assessing sustainable urban projects under ecosystem services and land take issues;
5. *Distance functions based methods*, where the minimization of the distance between an alternative and a reference point(s) with optimal properties is the main rule. Therefore, the assessment of the reference levels and the weights of the indicators is made by the decision-maker. This typology includes the goal programming, the compromise programming, the reference point method, the Technique for Order Preferences by Similarity to Ideal Solutions (TOPSIS) and the Complex Proportional Assessment (COPRAS) method. Chen et al. (2019) proposes a combination of AHP, Self-Organizing Map (SOM), Isometric Feature Mapping (Isomap) and TOPSIS to achieve the clustering, visualization, and ranking of regional natural disaster risk in China's regions.

Therefore, several MCDM can lead to building synthetic indexes and the selection could be driven by the following factors: i) type of available data, ii) purposes of the final synthetic index, iii) skill of the potential final users and iv) ability of the MCDM to take into account the elements that characterize the issue addressed. With regard to the natural disaster's resilience management, the MCDM must have the following features: i) to accomplish both quantitative and qualitative data's analysis, ii) to allow the scoring or ranking of the spatial risk level's distribution, iii) to be simple to be used and examined by the PA for improving the resilience process and increasing the public awareness on the risk, iv) to consider at least partial compensation among the criteria. By examining under these parameters of the natural disaster's resilience the main scoring MCDM retrieved, it is possible to show the strengths and weaknesses of them for accounting the risk level.

As shown in Table 2, TOPSIS, COPRAS ELECTRE, PROMETHEE and BoD techniques are less PA users friendly and are often integrated with other MCDM for improving their weaknesses, instead the WSM, WPM and the AHP are basically simpler, and for their implementations no specific skill are required. This feature improves their application in the natural disaster's management field (Ghosh and Mistri, 2021; Sekovski et al., 2020; Moghadas et al., 2019; Darko et al., 2019; Lin et al., 2019). About the compensation issues, it is important to highlight that the absence of compensability is not adequate to consider the real features of the resilience level for natural disaster's risk, therefore the ELECTRE and PROMETHEE techniques fail on this. Among the scoring MCDM analyzed, the AHP appears to have the features required: it is PA user friendly, able to assess both quantitative and qualitative data, a compensatory approach and with a clear and simple structure, by avoiding the possible risk of "black box" features for potential users.

However, if the choice of the MCDM is delegated to statistical

Table 2
Features of the main MCDM under the parameters of urban resilience to risks of natural disasters.

	MAIN PARAMETERS OF SYNTHETIC INDEXES FOR URBAN RESILIENCE AGAINST NATURAL DISASTER				
MCDM	Public administration friendly	Ability to manage both quantitative and qualitative data	Compensation allowed		
			Partial	Total	No compensability
WSM	✓	✗		✓	
WPM	✓	✗	✓		
AHP	✓	✓		✓	
TOPSIS	✗	✓	✓		
COPRAS	✗	✗	✓		
ELECTRE	✗	✓			✓
PROMETHEE	✗	✓			✓
BoD approach	✗	✗		✓	

analysis rather than to the subjectivity of the developer of the synthetic index, there are suitable indices aimed at examining the robustness and validity of the results obtained by different MCDM (Roy and Słowiński, 2013). The research of Ameri et al. (2018) improves the well-known Receiver Operating Characteristic (ROC) method to support the identification of the best MCDM among those compared.

3.2. *MCDM for the weights of indicators*

One of the most discussed phases during the synthetic index's construction is the determination of the weight of the indicators from which the final index can be derived. In fact, the aim of the weighting phase is twofold: firstly, it represents the explicit importance that is attributed to each indicators of the synthetic index; secondly, it also relates on the implicit importance of the indicators. Undoubtedly, the determination of the weights might have significant effect on the final index's results. In fact, the sensitivity analysis is always performed after the weight's determination in order to check the robustness of the assessed weights and to avoid that their influence on the final values could be too impactful (Ghorbanzadeh et al., 2018).

However, it is important to note that no weighting system is above criticism. Each approach has its advantages and disadvantages, and it is up to the developer of the index to choose a weighting system that is more suitable than the others, according to the theoretical framework (Greco et al., 2019). In fact, there are two possible options: the first one is not to distribute any weights to the indicators, therefore the final index could be simply the arithmetic average of the normalized indicators or the sum of the individual rankings that each unit obtains in each of the sub-indicators (Karagiannis, 2017). This option could lead to a problem of double counting: if two collinear indicators are aggregated in the synthetic index with weights of w_1 and w_2, the unique dimension that the two indicators measure will have a weight equal to the sum of them. In order to avoid this, the use of test indicators for statistical correlation (e.g. Pearson correlation coefficient) and the choice only of those which exhibit a low degree of correlation can reduce the problem of double counting. Conceptually, equal weights miss the aim of differentiation between essential and less significant indicators by considering them all equally (Greco et al., 2018).

The second option consists of choosing from a set of weighting schemes for determining the different importance of the indicators. Several weighting techniques exist and can derive from i) statistical models, such as Factor Analysis (FA), DEA, PCA and Unobserved Components Models (UCM), or from ii) participatory methods like Budget Allocation Processes (BAP), AHP and Conjoint Analysis (CA) (Locurcio et al., 2021). Statistical models could be used to group individual indicators according to their degree of correlation and for this reason the weights cannot be determined with these methods if no correlation exists between indicators. Other statistical methods, such as the Multiple Linear Regression Analysis, endogenously generate the weights through elaborations on the data (so called "data driven weights techniques"), but these models assume strict linearity, or more in general statistical relationships, that not always exist among indicators.

Instead, participatory methods that incorporate various stakeholders – experts, citizens and politicians – are generally seen as a conventional way for transparent judgments. However, since these techniques may yield alternative weighting schemes, the most suitable ones according to the purpose of the index should carefully been chosen. For example, in the BAP experts have a "budget" of N points to be distributed over a set of m indicators, allocating more budget for those indicators whose importance they want to stress. The BAP is efficient for a limited number of indicators because it can bring serious cognitive stress in the experts who are asked to allocate the budget (Lafuente et al., 2020). The CA is commonly used in consumer research and marketing because it is based on seeking the preferences of individuals (e.g. experts or the public) regarding a set of alternatives and then it decomposes them according to the individual indicators. In practice, the significance of an indicator is given by dividing the range of importance of that one in the respondent's opinion by the total sum of ranges of all the indicators. Its major drawbacks are represented by its overall complexity, the requirement of a large sample, and an overall pre-specified utility function, which is very difficult to be assessed (Mollayosefi et al., 2018).

According to Žižović and Pamucar (2019) the most used MCDM for determining weight coefficients of criteria are subjective models based on pairwise comparisons such as the AHP, the Best Worst Method (BWM) and the Decision Making Trial and Evaluation Laboratory (DEMATEL). The BWM consists of: i) the choice of the best and the worst criteria among the set of indicators, ii) the elaboration of pairwise comparisons between them and the others criteria by constructing the Best to Others and the Others to Worst vectors, iii) the definition of the weights of the criteria by solving optimization models. Compared to AHP, it has several advantages, especially in terms of reducing comparison times, but it is still a field of research undergoing improvement as regards the applicability to the assessment of the level of urban resilience for the risk of natural disasters. It also lacks an adequate software package that can reduce the complexity of the calculation and accelerate the readability of the results, even for non-expert users and for the PA, that is important in the field of the disaster risk reduction. Zavadskas et al. (2016) have shown in their research that the AHP is the most employed in the literature and also shared in the public opinions for determining weights due to its simple construction. Nevertheless, in the AHP a large number of comparisons makes the application of the model more time expensive, therefore very recently the BWM has begun to gain visibility (Rezaei, 2016). Its main advantage compared to the AHP is the smaller number of pair comparisons, that is (2n −3) instead of (n(n-1)2). However, many comparisons in pairs of criteria, defining the limits for the resolution of the non-linear model, make the application of BWM significantly more complex. Therefore, this model is still an experimental field of research to improve by testing the method to further applications. For these reasons, a Level Based Weight Assessment (LBWA) model has been developed by Žižović and Pamucar (2019) for determining weights of criteria through only (n-1) comparison. Given a set of *n* criteria the decision-maker determines the most important criterion and then groups the criteria according to the levels of significance. Within these levels it is performed the comparison of criteria by their significance. Based on the defined maximum value of the scale for the comparison of criteria I, the elasticity coefficient and the influence function of the criterion are defined. Finally, the weights coefficients of the criteria are determined as a product of the weight coefficient of the most significant criterion w_1 and the i-th preference function related to each of them. Despite the evident potentials that the LBWA model shows, it has been developed few years ago, therefore very few researches are retrieved in the field of synthetic indexes of natural disaster's risk management that prove its applicability (Bagheri et al., 2021). In fact, the Authors state the need for software development and implementation in real-world applications and the extension of the algorithm for the group decision making's issues. Also, one of the directions of LBWA model's improvement is constituted by the use of different uncertainty theories such as fuzzy sets, rough numbers, gray theory, etc. These improvements have just widely explored instead for the AHP that, in the natural disaster's management is still robust (Bakır and Atalık, 2021; Karamaşa et al., 2020). Another significant MCDM for reducing the number of comparisons of criteria during the weighting process is the FUll COnsistency Method (FUCOM) developed by Pamucar et al. (2018). This method has the following main advantages: i) significantly smaller number of pairwise comparisons (only n − 1), ii) it allows the calculation of the comparison consistency degree and the validation of the results by fully respecting the conditions of mathematical transitivity, iii) it enables the calculation of the reliable values of the weight coefficients of criteria that contribute to a rational judgment. The Authors compare the FUCOM's results with the ones obtained with the well-known AHP and the BWM for several multi-criteria examples retrieved in the literature. The reduction in the number of comparisons is very significant by growing the number of criteria, therefore it could be an important reference in the multi-hazard natural disaster's risk management. Moreover, it has minor steps to carry out than the LBWA: i) ranking, done according to the significance of the criteria, ii) comparison of the ranked criteria and determination of the advantage of the criterion of the rank (k) with reference to the criterion of the rank (k+1), iii) solving a model of minimization subject to two group of constraints, the FUCOM technique generates the weight of the criteria.

With reference to the features of the AHP weighting system, the FUCOM has more computational complexity than the pairwise comparison matrices, due to the final optimization model to set for obtaining the weights.

4. Part 1: the general methodology

The examination provided on the literature on MCDM for the construction of synthetic indexes and for the determination of the weighting system, highlights the following gaps/weaknesses: i) computational complexity of some MCDMs which therefore are not always PA user friendly; ii) lack of adequate software packages/implementations of weighting system to verify the adequacy of the natural disaster risk management characteristics; iii) absence of compensation in the MCDM developed to assess urban resilience to natural disasters; iv) scarcity of MCDM based on quantitative and qualitative data to build the synthetic index. Moreover, the georeferentiation of the final indexes results into a risk map, the sensitivity analysis and the validation of the obtained results are not always carried out in the existent MCDM applied to the natural disaster's management. Compared to other MCDM such as MAUT or MAVT, the pairwise comparisons help to make group decisions more rational, transparent, and understandable. Therefore, the proposed assessment model intends to fill the gaps retrieved in the literature. Moreover, its main innovative contributions are five: i) the context of application – no national and international researches exist on the city of Rome, even if has an heritage of incommensurable value to protect by natural hazards -; ii) the provision of a tool for the PA and the PE during the sustainable planning processes aimed at improving the resilience; iii) the territorial scale of analysis – there are not Italian researches that study the sub-urban scale; iv) the presence of some new criteria such as the value of the assets and the urban heat islands; v) the computational easiness with respect to other MCDM.

