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Holistic evaluation of the seismic urban risk using the fuzzy sets theory

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Abstract

Risk is defined, for management purposes, as the potential economic, social and environmental consequences of hazardous events that may occur in a specified period of time. From the perspective of this paper, risk requires a multidisciplinary evaluation that takes into account not only the expected physical damage, the number and type of casualties or economic losses, but also the conditions related to social fragility and lack of resilience conditions, which favour the second order effects when a hazard event strike an urban centre. The proposed general method of urban risk evaluation uses the fuzzy sets theory in order to manage qualitative concepts and variables involved in the evaluation. Finally, the method is applied in its single hazard version to the holistic seismic risk evaluation for the cities of Barcelona (Spain) and Bogotá (Colombia).

KEYWORDS**:** holistic approach, risk evaluation, seismic risk, socio-economic vulnerability.

1. INTRODUCTION

For management purposes, risk can be defined as the potential economic, social and environmental consequences of hazardous events that may occur in a specified period of time. However, in the past, in many cases the concept of risk has been defined in a fragmentary way, according to each scientific discipline involved in its appraisal [1]. Based on the formulation of the disaster risk [2] several methodologies for risk assessment have been developed from different perspectives in the last decades. From a holistic perspective, risk requires a multidisciplinary evaluation that takes into account not only the expected physical damage, the number and type of casualties or economic losses (first order impact), but also the conditions related to social fragility and lack of resilience conditions, which favour the second order effects (indirect impact) when a seismic hazard event strikes an urban centre [3,4,5] (see Figure 1).

Cardona in 2001 [6] developed a conceptual framework and a model for risk analysis of a city from a holistic perspective. It considers both "hard" and "soft" risk variables of the urban centre, taking into account exposure, socio-economic characteristics of the different localities (units) of the city and their disaster coping capacity or degree of resilience. One of the objectives of the model was to guide the decision-making in risk management, helping to identify the critical zones of the city and their vulnerability from different professional disciplines. Carreño in 2006 [7], developed an alternative method for Urban Risk Evaluation, starting from Cardona's model [6,8], in which urban risk is evaluated using composite indicators or indices. Expected building damage and losses in the infrastructure, obtained from loss scenarios, are basic information for the evaluation of a physical risk index in each unit of analysis. Often, when historical information is available, the seismic hazard can be usually identified and thus the most potential critical situation for the city. This paper proposes a new method using the fuzzy sets theory in order to have a more flexible tool in cases were the information is not available or incomplete.

The holistic evaluation of risk is achieved affecting the physical risk with an aggravation coefficient, obtained from contextual conditions, such as the socio-economic fragility and the lack of resilience, that aggravate initial physical loss scenario. Available data for these conditions at urban level are necessary to apply the method. Figure 1 shows the theoretical framework of the model.

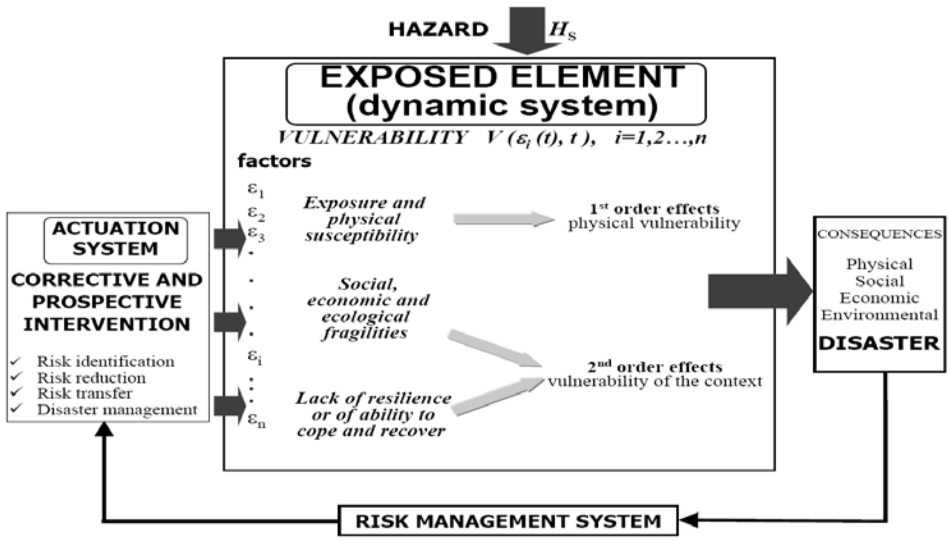

Figure 1: Theoretical Framework and Model for a Holistic Approach to Disaster Risk Assessment and Management. Adapted from [3,9,10,11]. Where, i is the severity of the event, V is the vulnerability, and ε_i are the vulnerability factors.

