Seismic risk evaluation for an urban centre

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Abstract

Risk has been defined, for management purposes, as the potential economic, social and environmental consequences of hazardous events that may occur in a specified period of time. However, in the past, the concept of risk has been defined in a fragmentary way in many cases, according to each scientific discipline involved in its appraisal. From the perspective of this article, risk requires a multidisciplinary evaluation that takes into account not only the expected physical damage, the number and type of casualties or economic losses (direct impact), but also the conditions related to social fragility and lack of resilience conditions, which favour the second order effects (indirect impact) when a hazard event strike a urban centre. The urban seismic risk evaluation is proposed from a holistic point of view; that is, an integrated and comprehensive approach to guide decision-making. Evaluation of the potential physical damage (hard approach) as the result of the convolution of hazard and physical vulnerability of buildings and infrastructure is the first step of this method. Subsequently, a set of social context conditions that aggravate the physical effects are also considered (soft approach). In the method here proposed, the holistic risk evaluation is based on urban risk indicators. According to this procedure, a physical risk index is obtained, for each unit of analysis, from existing loss scenarios, whereas the total risk index is obtained by factoring the former index by an impact factor, based on variables associated with the socio-economic conditions of each unit of analysis. Finally, examples of the model application are given for two urban centres: Bogotá and Barcelona.

Methodology of evaluation

The report Natural Disasters and Vulnerability Analysis (UNDRO, 1980) proposed the unification of disaster related definitions as hazard (H), vulnerability (V), exposed elements (E) and risk (R) and suggested one expression to associating them, that is considered a standard at present,

$$R = E \cdot H \cdot V \qquad (1)$$

Based on this formulation several methodologies for risk assessment have been developed from different perspectives in the last decades, and recently a holistic approach for the case of urban centres (Cardona and Hurtado 2000; Masure, 2003).

Cardona (2001) developed a conceptual framework and a model for seismic 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, socioeconomic characteristics of the different districts (units) of the city and their disaster coping capacity or degree of resilience. The model was made to guide the decision-making in risk management, helping to identify the critical zones of the city and their vulnerability from different professional disciplines.

This article presents an alternative method for urban risk evaluation based on Cardona's model (Cardona, 2001; Barbat and Cardona, 2003), using a holistic approach and describing seismic risk by means of indices. Expected building damage and losses in the infrastructure, obtained from future loss scenarios are basic information for the evaluation of physical risk in each unit of analysis. Starting from these data, a physical damage index is obtained. The holistic evaluation of risk by means of indices is achieved affecting the physical risk with an impact factor or aggravating coefficient, obtained from contextual conditions, such as the socioeconomic fragility and the lack of resilience, that aggravate initial physical loss scenario. Available data about these conditions at urban level are necessary to apply the method. An explanation of the model is made further and also some examples of application for the cities of Bogotá, Colombia, and Barcelona, Spain, are described to illustrate the benefits of this approach that contributes to the effectiveness of risk management, inviting to the action identifying the hard and soft weaknesses of the urban centre. Figure 1 shows the theoretical framework for the alternative model.
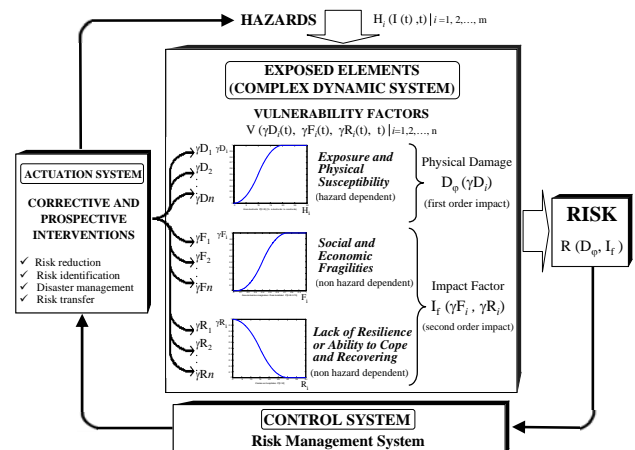

Fig. 1. Theoretical framework and model for holistic approach of disaster risk (adapted from Cardona and Barbat, 2000)

From a holistic perspective risk, R, is a function of the potential physical damage, D_j, and an impact factor, I_f. The former is obtained from the susceptibility, γD_i, of the exposed elements to hazards, H_i, regarding their potential intensities, I, of events in a period of time t, and the latter depends on the social fragilities, γF_i, and the issues related to lack of resilience, γR_i, of the disaster prone socio-technical system or context. Using the meta-concepts of the theory of control and complex system dynamics, to reduce risk it is necessary to intervene in corrective and prospective way the vulnerability factors and, when it is possible, the hazards directly. 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 social process.

In this paper the proposed holistic evaluation of risk is performed using 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, listed forward, are obtained from the loss scenarios effects and from socioeconomic and coping capacity information

of the exposed context (Barbat and Cardona, 2003; Carreño et al., 2005). The calculation of these descriptors is not the objective of this paper. More information on this subject can be found in Carreño et al. (2005). They are only input information data. The socioeconomic fragility and the lack of resilience are a set of factors (related to indirect or intangible effects) that aggravate the physical risk (potential direct effects). Thus, the total risk depends on the physical risk, and the indirect effects expressed as a factor

$$R_T = R_F(1+F) \qquad (2)$$

In this equation, known as Moncho's equation, R_T is the total risk index, R_F is the physical risk index and F is the impact factor. This coefficient depends on the weighted sum of a set of aggravating factors related to the socioeconomic fragility, F_{FSi}, and the lack of resilience of the exposed context, F_{FRj}

$$F = \sum_{i=1}^{m} w_{FSi} \times F_{FSi} + \sum_{j=1}^{m} w_{FRj} \times F_{FRj} \qquad (3)$$

where w_{FSi} and w_{FRj} are the weights or influences of each i and j factors and m and n are the total number of descriptors for social fragility and lack of resilience respectively.

The aggravating factors F_{FSi} and F_{FRj} are calculated using transformation functions shown in the figures 2 and 3. These functions standardise the gross values of the descriptors transforming them in commensurable factors. The weights w_{FSi} and w_{FRj} represent the relative importance of each factor and are calculated by means of the Analytic Hierarchy Process (AHP). It is used to derive ratio scales from both discrete and continuous pairwise comparisons (Saaty, 1980, 2001).

