Nat Hazards (2016) 80:1995–2021
DOI 10.1007/s11069-015-2056-4

ORIGINAL PAPER

Urban seismic risk index for Medellín, Colombia, based on probabilistic loss and casualties estimations

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Received: 12 April 2015 / Accepted: 16 October 2015 / Published online: 28 October 2015

Abstract Medellín is the second largest city of Colombia with more than 2 million inhabitants according to the latest census and with more than 240,000 public and private buildings. It is located on an intermediate seismic hazard area according to the seismic zonation of Colombia although no destructive earthquakes have occurred having as a consequence low seismic risk awareness among its inhabitants. Using the results of a fully probabilistic risk assessment of the city with a building by building resolution level and considering the dynamic soil response, average annual losses by sectors as well as casualties and other direct effects are obtained and aggregated at county level. Using the holistic evaluation module of the multi-hazard risk assessment CAPRA platform, *EvHo*, a comprehensive assessment that considered the social fragility and lack or resilience at county level is performed making use of a set of indicators with the objective of capturing

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the aggravating conditions of the initial physical impact. The urban seismic risk index, *USRi*, is obtained at county level which is useful to communicate risk to decision-makers and stakeholders besides making easy identifying potential zones that can be problematic in terms of several dimensions of the vulnerability. This case study is an example of how a multidisciplinary research on disaster risk reduction helps to show how risk analysis can be of high relevance for decision-making processes in disaster risk management.

Keywords Urban seismic risk index · Urban resilience · Holistic risk assessment · Probabilistic seismic risk analysis · CAPRA

1 Introduction

Several probabilistic seismic risk analyses have been conducted worldwide at different resolution levels and with different objectives, estimating the physical damage in terms of mean damage ratios (MDR), average annual losses (AAL) and probable maximum losses (PML) (Ordaz et al. 2000; Barbat et al. 2010; Lantada et al. 2010; Salgado-Gálvez et al. 2013, 2014a, 2015a, Zuloaga et al. 2013; Marulanda et al. 2013; IBRD and The World Bank 2013; Cardona et al. 2014; Silva et al. 2014; Ahmad et al. 2014). Quantifying risk from a physical point of view, although important, is only the first step in a comprehensive disaster risk management scheme (Cardona et al. 2008a, b; Cardona 2009; Marulanda et al. 2014) after which, it is important to further use those results in disaster risk management-related strategies. It is clear that the physical is not the only dimension and hence those results can be used as input data for a comprehensive, holistic, risk analysis (Cardona 2001; Carreño 2006; Carreño et al. 2007, 2012, 2014). A holistic approach has also been included in the MOVE framework (Birkmann et al. 2013), one that outlines key factors and different dimensions to be addressed when assessing vulnerability in the context of natural hazards, as considered herein.

This paper presents the complete and final results of the urban seismic risk index, *USRi*, estimation for the city of Medellín, Colombia, based on a holistic approach for which a preliminary assessment had been previously conducted (Salgado-Gálvez et al. 2014b). Medellín is the second largest city in Colombia with more than 2.2 million inhabitants in the urban area and where many industries and financial facilities have their headquarters. The city is located on a valley on the east side of the western cordillera of the North Andean zone and lies on an intermediate seismic hazard zone where earthquakes associated with different active seismic faults can generate important damages and disruptions on its infrastructure (AIS 2010a, b; Salgado-Gálvez et al. 2010, 2014a, c, 2015b). The urban area of the city is divided into 16 counties (*comunas*), each of them with approximately the same area but with important differences from a social, economic and infrastructure perspective. During recent years, Medellín has experienced a rapid urban growth and transformation, and different areas of the city have changed in terms of building classes, population density and availability of public spaces since low-rise houses have been demolished to build high-rise structures to accommodate a larger amount of inhabitants, a process clearly identifiable in the medium–high and high income zones of the city.

A holistic risk assessment at urban level, which accounts for the vulnerability in several of its dimensions, requires a combination of the physical risk results with aspects that reflect social fragility and lack of resilience (Carreño et al. 2012). In this context, social fragility is measured by means of variables that contribute to a *soft* risk related to the potential consequences over the social context, trying to capture issues related to human welfare such as social integration, mental and physical health, both at an individual and community level (Cardona 2001). On the other hand, lack of resilience is related to deficiencies in coping with the disasters and in recovering from them; these latest also contribute to the *soft* risk or the second-order impact factor over exposed communities. Resilience is an adaptive ability of a socioecological system to cope and absorb negative impacts as a result of the capacity to anticipate, respond and recover from damaging events; therefore, it is important to know the lack of resilience since it has been proven to be an important factor of the overall vulnerability; these aspects are captured by means of a set of indicators (Cardona 2001; Carreño et al. 2007).

For this case study, all the physical risk indicators are obtained starting from damage and loss events that can be calculated by using fully probabilistic methodologies, such as the one of the CAPRA[1] platform, by convoluting hazard and vulnerability for the exposed elements (Cardona et al. 2010; 2012; Salgado-Gálvez et al. 2014a; Velásquez et al. 2014). For this study, the probabilistic physical risk results obtained by Salgado-Gálvez et al. (2014a) using CAPRA are complemented by estimating injured, deaths, homeless and unemployed on a building by building basis, also based on a fully probabilistic approach and grouping the results by counties.

The *USRi* is defined as a combination of a physical risk index, R_F, and an aggravating coefficient, F, in the following way: $USRi = R_{\mathrm{F}}\ (1 + F)$ where R_{F} and F are composite indicators (Carreño 2006; Carreño et al. 2007). R_F is obtained from the probabilistic risk results, while F is obtained from available data regarding political, institutional and community organization aspects which usually reflect weak emergency response, lack of compliance of existing codes, economic and political instability and other factors that contribute to the risk creation process (Carreño et al. 2007; Renn 2008). This approach has also been applied at different resolution levels (Daniell et al. 2010; Burton and Silva 2014) and has been integrated in toolkits, guidebooks and databases for earthquake risk assessment (Khazai et al. 2013, 2014, 2015; Burton et al. 2014). Since not always the same information in terms of indicators is available for the area under study, each assessment constitutes a challenge in the way that the descriptors are selected and in some cases calculated.

The multi-hazard risk assessment CAPRA platform holistic risk assessment module, *EvHo* (CIMNE-RAG 2014), has been used in this work, which is a tool that incorporates directly the output files of the physical risk estimation made using CAPRA-GIS (ERN-AL 2011), the probabilistic risk calculator module of the CAPRA platform. The module defines factors and their corresponding weights to calculate R_{F} and F; it also incorporates a procedure based on transformation functions, allowing the conversion of each factor into commensurable units and calculates the aggravating coefficient for each analysis area. The *USRi* is obtained at county level according to the flowchart of Fig. 1. All these computations are made possible by the modular characteristics of the CAPRA platform. Since risk analysis can be performed at different resolution levels, the tool allows the selection of the desired level, and if the risk has been calculated on a more detailed scale, it groups the results into the desired units.

For the social fragility (F_{FSi}) and lack of resilience (F_{FRj}) indexes, the user can define the number of factors and assign the weights to be used in each category; as in the case of the physical risk, the user can also select the transformation function in conjunction with

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[1] Comprehensive approach to probabilistic risk assessment (www.ecapra.org).

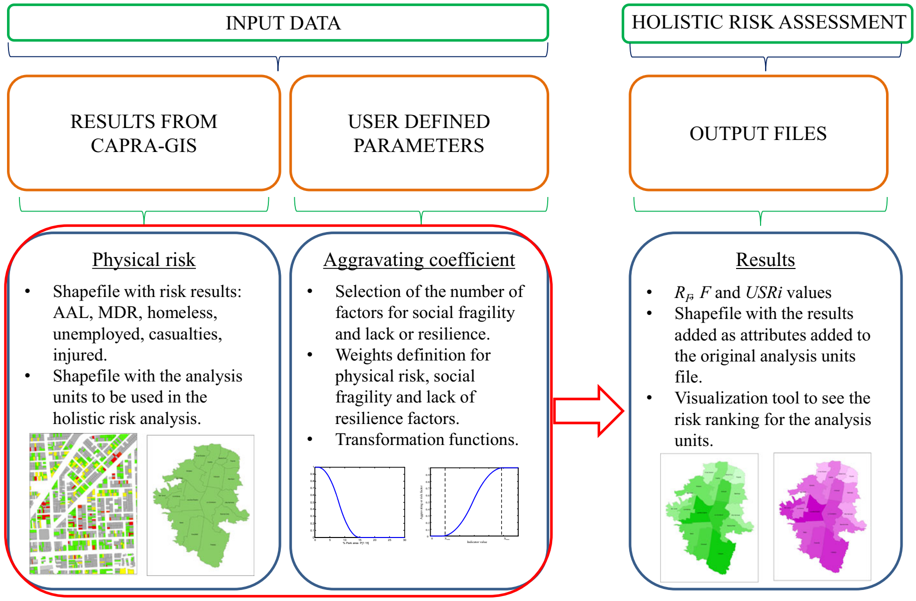

Fig. 1 CAPRA's holistic risk assessment module flowchart

the correspondent minimum and maximum limits for each factor. Once the above-mentioned parameters are defined by the user, the urban seismic risk index (*USRi*) is calculated for the selected resolution level and results can be exported into tables, charts and maps in *shapefile* format.