Using the meta-concepts of the theory of control and complex system dynamics, to reduce risk it is necessary to intervene in a corrective and prospective way the vulnerability factors. Then risk management requires a system of control (institutional structure) and an actuation system (public policies and actions) to implement the changes needed on the exposed elements or complex system where risk is a socio-environmental process.

2. HOLISTIC EVALUATION METHODOLOGY

The main objective of the proposed methodology is to measure seismic risk from an integrated and comprehensive perspective and to guide decision-making identifying the main multidisciplinary factors of vulnerability to be reduced or intervened. The first step of the method is the evaluation of the potential physical damage as the convolution of the seismic hazard and the physical vulnerability of buildings and infrastructure. Subsequently, a set of social context conditions that aggravate the physical effects are also considered. According to this procedure, a physical risk index and level are obtained, for each unit of analysis, from the existing loss scenarios, whereas the total risk index is obtained affecting the physical risk by aggravation conditions based on variables associated with the socio-economic conditions of each unit of analysis.

The proposed holistic evaluation method of risk uses a set of input variables, herein denominated descriptors. They reflect the physical risk and the aggravating conditions that contribute to the potential impact. Those descriptors are obtained from the loss scenarios and from socio-economic and coping capacity information of the exposed context [12].

Figure 2 shows the process of calculation of the total risk R_T for the units of analysis, starting from the descriptors of physical risk, X_{RFi}, and the descriptors of the aggravating coefficient F, X_{FSi} and X_{RFi}, using the weights w_{RFi}, w_{FSi} and w_{FRi} of each descriptor. These weights take values according to the expert opinion for each studied city applying the Analytic Hierarchical Process (AHP) [7,13].

The process is reflected in the following equation

$$R_T = R_F(1+F) \tag{1}$$

expression known as the Moncho’s Equation in the field of disaster risk indicators, where R_T is the total risk index, R_F is the physical risk index and F is the aggravating coefficient. This coefficient, F, depends on factors related to the socio-economic fragility, FS, and the lack of resilience of the exposed context, FR.

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A qualification for each descriptor is obtained by means of fuzzy sets (L_{RFi} or L_{Fi}) (see reference [14]). Membership functions for five levels of physical risk and aggravation are defined for each physical risk and aggravation descriptor, based on expert opinion. Figure 3 shows the membership functions for the fuzzy sets corresponding to the predefined physical risk levels of the *damaged area*. Using this type of functions, a physical risk index and qualification is obtained by means of the union and subsequent defuzzification, applying the method of the centroid of area (COA) of the group of descriptors (see Equations 2 and 3).

$$\mu_{RF}(X_{RFi}) = \max\left(w_{RF1} \times \mu_{LRFi}(L_{RF1}),\ldots, w_{RFi} \times \mu_{LRF_i}(L_{RFi})\right) \tag{2}$$

$$R_F = \left[\max\left(w_{RF1} \times \mu_{LRFi}(L_{RF1}),\ldots, w_{RFi} \times \mu_{LRF_i}(L_{RFi})\right)\right]_{centroid} \tag{3}$$

The aggravation factor, *F*, is evaluated by means of a similar process (see Equations 3 and 4); Figure 4 and 5 show examples of the membership functions used for the social fragility and lack of resilience descriptors corresponding to the aggravation level of *mortality rate* and *hospital beds*.

$$\mu_F(X_{FSi}, X_{FRi}) = \max\left(w_{FSi} \times \mu_{LF1}(L_{Fi}),\ldots, w_{FRi} \times \mu_{LF_i}(L_{Fi})\right) \tag{3}$$

$$F = \left[\max\left(w_{FSi} \times \mu_{LF1}(L_{F1}),\ldots, w_{FRi} \times \mu_{LFi}(L_{Fi})\right)\right]_{centroid} \tag{4}$$