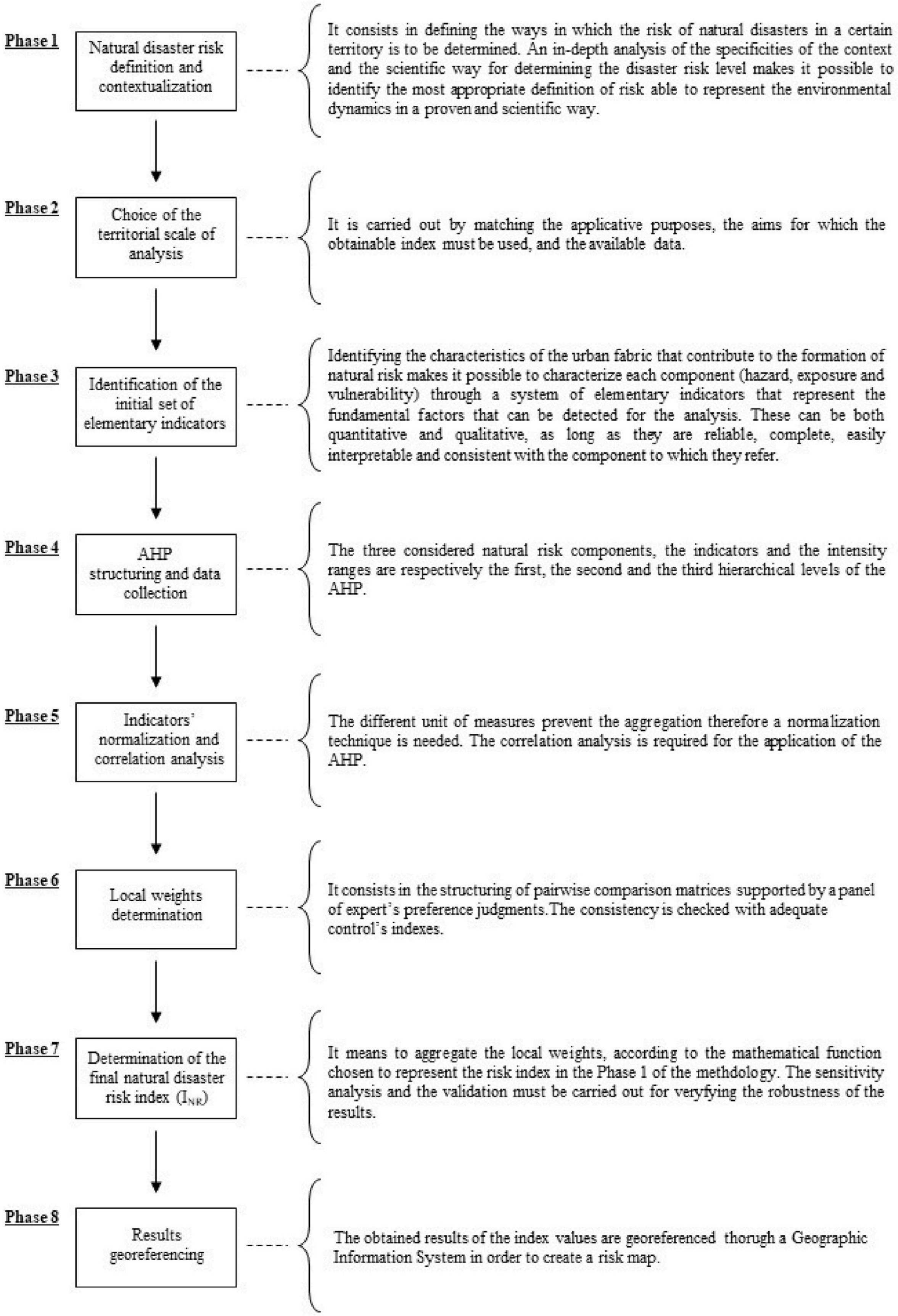
The construction of the I_{NR} is based on a protocol of eight phases, synthetically described in the flowchart of Fig. 1.

The proposed methodology allows to obtain a natural risk index (I_{NR}) by starting with the clear definition of the natural hazards to be assessed (Phase 1). Then, after having chosen the best territorial scale according to the purposes of the index (Phase 2), the selection of a set of *n* quantitative and qualitative for considering the most relevant socio-economic and environmental factors that better represent the three components of the natural risk concept - i) *hazard*, or the probability that a type of disaster can occur; ii) *exposure*, or the potential damages and losses that can be generated after the natural events happened; iii) *vulnerability*, or the intrinsic capacity to resist to a natural disaster - is carried out (Phase 3). Collecting the data and structuring the three hierarchical level of the AHP consists into assigning the first level to the three components of natural hazards, the second level to the indicator system and the third and last level to the intensity range (Phase 4). In order to reveal the effective spatial distribution of the I_{NR}, *m* range of variations – called intensity ranges – are accounted for the variability of the indicators' values at the territorial scale. After having collected all the data, the normalization is required in order to allow the aggregation into the final risk index I_{NR} (Phase 5). Then a pairwise matrix is structured in order to determinate the appropriate local weights (Phase 6). Therefore, the sensitivity analysis and the validation tests are performed (Phase 7). The georeferencing of the results is able to create a risk map where the critical sub-urban areas are immediately recognizable. The AHP multi-criteria technique is used i) to determine the importance of each of them, in terms of local weights derived from *k* pairwise comparison matrices developed with the exception of the components for which is assumed to be equally determinant in the natural risks formation process and ii) to aggregate them into the final risk index through a factorial weighted formula.

The phases are consequential and do not contemplate choice options by users, i.e. there are no decision-making steps to take depending on the existence or not of specific conditions (e.g. presence/absence of environmental factors, true/false tests, etc.). In the following sub-paragraphs the detailed description of the proposed methodology is reported.

Phase 1. Natural disaster risk definition and contextualization.

By defining the ways in which the risk of natural disasters in a certain territory is to be determined, an analysis of the specificities of the context should be carried out, in order to understand the typology and the intensity of natural disasters that affect it. An in-depth knowledge makes it possible to identify the most appropriate definition of risk able to represent the environmental dynamics in a proven and scientific way. In accordance with the International Standardization Organization's recent recommendation of 2018 "31,000 Risk management –Principles and guidelines" and the so-called "triangle of risk" proposed by Ingleton J. (1999) the risk is function of three components: *hazard, exposure* and *vulnerability* ($R = f(H, E, V)$). *Hazard* is the potentially damaging physical event, phenomenon or human activity, which may cause the loss of life or injury, property damage, social and economic disruption or environmental degradation, whereas *exposure* refers to people, environment and assets exposed to the hazard, as well as their economic



It consists in defining the ways in which the risk of natural disasters in a certain territory is to be determined. An in-depth analysis of the specificities of the context and the scientific way for determining the disaster risk level makes it possible to identify the most appropriate definition of risk able to represent the environmental dynamics in a proven and scientific way.

It is carried out by matching the applicative purposes, the aims for which the obtainable index must be used, and the available data.

Identifying the characteristics of the urban fabric that contribute to the formation of natural risk makes it possible to characterize each component (hazard, exposure and vulnerability) through a system of elementary indicators that represent the fundamental factors that can be detected for the analysis. These can be both quantitative and qualitative, as long as they are reliable, complete, easily interpretable and consistent with the component to which they refer.

The three considered natural risk components, the indicators and the intensity ranges are respectively the first, the second and the third hierarchical levels of the AHP.

The different unit of measures prevent the aggregation therefore a normalization technique is needed. The correlation analysis is required for the application of the AHP.

It consists in the structuring of pairwise comparison matrices supported by a panel of expert's preference judgments.The consistency is checked with adequate control's indexes.

It means to aggregate the local weights, according to the mathematical function chosen to represent the risk index in the Phase 1 of the methdology. The sensitivity analysis and the validation must be carried out for veryfying the robustness of the results.

The obtained results of the index values are georeferenced thorugh a Geographic Information System in order to create a risk map.

Fig. 1. Flowchart of the general methodology.

value; finally, *vulnerability* is the ability of elements exposed to the phenomenon to resist or be damaged by it (United Nations Office for Disaster Risk Reduction, 2004). The most generally applied is a factorial equation of the three components ($R = H\ x\ E\ x\ V$), but numerous other applications can also be detected in the literature (see Section 3). The contextualization, therefore, means a critical exam of the concreate features of the territory under evaluation in order to choose the most suitable risk's formula to apply.

Phase 2. Choice of the territorial scale of analysis.

In this phase, the applicative purposes, the aims for which the obtainable index must be used, and the possibility of available data are the three parameters from which it depends. If the evaluation is aimed at providing decision-making support to public (public administration) and private operators (real estate entrepreneurs, construction companies, investment companies) who operate in the planning of urban interventions of local interest (for example in neighborhoods, districts or areas of the city), it will be useful to adopt a sub-municipal scale. If, on the other hand, the index is aimed at monitoring the risk trend in the municipalities of a region or among the capitals and provinces of a nation, the metropolitan, provincial, regional or national scale may be more adequate. The territorial dimension chosen will not affect the possibility of ranking or comparing the individual areas (Frazier, 2012). Available data for the chosen dimension, instead, guide the decision due to the impossibility, if they don't exist, of carry out the entire analysis.

Phase 3. Identification of the initial set of the elementary indicators.

Identifying the characteristics of the urban fabric that contribute to the formation of natural risk makes it possible to characterize each component (*hazard, exposure* and *vulnerability*) through a system of elementary indicators that represent the fundamental factors that can be detected for the analysis. These can be both quantitative and qualitative, as long as they are reliable, complete, easily interpretable and consistent with the component to which they refer. Specifically, they can also derive from an elaboration/transformation of individual data, as in the case of a trend or of the variability of a certain characteristic of the area.

Phase 4. AHP structuring and data collection.

The risk components and the elementary indicators identified to represent them form the first two levels of the hierarchical structure of the AHP (Fig. 2). The last (third) level that complete the system is composed by the intensity ranges, or a number of variation values intervals of the indicators that allow to represent the variability of the information collected in the entire territorial area investigated. They can be identified by examining the average difference among the detected values of each indicators or the percentile of them. In this way, the components, indicators and intensity ranges represent the starting information system for the construction and determination of the risk index. The number of elementary indicators must be greater than or equal to 3 for each component, in order to allow the implementation of the subsequent operations of the methodology, whereas the intensity ranges must respect the sensitivity with which the indicator varies in order to be able to adequately take them into account in the index and ensure that this effectively represents the spatial distribution of the phenomenon. An example of the general structure and hierarchy of the elements is represented in Fig. 2.

Once the structure of the AHP has been completed, the data relating to the elementary indicators are collected and processed according to the territorial scale chosen. Then the identification of the intensity ranges for each one could be then carried out.

Phase 5. Indicators' normalization and correlation analysis.

The different units and measurement methods of the indicators do not allow to compare and aggregate them to form the risk index, therefore normalization is required. The technique used can produce a different result depending on whether it gives more importance to the highest and lowest values or to the average. Therefore, it should be chosen among those possible according to the purpose of the analysis. If cautionary natural risk assessments are required, techniques that give relevance to the highest and lowest values are preferred (for example z-score, min-max, distance to a references etc.); if instead assessments need to take into account all the average characteristics, other normalization techniques (for example, categorical scale) should be applied. After that, is necessary to guarantee the absence of high correlation among all the elementary indicators collected (level 2 of AHP). In fact, if there is a high correlation between two or more, the AHP could not be still suitable for the analysis, resulting inconsistent. Therefore, the highly correlated indicators (both positively and negatively) must be removed. If at the end of this operation the remaining elementary indicators for each component are less than 3, the conditions for applicability of the AHP do not exist and it is therefore necessary to identify new elementary indicators for that specific component. This until with after the repetition of the correlation analysis each component has at least 3 indicators. This condition is essential due to the impossibility of constructing pairwise comparison matrices of order 2 for determining the weights in the subsequent phases.

