

Urban Seismic Risk Index for Medellín, Colombia, based on probabilistic loss and casualties estimations

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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 hazard map of Colombia although no destructive earthquakes have recently 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 have been 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 of resilience at county level was performed making use of a set of indicators with the objective of capturing the aggravating conditions of the initial physical impact. The Urban Seismic Risk Index has been obtained at county level being useful to communicate risk to decision-makers and stakeholders besides making easy to identify 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 has helped 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.

1. INTRODUCTION

Several probabilistic seismic risk analysis 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; 2008b; 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, Carreño et al. 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 to different active seismic faults can generate important damages and disruptions on its infrastructure (AIS 2010; Salgado-Gálvez et al. 2010; 2014a; 2014c; 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. 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. 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 socio-ecological 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; aspects that are captured by means of a set of indicators.

For this case study, all the physical risk indicators are obtained starting from damage and loss

51 events that can be calculated by using fully probabilistic methodologies, such as the one of the
52 CAPRA¹ platform, by convoluting hazard and vulnerability for the exposed elements
53 (Cardona et al. 2010; 2012; Salgado-Gálvez et al. 2014a; Velásquez et al. 2014). For this
54 study, the probabilistic physical risk results obtained by Salgado-Gálvez et al. (2014a) using
55 CAPRA are complemented by estimating injured, deaths, homeless and unemployed on a
56 building by building basis, also based on a fully probabilistic approach and grouping the
57 results by counties.

58
59 The *USRi* is defined as a combination of a physical risk index, R_F , and an aggravating
60 coefficient, F , in the following way: $USRi = R_F (1+F)$ where R_F and F are composite
61 indicators (Carreño 2006; Carreño et al. 2007). R_F is obtained from the probabilistic risk
62 results, while F is obtained from available data regarding political, institutional and
63 community organization aspects which usually reflect weak emergency response, lack of
64 compliance of existing codes, economic and political instability and other factors that
65 contribute to the risk creation process (Carreño et al. 2007; Renn 2008). This approach has
66 also been applied at different resolution levels (Daniell et al. 2010; Burton and Silva 2014)
67 and has been integrated in toolkits, guidebooks and databases for earthquake risk assessment
68 (Khazai et al. 2014; 2015; Burton et al. 2014). Since not always the same information in terms
69 of indicators is available for the area under study, each assessment constitute a challenge in
70 the way that the descriptors are selected and in some cases calculated.

71
72 The multi-hazard risk assessment CAPRA platform holistic risk assessment module, *EvHo*,
73 (CIMNE-RAG 2014) has been used in this work, which is a tool that incorporates directly the
74 output files of the physical risk estimation made using CAPRA-GIS (ERN-AL 2011), the
75 probabilistic risk calculator module of the CAPRA platform. The module defines factors and
76 their corresponding weights to calculate R_F and F ; it also incorporates a procedure based on
77 transformation functions, allowing the conversion of each factor into commensurable units
78 and calculates the aggravating coefficient for each analysis area. The *USRi* is obtained at
79 county level according to the flowchart of Figure 1. All these computations are made possible
80 by the modular characteristics of the CAPRA platform. Since risk analysis can be performed
81 at different resolution levels, the tool allows the selection of the desired level, and if the risk
82 has been calculated on a more detailed scale, it groups the results into the desired units.

83
84 For the social fragility (F_{FSi}) and lack of resilience (F_{FRj}) indexes, the user can define the
85 number of factors and assign the weights to be used in each category; as in the case of the
86 physical risk, the user can also select the transformation function in conjunction with the
87 correspondent minimum and maximum limits for each factor. Once the above mentioned
88 parameters are defined by the user, the Urban Seismic Risk Index (*USRi*) is calculated for the
89 selected resolution level and results can be exported into tables, charts and maps in *shapefile*
90 format.

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¹ Comprehensive Approach to Probabilistic Risk Assessment (www.ecapra.org)

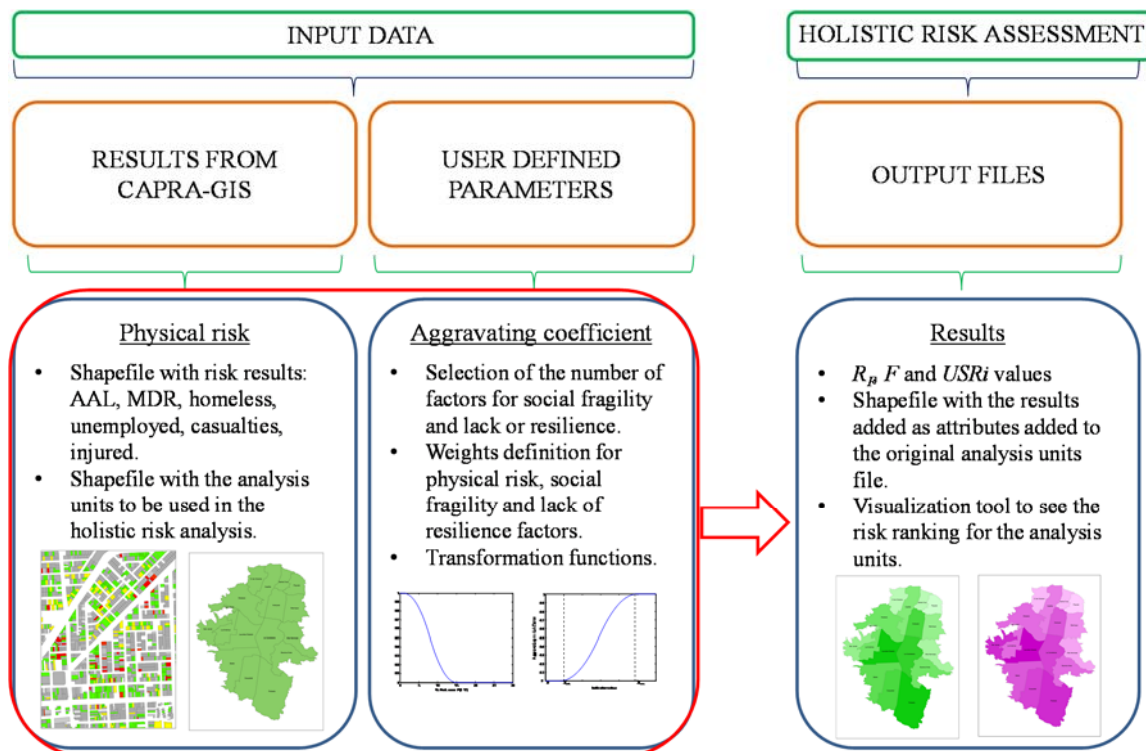


Figure 1 CAPRA's holistic risk assessment module flowchart

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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.

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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 USR_i 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.

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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 toward 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

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123 incorporates a set of probabilistic descriptors in the side of the physical risk that had never
124 been assessed in Medellín while, on the other hand, since the main purpose is to raise risk
125 awareness and, not a generally agreed practice on a holistic risk assessment framework exists,
126 the development of case studies that consider different methodologies (Brink and Davidson
127 2014) to obtain the input data can serve as examples for future comparisons of the
128 approaches.

129

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

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141 **2. PROBABILISTIC PHYSICAL SEISMIC RISK AND DIRECT IMPACT** 142 **ASSESSMENT**

143

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

152

153 **2.1 Physical seismic risk analysis methodology**

154

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

173 methodology and information for the physical risk analysis can be found in Salgado-Gálvez et
174 al. (2014a).

175

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

182

$$183 \quad v(l) = \sum_{i=1}^N \Pr(L > l | Event_i) \cdot F_A(Event_i) \quad (Eq. 1)$$

184

185 where $v(l)$ is the rate of exceedance of loss l , N is the total number of earthquake events that
186 comprise the stochastic set and conform with the seismic hazard in the area under analysis, F_A
187 $(Event_i)$ is the annual frequency of occurrence of the i^{th} earthquake event, while $\Pr(L > l | Event$
188 $i)$ is the probability of exceeding l , given that the i^{th} event occurred. The sum of the equation
189 includes all potentially damaging events from the stochastic set. The inverse value of $v(l)$ is
190 the return period of the loss l , denoted as Tr . Once the LEC is obtained, other risk metrics
191 such as the AAL can be obtained by calculating the area under the LEC. This metric
192 constitutes the first physical risk factor required to be determined for the study presented
193 herein. AAL can also be directly computed, leading to exactly the same value using the
194 following expression:

195

$$196 \quad AAL = \sum_{i=1}^N E(L | Event_i) \cdot F_A(Event_i) \quad (Eq. 2)$$

197

198 where $E(L | Event_i)$ is the expected loss value given the occurrence of the i^{th} event and
199 $F_A(Event_i)$ is the associated annual occurrence frequency of the same event. AAL constitutes
200 a robust indicator since it can represent risk at different resolution levels and also captures the
201 participation on the overall risk of the small and frequent events as well as the high and low
202 frequency events while also being insensitive to uncertainty as is explained later.