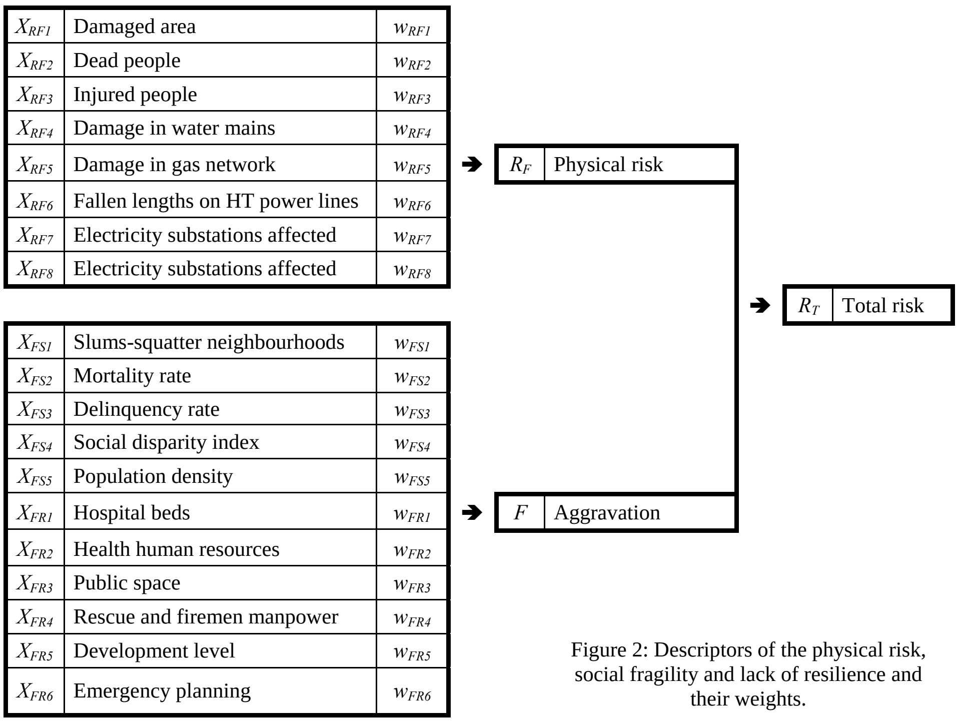

Figure 2: Descriptors of the physical risk, social fragility and lack of resilience and their weights.

Finally, the total risk is calculated applying a fuzzy rule base to the obtained qualifications of physical risk and aggravation. The used fuzzy rule base is shown in Table 1.

This method has the advantage that in case of unavailable or incomplete information, this can be replaced by the opinion of local experts of the studied city.

The proposed methodology has been applied to the cities of Barcelona, Spain and Bogotá, Colombia. The following section shows the obtained results.

Table 1: Fuzzy rule base used to evaluate the Total Risk.

Physical risk \ Aggravation	Low	Medium-low	Medium-high	High	Very high
Low	Low	Low	Medium-low	Medium-low	Medium-low
Medium-low	Medium-low	Medium-low	Medium-high	Medium-high	Medium-high
Medium-high	Medium-high	Medium-high	High	High	Very high
High	High	High	Very high	Very high	Very high
Very high	Very high	Very high	Very high	Very high	Very high

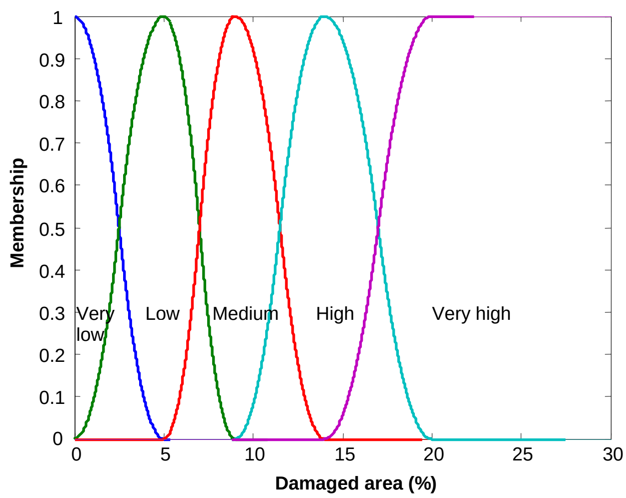

Figure 3: Membership functions for physical risk levels by *damaged area*.

