Methodology for provision assessment indexes based on Spatial Multi-Criteria Decision-Making
-ITALY-

Final Version

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1. Introduction

As widely discussed in (Skilodimou et al. 2019), natural hazard events are able to significantly affect the natural and artificial environment. In this context, natural disasters have the potential to affect and, in some cases, even to restrict human activities and interactions with the ecosystem. To minimize fatalities and reduce the economic impact that accompanies their occurrence, a proper planning is crucial. Accordingly, reliable information on the spatial distribution of natural disasters comprise a key tool for stakeholders and decision makers dealing with the management of the built environment and strategic intrastructures (Abdulwahid and Pradhan 2016; Chousianitis et al. 2016; Das et al. 2013; Hopkins 1977; Jebur et al. 2015; Pham et al. 2016).
Up until recently, and due to the fact that natural hazards are complex phenomena, the vast majority of the published studies have focused on the detailed examination of a single hazard phenomenon. However, a specific area usually is not affected solely by one natural hazard: two or more have the ability to act at the same time or consecutively. In this context, the utilization of one hazard map for each type of natural disaster can become unmanageable when multiple hazard types have to be taken into account (Bender 1991).
The solution to this difficulty is the adoption of multi-hazard analysis, which, enhanced with GIS-based methods that support a straightforward analysis of different kind of data, has been reliably used to develop natural hazard models and form the basis for vulnerability and risk management (El Morjani et al. 2007; F.E.M.A. 2004; Kappes et al. 2011; Schmidt et al. 2011).
Multirisk assessment at the regional level can be performed by means of various heuristic, statistical, and deterministic approaches (e.g., Ayalew and Yamagishi 2005; Svoray et al. 2005; Tsolaki-Fiaka et al. 2018).
Among such approaches, the Multi-Criteria Decision Aid (MCDA) methods have shown increasing popularity in the last two decades as one of the very fast growing areas of Operational Research (OR). The MCDA often deals with ranking of many concrete alternatives from the best to the worst ones based on multiple conflicting criteria. The MCDA is also concerned with theory and methodology that can treat complex problems encountered in management, business, engineering, science, and other areas of human activity. In recent years, several MCDA methods have been proposed to help in selecting the best compromise alternatives. The development of MCDA methods has been motivated not only by a variety of real-life problems requiring the consideration of multiple criteria, but also by practitioners' desire to propose enhanced decision-making techniques using recent advancements in mathematical optimization, scientific computing, and computer technology (Wiecek et al., 2008).
Among the many MCDA approaches, a relevant role is played by the analytical hierarchy processes (AHP), a multiple objective decision making approach developed by Saaty (1977),

which is among the most widely applied deterministic methods. It is a weight evaluation process which takes into account qualitative and quantitative parameters and ultimately results in the assessment of alternative solutions to a particular problem, among which the best solution is able to be identified (Saaty 1990, 2004). This method has been commonly combined with GIS for the assessment of a single natural hazard in local and regional scales (Fernán-dez and Lutz 2010; Karaman and Erden 2014; Peng et al. 2012; Pourghasemi et al. 2012) as well as for performing land use suitability evaluation (Baja et al. 2007; Bathrellos et al. 2012; Panagopoulos et al. 2012; Thapa and Muray-ama 2008; Youssef et al. 2011). Although highly accepted within the scientific community, the AHP approach has some drawbacks such as the lack of uncertainty estimation (Nefeslioglu et al. 2013).
Another prominent MCDA approach is the PROMETHEE method (Preference Ranking Organization Method for Enrichment Evaluations). PROMETHEE is one of the most recent MCDA methods, developed by Brans (1982) and further extended by Vincke and Brans (1985). PROMETHEE is an outranking method for a finite set of alternative actions to be ranked and selected among criteria, which are often conflicting. PROMETHEE is also a quite simple ranking method in conception and application compared with the other methods for multi-criteria analysis (Brans et al., 1986). Therefore, the number of practitioners who are applying the PROMETHEE method to practical multiplecriteria decision problems, and researchers who are interested insensitivity aspects of the PROMETHEE method, increases year by year as can be illustrated by increasing numbers of scholarly papers and conference presentations.
In the course of previous WP3 activities of the PMO-GATE project, flood and seismic hazards in the Ferrara area have been studied as single, independent hazards. Now, in WP4 and 5 we devote our efforts to suitably combine the risks stemming from the aforementioned hazards into a comprehensive multihazard assessment approach.
More precisely, within the framework of the PMO-GATE project, we propose a multi-hazard assessment approach based on the PROMETHEE scheme, considering flood and seismic hazards, so as to ultimately evaluate and rank the various homogeneous areas in the Ferrara province in terms of overall combined risk. We will particularly focus on the Ferrara municipality and the Cona area, which hosts the city hospital and therefore is of strategic importance. The final goal is to produce multi-hazard risk maps for the whole Ferrara territory which can be of support to stakeholders, decision and policy makers in the management of the built environment and strategic infrastructures.

