Oregon Risk Assessment Upgrade
Risk Assessment Work Group
Meeting 11

Wednesday, September 27, 2023
1-3 p.m.

Virtual:
Registration Required
Zoom link to be provided upon registration.

AGENDA

Item	Topic	Lead	Time	Duration
I.	Welcome & Purpose	Marian Lahav	1:00 p.m.	5 minutes
II.	Survey Update	Trisha Patterson	1:05 p.m.	30 minutes
III.	Design Subgroup Report	Christine Shirley	1:35 p.m.	5 minutes
IV.	Multi-Criteria Decision Process	Christine Shirley	1:40 p.m.	35 minutes
V.	Declaration of Collaboration	Christine Shirley	2:15 p.m.	30 minutes
VI.	Next Steps	Christine Shirley	2:45 p.m.	5 minutes
VII.	Next Meeting Preparation	Christine Shirley	2:50 p.m.	5 minutes
VIII.	Community Comment	Marian Lahav	2:55 p.m.	5 minutes
IX.	Adjourn		3:00 p.m.	

The meeting is accessible to persons with disabilities. To request an interpreter for the hearing impaired or for other accommodations for persons with disabilities, please make requests at least three business days before the meeting to Ashley Edwards, 971-718-4194, ashley.edwards@dlcd.oregon.gov, or by TTY: Oregon Relay Services, 800-735-2900.

Methodology for the Assessment of Multi-Hazard Risk in Urban Homogenous Zones

Article *in* Applied Sciences · December 2022

DOI: 10.3390/app122412843

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applied sciences

MDPI

Article

Methodology for the Assessment of Multi-Hazard Risk in Urban Homogenous Zones

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Abstract: The multi-hazard risk assessment of urban areas represents a comprehensive approach that can be used to reduce, manage and overcome the risks arising from the combination of different natural hazards. This paper presents a methodology for multi-hazard risk assessment based on Spatial Multi-Criteria Decision Making. The PROMETHEE method was used to assess multi-hazard risks caused by seismic, flood and extreme sea waves impact. The methodology is applied for multi-hazard risk evaluation of the urban area of Kaštel Kambelovac, located on the Croatian coast of the Adriatic Sea. The settlement is placed in a zone of high seismic risk with a large number of old stone historical buildings which are vulnerable to the earthquakes. Being located along the low-lying coast, this area is also threatened by floods due to climate change-induced sea level rises. Furthermore, the settlement is exposed to flooding caused by extreme sea waves generated by severe wind. In the present contribution, the multi-hazard risk is assessed for different scenarios and different levels, based on exposure and vulnerability for each of the natural hazards and the influence of additional criteria to the overall risk in homogenous zones. Single-risk analysis has shown that the seismic risk is dominant for the whole pilot area. The results of multi-hazard assessment have shown that in all combinations the highest risk is present in the historical part of Kaštel Kambelovac. This is because the historical part is most exposed to sea floods and extreme waves, as well as due to the fact that a significant number of historical buildings is located in this area.

Keywords: risk assessment; multi hazard; multi-hazard risk assessment; multi-criteria decision-making; GIS; PROMETHEE method

Citation: Mladineo, N.; Mladineo, M.; Benvenuti, E.; Kekez, T.; Nikolić, Ž. Methodology for the Assessment of Multi-Hazard Risk in Urban Homogenous Zones. *Appl. Sci.* **2022**, *12*, 12843. https://doi.org/10.3390/app122412843

Academic Editor: Jianbo Gao

Received: 27 October 2022
Accepted: 9 December 2022
Published: 14 December 2022

1. Introduction

Natural hazards are threatening the population throughout the world more than ever. Efficient planning and preparation are vital, since the question "will the disaster happen?", has changed into "when will it happen?". Enhancing the safety and resilience for disasters requires knowledge about individual territorial hazards, vulnerabilities and risks. Appropriate multi-risk methodology based on existing data and knowledge should produce an interactive and easily understanding map that will enable the visualization of individual and combined risks. Integration of this methodology into the Geographic Information System gives important information to local and regional authorities for preventing, managing and overcoming multi-hazard natural disasters [1], such as river and sea floods, meteotsunamis (or extreme sea waves) and earthquakes. To reduce the possible loss of life and damage to property caused by hazards [2], it is crucial to conduct risk assessments and make decisions pertaining to natural hazards before the hazards occur [3].

A common practice in the hazard risk assessment is to focus on the hazard frequency and intensity in combination with area vulnerability or severity of damage caused by the hazard [4]. Furthermore, the severity is not just the result of hazard intensity and area vulnerability, but it is also influenced by the coping capacity of the emergency units in the area [5]. Hazard occurs in some periods with particular intensity and causes damage in relation to area vulnerability and coping capacity. A brief literature survey was made among scientific and professional papers to investigate what are the common factors used to calculate the risk of natural hazards (Table 1).

Table 1. Brief literature survey on factors used to calculate the risk of natural hazards.

Approach	Factors				Output	Source
	Frequency	Intensity	Vulnerability	Other		
Single hazard	Yes	No	No	Damage	Risk	Di Mauro et al. [6]
Multi-hazard	Yes	Yes	Yes	Coping capacity	Risk	Fleischhauer et al. [7]
Multi-hazard	No	Yes	Yes	Coping capacity	Integrated risk	Greiving et al. [5]
Single hazard	Yes	Yes	No	No	Risk	Kunz et al. [8]
Multi-hazard	Yes	Yes	Yes	Consequence (loss)	Risk	Liu et al. [9]
Multi-hazard	Yes	No	No	Aggregated losses	Risk	Mignan et al. [10]
Single hazard	No	No	Yes	Hazard exposure, Exposed value	Risk index	Munich Re Group [11]
Single hazard	Yes	Yes	No	Area impact	Hazard score	Odeh Engineers, Inc. [12]
Multi-hazard	Yes	Yes	Yes	Elements at risk, Temporal/Spatial probability	Risk	Van Westen [13]

Table 1 shows that hazard frequency (or probability of occurrence) is the most common factor used in risk assessment. Some approaches are focused on hazard intensity and some of them on vulnerability in combination with damage or loss. However, half of the papers dealing with multi-hazard approach are taking into account all three emphasized factors—frequency, intensity and vulnerability—including other factors. In the context of the multi-hazard risk assessment, many factors are used. Since each factor can represent one criterion, evaluation of these factors can be used as an input matrix for the Multi-Criteria Analysis (MCA). The reason for using so many criteria (factors) for multi-hazard risk assessments is due to its complexity. According to the standard for risk assessment IEC 31010:2009 [14], the risk assessment is the overall following process: risk identification, risk analysis and risk evaluation, and it is recommended to use multi-criteria analysis or multi-criteria decision-analysis method for the risk assessment.

The problem of the multi-hazard risk assessment is not just in designing a proper calculation to aggregate all hazard risks in one area [15,16], but also to take into account hazards' mutual correlation [9], since one hazard can trigger another one. For instance, fire is usually spread after earthquakes, and earthquakes can produce tsunamis, thus flooding the area.

Although the world is dealing with hazards that have an increasing frequency, like flood disasters that are caused by extreme climate and urbanization processes [17], another problem of the single-hazard or multi-hazard risk assessment lies in a specific type of hazards. There are specific hazards, earthquakes, for instance, that can be represented as low-probability/high-consequence events [10]. This issue represents a large problem, as earthquakes can have high intensity while their frequency is usually very low, so the risk calculation of multiplying intensity and frequency will result in a low risk level. Therefore, additional factors need to be taken into calculation to emphasize the risk from earthquakes and similar hazards that are low-probability/high-consequence events.

Vulnerability is one of the most important factors in the risk assessment [18]. Namely, high vulnerability of some areas can result in severe losses during a low-intensity hazard, and low vulnerability can result in minor losses during a high-intensity hazard. Many different criteria are used for vulnerability calculation, because the criteria set is also defined by the type of hazard [4]. However, assessing the vulnerability to natural hazards such as earthquakes can be characterized as an ill-structured problem or a problem without unique, identifiable and objectively optimal solution. A review of the literature indicates a number of contrasting definitions of what vulnerability means, as well as numerous conflicting perspectives on what should or should not be included within the broad assessment of vulnerability in cities [19]. For instance, some authors also include coping capacity (emergency units) of the area in the vulnerability analysis [5]. But this is not necessarily a good approach, since coping capacity is something that can dynamically change each year, and other common vulnerability criteria (building age, building structure, building height, etc.) are less or more static. Furthermore, it is important to mention that different vulnerability analyses are used at different scales [20]. The different criteria sets (factors) are used and sometimes different methods must be used, as well.

The aim of this study is the assessment of multi-hazard risk for Kaštel Kambelovac, a small city placed along the Adriatic Sea near the city of Split, Croatia (Figure 1).

(**a**) (**b**)

Figure 1. The City of Kaštela: (**a**) Historical center of Kaštel Kambelovac [21]; (**b**) Coastal flooding events in the City of Kaštela [22,23].

Due to its location in a zone of high seismic risk and considering the large number of stone-made and several-centuries-old historical buildings, Kaštela is a settlement with pronounced seismic vulnerability and risk [18]. The historical center, built right next to the low-lying coast, is also threatened by floods due to rising sea levels caused by climate change. Furthermore, the settlement is exposed to flooding caused by extreme sea waves generated by severe wind. Therefore, the present multi-hazard risk assessment is aimed at determining the combined risk of the settlement caused by earthquakes, sea floods and extreme sea waves. The multi-hazard risk investigation of the Kaštel Kambelovac is a part of the project "Preventing, managing, and overcoming natural-hazards risks to mitigate economic and social impact" (PMO-GATE) [24].

The main challenge in the multi-hazard risk assessment is to evaluate, use and mutually compare different mathematical variables that describe the hazard's frequency, intensity and vulnerability. In this research, this issue is addressed by using the multi-criteria analysis that is commonly used to evaluate and compare quantitative and qualitative criteria in completely different units and the order of magnitude. However, a proper multi-criteria analysis must be selected. An additional challenge in the multi-hazard risk assessment is the data collection and evaluation, which can become complex on the settlement or regional level. Therefore, a proper spatial analysis must be used to organize and aggregate spatial thematic layers. Accordingly, the Geographic Information System is used in combination with multi-criteria analysis in order to establish a Spatial Multi-Criteria Decision Making system.

2. Methodology

The methodology used in this research relies on the combination of the Multi-Criteria Analysis/Multi-Criteria Decision-Making (MCA/MCDM) and Geographic Information System (GIS) to evaluate and visualize this risk assessment in this particular area. The advantage of GIS is in its ability to visualize spatial data (Figure 2) and enhance the spatial decision-making in the risk assessment [25–27].

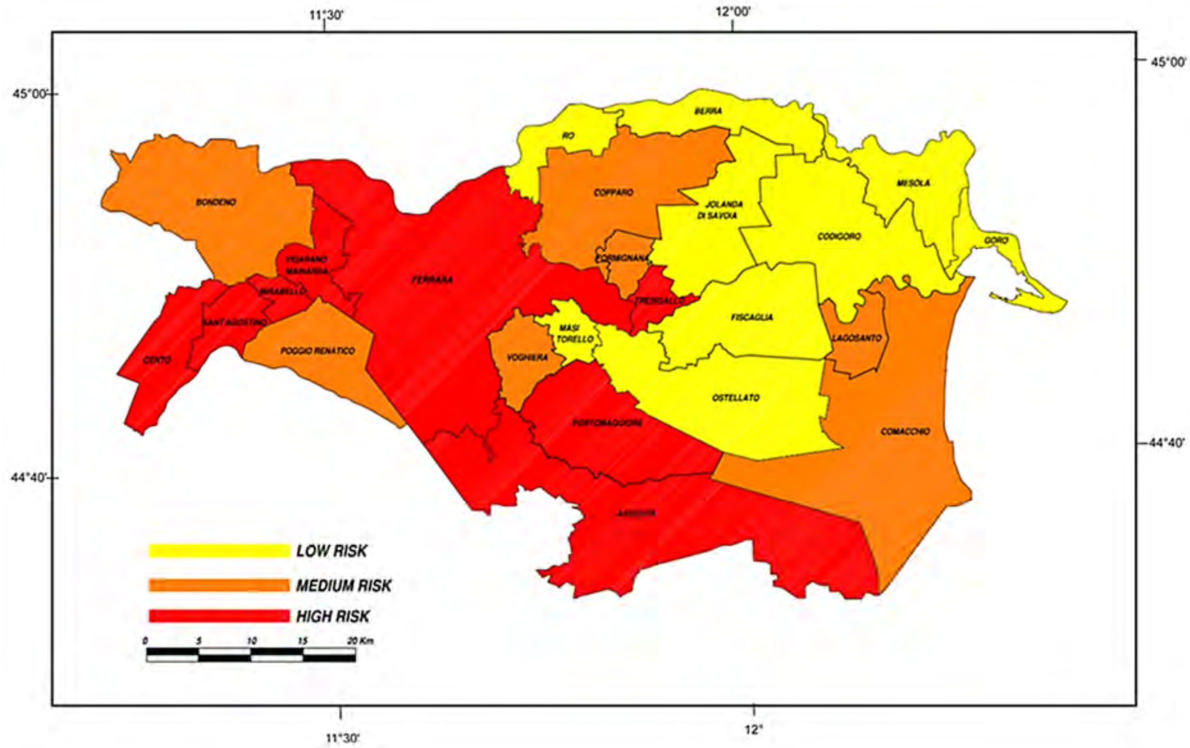


Figure 2. An example of multiple-risk map for the Ferrara province [15].

Furthermore, GIS supports the usage of the multi-scale approach and different criteria sets: the vulnerability analysis can be made for each building, the whole settlement, the settlement's municipality, and for the whole region. The multi-scale approach was discussed in the already-mentioned paper by Vicente et al. [20], but greater contribution was given by Aubrecht et al. [28] that presented multi-level geospatial modeling of vulnerability indicators from building level to country level. Another example of a multi-level and multi-criteria approach is presented in Figure 3.

Regarding the risk assessment, it is usually made for a particular assessment area. These areas need to be defined by mutual spatial characteristics or by some already defined urban entity.

The first and simplest approach is to use some administrative areas as assessment areas: settlements, municipalities, provinces, counties, etc. This approach was used in the combined seismic and flood risk assessment for municipalities in the province of Ferrara [15].

The second approach is the definition of assessment areas as "working units" by using a grid of blocks. The working unit is the geographical entity in which the calculations will be computed, hereby controlling the geographical resolution of the study. The definition of the working unit depends strongly on two factors: the geographical unit in which the original data is expressed and the scale of the study. For instance, in the urban-scale seismic risk study for city Almería, a 200 m squared grid was considered appropriate to cover the entire city of Almería, totaling an amount of 400 equal cells or working units [27].

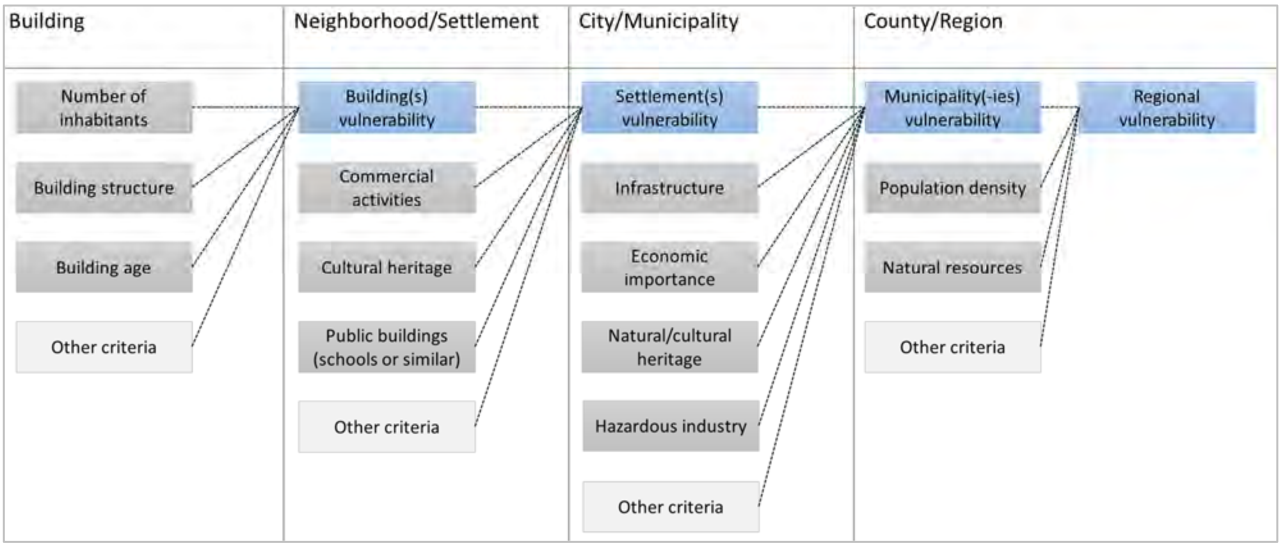


Figure 3. Vulnerability analysis at different scales with multi-criteria approach.

The third approach is to define assessment areas as "homogeneous zones", which are generated by intersecting relevant thematic layers in the assessment area. The intersection of the defined number of layers becomes an assessment area (zone). This approach has been used in this research for Croatian settlement Kaštel Kambelovac, a part of Kaštela City.

2.1. Multi-Criteria Analysis and Decision-Making Approach to Risk Assessment

In the analysis of natural hazards, impacts are often expressed in terms of hazard, vulnerability and exposure. A hazard (H) presents the probability that a harmful event will appear in a particular area and in a certain time interval. Vulnerability (V) is defined as the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard. Exposure (E) is the totality of people, property, systems or other elements present in hazard zones that are thereby subject to potential losses.

In this research, the hazard (H) is presented by seismic hazard maps with a Peak Ground Acceleration—PGA for the earthquake, while, in the case of sea floods and extreme sea waves, it is based on a flood depth and a wave height in inundation areas, respectively. The exposure (E) that corresponds to the measure of hazard will be presented by intensity and Area Impact (e.g., area exposed to earthquake, flood or extreme waves). Furthermore, vulnerability is evaluated by vulnerability index on multiple levels (for the particular building, for the settlement, etc.) with the use of additional criteria set which is different for each level. Therefore, in this research, function f represents mathematical PROMETHEE (Preference Ranking Organisation METHod for Enrichment Evaluations) method [29] that will connect all criteria and assess the risk for the observed area.

Obviously, there are many other mathematical methods for multi-criteria analysis and decision-making, but some of them are better accepted and more widely used. Three of them have recently become the most popular: AHP [25], TOPSIS [26] and PROMETHEE [30,31]. There is also a need to decide which of the available methods is the most adequate for a particular problem, but very often, the outranking methods like PROMETHEE are the most suitable choice [32]. This is especially because PROMETHEE method can be simplified to be used by non-expert users [33,34].

Furthermore, using the concept of vulnerability makes it more explicit that the impacts of a hazard are also a function of the preventive and preparatory measures that are employed to reduce the risk. Depending on the particular risk analyzed, the measurement of risk can be carried out with a greater number of different variables and factors, depending inter alia on the complexity of the chain of impacts, the number of impact factors considered and the requisite level of precision. The scheme of assessment of single-hazard and multi-hazard exposure for the investigated coastal urban area is shown in Figure 4.

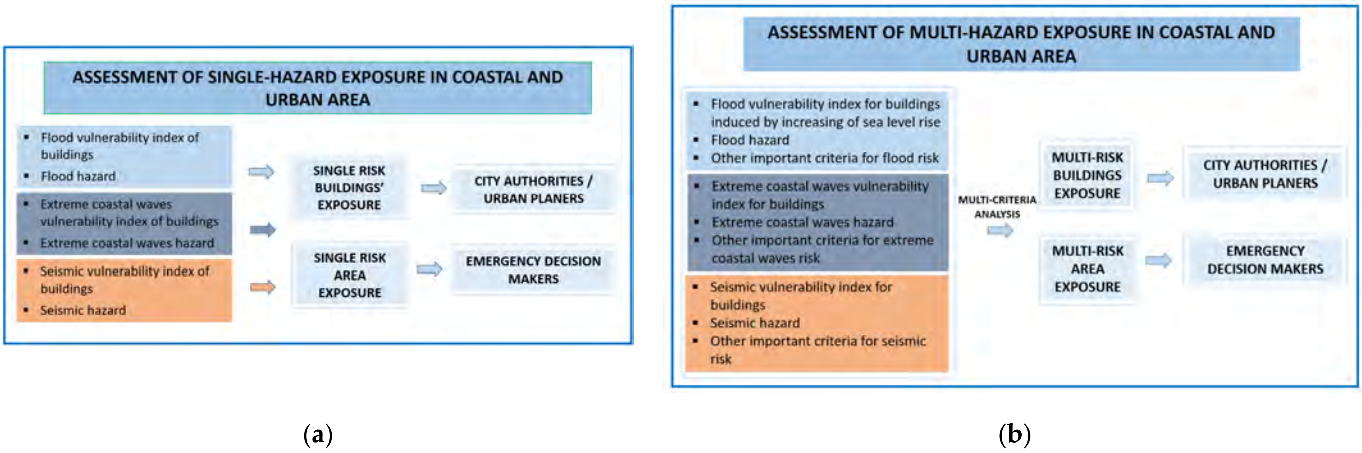


Figure 4. The scheme of the risk assessment for investigated area: (**a**) single-hazard exposure; (**b**) multi-hazard exposure.