203

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

213

214 **2.2 Physical risk results for Medellín**

215

216 Physical risk is calculated on a building by building resolution level and the obtained results
217 are grouped by counties according to the location of each dwelling. It is well known that for
218 the calculation of the AAL an arithmetical aggregation process can be applied to both
219 counties and sectors. Table 1 shows the values in relative terms to the total exposed value by

220 county and by sector in Medellín. Blank values (-) correspond to sectors that are not
 221 representative in the corresponding county. AAL seeks to give an overall and comprehensive
 222 representation of the risk levels, through a robust indicator and not only by loss values for
 223 earthquake events. AAL is calculated considering the participation of all the events, by
 224 multiplying the expected loss by its annual occurrence frequency, for each event. The AAL,
 225 when calculated by means of Equation 2, cannot have associated any uncertainty measure
 226 because it represents the loss results in annualized terms which, on the other hand, represent a
 227 mathematical expectation, not an uncertainty measure.

228
 229 **Table 1** Relative AAL (%) by county and by sector in Medellín

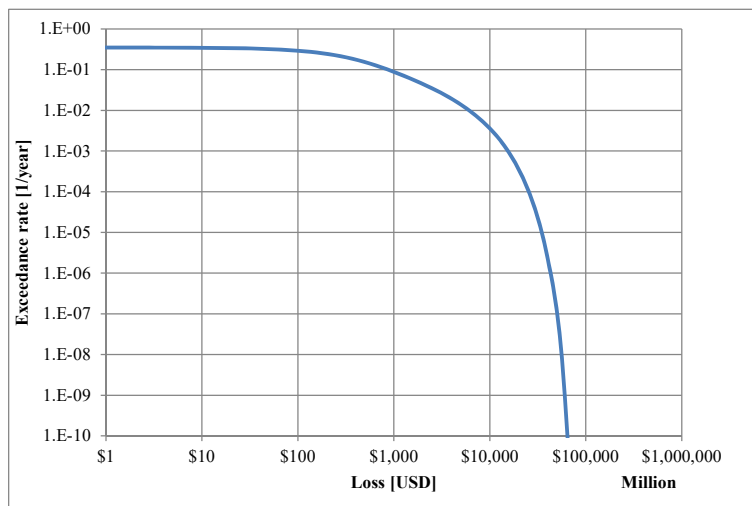
County	Sector			
	Commercial	Industrial	Institutional	Residential
1- Popular	2.95	-	-	2.65
2 - Santa Cruz	1.26	-	-	1.59
3 - Manrique	2.79	-	3.11	2.67
4- Aranjuez	1.51	-	1.43	1.53
5 - Castilla	2.57	2.75	2.94	2.81
6 - Doce de Octubre	3.25	-	-	3.39
7 - Robledo	1.93	-	2.20	2.21
8 - Villa Hermosa	6.68	-	-	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

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 231
 232 **2.3 Death, injured, homeless and unemployed estimation for Medellín**
 233

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

245
 246 The event was chosen out of the more than 2,500 included in the stochastic set with the
 247 selection criteria of that event generating a direct economic loss of similar order of magnitude
 248 than that of a 500 years mean return period. That value is read from the LEC shown in Figure
 249 2 and that return period is considered of relevance for the design of emergency plans in
 250 Colombia (SDPAE 2002). It is important to bear in mind that the return period of the loss is
 251 different from the return period of the seismic event since, in this case, there is correlation in
 252 the losses and uncertainties in the ground motion and physical vulnerability values (Bazzurro
 253 and Luco 2005; Bommer and Crowley 2006; Park et al. 2007; Crowley et al. 2008; Salgado-
 254 Gálvez et al. 2014a). The expected loss for the selected return period obtained from the LEC

255 is estimated in around 12 billion USD² which represents about 14% of the total exposed
 256 value. Loss exceedance rates are calculated by using the total probability theorem and because
 257 of that, for any loss level, the exceedance rate is calculated as the sum of all the events with
 258 probability of exceeding said loss level. In this case, the uncertainty is being considered in the
 259 calculation of the exceedance probabilities and then, the annual exceedance rates obtained
 260 cannot have associated an uncertainty measure because they are probabilities calculated for a
 261 specific loss value.
 262



263
 264 **Figure 2** LEC for the portfolio of buildings of Medellín (Salgado-Gálvez et al. 2014a)
 265

266 Three different sets of vulnerability functions were used to calculate the required factors. The
 267 first set corresponds to the physical vulnerability functions to calculate the mean damage ratio
 268 (MDR) for each element which captures the distribution of damage values in each building
 269 class given a seismic intensity. If this parameter has a value higher than 20%, the building is
 270 considered to be unsafe to be occupied and thus, depending on its use, its occupants are
 271 considered either homeless or unemployed. The second and third sets of functions have to do
 272 with the deaths and injured estimation and depend on the building class.
 273

274 For the estimation of deaths and injuries, fatality rates proposed by Jaiswal et al. (2011) were
 275 selected and also, a workday scenario is assumed. Given that occupation is a dynamic
 276 parameter and the day and time of the earthquake cannot be established with this approach, a
 277 rate of 60% occupancy, which corresponds to an average occupation according to Liel and
 278 Deierlein (2012), was used for the calculation, as previously chosen in Salgado-Gálvez et al.
 279 (2015c).
 280

281 The selected seismic event is associated to the Romeral Fault System which is the one that
 282 controls the seismic hazard level for medium and long return periods in Medellín (AIS 2010).
 283 Table 2 shows the characteristics of the selected event in terms of location, depth and
 284 magnitude.
 285

286 **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

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

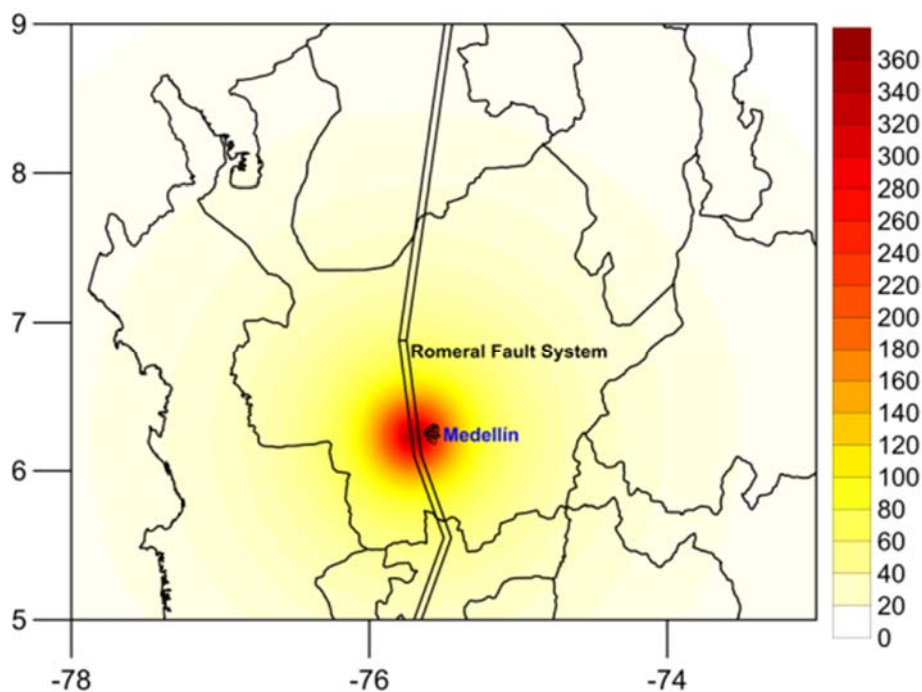
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Table 3 shows the estimated direct impact results of the selected event in terms of economic loss, deaths, and injuries as well as homeless and unemployed, while Figure 3 shows the shakemap in terms of the peak ground acceleration (PGA), at bedrock 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.