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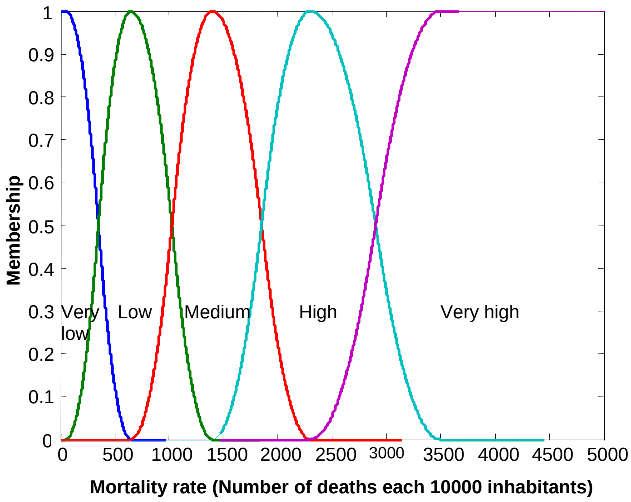

Figure 4: Membership functions for different aggravation levels by *mortality rate*.

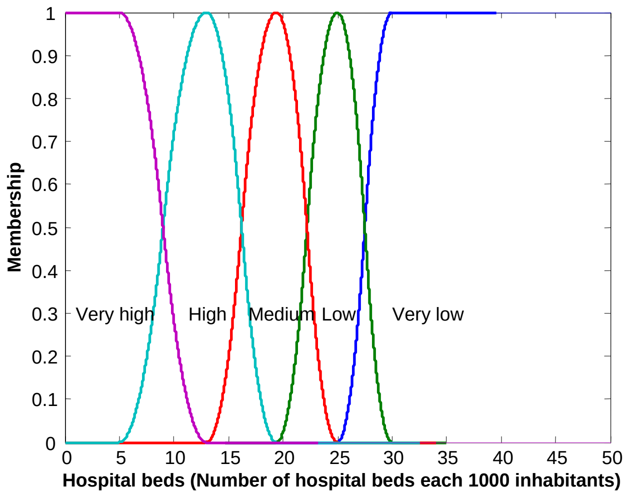

Figure 5: Membership functions for the aggravation levels by *hospital beds*.

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3. CASES OF STUDY

3.1 Barcelona, Spain

The city of Barcelona, Spain, is subdivided in ten districts (see Figure 6), which are directed by a Mayor. The districts have management competences in subjects like urbanism, public space, infrastructure maintenance, etc. They are: Ciutat Vella, Eixample, Sants-Montjuïc, Les Corts, Sarrià-Sant Gervasi, Gràcia, Horta-Guinardó, Nou Barris, Sant Andreu and Sant Martí. The districts are subdivided in 38 neighbourhoods or large statistical zones. Barcelona is also subdivided in 248 small statistical zones (ZRP). The physical risk index was calculated from a probabilistic risk scenario developed in the framework of the Risk-UE project [15,16,17,18,19]. This scenario was calculated considering the 248 small ZRP zones. The impact factor was calculated by district, due to the availability of data at this level only.

Figure 7 shows the obtained physical risk levels obtained for the 248 ZRP of Barcelona, were the most part of the city has a medium-low physical risk level, and the rest has a medium-high physical risk level. Figure 8 shows the results of the aggravating coefficient for each district of Barcelona. Figures 9 and 10 show the results of the aggravating coefficient and the corresponding aggravation level for the district of the city of Barcelona.

The total risk levels obtained are shown in Figure 11, were the areas of Barcelona correspond to high and medium-high level of total risk.

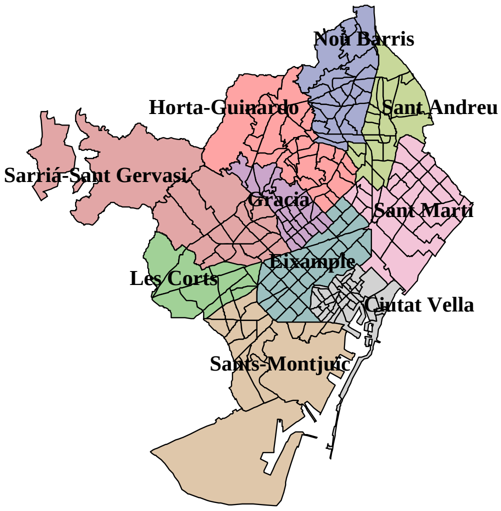

Figure 6: Territorial division of Barcelona.