The physical risk, R_F, is evaluated in the same way, using the transformation functions showed in the Figure 3

$$R_F = \sum_{i=1}^{p} w_{RFi} \times F_{RFi} \qquad (4)$$

where p is the total number of descriptors of physical risk index, F_{RFi} are the component factors and w_{RFi} are their weights respectively. The factors of physical risk, F_{RFi}, are calculated using the gross values of physical risk descriptors such as the number of deaths, injured or the destroyed area, and so on. The transformation functions take values between 0 and 1 (see figures 2, 3 and 4).
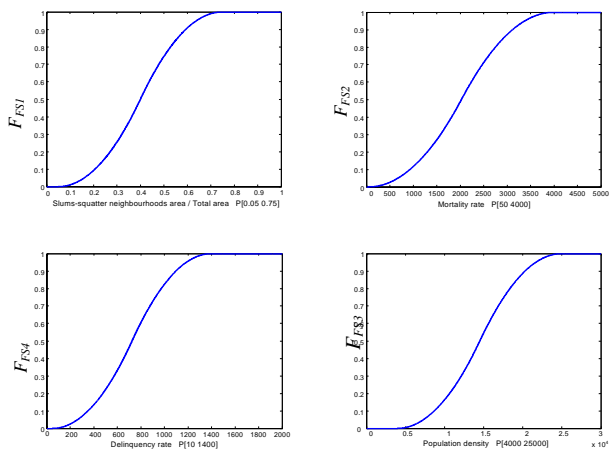

Fig. 2. Transformation functions used to standardise the social fragility factors

It is estimated that the indirect effects of hazard events, sized by the factor F in equation 2, can be the same order of the direct effects. According to the Economic Commission for Latin America and the Caribbean (ECLAC), it is estimated that the indirect economic effects of a natural disaster depend on the type of phenomenon. The order of magnitude of the indirect

economic effects for a "wet" disaster (as one caused by a flood) could be of 0.50 to 0.75 of the direct effects. In the case of a "dry" disaster (caused by an earthquake, for example), the indirect effects could be about the 0.75 to 1.00 of the direct effects, due to the kind of damage (destruction of livelihoods, infrastructure, housing, etc.). This means that the total impact, R_T, could be between 1.5 and 2 times R_F. In this method, the maximum value selected was the latter. For this reason, the impact factor, F, takes values between 0 and 1 in equation 2, in this case.

In order to develop the transformation functions sigmoid functions were used (see figures 2 to 4). The maximum and minimum values (for the values 1 or 0 of each factor) were fixed using existing information about disasters as well as experts opinions. For the lack of resilience descriptors, related to the level of development of the community and the emergency planning or preparedness, a linear relation was assumed. Table 1 presents the variables used to reflecting the social fragility and the lack of resilience in the estimation of F.
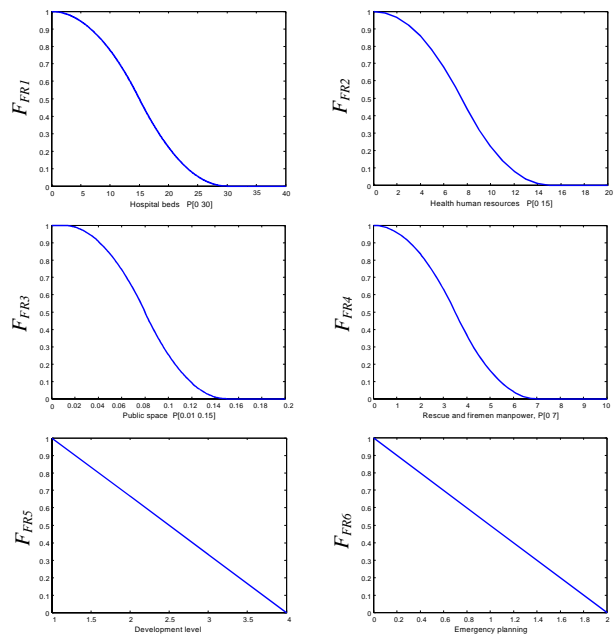

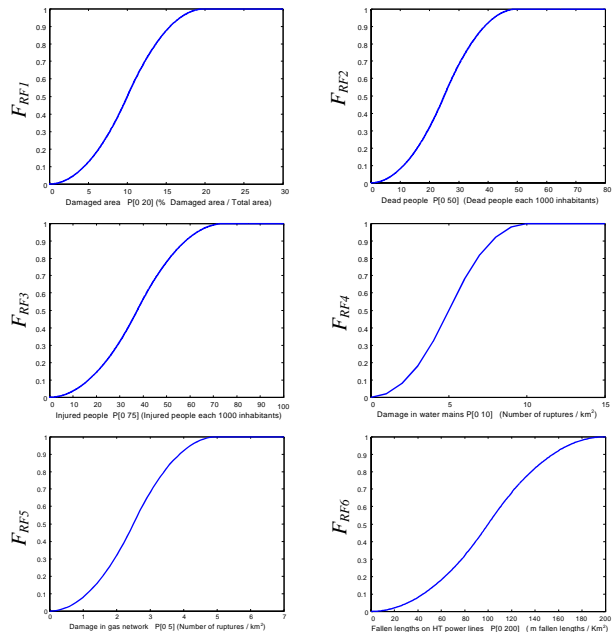Fig. 3. Transformation functions used to standardise the lack of resilience factors

Fig. 4. Transformation functions used to standardise the physical risk factors

Figures 2 to 4 show the values of the descriptors in the *x-axis* of the transformation functions. The corresponding factors, or scaled values, are given in the *y-axis*.

TABLE 1: Descriptors used to evaluate the impact factor *F*

Aspect	Descriptor
Social fragility	Slums-squatter neighbourhoods
	Mortality rate
	Delinquency rate
	Social disparity index
	Population density
Lack of resilience	Hospital beds
	Health human resources
	Public space
	Rescue and firemen manpower
	Development level
	Preparedness emergecy planning

Table 2 presents the initial measurement units of each descriptor of social fragility and resilience. Table 3 shows the descriptors of the physical risk. The factors for a city are obtained in each case using the transformation functions and variables with the units of abovementioned tables.