The whole process is performed within a framework in which uncertainties related to the physical damage and loss assessment are also considered by using probabilistic methodologies. Scientific uncertainties become philosophical uncertainties since there will be an impact on society when a decision is made; thus, it is important to know where they are and how they have been considered or not (Caers 2011), and since the objective of this kind of assessments is to derive in actions related to risk reduction, this aspect is worth to be at hand.

Obtaining risk results from a holistic perspective highlights the socioeconomic factors that contribute most to the aggravating coefficient, *F*, and they should help stakeholders and policy makers in the integral disaster risk management. Measuring risk with the same methodology in all counties of an urban area like Medellín allows a direct and appropriate comparison of the obtained results, and it can help in prioritizing the areas for developing disaster risk reduction and management strategies. Also, the final result can be disaggregated and the main risk drivers after the holistic risk assessment can be highlighted; and in this stage of the study, after complementing the preliminary results obtained by Salgado-Gálvez et al. (2014a), for the first time this procedure is performed and shown for the county with the highest *USRi* to clearly present which are the descriptors that are contributing the most in each of the indexes (physical risk, social fragility and lack of resilience), and then, the results are a useful basis for the development of specific strategies to improve their performance in their corresponding fields of action.

Holistic evaluations of seismic risk at urban level have been performed in recent years for different cities worldwide (Carreño et al. 2007; Marulanda et al. 2013) as well as at country level (Burton and Silva 2014) and have proven to be a useful way to evaluate, compare and communicate risk while promoting effective actions towards the intervention of vulnerability conditions measured at its different dimensions. Although at first it can be seen simply as another case study based on a well-known methodology, on the one hand, this study incorporates a set of probabilistic descriptors in the side of the physical risk that had never been assessed in Medellín, while, on the other hand, since the main purpose is to raise risk awareness, and not a generally agreed practice on a holistic risk assessment framework exists, the development of case studies that consider different methodologies (Brink and Davidson 2014) to obtain the input data can serve as examples for future comparisons of the approaches.

This is the first time that a study following the above-mentioned methodology is conducted with a high resolution in all the aspects (seismic hazard, exposure and socioeconomic descriptors) and the results are useful to identify risk driver factors that are not associated only with the physical vulnerability of the dwellings but also with social and poverty factors that should be examined and tackled in an integral way, stressing out that poverty is not necessarily the same as vulnerability. The importance of risk analysis has been understood at different decision-making levels, but the need of being incorporated as a development issue by governments is still on its way. Finally, it also constitutes an example of how an integrated research on disaster risk reduction can reduce the gap between the risk analysis and its relevance for risk management decision-making processes (Salgado-Gálvez et al. 2014b).

2 Probabilistic physical seismic risk and direct impact assessment

The seismic risk analysis from a holistic perspective requires the calculation of a set of factors that are related to the direct effects of the hazardous events on the exposed elements and to the consequences in terms of the possibility of occupying the buildings after the city has been struck by an earthquake. The first factor corresponds to the AAL by sector, where four different categories are included (residential, commercial, institutional and industrial). The other factors are related to the expected number of deaths, injuries, homeless and unemployed. This section presents the methodology followed for the calculation of these factors.

2.1 Physical seismic risk analysis methodology

For a fully probabilistic seismic risk analysis, different input data for the hazard, exposure and physical vulnerability are required. Seismic hazard is represented by means of a set of stochastic events generated using the program CRISIS 2007 (Ordaz et al. 2007), which is the seismic hazard module of CAPRA; each event associated with the different seismogenetic sources identified at country level (AIS 1996, 2010; Paris et al. 2000; Taboada et al. 2000; Pulido 2003; Salgado-Gálvez et al. 2010, 2015b); for each event, hazard intensities in terms of their first two statistical moments are obtained for different spectral ordinates to take into account the fact that structures with different dynamic characteristics have different earthquake solicitations for the same event. Since the city also has a seismic microzonation (SIMPAD et al. 1999), it has been considered in the analysis by determining spectral transfer functions for each homogeneous soil zone in order to calculate the hazard intensities at ground level. The exposure database consists of the portfolio of buildings, both public and private, and is comprised by 241,876 elements (Alcaldía de Medellín 2010) that have been identified, characterized and associated with a building class. Physical vulnerability is represented by means of vulnerability functions that allow both a continuous and probabilistic representation of the loss associated with different hazard intensities, in this case corresponding to the spectral acceleration for 5 % damping, an intensity measure that correlates well with the seismic performance of structures (Luco and Cornell 2007). More details about the employed methodology and information for the physical risk analysis can be found in Salgado-Gálvez et al. (2014a).

Since all input data have been represented using a probabilistic approach, the loss calculation process can follow the methodology proposed by Ordaz (2000) and that is used in the CAPRA platform, where a convolution between the hazard and vulnerability of the exposed elements is performed. The main output of these assessments is the loss exceedance curve (LEC) which relates loss values in monetary units, with their annual exceedance rates. The LEC is calculated using the following expression:

$$v(l) = \sum_{i=1}^{N} \Pr(L > l|Event_{\mathrm{i}}) \cdot F_A(Event_{\mathrm{i}}) \tag{1}$$

where $v(l)$ is the rate of exceedance of loss l, N is the total number of earthquake events that comprise the stochastic set and conform with the seismic hazard in the area under analysis, F_A $(Event_{\mathrm{i}})$ is the annual frequency of occurrence of the ith earthquake event, while $\Pr(L > l|Event_{\mathrm{i}})$ is the probability of exceeding l, given that the ith event occurred. The sum of the equation includes all potentially damaging events from the stochastic set. The inverse value of $v(l)$ is the return period of the loss l, denoted as Tr. Once the LEC is obtained, other risk metrics such as the AAL can be obtained by calculating the area under the LEC. This metric constitutes the first physical risk factor required to be determined for the study presented herein. AAL can also be directly computed, leading to exactly the same value using the following expression:

$$\mathrm{AAL} = \sum_{i=1}^{N} E(L|\mathrm{Event}_i) \cdot F_{\mathrm{A}}(\mathrm{Event}_i) \tag{2}$$

where $E(L|\mathrm{Event}_i)$ is the expected loss value given the occurrence of the ith event and $F_{\mathrm{A}}(\mathrm{Event}_i)$ is the associated annual occurrence frequency of the same event. AAL constitutes a robust indicator since it can represent risk at different resolution levels and also captures the participation on the overall risk of the small and frequent events as well as the high and low frequency events while also being insensitive to uncertainty as is explained later (Ordaz 2000).

Uncertainties related to hazard and physical vulnerability, defined according to their characteristics (temporal and spatial for the hazard and intensity-dependent for the vulnerability), are considered in the loss assessment; thus the result of the calculation process is a specific loss probability distribution for each hazard event. In the case of risk results in terms of losses, a Beta distribution is defined through a central value (mean) and its dispersion or uncertainty measure (variance). The latter is considered an appropriate probability distribution for modelling losses since results are always defined between 0.0 (no loss) and 1.0 (total loss), and since only direct losses are considered at this stage, the maximum possible loss is then the total exposed value.

2.2 Physical risk results for Medellín

Physical risk is calculated on a building by building resolution level, and the obtained results are grouped by counties according to the location of each dwelling. It is well known that for the calculation of the AAL an arithmetical aggregation process can be applied to both counties and sectors. Table 1 shows the values in relative terms to the total exposed value by county and by sector in Medellín. Blank values (–) correspond to sectors that are not representative in the corresponding county. AAL seeks to give an overall and comprehensive representation of the risk levels, through a robust indicator and not only by loss values for earthquake events. AAL is calculated considering the participation of all the events, by multiplying the expected loss by its annual occurrence frequency, for each event. The AAL, when calculated by means of Eq. 2, cannot have associated any uncertainty measure because it represents the loss results in annualized terms which, on the other hand, represent a mathematical expectation, not an uncertainty measure.