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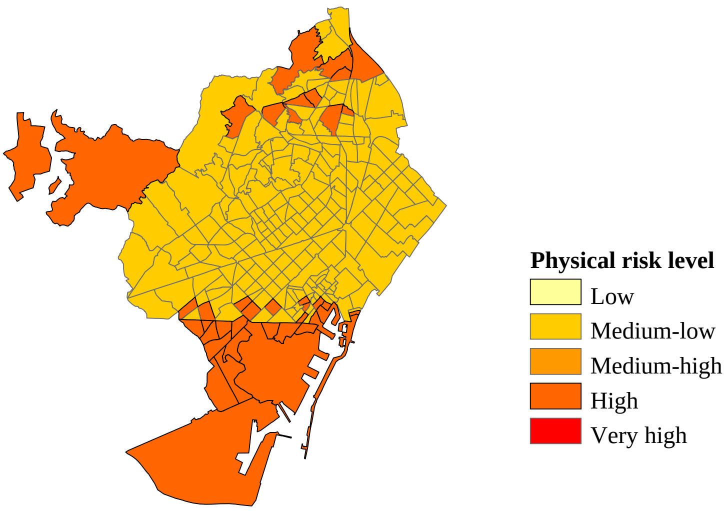

Figure 7: Physical risk levels of Barcelona

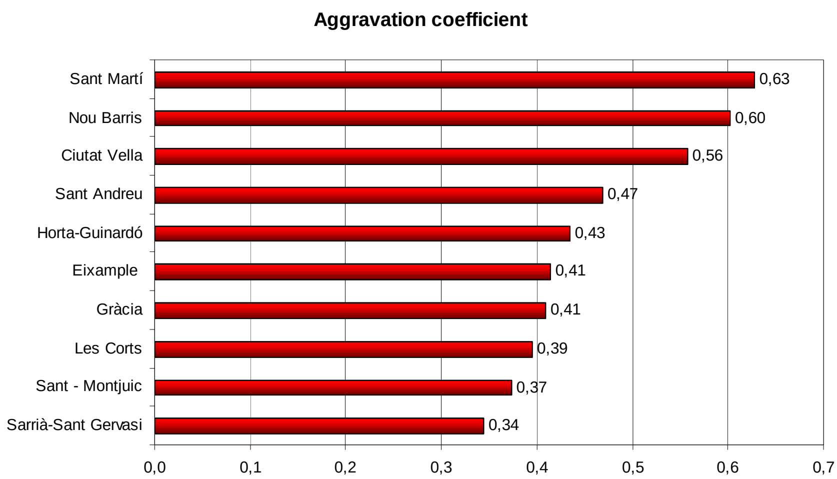

Figure 8: Aggravation coefficient of Barcelona's districts

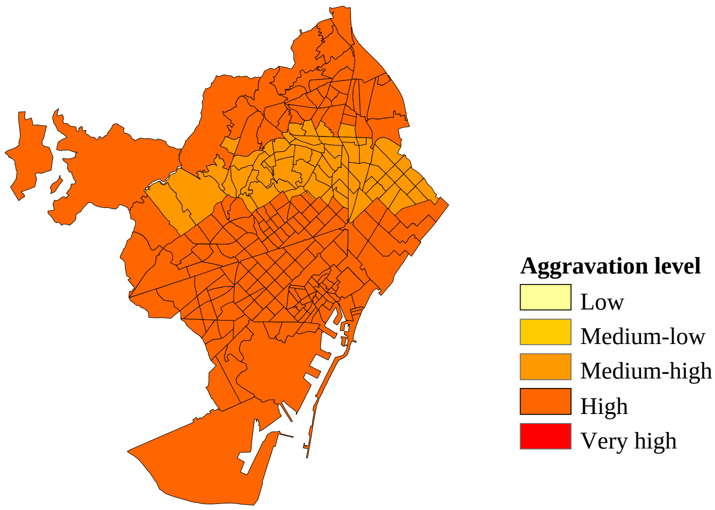

Figure 9: Aggravation level of the districts of Barcelona.