Phase 6. Local weight determination.

Each element that constitutes the system underlying the methodology for constructing the proposed natural risk index contributes in a different way to the determination of the index, and therefore, differently affect the level of risk. The importance of each element is determined through the construction of pairwise comparison matrices assisted by a panel of experts on the topic (environmental technicians, experts, architects and scholars) who formulate judgments of preference

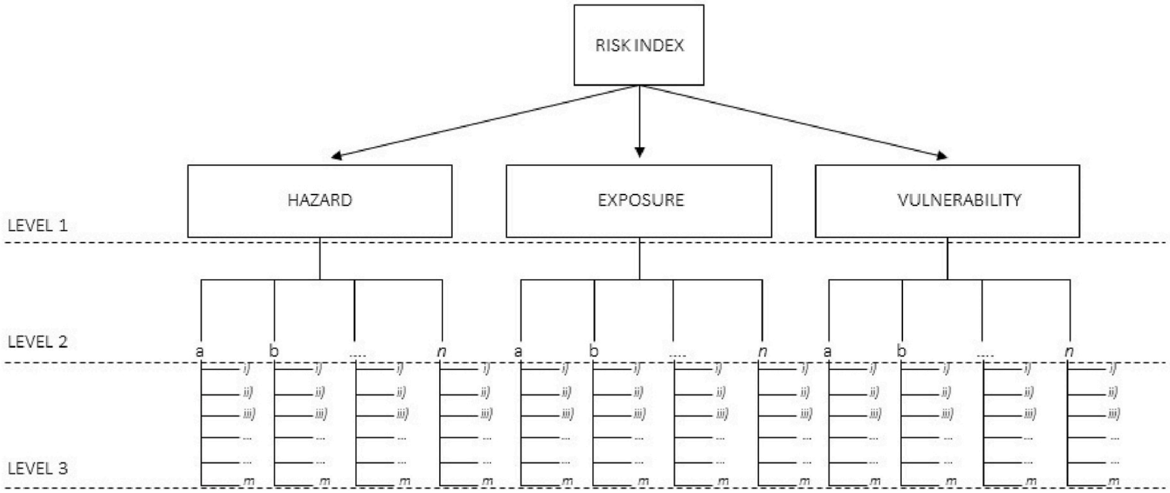


Fig. 2. Example of the general structure and hierarchy level of the AHP system.

for all the elements. The preferable assessment scale – able to transform the verbal judgement into numerical on–s - is the one proposed by Saaty (2008). Relevance is assumed by the control of the consistency of the opinions through the Consistency Ratio (CR), i.e. the fraction between the consistency of a given evaluation matrix and the associated Random Index, a tabulated value that correspond to the order of the matrix. If the CR is less than 0.1 the judgments are well formulated, otherwise they will have to be expressed with more attention.

Phase 7. Determination of the final natural disaster risk index (I_{NR}).

According to the definition of natural risk assumed as factorial formula in Phase 1 of this methodology (Balica, 2012), the determination of the risk index is carried out by applying the following Equation n.1:

$$\mathrm{I_{NR}} = P_{\mathrm{h}} \left(\sum_{n=1}^{n} v_{n,h} \cdot w_{n,m} \right) \cdot p_e \left(\sum_{n=1}^{n} v_{n,e} \cdot w_{n,m} \right) \cdot p_v \left(\sum_{n=1}^{n} v_{n,v} \cdot w_{n,m} \right) \tag{1}$$

With:

- p_h , p_e and p_v the local weights of the three risk components, respectively *hazard, exposure* and *vulnerability*;
- $v_{n,h}$, $v_{n,e}$ and $v_{n,v}$ the local weights determined through the pairwise comparisons matrices for the *n-th* indicators related to the *hazard* and the other two components, corresponding to *exposure* and *vulnerability*;
- $w_{n,m}$ is the weight of the defined *m-th* intensity range associated to the *n-th* indicator related to one of the risk components.

Eq. (1) refers to a weighted factorial formula of the three risk components based on the importance of each elements determined through the AHP's comparisons.

The sensitivity analysis evaluates the robustness of the entire weights, by examining the variation of the index's values produced by changing the importance of system's elements. It should be carried out for one of the hierarchical levels (e.g. components or indicators or intensity range) by constantly checking the CR. After that, it is necessary to carry out the validation, i.e. the assessment of the explanatory and predictive power of the index by using real world data, or experts' approval or comparisons with the results obtained by other model's applications on the same territorial scale. The type of validation must be chosen according to the availability of adequate data. In this way, the validation certifies the index's ability to be truly used to support real-world disaster planning.

Phase 8. Results georeferencing.

The index obtained expresses the natural risk of a single spatial portion of the therefore its georeferencing within the territorial perimeters chosen to conduct the assessment can be very useful. Numerous geographic information system (GIS) available online or through software implementation can be used for visualizing the spatial distribution of the index in the context analyzed. In this way, the georeferenced representation will facilitate the understanding, dissemination and acquisition of the results obtained with the proposed methodology, supporting the operators involved.

5. Part 2: methodology application

With reference to the territorial context of the city of Rome, the proposed protocol of phases is applied for the assessment of the level of natural risk to which the 155 administrative subdivisions that form the city are exposed. On the basis of the social, environmental and economic characterization of the context in analysis, the index obtainable from the proposed methodology is used to compare and rank the administrative areas of the municipal territory, so as to identify the most critical ones for which it is necessary to formulate interventions that improve the resilience's level. The choice of Rome depends on two main reasons: one is related to the highest rate of natural disasters that have occurred between the 2010–2020 period, the second instead concern the peculiarities of this city, characterized by high antique and fragile real estate assets of inestimable architectural, historical and cultural value built on soils with a high seismic and hydro-geological profile (Legambiente, 2020).

Phase 1. Natural disaster risk definition and contextualization.

The Italian territory is almost totally affected by geo-lithological and morphological conditions that expose it to high levels of natural risk, specifically volcanic and hydro-geological. The city of Rome is located in an area particularly close to the central areas of the country where high intensity seismic phenomena have always taken place (for example the earthquake that destroyed the nearby city o' L'Aquila in 2016) and it is in fact affected by 3 distinct levels of seismic risk: in the South-East the highest dang–r - grade 2 -, while in the North-West there is less ri–k - grade 3 -. In addition to this, the geo-lithological fragility conditions of the soil on which it stands make it frequently subject to landslides and alluvial phenomena, as declared by the Civil Protection Plans of the city of 2019 (https://www.comune.roma.it/web-resources/cms/documents/Fasc1_InformazioniCarattereGenerale.pdf).

Therefore, in this case study Hazard refers to the seismic, landslides and alluvial phenomena that affect the city, Exposure is intended the demographic, productivity and environmental features of the residential and non-residential public and private assets and the people that live or work within the administrative area considered, and then the Vulnerability consists of the built and natural environment conditions that define the capacity to reduce the potential damages and losses generated by the phenomena considered. Therefore, the proposed index is calculated according to Eq. (1) provided.

Phase 2. Choice of the territorial scale of analysis.

In order to support the public and private subjects in the decision-making process of sustainable urban planning, the territorial scale of analysis adopted is the sub-urban one. The survey unit are the 155 administrative territorial sub-division established in 1977 for statistical purposes and for planning and management of the territory, according to criteria of homogeneity from the urbanistic point of view (Fig. 3).

The alphanumeric codes that identify them are made up of the number of the governmental section to which they belong (according to the old numbering) and a progressive letter. It is possible, in fact, detect numerous information at this territorial scale.

Phase 3. identification of the initial set of the elementary indicators.

This phase is carried out by previously examining the characteristics of the urban fabric of Rome that contribute to forming the resilience level against natural disaster related to seismic, landslides and alluvial phenomena. The scientific reports done by Higher Institute for Environmental Protection and Research (HIEPR), the consultation with the socio-economic and environmental operators and the support of the research on similar case (Luberti et al., 2015), led to the identification of the initial set of the 23 elementary indicators for each administrative unit as reported in Table 3. Every risk component (Column n.1) is represented by a number of indicators (Column n.2) coherently determined with the analysis (Column n.3) and that have different unit of measure, both quantitative and qualitative (Column n.4), collected with the use of multiple sources, like geo-statistical software and documents (Column n.5). Due to the inestimable cultural and historical importance of the heritage that characterizes the city of Rome, the average unit market value of residential and non-residential asset is considered for measuring *exposure*. In fact, in the context of natural disasters, stocks value represents the usual choice of determining the expected losses, as a *proxy* of the monetary resources to be used for their restoration (De Bono and Mora, 2014; UNISDR, 2013; World Bank, 2006).

In some cases, a score has been attributed in order to detect plural existent conditions – such as the indicator c) of the *Hazard* component – or for the impossibility to have an average reference value for each administrative zone – as in the case of the indicator a) of the *Hazard* component -. In general, the entire numbers of indicators chosen for representing the three natural disasters analyzed for the city of Rome,

Fig. 3. Administrative sub-division of the municipal territory of the city of Rome.

are determined through the scoring rules following described:

Indicator a).

- seismic zone 2B (average danger) → score 1
- seismic zone 3A (high danger) → score 3
- seismic zone 3B (max danger)→ score 5

Indicator b).

- Absence of conditions deriving from hydraulic and alluvial risk → score 1
- Presence of sporadic flooding events → score 3
- Surface area involved by average hydraulic risk “R2” $\leq$ 20% total surface → score 5
- Extension of surface affected by average hydraulic risk “R2” between 20% and 50% of the total surface → score 7
- Area with average hydraulic risk “R2” $\geq$ 50% total surface → score 9
- Area affected by high hydraulic risk “R3” $\leq$ 20% total surface → score 11
- Extension of surface touched by high hydraulic risk “R3” between 20% and 50% of the total surface → score 13
- Surface impacted by high hydraulic risk “R3” $\geq$ 50% total surface → score 15
- Extension of the area affected by very high hydraulic risk “R4” $\leq$ 20% total surface → score 17
- Area involved with very high hydraulic risk “R4” $\geq$ 20% total surface → score 19

Indicator c).

- Presence of at least 1 of the following phenomena: i) sinking of the ground level, ii) movements landslides, iii) landslide areas and iv) areas with sporadic landslides → score 1
- Presence of at least 2 of the following phenomena: i) sinking of the plane of
- countryside, ii) landslides, iii) landslide areas and iv) areas with sporadic landslides → score 3

Table 3
Features of the initial set of indicators for the risk components.