2.2. Risk Assessment of Buildings

In this research, the risk assessment is made for different levels, starting from the lowest level (micro level), i.e., an individual building. At this micro level, the risk assessment of a single-hazard exposure is based on the calculation of vulnerability indexes of buildings for individual natural disasters:

- Flood vulnerability index for buildings,
- Extreme coastal waves vulnerability index for buildings,
- Seismic vulnerability index for buildings,

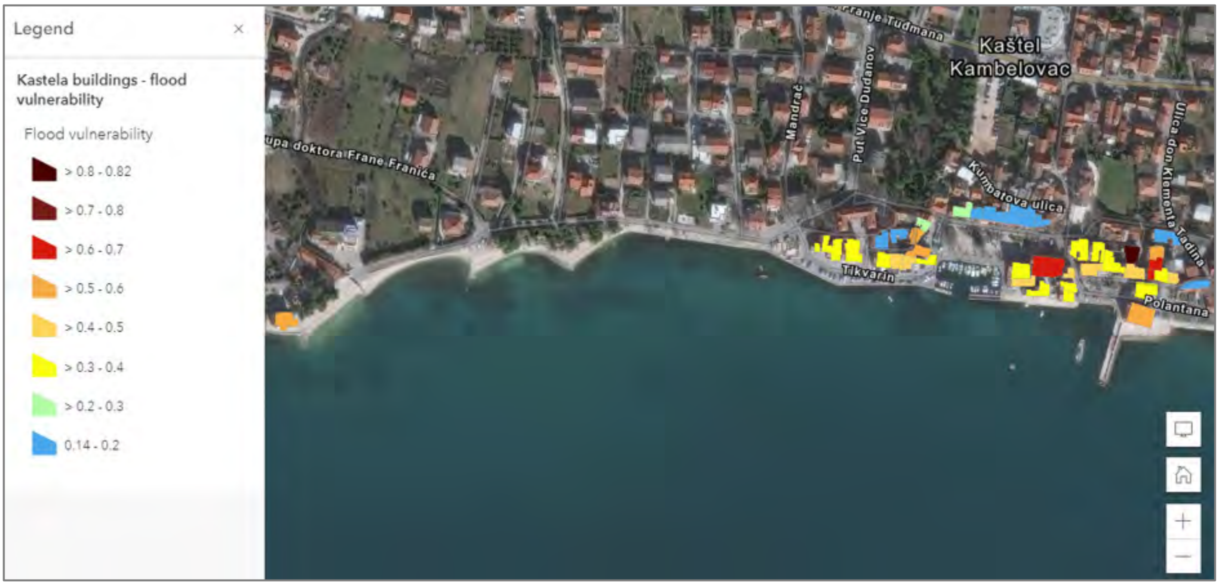
as well as on assessment of the single hazards:

- Flood hazard,
- Extreme coastal waves hazard,
- Seismic hazard.

Seismic vulnerability indexes of the buildings for investigated area are calculated according to the seismic vulnerability method [35]. The method is based on the evaluation of 11 geometrical, structural and non-structural vulnerability parameters of the building. They consider the influence of the type and quality of the structural system, the shear resistance in two horizontal directions, the position and the foundations, the properties of floors, the configuration in plan and elevation, the maximum wall spacing, the roof's typology and weight, the existence of non-structural elements, and the state of preservation. Four possibilities for each parameter were decided: from "A", indicating an optimal state, to "D", indicating a poor state. The relative importance of each parameter in the overall vulnerability is computed by using weight coefficients relating to each parameter. Finally, the vulnerability index I_v is calculated in a form $I_V = \sum_i s_{vi} w_i$, where s_{vi} is the numerical score for each class, and w_i is the weight of each parameter. The vulnerability index is normalized in a 0–100% range; a low index indicates high seismic resistance and low vulnerability, while a high vulnerability index is characteristic of the buildings with low seismic resistance and high vulnerability. Vulnerability indexes of the buildings located in the pilot area are presented in Figure 5 [35].

Figure 5. Seismic vulnerability index of buildings divided into 10% intervals.

The flood vulnerability index and the extreme coastal waves vulnerability index are calculated according to the methodology developed in the PMO-GATE project [25]. This methodology is based on the approach of Miranda and Ferreira [36], which takes into consideration different parameters such as building material, overall object condition, number of storeys, building age, importance of exposed objects and level of exposure. The approach has been modified for application in the multicriteria analysis, with each vulnerability index calculated as the weighted sum of set of parameters and evaluated through vulnerability classes (Figure 6).



(a)

(**b**)

Figure 6. Vulnerability index of buildings for: (**a**) sea floods; (**b**) extreme sea waves.

The seismic hazard for Croatia is presented with two maps for return periods of 475 and 95 years, expressed in terms of the peak ground acceleration during an earthquake for a soil class A [37]. According to HRN EN 1998-1:2011 [36], the soil types A, B, C, D and E, may be used to account for the influence of local ground conditions on the seismic action. The site can be classified according to the value of the average shear wave velocity $v_{s,30}$. An investigation of the deep geology and characteristics of the terrains, performed at pilot area [38], has shown that shear wave velocity $v_{s,30}$ is higher than 800 m/s at the wholearea, which define soil class A. Therefore, local ground conditions do not influence to seismic hazard in the investigated area, i.e., the seismic hazard for all buildings at the pilot area has been assumed to be constant [35].

The flood hazard caused by climate-induced sea level rise is estimated according to IPCC Fifth Assessment Report (AR5) [39] and Strategy for climate change adaptation for The Republic of Croatia [40], considering changes in the mean sea level. However, the EU Flood Directive [41] requires an analysis of a high, moderate and low probability scenario in the flood hazard assessment. The sea level in the Adriatic Sea is dominantly caused by sea tides and the effect of the barometric pressure [42]. The tidal component can be represented by the set of periodic functions [43], and the residual sea level can be represented with a probability distribution due to its randomness and stochastic behavior. In order to fulfil the Flood Directive requirements, probability scenarios are estimated from the particular probability distribution, corresponding to the return periods of 25, 100 and 250 years, respectively [44]. Finally, sea level is estimated as a superposition of mean sea level, maximum estimated tide and each probabilistic scenario. The distribution of the critical zones most prone to flood due to the impacts of climate change on sea level rise for the most critical scenario for year 2100 is shown in Figure 7 [45].

Figure 7. Distribution of critical zones most prone to flood due to impact of climate changes on sea level rise: scenario for year 2100.

The extreme coastal waves hazard is determined based on the evaluation of wave heights and their propagation toward the coast (Figure 8). The methodology for computing the wave heights by using values of wind speeds in critical wind directions for the investigated area has been developed [46], where probability distribution function is used to fit wind speed histograms and to evaluate return period values.

Figure 8. Distribution of critical zones most prone to extreme sea waves exposure.

Vulnerability indexes of buildings for individual natural disasters coupled by the corresponding hazards are the basis for the multi-hazard risk assessment of the area [47].

2.3. Risk Assessment of Homogenous Zones

At the higher level of analysis, which is the intermediate level, the previously-analyzed objects are grouped into spatial units (assessment area) that are called "homogeneous zones" [47]. The process of creation of homogenous zones for the pilot site is presented in Figure 9. In this case, three different layers are intersected: a layer of specific urban characteristics, a layer of areas surrounded by the main roads and a layer of terrain height.

(a) (b) (c) (d)

Figure 9. The creation of homogenous zones: (**a**) four areas defined by specific urban characteristics; (**b**) four areas defined by main roads; (**c**) three areas defined by terrain (contours 5 and 10 m); (**d**) intersection of layers resulted with 15 homogenous zones.

The seismic vulnerability indexes of individual buildings are used to calculate the seismic vulnerability index of a homogeneous zone. In the same way, the other vulnerabilities indexes are evaluated. However, it is important to highlight that the additional criteria are very important at this level of analysis. Since homogeneous zones have complex characteristics, additional criteria are used for both single-hazard and a multi-hazard approach, beside vulnerability and hazard.

The literature review shows that the level of risk to the community depends on a number of other parameters whose activation in a particular hazard reduces the resilience to extraordinary events. Each area due to difference in size requires a special approach in identifying the relevant parameters. For example, the most common parameters (criteria) for seismic hazard are grouped into area characteristics (geology, soil, slope, historical earthquake events, fault line, etc.), the characteristics of human intervention in space (land use, built communal infrastructure and roads, etc.), and social characteristics (housing density, social purpose of buildings, social structure, etc.).

For the pilot site at the intermediate level, additional parameters that can be quantified are detected, different for each homogeneous zone. They represent additional criteria for the risk assessment of homogenous zones: communal infrastructure, road network, construction density (distance between buildings), inhabitation density, importance factor (public building, school, etc.), and historical buildings.

3. Results

3.1. Single-Hazard Risk Asssessment of Homogenous Zones

Single-hazard risk assessment is made for 14 homogeneous zones of the pilot site. Since the flood and extreme waves are affecting only a small coastal area, the seismic risk assessment will be presented here. The input data are calculated, or expert estimates are given for the following criteria:

- Seismic hazard—PGA,
- Buildings' seismic vulnerability,
- Geology,
- Communal infrastructure—electricity supply,
- Communal infrastructure—water supply and drainage,
- Road network,
- Construction density (distance between buildings),
- Inhabitation density,
- Importance factor (public, school, etc.),
- Historical buildings.

Since seismic hazard (PGA) and geology have the same values in each of the 14 homogeneous zones, they do not need be included in the numerical processing. The average seismic vulnerability has been calculated for each homogenous zone (Table 2).

Table 2. The basic data of homogenous zones and average seismic vulnerability index.

Homogenous Zone (HZ)	Area (m^2)	Number of Buildings	Seismic Vulnerability Index of Homogenous Zone
HZ1	58.627	56	0.133
HZ2	21.865	29	0.174
HZ3	57.189	54	0.116
HZ4	30.925	25	0.120
HZ5	26.972	38	0.132
HZ6	7.763	4	0.194
HZ7	7.767	20	0.435
HZ8	16.168	19	0.162
HZ9	60.068	38	0.136
HZ10	38.133	14	0.171
HZ11	24.972	35	0.156
HZ12	12.696	17	0.448
HZ13	24.903	71	0.493
HZ14	40.782	48	0.187

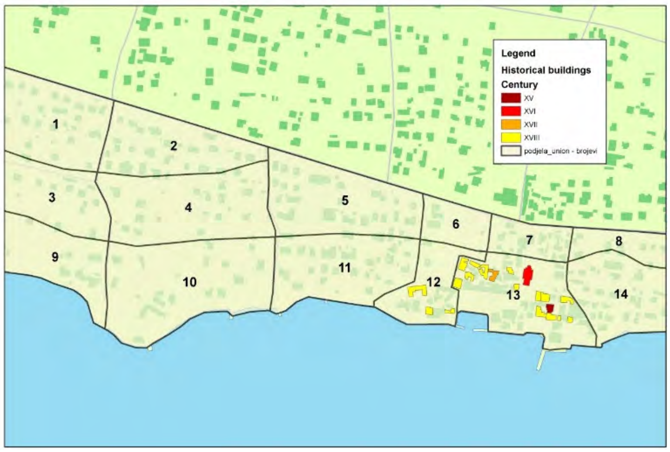
The criterion inhabitation density is generated from a digitized population census. For all other additional criteria a profound GIS analysis has been made, and criteria evaluations for each homogenous zone have been calculated or estimated (Figure 10).

(**a**) (**b**)

(**c**)

(**d**)

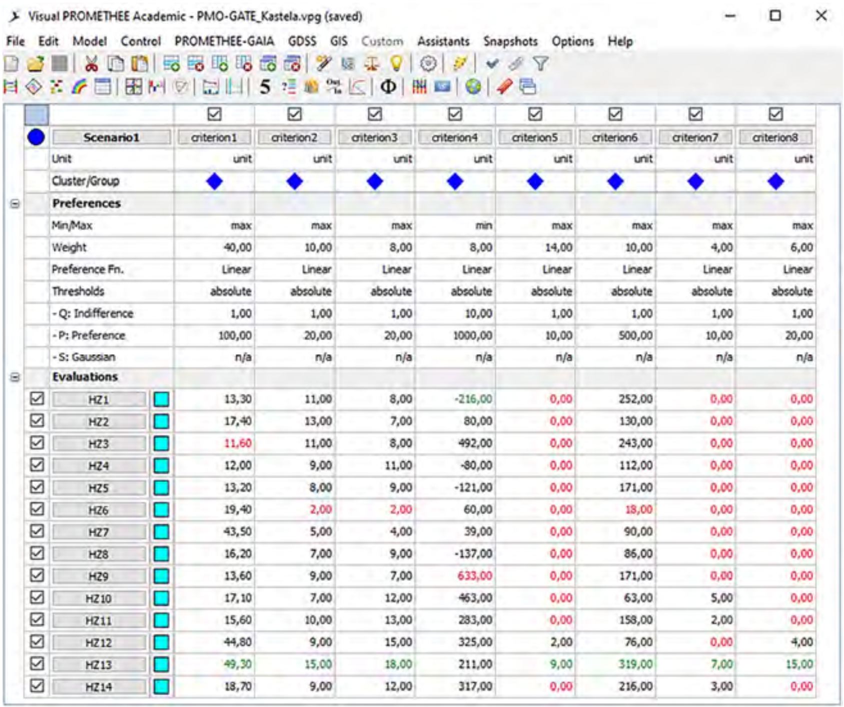
(**e**)



(**f**)

Figure 10. GIS analysis of additional criteria: (**a**) electricity supply; (**b**) water supply and drainage; (**c**) road network; (**d**) construction density; (**e**) importance factor (public, school, etc.); (**f**) historical buildings.

All the above-mentioned data have been collected into the decision matrix to be used by the PROMETHEE method with the help of Visual PROMETHEE software (Figure 11).



Visual PROMETHEE Academic - PMO-GATE_Kastela.vpg (saved)

File Edit Model Control PROMETHEE-GAIA GDSS GIS Custom Assistants Snapshots Options Help

Scenario1	criterion1	criterion2	criterion3	criterion4	criterion5	criterion6	criterion7	criterion8
Unit	unit	unit	unit	unit	unit	unit	unit	unit
Cluster/Group								
Preferences								
Min/Max	max	max	max	min	max	max	max	max
Weight	40,00	10,00	8,00	8,00	14,00	10,00	4,00	6,00
Preference Fn.	Linear	Linear	Linear	Linear	Linear	Linear	Linear	Linear
Thresholds	absolute	absolute	absolute	absolute	absolute	absolute	absolute	absolute
- Q: Indifference	1,00	1,00	1,00	10,00	1,00	1,00	1,00	1,00
- P: Preference	100,00	20,00	20,00	1000,00	10,00	500,00	10,00	20,00
- S: Gaussian	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Evaluations								
HZ1	13,30	11,00	8,00	-216,00	0,00	252,00	0,00	0,00
HZ2	17,40	13,00	7,00	80,00	0,00	130,00	0,00	0,00
HZ3	11,60	11,00	8,00	492,00	0,00	243,00	0,00	0,00
HZ4	12,00	9,00	11,00	-80,00	0,00	112,00	0,00	0,00
HZ5	13,20	8,00	9,00	-121,00	0,00	171,00	0,00	0,00
HZ6	19,40	2,00	2,00	60,00	0,00	18,00	0,00	0,00
HZ7	43,50	5,00	4,00	39,00	0,00	90,00	0,00	0,00
HZ8	16,20	7,00	9,00	-137,00	0,00	86,00	0,00	0,00
HZ9	13,60	9,00	7,00	633,00	0,00	171,00	0,00	0,00
HZ10	17,10	7,00	12,00	463,00	0,00	63,00	5,00	0,00
HZ11	15,60	10,00	13,00	283,00	0,00	158,00	2,00	0,00
HZ12	44,80	9,00	15,00	325,00	2,00	76,00	0,00	4,00
HZ13	49,30	15,00	18,00	211,00	9,00	319,00	7,00	15,00
HZ14	18,70	9,00	12,00	317,00	0,00	216,00	3,00	0,00

Figure 11. Homogenous zones input data for PROMETHEE method (decision matrix).

The preliminary results of the PROMETHEE method are given in Figure 12, in which better rank represents higher risk. It means that the best-ranked homogenous zone HZ13 has the highest seismic risk in this case.

PROMETHEE Flow Table

Rank	action	Phi	Phi+	Phi-
1	HZ13	0,3993	0,4104	0,0111
2	HZ12	0,0975	0,1512	0,0537
3	HZ7	0,0302	0,1110	0,0808
4	HZ1	0,0025	0,0684	0,0659
5	HZ14	-0,0142	0,0518	0,0659
6	HZ2	-0,0269	0,0451	0,0720
7	HZ11	-0,0317	0,0395	0,0713
8	HZ5	-0,0318	0,0418	0,0735
9	HZ4	-0,0401	0,0387	0,0787
10	HZ8	-0,0420	0,0375	0,0795
11	HZ10	-0,0644	0,0349	0,0993
12	HZ3	-0,0654	0,0347	0,1000
13	HZ9	-0,0975	0,0166	0,1141
14	HZ6	-0,1156	0,0250	0,1407

Figure 12. Results of the PROMETHEE method for 14 homogeneous zones (better rank represents higher risk).

Visual representation of the results has been made in GIS, where green represents low risk and red represents high risk (Figure 13).

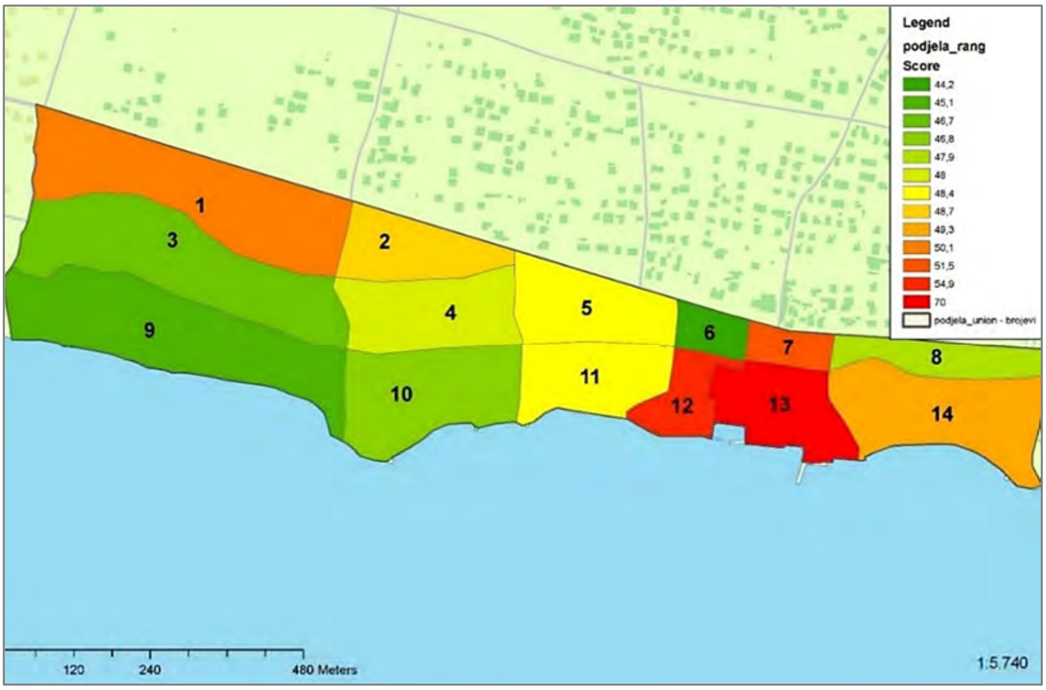


Figure 13. Seismic risk assessment for homogenous zones (green represents low risk, red represents high risk).

3.2. Multi-Hazard Risk Asssessment of Homogenous Zones

Three natural-hazards—seismic, flood and extreme waves—are combined and evaluated together to assess the multi-hazard risk, and the analysis is made on the level of homogenous zones.