2. Study area description

The territory of Ferrara province is located at the north-easterly extremity of the Pianura Padana (a flatland area in the north part of Italy), and it is bathed by the Adriatic Sea on the east side. Ferrara territory is characterised by minimum land slopes and its altimetry is mainly under the sea mean level. In specific, more than 40% of the territory is under the mean sea level, as it is represented in Fig. 1. Moreover, the eastern part of the territory is affected by ground lowering phenomena as well. These soil modifications, caused mainly by anthropic and artificial actions, produced lowering until 2.5 m depth.
The rainwater runoff is artificially regulated by a complex system of canals that converge in a great number of water-lifting plants, which permit the runoff lifting toward the sea. Without these water-lifting plants, the entire territory, finite among Po, Reno and Panaro rivers and the sea, would be entirely flooded.

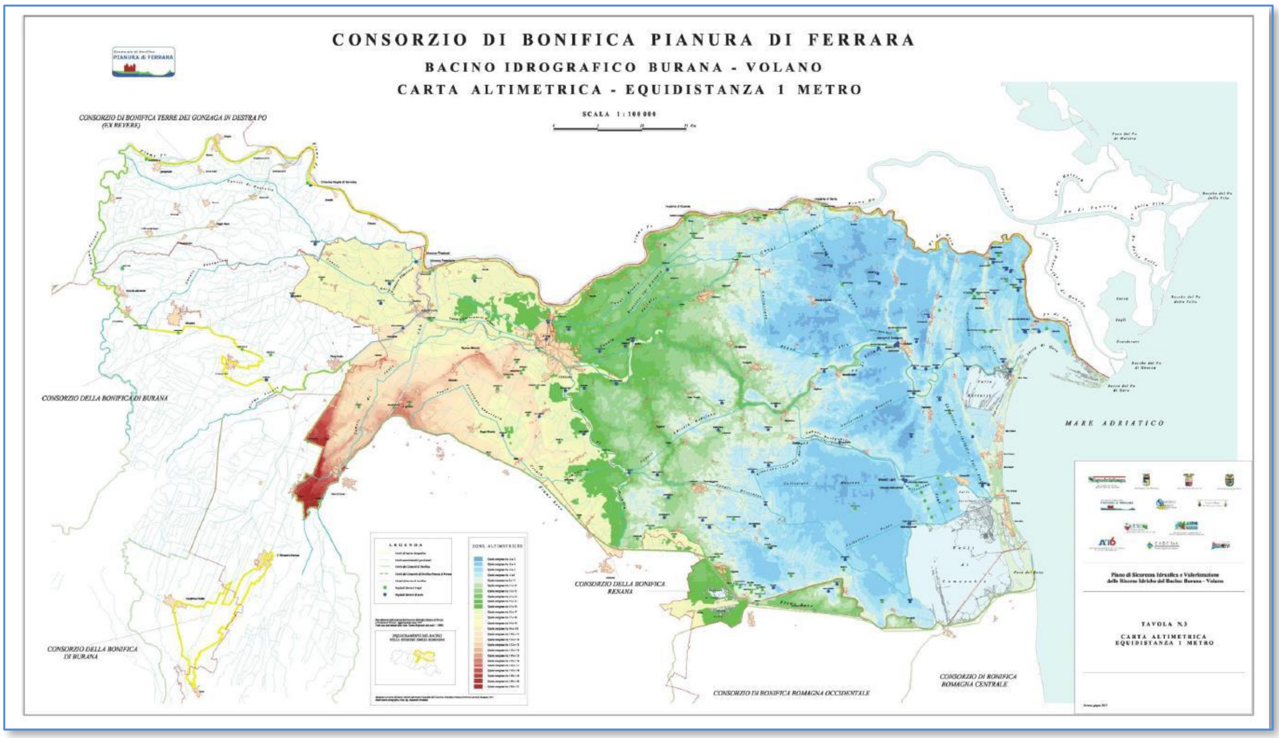

Figure 1. Ferrara province altimetry.