TABLE 2: Aggravating descriptors, their units and identifiers

	Descriptor	Units
X_{FS1}	Slums-squatter neighbourhoods	Slum-squatter neighbourhoods area / Total area
X_{FS2}	Mortality rate	Number of deaths each 10,000 inhabitants
X_{FS3}	Delinquency rate	Number of crimes each 100,000 inhabitants
X_{FS4}	Social disparity index	Index between 0 y 1
X_{FS5}	Population density	Inhabitants / Km^2 of build area
X_{FR1}	Hospital beds	Number of hospital beds each 1000 inhabitants
X_{FR2}	Health human resources	Health human resources each 1000 inhabitants
X_{FR3}	Public space	Public space area/ Total area
X_{FR4}	Rescue and firemen manpower	Rescue and firemen manpower each 10000 inhabitants
X_{FR5}	Development level	Qualification between 1 and 4
X_{FR6}	Emergency planning	Qualification between 0 and 2

Figure 5 shows the process of calculation of the total risk index for the units of analysis, R_T, starting from the factors of physical risk, F_{RFi}, and of aggravating, F_{FSi} and F_{RFi}, and using the weights w_{RFi}, w_{FSi} and w_{FRi} of each factor. These weights take values according to the expert opinion for each studied city

applying the Analytic Hierarchical Process (AHP). Using the factors obtained applying the functions of figures 2 to 4, the physical risk index is calculated by applying equation 4, the impact factor by means of equation 3 and, finally, the total risk is calculated by means of equation 2.

This new model improves conceptual and methodological aspects of the first Cardona's proposal, refining the applied numerical techniques and turning it into a more versatile tool. The conceptual improvements provide a more solid theoretical and analytical support to the new model, eliminating unnecessary and dubious aspects of the previous method, given more transparency and applicability in some cases. The new approach preserves the use of indicators and fuzzy sets or membership functions, proposed originally, but in a different way. It also improves the procedure of normalisation and calculates the final indices in an absolute (non relative) manner. This feature facilitates the comparison of risk among cities. Finally, the earlier model takes into account descriptors of physical risk, seismic hazard, physical exposure, socioeconomic fragility, and lack of resilience; in the new approach, seismic hazard and the physical exposure have been eliminated because they are redundant due to they have been included into the physical risk variables.

TABLE 3: Physical risk descriptors, their units and identifiers

	Descriptors	Units
X_{RF1}	Damaged area	Percentage (damaged area / build area)
X_{RF2}	Dead people	Number of dead people each 1000 inhabitants
X_{RF3}	Injured people	Number of injured people each 1000 inhabitants
X_{RF4}	Ruptures in water mains	Number of ruptures / Km^2
X_{RF5}	Rupture in gas network	Number of ruptures / Km^2
X_{RF6}	Fallen lengths on HT power lines	Metres of fallen lengths / Km^2
X_{RF7}	Telephone exchanges affected	Vulnerability index
X_{RF8}	Electricity substations affected	Vulnerability index
X_{RF9}	Damage in the road network.	Damage index

EXAMPLE OF APPLICATION: SEISMIC RISK OF BOGOTÁ

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 6: Usaquén, Chapinero, 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.

As it is well known, the seismic hazard is the most significant threat for Bogotá. The scenario of seismic physical risk illustrated in Figure 7 was used as a starting point for the application of the model. It displays the mean damaged area in predefined cells or zones considering a strong near field earthquake with 0.2g acceleration at the bedrock (Universidad de Los Andes, 1996).

Tables 4 and 5 show the weights computed using the AHP, for the components of the physical risk and for the aggravating factors, respectively. The weights are calculated in Carreño et

al. (2005). Tables 6 and 8 show the values of the descriptors used in this application, which represent the physical risk, the social fragility and the lack of resilience, respectively. Table 7 shows the values of the factors of physical risk obtained by applying the functions of the Figure 4. Table 9 shows the aggravating factors due to the social fragility and the lack of resilience; they are obtained by the applying the functions of figures 2 and 3. The physical risk index, R_F, and the impact factor, F, are also indicated in these tables. In addition, the average values for the city are shown. They average values are have been calculated normalising by the density of population. Table 10 shows the results for the physical risk, the impact factor and the total risk of each locality and the average values for the city.

F_{RF1}	Damaged area	w_{RF1}
F_{RF2}	Dead people	w_{RF2}
F_{RF3}	Injured people	w_{RF3}
F_{RF4}	Damage in water mains	w_{RF4}
F_{RF5}	Damage in gas network	w_{RF5}
F_{RF6}	Fallen lengths on HT power lines	w_{RF6}
F_{RF7}	Electricity substations affected	w_{RF7}
F_{RF8}	Electricity substations affected	w_{RF8}

→ R_F Physical risk

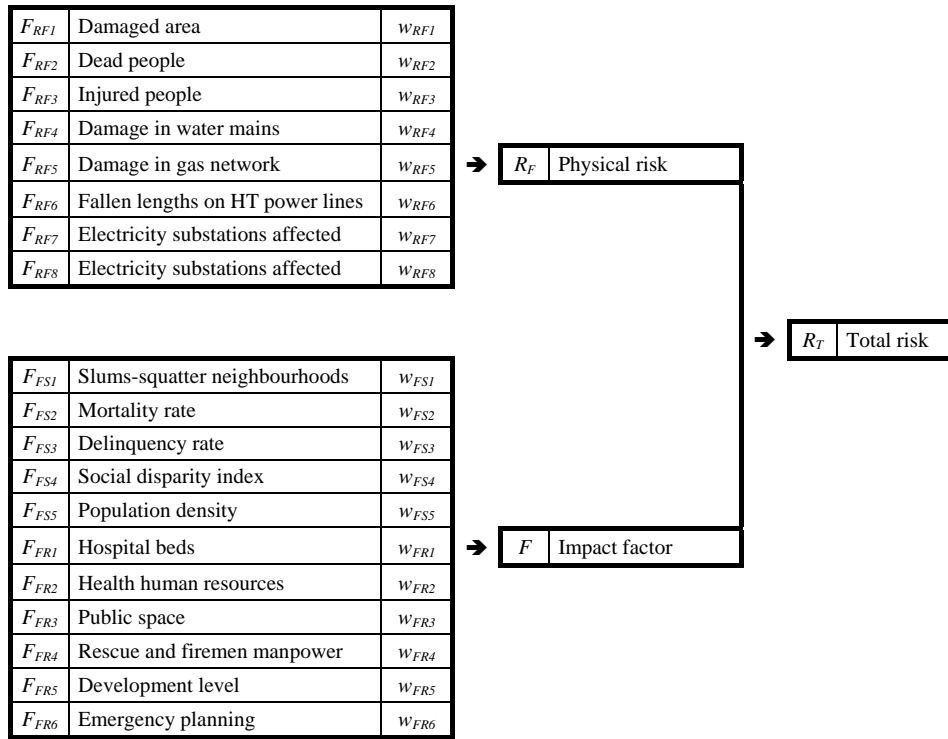| F_{FS1}	Slums-squatter neighbourhoods	w_{FS1}
F_{FS2}	Mortality rate	w_{FS2}
F_{FS3}	Delinquency rate	w_{FS3}
F_{FS4}	Social disparity index	w_{FS4}
F_{FS5}	Population density	w_{FS5}
F_{FR1}	Hospital beds	w_{FR1}
F_{FR2}	Health human resources	w_{FR2}
F_{FR3}	Public space	w_{FR3}
F_{FR4}	Rescue and firemen manpower	w_{FR4}
F_{FR5}	Development level	w_{FR5}
F_{FR6}	Emergency planning	w_{FR6}