2.3 Death, injured, homeless and unemployed estimation for Medellín

A fully probabilistic risk analysis is normally conducted for the complete set of hazardous events that comprise the hazard representation. However, for the purpose of estimating death, injured, homeless and unemployed, this study has been conducted for a single event where only one event is considered as N in Eq. 1. By setting the annual frequency of occurrence of the selected one to 1.0, Eq. 1 will provide the probability of occurrence of the loss given the occurrence of the selected event, and not the annual frequencies of occurrence. Though the annual frequency of occurrence of it has been set equal to 1.0, and it represents a deterministic approach for the temporal probability of occurrence, hazard intensities are computed for the first two statistical moments representing the hazard uncertainties that, together with the vulnerability uncertainties, are included in the loss calculation process as explained above; therefore, the loss calculation is still probabilistic.

The event was chosen out of the more than 2500 included in the stochastic set with the selection criteria of that event generating a direct economic loss of similar order of magnitude than that of a 500-year mean return period. That value is read from the LEC shown in Fig. 2, and that return period is considered of relevance for the design of emergency plans in Colombia (SDPAE 2002). It is important to bear in mind that the return period of the loss is different from the return period of the seismic event since, in this case, there is correlation in the losses and uncertainties in the ground motion and physical vulnerability values (Bazzurro and Luco 2005; Bommer and Crowley 2006; Park et al. 2007; Crowley et al. 2008; Salgado-Gálvez et al. 2014a). The expected loss for the selected return period obtained from the LEC is estimated in around 12 billion USD[2] which represents about 14 % of the total exposed value. Loss exceedance rates are calculated by using the total probability theorem and because of that, for any loss level, the exceedance rate is calculated as the sum of all the events with probability of exceeding said loss level. In this case, the uncertainty is being considered in the calculation of the exceedance probabilities and then, the annual exceedance rates obtained cannot have associated an uncertainty measure because they are probabilities calculated for a specific loss value.

Three different sets of vulnerability functions were used to calculate the required factors. The first set corresponds to the physical vulnerability functions to calculate the mean damage ratio (MDR) for each element which captures the distribution of damage values in

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[2] An exchange rate of 1USD = 3,000COP has been used in this study.

Table 1 Relative AAL (‰) by county and by sector in Medellín

County	Sector			
	Commercial	Industrial	Institutional	Residential
1. Popular	2.95	–	–	2.65
2. Santa Cruz	1.26	–	–	1.59
3. Manrique	2.79	–	3.11	2.67
4. Aranjuez	1.51	–	1.43	1.53
5. Castilla	2.57	2.75	2.94	2.81
6. Doce de Octubre	3.25	–	–	3.39
7. Robledo	1.93	–	2.20	2.21
8. Villa Hermosa	6.68	–	–	5.89
9. Buenos Aires	6.03	–	–	5.70
10. La Candelaria	3.68	3.70	3.76	3.41
11. Laureles-Estadio	3.72	–	3.27	3.55
12. La América	4.42	–	–	4.66
13. San Javier	3.22	–	–	2.93
14. Poblado	5.12	4.67	–	4.85
15. Guayabal	3.80	3.38	–	3.40
16. Belén	3.30	–	3.59	3.49

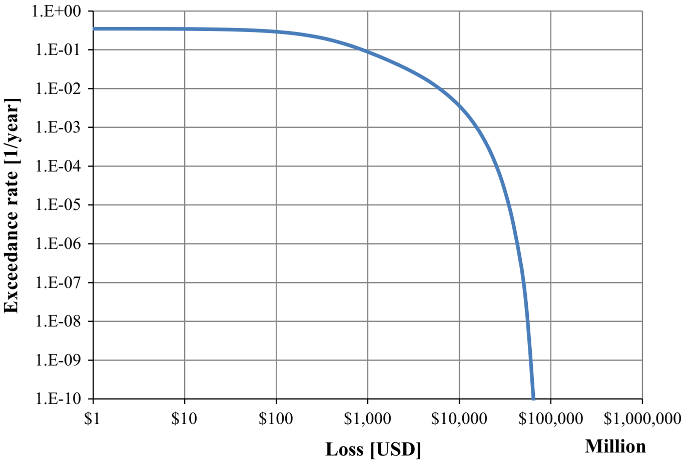

Fig. 2 LEC for the portfolio of buildings of Medellín (Salgado-Gálvez et al. 2014a)

each building class given a seismic intensity. If this parameter has a value higher than 20 %, the building is considered to be unsafe to be occupied and thus, depending on its use, its occupants are considered either homeless or unemployed. The second and third sets of functions have to do with the deaths and injured estimation and depend on the building class.

For the estimation of deaths and injuries, fatality rates proposed by Jaiswal et al. (2011) were selected and also, a workday scenario is assumed. Given that occupation is a dynamic parameter and the day and time of the earthquake cannot be established with this approach, a rate of 60 % occupancy, which corresponds to an average occupation according to Liel and Deierlein (2012), was used for the calculation, as previously chosen in Salgado-Gálvez et al. (2015c).

The selected seismic event is associated with the Romeral Fault System which is the one that controls the seismic hazard level for medium and long return periods in Medellín (AIS 2010). Table 2 shows the characteristics of the selected event in terms of location, depth and magnitude.

Table 3 shows the estimated direct impact results of the selected event in terms of economic loss, deaths and injuries as well as homeless and unemployed, while Fig. 3 shows the shakemap in terms of the peak ground acceleration (PGA), at bedrock level, of the selected event in the area of analysis. That value was modified through the transfer functions to account for the local dynamic soil response. Figure 4 shows the MDR distribution for Medellín.

From the obtained results, it can be seen that the highest MDR occurs in *Villa Hermosa* County which is located on the eastern part of the city where the high structural vulnerability is due to the large number of masonry units combined with the amplification factors in the short period range given the soil characteristics of the city (SIMPAD et al. 1999). Though *Aranjuez* County has a significant participation of masonry dwellings, because of local soil response characteristics, far less damage and losses are observed for this event. More details about the characteristics of the assets as well as the assigned vulnerability functions are given by Salgado-Gálvez et al. (2014a). To better understand the building stock distribution along the city, Table 4 shows the percentage of building classes and the total number of dwellings by County.

Figure 5 shows the homeless estimation, while Fig. 6 shows the unemployed estimation, both at county level.

Figures 7 and 8 show the expected deaths and injuries estimation due to the occurrence of this event where results have been grouped again at county level and per hundred thousand inhabitants.

It can be observed from these results that homelessness and unemployment estimations are higher for *Villa Hermosa*, *La América*, *Belén*, *Guayabal* and *Manrique* counties, while higher death rates due to the occurrence of an event with those characteristics are expected in *Poblado* and *Laureles Estadio* counties. Even though these two counties have the highest income levels, they have high human density indexes and high-rise buildings with similar characteristics that are more vulnerable, from the deaths and injuries point of view, if compared with low-rise masonry units.

3 Holistic seismic risk assessment of Medellín

A comprehensive risk management strategy has to be based on a multidisciplinary approach that takes into account not only the physical damage and the direct impact but also a set of socioeconomic factors that favour the second-order effects and consider the intangible impact in case an earthquake event strikes the city (Cardona and Hurtado 2000; Benson 2003; Cannon 2003; Cutter et al. 2003; Davis 2003; Carreño et al. 2007, 2014; Barbat et al. 2010; Khazai et al. 2014). This can be achieved by using a holistic seismic risk

Table 2 General characteristics of the selected event

Longitude	−75.69°
Latitude	6.24°
Depth	12 km
Magnitude	6.9
Mean return period	306 years

Table 3 Result of the direct losses for the selected event

Seismogenetic source	Romeral Fault System
Expected loss (million USD)	10,963
Deaths	51,780
Injuries	68,165
Homeless	177,671
Unemployed	37,547

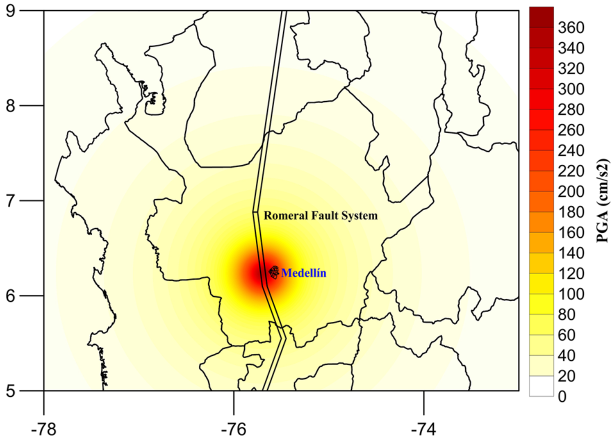

Fig. 3 Shakemap for PGA of the selected event (cm/s^2) at bedrock level

assessment where physical damages are aggravated by a set of socioeconomic conditions allowing comprehensive risk evaluations that are useful for decision-making processes. This approach also allows quantifying the resilience of the analysed communities, that is, their capacity to cope with the negative effects after the occurrence of an earthquake. Detailed information about this methodology can be found in Carreño (2006), Carreño et al. (2007) and Barbat et al. (2011).