Natural risk component	Indicators	Description	Unit ofmeasure	Source
HAZARD	a) Seismic	a) Seismic zoning of the city based on the ground acceleration	a) Ordinal scale	a) Civil Protection Plans of the city
	b) Alluvial and hydraulic	b) Presence of certain hydraulic or alluvial risk conditions and extent of the surface affected	b) Ordinal scale	b) Official map of the danger and geological vulnerability of the municipal area
	c) Landslide	c) Presence of certain risk conditions and extent of the surface affected by landslides	c) Ordinal scale	c) Official map of the danger and geological vulnerability of the municipal area
EXPOSURE	a) Population density	a) Number of inhabitants on unit km^2 of the administrative surface	a) Inhab./km^2	a) U-Geo Urbistat database
	b) Foreign resident	b) Percentage of foreign resident on total inhabitants	b) Percentage	b) U-Geo Urbistat database
	c) Daily tourist presences	c) Number of tourists passing from 8 a.m. to 8 p.m.	c) Number	c) U-Geo Urbistat database
	d) Diurnal population	d) Number of people passing from 8 a.m. to 8 p.m.	d) Number	d) U-Geo Urbistat database
	e) Touristic accommodations	e) Number of hotels and apartments for foreigners	e) Number	e) U-Geo Urbistat database
	f) Local productive activities	f) Number of effective commercial activities	f) Number	f) U-Geo Urbistat database
	g) Disposable income	g) Disposable income per inhabitant	g) €/inhab.	g) U-Geo Urbistat database
	h) Buildings	h) Number of public and private buildings	h) Number	h) U-Geo Urbistat database
	i) Value of residential assets	i) Average unit market value of residential buildings	i) €/m^2	i) Real Estate Market Observatory of the Italian Revenue Agency
	j) Value of non-residential assets	j) Average unit market value of non-residential buildings	j) €/m^2	j) Real Estate Market Observatory of the Italian Revenue Agency
	k) Intensity of agricultural activities	k) Extent of surface intended for agricultural uses	k) Ordinal scale	k) Official map of land use and vegetation physiognomies
VULNERABILITY	a) Soil drainage and filtration capacity	a) Land take rate	a) Impermeable surface/total administrative territorial surface	a) HIEPR report
	b) Young fragile people	b) Percentage of young people under 11 years old on total inhabitants	b) Percentage on total inhabitants	b) U-Geo Urbistat database
	c) Adult fragile people	c) Percentage of old people above 65 years old on total inhabitants	c) Percentage on total inhabitants	c) U-Geo Urbistat database
	d) Inhabitants	d) Number of inhabitants	d) Total number of residents	d) U-Geo Urbistat database
	e) Dangerous buildings	e) Percentage of abandoned or disused buildings on total properties	e) Percentage on total buildings	e) U-Geo Urbistat database
	f) Fragile buildings	f) Percentage of buildings constructed before the 1970 on total properties	f) Percentage on total buildings	f) U-Geo Urbistat database
	g) Air pollution level	g) Average annual concentrations (μg/m^3) of $PM_{2.5}$ dust	g) Ordinal scale	g) http://romariasalute.it/?page_id=451
	h) Winter urban heat island	h) Average C° degrees of winter temperature measured on the ground	h) C°	h) Marando et al. (2019)
	i) Summer urban heat island	i) Average C° degrees of summer temperature measured on the ground	i) C°	i) Marando et al. (2019)

- Presence of at least 3 of the following phenomena: i) sinking of the plane of
- countryside, ii) landslides, iii) landslide areas and iv) areas with sporadic landslides → score 5
- Presence of the following phenomena: i) sinking of the plane of countryside, ii) landslides, iii) landslide areas and iv) areas with sporadic landslides → score 7

The adopted scoring rules derive from the consultation of a panel of technicians and engineers who support the Civil Protection in the development of the city's urban planning. It permits to standardize the several information data that the work wants to detect and reveal on the indicators considered. Moreover, the scoring rules adopted allow to highlight the differences among the administrative units.

The *Exposure* indicators from a) to h) provide info on the potential social losses and are collected by the U-Geo Urbistat database, a private system which contains georeferenced info on population and built environment at different territorial scale according to the National Institute of Statistic (ISTAT) data release about the last census of 2019 and 2020.

The indicators related to the values of residential and non-residential assets within the administrative area are utilized to represent the potential damage provoked on the properties. They are detected from the Real Estate Market Observatory (REMO) of the Italian Revenue Agency, an institute that every six months provides quotations on the unit market and rental values in the local real estate market areas that constitutes the city and for different type of buildings (https://www1.agenziaentrate.gov.it/servizi/Consultazione/ricerca.htm). Therefore, the unit average market values of the residential asset are determined through the mean quotation of the apartments, garage and uncovered parking space, instead for the non-residential properties the average quotation of shops, offices and laboratories, both of them updated on the second semester of 2020.

The intensity of the agricultural activity (k) refers to the local productivity potential injuries by considering the surface within the administrative unit intended for i) arable land, ii) permanent and iii) heterogeneous crops. Depending on whether the extension of the agricultural area used is absent, less than 20%, between 20% and 50% and more than 50% of the land area of the entire administrative unit, a score of 1, 3, 5 and 7 is respectively assigned.

The *Vulnerability* indicators show the critical and optimal conditions that, in the case of a natural disaster occurrence, increase or decrease damages of social, economic and natural environment. In other words, they are the most influential parameters that determine the resilience level of the administrative area. In particular, the soil drainage and filtration capacity – or the land take rate – is calculated with the sum of all the km^2 of impermeable surface discovered by HIEPR from the 2016 to 2019 in the administrative units. The indicators related to the most fragile population and buildings – from b) to f) – are collected by acquiring the social info of the U-Geo Urbistat database updated to the last census of 2019. The air pollution level (g) is a qualitative indicator determined by calculating the $PM_{2.5}$ concentration and assigning a score as follows: from 13.0 to 17.5 μg/m^3 → score 1; between 17.5 and 20.0 μg/m^3 → score 3; from 20.0 to 28.5 m^3 → score 5. For establishing the linkages between urban heat island and natural risk disasters in the city of Rome, the indicators h) and i) are proxy variables and refer to the average temperature of the soil extrapolated in the research work of Marando et al. (2019).

Phase 4. AHP structuring and data collection.

As represented in Fig. 2 the three risk component, identified in *hazard, exposure* and *vulnerability* form the first hierarchical level of the AHP multicriteria technique, whereas the initial set of 23 indicators, respectively 3 for the *hazard*, 11 for the *exposure* and 9 for the *vulnerability*, constitute the second hierarchical level. The analysis of the data collected for every administrative unit within the municipal territory of Rome, allows to know the variability and therefore identify the number of intensity ranges for each indicator, that constitute the third hierarchical level of the AHP structure.

Phase 5. indicators' normalization and correlation analysis.

This phase allows to define a robust indicators-based system for the final risk index. Due to the several different units of measures of the 23 initial indicators collected, the z-score normalization technique is applied to obtain values that can be compared and aggregated into the I_{NR}. Indicating with μ the average value of the *n-th* indicator among the 155 administrative units, with σ the associated standard deviation and with x the collected value, the normalization is obtained by applying Eq. (2):

$$x_n = \frac{x - \mu}{\sigma} \tag{2a}$$

Table A1 of the Supplementary File provides the correlation analysis with the Pearson's coefficient.

For the *Vulnerability* component, the number of inhabitants (indicator d) appear to be highly correlated (Pearson coefficient = 1,00) with the *Exposure* component's indicator e) – touristic accommodations -. Similar condition is verified for the *Exposure* indicators related to: i) the diurnal population and the number of local productive activities d) - f) and ii) the value of the residential assets with the value of the non-residential onI (i and j). Therefore, in accordance with the examination of the highest average correlation level but also reducing redundancy, the number of inhabitants, the value of the non-residential asset and the daily population are removed. In this way, the final set of 20 indicators thus constituted – 3 for the *Hazard*, 9 for the *Exposure* and 8 for the *Vulnerability* component - is obtained (Fig. 4).

Phase 6. local weight determination.

A panel of expert composed by geological technician, architects, engineers, and real estate operators support the phase of the judgements that are able to identify the relative importance of each intensity range and indicators. In this study the weight of the three risk components (level 1) is assumed to be the same, equal to 1, according to the shared panel of expert's suggestion for which the difference among them, in terms of contribution to the formation of natural risk, is little for the territorial context of the city of Rome, the conditions of which, therefore, allow it to be taken into account equally. For these reasons, the local weight determination phase regards only the intensity ranges and indicators levels. In particular, 1 pairwise comparison matrix of order 3 is created for the relative importance of three indicators with respect to the *Hazard* component; 1 matrix of order 9 is constructed for the relative significance of the nine *Exposure*'s indicators and a 8 × 8 pairwise matrix is intended for determining the local weights of the eights *Vulnerability*'s factors. For the intensity ranges, instead, the following pairwise comparisons listed in Table 4 are made:

It should be noted that the quality of the outputs of the AHP depends

Table 4
List of comparison matrix for the local weights' determination of the intensity ranges.

Risk component	Indicators	Pairwise matrix
HAZARD	a)	• One of order 3
	b)	• One of order 10
	c)	• One of order 4
EXPOSURE	a)	• One of order 10
	b)	• One of order 6
	c)	• One of order 6
	e)	• One of order 6
	f)	• One of order 10
	g)	• One of order 10
	h)	• One of order 10
	i)	• One of order 10
	k)	• One of order 4
VULNERABILITY	a)	• One of order 10
	b)	• One of order 6
	c)	• One of order 6
	e)	• One of order 6
	f)	• One of order 6
	g)	• One of order 3
	h)	• One of order 6
	i)	• One of order 6

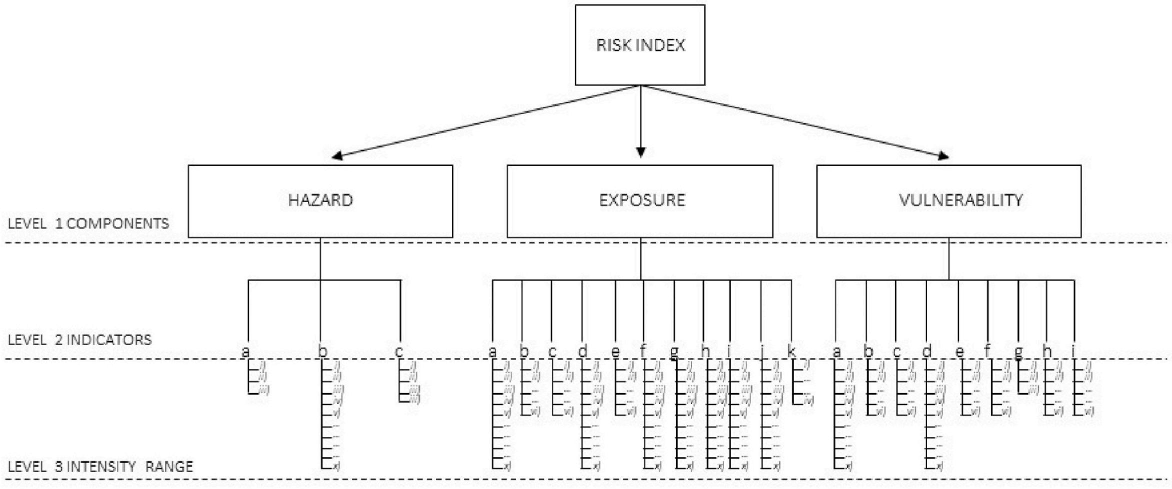


Fig. 4. Final set of indicators system.

on the consistency of the pairwise comparison judgments. Considering n ordered indicators or intensity ranges, a $n_x n$ judgment's matrix is defined: each element of the upper diagonal side $a_{ij} > 0$ is the results of the comparison between the *i-th* with the *j-th* element through the application of the Saaty's fundament scale (Table 5).

The coherence is verified by considering the principal eigenvalue $\lambda_{\max}$ for determining the Consistency Index (CI) with Eq. (2):

$$CI = (\lambda_{max} - n) / (n-1) \tag{2b}$$

Therefore, to check the effective consistency of the judgments the final Consistency Ratio (CR) is calculated as expressed in Eq. (3).

$$CR = [(\lambda_{max} - n) / (n-1)]/RI \tag{3}$$

Where $\lambda_{\max}$ is the principal eigenvalue, n the order of the pairwise matrix and RI the Random Index, or a tabulated value that vary according to the order n of the matrix and reported in Figure A2 of Supplementary Files. The maximum threshold of the CR is 0.1, and it increases if the inconsistency of the judgment's matrix rises. If it is exceeded, a three-step procedure is followed: i) identification of the most inconsistent judgment in the pairwise matrix; ii) survey with the panel of experts, to determine a new reasonable judgment so that it would reduce the inconsistency; iii) validation of the reasonable value with respect to the others (Saaty, 2001). Therefore, the level of consistency verified for the indicators and intensity range levels is reported in Table A2 of the Supplementary File. Finally, the local weights are determined for each indicator and intensity range, in order to obtain the essential parameters to aggregate in the final risk index. In Table 6 the local weights are reported.