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

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

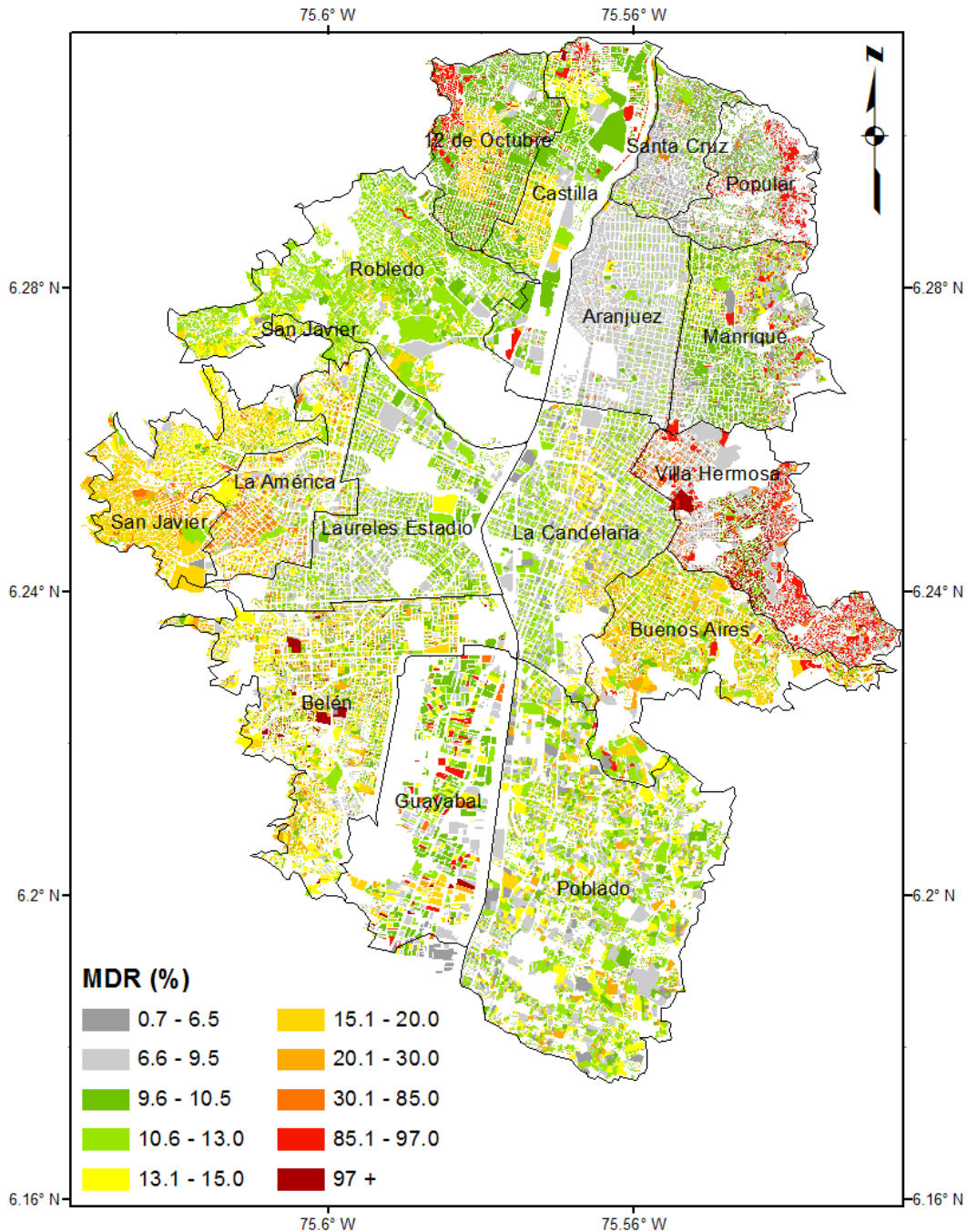


Figure 4 MDR (%) estimation for the portfolio of buildings in Medellín

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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.

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%	-	14.7%	35.3%	-	-	11,274
11 - Laureles Estadio	29.8%	-	5.1%	65.1%	-	-	9,832
12 - La América	90.0%	-	-	10.0%	-	-	8,868
13 - San Javier	80.2%	10.2%	-	9.6%	-	-	18,599
14 - Poblado	20.2%	-	10.1%	25.0%	44.7%	-	8,747
15 - Guayabal	36.2%	-	39.4%	24.4%	-	-	668
16 - Belén	85.0%	-	-	15.0%	-	-	21,950

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

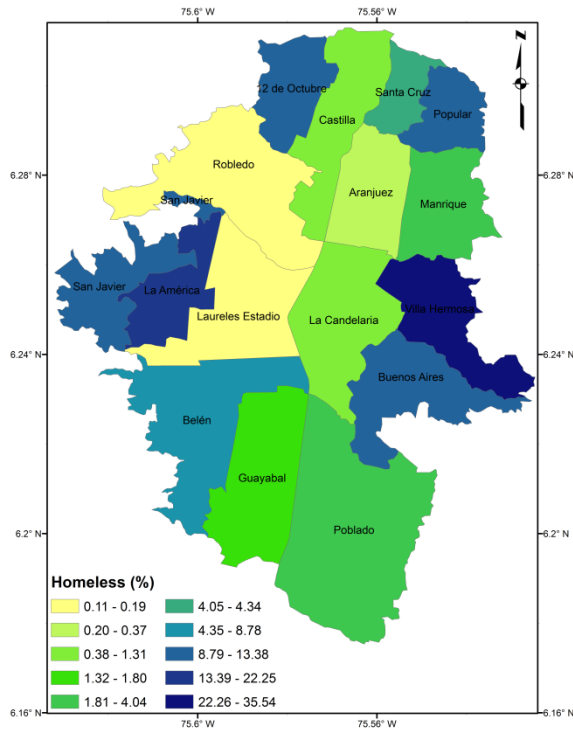


Figure 5 Homeless estimation for Medellín

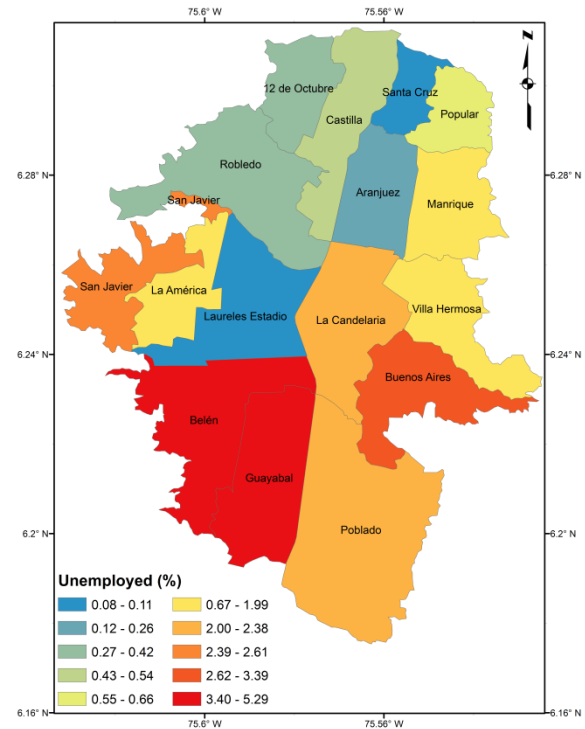


Figure 6 Unemployed estimation for Medellín

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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.