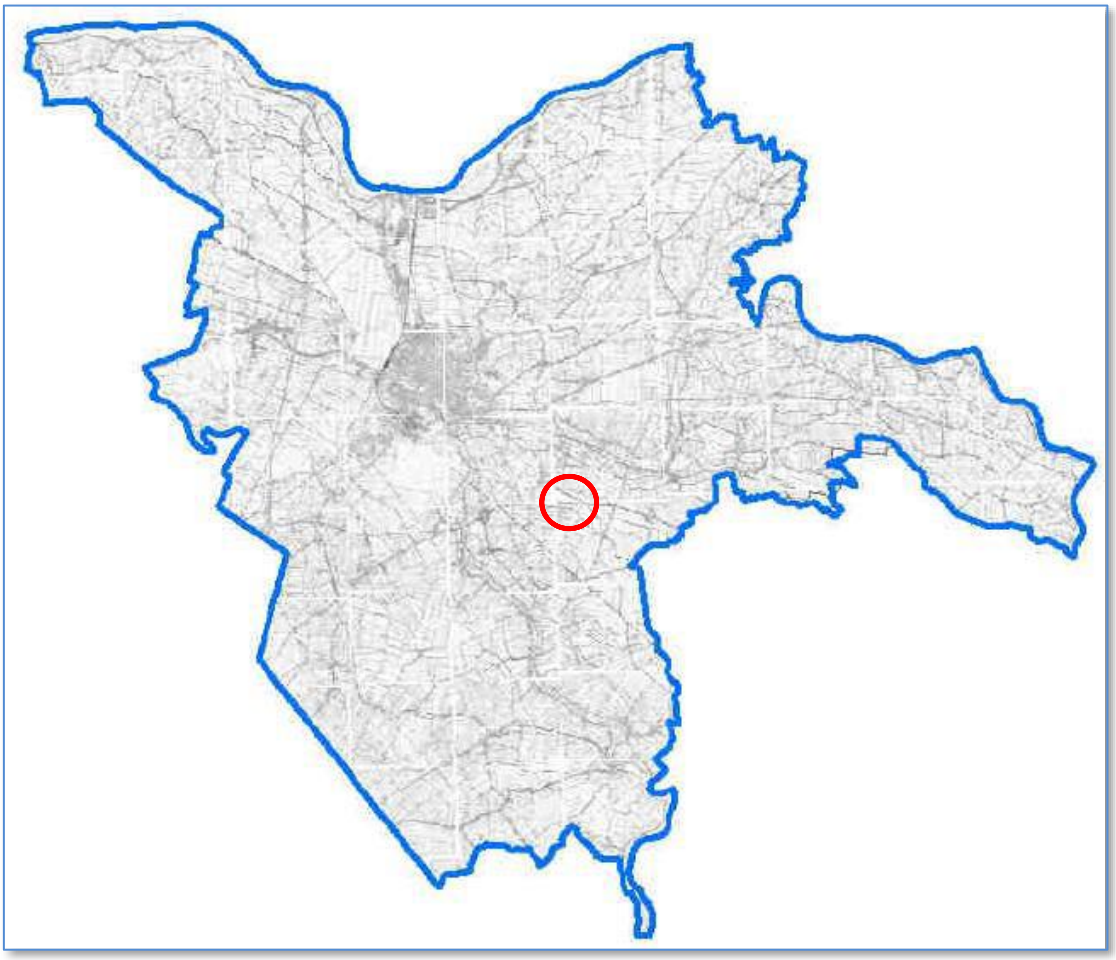

Figure 2. The municipality of Ferrara with the Cona area in evidence.

The complex system of canals, divided in the territory between “Acque alte” and “Acque basse” systems, connected by water-lifting plants, permits to maintain the land in a dry state, to lift water toward the sea, and regulate the water needed for irrigation, deriving it from the rivers and canals reticulation surrounding the area. The complex-regulated hydraulic regime of Ferrara municipality is, therefore, one of the most important element for the safety and the valorisation of the territory.

Within the Ferrara province, the municipality of Ferrara covers a total surface of 405.16km2 and is depicted in Fig. 2. Cona, depicted in Fig. 2 by a red circle, is located 10km east of the city center and its territory comprises the villages of Cocomaro di Cona, Codrea and Quartesana.

3. The PROMETHEE method

3.1 History

The PROMETHEE family of outranking methods (Behzadian et al. 2010), including the PROMETHEE I for partial ranking of the alternatives and the PROM-ETHEE II for complete ranking of the alternatives, were developed by Brans and presented for the first time in 1982 at a conference organized by Nadeau and Landry at the University Laval, Quebec,Canada (Brans, 1982). A few years later, several versions of the PROMETHEE methods such as the PROMETHEE III for ranking based on interval, the PROMETHEE IV for complete or partial ranking of the alternativeswhen the set of viable solutions is continuous, the PROMETHEE V for problems with segmentation constraints (Brans and Mareschal,1992), the PROMETHEE VI for the human brain representation (Brans and Mareschal, 1995), the PROMETHEE GDSS for