The two combined risk analysis are made: combination of two risks for seismic and flood hazard; and combination of three risks for seismic, flood and extreme waves hazard. Each analysis is made on three levels. The first level of analysis is based on hazard and vulnerability data aggregated for each homogenous zone. A second and third level of analysis are using additional criteria for each homogenous zone (Table 3).

Table 3. Combined risks analysis and criteria for each level of analysis.

Level	Combined Seismic-Flood Risk: Scenario S-F	Combined Seismic-Flood-Extreme Waves Risk: Scenario S-F-EW
Level 1 criteria	Seismic hazard (1.1) Seismic vulnerability (1.2) Flood hazard (1.3) Flood vulnerability (1.4)	Seismic hazard (1.1) Seismic vulnerability (1.2) Flood hazard (1.3) Flood vulnerability (1.4) Extreme waves hazard (1.5) Extreme waves vulnerability (1.6)
Level 2 criteria	Seismic hazard (1.1) Seismic vulnerability (1.2) Flood hazard (1.3) Flood vulnerability (1.4) Construction density (2.1) Inhabitation density (2.2) Importance factor (2.3) Historical buildings (2.4)	Seismic hazard (1.1) Seismic vulnerability (1.2) Flood hazard (1.3) Flood vulnerability (1.4) Extreme waves hazard (1.5) Extreme waves vulnerability (1.6) Construction density (2.1) Inhabitation density (2.2) Importance factor (2.3) Historical buildings (2.4)
Level 3 criteria	Seismic hazard (1.1) Seismic vulnerability (1.2) Flood hazard (1.3) Flood vulnerability (1.4) Construction density (2.1) Inhabitation density (2.2) Importance factor (2.3) Historical buildings (2.4) Electrical infrastructure (3.1) Water supply infrastructure (3.2) Road network (3.3)	Seismic hazard (1.1) Seismic vulnerability (1.2) Flood hazard (1.3) Flood vulnerability (1.4) Extreme waves hazard (1.5) Extreme waves vulnerability (1.6) Construction density (2.1) Inhabitation density (2.2) Importance factor (2.3) Historical buildings (2.4) Electrical infrastructure (3.1) Water supply infrastructure (3.2) Road network (3.3)

Therefore, six multicriteria analyses are made on three different levels for each of the two scenarios. These multi-criteria analyses are classifying homogenous zones in accordance with multi-hazard risk.

The first analysis is the combined seismic-flood risk (Scenario S-F) on three different levels. Each level represents different criteria sets. Criteria are grouped in two major groups: main criteria, which are related to hazard and vulnerability and additional criteria, which are related to some important spatial data. Each criteria group has its own weight. In this case, an equal weight is given to each group—50%. An example of distribution of the criteria weights within the group are presented in Table 4. Criteria weights in this particular application are estimated comparing the estimated Expected Annual Damage values for each observed natural hazard. The Expected Annual Damage concept is based on the combination of occurrence probability and corresponding damage caused by each natural hazard [48], and it has proved to be an effective method since it enables a practical comparison of significantly different natural phenomena.

Table 4. An example of criteria weights for combined seismic-flood risk for Scenario S-F Level 2.

Criteria Group	Group Weight	Criteria	Criteria Weight
Main criteria	50%	Seismic hazard (1.1)	21.7%
		Seismic vulnerability (1.2)	21.7%
		Flood hazard (1.3)	3.3%
		Flood vulnerability (1.4)	3.3%
Additional criteria *(n—number of additional criteria)*	50%	Construction density (2.1)	50/*n* = 12.5%
		Inhabitation density (2.2)	50/*n* = 12.5%
		Importance factor (2.3)	50/*n* = 12.5%
		Historical buildings (2.4)	50/*n* = 12.5%

The input data for analysis is presented as a matrix with alternatives, in this case 14 homogenous zones (HZ) and up to 11 criteria depending on the level of analysis (Figure 14).

Short Name	1.1 Seismic vuln.	1.2 Seismic haz.	1.3 Flood vuln.	1.4 Flood haz.	2.1 Constr. dens.	2.2 Inhab. dens.	2.3 Import. fact.	2.4 Histor. build.	3.1 Comm. infr. el.	3.2 Comm. infr. wtr.	3.3 Road net.
HZ 1	13.3	0.22	0	0	0	252	0	0	11	8	-216
HZ 2	17.4	0.22	0	0	0	130	0	0	13	7	80
HZ 3	11.6	0.22	0	0	0	243	0	0	11	8	492
HZ 4	12	0.22	0	0	0	112	0	0	9	11	-80
HZ 5	13.2	0.22	0	0	0	171	0	0	8	9	-121
HZ 6	19.4	0.22	0	0	0	18	0	0	2	2	60
HZ 7	43.5	0.22	0	0	0	90	0	0	5	4	39
HZ 8	16.2	0.22	0	0	0	86	0	0	7	9	-137
HZ 9	13.6	0.22	0	0	0	171	0	0	9	7	633
HZ 10	17.1	0.22	4	1.36	0	63	5	0	7	12	463
HZ 11	15.6	0.22	0	0	0	158	2	0	10	13	283
HZ 12	44.8	0.22	18.6	1.36	2	76	0	4	9	15	325
HZ 13	49.3	0.22	15.04	1.36	9	319	7	15	15	18	211
HZ 14	18.7	0.22	1.52	1.36	0	216	3	0	9	12	317

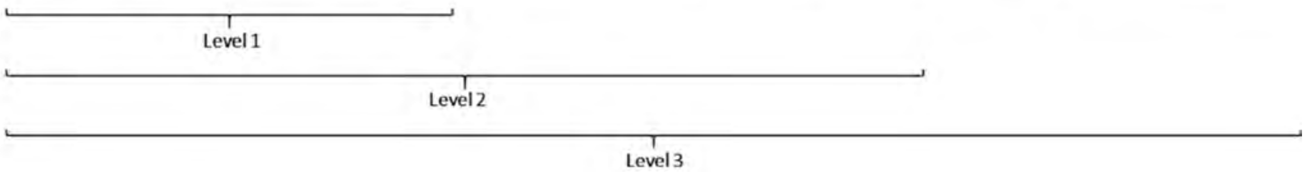


Figure 14. Input matrix for combined seismic-flood risk (Scenario S-F) multi-criteria analysis with criteria evaluation for all three levels.

The input data (Figure 14) and criteria weights (Table 4) are imported in a multi-criteria analysis application based on the PROMETHEE method and results have been calculated for all three levels of analysis. The first analysis was made for the criteria set defined as Level 1, a second analysis for Level 2 and a third for Level 3. The criteria for each analysis were submitted to PROMETHEE method and the results for all three levels are presented in Figures 15, 16 and 17, respectively. There are no significant variations in results except zone HZ 13, which becomes more exposed when additional criteria are used (Level 1 and 2). At the end, the results are exported into GIS for better visualization and a further analysis of results (Figure 18).

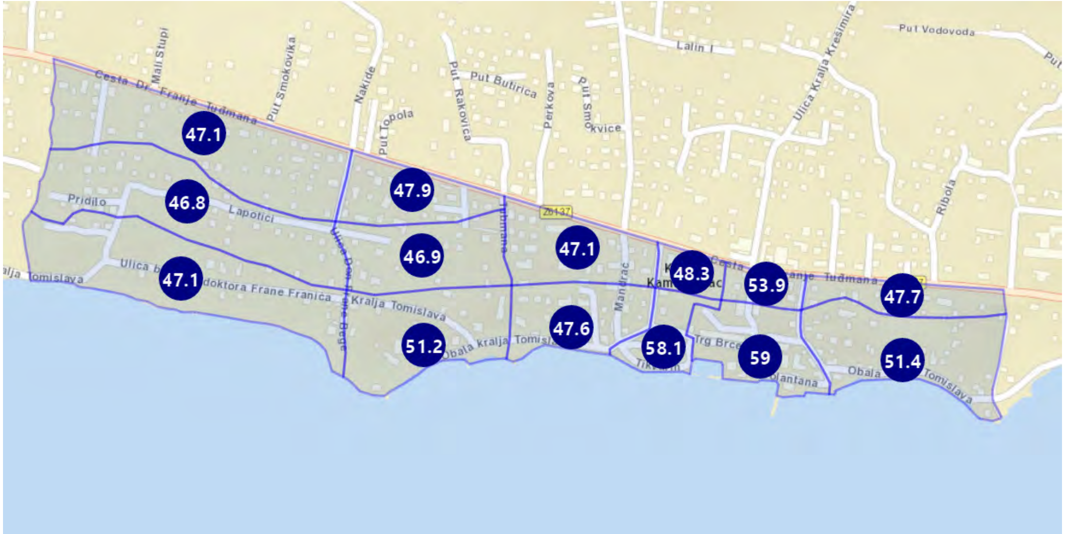


Figure 15. Results of risk analysis for seismic and flood hazard for Level 1 (Scenario S-F L1).

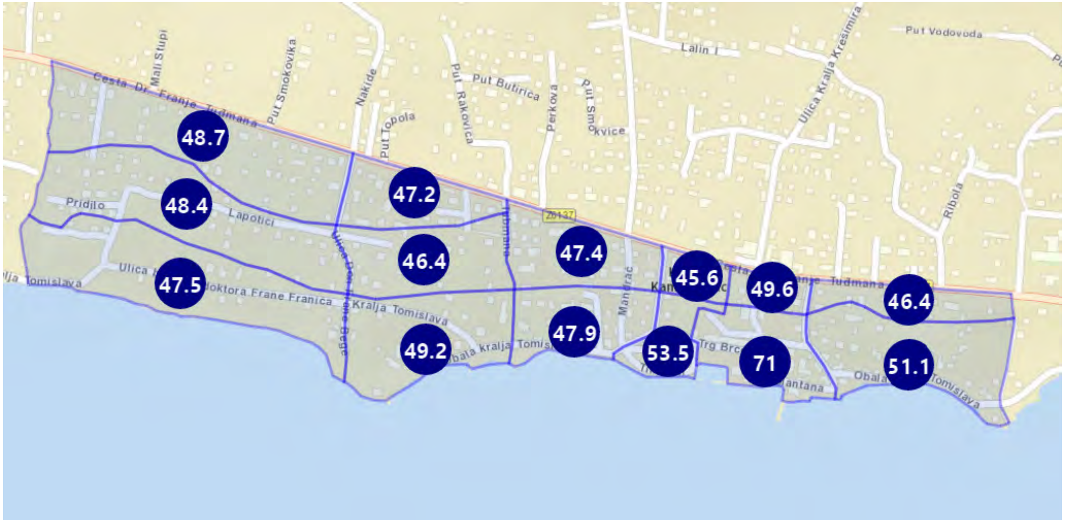


Figure 16. Results of risk analysis for seismic and flood hazard for Level 2 (Scenario S-F L2).

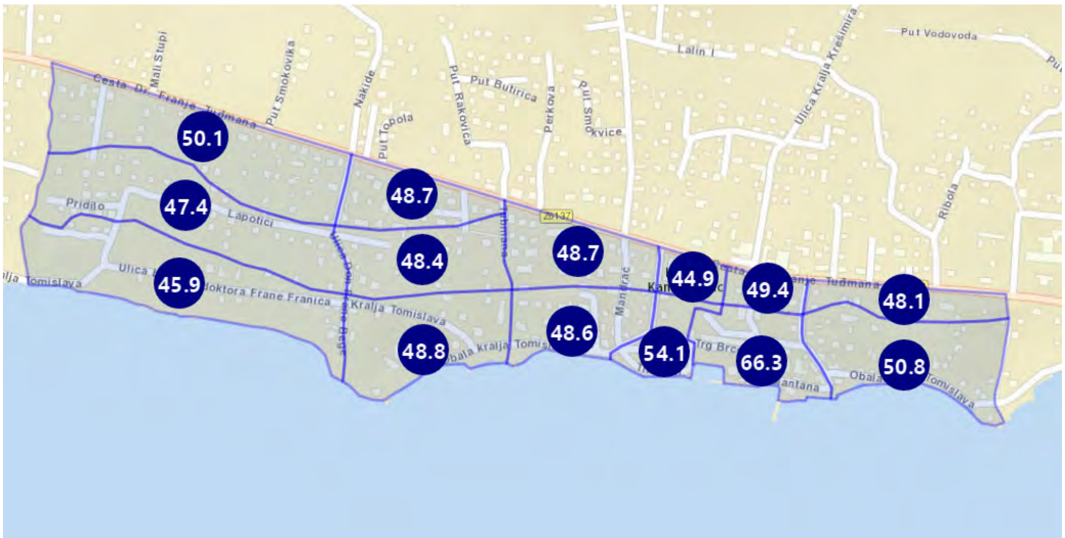


Figure 17. Results of risk analysis for seismic and flood hazard for Level 3 (Scenario S-F L3).

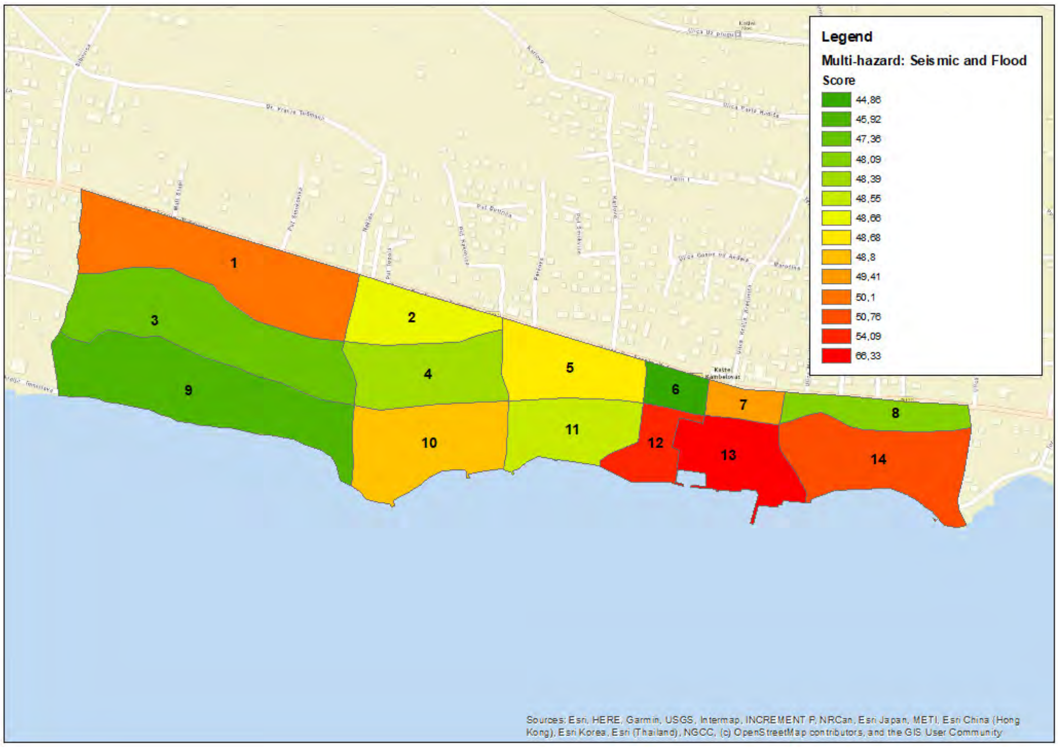


Figure 18. GIS visualization of risk for seismic and flood hazard for Level 3 (Scenario S-F L3).

The second analysis is a combined seismic–flood–extreme waves risk (Scenario S-F-EW) on three different levels. Again, each level represents different criteria sets, and criteria are grouped into two groups: main criteria, which are related to hazard and additional criteria, which are related to some important spatial data. Each criteria group has its own weight. In this case, an equal weight is given to each group: 50%. Other criteria weights are presented in Table 5. The input data for analysis are presented as a matrix with alternatives, in this case 14 homogenous zones (HZ) and up to 13 criteria depending on the level of analysis (Figure 19).

Table 5. An example of criteria weights for combined seismic–flood–extreme waves risk for Scenario S-F-EW Level 2.

Criteria Group	Group Weight	Criteria	Criteria Weight
Main criteria	50%	Seismic hazard (1.1)	19.5%
		Seismic vulnerability (1.2)	19.5%
		Flood hazard (1.3)	2.5%
		Flood vulnerability (1.4)	2.5%
		Extreme waves hazard (1.5)	3.0%
		Extreme waves vulnerability (1.6)	3.0%
Additional criteria *(n—number of additional criteria)*	50%	Construction density (2.1)	50/*n* = 12.5%
		Inhabitation density (2.2)	50/*n* = 12.5%
		Importance factor (2.3)	50/*n* = 12.5%
		Historical buildings (2.4)	50/*n* = 12.5%

Short Name	1.1 Seismic vuln.	1.2 Seismic haz.	1.3 Flood vuln.	1.4 Flood haz.	1.5 Extr. wav. vuln.	1.6 Extr. wav. haz.	2.1 Constr. dens.	2.2 Inhab. dens.	2.3 Import. fact.	2.4 Histor. build.	3.1 Comm. infr. el.	3.2 Comm. infr. wtr.	3.3 Road net.
HZ 1	13.3	0.22	0	0	0	0	0	252	0	0	11	8	-216
HZ 2	17.4	0.22	0	0	0	0	0	130	0	0	13	7	80
HZ 3	11.6	0.22	0	0	0	0	0	243	0	0	11	8	492
HZ 4	12	0.22	0	0	0	0	0	112	0	0	9	11	-80
HZ 5	13.2	0.22	0	0	0	0	0	171	0	0	8	9	-121
HZ 6	19.4	0.22	0	0	0	0	0	18	0	0	2	2	60
HZ 7	43.5	0.22	0	0	0	0	0	90	0	0	5	4	39
HZ 8	16.2	0.22	0	0	0	0	0	86	0	0	7	9	-137
HZ 9	13.6	0.22	0	0	0	0	0	171	0	0	9	7	633
HZ 10	17.1	0.22	4	1.36	0	0	0	63	5	0	7	12	463
HZ 11	15.6	0.22	0	0	0	0	0	158	2	0	10	13	283
HZ 12	44.8	0.22	18.6	1.36	5.14	1.639	2	76	0	4	9	15	325
HZ 13	49.3	0.22	15.04	1.36	14.82	1.539	9	319	7	15	15	18	211
HZ 14	18.7	0.22	1.52	1.36	1.52	1.359	0	216	3	0	9	12	317

Level 1

Level 2

Level 3

Figure 19. Input matrix for combined seismic–flood–extreme waves risk (Scenario S-F-EW) multi-criteria analysis with criteria evaluation for all three levels.

The input data (Figure 19) and criteria weights (Table 5) are imported in a multi-criteria analysis application based on PROMETHEE method and results have been calculated for all three levels of analysis. The first analysis was made for a criteria set defined as Level 1, a second analysis for Level 2 and a third for Level 3. The criteria for each analysis were submitted to PROMETHEE method and the results for all 3 levels are presented in Figures 20–22, respectively. Again, there are no significant variations in results except zone HZ 13, which becomes more exposed when additional criteria are used (Level 1 and 2). At the end, the results are exported into GIS for better visualization and a further analysis of results (Figure 23).

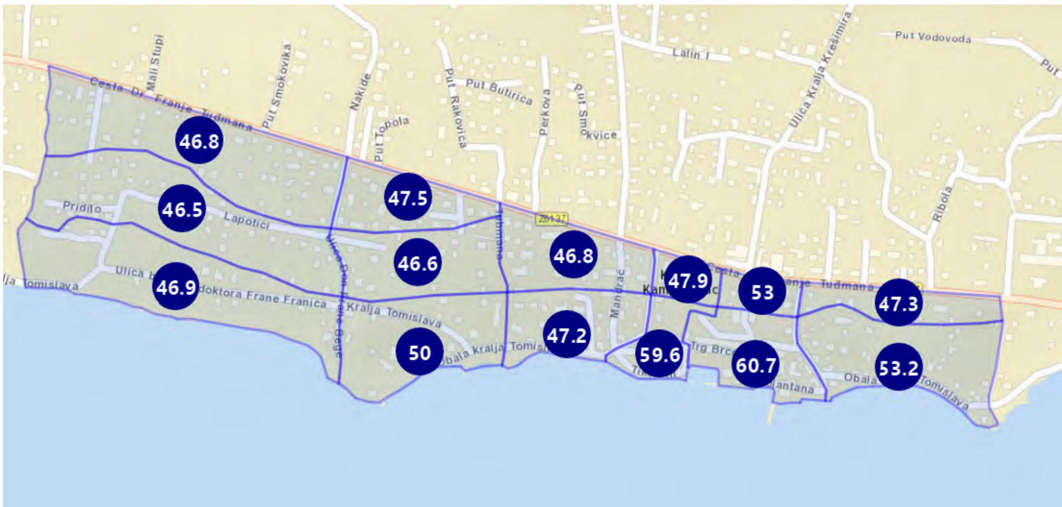


Figure 20. Results of the risk analysis for seismic, flood and extreme waves hazards for Level 1 (Scenario S-F-EW L1).