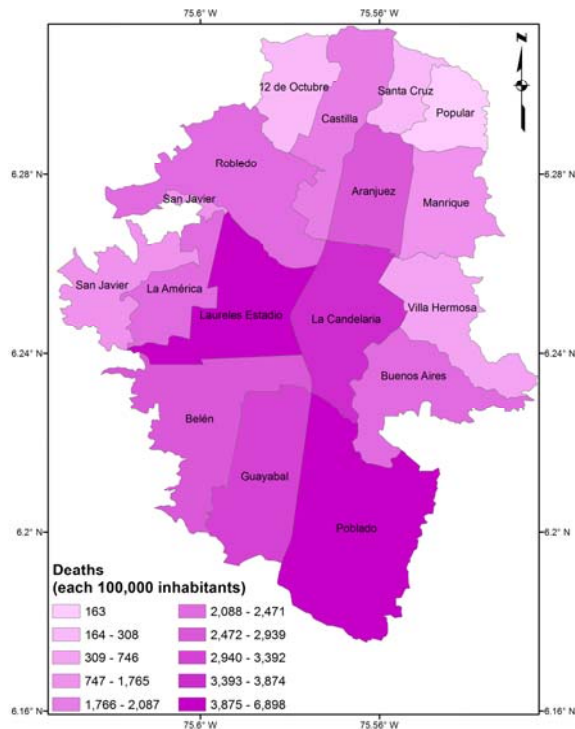


Figure 7 Deaths estimation for Medellín

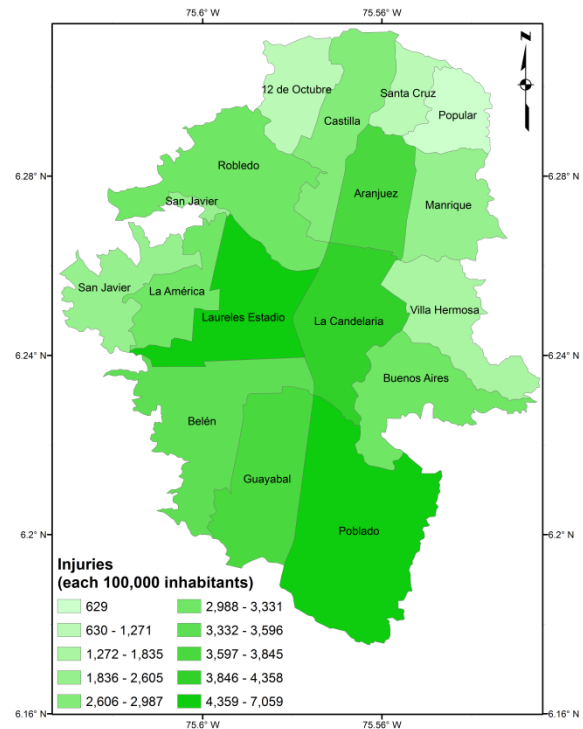


Figure 8 Injuries estimation for Medellín

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

335

336 3. HOLISTIC SEISMIC RISK ASSESSMENT OF MEDELLÍN

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338 A comprehensive risk management strategy has to be based on a multidisciplinary approach
 339 that takes into account not only the physical damage and the direct impact but also a set of
 340 socioeconomic factors that favour the second order effects and consider the intangible impact
 341 in case an earthquake event strikes the city (Cardona and Hurtado 2000; Benson 2003;
 342 Cannon 2003; Cutter et al. 2003; Davis 2003; Carreño et al. 2007; Barbat et al. 2010; Khazai
 343 et al. 2014). This can be achieved by using a holistic seismic risk assessment where physical
 344 damages are aggravated by a set of socioeconomic conditions allowing comprehensive risk
 345 evaluations that are useful for decision-making processes. This approach also allows
 346 quantifying the resilience of the analysed communities, that is, their capacity to cope with the
 347 negative effects after the occurrence of an earthquake. Detailed information about this
 348 methodology can be found in Carreño (2006), Carreño et al. (2007) and Barbat et al. (2011).

349

350 The methodology used in this study does not require the use of the exact same factors in each
 351 case study, not even in terms of the number of descriptors used, as long as the characteristics
 352 to be captured are well reflected by the ones that are chosen. The explanation is that,
 353 depending on prevalent conditions of the area under analysis, some factors can be more
 354 relevant than others. For this study, physical damage is obtained from the results of the

355 probabilistic approach, already shown in section 2, which is considered to have a higher
 356 robustness if compared with previous holistic seismic risk evaluations performed before
 357 because of the available information and its quality (Carreño et al. 2007; Marulanda et al.
 358 2013).

359
 360 As it was mentioned before, holistic seismic risk analysis can be performed at different scales
 361 but also can account for multi-hazard approaches (Jaramillo 2014). For this study, the
 362 resolution level has been set to counties and the hazard limited to earthquakes since this is the
 363 only catastrophic peril expected for the city.

364 365 **3.1 Methodology for the holistic risk assessment**

366
 367 Applying the holistic risk evaluation methodology proposed by Cardona (2001) and Carreño
 368 et al. (2007), the urban seismic risk index USR_i is calculated starting from a physical risk
 369 index, R_F , and an aggravating coefficient, F , which accounts for the socioeconomic fragility
 370 and lack of resilience of the analysis area. USR_i is calculated by using the equation
 371

$$372 \quad USR_i = R_F(1 + F) \quad (Eq. 3)$$

373
 374 known in the literature as *Moncho's Equation*. The physical risk index, R_F , is calculated
 375 considering a set of factors as well as their associated weights by means of the following
 376 expression:
 377

$$378 \quad R_F = \sum_{i=1}^p F_{RFi} \cdot w_{RFi} \quad (Eq. 4)$$

379
 380 where F_{RFi} are the p physical risk factors and w_{RFi} their corresponding weights. In this case, 8
 381 factors were considered to obtain R_F which were calculated from the results of the
 382 probabilistic seismic risk analysis of the buildings in Medellín described in section 2, in
 383 which both their structural characteristics and their mean occupation values were considered.
 384

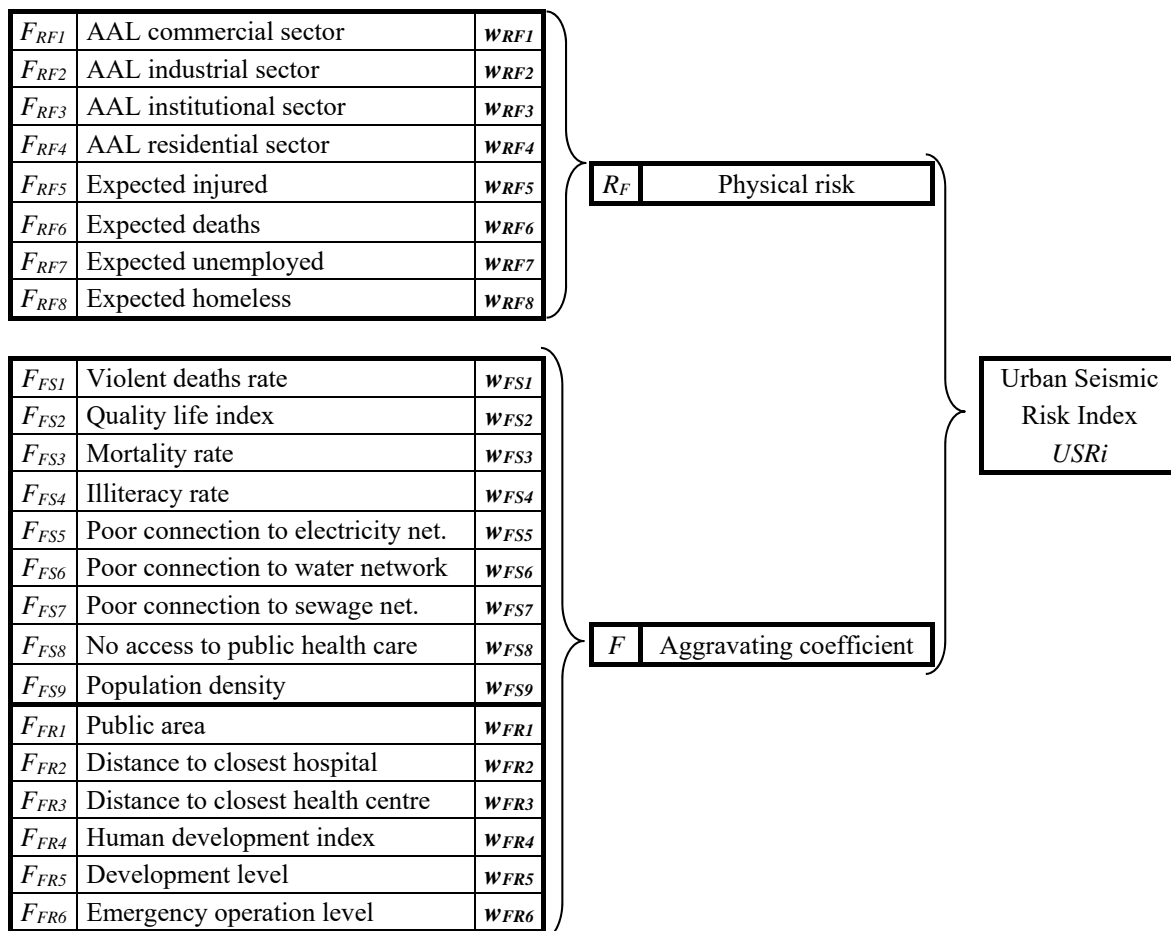
385 The aggravating coefficient, F , is calculated as follows:
 386

$$387 \quad F = \sum_{i=1}^m F_{FSi} \cdot w_{FSi} + \sum_{j=1}^n F_{FRj} \cdot w_{FRj} \quad (Eq. 5)$$

388
 389 where F_{FSi} and F_{FRj} are the aggravating factors, w_{FSi} and w_{FRj} are the associated weights of
 390 each i and j factor and m and n are the total number of factors for social fragility and lack of
 391 resilience, respectively. For this case, 9 descriptors were used to capture the social fragility
 392 conditions on each county while 6 descriptors are considered to capture the lack of resilience.
 393 Most of the descriptors were obtained using data from the local authorities (Alcaldía de
 394 Medellín 2012a; 2012b; Proantioquia et al. 2012; DAP 2012) with the exception of the
 395 calculation of public areas and distances to the closest hospitals and health centres, where
 396 geographical information system (GIS) tools were used. Figure 9 shows the summary of the
 397 descriptors used in this analysis where the ones denoted as F_{RFi} are related to the physical risk
 398 index, the ones denoted as F_{FSi} are related to the social fragility and the ones denoted as F_{FRi}
 399 are related to the lack of resilience.