The methodology used in this study does not require the use of the exact same factors in each case study, not even in terms of the number of descriptors used, as long as the characteristics to be captured are well reflected by the ones that are chosen. The explanation is that, depending on prevalent conditions of the area under analysis, some factors can be more relevant than others. For this study, physical damage is obtained from the results of the probabilistic approach, already shown in Sect. 2, which is considered to have a higher robustness if compared with previous holistic seismic risk evaluations performed

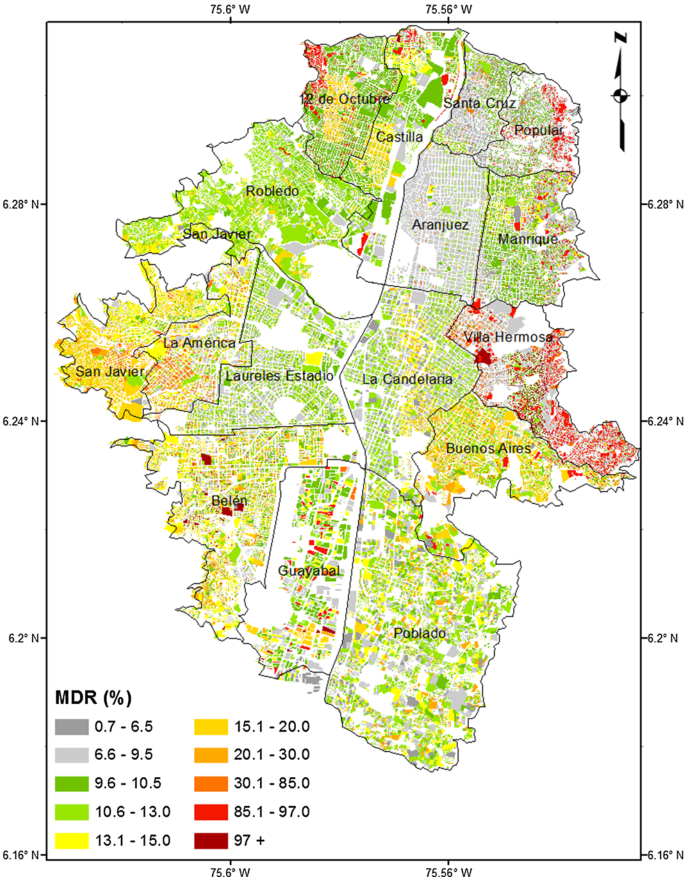

Fig. 4 MDR (%) estimation for the portfolio of buildings in Medellín

before because of the available information and its quality (Carreño et al. 2007; Marulanda et al. 2013).

As it was mentioned before, holistic seismic risk analysis can be performed at different scales but also can account for multi-hazard approaches (Jaramillo 2014). For this study, the resolution level has been set to counties and the hazard limited to earthquakes since this is the only catastrophic peril expected for the city.

3.1 Methodology for the holistic risk assessment

Applying the holistic risk evaluation methodology proposed by Cardona (2001) and Carreño et al. (2007), the urban seismic risk index *USRi* is calculated starting from a physical risk index, R_F, and an aggravating coefficient, F, which accounts for the socioeconomic fragility and lack of resilience of the analysis area. *USRi* is calculated by using the equation

$$USRi = R_{\mathrm{F}}(1 + F) \tag{3}$$

Table 4 Building class distribution by county

County	Building class (%)						Number of dwellings
	Masonry units	Wooden units	Steel units	Reinforced concrete frames units	Reinforced concrete shear wall units	Non-engineered units	
1. Popular	40.1	30.1	–	–	–	29.8	16,629
2. Santa Cruz	65.5	29.7	–	–	–	4.9	13,016
3. Manrique	85.0	–	–	15.0	–	–	21,037
4. Aranjuez	69.4	–	–	30.6	–	–	18,708
5. Castilla	90.0	–	–	10.0	–	–	12,597
6. Doce de Octubre	84.8	15.2	–	–	–	–	19,909
7. Robledo	80.1	10.1	–	9.7	–	–	20,674
8. Villa Hermosa	95.0	–	–	5.0	–	–	21,819
9. Buenos Aires	89.9	–	–	10.1	–	–	17,549
10. La Candelaria	49.9	–	0.1	35.3	–	–	11,274
11. Laureles Estadio	29.8	–	0.1	65.1	–	–	9832
12. La América	90.0	–	–	10.0	–	–	8868
13. San Javier	80.2	10.2	–	9.6	–	–	18,599
14. Poblado	20.2	–	0.1	25.0	44.7	–	8747
15. Guayabal	36.2	–	0.4	24.4	–	–	668
16. Belén	85.0	–	–	15.0	–	–	21,950

known in the literature as *Moncho's Equation* (Carreño et al. 2007). The physical risk index, R_F, is calculated considering a set of factors as well as their associated weights by means of the following expression:

$$R_F = \sum_{i=1}^{p} F_{RFi} \cdot w_{RFi} \tag{4}$$

where F_{RFi} are the p physical risk factors and w_{RFi} their corresponding weights. In this case, 8 factors were considered to obtain R_F which were calculated from the results of the probabilistic seismic risk analysis of the buildings in Medellín described in Sect. 2, in which both their structural characteristics and their mean occupation values were considered.

The aggravating coefficient, F, is calculated as follows:

$$F = \sum_{i=1}^{m} F_{FSi} \cdot w_{FSi} + \sum_{j=1}^{n} F_{FRj} \cdot w_{FRj} \tag{5}$$

where F_{FSi} and F_{FRj} are the aggravating factors, w_{FSi} and w_{FRj} are the associated weights of each i and j factor, and m and n are the total number of factors for social fragility and lack of resilience, respectively. For this case, 9 descriptors were used to capture the social fragility conditions on each county, while 6 descriptors are considered to capture the lack of resilience. Most of the descriptors were obtained using data from the local authorities (Alcaldía de Medellín 2012a, b; Proantioquia et al. 2012; DAP 2012) with the exception of

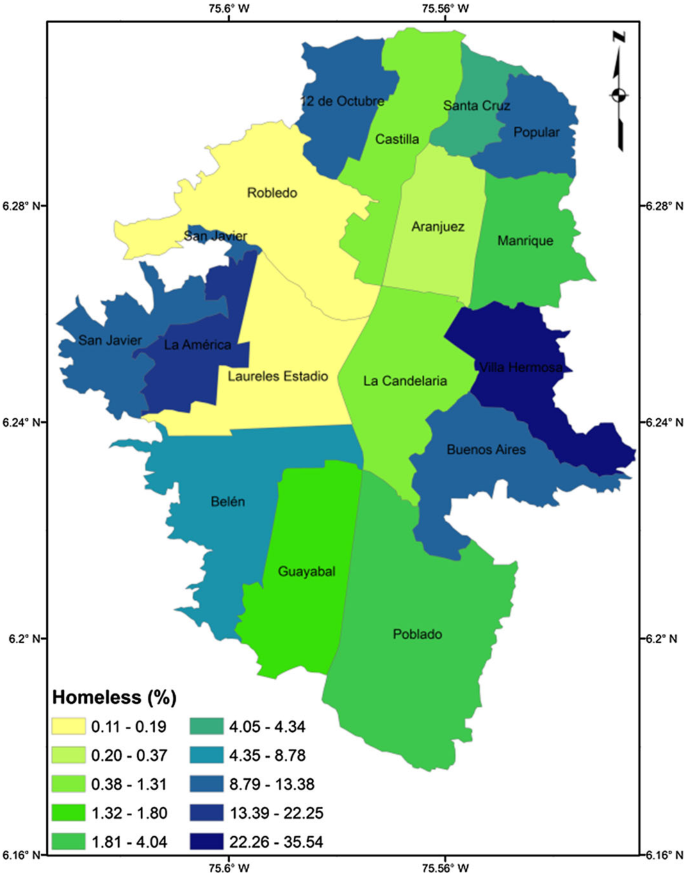

Fig. 5 Homeless estimation for Medellín

the calculation of public areas and distances to the closest hospitals and health centres, where geographical information system (GIS) tools were used. Figure 9 shows the summary of the descriptors used in this analysis where the ones denoted as F_{RFi} are related to the physical risk index, the ones denoted as F_{FSi} are related to the social fragility and the ones denoted as F_{FR1} are related to the lack of resilience.