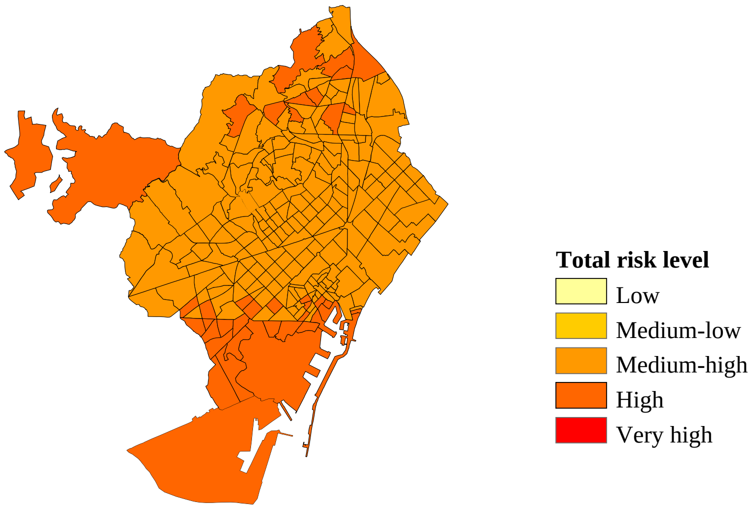

Figure 10: Total risk levels of Barcelona.

3.2 Bogota, Colombia

In Bogotá, the capital of Colombia, the localities are political-administrative subdivisions of the urban territory, with clear competences in financing and application of resources. They were created with the objective of attending in an effective way the necessities of the population of each territory. Since 1992, Bogotá has 20 localities which can be seen in Figure 11: Usaquén, Chapinero,

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Santafé, San Cristóbal, Usme, Tunjuelito, Bosa, Ciudad Kennedy, Fontibón, Engativa, Suba, Barrios Unidos, Teusaquillo, Mártires, Antonio Nariño, Puente Aranda, Candelaria, Rafael Uribe, Ciudad Bolívar y Sumapaz. In this study, only 19 of these localities are considered, because the locality of Sumapaz corresponds to the rural area.

Figure 12 shows the obtained physical risk levels obtained for the 117 UPZs of Bogota beased on an existent scenario [20]. Figure 13 shows the results of the aggravating coefficient for each locality of Bogota. The obtained results of the aggravation coefficient for the localities of Bogota correspond to the high level of aggravation; this means that although the localities have several differences, in average, the aggravation due to the lack of resilience and the social fragilities is similar. Figure 14 shows the results of total risk.

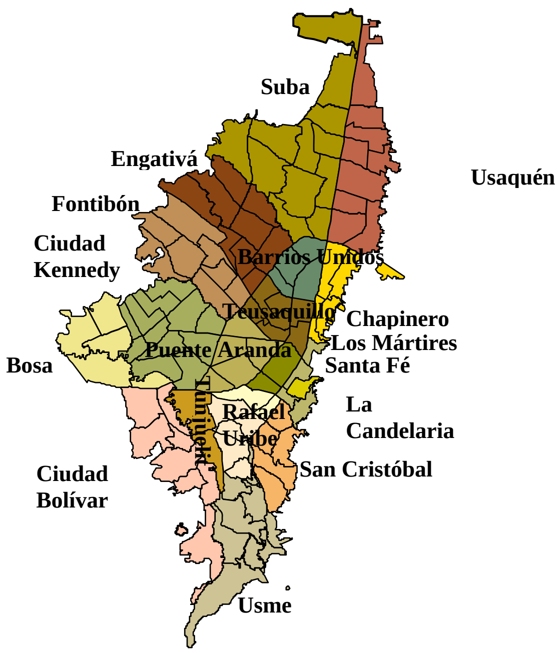

Figure 11: Political-administrative division of Bogotá, Colombia.

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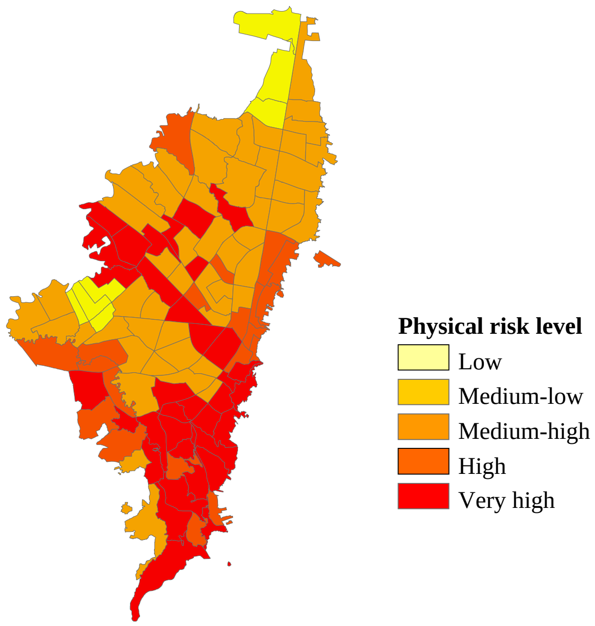

Figure 12: Physical risk levels for Bogota.