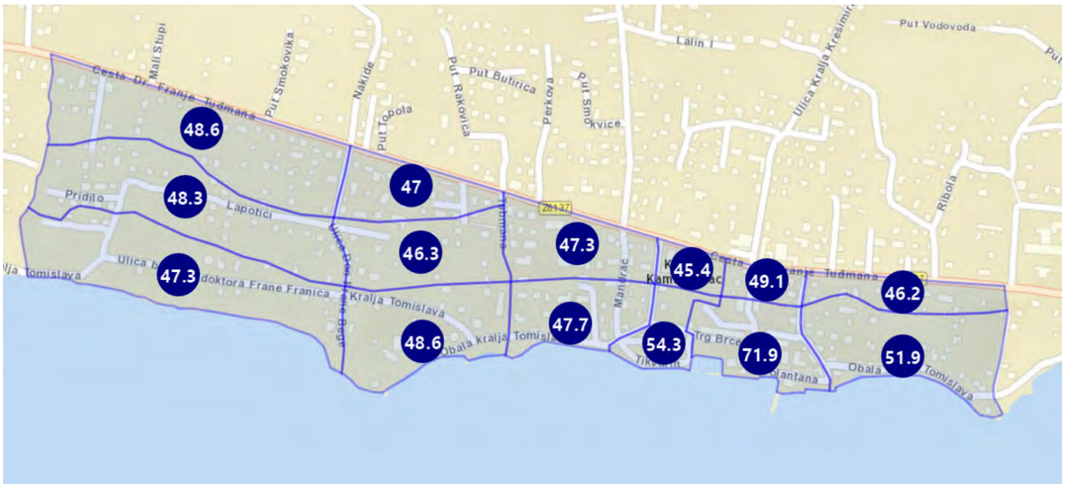


Figure 21. Results of the risk analysis for seismic, flood and extreme waves hazards for Level 2 (Scenario S-F-EW L2).

Figure 22. Results of the combined risk analysis for seismic, flood and extreme waves hazards for Level 3 (Scenario S-F-EW L3).

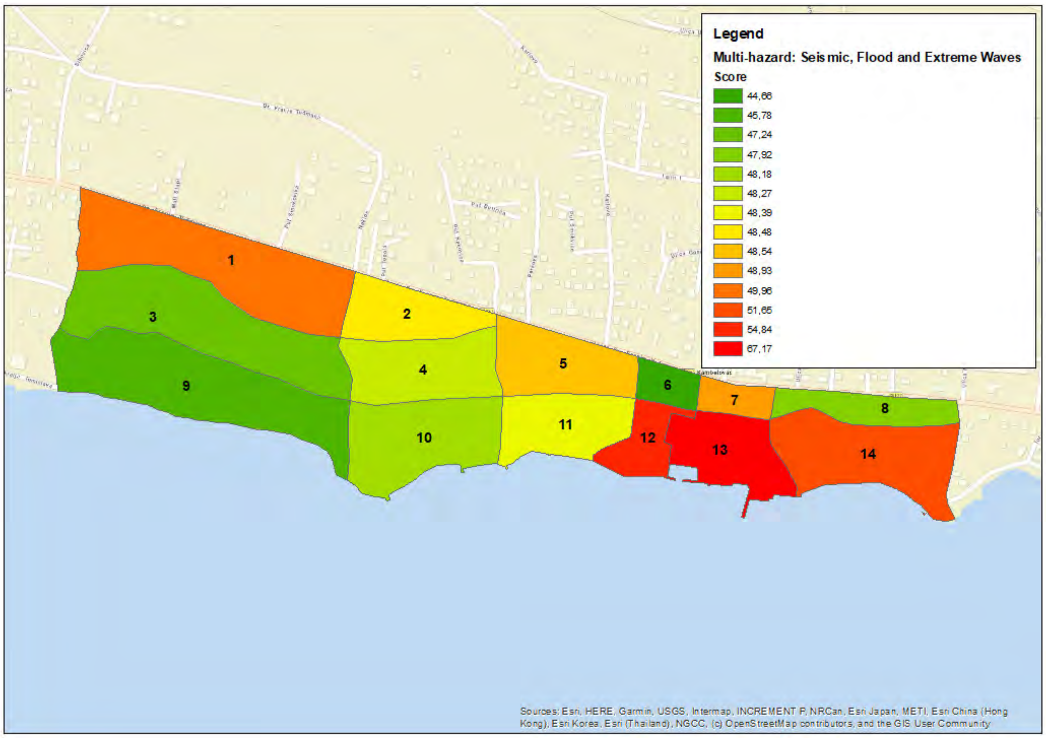


Figure 23. GIS visualization of risk for seismic, flood and extreme waves hazard for Level 3 (Scenario S-F-EW L3).

4. Conclusions

The multi-hazard risk assessment of urban areas is an important step in the risk management process. It can be used to reduce, manage and overcome the risks arising from the combination of different multiple hazards. This paper uses Spatial Multi-Criteria Decision-Making based on PROMETHEE method, coupled with the Geographic Information System, to assess the single-hazard and multi-hazard risk caused by seismic, sea floods and extreme sea waves. A case study for the application of the method is Kaštel Kambelovac, an urban settlement placed at the Croatian part of the Adriatic coast. The observed area has been divided into the homogenous zones that have been identified as areas of the test site with some mutual spatial characteristics. The homogeneity was identified by intersecting spatial layers in the GIS. The multi-hazard risk assessment method is based on the validation of the main components of the risk caused by natural hazard phenomena, such us vulnerability expressed in terms of the vulnerability index, hazard and influence of additional criteria, to overall risk in homogenous zones. The main specificity of this research is multi-hazard risk evaluation based on a previous detailed calculation of vulnerability indexes of each building in the test area for all observed threats.

The methodology ranks the various homogenous zones in terms of the relative proneness to coupled seismic, sea floods and extreme sea waves hazards. It enables a risk analysis for different scenarios for both single and multiple hazards at the level of buildings and homogenous zones. In the case study presented here, the analysis has shown that the seismic risk is a dominant threat in all scenarios. The results of a multi-hazard analysis for the combination of seismic and sea floods hazard have shown that the area with the highest risk is related to the historical part of Kaštel Kambelovac. This is due to the fact that this area, along with high seismic risk, has the highest level of exposure to flooding. Furthermore, the vulnerability of exposed objects in the historical part is highest for both hazards. Likewise, the results of the multi-hazard analysis for the combination of seismic, sea floods and extreme waves hazard are analogous to previous ones, showing that the highest risk is again in the historical part of Kaštel Kambelovac. The vulnerability of exposed objects to extreme waves is the highest in the historical part, and this particular area is most exposed to extreme waves due its low-lying coast. Performed analyses provide useful information for decision makers and public authorities to define priorities in future interventions through the process of risk management planning.

Author Contributions: Conceptualization, Ž.N. and N.M.; data curation, M.M., N.M. and T.K.; funding acquisition, Ž.N. and E.B.; investigation, Ž.N., N.M., M.M., E.B. and T.K.; methodology, N.M. and M.M. and Ž.N.; software, N.M. and M.M.; supervision, Ž.N. and E.B.; validation, Ž.N., N.M., M.M., E.B. and T.K.; visualization, M.M. and T.K.; writing—original draft, Ž.N., N.M., M.M., E.B. and T.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the European Union, Programme Interreg Italy–Croatia, Project "Preventing, managing and overcoming natural-hazards risks to mitigate economic and social impact"—PMO-GATE ID 10046122. The research is also partially supported through project KK.01.1.1.02.0027, co-financed by the Croatian Government and the European Union through the European Regional Development Fund—the Competitiveness and Cohesion Operational Programme.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Some of the datasets that were analyzed in this research are publicly available on the website of PMO-GATE project: https://www.italy-croatia.eu/web/pmo-gate (accessed on 25 October 2022).

Acknowledgments: This research was part of the Work Packages 4 and 5 of the European Union, Programme Interreg Italy–Croatia, Project "Preventing, managing and overcoming natural-hazards risks to mitigate economic and social impact"—PMO-GATE ID 10046122. The results of this research were published in the Deliverables: "4.1.1. Methodology for provision assessment indexes based on Spatial Multi-Criteria Decision-Making—Croatia" and "5.1.6. Map of spatial distribution of the critical zones most prone to flood, extreme waves and seismic risks for HR test site".

Conflicts of Interest: The authors declare no conflict of interest.

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A PROMETHEE Multiple-Criteria Approach to Combined Seismic and Flood Risk Assessment at the Regional Scale

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Abstract: Social vulnerability is deeply affected by the increase in hazardous events such as earthquakes and floods. Such hazards have the potential to greatly affect communities, including in developed countries. Governments and stakeholders must adopt suitable risk reduction strategies. This study is aimed at proposing a qualitative multi-hazard risk analysis methodology in the case of combined seismic and flood risk using PROMETHEE, a Multiple-Criteria Decision Analysis technique. The present case study is a multi-hazard risk assessment of the Ferrara province (Italy). The proposed approach is an original and flexible methodology to qualitatively prioritize urban centers affected by multi-hazard risks at the regional scale. It delivers a useful tool to stakeholders involved in the processes of hazard management and disaster mitigation.

Keywords: risk assessment; multi hazard; seismic risk; flood risk; multiple-criteria decision analysis; PROMETHEE algorithm

Citation: Soldati, A.; Chiozzi, A.; Nikolić, Ž.; Vaccaro, C.; Benvenuti, E. A PROMETHEE Multiple-Criteria Approach to Combined Seismic and Flood Risk Assessment at the Regional Scale. *Appl. Sci.* **2022**, *12*, 1527. https://doi.org/10.3390/app12031527

Academic Editor: Igal M. Shohet

Received: 30 November 2021
Accepted: 27 January 2022
Published: 31 January 2022

1. Introduction

Many areas in Europe and worldwide are increasingly subjected to catastrophic events. These events intensify the exposure of these territories to multi-risk events and make societies more vulnerable to entangled risks [1–7]. Globalization and climate changes are the main culprits of these multi-risk dynamics. Globalization, indeed, makes countries closely linked and interdependent, so communities are not only vulnerable to local extreme events but also to those occurring outside their national territories. Climate change increases, among others, the frequency and intensity of extreme meteorological phenomena, hydrological and flood risk, as well as the risk of fires. The awareness of this worrying trend has determined the need for adequate tools to address and mitigate these risks, as well as information campaigns to foster resilience and coping capacity of communities [5–7].

Understanding risks involving vast inhabited areas is therefore paramount, particularly when assessing potential losses produced by a combination of multiple hazards. Hereafter, a hazard refers to the probability of occurrence in a specified period of a potentially damaging event of a given magnitude in a given area [8]. Total risk is a measure of the expected human (casualties, injuries) and economic (damage to property, activity disruption) losses due to adverse natural phenomena. Such a measure is assumed to be the product of hazard, vulnerability, and exposure instances [9]. Many areas on Earth are subjected to the effects of coexisting multiple hazards, among which floods [3,8] and earthquakes are some of the most widespread [5–7]. Though inhabited environments are affected by multiple hazardous processes, most studies focus on a single hazard [8].

The choice to adopt a multi-risk analysis approach has the potential to play a fundamental role in increasing urban resilience, an essential factor for sustainable development, enabling cities to prepare, respond, and recover when hit by catastrophic events, and therefore prevent or contain economic, environmental, and social losses [1]. However, performing a multi-risk analysis with the tools and methodologies available today raises numerous challenges and difficulties [10–20]. For instance, an updated analysis of multi-hazard aggregated risk for infrastructures considering multiple potential threats has recently been proposed in reference [5].

Risk assessment is indeed carried out through independent procedures that adopt different estimation metrics. This makes comparisons difficult and precludes considering correlations or cascading effects [11]. On the contrary, the Multiple-Criteria Decision Analysis (MCDA) technique is a promising approach in multiple-hazard risk analysis, even if this route has been scarcely explored to date [21–24].

To pave the way for sustainable land-use plans and risk-mitigation strategies, we must analyze, quantify, and, especially, compare all concurrent risks [25]. To date, single-risk assessment is generally performed by means of independent procedures, whose results cannot be compared. The purpose of this paper is to devise an approach for the qualitative assessment of combined risks at the regional scale. In particular, the objective is to jointly analyze the flood and seismic risk for the Ferrara province area. The proposed approach is based on the suitable use of the Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE), a Multiple-Criteria Decision Analysis technique [26–29]. The province of Ferrara is in a flatland area in the northern part of Italy. Historically, it has been mainly hit by floods and seismic events. Though floods are exogeneous processes, whereas earthquakes are exogenic, we assume flood and seismic hazards to be the two relevant hazards for determining a priority list. This priority list is meant to be useful to stakeholders and public agencies called to rapidly implement investment plans aimed to prevent economic and life losses and foster the coping capacity of communities to manage the adverse conditions induced by natural disasters. Particularly, the present objective is to prioritize this among the different municipalities. Therefore, the adopted level of observation is at the scale of the area included within each municipality.

Assuming the municipalities of the province of Ferrara as the alternatives of the multiple-criteria analysis, the proposed approach defines a priority ranking among all the alternatives. The outcome is represented by qualitative risk maps. These maps are useful tools for stakeholders involved in community management and risk prevention.

Among the Multi-Risk Methodologies applied in Italian territories, we recall here the works by Gallina et al. [23,24] for the assessment of the impact of sea-level rise, coastal erosion, and storm surge induced by climate changes in coastal zones in North Italy. Flood and seismic risks have been multi-assessed through a Machine Learning framework recently devised by the authors for the Emilia Romagna region [30]. Up to now, the present contribution is the very first to use an MCDA approach for multi-risk analysis of combined flood and earthquake risks, while no other relevant contributions exist dealing with multi-hazard analyses of the Province of Ferrara.

2. Materials and Methods

2.1. Geographical Context and Single Risk Description

To introduce the concept of multi-risk assessment, it is first necessary to discuss the concept of single risk. Risk is basically defined as the product of three parameters: Hazard, vulnerability, and exposure [9]. A hazard represents the probability that an adverse event will occur in a specific area and in a specific time interval. Vulnerability, on the other hand, is an intrinsic characteristic of a system; it represents its propensity to suffer a certain level of damage following the occurrence of a hazard event. Finally, exposure indicates the presence of people, critical infrastructures, natural and cultural heritage, and much more still in hazard zones that are thereby subject to potential losses [4].

The concept of multi-risk follows as the overall risk from a multi-hazard and multi-vulnerability perspective. The term multi-hazard indicates several hazards affecting the same exposed elements (with or without space–time coincidence) or the occurrence of a hazard event that triggers another one giving rise to a domino or cascade effect. Furthermore, the term multi-vulnerability indicates those circumstances where several elements are sensitive to different possible vulnerabilities towards the various hazards affecting them or vulnerabilities that vary over time [10,11].

The territory of the province of Ferrara is located at the north-eastern extremity of the Padana Plain, a flat land area in the north part of Italy crossed by the Po River and bathed by the Adriatic Sea on the east side. It is characterized by minimum land slopes and its altimetry is mainly under the mean sea level, as almost half of its area is below the mean sea level, as shown in Figure 1. Moreover, the eastern part of the territory is affected by subsidence phenomena as well. These ground-level modifications, caused mainly by anthropogenic actions as well as by geological and neotectonic factors [31,32], produced a subsidence rate of up to −2.5 mm/year [31]. The main watercourses that flow through the Ferrara province are the Po River, which marks the northern border of the Reno River, and the Idice and Sillaro streams, which are not tributaries of the Po River, and cross the province in their last stretch. Furthermore, numerous artificial canals flow through the Ferrara Province, including the Cavo Napoleonico, which connects the Po and Reno rivers, and the Idrovia Ferrarese.

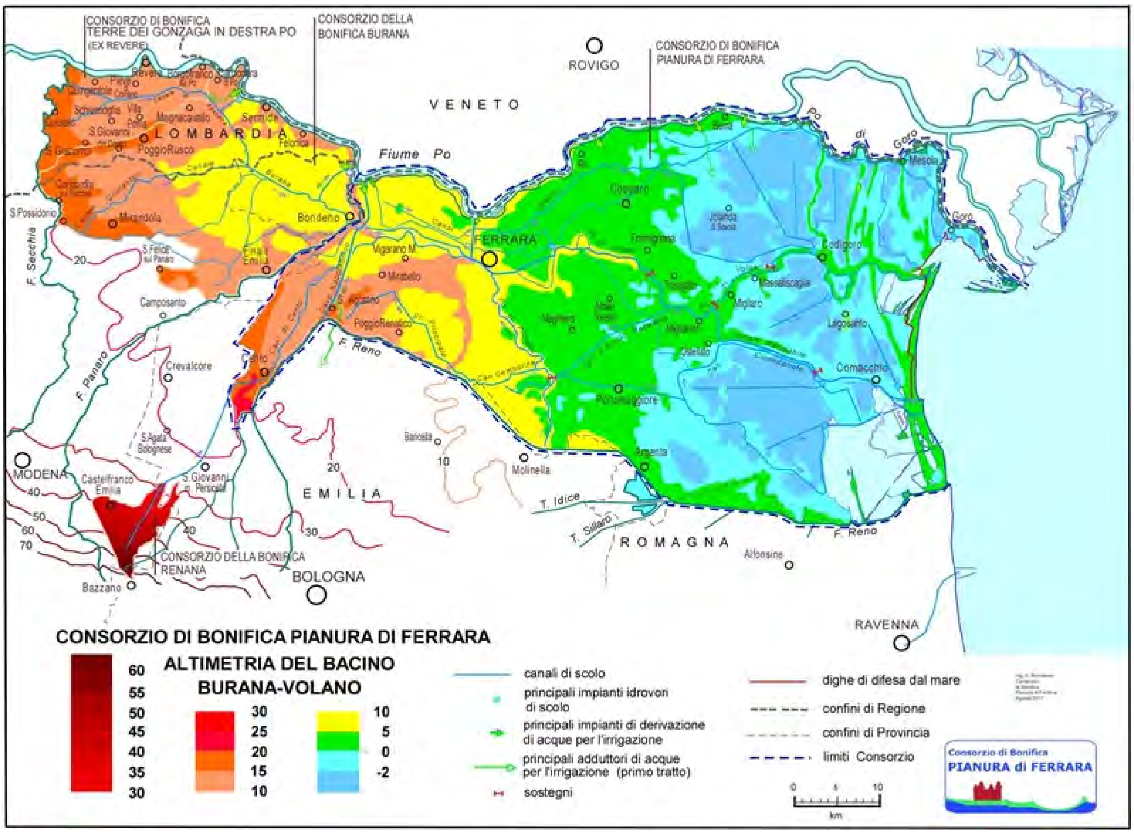


Figure 1. Altimetric map of Ferrara province (free source https://www.bonificaferrara.it/images/Allegati/SITL/4d-3-altimetria(100).pdf, accessed on 3 January 2022, made available by Consorzio di Bonifica Pianura di Ferrara). The minimum and maximum extremal values of the ground level over the sea in the legend are −2 m (dark blue) and 60 m (dark red), respectively.

The province of Ferrara includes 23 municipalities. Attention is hereafter restricted to the two main risks of the area under study, namely flood and seismic risks. Site effects associated with inherent geological morphology and instability issues such as liquefaction were not considered, for simplicity. Desertification is another risk that has been emerging in recent years in the Po delta plain [10]. However, it has not been considered in the present contribution. Hereafter, flood risk refers to the risk that depends on the probability of occurrence of a flood, evaluated concerning the different typologies of watercourses that flow through the territory. The flood risk for the selected region was quantified by the Land Reclamation Authority of the province of Ferrara (Consorzio di Bonifica Pianura di Ferrara), and accounts for flood hazard, exposure, and vulnerability parameters.

Seismic risk depends on the peak ground acceleration (PGA) as well as on the vulnerability of the built environment and the exposure of people and economic activities. We exploited the map of seismic hazard provided by the Italian Institute of Volcanology and Geophysics (INGV), and the seismic classification of municipalities in Emilia (free source https://ambiente.regione.emilia-romagna.it/en/geologia/seismic-risk/seismic-classification, accessed on 26 January 2022), shown in Figure 2a. In Figure 2b, Italy is divided into different areas according to peak ground acceleration values [33] (free source http://zonesismiche.mi.ingv.it/, accessed on 26 January 2022).