The selection of the descriptors for R_{F} was based on the outcomes that could be extracted from the fully probabilistic seismic risk analysis, while existing and available indicators that capture social fragility and lack of resilience issues were selected for the evaluation of F.

It is evident that each of the factors used in the calculation of the *USRi* captures different aspects and is quantified in different units. Because of that, certain scaling procedures are needed to standardize the values of each descriptor and convert them into commensurable factors. In this case, transformation functions were used to standardize the physical risk, social fragility and lack of resilience factors selected for this study. Some of them are shown in Fig. 10. The factors and their units, as well as the [min, max] values, are shown on the abscissa and also, depending on the nature of the descriptor, the shape and characteristics of the functions vary and, because of that, for example functions related to

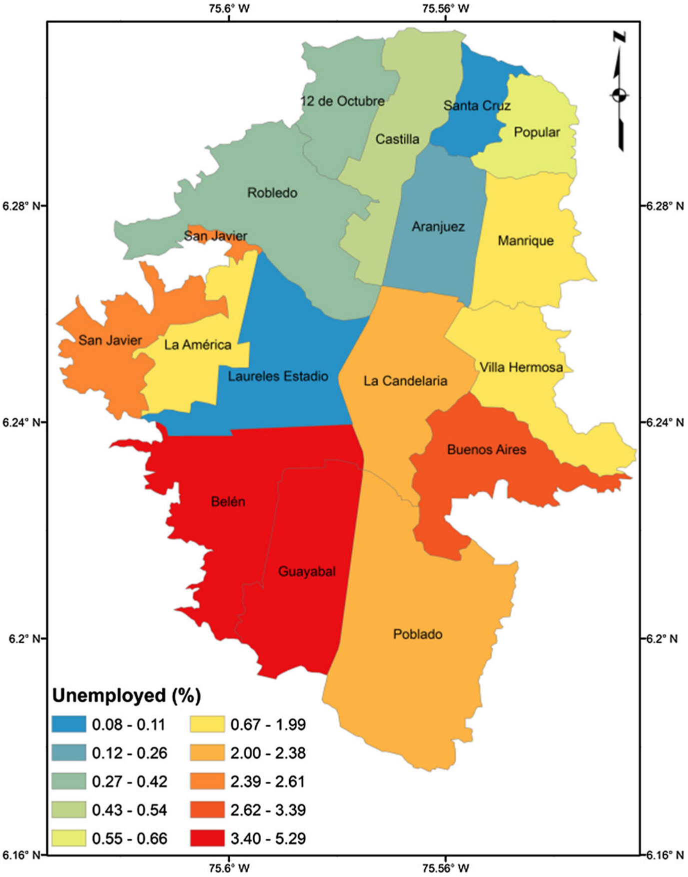

Fig. 6 Unemployed estimation for Medellín

descriptors of the physical risk have an increasing shape, while those related to resilience have a decreasing one; that is, the higher the value of the factors, the lower their aggravation. The transformation functions can be understood as risk and aggravating probability distribution functions or as the membership functions of the linguistic benchmarking of high risk or high aggravation.

The values on the abscissa of the transformation functions correspond to the values of the descriptors, while the ordinate corresponds to the final value of each factor, either related to the physical risk or to the aggravating factor. In all cases, values of the factor lie between 0 and 1. Since the transformation functions are membership functions, for high risk and aggravating coefficient levels, 0 corresponds to non-membership, while 1 means full membership. Limit values, denoted as X_{MIN} and X_{MAX} are defined by using expert criteria and information about previous disasters in the region. Relative weights w_{FSi} and w_{FRj} that associate the importance of each of the factors on the index calculation are obtained by using an analytic hierarchy process (AHP) that gives ratio scales from both discrete and continuous paired comparisons (Saaty and Vargas 1991; Carreño 2006; Carreño et al. 2012). AHP process was based on participation of local stakeholders and national disaster risk reduction and management experts for the definition of the weights of

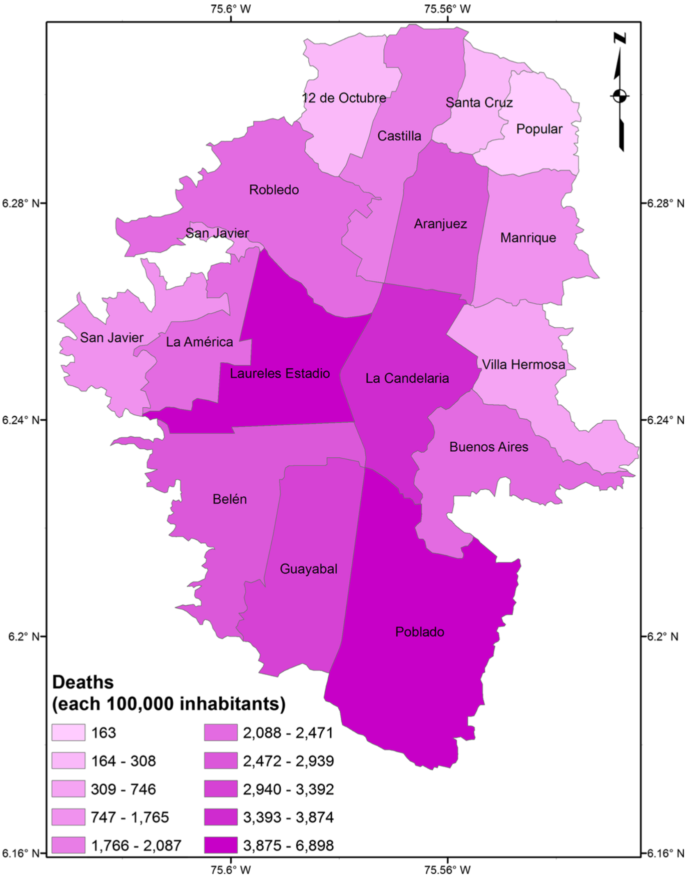

Fig. 7 Deaths estimation for Medellín

the aggravating coefficient factors, while, for the ones associated to the physical risk factors, besides the above-mentioned participants, the authors also participated.

Tables 5 and 6 present the associated weights for the physical risk and the aggravating coefficient factors.

3.2 Results of the holistic risk assessment for Medellín

This section presents the results obtained using the methodology in terms of R_F, F and *USRi*. Table 7 presents the results of this study for the 16 counties of Medellín sorted in descending order according to the *USRi* results.

Since the results have been obtained using a GIS tool, maps with the distribution of the results can be built and could be of help to decision-makers for communicative and comparison purposes among them. For each index, a ranking has been generated to classify each result into low, medium–low, medium–high, high and very high categories. Figure 11 shows the R_F at county level. The highest R_F values are found in *Villa Hermosa* and *Poblado*, while the lowest values are found in *Popular* and *Santa Cruz*. This is an interesting finding since the two lowest results correspond to low-income areas and can be

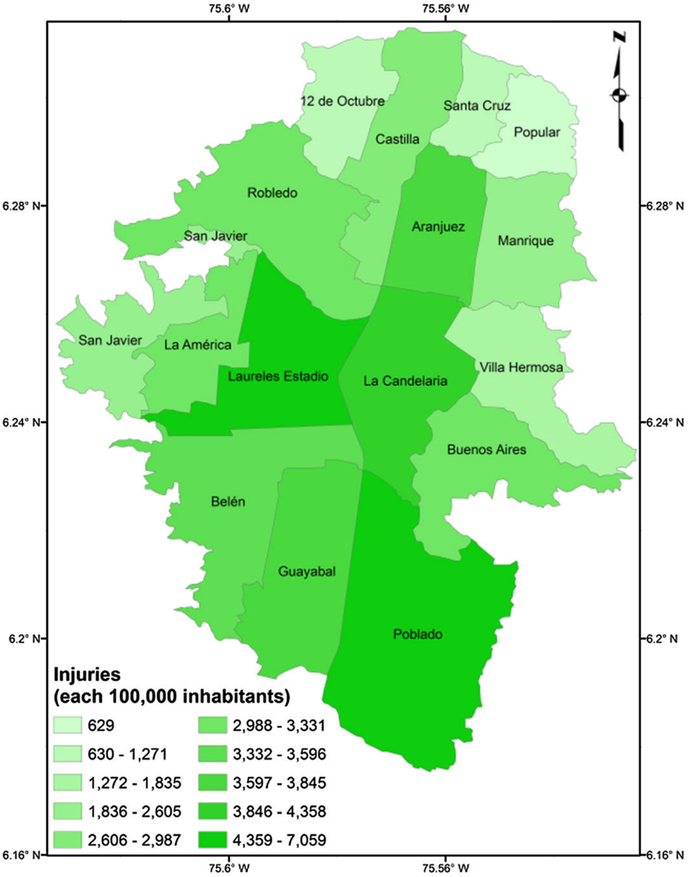

Fig. 8 Injuries estimation for Medellín

explained by the low injury and death rates associated with the building classes in these areas since they correspond to non-engineered systems, typically made from light materials, that do not represent, in general terms, harm to the inhabitants. Another finding of interest is that, even though *Poblado* has the best socioeconomic conditions, a disorganized urbanization process has been developed in the area and high-rise structures, not always complying with the requirements established by the Colombian earthquake-resistant building code, have been built. Its large R_{F} value is explained by the high physical vulnerability and the consequences in terms of expected deaths, injured and homeless in it. In terms of the categories used to aggregate the results, only *Villa Hermosa* has a high physical risk index category, while medium–high values are found at *Poblado*, *Laureles Estadio*, *La Candelaria*, *La América* and *Buenos Aires.*