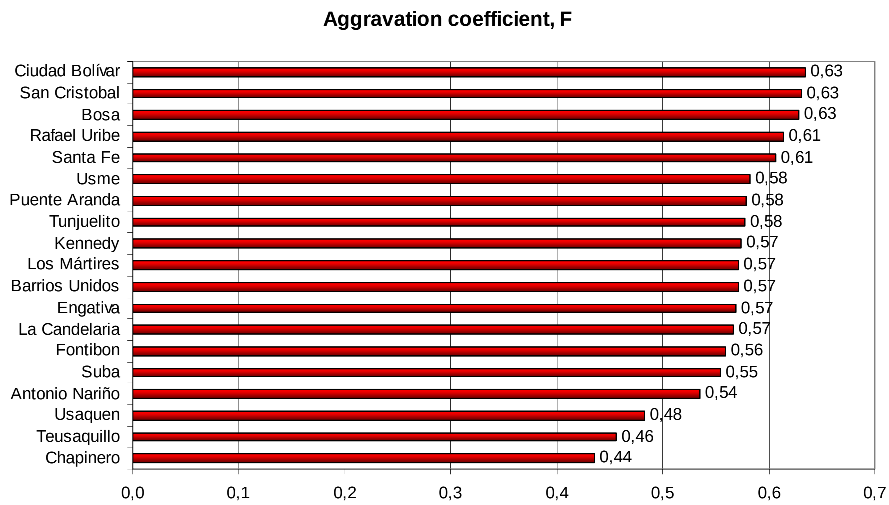

Figure 13: Aggravation coefficient of Bogota’s localities.

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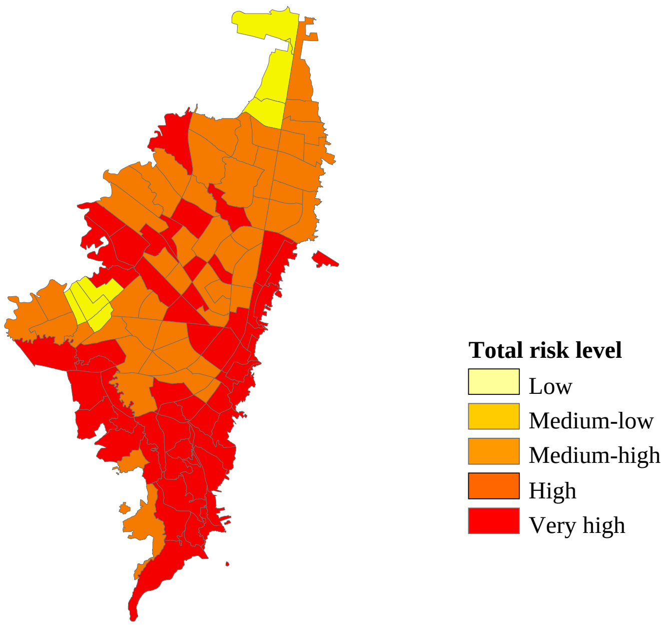

Figure 14: Total risk levels of Bogota.

4. CONCLUSIONS

A simplified but multidisciplinary model of the urban seismic risk has been proposed in this paper, based on the parametric use of variables that reflect different aspects of such risk. This model is formulated in the most realistic possible manner using the fuzzy sets theory, to which corrections or alternative figures may be continuously introduced. The consideration of physical aspects allowed the construction of a physical risk index. Also, the contextual variables (social, economic, etc.) allowed the construction of an aggravation coefficient. The former is built from the information about the seismic scenarios of physical damage (direct effects) and the latter is the result from the estimation of aggravating conditions (indirect effects) based on descriptors and factors related to the social fragility and the lack of resilience of the exposed elements. the application of fuzzy sets is proposed for the case in which the necessary information is not available, starting from this can be replaced by experts opinion.

This new fuzzy model for holistic evaluation of risk facilitates the integrated risk management by the different stakeholders involved in risk reduction decision-making. The proposed method has been applied to the cities of Barcelona (Spain) and Bogota (Colombia), proved to be robust, and allowed to identify the most relevant aspects of the total risk index, with no need for further analysis and interpretation of results.

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