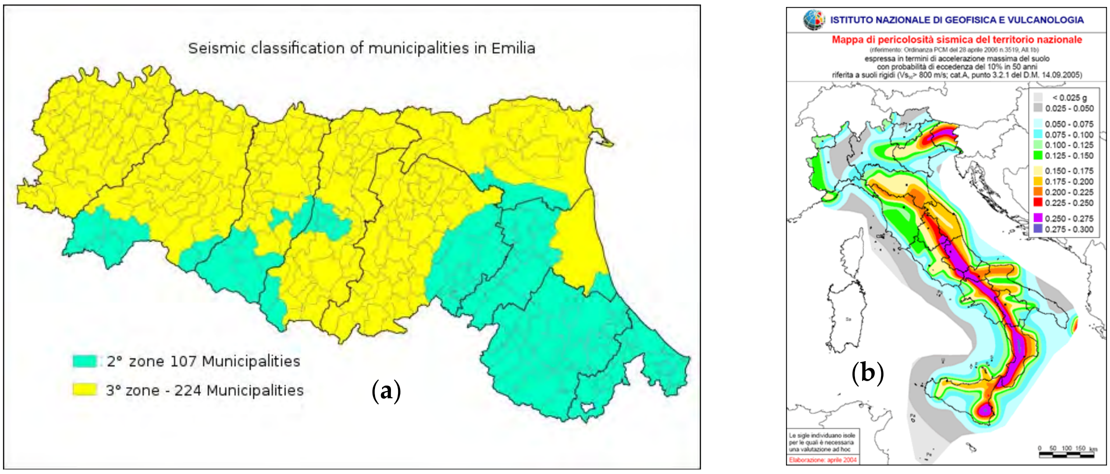


Figure 2. (**a**) Seismic classification of municipalities in Emilia (https://ambiente.regione.emilia-romagna.it/en/geologia/seismic-risk/seismic-classification, accessed on 26 January 2022). (**b**) Seismic Hazard Map of Italy (free source from INGV webpage http://zonesismiche.mi.ingv.it/, accessed on 26 January 2022).

Finally, we used the database made available by the Italian National Institute of Statistics (Istat). This database was used in 2018 by the Italian Superior Institute for Environmental Protection and Research (ISPRA) to produce seismic, hydrogeological, volcanic, and social vulnerability hazard maps for the entire Italian peninsula. The reader is referred to the pertinent report by Trigila et al. [34] to obtain a detailed description of ISPRA's methodology for the processing of the data.

2.2. The PROMETHEE Method

The proposed multi-hazard risk analysis procedure for the region under study is based on PROMETHEE [26–29], a Multiple-Criteria Decision Analysis method. It belongs to the class of aggregation methods based on outranking relationships. It is known for its simplicity and the ability to analyze information from multiple sources. PROMETHEE allows one to jointly compare data originally expressed in different units and scales. A flux diagram explaining the various steps of the PROMETHEE-based analysis can be found in reference [29].

PROMETHEE deals with maximization or minimization problems with k different criteria of the kind

$$\max(or\min)\{g_1(a), g_2(a), \ldots, g_k(a) | a \in A\}, \quad (1)$$

where A is a finite set of possible alternatives and function $g_j(a)$ represents the performance of the j-th criterion. Let us consider two alternatives, $(a,b) \in A$. We have the following cases:

$$\begin{cases} \forall j : g_j(a) \geq g_j(b) \\ \exists k : g_k(a) > g_k(b) \end{cases} \Leftrightarrow aPb,$$

$$\forall j : g_j(a) = g_j(b) \Leftrightarrow aIb, \quad (2)$$

$$\begin{cases} \exists s : g_s(a) > g_s(b) \\ \exists r : g_r(a) < g_r(b) \end{cases} \Leftrightarrow aRb,$$

where P, I, and R denote preference (P), indifference (I), or incompatibility relations (R) of one alternative over the other, respectively.

By comparing all the alternatives for each criterion, a hierarchy of alternatives belonging to the starting space A will be obtained. When comparing two actions,$(a,b) \in A$. the result of this comparison is expressed in terms of the preference function $\wp : A \times A \to (0,1)$ that represents the intensity of the preference of alternative a towards alternative b. Therefore, $\wp(a,b) = 0$ indicates no preference of a over b (or indifference), $\wp(a,b) \simeq 0$ indicates a weak preference of a over b, $\wp(a,b) \simeq 1$ indicates a strong preference of a over b, and $\wp(a,b) = 1$ indicates a strict preference of a over b. In practice, the preference function will often be a function of the difference between the evaluations of the two alternatives considered:

$$\wp(a,b) = P(g(a) - g(b)) = P(d), \quad (3)$$

where P is a non-decreasing function, equal to zero for negative values of d. PROMETHEE offers six types of preference functions (see Table 1).

Table 1. Types of preference function.

Generalized Criterion	Definition	Parameters to Fix
Type 1: usual criterion	$P(d) = \begin{cases} 0 & d \leq 0 \\ 1 & d > 0 \end{cases}$	-
Type 2: U-shape criterion	$P(d) = \begin{cases} 0 & d \leq q \\ 1 & d > q \end{cases}$	q
Type 3: V-shape criterion	$P(d) = \begin{cases} 0 & d \leq p \\ \frac{d}{p} & 0 \leq d \leq p \\ 1 & d > p \end{cases}$	p
Type 4: Level criterion	$P(d) = \begin{cases} 0 & d \leq q \\ \frac{1}{2} & q \leq d \leq p \\ 1 & d > p \end{cases}$	p, q
Type 5: V-shape with indifference criterion	$P(d) = \begin{cases} 0 & d \leq q \\ \frac{d-q}{p-q} & q \leq d \leq p \\ 1 & d > p \end{cases}$	p, q
Type 6: Gaussian criterion	$P(d) = \begin{cases} 0 & d \leq 0 \\ 1 - e^{-\frac{d^2}{2s^2}} & d > 0 \end{cases}$	s

Therefore, a preference index is defined as follows:

$$\begin{cases} \pi(a,b) = \sum_{j=1}^{k} P_j(a,b)w_j \\ \pi(b,a) = \sum_{j=1}^{k} P_j(b,a)w_j \end{cases}, \quad (4)$$

where $\pi(a,b)$ expresses the degree to which a is preferred to b over all criteria and vice versa, and w_j is the weight of each criterion and expresses a measure of the importance of the relative criterion.

For all the criteria, a classification is available for the various alternatives necessary to define the so-called outranking flows, which are the fundamental units for the PROMETHEE methodology. Each alternative a faces $(n-1)$ other alternatives that belong to the generic space A. The two following outranking flows are defined:

$$\begin{cases} \Theta^{+}(a) = \frac{1}{n-1}\sum\limits_{x \in A} \pi(a,x) \\ \Theta^{-}(a) = \frac{1}{n-1}\sum\limits_{x \in A} \pi(x,a) \end{cases}, \tag{5}$$

where x represents the deviation of the specific preference function with respect to the same function of preference for the other alternatives. $\Theta^{+}(a)$ expresses how alternative a outranks all the others, otherwise $\Theta^{-}(a)$ expresses how alternative a is outranked by all the others. The higher $\Theta^{+}(a)$ (lower $\Theta^{-}(a)$) is, the more likely alternative a is strongest; otherwise, alternative a, compared to the others, is weakest when $\Theta^{+}(a)$ assumes small values. Once these two flows have been defined, it becomes very simple to make comparisons between alternatives and subsequently establish their order.

PROMETHEE offers several ways to view the results; the main ones are illustrated below:

- PROMETHEE I Partial Ranking: This is a partial ranking of the alternatives, based on positive and negative flows, and includes preferences, indifference, and incomparability. This scheme allows, therefore, to compare, where possible, the alternatives and establish their partial order of preference through the indices and the related outranking flows.
- PROMETHEE II Complete Ranking: This is useful when the decision maker needs a complete hierarchy among the alternatives of the problem. In this case, the alternatives will be compared in relation to their net flow $\Theta(a) = \Theta(a)^{+} - \Theta^{-}(a)$. PROMETHEE II allows a complete classification of the alternatives; however, it is less realistic and poor in information as it eliminates any possible factor of incomparability between the different alternatives.
- PROMETHEE Table: This displays the Θ, Θ^{+}, and Θ^{-} scores. The actions are ranked according to the PROMETHEE II complete ranking.
- PROMETHEE Rainbow: This is a diagram that allows one to highlight, for each alternative, the criteria that positively or negatively affect the final result.
- Profile of alternatives: This is a diagram that shows, for each alternative, the net flow Θ of each criterion.

2.3. Data Collection and Processing

Both flood and seismic risks have been included in PROMETHEE as criteria according to their components (hazard, exposure, and vulnerability), while the municipalities, i.e., the object on which to evaluate the criteria, are the alternatives. Risk parameters for each municipality are made available by the National Institute of Vulcanology and Geophysics (INGV), the Italian National Institute of Statistics (Istat), and the Land Reclamation Authorities of the Province of Ferrara. Accordingly, we have drawn from the aforementioned databases a simplified map of the flood risk. In particular, Figure 3 displays the flood hazard for the Province of Ferrara in terms of the probability of floods. In this map, the classification is based on Italian Government Decree n. 49/2010 [35]. Accordingly, frequent floods are defined as those having a high probability of occurrence, with a return period of $20 \leq T \leq 50$ years (P3); infrequent floods have an average probability of occurrence with a return period of $100 \leq T \leq 200$ years (P2); finally, low-probability floods have a return period of $200 < T \leq 500$ years (P1).

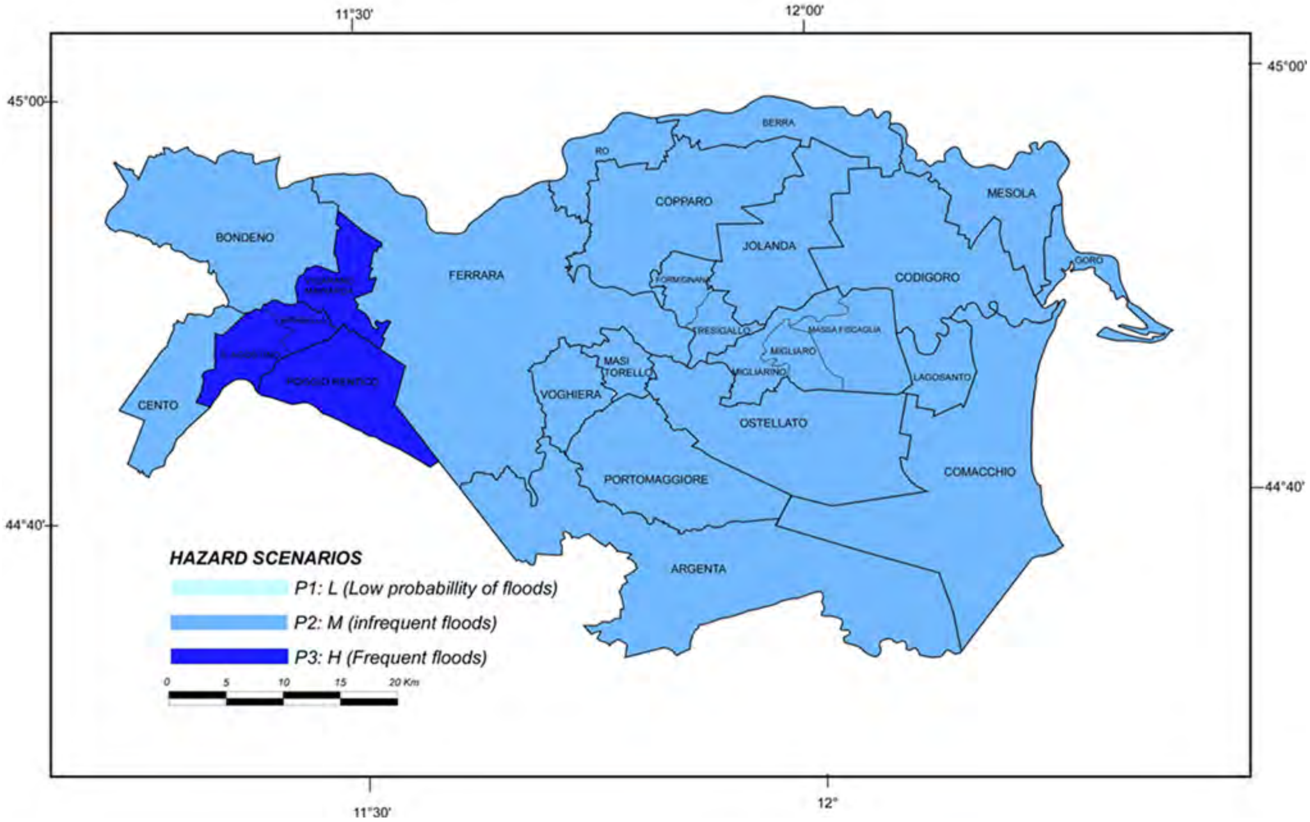


Figure 3. Map of the flood hazard for the province of Ferrara in terms of probability of flood.

Figure 4 provides a map of the seismic hazard for the province of Ferrara in terms of peak ground acceleration (PGA). The PGA-intervals are indicated in the legend.

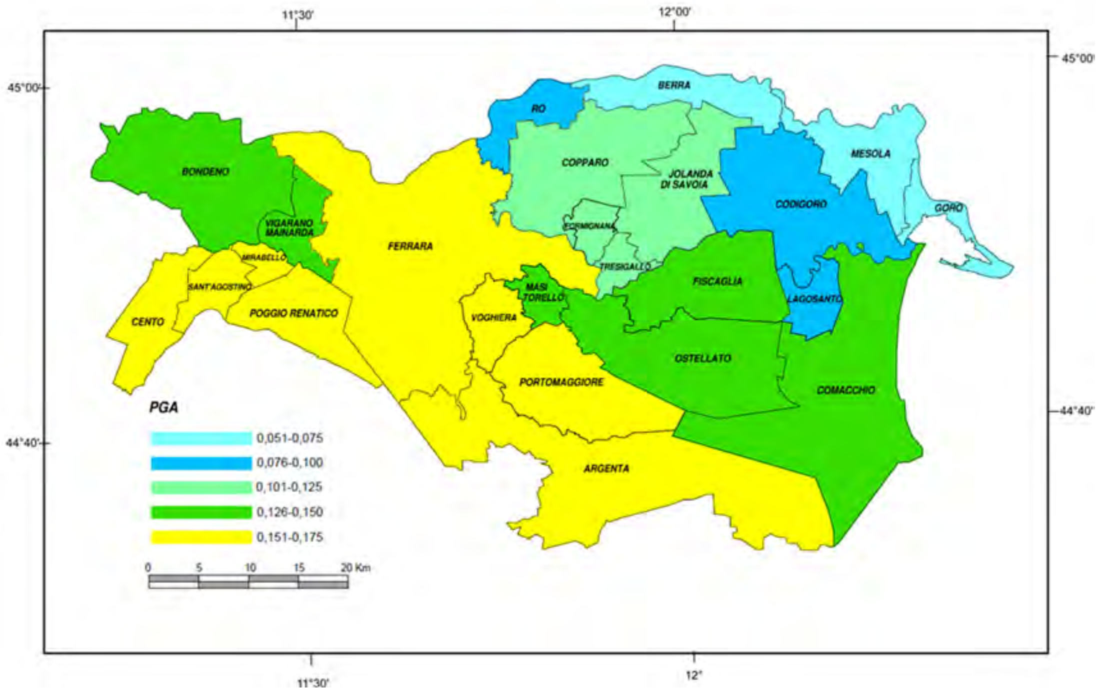


Figure 4. Map of the seismic hazard for the province of Ferrara in terms of peak ground acceleration.

As for exposure-related criteria, for each municipality, we adopted three parameters: Land use percentage, the number of strategic buildings, and population density. All of them were drawn from the Istat database. The strategic buildings were defined based on the presence and number of halls, police stations, fire brigade buildings, schools, universities, water lifting plants, hospitals, and civil protection centers. This information was obtained from the website of the province of Ferrara (http://www.provincia.fe.it/, 1 October 2021), as per educational and public institutions and centers, and from the website of the Consorzio di Bonifica Pianura di Ferrara as per water lifting plants (https://www.bonificaferrara.it/, 1 October 2021).

Specifically, four classes of land use percentages were obtained based on the ratio between the urbanized area divided by the total area. In synthesis, we collected the municipalities into four land use classes (Figure 5), four classes in terms of the number of strategic buildings (Figure 6), and four classes of population density (Figure 7).

As for the vulnerability criteria, we adopted a single non-dimensionalized parameter, which accounts for the average age of buildings. Knowing the age of construction and the corresponding number of buildings, we computed the following vulnerability index:

$$I_v = \frac{A\,\alpha_1 + B\,\alpha_2 + C\,\alpha_3 + D\,\alpha_4}{A + B + C + D},$$

where $A,\ B,\ C\ e\ D$ represent the number of buildings built between the end of 1800 and 1945; the number of buildings built between 1946 and 1980; the number of buildings built between 1981 and 2000, and finally, the number of buildings built from 2001 up to now. $\alpha_1,\ \alpha_2,\ \alpha_3\ e\ \alpha_4$ are coefficients equal to 1, 0.75, 0.5, and 0.25, respectively. The vulnerability index I_v results in being mainly related to the age of buildings, and its map is shown in Figure 8.

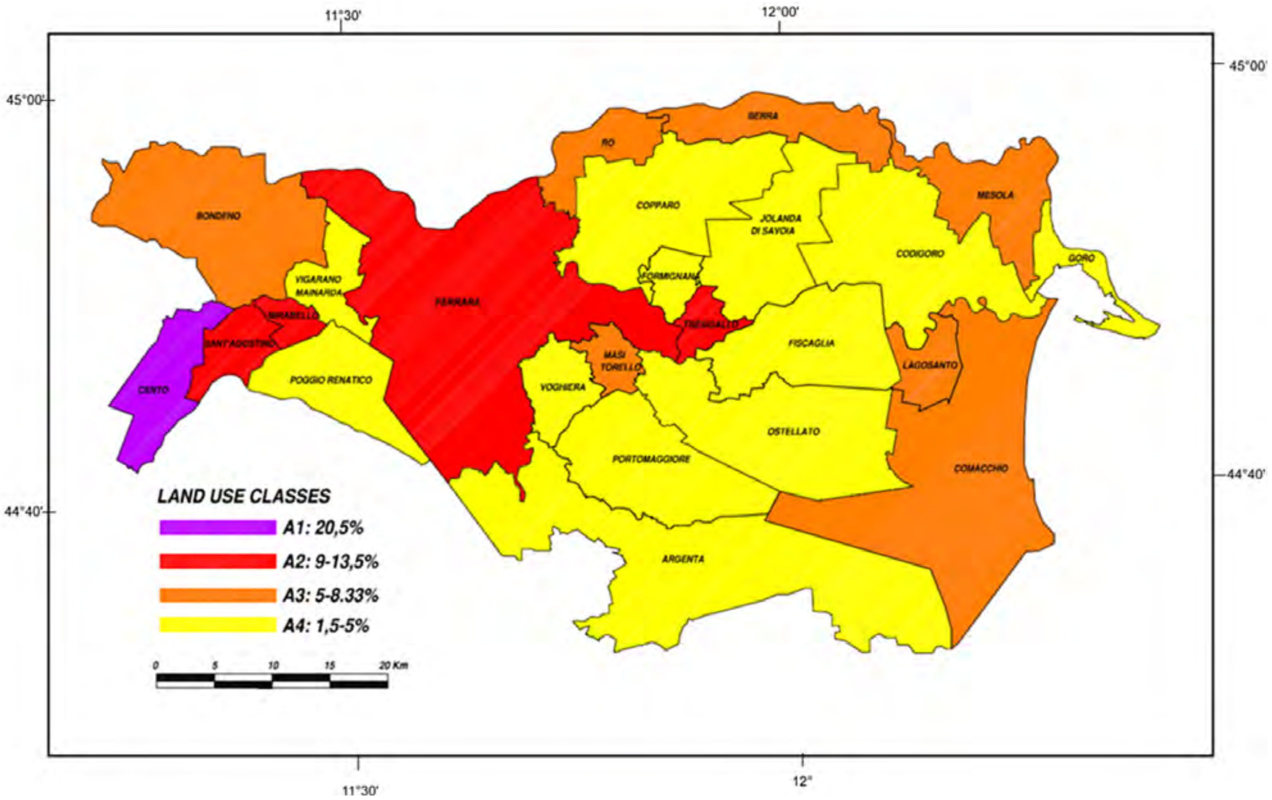


Figure 5. Land use map for the province of Ferrara.