Phase 7. determination of the final natural disaster risk index (I_{NR}).

The application of the proposed methodology provides a risk index related to the natural disaster level for the entire urban area within the *i-th* administrative unit considered in the analysis. Therefore, according to the risk definition specified in the *Phase 1. Natural disaster risk definition and contextualization* for the city of Rome and by employing the arithmetic formula of Eq. (1) for each of the 155 administrative units considered, the final natural disaster risk index (I_{NR}) is obtained.

Successively, a sensitivity analysis is performed for verifying the accuracy and robustness of the index by considering 4 scenarios characterized by different average weights of the indicators pertaining to each of the three risk components. In particular, the analysis intends to verify the ranking differences that occur between the risk level of the 155 administrative units, with a focus on the highest and lowest risk units, therefore the top 10% and the last 10% of the total considered. In every scenarios the CR are constantly checked and guaranteed.

The "Scenario 0" refers to the local weights derived by the pairwise comparison matrices and the panel of expert judgments on the indicators and intensity ranges detected for each administrative unit. Its ranking is the comparative reference for the evaluation of its robustness with the other 3 scenarios characterized by equal importance of all the indicators (Scenario 1), greater relevance of those that affect the vulnerability of the urban area (Scenario 2) and much more attention on the exposure's urban features (Scenario 3) while keeping constant the weights of the other two components in both cases, in order to assess the effects generated on the final risk index by each sub-set of indicators.

Table 5
Saaty's fundamental verbal scale.

aij	Verbal scale
1	Equal importance
3	Moderate importance of i over j
5	Strong importance of i over j
7	Very strong importance of i over j
9	High importance of i over j
1.5-2.5-4-6-8 etc	Intermediate importance between i and j
1/3, 1/5. etc	Reciprocal of the lower side of diagonal

The results obtained are shown in Table 7 where, below the average weights of the indicators of each scenario, the relative ranking referring to 10% of the upper and lower units, listed by decreasing levels of the risk index, is reported.

The results obtained confirm the robustness of the weights delivered in the reference "Scenario 0". In fact, it is possible to note that as the average weight of the *vulnerability* indicators increases or is the same of the other two components (Scenario 1 and 2), the ranks of the riskiest 10% of the administrative units don't change significantly, as happens for the most resilient ones (lower 10%). The *17b* unit, remains at the first position whereas the *7e* and *7g* are confirmed as those with the absolute lowest natural risk index level in the entire municipal area. The rank is a little bit different in the case of the "Scenario 3", for which more relevance is attributed to the *exposure*'s sub-set of indicators, with unit *16d* rising from third to first place and *17b* falling to third, while nothing changes for the most resilient ones.

After having checked the robustness of the indicators' weights, the last step toward constructing a sound risk index is represented by the validation of the model. Index validation is an important final step in index creation, but it is rarely performed. Many resilience indices rely on theoretical justifications that do not guarantee that the metrics selected will meaningfully relate to specific outcomes of interest. Empirical validation, on the other hand, assesses the explanatory power of an index using real world observations and can estimate the ability of an index to explain a variety of disaster losses, thereby giving confidence in index ability and performance to end users (Bakkensen et al., 2017). Model validation consists of several methods that can be applied for judging the accuracy in making relevant and consistent results. Several modalities for validation exist, classified as follows: i) expert validation, when the results obtained are checked by a panel of sector specialists who, on the basis of their extensive experience, judge the reliability the index values; ii) observed data validation, or the comparison with existent information on the natural hazards considered that can confirm the results (e.g number of death, destroyed buildings, economic losses etc.); iii) algorithm validation, that is carried out when the index's values provided by another synthetic index's building model are compared with those of the proposed technique.

In the present research a validation based on algorithm's comparison is implemented. In particular, the BoD approach is used for creating a natural disaster's risk index for the same territorial scale considered with the AHP in order to compare the ranking of the final results among the administrative units. As just described in a previous study (Morano et al., 2021), in the BoD approach the synthetic index is defined as the ratio of the actual indicator's normalized value of an administrative units to its benchmark reference. In Eq. (4) the mathematical function used to calculate the natural disaster's risk index through the BoD approach is reported:

$$I_{NR}(BoD) = \frac{\sum_{i=1}^{N} I_n \cdot w_n}{\sum_{i=1}^{N} I_n^* \cdot w_n^*} \tag{4}$$

Where I_n is the normalized value of the *n-th* indica–ors - of the final set obtained by removing the high correlated–one - for each administrative unit and w_n represents the corresponding weight. Below the ratio there are instead the benchmark elements and therefore I^*_n is the value of the *n-th* indicators that refers to the hypothetical administrative unit that has the best overall performance, given the set of weights w^*_n to be calculated as a solution of the following maximization problem:

$$\text{OBJECTIVE FUNCTION Max!} \left(\sum_{i=1}^{N} I_n^* \cdot w_n^* \right)$$

$$\text{CONSTRAINTS} \quad \sum_{i=1}^{N} I_n^* \cdot w_n^* \geq 0 \quad w_n^* \geq 0$$

Table 6
Local weights of risks components, indicators and intensity ranges obtained.

Component	Local weight	Indicators	Local weight	Intensity range	Local weight
HAZARD	1	a) seismic	0.93	Equal to 1	0.45
				Equal to 3	0.67
				Equal to 5	1.00
		b) alluvial and hydraulic	1.00	Equal to 1	0.14
				Equal to 3	0.17
				Equal to 5	0.24
				Equal to 7	0.29
				Equal to 9	0.36
				Equal to 11	0.45
				Equal to 13	0.51
				Equal to 15	0.72
				Equal to 17	0.90
				Equal to 19	1.00
		c) landslides	0.97	Equal to 1	0.43
				Equal to 3	0.53
				Equal to 5	0.83
				Equal to 7	1.00
EXPOSURE	1	a) population density	1.00	<160.78	0.14
				160.78–511.56	0.18
				511.56–1224.44	0.23
				1224.44–2753.72	0.30
				2753.72–5275.9	0.36
				5275.9–6275.24	0.45
				6275.24–8034	0.55
				8034–10,751.2	0.66
				10,751.2–14,252.8	0.82
				>14,252.8	1.00
		b) foreign residents	0.26	<6.38	0.26
				6.38–9.2	0.42
				9.2–11.1	0.53
				11.1–14.58	0.65
				14.58–22.52	0.83
				>22.52	1.00
		c) daily tourist precences	0.37	<45.2	0.11
				45.2–102.6	0.15
				102.6–217	0.21
				217–449.2	0.28
				449.2–2200.8	0.64
				>2200.8	1.00
		e) touristic accomodations	0.47	<10	0.32
				10–57	0.46
				57–110	0.53
				110–173.8	0.68
				173.8–263.4	0.71
				>263.4	1.00
		f) local productive activities	0.51	<260.2	0.13
				260.2–477	0.17
				477–632.8	0.24
				362.8–877.8	0.30
				877.8–1213	0.34
				1213–1516.6	0.46
				1516.6–1977.6	0.55
				1977.6–3041.6	0.60
				3041.6–4096.6	0.74
				>4096.6	1.00
		g) disposable income	0.51	<15,370.2	0.12
				15,370.2–16,306.4	0.17
				16,306.4–17,407.4	0.24
				17,407.4–18,810.2	0.30
				18,810.2–19,954	0.34
				19,954–21,769.6	0.47
				21,769.6–23,408.8	0.55
				23,408.8–26,085.4	0.60
				26,085.4–31,550.4	0.74
				>31,550.4	1.00
		h) buildings	0.24	<188	0.10
				188–299.2	0.15
				299.2–419	0.20
				419–560	0.24
				560–810	0.32
				810–973.8	0.42
				973.8–1172.6	0.51
				1172.6–1710.6	0.62
				1710.6–2336	0.79

(*continued on next page*)

Table 6 (*continued*)

Component	Local weight	Indicators	Local weight	Intensity range	Local weight
				>2336	1.00
		i) value of residential assets	0.68	<1434.58	0.14
				1434.58–1553.44	0.17
				1553.44–1619.47	0.24
				1619.47–1723.13	0.29
				1723.13–1798.13	0.35
				1798.13–1933.75	0.45
				1973.75–2138.10	0.56
				2138.10–2525.83	0.71
				2525.83–3417.50	0.83
				>3417.50	1.00
		k) intensity of agricultural activities	0.63	Equal to 1	0.14
				Equal to 3	0.43
				Equal to 5	0.71
				Equal to 7	1.00
VULNERABILITY	1	a) soil drainage and filtration capacity	0.52	<446.23	0.08
				446.23–650.01	0.10
				650.01–778.91	0.13
				778.91–986.44	0.17
				986.44–1203.31	0.20
				1203.31–1317.13	0.30
				1317.13–1563.42	0.41
				1563.42–1886.3	0.58
				1886.3–2579.13	0.75
				>2579.13	1.00
		b) young fragile people	0.85	<7.84	0.24
				7.84–9.1	0.39
				9.1–9.8	0.51
				9.8–11.4	0.69
				11.4–13.7	0.85
				>13.7	1.00
		c) adult fragile people	1.00	<13.9	0.26
				13.9–17.62	0.43
				17.62–21.9	0.53
				21.9–25.88	0.70
				25.88–28.82	0.85
				>28.82	1.00
		e) dangerous buildings	0.34	<2.84	0.17
				2.84–6.3	0.21
				6.3–9.7	0.32
				9.7–12.98	0.52
				12.98–21.46	0.75
				>21.46	1.00
		f) fragile buildings	0.59	<19.14	0.17
				19.14–42.82	0.25
				42.82–64.9	0.34
				64.9–87.66	0.52
				87.66–97.46	0.82
				>97.46	1.00
		g) air pollution level	0.12	Equal to 1	1.00
				Equal to 3	0.45
				Equal to 5	0.18
		h) winter urban heat island	0.13	<8.21	0.16
				8.21–8.26	0.23
				8.26–9.68	0.33
				9.68–11.07	0.49
				11.07–12.49	0.73
				>12.49	1.00
		i) summer urban heat island	0.14	<35.98	0.17
				35.98–38.82	0.22
				38.82–38.90	0.34
				38.90–44.48	0.49
				44.48–44.54	0.72
				>44.54	1.00

A problem of linear programming is set to choose the weights that maximize the risk index value. The highest relative weights are assigned to the indicators for which the i-th administrative units achieves the best relative performance in comparison to the others of the city of Rome. The only constraints regard the non-negativity. For the w_n weights that refer to the actual condition of the administrative units, a BAP is done by asking to the same panel of expert the importance of each of the 20 indicators affecting natural disasters' level in Rome. As a result, the risk index ranges between 0 and 1, the higher value the better performance in relative terms. For more administrative units the value of the index could be equal to 1.

Therefore, according to the results of the BoD approach (I_{NR} *BoD*) and the ones obtained with the AHP (I_{NR} *AHP*), the comparison of the risk values that represent the resilience level of the 155 administrative units of the city of Rome is carried out in Table 8.

As shown in Table 8, the values of the two assessment models are quite consistent with each other. The differences in the ranking of the administrative units are mostly for the intermediate positions. The upper

Table 7
Sensitivity analysis results.