In all counties, the descriptors that, after considering their relative weights, contribute the most to R_F are the ones that account for deaths and homeless. The estimation of these descriptors is directly related to the physical damage of the dwellings, and thus, a reduction on these descriptors can be achieved through the development of retrofitting schemes of at least essential buildings such as hospitals and schools, while also decreasing the physical vulnerability of new infrastructure by enforcement on the use of the earthquake building

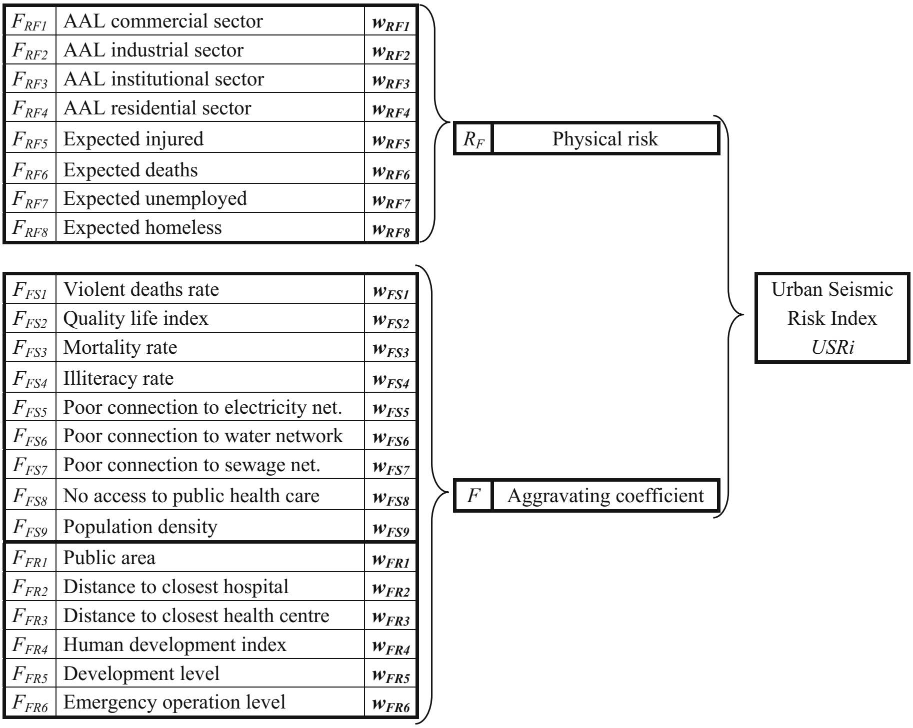

Fig. 9 Factors used for the holistic seismic risk evaluation in Medellín (adapted from Carreño et al. 2007)

code. Reducing the existing vulnerability is an ideal approach, but incentives to do so must be created, even more when seismic risk perception is low because of the low occurrence rate of earthquakes in Medellín.

Figure 12 shows the aggravating coefficient, F, at county level. The highest F is found at *San Javier* which constitutes a problematic area of the city from the social, urban planning and security perspective. Additionally, marginal areas, such as the ones that exist in *Villa Hermosa* and *Popular*, contribute to the large aggravating coefficients. Better characteristics can be found in *Laureles Estadio* and *Poblado* which are the wealthiest and more urban developed areas, though not necessarily organized, of Medellín. *Belén* constitutes an interesting case because, despite the fact that it does not have the best economic conditions, it presents a low aggravating coefficient because of the presence of several hospitals and medical centres.

From the results, the descriptors for social fragility and lack of resilience that most contribute to the aggravating coefficient, F, are the population density and the public area, respectively. These issues can be addressed by integrating the results with urban planning actions that can account for the improvement of today's conditions regarding those topics and need to be included in the development plans of the city. The population density captured here is not proportional to the casualties estimation performed for the estimation of R_F since the vulnerability functions vary from building class to building class and, as shown in Table 4, that distribution has significant variations along different areas of the city.

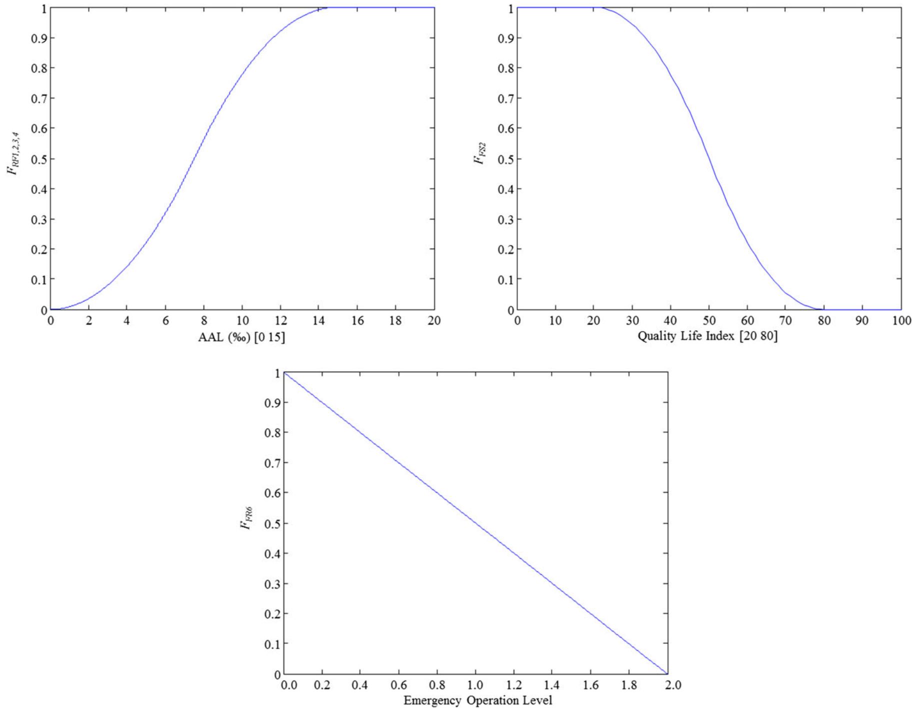

Fig. 10 Examples of transformation functions

Table 5 Weights for the physical risk factors

Factor	Weight
F_{RF1}	0.15
F_{RF2}	0.15
F_{RF3}	0.15
F_{RF4}	0.10
F_{RF5}	0.10
F_{RF6}	0.10
F_{RF7}	0.20
F_{RF8}	0.05

Figure 13 shows the *USRi* at county level. The highest *USRi* is found in *Villa Hermosa* followed by *Poblado* since a high R_F value is combined with an intermediate F, whereas important increases in the final results are observed in *La América*, *Laureles Estadio*, *Buenos Aires* and *La Candelaria,* reflecting the importance of accounting for socioeconomic characteristics, additional to the traditional physical seismic risk results. From here, it can be concluded that even if income levels are useful to determine the vulnerability of a certain area, from either the physical or social dimension, it is not the only driver that influences the final result. Finally, Fig. 14 shows the ranking in terms of the *USRi* to better understand the differences on the results between the counties.