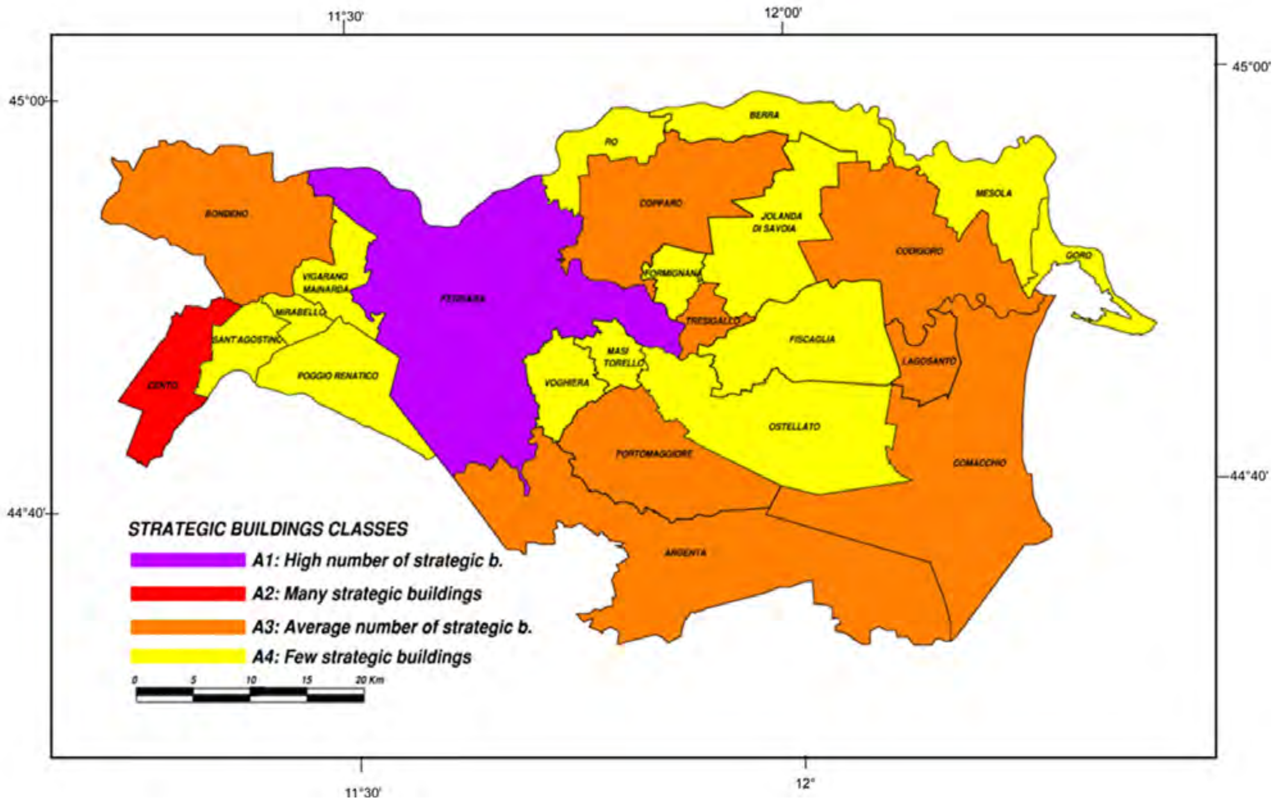


Figure 6. Map of strategic buildings incidence for the province of Ferrara.

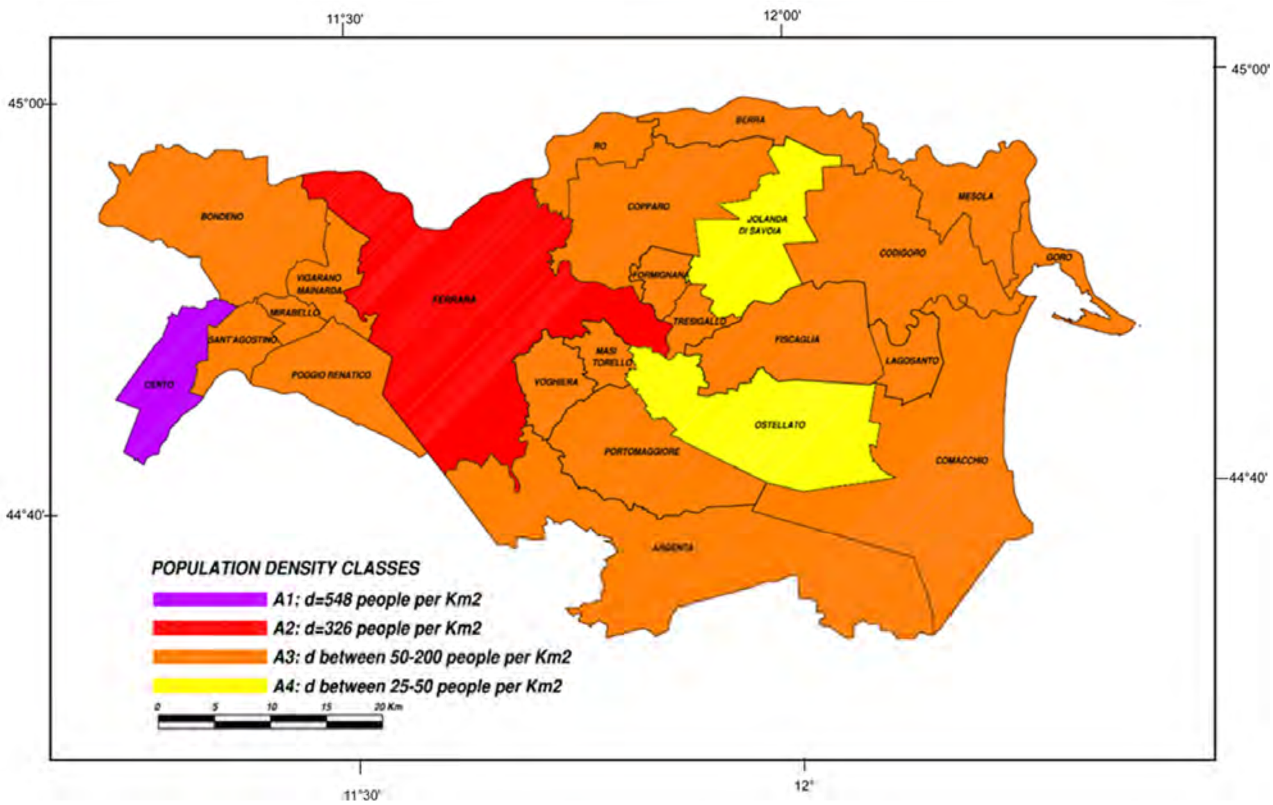


Figure 7. Map of the population density for the province of Ferrara.

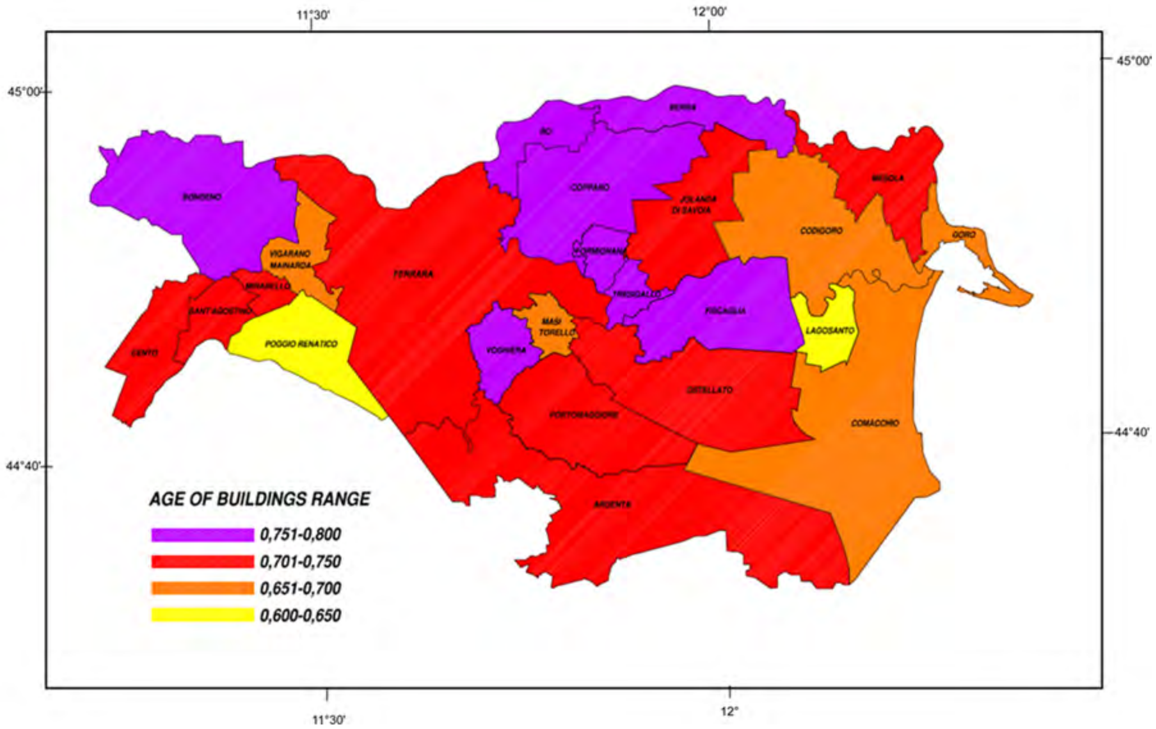


Figure 8. Map of the vulnerability parameter for the province of Ferrara computed as a function of the building age.

2.4. Normalization and Weight Assignment

All the data have been collected in an evaluation matrix, whose rows correspond to each alternative (i.e., each municipality), while each column corresponds to each selected criterion. In other words, the *i*,*j*-th element of the evaluation matrix expresses the value of the *i*-th alternative relating to the attribute of the *j*-th criterion and describes the performance of each alternative regarding each criterion.

It should be noted that criteria are represented through different scales and units. This precludes mutual comparisons. Thus, it is necessary to further homogenize the data contained in the evaluation matrix and proceed with comparisons through normalization. Through the preference function, the performance of the alternatives is transformed into a dimensionless value, ranging from o to 1. As a first attempt, we adopted the Type 1 preference function described in Table 1, which does not require the definition of any threshold. Subsequently, the linear preference function was also used.

Finally, we attributed weights to each criterion. Through this step, decision makers can make their preferences explicit, since it is not ensured that all the criteria take on the same importance. We first decided to attribute the same weight to each criterion. Then, a sensitivity analysis was performed with varying weights.

The risk maps shown in the following sections indicate three classes of risk levels, namely low, medium, high. It is emphasized that this classification must be intended as a pure ranking in terms of the relative urgence of investments. It does not at all intend to indicate the level of safety in absolute terms of the various municipalities. This classification answers the question as to whether the method can provide the priority level associated with a certain municipality and help to decide how to distribute investments over various municipalities.

2.5. Sensitivity Analysis

To verify the reliability of the results obtained, a sensitivity analysis was carried out. During this sensitivity analysis, we retraced the procedure by which the results were obtained and identified the steps most affected by uncertainties and subjectivity, considering their influence on the final ranking. Specifically, the choice of the preference function and the choice of weights appeared to be the most subjective. As for the choice of the preference function, a previous study [26] recommends assuming a linear preference function endowed with the definition of p, q thresholds. Two approaches are adopted for the determination of p and q: The so-called zero-max method, which imposes that the indifference threshold q is assigned the value of zero while the preference threshold p is set to be equal to the maximum difference between the evaluations of the criteria.

The mean-std method requires the calculation of the average value and the standard deviation of a set of differences between the evaluations of the criteria. In the mean-std method, the indifference threshold is assigned the value of the difference between the average value and standard deviation, while the sum between the average value and standard deviation is assigned to the preference threshold. Following [26–28], we adopted the preference function of the linear type for the quantitative criteria, that is flood hazard, land use, the age of buildings, and population density. However, the algorithm was also run by choosing the usual preference function, which is the simplest possible one. The thresholds were computed as shown in Table 2. As for the sensitivity on the weights, the four scenarios described in Table 3 have been considered.

Table 2. Preference functions and the associated thresholds p, q, and s.

	Criteria					
	Flood Hazard	**PGA**	**Land Use**	**Strategic Buildings**	**Age of Buildings**	**Population Density**
Min/Max	max	Max	max	max	max	max
Weight	1	1	1	1	1	1
Preference function	Usual	Linear	Linear	Usual	Linear	Linear
Thresholds	absolute	Absolute	absolute	absolute	absolute	absolute
q: Indifference, zero-max	n/a	0.000	0.0000	n/a	0.000	0.000
p: Preference (zero-max)	n/a	0.098	0.1896	n/a	0.158	523.00
s: Gaussian (zero-max)	n/a	n/a	n/a	n/a	n/a	n/a
q: Indifference (mean-std)	n/a	0.093	0.0261	n/a	0.0676	16.10
p: Preference (mean-std)	n/a	0.155	0.1081	n/a	0.766	238.60
s: Gaussian (mean-std)	n/a	n/a	n/a	n/a	n/a	n/a

Table 3. Sensitivity analysis on the weights of the criteria.

Sensitivity Analysis: Increase of Single Criteria Weights	
Scenario 0	All criteria have the same weight. p = 17%
Scenario 1	Increase the weight of the i-th criterion by 50% compared to its initial value. $p_i = 25.5\%$; $p_{\text{other criteria}} = 14.9\%$
Scenario 2	Increase the weight of the i-th criterion by 50% compared to its previous value. $p_i = 38.2\%$; $p_{\text{other criteria}} = 12.3\%$
Scenario 3	Increase the weight of the i-th criterion by 50% compared to its previous value. $p_i = 57.4\%$; $p_{\text{other criteria}} = 8.5\%$

3. Results

In the following Section, we describe the outcomes of the multiple-criteria analysis for the usual and linear preference function as well as the results of the sensitivity analysis performed for varying weight changes.

3.1. Usual Preference Function

When the usual preference function is used, the algorithm assumes equal weights. We recall that, here, thresholds p and q are not required. Basically, what is provided to the analyst is an order of priority where the municipalities in the province of Ferrara are ordered from the most sensitive to combined flood and seismic risk to the one that is least affected. Table 4 shows the final ranking of the alternatives.

Table 4. Ranking of alternatives for the usual preference function.

Rank	Alternatives	Θ	Θ^+	Θ^-
1	Ferrara	0.6111	0.7302	0.119
2	Cento	0.5873	0.7222	0.1349
3	Tresigallo	0.4127	0.6111	0.1984
4	Vigarano Mainarda	0.2857	0.5873	0.3016
5	Mirabello + Sant'Agostino	0.2698	0.5794	0.3095
6	Argenta + Portomaggiore	0.2381	0.5238	0.2857
7	Bondeno	0.1825	0.4921	0.3095
8	Copparo	0.0238	0.4127	0.3889
9	Poggio Renatico	0.0238	0.4524	0.4286
10	Comacchio	0.0000	0.4048	0.4048
10	Formignana	0.0000	0.381	0.381
12	Voghiera	−0.0238	0.3651	0.3889
13	Lagosanto	−0.0317	0.3889	0.4206
14	Berra	−0.1587	0.3016	0.4603
15	Masi Torello	−0.1746	0.2937	0.4683
16	Ro	−0.1905	0.2857	0.4762
17	Fiscaglia	−0.2063	0.2778	0.4841
18	Mesola	−0.2857	0.2381	0.5238
19	Ostellato	−0.3571	0.1984	0.5556
20	Goro	−0.3651	0.1984	0.5635
21	Codigoro	−0.3651	0.2222	0.5873
22	Jolanda di Savoia	−0.4762	0.1429	0.619

This is not the only way to visualize the results: The PROMETHEE rainbow plot, shown in Figure 9, allows one to highlight, for each alternative, the criteria that positively or negatively affect the results. In Figure 9, the colors are representative of the criterion: Yellow indicates the criteria relating to exposure, red is used for seismic hazard, green for vulnerability, and blue for flood hazard. For example, for the municipality of Ferrara (first in the ranking), it can be observed that the criterion that has a negative effect is the one relating to the flood hazard, whereas the other criteria have a positive effect on the Ferrara municipality. On the contrary, in the municipality of Jolanda di Savoia (last in the ranking), the only criterion that has a positive influence is the one relating to vulnerability, while all the others have a negative influence.

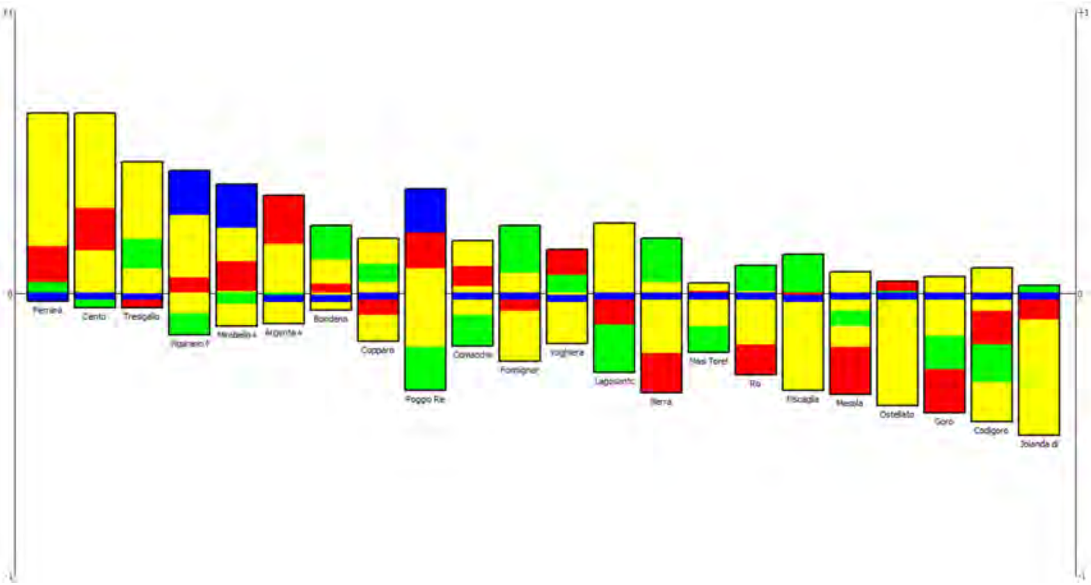


Figure 9. PROMETHEE rainbow plot for the usual preference function. On the vertical axis, the preference function Θ is reported. The yellow bar indicates the criteria relating to exposure, red is used for seismic hazard, green for vulnerability, and blue for hydraulic hazard.

Based on the ranking provided by PROMETHEE, it is possible to create a risk map of the municipalities of the province of Ferrara that highlights high-priority areas as those with a high level of combined flood and seismic risk, medium priority areas as the areas characterized by a medium combined-risk level, and, finally, low combined-risk areas.

This map is shown in Figure 10. It can be seen that the three risk levels are identified by three different colors: Red is used for high risk, orange for medium risk, and yellow for low risk.

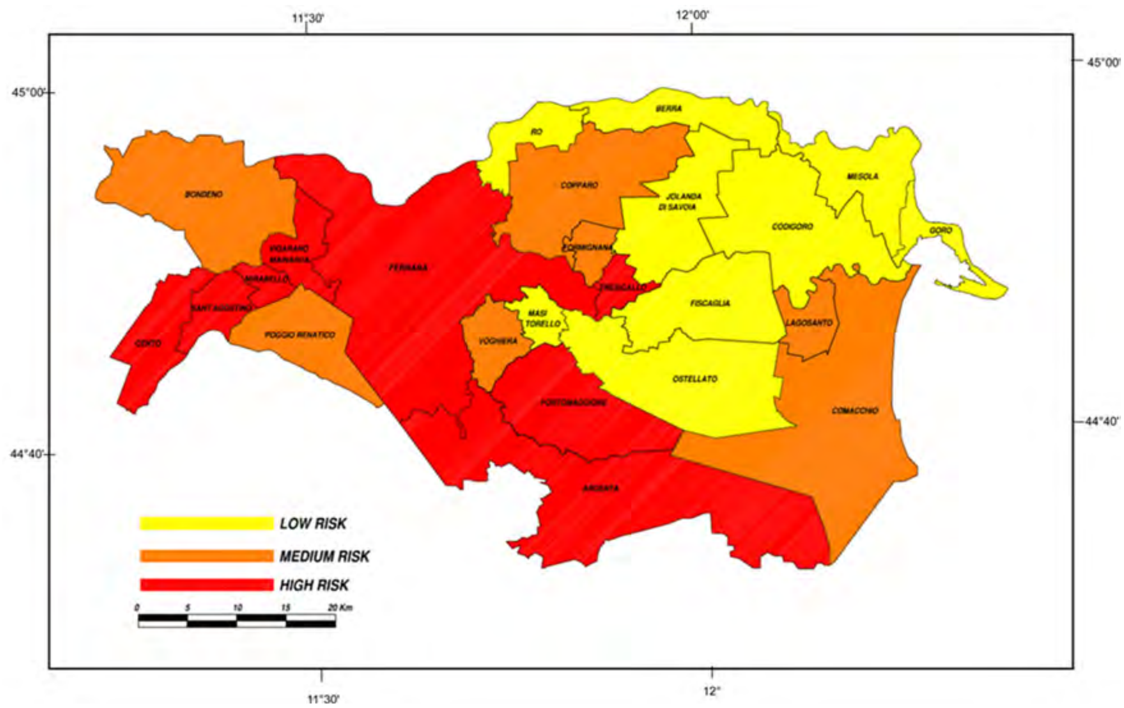


Figure 10. Multiple-risk map for the Ferrara province obtained for the usual preference function (Type 1 in Table 1). The risk levels strictly indicate the relative priority ranking for decision-makers and do not indicate the effective safety level of the various municipalities.