400

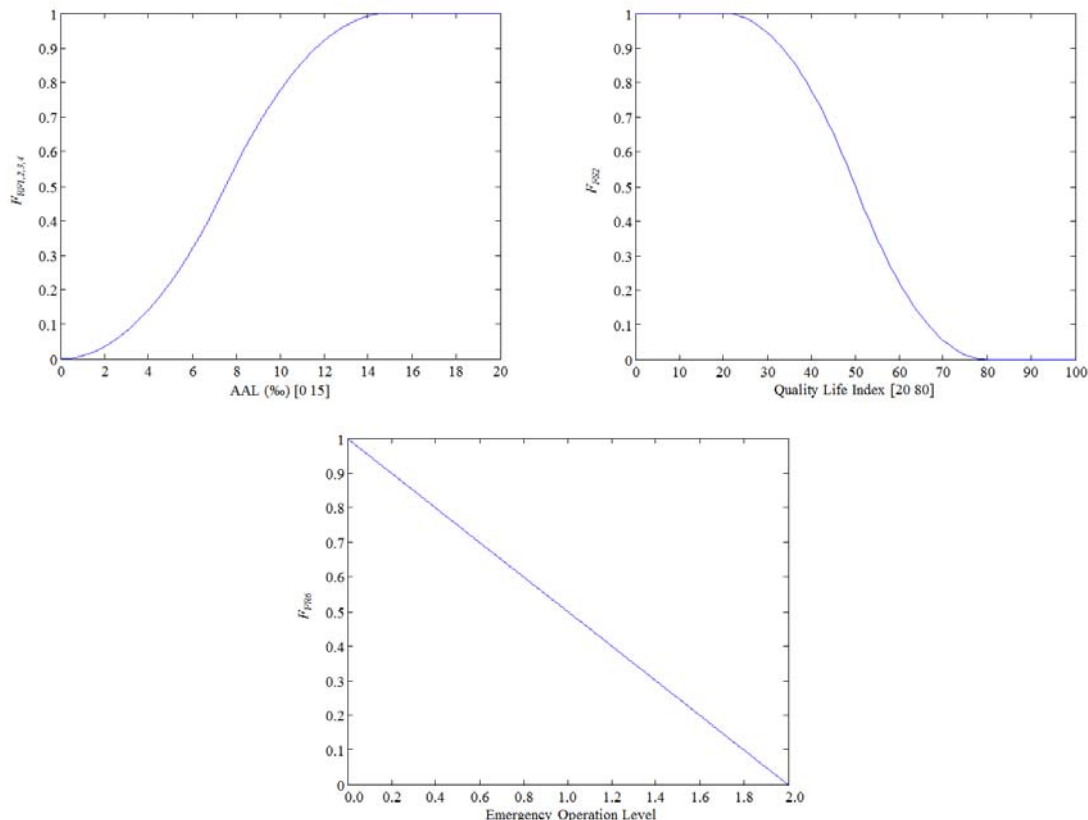
401 The selection of the descriptors for R_F was based on the outcomes that could be extracted
 402 from the fully probabilistic seismic risk analysis, while existing and available indicators that
 403 capture social fragility and lack of resilience issues were selected for the evaluation of F .
 404



405 **Figure 9** Factors used for the holistic seismic risk evaluation in Medellín

406
 407 It is evident that each of the factors used in the calculation of the $USRi$ captures different
 408 aspects and is quantified in different units. Because of that, certain scaling procedures are
 409 needed to standardize the values of each descriptor and convert them into commensurable
 410 factors. In this case, transformation functions were used to standardize the physical risk,
 411 social fragility and lack of resilience factors selected for this study. Some of them are shown
 412 in Figure 10. The factors and their units, as well as the [min, max] values are shown on the
 413 abscissa and also, depending on the nature of the descriptor, the shape and characteristics of
 414 the functions vary and, because of that, for example functions related to descriptors of the
 415 physical risk have an increasing shape while those related to resilience have a decreasing one;
 416 that is, the higher the value of the factors, the lower their aggravation. The transformation
 417 functions can be understood as risk and aggravating probability distribution functions or as
 418 the membership functions of the linguistic benchmarking of high risk or high aggravation.
 419

420



421

422

423

424 The values on the abscissa of the transformation functions correspond to the values of the
 425 descriptors while the ordinate corresponds to the final value of each factor, either related to
 426 the physical risk or to the aggravating factor. In all cases, values of the factor lie between 0
 427 and 1. Since the transformation functions are membership functions, for high risk and
 428 aggravating coefficient levels, 0 corresponds to non-membership while 1 means full
 429 membership. Limit values, denoted as X_{MIN} and X_{MAX} are defined by using expert criteria and
 430 information about previous disasters in the region. Relative weights w_{FSi} and w_{FRj} that
 431 associate the importance of each of the factors on the index calculation are obtained by using
 432 an Analytic Hierarchy Process (AHP) that gives ratio scales from both discrete and
 433 continuous paired comparisons (Saaty and Vargas 1991; Carreño 2006; Carreño et al. 2007).
 434 AHP process was based on participation of local stakeholders and national disaster risk
 435 reduction and management experts for the definition of the weights of the aggravating
 436 coefficient factors, while, for the ones associated to the physical risk factors, besides the
 437 above mentioned participants, the authors also participated.

438

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

441

442

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

443

444

445

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

446

447

3.2 Results of the holistic risk assessment for Medellín

449

450 This section presents the results obtained using the methodology in terms of R_F , F and USR_i .

451 Table 7 presents the results of this study for the 16 counties of Medellín sorted in descending

452 order according to the USR_i results.

453

Table 7 Results obtained for Medellín

County	R_F	F	USR_i
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

455
456

457 Since the results have been obtained using a GIS tool, maps with the distribution of the results
 458 can be built and could be of help to decision-makers for communicative and comparison
 459 purposes among them. For each index, a ranking has been generated to classify each result
 460 into low, medium-low, medium-high, high and very high categories. Figure 11 shows the R_F
 461 at county level. The highest R_F values are found in *Villa Hermosa* and *Poblado* while the
 462 lowest values are found in *Popular* and *Santa Cruz*. This is an interesting finding since the
 463 two lowest results correspond to low-income areas and can be explained by the low injury and
 464 death rates associated to the building classes in these areas since they correspond to non-
 465 engineered systems, typically made from light materials, that do not represent, in general
 466 terms, harm to the inhabitants. Another finding of interest is that, even though *Poblado* has
 467 the best socioeconomic conditions, a disorganized urbanization process has been developed in
 468 the area and high rise structures, not always complying with the requirements established by
 469 the Colombian earthquake resistant building code, have been built. Its large R_F value is
 470 explained by the high physical vulnerability and the consequences in terms of expected
 471 deaths, injured and homeless in it. In terms of the categories used to aggregate the results,
 472 only *Villa Hermosa* has a high physical risk index category, while medium-high values are
 473 found at *Poblado*, *Laureles Estadio*, *La Candelaria*, *La América* and *Buenos Aires*.

474

475 In all counties, the descriptors that, after considering their relative weights, contribute the
 476 most to R_F are the ones that account for deaths and homeless. The estimation of these
 477 descriptors is directly related to the physical damage of the dwellings and, thus, a reduction on
 478 these descriptors can be achieved through the development of retrofitting schemes of at least
 479 essential buildings such as hospitals and schools, while also decreasing the physical
 480 vulnerability of new infrastructure by enforcement on the use of the earthquake building code.
 481 Reducing the existing vulnerability is an ideal approach, but incentives to do so must be
 482 created, even more when seismic risk perception is low because of the low occurrence rate of
 483 earthquakes in Medellín.