Table 6 Weights for the aggravating coefficient factors

Factor	Weight
F_{FS1}	0.03
F_{FS2}	0.06
F_{FS3}	0.03
F_{FS4}	0.12
F_{FS5}	0.05
F_{FS6}	0.05
F_{FS7}	0.05
F_{FS8}	0.10
F_{FS9}	0.07
F_{FR1}	0.08
F_{FR2}	0.04
F_{FR3}	0.08
F_{FR4}	0.08
F_{FR5}	0.06
F_{FR6}	0.10

Table 7 Results obtained for Medellín

County	R_F	F	*USRi*
Villa Hermosa	0.31	0.28	0.39
La América	0.28	0.32	0.37
Poblado	0.28	0.20	0.34
Laureles Estadio	0.24	0.27	0.31
La Candelaria	0.22	0.33	0.29
Buenos Aires	0.22	0.28	0.28
Guayabal	0.18	0.29	0.23
Belén	0.17	0.20	0.21
Aranjuez	0.12	0.32	0.16
San Javier	0.10	0.41	0.15
Castilla	0.10	0.30	0.13
Robledo	0.09	0.31	0.12
Manrique	0.08	0.33	0.10
Doce de Octubre	0.07	0.28	0.08
Popular	0.06	0.34	0.08
Santa Cruz	0.02	0.29	0.02

3.3 Disaggregation of the holistic assessment of risk at county level

Given that the *USRi* is a composite indicator, after obtaining the final result it is possible to disaggregate it and to see the contribution of the different descriptors related to the physical risk and/or the social fragility and lack of resilience. This disaggregation can be made for the 16 counties of Medellín. As an example, the mentioned disaggregation is presented for the *Villa Hermosa* County, the one with the highest *USRi*.

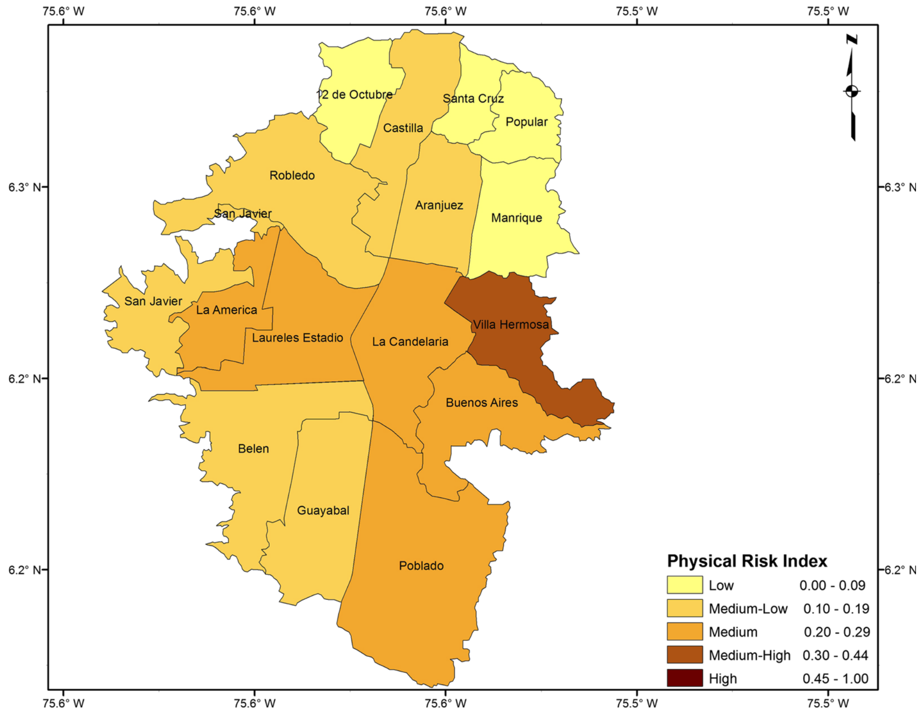

Fig. 11 Physical risk index by county level for Medellín

For R_F, as it can be seen in Fig. 15, the descriptor with higher participation is the F_{RF7} (using the same notation as Fig. 9) which is related to the number of homeless which, as was explained above, is directly related to the calculated MDR given the occurrence of the selected earthquake event. For the social fragility descriptors, the one with higher participation is F_{FS1} related to the violent deaths rate, as it can be seen in Fig. 16. Finally, for the lack of resilience descriptors, the one with higher overall participation is F_{FR1}, associated with the available public space, as shown in Fig. 17.

Besides allowing identifying the factors that mostly contribute to the *USRi* either in overall terms or by category, the disaggregation process highlights the necessity of a multidisciplinary approach in a comprehensive seismic risk assessment framework since the risk drivers may be related to different origins such as building code compliance and enforcement, urban planning and territorial management, as it has been explained for the *Villa Hermosa* County. The results of this study can be integrated into other assessments related to the performance of the disaster risk management strategies in the city, such as the one developed by López (2010). Also, incorporating these aspects in the disaster risk management scheme at local level is of high importance in a city where the perception of seismic hazard and risk is low by its inhabitants, but, where not only because of the geological and tectonic conditions but to the social, economic and urban planning ones, the occurrence of an earthquake can lead to disastrous consequences.

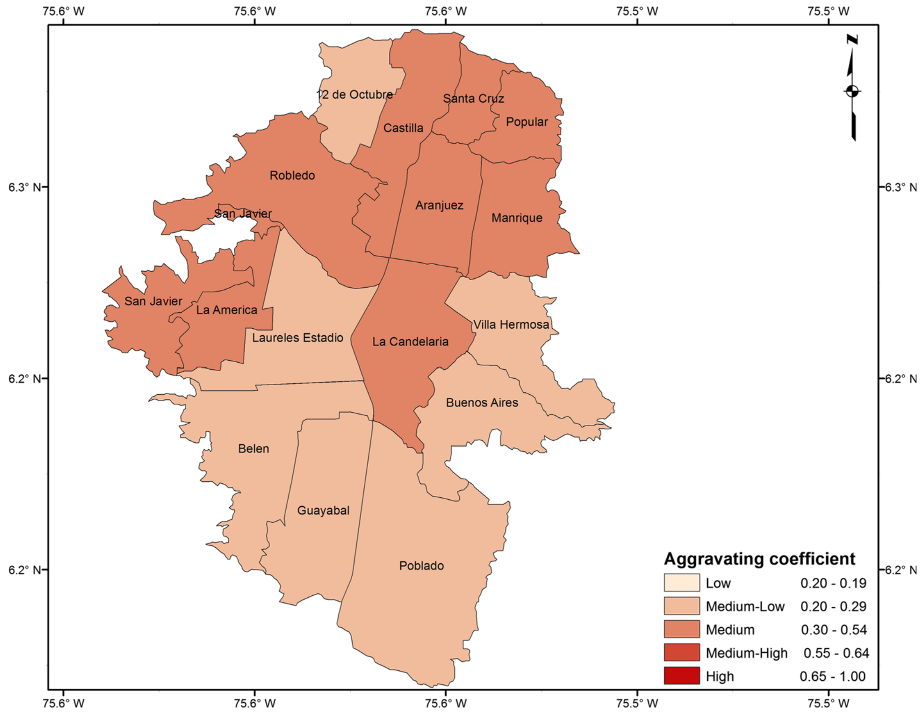

Fig. 12 Aggravating coefficients by county for Medellín

4 Conclusions

Probabilistic risk assessment methodologies, such as the one used by the CAPRA platform, include advanced tools to quantify expected losses on a portfolio of exposed assets given the occurrence of hazardous events. These tools must be understood as models that are intended to represent a reliable order of magnitude of the expected losses and not to predict events and exact amounts. It is important to obtain physical risk results using a probabilistic approach, considering the inherent uncertainties, but it is also essential to move towards the use of the results within a multidisciplinary disaster risk management framework, such as the one of this study. When calculating physical losses with this approach, it is important to take into account the correlation between the losses since its exclusion may lead to underestimation of them; details about how this issue is dealt with, within the CAPRA platform, can be found in Salgado-Gálvez et al. (2014a).