→ F Impact factor

→ R_T Total risk

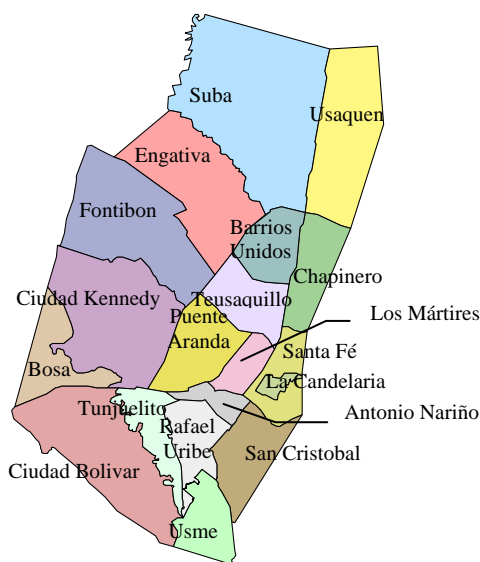Fig. 5. Factors of physical risk, social fragility and lack of resilience and their weights

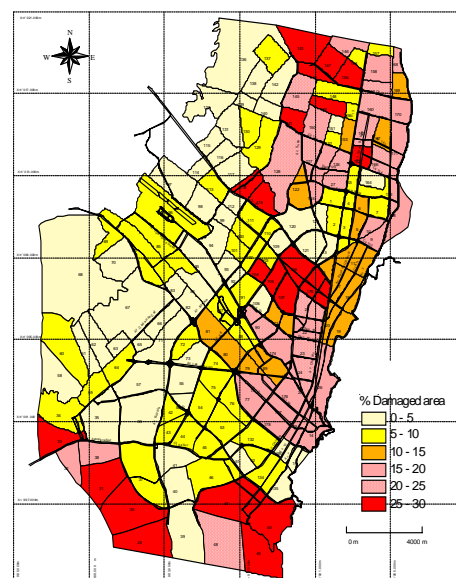Fig. 6. Political-administrative division of Bogotá, Colombia

Fig. 7. One scenario of physical seismic risk, Universidad de los Andes (1996)

TABLE 4: Physical risk descriptors, their units and identifiers

Factor	Weight	Weight value
F_{RF1}	w_{RF1}	0.31
F_{RF2}	w_{RF2}	0.10
F_{RF3}	w_{RF3}	0.10
F_{RF4}	w_{RF4}	0.19
F_{RF5}	w_{RF5}	0.11
F_{RF6}	w_{RF6}	0.11
F_{RF7}	w_{RF7}	0.04
F_{RF8}	w_{RF8}	0.04

TABLE 5: Weights for the factors of the aggravating conditions

Factor	Weight	Weight value
F_{FS1}	w_{FS1}	0.18
F_{FS2}	w_{FS2}	0.04
F_{FS3}	w_{FS3}	0.04
F_{FS4}	w_{FS4}	0.18
F_{FS5}	w_{FS5}	0.18
F_{FR1}	w_{FR1}	0.06
F_{FR2}	w_{FR2}	0.06
F_{FR3}	w_{FR3}	0.04
F_{FR4}	w_{FR4}	0.03
F_{FR5}	w_{FR5}	0.09
F_{FR6}	w_{FR6}	0.09

TABLE 6: Descriptor values of the physical risk, R_F

Locality	X_{RF1}	X_{RF2}	X_{RF3}	X_{RF4}	X_{RF5}	X_{RF6}	X_{RF7}	X_{RF8}
Usaquen	15.1186	4	27	2	0	24	0.70	0.83
Chapinero	5.0302	5	27	5	0	81	0.77	0.90
Santafé	6.6070	3	16	7	0	63	0.62	0.90
San Cristóbal	4.9278	2	13	4	0	34	0.68	0.90
Usme	10.5870	0	1	1	1	14	0.67	0.90
Tunjuelito	3.5494	0	1	1	0	7	0.58	0.70
Bosa	4.2461	2	12	3	1	42	0.73	0.90
Ciudad Kennedy	4.8198	0	2	1	0	11	0.54	0.70
Fontibón	5.3163	1	7	1	0	5	0.64	0.70
Engativa	6.8777	1	5	1	0	3	0.66	0.80
Suba	13.8449	2	13	1	0	19	0.66	0.77
Barrios Unidos	12.2659	4	27	2	1	45	0.75	0.90
Teusaquillo	10.2985	8	41	4	0	36	0.74	0.90
Mártires	7.0283	6	30	2	0	18	0.66	0.70
Antonio Nariño	4.0287	0	2	2	0	17	0.67	0.80
Puente Aranda	5.7006	1	6	2	0	20	0.69	0.70
Candelaria	8.9515	9	44	6	0	81	0.67	0.90
Rafael Uribe Uribe	3.2433	1	11	2	0	29	0.65	0.90
Ciudad Bolívar	8.8908	1	11	1	1	21	0.64	0.90