group decision-making (Macharis et al., 1998), and the visual interactive module GAIA (Geometrical Analysis for Interactive Aid) for graphical representation (Mareschal & Brans, 1988) were developed to help in more complicated decision-making situations (Brans and Mareschal, 2005). Figueira et al. (2004) has recently proposed two extended approaches on PROMETHEE, called as the PROMETHEE TRI for dealing with sorting problems and the PROMETHEE CLUSTER for nominal classification. The methods of PROMETHEE have successfully been applied in many fields and a number of researchers have used them in decision-making problems. The PROMETHEE methods have some requisites of an appropriate multi-criteria method and their success is basically due to their mathematical properties and to their particular friendliness of use (Brans and Mareschal, 2005).

3.2 PROMETHEE II stepwise procedure

This part of the report briefly describes PROMETHEE II, which is intended to provide a complete ranking of a finite set of feasible alternatives from the best to the worst. This method is fundamen-tal to implement the other PROMETHEE methods and the majority of researchers have referred to this version of the PROMETHEE methods.
The basic principle of PROMETHEE II is based on a pair-wise comparison of alternatives along each recognized criterion. Alternatives are evaluated according to different criteria, which have to be maximized or minimized. The implementation of the PROMETHEE II requires two additional types of information:

Step 1. Determination of deviations based on pair-wise comparisons

$$d_j(a,b) = g_j(a) - g_j(b) \qquad (1)$$

Where $d_j(a,b)$ denotes the difference between the evaluations of a and b on each criterion.