484

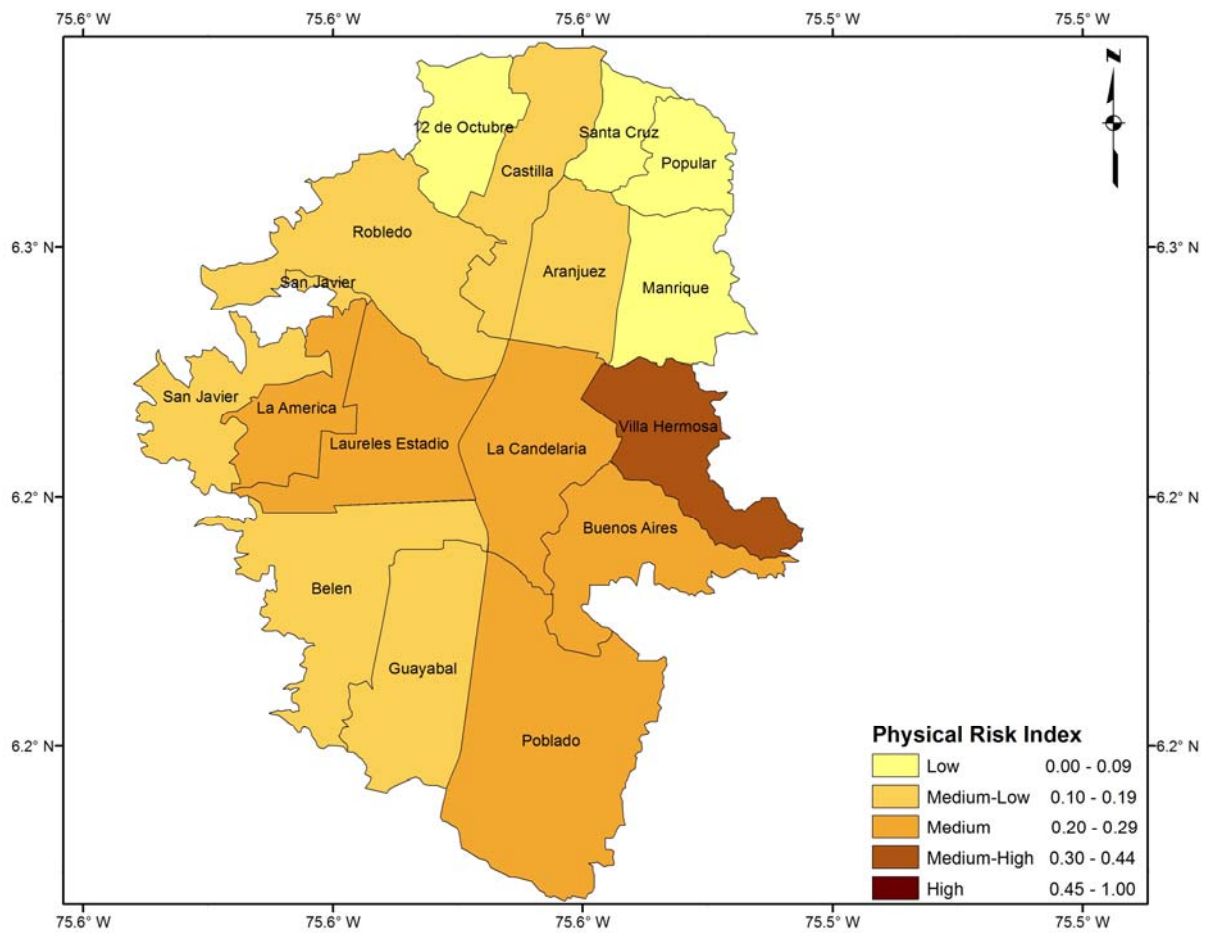


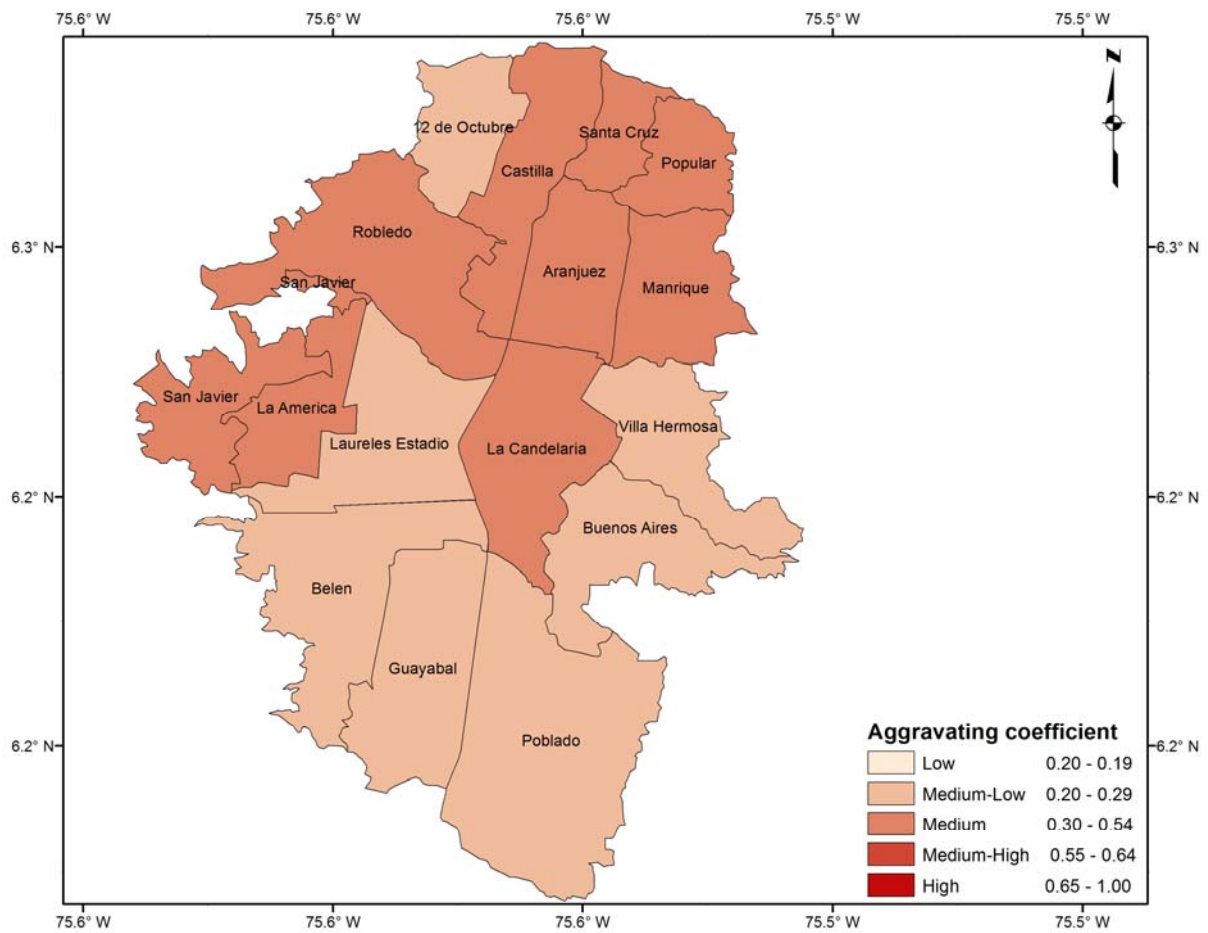
Figure 11 Physical risk index by county level for Medellín

485
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487

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.

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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.



507
508 **Figure 12** Aggravating coefficients by county for Medellín
509

510 Figure 13 shows the USR_i at county level. The highest USR_i is found in *Villa Hermosa*
511 followed by *Poblado* since a high R_F value is combined with an intermediate F , whereas
512 important increases in the final results are observed in *La América*, *Laureles Estadio*, *Buenos*
513 *Aires* and *La Candelaria*, reflecting the importance of accounting for socioeconomic
514 characteristics, additional to the traditional physical seismic risk results. From here, it can be
515 concluded that even if income levels are useful to determine the vulnerability of a certain
516 area, from either the physical or social dimension, it is not the only driver that influences the
517 final result. Finally, Figure 14 shows the ranking in terms of the USR_i to better understand the
518 differences on the results between the counties.
519