TABLE 7: Factors, F_{RF}, and the physical risk index, R_F

Locality	F_{RF1}	F_{RF2}	F_{RF3}	F_{RF4}	F_{RF5}	F_{RF6}	F_{RF7}	F_{RF8}	R_F
Usaquen	0.881	0.0128	0.259	0.08	0	0.0288	0.70	0.83	0.386
Chapinero	0.127	0.02	0.259	0.50	0	0.328	0.77	0.90	0.264
Santafé	0.218	0.0072	0.091	0.82	0	0.198	0.62	0.90	0.314
San Cristobal	0.121	0.0032	0.0601	0.32	0	0.0578	0.68	0.90	0.175
Usme	0.557	0	0.000356	0.02	0.08	0.0098	0.67	0.90	0.253
Tunjuelito	0.063	0	0.000356	0.02	0	0.00245	0.58	0.70	0.076
Bosa	0.090	0.0032	0.0512	0.18	0.08	0.0882	0.73	0.90	0.152
Ciudad Kennedy	0.116	0	0.00142	0.02	0	0.00605	0.54	0.70	0.092
Fontibón	0.141	0.0008	0.0174	0.02	0	0.00125	0.64	0.70	0.105
Engativa	0.237	0.0008	0.00889	0.02	0	0.00045	0.66	0.80	0.139
Suba	0.811	0.0032	0.0601	0.02	0	0.0181	0.66	0.77	0.326
Barrios Unidos	0.701	0.0128	0.259	0.08	0.08	0.101	0.75	0.90	0.350
Teusaquillo	0.529	0.0512	0.589	0.32	0	0.0648	0.74	0.90	0.366
Mártires	0.247	0.0288	0.32	0.08	0	0.0162	0.66	0.70	0.186
Antonio Nariño	0.081	0	0.00142	0.08	0	0.145	0.67	0.80	0.116
Puente Aranda	0.162	0.0008	0.0128	0.08	0	0.02	0.69	0.70	0.126
Candelaria	0.401	0.0648	0.658	0.68	0	0.328	0.67	0.90	0.426
Rafael Uribe Uribe	0.053	0.0008	0.043	0.08	0	0.042	0.65	0.90	0.103
Ciudad Bolívar	0.395	0.0008	0.043	0.02	0.08	0.022	0.64	0.90	0.206
Bogotá	*0.410*	*0.0039*	*0.0536*	*0.0924*	*0.0486*	*0.0379*	*0.6645*	*0.8630*	*0.2246*

TABLE 8: Values of aggravating descriptors for social fragility and lack of resilience factors of Bogotá

Locality	X_{FS1}	X_{FS2}	X_{FS3}	X_{FS4}	X_{FS5}	X_{FR1}	X_{FR2}	X_{FR3}	X_{FR4}	X_{FR5}	X_{FR6}
Usaquen	0.311	1260	433	0.33	12720.00	0.17937	28	0.0496	0.844	4	2
Chapinero	0.161	1786	1282	0.00	9655.00	0.49088	89	0.0129	3.231	4	1
Santafé	0.370	1082	1034	0.36	19223.00	0.62909	143	0.0032	3.382	3	2
San Cristóbal	0.614	1511	216	0.82	32242.00	0.10353	19	0.0148	3.882	1	2
Usme	1.476	421	74	1.00	353106.00	0.06368	2	0	7.323	1	2
Tunjuelito	0.738	715	322	0.45	33095.00	0.17567	13	0.0978	4.504	2	2
Bosa	1.076	664	258	0.51	17383.00	0.04872	3	0.0359	7.837	1	1
Ciudad Kennedy	0.501	1433	380	0.44	22352.00	0.06875	8	0.0202	3.454	2	1
Fontibón	0.340	1000	275	0.39	9795.00	0.02736	4	0.0109	3.870	3	2
Engativa	0.257	2789	278	0.41	22488.00	0.06770	7	0.0005	3.371	2	2
Suba	0.326	1880	316	0.41	12658.00	0.08701	15	0.0257	4.202	2	2
Barrios Unidos	0.001	950	509	0.29	16908.00	0.15437	33	0.1170	6.175	4	1
Teusaquillo	0.166	0	888	0.05	11536.00	0.51755	20	0.1126	1.540	4	2
Mártires	0.201	570	831	0.33	11902.00	1.14030	103	0.0271	25.426	3	1
Antonio Nariño	0.112	534	513	0.20	20414.00	0.09494	5	0.0131	8.884	4	1
Puente Aranda	0.058	1147	448	0.37	15203.00	0.03858	4	0.0030	1.488	3	2
Candelaria	0.775	0	904	0.34	11422.00	0.00000	0	0	0	3	0
Rafael Uribe Uribe	0.532	927	288	0.50	23125.00	0.01863	11	0.00133	3.696	1	2
Ciudad Bolívar	0.418	970	162	0.92	28058.00	0.07044	3	0	5.880	1	2

TABLE 9: Impact factor, F, computed with aggravating factors of social fragility, F_{FS}, and lack of resilience, F_{FR}

Locality	F_{FS1}	F_{FS2}	F_{FS3}	F_{FS4}	F_{FS5}	F_{FR1}	F_{FR2}	F_{FR3}	F_{FR4}	F_{FR5}	F_{FR6}	F
Usaquen	0.278	0.0150	0.1610	0.327	0.345	1	0	0.840	0.969	0	0	0.309
Chapinero	0.0503	0.1370	0.985	0.000	0.145	0.999	0	0.999	0.575	0	0.5	0.245
Santafe	0.418	0.00149	0.853	0.362	0.849	0.999	0	1	0.533	0.3	0	0.478
San Cristóbal	0.925	0.0580	0.030	0.816	1.000	1	0	0.998	0.396	1	0	0.707
Usme	1.000	0	0.000632	1.000	1.000	0.999	0.964	1	0.000	1	0	0.797
Tunjuelito	0.999	0	0.0812	0.449	1.000	1	0.0356	0.278	0.255	0.6	0	0.587
Bosa	1.000	0	0.0475	0.515	0.737	1	0.92	0.932	0.000	1	0.5	0.701
Ciudad Kennedy	0.747	0.0417	0.120	0.440	0.968	1	0.436	0.989	0.513	0.6	0.5	0.643
Fontibón	0.343	0.0000	0.056	0.385	0.152	1	0.858	1	0.399	0.3	0	0.358
Engativa	0.175	0.6740	0.057	0.409	0.971	1	0.564	1	0.536	0.6	0	0.521
Suba	0.311	0.1720	0.078	0.415	0.340	0.998	0	0.975	0.321	0.6	0	0.369
Barrios Unidos	0.000	0	0.231	0.290	0.703	1	0	0.111	0.030	0	0.5	0.302
Teusaquillo	0.0549	0	0.712	0.050	0.258	0.999	0	0.143	0.904	0	0	0.193
Mártires	0.0931	0	0.645	0.331	0.283	0.997	0	0.97	0.000	0.3	0.5	0.325
Antonio Nariño	0.0157	0	0.235	0.198	0.905	1	0.778	0.999	0.000	0	0.5	0.407
Puente Aranda	0.000261	0.0048	0.174	0.373	0.565	1	0.858	1	0.911	0.3	0	0.391
Candelaria	1.000	0	0.730	0.340	0.250	1	1	1	1.000	0.3	1	0.631
Rafael Uribe Uribe	0.806	0	0.0622	0.503	0.984	1	0.142	1	0.445	1	0	0.635
Ciudad Bolívar	0.550	0	0.0138	0.920	1.000	1	0.92	1	0.049	1	0	0.700
Bogotá	*0.762*	*0.032*	*0.111*	*0.736*	*0.880*	*0.999*	*0.670*	*0.922*	*0.188*	*0.774*	*0.089*	*0.663*