3.2. Linear Preference Function

The ranking of alternatives for the linear preference function and zero-max method is shown in Table 5, while the corresponding multi-risk map is shown in Figure 11. These maps were obtained by associating the quantitative criteria, i.e., flood hazard, land use, age of buildings, and population density, with a linear preference function, while thresholds q and p were determined with the zero-max method.

Table 5. Ranking of alternatives for the linear preference function and zero-max method.

Rank	Alternatives	Θ	Θ^+	Θ^-
1	Cento	0.459	0.5086	0.0496
2	Ferrara	0.3545	0.393	0.0385
3	Tresigallo	0.1821	0.2642	0.0821
4	Mirabello + Sant'Agostino	0.1444	0.2622	0.1179
5	Argenta + Portomaggiore	0.1352	0.2182	0.0829
6	Bondeno	0.1257	0.2069	0.0812
7	Vigarano Mainarda	0.112	0.255	0.143
8	Copparo	0.0505	0.1684	0.1179
9	Poggio Renatico	0.031	0.2216	0.1906
10	Comacchio	0.0224	0.1631	0.1406
10	Voghiera	−0.0422	0.0984	0.1406
12	Formignana	−0.0721	0.0937	0.1657
13	Fiscaglia	−0.0761	0.0868	0.1628
14	Lagosanto	−0.0898	0.1385	0.2283
15	Codigoro	−0.101	0.1155	0.2164
16	Ostellato	−0.1092	0.0736	0.1828
17	Ro	−0.1362	0.0589	0.195
18	Masi Torello	−0.1371	0.0557	0.1928
19	Berra	−0.1551	0.0688	0.2239
20	Jolanda di Savoia	−0.1947	0.0408	0.2355
21	Mesola	−0.2203	0.0353	0.2556
22	Goro	−0.283	0.0137	0.2968

For a linear preference function of the aforementioned quantitative criteria, and thresholds q and p determined by the mean-std method, we obtained the results shown in Table 6 and Figure 12.

By comparing the results obtained from the usual and the linear preference functions, it can be understood that changes of the preference function do not reflect large changes of the final risk maps. The only difference is that the risk levels of the municipality of Vigarano Mainarda swap with Bondeno, and Fiscaglia swaps with Lagosanto.

By comparing the maps in Figures 11 and 12, obtained with the thresholds chosen with the zero-max and mean-std methods, respectively, we observe that the risk levels of Lagosanto, Vigarano Mainarda, and Codigoro increase. Particularly, we observe that the choice of the preference function affects the final ranking of the alternatives especially when the thresholds are chosen according to the mean-std method.

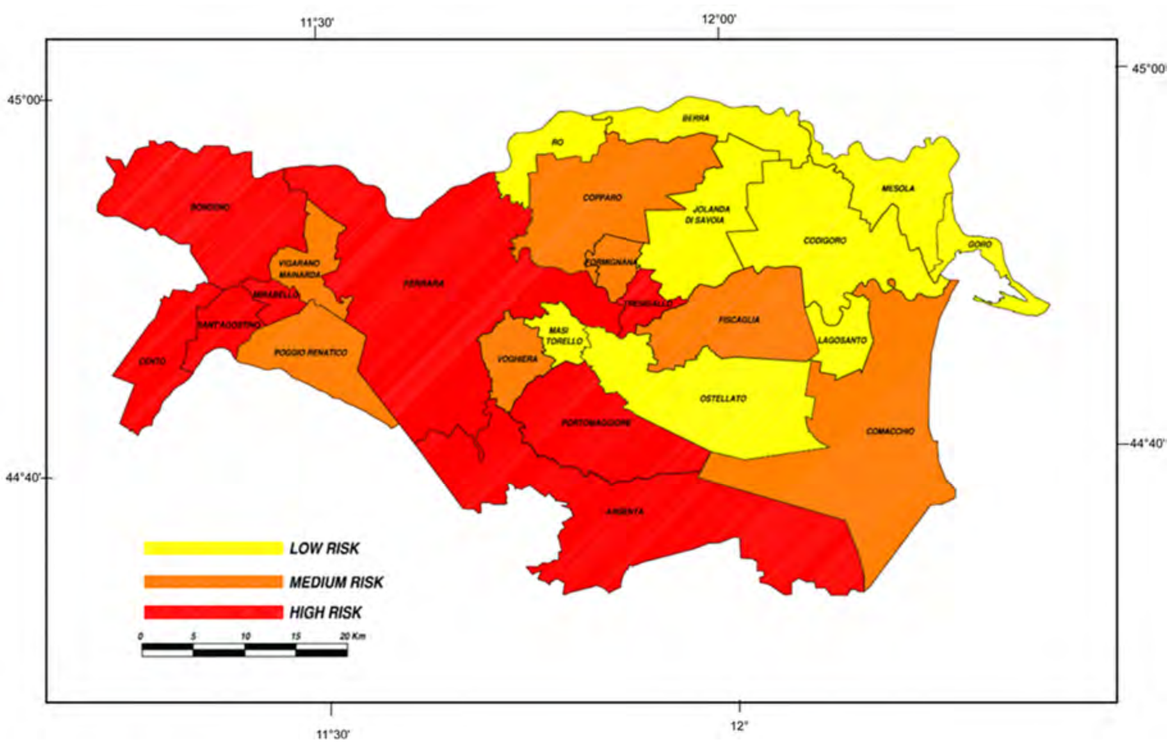


Figure 11. Multiple-risk map for the Ferrara province for the linear preference function with the thresholds chosen with the zero-max method. The risk levels strictly indicate the relative priority ranking for decision-makers and do not indicate the effective safety level of the various municipalities.

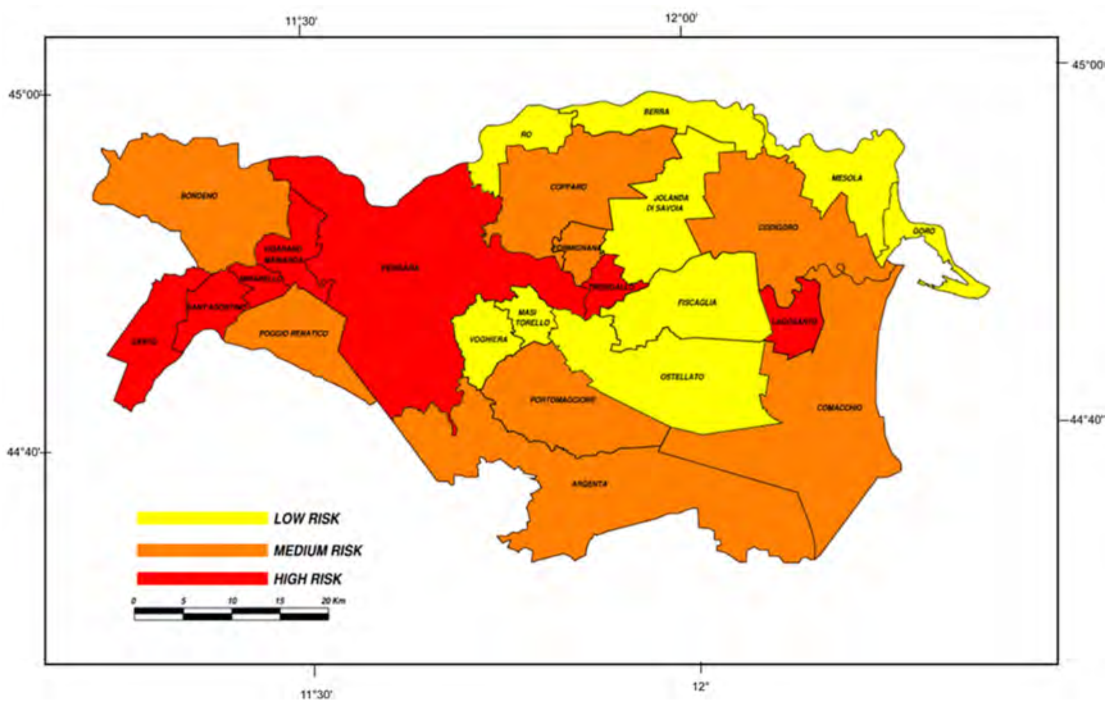


Figure 12. Multiple-risk map for the Ferrara province for the linear preference function with the thresholds chosen with the mean-std method. The risk levels strictly indicate the relative priority ranking for decision-makers and do not indicate the effective safety level of the various municipalities.

Table 6. Ranking of alternatives for the linear preference function and std-mean method.

Rank	Alternatives	Θ	Θ^+	Θ^-
1	Cento	0.4532	0.4849	0.0317
2	Ferrara	0.3769	0.4123	0.0354
3	Tresigallo	0.2051	0.2613	0.0562
4	Vigarano Mainarda	0.1219	0.2185	0.0966
5	Mirabello+ Sant'Agostino	0.078	0.1835	0.1056
6	Lagosanto	0.0597	0.1319	0.0722
7	Poggio Renatico	0.0523	0.167	0.1147
8	Argenta + Portomaggiore	0.0307	0.1133	0.0826
9	Copparo	0.0261	0.1107	0.0846
10	Bondeno	0.0222	0.1075	0.0853
11	Comacchio	0.0217	0.1075	0.0857
12	Codigoro	0.0125	0.1053	0.0928
13	Formignana	−0.1232	0.0146	0.1378
14	Masi Torello	−0.1275	0.0086	0.1361
15	Goro	−0.1278	0.0106	0.1384
16	Mesola	−0.1317	0.0069	0.1386
17	Berra	−0.1383	0.0046	0.1429
18	Voghiera	−0.1383	0.0041	0.1424
19	Ro	−0.1385	0.004	0.1425
20	Fiscaglia	−0.1497	0.002	0.1517
21	Ostellato	−0.1839	0	0.1839
22	Jolanda di Savoia	−0.2014	0	0.2014

Regardless of the preference function chosen, the maps obtained present a similar risk trend, i.e., the territory is divided into two parts: The municipalities of the western part of the territory of the province of Ferrara, plus Ferrara and Tresigallo, are characterized by a medium–high risk level; the upper-eastern part of the province is characterized by a medium–low risk level.

3.3. Sensitivity Analysis on the Choice of Weights

As introduced in Section 2, the sensitivity analysis on the weights was performed by first increasing the weight of each individual criterion at a time, and then assuming the simultaneous increase in the weights of the three "exposure"-related criteria, namely land use, population density, and strategic buildings. Specifically, the weights were changed according to Scenarios 0, 1, 2, and 3 described in Table 3.

For the sake of brevity, we present hereafter the results obtained by assuming the usual preference function. For the reader's convenience, the results are reported as maps, as in the previous sections.

In the first part of the analysis, the criteria are changed according to the following order: Flood hazard, PGA, land use, strategic buildings, age of buildings, and population density. Hereafter, we omit the maps obtained for the changes of the weights relating to the criteria of strategic buildings and age of buildings, for brevity. Figures 13 and 14 illustrate the various risk maps obtained by increasing the weights.

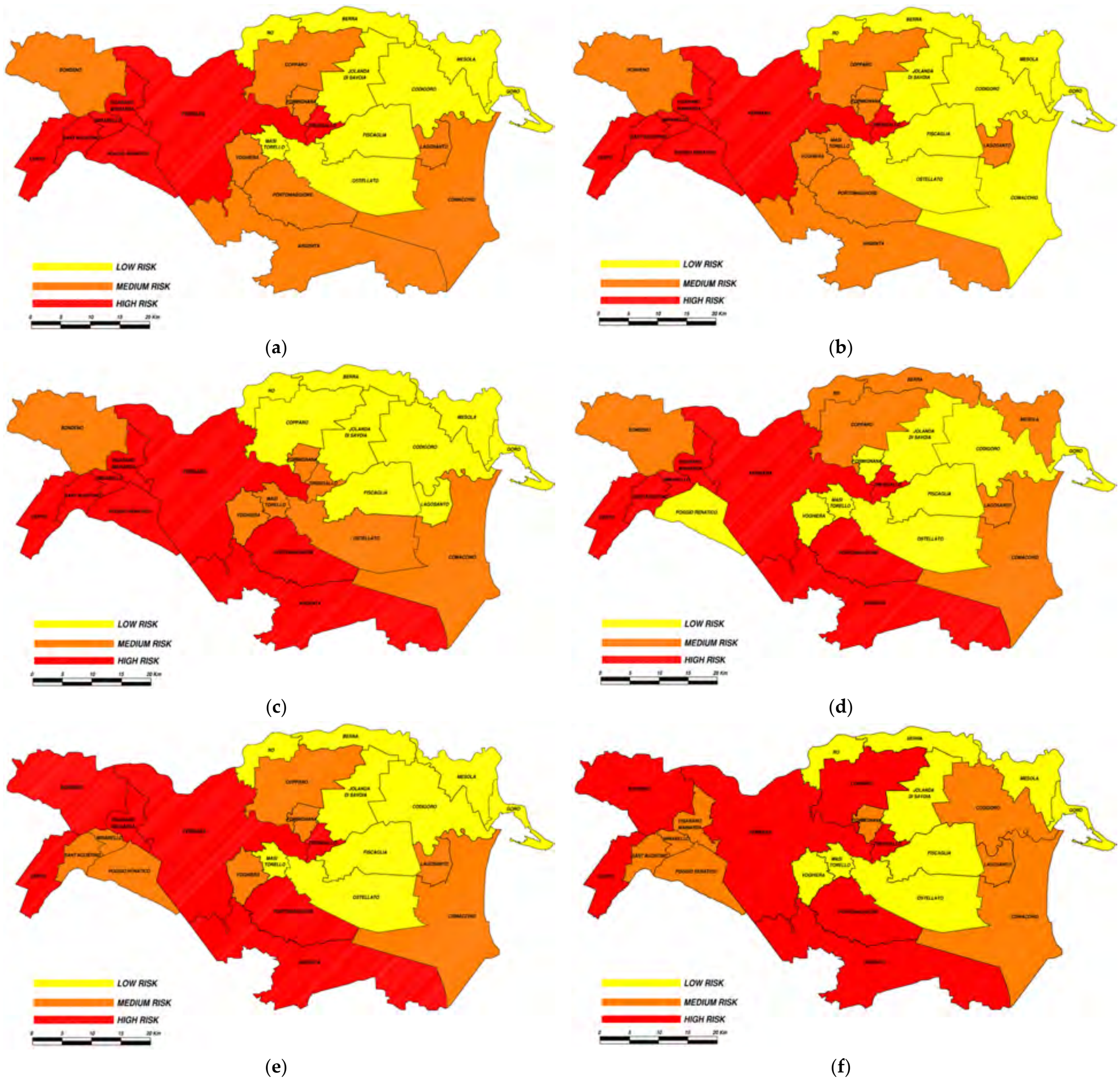
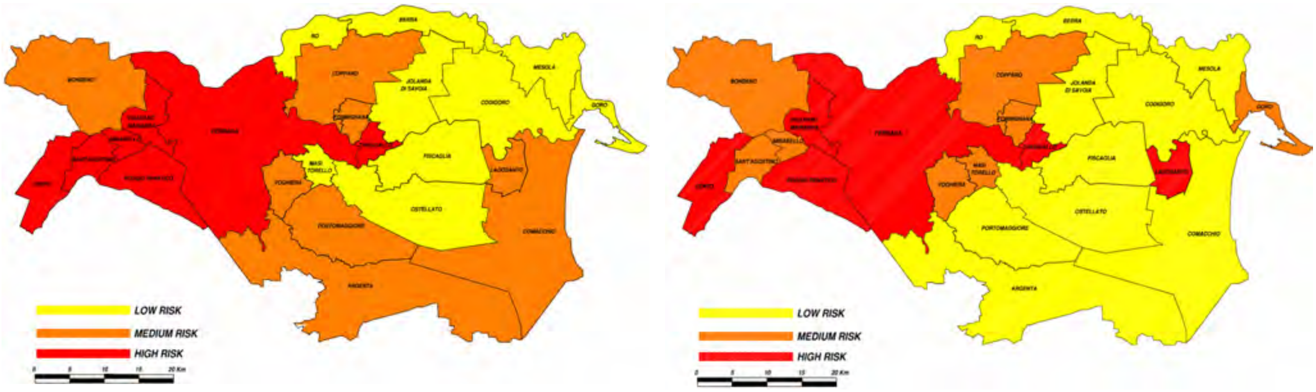


Figure 13. Weights sensitivity analysis, multi-risk maps; (**a**) flood hazard weight increase assuming Scenarios 2 or 3; (**b**) PGA weight increase assuming Scenario 1; (**c**) PGA weight increase assuming Scenario 2; (**d**) land use weight increase assuming Scenarios 2 or 3; (**e**) strategic buildings weight increase assuming Scenario 1; (**f**) strategic buildings weight increase assuming Scenarios 2 or 3. The risk levels strictly indicate the relative priority ranking for decision-makers and do not indicate the effective safety level of the various municipalities.

With Scenario 1 based on the variation of the flood hazard weight, the ranking of the municipalities remains almost unchanged, as the multi-risk map is identical to that of Scenario 0. On the other hand, the maps change when Scenarios 2 and 3 are adopted, as shown in Figure 13a. More marked differences can be observed when the weight of the PGA (Figure 13b,c) is changed. By increasing the weight of the land-use criterion, an increase in Scenario 1 does not reflect evident changes in the multi-risk map (Figure 13d). On the other hand, changes in Scenarios 2 and 3 affect the multi-risk map. Looking back at the strategic building criterion, we observe differences in the risk map when the first change of Scenario 1 is applied, compared to Scenario 0 (Figure 13e), and more so with the last two increases of Scenario 2 (Figure 13f). For the criterion of population density, the first increase in the weight according to Scenario 1 does not affect the map (see Figure 14a), while the subsequent increases in the weight bring about noticeable modifications. In particular, the multi-risk map reported in Figure 14b assigns a comparatively low level of attention to the Argenta municipality, which, however, is associated with a medium seismicity level according to the territorial classification of Figure 2a. Depending on the stakeholders' expectations, this might suggest that weights should not be varied to the extent of downgrading the seismic risk level of certain municipalities classified at medium to high seismic risk.



(**a**) (**b**)

Figure 14. Weights sensitivity analysis, multi-risk maps; (**a**) Scenario 2, population density weight increase; (**b**) Scenario 3, population density weight increase. The risk levels strictly indicate the relative priority ranking for decision-makers and do not indicate the effective safety level of the various municipalities.

Lastly, results of the sensitivity on the weight choice for the criteria related to exposure are presented in Table 7. Proceeding as illustrated in Section 2, the first increase in the weight does not alter the risk map, which remains the same as in Scenario 0, whereas with the changes of Scenario 2, greater variations can be observed.

Therefore, concluding the sensitivity analysis of weights, it can be inferred that, in general, the results are sensitive to the increase in the weights of the criteria, determining a risk map that varies from case to case, causing the risk of some municipalities to decrease while that of others increased. However, these variations do not upset the overall trend, which highlights a territory divided into two parts, that of the municipalities of the western part of the territory of the province of Ferrara characterized by a medium–high risk level, and the municipalities of the north-eastern area characterized by a medium–low risk level.

3.4. Remarks on the Limitations of the Analysis

The proposed methodology requires the definition of several parameters, criteria, and weights, whose choice resulted in being strongly dependent on the expectations of stakeholders and end-users. Thus, the obtained results should be seen as a first attempt towards the proposal of an MCDA methodology that does not require great mathematical expertise, is flexible, and can be easily adapted to many situations. Nevertheless, further efforts are necessary in order for the tool to be readily exploited by public authorities and decision makers. Furthermore, it is worth highlighting other limitations inherent in the present analysis.

The first type of limitation is mainly related to the availability of data. Indeed, the choice of the criteria was based on the availability of the relevant information, which led, for some criteria, to a purely qualitative evaluation. Greater availability, accuracy, and ease of retrieval of the data would lead to the creation of a more complete and more precise analysis, and it could also contribute to the development of operational tools and software.