Regarding the risk identification process, building by building information is useful since the individual location of a dwelling in a large city such as Medellín can lead to significant changes on its individual expected damages and losses due to geographical variations on the hazard intensities, a fact that is heightened when a seismic microzonation study is included. On the other hand, when communicating aggregated risk through maps, results should be grouped in larger divisions such as counties in order to avoid misleading conclusions. Catastrophe risk models are based on the large numbers law (Grossi et al. 2008), where a statistically significant number of elements are required to obtain a reliable estimation of the risk results but seen as a whole and not on an individual basis. For that

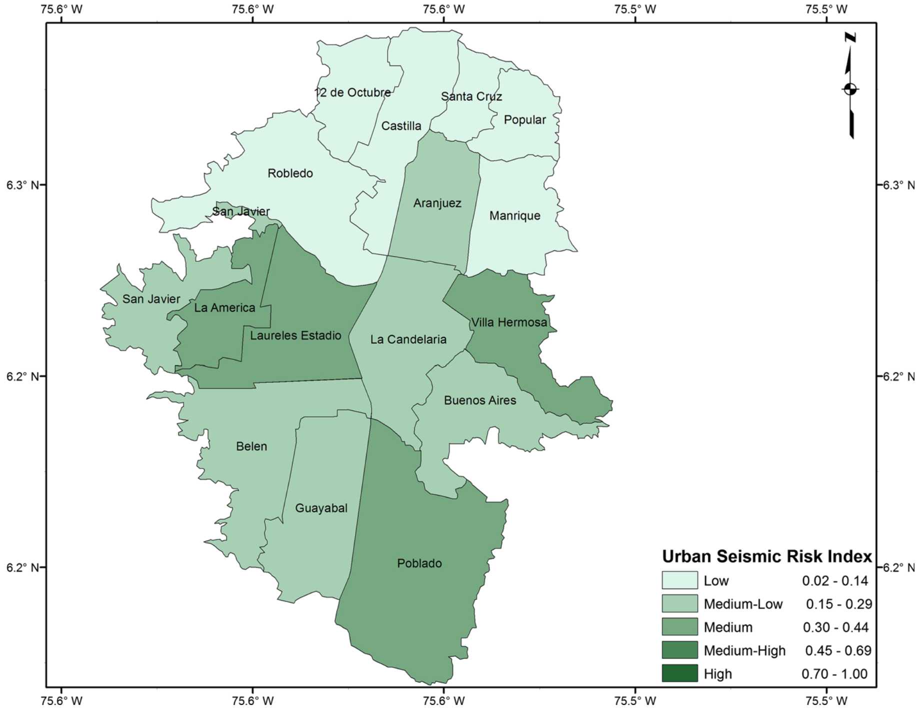

Fig. 13 *USRi* results by county for Medellín

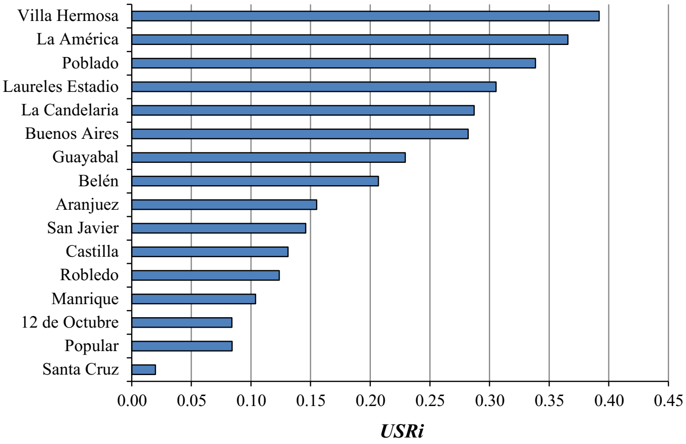

Fig. 14 *USRi* ranking for Medellín

reason, the physical risk results have been grouped at county level which constitutes the administrative division for Medellín. Grouping results on administrative areas can also facilitate the decision-making process since comprehensive schemes can be developed by establishing actions that, in overall, can reduce today's risk conditions.

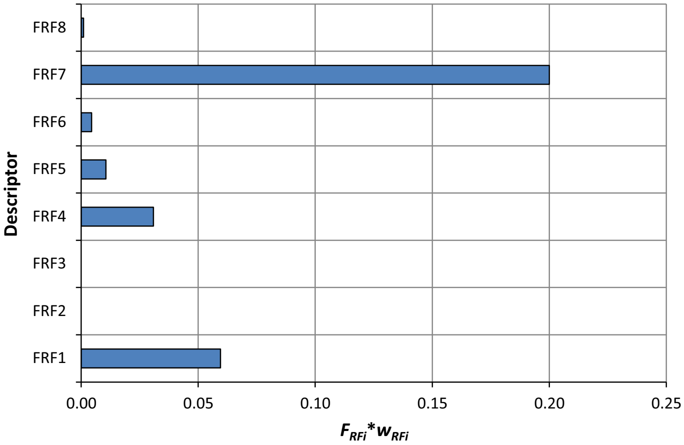

Fig. 15 F_{RFi} disaggregation for *Villa Hermosa* County

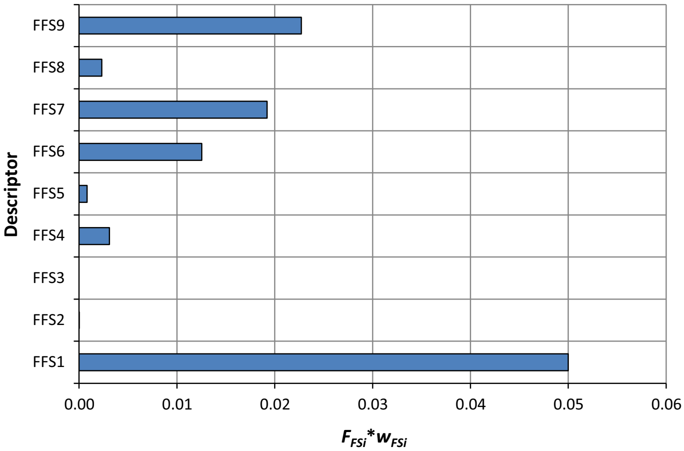

Fig. 16 F_{FSi} disaggregation for *Villa Hermosa* County

It is relevant to quantify seismic risk from both a physical and a holistic perspective because even though earthquakes are not the most common hazardous event in the city if compared to flash floods or landslides (which are not considered catastrophic); an event like this can lead to correlated damages and deaths, as well as to important disruptions occurring at the same time in different zones within the city. Also, though the uncertainties related to the physical seismic risk assessment have been accounted for, future research is needed in order to incorporate the ones existing in the considered socioeconomic characteristics (Burton and Silva 2014). Those cannot be handled by means of probability distributions, but nevertheless it is important to highlight that within the methodology explained and used herein, sensitivity tests on input data, weight and transformation functions using Monte Carlo simulations have shown how, at urban level, the risk rankings and risk level ranges derived from the composite indicator are robust (Marulanda et al. 2009).

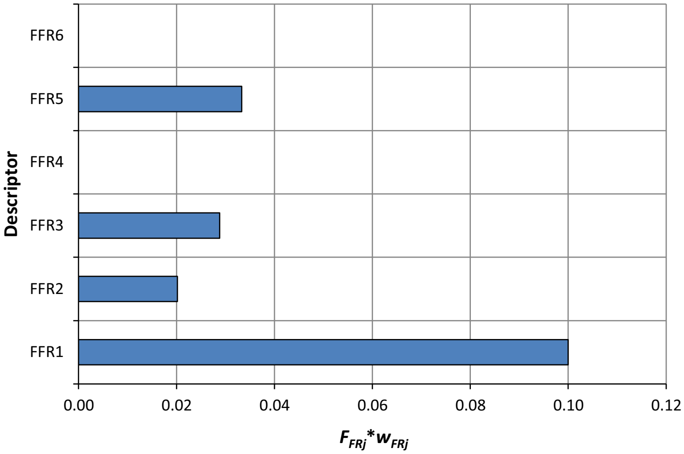

Fig. 17 F_{FRi} disaggregation for *Villa Hermosa* County

Seismic risk assessed from a hard, soft or holistic approach is intended to contribute to the effectiveness of management strategies which largely depend on the decision-making process. Though this methodology can be understood as a simplified representation of the seismic risk at urban level, it performs a multidisciplinary approach that accounts not only for the physical damage but for social, institutional, economic and organizational issues that influence the risk results. Vulnerability is not only seen as a risk factor determined by the physical characteristics of a group of buildings, but also as being related to social fragility and lack of resilience of the exposed communities, while poverty must be understood as a vulnerability driver and not vulnerability itself.

A disaster risk reduction management scheme must involve an interdisciplinary process and the holistic evaluation contributes to this process, not only by considering the socioeconomic factor but by being a useful way to communicate risk through the identification of the critical areas of a city where the vulnerability is assessed considering different perspectives.

Finally, these kinds of evaluations can be periodically updated to evaluate the effectiveness of the prevention and mitigation strategies defined for the area of analysis while highlighting the most important measures to be taken that are needed to decrease either the physical vulnerability, the social fragility conditions or the lack of resilience.

Acknowledgments The authors are grateful for the support of the Ministry of Education and Science of Spain “Enfoque integral y probabilista para la evaluación del riesgo sísmico en España”—CoPASRE (CGL2011-29063). Also to the Spain’s Ministry of Economy and Competitiveness in the framework of the researcher’s formation program (FPI) and the support of the “Paul C. Bell, Jr.” risk management program of the Florida International University (FIU). This work has also been partially sponsored by the European Commission (project DESURBS-FP7-2011-261652). Finally the authors would like to thank an anonymous reviewer whose comments helped to improve the original version of the manuscript.

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