Step 2: Application of the preference function

$$P_j(a,b) = F_j[d_j(a,b)] \qquad j=1,\ldots,k \qquad (2)$$

Where $P_j(a,b)$ denotes the preference of alternative a with regard to alternative b on each criterion, as a function of $d_j(a,b)$.

Step 3: Calculation of an overall or global preference index

$$\forall a,b \in A, \qquad \pi(a,b) = \sum_{j=1}^{k} P_j(a,b) w_j \qquad (3)$$

Where $\pi(a,b)$ of a over b (from 0 to 1) is defined as the weighted sum $p(a,b)$ of for each criterion, and w_j is the weight associated with jth criterion.

Step 4: Calculation of outranking flows/ The PROMETHEE I partial ranking

$$\phi^+(a) = \frac{1}{n-1} \sum_{x \in A} \pi(a,x) \qquad (4) \qquad \text{and} \qquad \phi^-(a) = \frac{1}{n-1} \sum_{x \in A} \pi(x,a) \qquad (5)$$

Where $\phi^+(a)$ and $\phi^-(a)$ denote the positive outranking flow and negative outranking flow for each alternative, respectively.

Step 5: Calculation of net outranking flow/ The PROMETHEE II complete ranking

$$\phi(a) = \phi^+(a) - \phi^-(a) \qquad (6)$$

Where $\phi(a)$ denotes the net outranking flow for each alternative.

Figure 3. Stepwise procedure for PROMETHEE II (Behzadian et al. 2010)

- *The weight*. Determination of the weights is an important step in most multi-criteria methods. PROMETHEE II assumes that the decision-maker is able to weigh the criteria appropriately, at least when the number of criteria is not too large (Macharis et al., 2004).
- *The preference function*. For each criterion, the preference function translates the difference between the evaluations obtained by two alternatives into a preference degree ranging from zero to one. In order to facilitate the selection of a specific preference function,Vincke and Brans(1985) proposed six basic types: (1) usual criterion, (2) *U*-shape criterion, (3) *V*-shape criterion, (4) level criterion, (5) *V*-shape within difference criterion and (6) Gaussian criterion. These six types are particularly easy to define. For each criterion, the value of an indifference threshold, *q*; the value of a strict preference threshold, *p*; and the value of an intermediate value between *p* and *q*, *s*,has to be fixed (Brans and Mareschal, 1992). In each case, these parameters

have a clear significance for the decision-maker. Fig. 3 presents the stepwise procedure for implementing PROMETHEE II. The procedure is started to determine deviations basedon pair-wise comparisons. It is followed by using a relevant preference function for each criterion in Step 2, calculating global preference index in Step 3, and calculating positive and negative outranking flows for each alternative and partial ranking in Step 4. The procedure is come to an end with the calculation of net outranking flow for each alternative and complete ranking.

3.3 The software packages

Two PROMETHEE software packages, including PROMCALC and DECISION LAB, have been developed to facilitate the PROMETHEE process. PROMCALC was published by the authors of the method (Mareschal and Brans, 1986). It was provided for all types of multi-criteria problems, the PROMETHEE I, II, V, VI as well as the GAIA visual module. DECISION LAB, developed in collaboration with the Canadian company Visual Decision (Decision Lab, 2000, 1999), is the current software implementation of the PROMETHEE and GAIA methods. It replaces the PROMCALC software that the authors had previously developed. By using DECISION LAB, decision-makers can improve the quality and reliability of the decision-making processes, because of the structured procedure, accompanied by computational help, and the analytical aids (Geldermann and Zhang,2001).

4. Individual hazard assessment maps

4.1 Flood risk

As an example of flood risk map, the following Fig. 4 represents the flood risk map for the territory of Ferrara. The development of this map is carried out following the flood hazard map presented in Deliverable 3.1.1, Part 1, Section 3 for the Ferrara municipality area, so accordingly to specific land uses and exposed elements in the area.