TABLE 10: Total risk of Bogotá

Locality	R_F	F	R_T
Usaquen	0.386	0.309	0.505
Chapinero	0.264	0.245	0.329
Santafé	0.314	0.478	0.464
San Cristóbal	0.175	0.707	0.298
Usme	0.253	0.797	0.454
Tunjuelito	0.076	0.587	0.121
Bosa	0.152	0.701	0.258
Ciudad Kennedy	0.092	0.643	0.150
Fontibón	0.105	0.358	0.142
Engativa	0.139	0.521	0.211
Suba	0.326	0.369	0.446
Barrios Unidos	0.350	0.302	0.456
Teusaquillo	0.366	0.193	0.436
Mártires	0.186	0.325	0.246
Antonio Nariño	0.116	0.407	0.163
Puente Aranda	0.126	0.391	0.175
Candelaria	0.426	0.631	0.694
Rafael Uribe Uribe	0.103	0.635	0.169
Ciudad Bolivar	0.206	0.700	0.350
Bogotá	*0.225*	*0.663*	*0.374*

Figures 8 to 12 display graphically the results of the holistic evaluation of the seismic risk of Bogotá using the proposed model. These figures show that the locality of Candelaria has the most critical situation from the point of view of the physical and total seismic risk, because its impact factor is significant, although it is not the highest of the city. The localities with greater impact factor are Usme, San Cristóbal, Bosa and Ciudad Bolivar, whereas the lowest values are those of Barrios Unidos, Chapinero and Teusaquillo. High values of the greater physical risk index, in addition to Candelaria, are the localities of Usaquén, Barrios Unidos and Teusaquillo, whereas the physical risk index is less in Ciudad Kennedy and Tunjuelito. The greater values of total risk index appear in the localities of Candelaria, Usaquen, Santafé and Barrios Unidos, and the smaller values are those of Ciudad Kennedy, Fontibón and Tunjuelito.

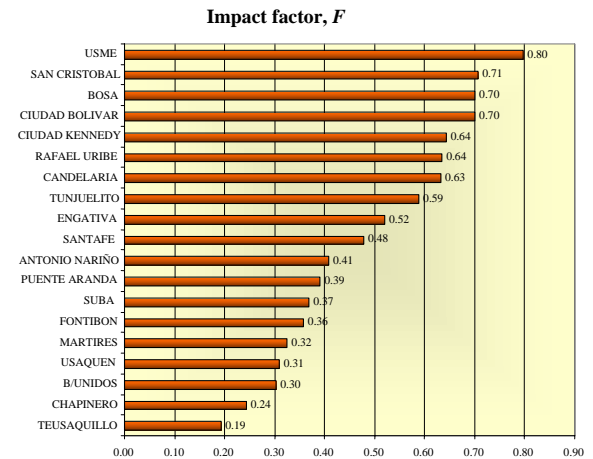Fig. 9. Total risk index, R_T, for the localities of Bogotá

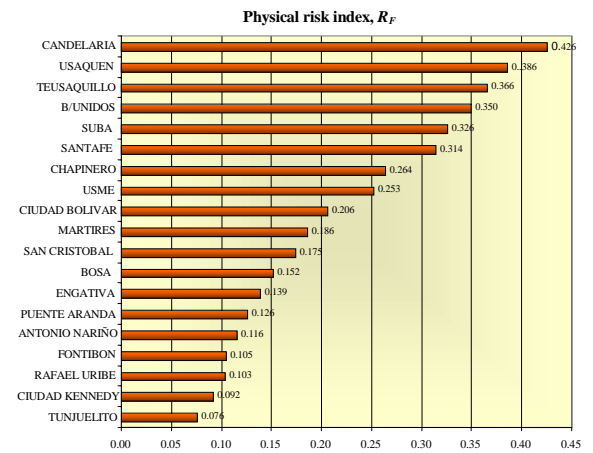Fig. 8. Physical risk index, R_F, for the localities of Bogotá

Fig. 10. Physical risk index for the localities of Bogotá, in descendent order
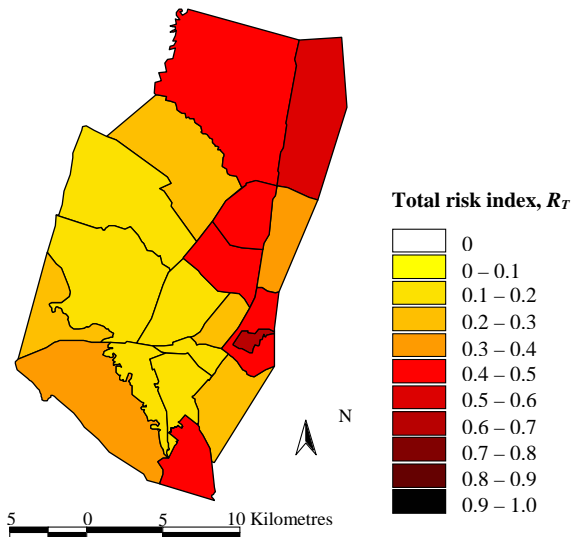
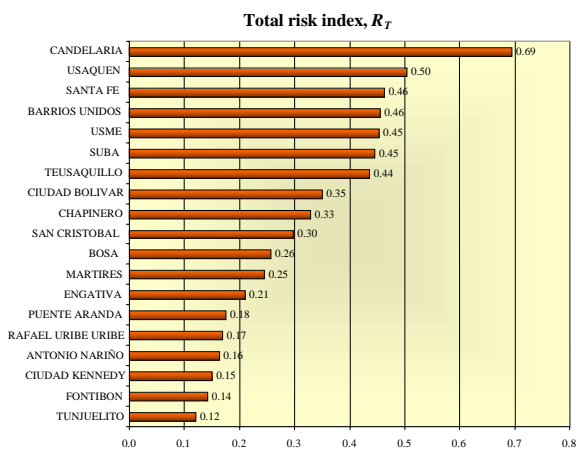Fig. 11. Impact factor for the localities of Bogotá, in descendent order