Sub-set indicators		Average weights			
		Scenario 0	Scenario 1	Scenario 2	Scenario 3
Vulnerability risk component		0.46	0.53	0.71	0.46
Exposure risk component		0.49	0.53	0.49	0.78
Hazard risk component		0.97	0.53	0.97	0.97
RANKING	HIGHER 10%	17b - 19a - 16d - 18b - 19g - 1e - 20d - 16f - 18a - 1f - 2d - 13f - 19b - 3a - 18f	17b - 19a - 18b - 16d - 1e - 19g - 1f - 13f - 18a - 20d - 16f - 2d - 20a - 13e - 3a	17b - 16d - 19a -1e - 1f - 19g - 2d –16f - 18b - 3a - 15a –13f - 15g - 13e - 19b	16d - 19a - 17b–18b - 1e - 13e - 20d - 19b - 18a - 15a - 19g - 16f - 1f - 2d - 16b
	LOWER 10%	7e - 7g - 10x - 12m - 8a - 12x - 11g - 10f - 10e - 7d - 10i - 10g - 11d - 11f - 11b	7e - 7g - 10x - 8a –10f - 12m - 12x –11g - 10e -7d - 10i - 11d - 4d –11f - 10g	7e - 7g–11g - 12m - 10x - 11d - 10e - 12x - 8a - 10i - 7d - 11f - 10g - 4d - 10f	7e - 7g–11g - 12m - 10x - 11d - 8a - 10e - 12x - 7d - 10i - 10g - 10f –11f - 5d

side highlights the elevated risk levels of the *17b, 19a, 16d, 18b* administrative units whereas the most resilient are confirmed to be the *12m, 10x, 7g, 7e.* The validation process based on the comparison of the risk values obtained between the AHP and BoD approaches allows to underline the robustness of the risk index provided by the AHP, demonstrating its usefulness but above all the possibility of obtaining valid results in a simpler way.

Phase 8. results georeferencing.

The application of the methodology allowed to get 155 natural disaster risk indexes (I_{NR}), whose normalized values between 0 and 1 are represented in the map of Fig. 5 throughout a georeferencing process performed with a GIS software. Six ranges of risk values, each of them associated to a color, are identified for an immediate visualization of the spatial distribution of the I_{NR} described in Fig. 5.

6. Results discussion

By observing the risk map of Fig. 5, about 37% of the 155 administrative units of the city of Rome falls within the medium-high risk level, instead the remaining 63% appears to be more resilient and less exposed to the three natural disasters considered in the analysis (seismic, alluvial and landslide).

Taking into account that the "Tevere" river represents a divider of the city into two parties - the first one on its western side and the second one on its eastern side - the general worst condition of the western side (color red) is immediately evident. The areas closer to the "Tevere" are highly exposed because, in fact, in addition to being subject to flooding of the river floods, are located in zones with medium-high risk of seismic and landslides. To those ones the administrative units with the highest risk index value are included: the *17b*, *19a* and *16d* with values of I_{NR} respectively equal to 1.00, 0.89 and 0.86. Regarding the component of *Exposure,* the indicator f) "local productive activities" has a considerable weight on the *17b* area, as it has about 12,943 activities resulting as the maximum number of the city. For the *Vulnerability*, instead, the *17b* area is characterized by the 98% of the buildings of fragile type constructed before the 1930 - indicator f) fragile building -, therefore, highly inadequate to withstand the natural disasters to which the city is subjected, increasing the risk of human damage. Moreover, for the *19a* administrative area the percentage of fragile buildings related to the *Vulnerability* component is high, equal to 91.7%. This condition with the value of the indicators a), g) and i) – or population density, disposable income and value of the residential asset – related to the *Exposure* component significantly higher than the average of the city determines that the administrative zone is not very resilient but extremely vulnerable to multi-hazards. For the *16d* administrative zone, instead, the indicator a) soil drainage and filtration capacity of the *Vulnerability* component, affects in a serious way its risk level. In fact, with about 1742 ha of natural soil transformed into impermeable for constructing buildings, roads and infrastructures, the *16d* is one of the suburban areas of Rome that has only 10% filtration capacity. Furthermore, for the *Exposure* component the prestigious residential assets with a value - indicator i) - above the city average is important to point out which, together with the previous indicators, gives to the administrative unit a considerable fragility.

On the Eastern side of the "Tevere" river, the natural risk levels are minor, especially in the sub-urban areas far from its river. On the South-East area of the city the most resilient administrative units are located: the *7e* and *7g* with I_{NR} equal to 0.12 and 0.16. From the point of view of the *Hazard* component, both two areas score 1 to all of the three natural hazards considered. Regarding the *Exposure* component, the indicators i) and k) – value of the residential assets and extension of the cultivated surface – are for both the areas very low, respectively 1387.50 €/m^2 and score 1 for the *7e* and 1553.33 €/m^2 and score 3 for the *7g*. The contingence that the residential asset is not so prestigious is due to the fact that the buildings in these areas have been recently built, often with economic features but the overall performance from a structural point of view is much better than the ones located on the western side of the "Tevere" and close to it. The limited extension of the cultivated surface means small economic damages to crops. About the *Vulnerability* component, instead, the indicators a), b), c), d) and f) - soil drainage and filtration capacity, young fragile people, adult fragile people, dangerous buildings, fragile buildings – are characterized by very low rating. This means that a low rate of natural soil has been waterproofed (only 406 and 383 ha), fragile population does not live there (a median of 13.9% for the *7e* and 15.7% for the *7g*) and the buildings are recently built and therefore performing (an average of 7% for the *7e* and 33% for the *7g* on the total number of buildings). All these features give to the administrative units *7e* and *7g* more strength to resist and minimize the potential damages and losses that could derive from the occurrence of the natural hazards considered.

In general terms, the following recommendations for improving the resilience level of the most vulnerable sub-urban areas of the city are provided:

- Structural conservation and refurbishment of the old and fragile buildings;
- Extension and creation of new urban green areas that increase the soil filtration capacity of the most impermeable urban surfaces;
- Adequate civil protection that supports the fragile population that lives there during hazard's attack;
- Better maintenance action of the "Tevere" river and the related network to prevent the most damaging floods.

The heterogeneity with which the level of natural risk is spatially distributed into the city of Rome highlights how the different features of the urban tissue affect the vulnerability. For efficient improvements, specific and adequate urban planning plans need to be urgently included in the urban transformation's procedure (e.g. public-private partnership) (Morano et al., 2021).

7. Conclusions

The increase of floods, earthquake and landslides is linked to the worsening condition of the natural environment provided by the increasing activity of the human development and, in particular, the land take and the unsustainable urban soil uses. The risk of natural disasters has thus increased, determining that the public authorities involved are affected by more difficult and expensive processes of recovery after the occurrence of disasters. For these reasons, the need of

Table 8

Validation of the results of the risk index obtained with the AHP and the BoD approach.

Administrative Unit	$\mathrm{I_{NR}(AHP)} = p_h\ ((\sum_{n=1}^{n} v_{n,h} \cdot w_{n,m}\ ) \cdot p_e(\sum_{n=1}^{n} v_{n,e}\ \cdot w_{n,m}\ )\cdot p_v(\sum_{n=1}^{n} v_{n,v}\ \cdot w_{n,m}\ )$	$\mathrm{I_{NR}(BoD)} = \frac{\sum_{i=1}^{N} I_n \cdot w_n}{\sum_{i=1}^{N} I_n^* \cdot w_n^*}$
17b	1.00	1.00
19a	0.89	1.00
16d	0.86	1.00
18b	0.82	1.00
19g	0.82	0.90
1e	0.81	0.94
20d	0.80	0.91
16f	0.79	0.90
18a	0.79	0.88
1f	0.78	0.89
2d	0.78	0.87
13f	0.76	0.86
19b	0.74	0.84
3a	0.73	0.84
18f	0.73	0.82
20a	0.72	0.83
13e	0.72	0.76
15g	0.71	0.75
15a	0.70	0.76
1a	0.69	0.73
16b	0.69	0.72
20m	0.68	0.68
18d	0.68	0.69
2e	0.68	0.71
13b	0.67	0.67
20h	0.67	0.65
17a	0.65	0.63
19d	0.63	0.63
15d	0.62	0.62
20e	0.61	0.62
16a	0.61	0.61
20c	0.61	0.62
13g	0.60	0.59
20n	0.59	0.59
13i	0.58	0.57
2c	0.57	0.56
2b	0.55	0.54
17c	0.55	0.54
20i	0.55	0.56
9a	0.54	0.54
6a	0.54	0.55
15b	0.54	0.55
15f	0.54	0.53
4h	0.53	0.54
11x	0.52	0.54
4b	0.52	0.51
12a	0.52	0.53
13d	0.51	0.53
15e	0.51	0.52
12h	0.51	0.50
18c	0.50	0.52
19c	0.50	0.52
4a	0.50	0.51
19h	0.50	0.51
7a	0.50	0.50
1b	0.48	0.49
9b	0.48	0.48
10d	0.47	0.50
19e	0.47	0.50
10b	0.46	0.50
8e	0.46	0.50
13c	0.45	0.49
4c	0.45	0.48
11c	0.45	0.49
1d	0.45	0.49
19f	0.45	0.47
12i	0.45	0.47
20x	0.45	0.45
20l	0.44	0.47
4e	0.44	0.46
1g	0.44	0.46
20g	0.44	0.46
9d	0.43	0.45

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Table 8 (*continued*)

Administrative Unit	$I_{NR}(AHP) = p_h\ ((\sum_{n=1}^{n} v_{n,h} \cdot w_{n,m}\ ) \cdot p_e(\sum_{n=1}^{n} v_{n,e}\ \cdot w_{n,m}\ )\cdot p_v(\sum_{n=1}^{n} v_{n,v}\ \cdot w_{n,m}\ )$	$I_{NR}(BoD) = \frac{\sum_{i=1}^{N} I_n \cdot w_n}{\sum_{i=1}^{N} I_n^* \cdot w_n^*}$
20b	0.43	0.44
20°	0.43	0.43
12e	0.43	0.44
5g	0.43	0.45
3b	0.43	0.45
20f	0.42	0.45
5e	0.42	0.44
15c	0.42	0.44
5l	0.41	0.43
2x	0.41	0.43
13a	0.41	0.43
9e	0.41	0.43
16c	0.40	0.43
8f	0.40	0.42
4°	0.40	0.42
1c	0.39	0.42
3x	0.39	0.41
8g	0.39	0.41
11e	0.39	0.41
4n	0.39	0.39
18e	0.38	0.39
4i	0.38	0.38
12c	0.38	0.38
8h	0.38	0.37
1x	0.37	0.36
5c	0.37	0.36
12l	0.37	0.35
5h	0.36	0.35
13h	0.36	0.34
4f	0.36	0.34
10a	0.35	0.34
12f	0.35	0.34
6d	0.35	0.34
12b	0.35	0.33
4g	0.34	0.33
16x	0.34	0.30
6c	0.34	0.29
4m	0.33	0.29
6b	0.32	0.29
7c	0.32	0.28
4l	0.32	0.30
5b	0.32	0.30
2a	0.32	0.30
8b	0.31	0.30
12n	0.31	0.30
12g	0.30	0.29
8c	0.30	0.29
2y	0.30	0.29
9c	0.30	0.27
12d	0.29	0.27
11a	0.29	0.27
16e	0.29	0.27
5i	0.28	0.27
7b	0.28	0.26
10c	0.28	0.25
7f	0.28	0.24
13x	0.28	0.24
5a	0.28	0.24
10l	0.27	0.24
8d	0.27	0.24
10h	0.26	0.22
5f	0.26	0.22
11y	0.25	0.20
3y	0.25	0.17
5d	0.24	0.17
4d	0.24	0.16
7h	0.24	0.16
11b	0.23	0.15
11f	0.22	0.14
11d	0.21	0.14
10g	0.21	0.14
10i	0.21	0.14
7d	0.20	0.14
10e	0.19	0.13

(*continued on next page*)

Table 8 (*continued*)