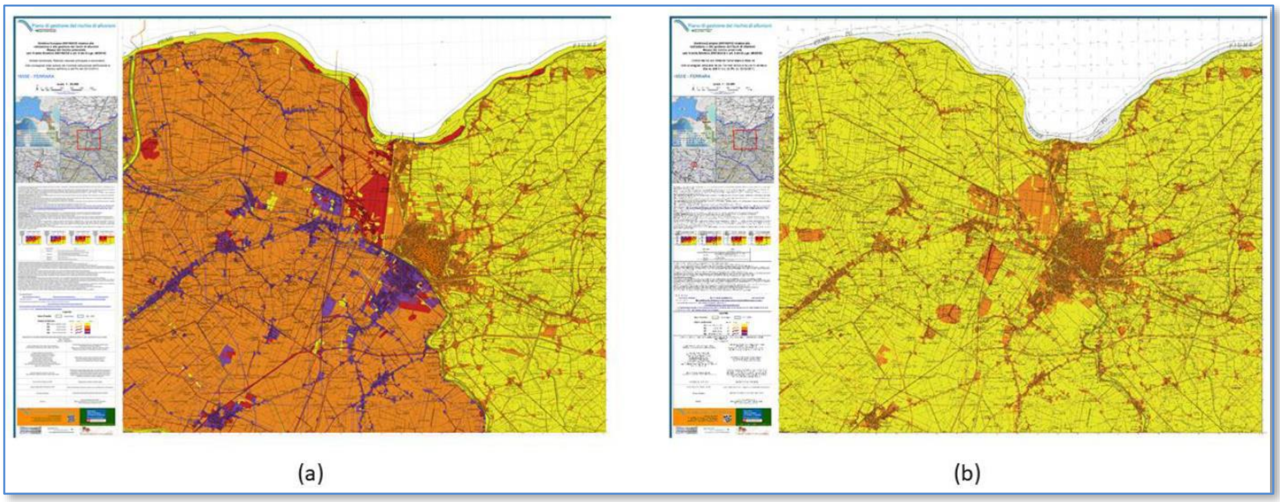

Figure 4. Flood risk maps in Ferrara territory evaluated for the Primary watercourses network (a) and the Secondary watercourse network (b).

Therefore, equally to flood hazard maps, Fig. 4(a) is flood risk for the Primary water courses network and Fig. 4(b) is for the Secondary watercourses network.
The Flood risk evaluation and management plan, D. Lgs. 49/2010 (Article n. 7 of the EU Floods Directive 2007/60/EC) can be analysed in order to see the classification of the exponential damage and the matrices created to assess the flood risk. Deliverable 3.1.1, Part 2 also contains the flood risk map for coastal areas of the Ferrara province.

4.2 Seismic risk

Seismic risk for the municipality of Ferrara has been analized in detail in Deliverable 3.3.2 Part I. The territory of the municipality of Ferrara falls within zone 912 of the seismic zonation ZS9. The maximum expected magnitudo is M = 6.14. The territory of Ferrara was struck by destructive earthquakes in May-June 2012, with two main sequences on May 20-29 with magnitude M 5.9 and 5.8, respectively. Maximum recorded horizontal accelerations were less than 0.1g.
The design seismic accelerations, provided by the Italian Building Code (NTC2018), are reported in Fig. 5 in terms of peak ground acceleration expected on a rigid soil (PGA0) on a return period Tr = 475 years.