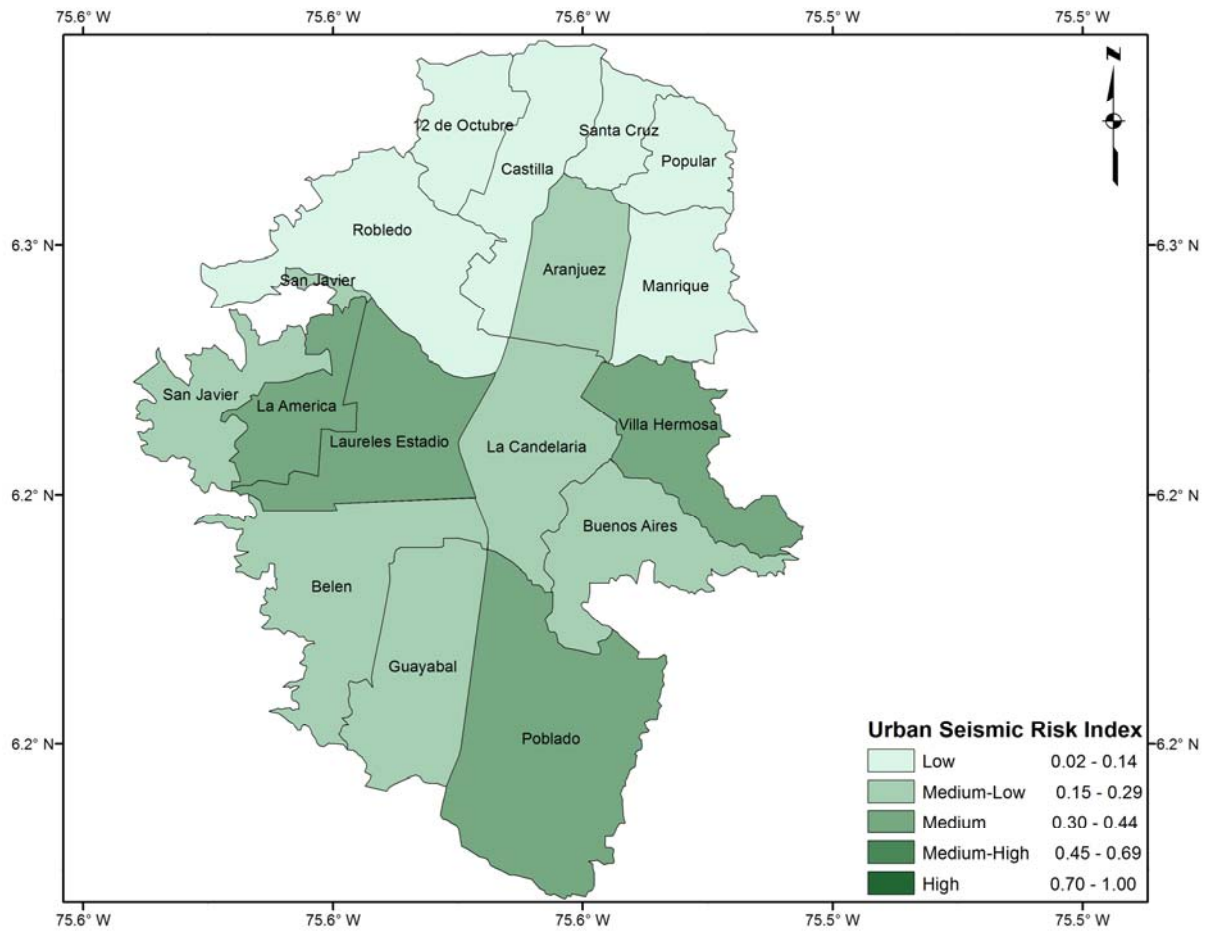


Figure 13 USRi results by county for Medellín

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521
522

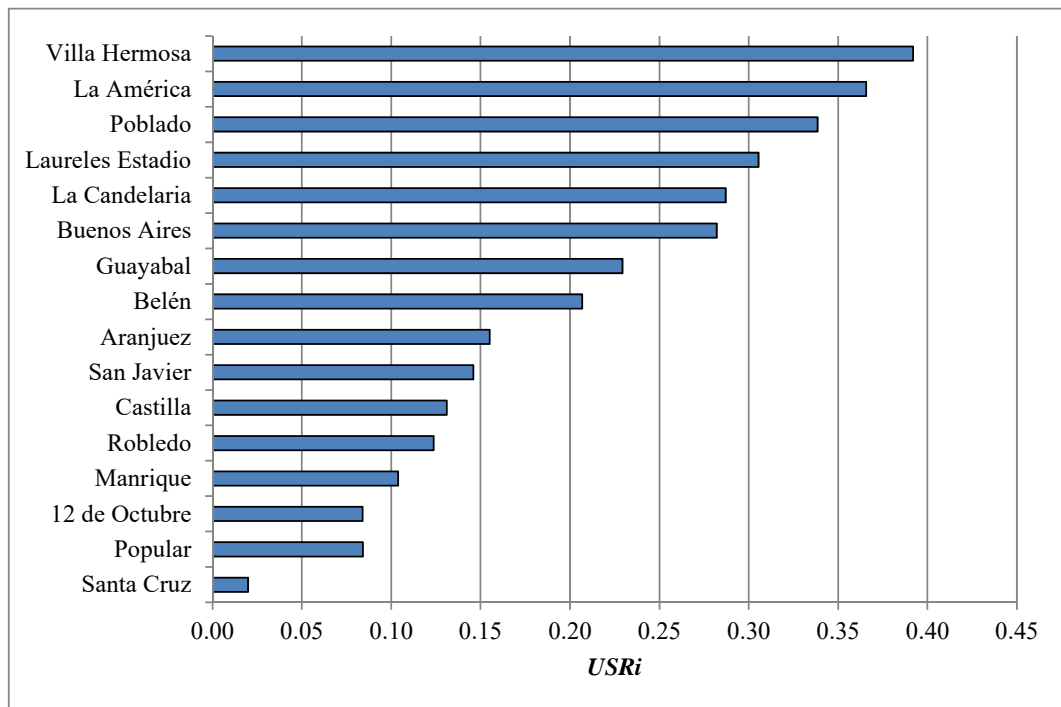


Figure 14 USRi ranking for Medellín

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525

526 **3.3 Disaggregation of the holistic assessment of risk at county level**

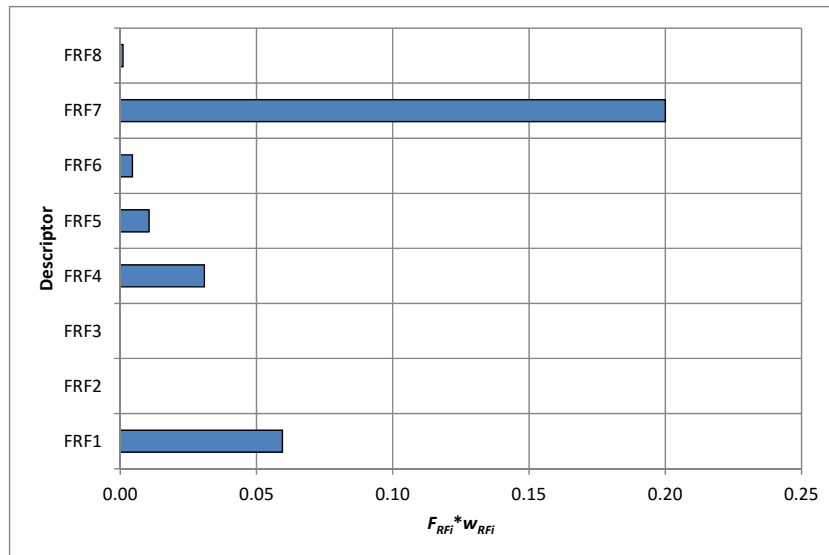
527

528 Given that the USR_i is a composite indicator, after obtaining the final result it is possible to
 529 disaggregate it and to see the contribution of the different descriptors related to the physical
 530 risk and/or the social fragility and lack of resilience. This disaggregation can be made for the
 531 16 counties of Medellín. As an example, the mentioned disaggregation is presented for the
 532 *Villa Hermosa* County, the one with the highest USR_i .