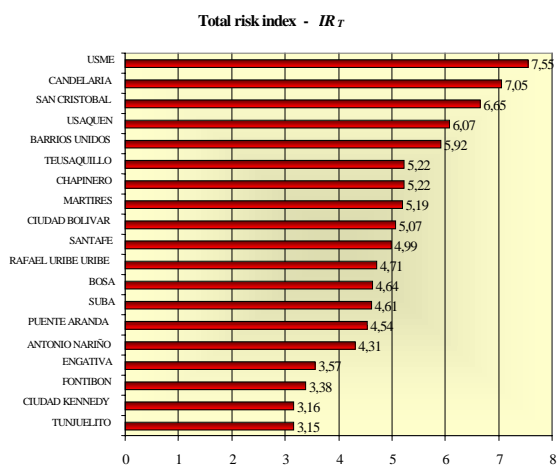Fig. 12. Total risk index for the localities of Bogotá, in descendent order

Fig. 13. Total risk index for the localities of Bogotá, obtained with the Cardona's model

EXAMPLE OF APPLICATION: SEISMIC RISK OF BARCELONA

The city of Barcelona, Spain, is subdivided in ten districts (see Figure 14), 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 (ICC/CIMNE, 2004). 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.

Table 11 presents examples of the physical risk factors obtained by physical risk descriptors for the 248 ZRP. Table 12 displays the aggravating factors obtained by applying the transformation functions to values for descriptors of social fragility and lack of resilience. In addition, Table 14, at the bottom, shows the average values of the factors for the city, normalised using the density of population. Table 13 presents some examples of the final results of the physical risk index, the impact factor and total risk index for each ZRP zone. The weights are the same as those used in Bogotá (tables 4 and 5).
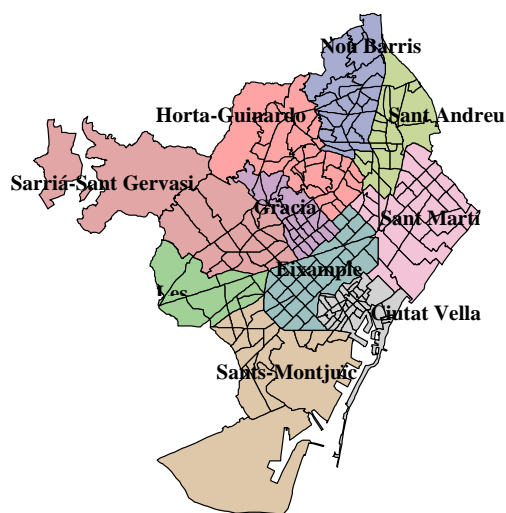

Fig. 14. Territorial division of Barcelona

Figures 15 to 17 show the results for the physical risk index, the impact factor and the total risk index for Barcelona using the model proposed above.
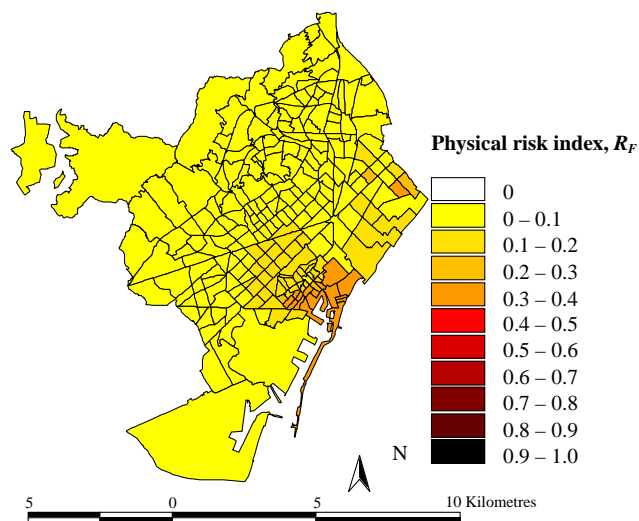

Fig. 15. Physical risk index for Barcelona, using the 248 small statistical zones (ZRP)
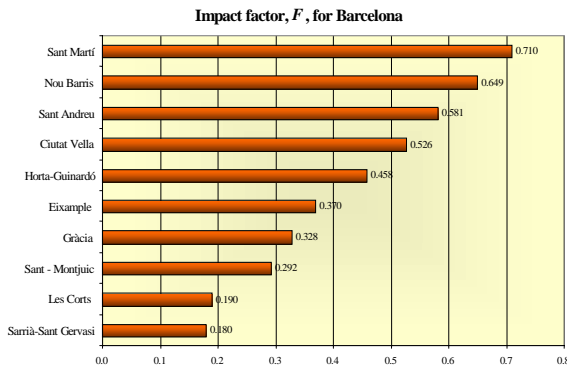
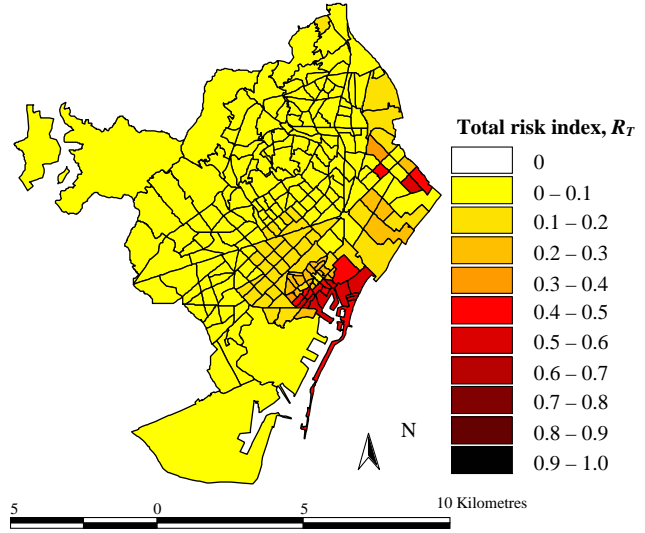Fig. 16. Impact factor for the districts of Barcelona