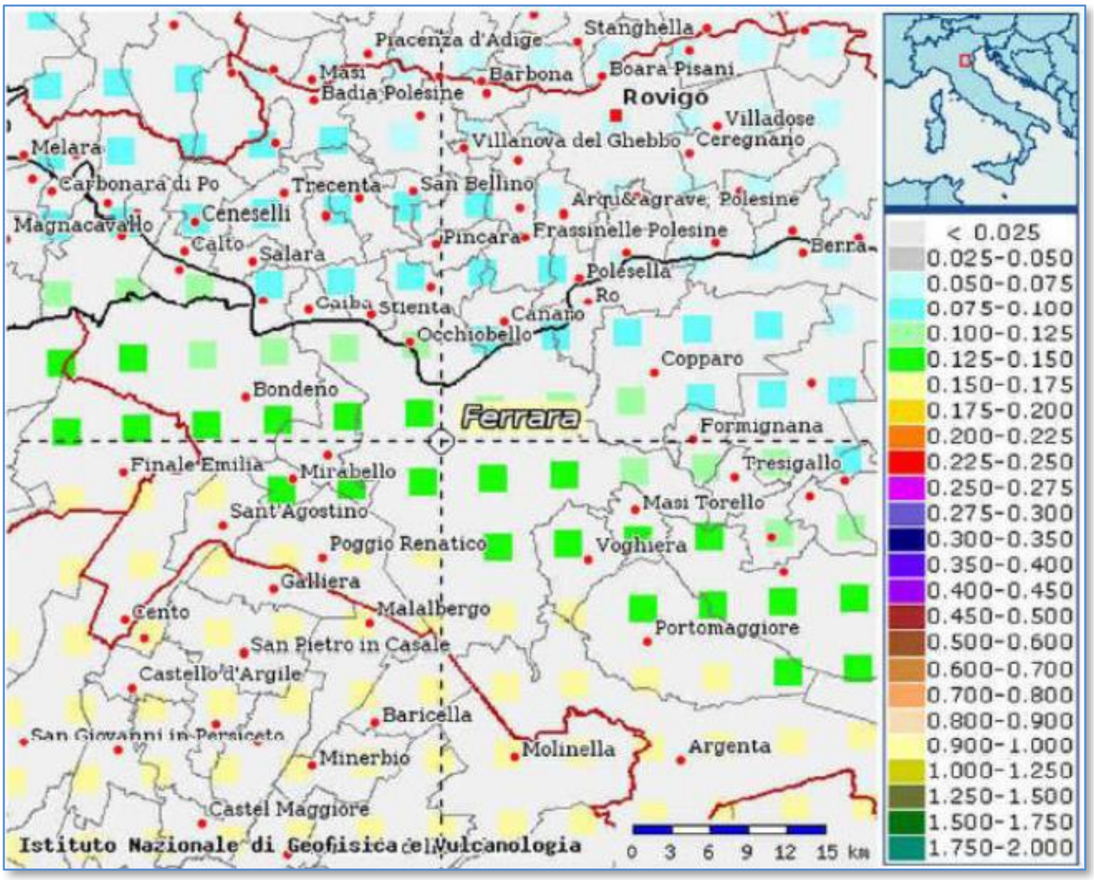

Figure 5. Maximum peak ground accelerations expected on a rigid soil for the municipality of Ferrara.

5. PROMETHEE scheme for multihazard risk assessment

In WP4 we propose to employ the PROMETHEE method to rank different homogeneous areas of the Ferrara province, with a focus on the Ferrara municipality, in terms of the combined seismic and flood risks. The final aim is to produce a multi-hazard risk map for the Ferrara territory as a tool for stakeholders and decision makers engaged in the management of strategic structures and infrastructures.

The procedure entails the subdivision of the Ferrara province into a number of areas which prove to be homogeneous according to different criteria, which will be used in the PROMETHEE ranking algorithm:

1- Flood risk as from Deliverables in WP3

2- Peak Ground Acceleration distribution

3- Seismic microzonation
4- Land use (Urban areas, Suburban, Cropland, Woodland)
5- Building vulnerability index
6- Building use class (and strategic importance factors)
7- Population density

To each criteria a numerical weight and a preference function are suitably assigned so that a ranking in term of overall multihazard risk can be assessed among each homogeneous area.

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