Table 7. Sensitivity analysis on the exposure factor, ranking of alternatives (EXP: EXPOSURE).

	Scenario 1: WEIGHT = 0.22; OTHERS = 011				Scenario 2: WEIGHT = 0.32; OTHERS = 0.01			
Rank	**Alternativa**	**Θ**	**Θ+**	**Θ−**	**Alternativa**	**Θ**	**Θ+**	**Θ−**
1	Ferrara	0.7153	0.8064	0.0911	Cento	0.9452	0.9683	0.0231
2	Cento	0.7093	0.8061	0.0968	Ferrara	0.9168	0.9538	0.037
3	Tresigallo	0.5092	0.6746	0.1654	Tresigallo	0.696	0.7975	0.1015
4	Vigarano Mainarda	0.2908	0.5771	0.2863	Lagosanto	0.4603	0.6797	0.2193
5	Argenta + Portomaggiore	0.2279	0.534	0.306	Vigarano Mainarda	0.3006	0.5575	0.2569
6	Mirabello + Sant'Agostino	0.219	0.5413	0.3222	Argenta + Portomaggiore	0.2083	0.5536	0.3454
7	Bondeno	0.1597	0.4971	0.3375	Mirabello + Sant'Agostino	0.1207	0.4675	0.3468
8	Lagosanto	0.1359	0.488	0.352	Bondeno	0.1154	0.507	0.3915
9	Copparo	0.0416	0.4381	0.3965	Comacchio	0.1044	0.5017	0.3973
10	Comacchio	0.0356	0.4378	0.4022	Copparo	0.076	0.4873	0.4113
11	Poggio Renatico	−0.0499	0.4041	0.454	Mesola	−0.0919	0.3574	0.4493
12	Formignana	−0.0661	0.3555	0.4216	Masi Torello	−0.1448	0.3309	0.4757
13	Voghiera	−0.1127	0.3295	0.4422	Goro	−0.1563	0.3252	0.4815
14	Masi Torello	−0.1644	0.3064	0.4708	Codigoro	−0.1861	0.3564	0.5426
15	Berra	−0.2045	0.2863	0.4908	Poggio Renatico	−0.1924	0.3107	0.5031
16	Mesola	−0.2197	0.2787	0.4984	Formignana	−0.1938	0.3064	0.5002
17	Ro	−0.226	0.2756	0.5016	Voghiera	−0.2848	0.2607	0.5455
18	Goro	−0.2939	0.2416	0.5355	Berra	−0.2929	0.2569	0.5498
19	Codigoro	−0.3041	0.268	0.5721	Ro	−0.2949	0.2559	0.5507
20	Fiscaglia	−0.3385	0.2193	0.5578	Fiscaglia	−0.594	0.1063	0.7003
21	Ostellato	−0.4816	0.1451	0.6267	Ostellato	−0.7225	0.0418	0.7643
22	Jolanda di Savoia	−0.5829	0.0971	0.68	Jolanda di Savoia	−0.7893	0.0087	0.798

Secondly, this analysis neglected cascade effects, an aspect that deserves further investigation in the future [11].

Thirdly, the present contribution does not consider the impact of modeling assumptions on the seismic risk assessment. At the relevant scale of observations of the present analysis, specific structural aspects connected to the vulnerability levels of the buildings cannot be easily considered. In this regard, we recall that specific structural aspects and modeling assumptions play, among others, a key role for seismic risk evaluation at both the building and the urban scale [36]. A recent study focusing on South America has shown the uncertainties and biases that the use of simplified models or heterogenous data may produce in the determination of seismic vulnerability [36]. For completeness, seismic risk evaluation is extensively discussed, for instance, in the aforementioned contributions [36–39] and the references cited therein.

Finally, we recall that the seismic classification shown in Figure 2 has been merely used as a technical-administrative reference for establishing the priority of actions and measures aimed at preventing and mitigating seismic risk. It must not be used to determine the local seismic action or for the structural design of buildings, which, instead, rely upon more detailed maps highlighting, for instance, the presence of site effects due to the inherent geological structure of the ground or instability effects such as liquefaction. Therefore, the present analysis should be purposefully extended in order to consider the aforementioned local effects [40].

4. Conclusions

For the present case study, the application of the Multiple-Criteria Decision Analysis (MCDA) methodology through the PROMETHEE algorithm has proved an innovative and promising operational tool. Its potential derives from the ability to both analyze information from various sources and jointly systematize data expressed in different units and scales. The application of this methodology has made it possible to rank the various municipalities in terms of the relative proneness to joint flood and seismic hazards. We recall that the objective of the methodology is not to quantify the safety level in absolute terms of the various municipalities. Its scope is, indeed, to provide useful information for decision makers and public authorities to define future intervention priorities. We further emphasize that, in the authors'opinion, the present study is original as it applies the PROMETHEE algorithm for the first time to a multi-risk assessment of seismic and flood hazards.

Depending on the territory to be studied, the relevant risks could be different, and therefore, different criteria must be used to express them. Nevertheless, the generalization to other multi-risk analyses and different case studies deserves further considerable efforts and thoughtful insights. Full validation of the present methodology is also of utmost importance and calls for new developments. However, the proposed methodology is flexible. This suggests that, with due precautions and adaptations, it is possible to apply it to different risk scenarios, such as scenarios including coastal floods and landslides, while keeping the same applicative scheme.

Finally, the obtained results have shown that the proposed methodology is an operational tool that, once further validated, can be used by end users, whether modelers or decision makers, to urgently allocate resources and increase the coping capacity of communities in the case of catastrophic events.

Author Contributions: Conceptualization, Ž.N., A.C., C.V. and E.B.; methodology, Ž.N., A.S. and A.C.; software, A.S.; validation, A.S., A.C. and C.V.; formal analysis A.S., A.C., Ž.N. and C.V.; resources E.B.; data curation, A.S.; writing—original draft preparation, A.S. and A.C.; writing—review and editing, A.C., C.V., Ž.N. and E.B.; visualization, A.S. and A.C.; supervision, E.B.; project administration, E.B.; funding acquisition, E.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the EUROPEAN UNION, Programme Interreg Italy-Croatia, Project "Preventing, managing and overcoming natural-hazards risks to mitigate economic and social impact"—PMO-GATE ID 10046122.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Publicly available datasets and figures were analyzed in this study. This data can be found here: https://www.bonificaferrara.it/images, https://www4.istat.it/it/mappa-rischi/documentazione, https://ambiente.regione.emilia-romagna.it/en/geologia/seismic-risk/seismic-classification, http://zonesismiche.mi.ingv.it, http://www.provincia.fe.it. (accessed on 26 January 2022).

Acknowledgments: The authors are very grateful to Consorzio di Bonifica Pianura di Ferrara for making the flood maps freely available, and, particularly, to Eng. Alessandro Bondesan for his kind support in georeferencing the maps.

Conflicts of Interest: The authors declare no conflict of interest.

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Natural Hazards Risk Assessment Upgrade

Proposal to use the PROMETHEE multi-criteria approach in the natural hazard risk assessment upgrade
by: Christine Shirley, DLCD
September 20, 2023

Background

Over the last few months, we have explored what you and our users desire from a natural hazards risk assessment upgrade. We have also explored various methods to achieve those desires.

After examining several methods by which to achieve these desires, I propose use of a multi-criteria decision analysis model called PROMTHTHEE to evaluate vulnerability to natural hazard events.

Why?

The PROTETHEE method aids decision making by balancing a set of criteria that users deem important to their decision. The outcome of the process is a ranked list of evaluated items. The “items” could be different products, operations, policies, or geographic areas. In our case we would evaluate counties, census tracts, or other geographic unit using sets of criteria applicable to each hazard. The outcome of using the PROMETHEE process would be a ranked list of most vulnerable areas by hazard or combination hazards.

The method identifies vulnerabilities by using criteria customized to the characteristics of each hazard. Criteria can be weighted, allowing users to perform sensitivity analysis. Does, or how much does, changing the weight of a criteria affect overall ranking within the hazard category? Furthermore, the assignment of preference functions within PROMETHEE allows users to control when the magnitudes of differences between areas warrant concern or further investigation.

PROMETHEE is not a black box. Users always have access to results of intermediate calculations that lead to ranking. This allows users to explore what is driving vulnerability, within the model space.

Method Description

PROMETHEE starts by defining a set of criteria to be evaluated for a set of proposed “actions.” In our case the “action” is to identify census tracts (or other areas) that are most vulnerable to the effects of natural hazard events. For each hazard type, analysts establish a set of criteria that describe what makes an area vulnerable to harm caused by the natural hazard. For example, criteria that describe flood vulnerability might include extent of flood in the geographic area, development density, number of critical facilities, building characteristics, population density, and poverty rates (or social vulnerability) (see Soladati et al. 2022). Note that these criteria do not need to be in the same units of measure. Criteria need only be area, expected dollar losses, percentages, precalculated unitless index (SVI), a Likert scale, or any other numeric value. These are set out in a matrix, with the rows representing the “action” and the columns representing the criteria to be evaluated for each action.

The analyst then decides which preference function to use for each criterion and whether and how to weight them.

A second matrix is constructed from the first by performing a pairwise comparison of actions across all criteria. This is accomplished by subtracting criteria values from action A from action B, or vice versa depending on whether the analyst wants to maximize of minimize the differences.

Negative values are removed from the resulting matrix2, and then the weighting and preference functions are applied, resulting in a third matrix that shows the value of the pairwise preference functions for each action and its criteria. These values range from 0 to 1.

Criteria preference function values are averaged across each pairwise comparison in matrix3. The resulting averages are organized into a fourth matrix, called the preference index. Rows and columns of the preference index are summed and subtracted from each other to establish a ranking of projects. The Soladati paper shows cases where the highest-ranking provinces are the most vulnerable to harm (Tables 4, 5, 6, & 7).

Other ways of using the preference index have been suggested in the literature to provide decision makers with information besides simple ranking. I have not yet examined whether these are useful to our objective of finding places most vulnerable to the effects of natural hazards.

Next steps

I propose that the work group endorse use PROMETHEE in the Oregon Natural Hazards Risk Assessment Upgrade to evaluate vulnerability. Highest ranking (most vulnerable) areas will be further evaluated to determine drivers of vulnerability and specific vulnerable assets or people. In this way, potential mitigation projects can be identified in the most vulnerable areas. This will be in addition to other FEMA-required activities, such as identifying vulnerable state owned or leased buildings.

If endorsed for use, subject matter experts will be called upon to identify evaluation criteria, preference functions and weights to be used in the PROMETHEE analysis.

I propose that the method be tested and used in the state plan risk assessment. Following a successful test, a user interface will be developed to allow others to perform natural hazard vulnerability assessments using PROMETHEE as one of the tools provided for use in the risk assessment upgrade.

Further Reading

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Risk Assessment Upgrade
Risk Assessment Work Group
DRAFT Declaration of Collaboration

Vision

The State of Oregon's risk assessment model provides a strong foundation for strategically allocating natural hazards mitigation resources.

Project Background

A natural hazards risk assessment provides the factual basis for making decisions on how to invest most effectively in natural hazards mitigation. Oregon's natural hazards risk assessment is the foundation of the Oregon Natural Hazards Mitigation Plan, upon which the state, local governments, and federally recognized Native American Tribes (Tribes) rely for eligibility for certain pre-and post-disaster natural hazards mitigation funds from FEMA. Currently, it is not sophisticated enough to effectively guide natural hazard mitigation investment decisions.

Risk assessment tools have been developed by FEMA and others, but for various reasons none meet the mark for Oregon's needs. This project is to develop a risk assessment tool that *will* meet Oregon's needs for driving state, local, and Tribes' natural hazards mitigation investment decisions.

Charge

- Develop and implement a public-facing comprehensive risk assessment tool in a geospatial environment that will respond to FEMA's new requirements for incorporating climate change influences on natural hazards, climate adaptation, social vulnerability, lifelines, and equity.
- Incorporate additional elements and information that enhance the tool to further Oregon's natural hazards mitigation and climate adaptation aspirations.
- Design the tool in a way that useful not only for the state, but also for Tribes, cities, counties, special districts, and others for natural hazards mitigation planning.
- Complete the project by January 31, 2025. If additional time is needed and a grant extension is approved by FEMA, complete the project no later than March 14, 2026.

Deliverables

Working with the Oregon Department of Emergency Management (OEM) and the Department of Land Conservation and Development (DLCD), the Risk Assessment Work Group will deliver a risk assessment that:

- Meets or exceeds FEMA requirements.
- Applies an equity lens to consider potentially disparate impacts on socially vulnerable populations and underserved communities.
- Employs data analysis techniques that express social vulnerability meaningfully and consistently statewide.
- Is scientifically defensible.

- Incorporates climate change as an integral part of the hazard characterization.
- Is scalable.
- Allows weighting of inputs and indexing.
- Is usable by Tribes and local governments.
- Addresses a wide array of vulnerabilities including:
    - Additional critical facilities
    - Lifelines
    - Social Vulnerability
    - Underserved Communities
    - Historic and Cultural Resources
    - Ecosystem Resources

OEM, DLCD, and the Risk Assessment Work Group will also deliver risk assessment data for analysis during the 2025 Oregon NHMP Update. Work to complete the risk assessment and make it usable by Tribes and local governments will continue after the Oregon NHMP Update delivery date.

Project Management Team and Work Group Members Responsibilities

Project Management Team

Project Sponsors: **Kirstin Greene, DLCD; Stephen Richardson, OEM**
Provide resources and overall support.

Project Director: **Matt Crall, DLCD**
Monitor project and support Project Manager.
Monitor budget and support Grants Coordinator.

Project Manager: **Christine Shirley, DLCD**
Manage Project.
Facilitate Risk Assessment Work Group.
Contribute risk assessment and climate change expertise.
Negotiate scopes of work for professional services.
Submit quarterly reports.
Submit deliverable to OEM.

Project Management Associate: **Marian Lahav, DLCD**
Assist with Risk Assessment Work Group management.
Advise and support Project Manager.
Design and supervise implementation of Communications and Engagement Plan.

Project Management Associate: **Joseph Murray, OEM**
Assist with Risk Assessment Work Group management.
Advise and support Project Manager.
Contribute expertise.

Project Grant Manager: **Ashley Edwards, DLCD**
Manage grant.
Provide administrative support for the Risk Assessment.

Communications Support: **Sadie Carney, DLCD**
Christine Crabb (“CC”), OEM
Zachary Stella, OEM
Assist with design and implementation of Communications and Engagement Plan.

Risk Assessment Work Group Members

Ultimately, the objective of the Work Group is to fulfill the Work Group's charge and produce the final project deliverable by January 31, 2025. To accomplish this objective, Work Group members will bring their knowledge, lived experience, resources, and expertise to the project and work collaboratively.

Currently, Oregon assesses risk from twelve natural hazards: coastal hazards, dam safety, drought, earthquakes, extreme heat, floods, landslides, tsunamis, volcanic hazards, wildfires, windstorms, and winter storms with climate change as an overlay on applicable hazards. Oregon's current risk assessment includes inventories of state buildings and critical facilities, local critical facilities, some historic and archaeological resources and estimates the potential dollar loss from each hazard. FEMA's new risk assessment requirements effective April 2023 include analysis of climate adaptation, social vulnerability, underserved communities, lifelines, and consideration of equity. For efficiency and effectiveness, Work Group members must have expertise in at least one of the areas to be included in the risk assessment, such as but not limited to natural hazards, climate change, land use and development, housing, public health, social services, natural and cultural resources, energy, communications, and transportation.

Work Group members representing each sector, lifeline, or discipline determine the data inputs and the method for assessing risk. A subgroup will build the geospatial environment, test, debug, and run the model. Other subgroups will provide the data and information that will populate the model, and bring the perspectives that will help interpret the results. For each of project Phases 3 and 4, OEM and DLCD staff and the Work Group will produce a report describing the process, methods, and results. The report will be subject to community review and comment. Work Group members will assist OEM and DLCD staff with addressing comments received.

Every Work Group member is necessary for developing the product and achieving the vision. Risk Assessment Work Group members will advise DLCD and OEM staff throughout the project.

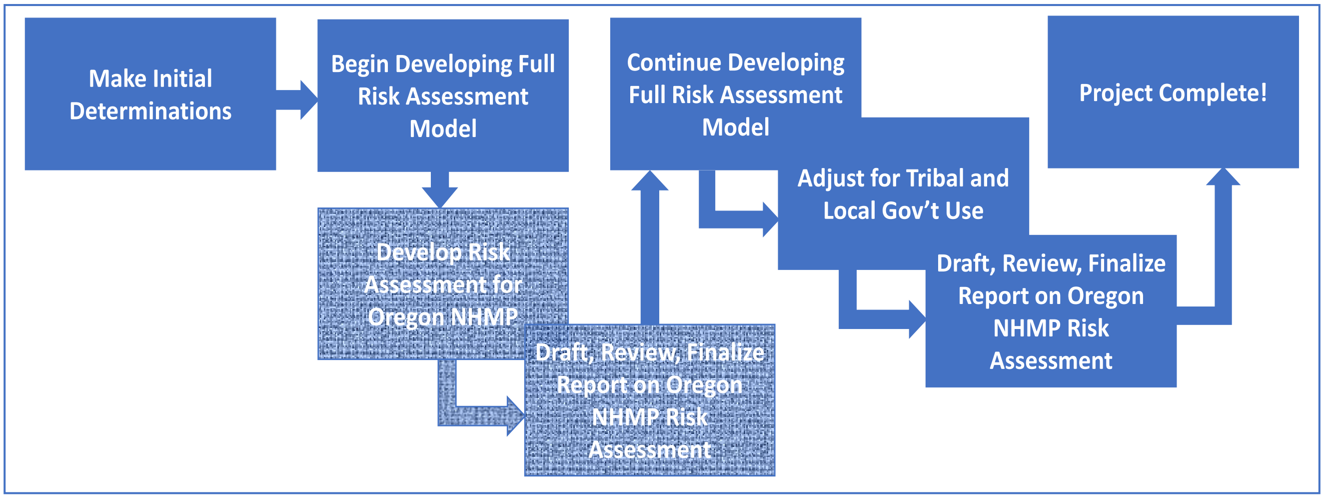
Project Management Team and Risk Assessment Work Group Meetings

The **Project Management Team** will meet twice a month to ensure communication and coordination between OEM and DLCD staff, to assess project progress, and to resolve any issues that arise.

The full **Risk Assessment Work Group** will meet twice a month, generally on the second and fourth weeks of the month, for the first several meetings and then monthly to gather data, determine which data and elements to include, and determine the methods and techniques to be used. From Fall 2023, subgroups will meet for reviews, discussion, input, and advice. OEM and DLCD staff will call full Work Group meetings as needed.

OEM and DLCD staff and the Work Group will complete the project by January 31, 2025. If additional time is needed and a grant extension is approved by FEMA, complete the project no later than March 14, 2026.

Workflow



Agreements

<u>Workgroup members agree to:</u>

1. Listen with respect, seeking to understand each other's perspectives.
2. Undertake their commitments (as negotiated) to produce project deliverables on time.
3. Share relevant information that assists the group in achieving its charge.
4. Attend meetings at which their expertise is necessary as indicated by the Project Manager or agenda. A member may designate an alternate to attend a meeting when the member cannot.
5. Raise concerns for discussion at the earliest point in the process.
6. Be tough on issues and questions, rather than on people and organizations.
7. Refer any media inquiries about this Work Group to Sadie Carney, sadie.carney@dlcd.oregon.gov.

<u>DLCD and OEM staff agree to:</u>

1. Post agenda and meeting materials a reasonable amount of time in advance of each meeting.
2. Be respectful of Work Group members' time by adhering to the agenda.
3. Be responsive to questions and concerns raised by Work Group members.
4. Manage the project to completion.

Commitments

The following commitments are made by each of the participating Tribes, agencies, organizations, or individuals for development of the risk assessment tool through January 2025 or through March 14, 2026 at the latest should further work be necessary and a grant extension approved by FEMA.

Sample minimal agreement on agency, organization, or individual letterhead

May include introductory language indicating the Tribe's, agency's, organization's or individual's interest or stake in the project.

The Oregon Department of X agrees to:

- Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua.
- Ut enim ad minim veniam, quis nostrud exercitation ullamco laboris nisi ut aliquip ex ea commodo consequat.
- Duis aute irure dolor in reprehenderit in voluptate velit esse cillum dolore eu fugiat nulla pariatur.
- Excepteur sint occaecat cupidatat non proident, sunt in culpa qui officia deserunt mollit anim id est laborum.

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Name of Signatory with Authority to Sign
Signatory's Title
Name of Tribe, agency, organization or individual