Administrative Unit	$I_{NR}(AHP) = p_h\left(\left(\sum_{n=1}^{n} v_{n,h} \cdot w_{n,m}\right) \cdot p_e\left(\sum_{n=1}^{n} v_{n,e} \cdot w_{n,m}\right) \cdot p_v\left(\sum_{n=1}^{n} v_{n,v} \cdot w_{n,m}\right)\right.$	$I_{NR}(BoD) = \frac{\sum_{i=1}^{N} I_n \cdot w_n}{\sum_{i=1}^{N} I_n^* \cdot w_n^*}$
10f	0.18	0.13
11g	0.18	0.11
12x	0.18	0.11
8a	0.18	0.11
12m	0.17	0.10
10x	0.17	0.09
7g	0.16	0.08
7e	0.12	0.08

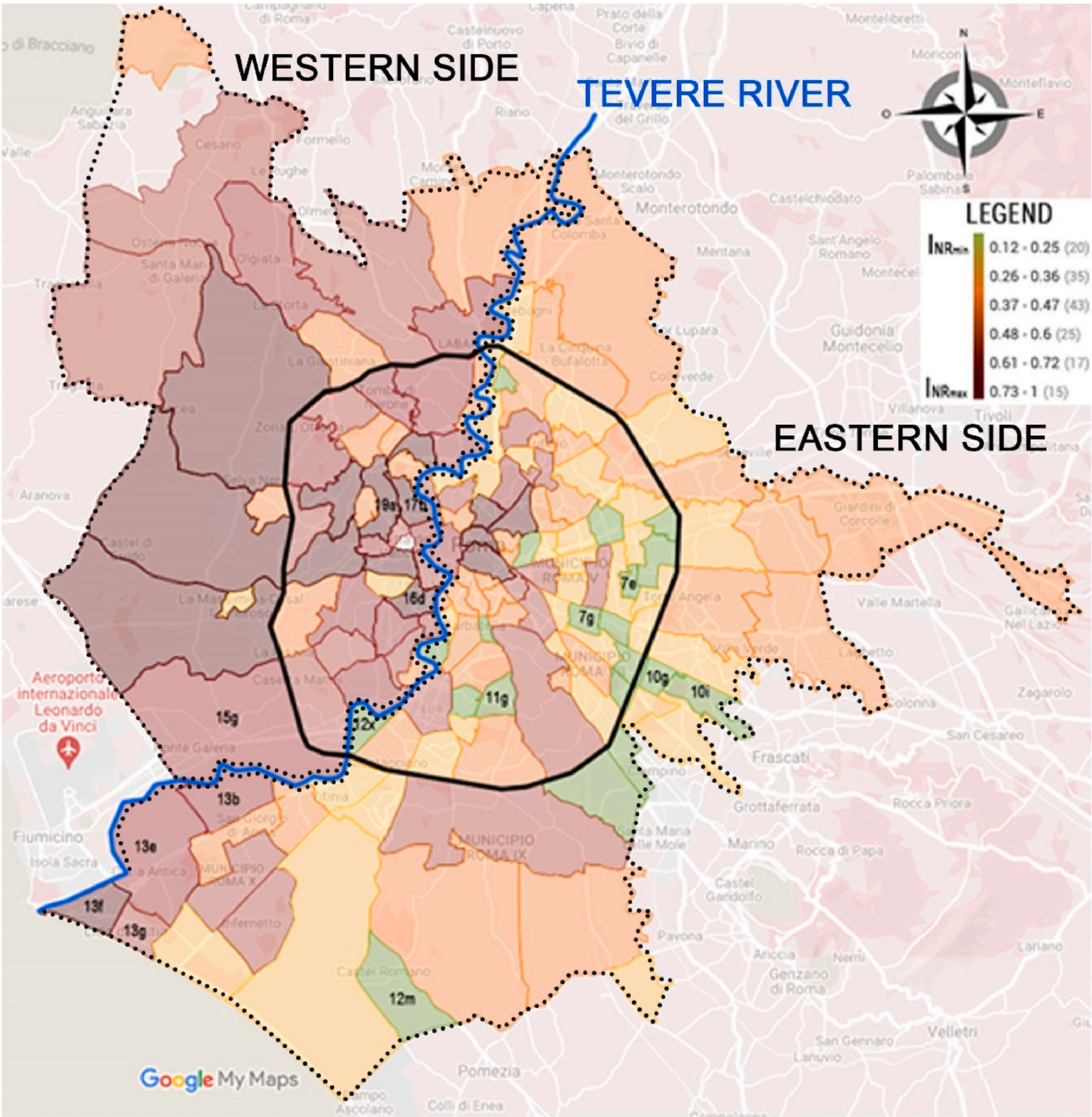


Fig. 5. Map of the spatial distribution of the natural disaster risk indexes obtained for the city of Rome.

having adequate knowledge of the most critical or resilient areas within the city is essential to provide efficient management of this kind of diseases. Due to the multidimensionality that characterizes the natural disasters, the MCDM have been largely applied for creating adequate synthetic indexes that can represent the risk levels of the territorial context under analysis. It is important to highlight that the main useful parameters that the assessment model requires for supporting the urban resilience improvement are: i) the ability to accomplish both quantitative and qualitative data's analysis, ii) the scoring or ranking of the spatial risk level's distribution, iii) the transparency and the simplicity to be used and examined by the PA for improving the resilience process and increasing the public awareness on the risk, iv) the possibility to allow at least partial compensation among the criteria. By examining the related literature on the MCDM developed for building synthetic index, the following gaps/weaknesses have been retrieved: i) computational complexity of some MCDMs which therefore are not always public administrations' user friendly; ii) lack of adequate software packages/implementations of weighting system to verify the adequacy of the natural disaster risk management characteristics; iii) absence of compensation in the MCDM developed to assess urban resilience to natural disasters; iv) scarcity of MCDM based on quantitative and qualitative data to build the synthetic index. Moreover, the georeferentiation of the final indexes results into a risk map, the sensitivity analysis and the validation of the obtained results have been performed to the natural disaster's management. Therefore, the proposed assessment model intends to fill the gaps retrieved in the literature. Moreover, its main innovative contributions are five: i) the context of application – no national and international researches exist on the city of Rome even if it has an heritage of incommensurable value to protect by natural hazards -; ii) the provision of a tool for the PA and the PE during the sustainable planning processes aimed at improving the resilience; iii) the territorial scale of analysis – there are not Italian researches that study the sub-urban scale; iv) the presence of some new criteria such as the value of the assets and the urban heat islands; v) the computational easiness with respect to other MCDM.

The present research has been aimed at giving the possibility to the PA and the PE involved in the sustainable planning processes for increasing the urban resilience to identify the most critical sub-urban areas within the city of Rome, exposed to multiple natural hazards, through a synthetic index (I_{NR}). In this way, the research has contributed on the outlined framework by representing a decision support system adopting by the PA and the PE with a very simple and clear structure. In fact, it has represented an *ex ante* evaluation tool for ranking the most critical/vulnerable urban areas of Rome among the 155 administrative units considered.

The analysis of the obtained results, after the sensitivity and validation tests carried out through the comparison with the BoD approach, has shown that the "Tevere" river is a significant factor that increases the vulnerability of the near urban areas. In particular, his west side is more critical, especially for the fact that, in addition to the proximity to it and its floods, these areas are also characterized by high locational (both seismic and landslides) risks. Moreover, with regard to the *Exposure* component, the most weighted indicators are extremely high in these areas. The same has been detected for the most relevant *Vulnerability* component's indicators. Thanks to the proposed model it has been also possible to identify the indicators that, most of all, affect the natural disaster's risk level in the city of Rome and that are: soil drainage and filtration capacity, presence of young fragile people and adult fragile people, existence of dangerous and fragile buildings, value of the residential assets, predisposition of the territory to hazards (e.g to seismic, landslides, floods etc.).

Future insights of the work will concern the improvement of the model's limits, therefore the possibility to set the weights in an more objective way, the removal of the scoring rules in order to analyze the direct quantitative or qualitative data, the opportunity to access to more kind of available data for the indicators system by including factors on the ecosystem services provided in the different urban areas, to analyze their link with the natural disaster mitigation and the urban resilience. Moreover, it could be useful to test the efficiency of the model to other international territorial context just studied in the literature in order to directly compare and evaluate the robustness of the results.

CRediT authorship contribution statement

Debora Anelli: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Francesco Tajani:** Visualization, Supervision, Validation, Writing – review & editing. **Rossana Ranieri:** Investigation, Visualization, Writing – original draft.

Declaration of competing interest

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

Data availability

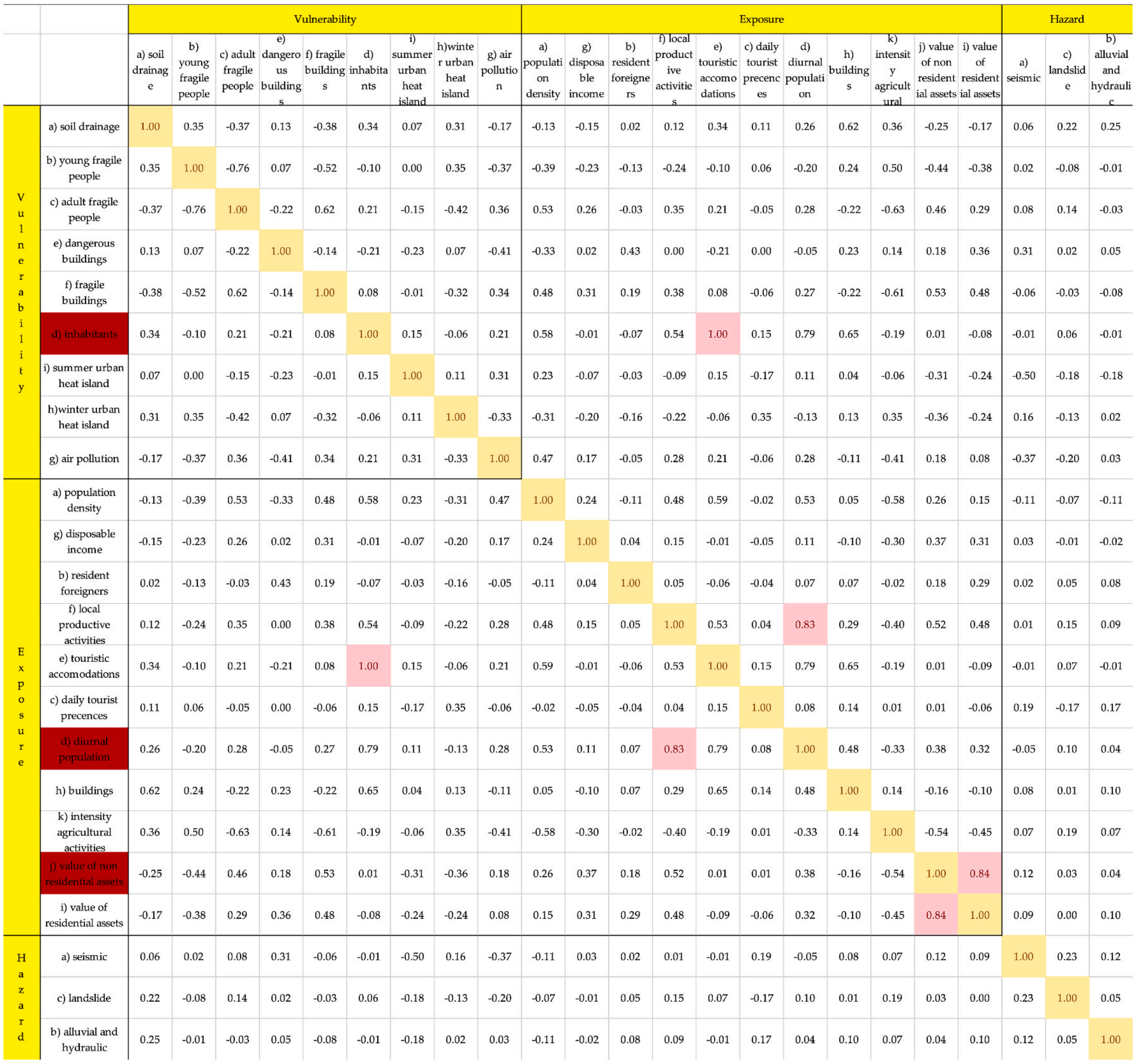
The Authors are available for providing the data used.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.133496.