Fig. 17. Total risk index for Barcelona, using the 248 small statistical zones (ZRP)

TABLE 11: Factors and physical risk index, R_F, for Barcelona

ZRP	F_{RF1}	F_{RF2}	F_{RF3}	F_{RF4}	F_{RF5}	F_{RF6}	F_{RF7}	F_{RF8}	F_{RF9}	R_F
001	0.952	0.0288	0.0512	0.02	0.02	0.02	0.17	0.32	0.025	0.306
002	0.999	0.08	0.157	0.02	0.02	0.02	0.17	0.32	0	0.331
003	1	0.0648	0.128	0.02	0.02	0.02	0.17	0.32	0	0.328
004	1	0.0288	0.0512	0.02	0.02	0.02	0.17	0.32	0.2	0.336
...	...	...	...	...	...	...	...	...	...	...
245	0.353	0.205	0.411	0.02	0.02	0.02	0.17	0.32	0	0.183
246	0.0544	0.0392	0.08	0.02	0.02	0.02	0.17	0.32	0.025	0.054
247	0.0544	0.0512	0.115	0.02	0.02	0.02	0.17	0.32	0.025	0.058
248	0.12	0.0648	0.142	0.02	0.02	0.02	0.17	0.32	0	0.078
Barcelona	*0.152*	*0.017*	*0.033*	*0.020*	*0.020*	*0.020*	*0.170*	*0.320*	*0.031*	*0.076*

TABLE 12: Impact factor, F, computed with aggravating factors of social fragility, F_{FS}, and lack of resilience, F_{FR} for Barcelona

District	F_{FS1}	F_{FS2}	F_{FS3}	F_{FS4}	F_{FS5}	F_{FR1}	F_{FR2}	F_{FR3}	F_{FR4}	F_{FR5}	F
Ciutat Vella	0.255	0.00061	0.0452	1	0.342	0.964	0.858	0.461	0.383	1	0.5259
Eixample	0	0.00061	0.000111	0.633	0.471	0.925	0.68	0.993	0.0801	0.3	0.3698
Sant - Montjuic	0	0.000347	0.000612	0.633	0.0364	1	1	0.0806	0.461	0.3	0.2920
Les Corts	0	0.000123	0	0.0408	0.461	0.755	0.222	0.893	0.0801	0	0.1905
Sarrià-Sant Gervasi	0	0.00026	0	0	0.265	0.769	0.222	0.991	0.889	0	0.1799
Gràcia	0	0.000542	0	0.163	0.678	0.894	0.564	0.949	0.589	0.3	0.3284
Horta-Guinardó	0.0102	0.00026	0	1	0.947	0.436	0	0	0.589	0.6	0.4579
Nou Barris	0.0918	0.00026	0	1	1	1	1	0.889	0.578	1	0.6493
Sant Andreu	0.0102	0.000215	0	1	0.882	0.997	0.991	0.99	0.578	0.6	0.5810
Sant Martí	0.5	0.000237	0	1	0.84	1	1	0.943	0.955	1	0.7099
Barcelona	*0.10*	*0.00033*	*0.00352*	*0.72*	*0.69*	*0.87*	*0.66*	*0.75*	*0.54*	*0.58*	*0.47*

TABLE 13: Seismic total risk of Barcelona

ZRP	R_F	F	R_T
001	0.306	0.526	0.467
002	0.331	0.526	0.506
003	0.328	0.526	0.500
004	0.336	0.526	0.513
...	...	...	...
245	0.183	0.710	0.313
246	0.054	0.710	0.092
247	0.058	0.710	0.100
248	0.078	0.710	0.134
Barcelona	*0.0759*	*0.47*	*0.115*

COMPARISON AND DISCUSSION OF THE RESULTS

The results obtained for Bogotá have been compared with those obtained for Barcelona. Table 14 shows the average risk values for both cities. Bogotá is located in a zone with intermediate seismic hazard, whereas Barcelona is located in a zone with low to moderate seismic hazard. The average values obtained for the physical risk index, R_F, reflect this situation. It is interesting to remark that the results obtained for the impact factor, F, are not so different for both cities. The lowest values of this impact factor are similar (0.193 for the locality of Teusaquillo in Bogotá and 0.1799 for the district of Sarrià in Barcelona). The difference between the highest values in the two cities is more noticeable (0.797 for the locality of Usme in Bogotá and 0.7099 for the district of Sant Marti in Barcelona). The methodology allows performing the future comparison among other different cities worldwide. This new approach permits a unified holistic evaluation of risk.

TABLE 14: Comparison of the mean values between Bogotá and Barcelona

Index	Bogotá.	Barcelona
Physical risk, R_F	0.225	0.0759
Impact factor, F	0.663	0.47
Total risk, R_T	0.374	0.1150

CONCLUSIONS

Risk estimation requires a multidisciplinary approach that takes into account not only the expected physical damage, the number and type of casualties or economic losses, but also other social, organizational and institutional factors related to the development of communities that contribute to the creation of risk. At the urban level, for example, vulnerability seen as an internal risk factor should be related not only to the level of exposure or the physical susceptibility of the buildings and infrastructure material elements potentially affected, but also to the social fragility and the lack of resilience of the exposed community. The absence of institutional and community organization, weak preparedness for emergency response, political instability and the lack of economic health in a geographical area contribute to increased risk increasing. Therefore, the potential negative consequences are not only related to the impact of the hazardous event as such, but also to the capacity to absorb the impact and the control of its implications in a given geographical area.

For the modelling, a simplified but multidisciplinary representation of urban seismic risk has been suggested, based on the parametric use of variables that reflect aspects or factors of such risk. This parametric approach is not more than a model formulated in the most realistic possible form, 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 impact factor. 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.

This new model for holistic evaluation of risk facilitates the integrated risk management by the different stakeholders involved on risk reduction decision-making. It permits the follow-up of the risk situation and the effectiveness and efficiency of the prevention and mitigation measures can be easily achieved. Results can be verified and the mitigation priorities can be established as regards the prevention and planning actions to modify those conditions having a greater influence on risk in the city. Once the results have been expressed in graphs for each locality or district, it is easy to identify the most relevant aspects of the total risk index, with no need for further analysis and interpretation of results. Finally, this method allows to compare risk among different cities around the world and to perform a multi-hazard risk analysis.

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