Appendix A

Table A.1
Pearson correlations analysis's results.



		Vulnerability									Exposure											Hazard		
		a) soil drainage	b) young fragile people	c) adult fragile people	e) dangerous buildings	f) fragile buildings	d) inhabitants	i) summer urban heat island	h)winter urban heat island	g) air pollution	a) population density	g) disposable income	b) resident foreigners	f) local productive activities	e) touristic accomodations	c) daily tourist precences	d) diurnal population	h) buildings	k) intensity agricultural	j) value of non residential assets	i) value of residential assets	a) seismic	c) landslide	b) alluvial and hydraulic
Vulnerability	a) soil drainage	1.00	0.35	-0.37	0.13	-0.38	0.34	0.07	0.31	-0.17	-0.13	-0.15	0.02	0.12	0.34	0.11	0.26	0.62	0.36	-0.25	-0.17	0.06	0.22	0.25
	b) young fragile people	0.35	1.00	-0.76	0.07	-0.52	-0.10	0.00	0.35	-0.37	-0.39	-0.23	-0.13	-0.24	-0.10	0.06	-0.20	0.24	0.50	-0.44	-0.38	0.02	-0.08	-0.01
	c) adult fragile people	-0.37	-0.76	1.00	-0.22	0.62	0.21	-0.15	-0.42	0.36	0.53	0.26	-0.03	0.35	0.21	-0.05	0.28	-0.22	-0.63	0.46	0.29	0.08	0.14	-0.03
	e) dangerous buildings	0.13	0.07	-0.22	1.00	-0.14	-0.21	-0.23	0.07	-0.41	-0.33	0.02	0.43	0.00	-0.21	0.00	-0.05	0.23	0.14	0.18	0.36	0.31	0.02	0.05
	f) fragile buildings	-0.38	-0.52	0.62	-0.14	1.00	0.08	-0.01	-0.32	0.34	0.48	0.31	0.19	0.38	0.08	-0.06	0.27	-0.22	-0.61	0.53	0.48	-0.06	-0.03	-0.08
	d) inhabitants	0.34	-0.10	0.21	-0.21	0.08	1.00	0.15	-0.06	0.21	0.58	-0.01	-0.07	0.54	1.00	0.15	0.79	0.65	-0.19	0.01	-0.08	-0.01	0.06	-0.01
	i) summer urban heat island	0.07	0.00	-0.15	-0.23	-0.01	0.15	1.00	0.11	0.31	0.23	-0.07	-0.03	-0.09	0.15	-0.17	0.11	0.04	-0.06	-0.31	-0.24	-0.50	-0.18	-0.18
	h)winter urban heat island	0.31	0.35	-0.42	0.07	-0.32	-0.06	0.11	1.00	-0.33	-0.31	-0.20	-0.16	-0.22	-0.06	0.35	-0.13	0.13	0.35	-0.36	-0.24	0.16	-0.13	0.02
	g) air pollution	-0.17	-0.37	0.36	-0.41	0.34	0.21	0.31	-0.33	1.00	0.47	0.17	-0.05	0.28	0.21	-0.06	0.28	-0.11	-0.41	0.18	0.08	-0.37	-0.20	0.03
Exposure	a) population density	-0.13	-0.39	0.53	-0.33	0.48	0.58	0.23	-0.31	0.47	1.00	0.24	-0.11	0.48	0.59	-0.02	0.53	0.05	-0.58	0.26	0.15	-0.11	-0.07	-0.11
	g) disposable income	-0.15	-0.23	0.26	0.02	0.31	-0.01	-0.07	-0.20	0.17	0.24	1.00	0.04	0.15	-0.01	-0.05	0.11	-0.10	-0.30	0.37	0.31	0.03	-0.01	-0.02
	b) resident foreigners	0.02	-0.13	-0.03	0.43	0.19	-0.07	-0.03	-0.16	-0.05	-0.11	0.04	1.00	0.05	-0.06	-0.04	0.07	0.07	-0.02	0.18	0.29	0.02	0.05	0.08
	f) local productive activities	0.12	-0.24	0.35	0.00	0.38	0.54	-0.09	-0.22	0.28	0.48	0.15	0.05	1.00	0.53	0.04	0.83	0.29	-0.40	0.52	0.48	0.01	0.15	0.09
	e) touristic accomodations	0.34	-0.10	0.21	-0.21	0.08	1.00	0.15	-0.06	0.21	0.59	-0.01	-0.06	0.53	1.00	0.15	0.79	0.65	-0.19	0.01	-0.09	-0.01	0.07	-0.01
	c) daily tourist precences	0.11	0.06	-0.05	0.00	-0.06	0.15	-0.17	0.35	-0.06	-0.02	-0.05	-0.04	0.04	0.15	1.00	0.08	0.14	0.01	0.01	-0.06	0.19	-0.17	0.17
	d) diurnal population	0.26	-0.20	0.28	-0.05	0.27	0.79	0.11	-0.13	0.28	0.53	0.11	0.07	0.83	0.79	0.08	1.00	0.48	-0.33	0.38	0.32	-0.05	0.10	0.04
	h) buildings	0.62	0.24	-0.22	0.23	-0.22	0.65	0.04	0.13	-0.11	0.05	-0.10	0.07	0.29	0.65	0.14	0.48	1.00	0.14	-0.16	-0.10	0.08	0.01	0.10
	k) intensity agricultural activities	0.36	0.50	-0.63	0.14	-0.61	-0.19	-0.06	0.35	-0.41	-0.58	-0.30	-0.02	-0.40	-0.19	0.01	-0.33	0.14	1.00	-0.54	-0.45	0.07	0.19	0.07
	j) value of non residential assets	-0.25	-0.44	0.46	0.18	0.53	0.01	-0.31	-0.36	0.18	0.26	0.37	0.18	0.52	0.01	0.01	0.38	-0.16	-0.54	1.00	0.84	0.12	0.03	0.04
	i) value of residential assets	-0.17	-0.38	0.29	0.36	0.48	-0.08	-0.24	-0.24	0.08	0.15	0.31	0.29	0.48	-0.09	-0.06	0.32	-0.10	-0.45	0.84	1.00	0.09	0.00	0.10
Hazard	a) seismic	0.06	0.02	0.08	0.31	-0.06	-0.01	-0.50	0.16	-0.37	-0.11	0.03	0.02	0.01	-0.01	0.19	-0.05	0.08	0.07	0.12	0.09	1.00	0.23	0.12
	c) landslide	0.22	-0.08	0.14	0.02	-0.03	0.06	-0.18	-0.13	-0.20	-0.07	-0.01	0.05	0.15	0.07	-0.17	0.10	0.01	0.19	0.03	0.00	0.23	1.00	0.05
	b) alluvial and hydraulic	0.25	-0.01	-0.03	0.05	-0.08	-0.01	-0.18	0.02	0.03	-0.11	-0.02	0.08	0.09	-0.01	0.17	0.04	0.10	0.07	0.04	0.10	0.12	0.05	1.00

Table A.2
Consistency ratio's results derived by the comparison matrices of indicators and intensity range

Component	Indicators	CR	Intensity range	CR
HAZARD	a) sesmic	0.001063	Equal to 1	0.000000
			Equal to 3	
			Equal to 5	
	b) alluvial and hydraulic		Equal to 1	0.000506
			Equal to 3	
			Equal to 5	
			Equal to 7	
			Equal to 9	
			Equal to 11	
			Equal to 13	
			Equal to 15	
			Equal to 17	
			Equal to 19	
	c) landslides		Equal to 1	0.002522
			Equal to 3	
			Equal to 5	
			Equal to 7	
EXPOSURE	a) population density	0.017069	<160.78	0.004930
			160.78–511.56	
			511.56–1224.44	
			1224.44–2753.72	
			2753.72–5275.9	
			5275.9–6275.24	
			6275.24–8034	
			8034–10,751.2	

(continued on next page)

Table A.2 (*continued*)

Component	Indicators	CR	Intensity range	CR
			10,751.2–14,252.8	
			>14,252.8	
	b) foreign residents		<6.38	0.002056
			6.38–9.2	
			9.2–11.1	
			11.1–14.58	
			14.58–22.52	
			>22.52	
	c) daily tourist precences		<45.2	0.004447
			45.2–102.6	
			102.6–217	
			217–449.2	
			449.2–2200.8	
			>2200.8	
	e) touristic accomodations		<10	0.002329
			10–57	
			57–110	
			110–173.8	
			173.8–263.4	
			>263.4	
	f) local productive activities		<260.2	0.001232
			260.2–477	
			477–632.8	
			362.8–877.8	
			877.8–1213	
			1213–1516.6	
			1516.6–1977.6	
			1977.6–3041.6	
			3041.6–4096.6	
			>4096.6	
	g) disposable income		<15,370.2	0.000953
			15,370.2–16,306.4	
			16,306.4–17,407.4	
			17,407.4–18,810.2	
			18,810.2–19,954	
			19,954–21,769.6	
			21,769.6–23,408.8	
			23,408.8–26,085.4	
			26,085.4–31,550.4	
			>31,550.4	
	h) buildings		<188	0.003975
			188–299.2	
			299.2–419	
			419–560	
			560–810	
			810–973.8	
			973.8–1172.6	
			1172.6–1710.6	
			1710.6–2336	
			>2336	
	i) value of residential assets		<1434.58	0.000040
			1434.58–1553.44	
			1553.44–1619.47	
			1619.47–1723.13	
			1723.13–1798.13	
			1798.13–1933.75	
			1973.75–2138.10	
			2138.10–2525.83	
			2525.83–3417.50	
			>3417.50	
	k) intensity of agricultural activities		Equal to 1	0.000000
			Equal to 3	
			Equal to 5	
			Equal to 7	
VULNERABILITY	a) soil drainage and filtration capacity	0.056166	<446.23	0.007573
			446.23–650.01	
			650.01–778.91	
			778.91–986.44	
			986.44–1203.31	
			1203.31–1317.13	
			1317.13–1563.42	
			1563.42–1886.3	
			1886.3–2579.13	
			>2579.13	
	b) young fragile people		<7.84	0.002257
			7.84–9.1	

(*continued on next page*)

Table A.2 (*continued*)

Component	Indicators	CR	Intensity range	CR
			9.1–9.8	
			9.8–11.4	
			11.4–13.7	
			>13.7	
	c) adult fragile people		<13.9	0.004114
			13.9–17.62	
			17.62–21.9	
			21.9–25.88	
			25.88–28.82	
			>28.82	
	e) dangerous buildings		<2.84	0.005501
			2.84–6.3	
			6.3–9.7	
			9.7–12.98	
			12.98–21.46	
			>21.46	
	f) fragile buildings		<19.14	0.006497
			19.14–42.82	
			42.82–64.9	
			64.9–87.66	
			87.66–97.46	
			>97.46	
	g) air pollution level		Equal to 1	0.000000
			Equal to 3	
			Equal to 5	
	h) winter urban heat island		<8.21	0.021883
			8.21–8.26	
			8.26–9.68	
			9.68–11.07	
			11.07–12.49	
			>12.49	
	i) summer urban heat island		<35.98	0.009640
			35.98–38.82	
			38.82–38.90	
			38.90–44.48	
			44.48–44.54	
			>44.54	

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