533

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

541

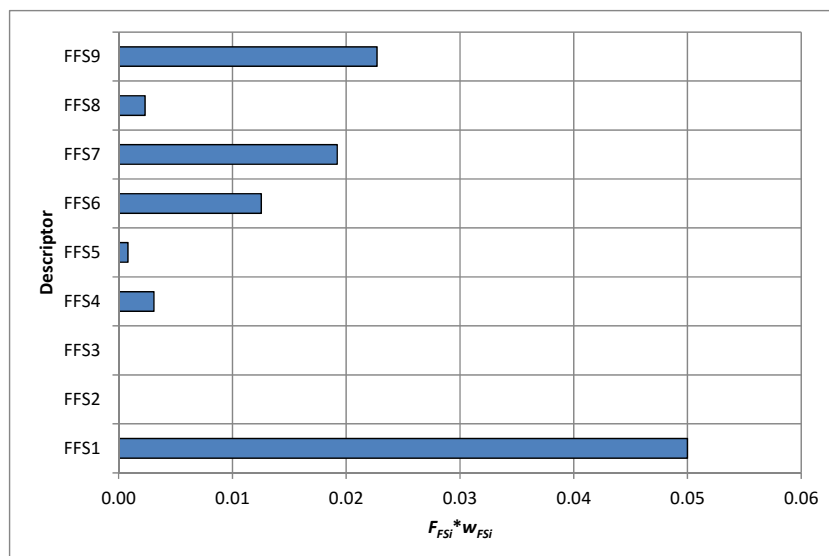


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Figure 15 F_{RFi} disaggregation for *Villa Hermosa* County

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545

546

Figure 16 F_{FSi} disaggregation for *Villa Hermosa* County

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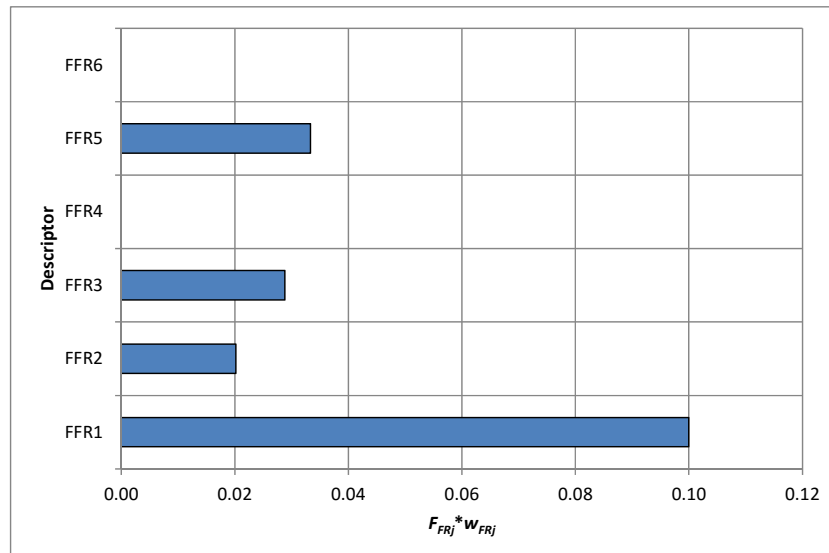


Figure 17 F_{FRi} disaggregation for Villa Hermosa County

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550

Besides allowing identifying the factors that mostly contribute to the USR_i either in overall terms or by category, the disaggregation process highlights the necessity of a multi-disciplinary 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.

563

564 4. CONCLUSIONS

565

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).

577

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.

583

584 Catastrophe risk models are based on the large numbers law, where a statistically significant
585 number of elements are required to obtain a reliable estimation of the risk results but seen as a
586 whole and not on an individual basis. For that reason the physical risk results have been
587 grouped at county level which constitutes the administrative division for Medellín. Grouping
588 results on administrative areas can also facilitate the decision-making process since
589 comprehensive schemes can be developed by establishing actions that, in overall, can reduce
590 today's risk conditions.

591

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

604

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

614

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

619

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

624

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626

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635

636 REFERENCES

637

638 Ahmad N., Ali Q., Crowley H. and Pinho R. (2014). Earthquake loss estimation of residential
639 buildings in Pakistan. *Nat. Hazards*. DOI: 10.1007/s11069-014-1174-8.

640

641 Alcaldía de Medellín, (2012a). Encuesta de calidad de vida 2011. Departamento Administrativo de
642 Planeación.

643

644 Alcaldía de Medellín, (2012b). Indicadores básicos. Situación de salud en Medellín 2011. Secretaría
645 de Salud de Medellín.

646

647 Alcaldía de Medellín. (2010). Geonetwork.

648 <http://poseidon.medellin.gov.co/geonetwork/srv/es/main.home> Accessed January 12th 2013.

649

650 Asociación Colombiana de Ingeniería Sísmica-AIS. (2010). Estudio General de Amenaza Sísmica de
651 Colombia. Comité AIS-300. Bogotá D.C., Colombia.

652

653 Asociación Colombiana de Ingeniería Sísmica-AIS. (1996). Estudio General de Amenaza Sísmica de
654 Colombia. Comité AIS-300. Bogotá D.C., Colombia.

655

656 Barbat A.H., Carreño M.L., Cardona O.D. and Marulanda M.C. (2011). Evaluación holística del riesgo
657 sísmico en zonas urbanas *Revista int. de métodos numér. para calc. y diseño en ing.* 27(1):3-27.

658

659 Barbat A.H., Carreño M.L., Pujades L.G., Lantada N., Cardona O.D. and Marulanda M.C. (2010).
660 Seismic vulnerability and risk evaluation methods for urban áreas. A review with application to a
661 pilot area. *Struct. and infrastruct. eng.* 6(1-2):17-38.

662

663 Bazzurro P. and Luco N. (2005). Accounting for uncertainty and correlation in earthquake loss
664 estimation. ICOSAR. ISBN 90 5986 040 4.

665

666 Benson C. (2003). The economy-wide impact of natural disasters in developing countries. Thesis.
667 University of London.

668

669 Birkmann J., Cardona O.D., Carreño M.L., Barbat A.H., Pelling M., Schneiderbauer S., Kienberger S.,
670 Keiler M., Alexander D., Zeil P. and Welle T. (2013). Framing vulnerability, risk and societal
671 responses: the MOVE framework. *Nat. Hazards* 67:193-211. DOI: 10.1007/s11069-013-0558-5.

672

673 Bommer J.J. and Crowley H. (2006). The influence of ground-motion variability in earthquake loss
674 modelling. *Bull. of earthq. Eng.* DOI: 10.1007/s10518-006-9008-z.

675

676 Brink S.A. and Davidson R.A. (2014). Framework for Comprehensive Assessment of a City's Natural
677 Disaster Risk. *Earthq. spectra*. DOI: 10.1193/021914EQS031M. In press.

678

679 Burton C.G., Khazai B. and Silva V. (2014). Social vulnerability and integrated risk assessment within
680 the Global Earthquake Model. Proceedings of the Tenth U.S. National conference on Earthquake
681 Engineering. Anchorage, United States of America.

682

683 Burton C.G. and Silva V. (2014). Integrated risk modelling within the Global Earthquake Model
684 (GEM): Test case application for Portugal. Proceedings of the Second European Conference on
685 Earthquake Engineering and Seismology. Istanbul, Turkey.

686

687 Caers J. (2011). Modeling Uncertainty in the Earth Sciences. Wiley-Blackwell.

688
689 Cannon T. (2003). Vulnerability analysis, livelihoods and disasters components and variables of
690 vulnerability: modelling and analysis for disaster risk management. Universidad Nacional de
691 Colombia. Manizales.
692
693 Cardona O.D. (2009). La gestión financiera del riesgo de desastres: Instrumentos financieros de
694 retención y transferencia para la Comunidad Andina. PREDECAN. Lima, Perú.
695
696 Cardona O.D. (2001). Estimación holística del riesgo sísmico utilizando sistemas dinámicos
697 complejos. Ph.D. Thesis. Universidad Politécnica de Cataluña. Barcelona, Spain.
698
699 Cardona O.D. and Hurtado J. (2000). Holistic seismic risk estimation of a metropolitan center. 12th
700 World Conference on Earthquake Engineering, Auckland, New Zealand.
701
702 Cardona O.D., Ordaz M., Mora M., Salgado-Gálvez M.A., Bernal G.A., Zuloaga-Romero D.,
703 Marulanda M.C., Yamín L. and González D. (2014). Global risk assessment: A fully probabilistic
704 seismic and tropical cyclone wind risk assessment. Int. j. of disaster risk reduct. 10:461-476.
705 DOI:10.1016/j.ijdr.2014.05.006.
706
707 Cardona O.D., Ordaz M., Reinoso E., Yamín L.E. and Barbat A.H. (2012). CAPRA – Comprehensive
708 Approach to Probabilistic Risk Assessment: International Initiative for Risk Management
709 Effectiveness. 15th World Conference on Earthquake Engineering. Lisbon, Portugal.
710
711 Cardona O.D., Ordaz M., Reinoso E., Yamín L.E. and Barbat A.H. (2010). Comprehensive Approach
712 to Probabilistic Risk Assessment (CAPRA); International initiative for disaster risk management
713 effectiveness. 14th European conference on earthquake engineering, Ohrid, Macedonia.
714
715 Cardona O.D., Ordaz M.G., Yamín L.E., Marulanda M.C. and Barbat A.H. (2008a). Earthquake loss
716 assessment for integrated disaster risk management. J. of earthq. eng. 12(S2):48-59.
717
718 Cardona O.D., Ordaz M.G., Marulanda M.C. and Barbat A.H. (2008b). Estimation of probabilistic
719 seismic losses and the public economic resilience – An approach for macroeconomic impact
720 evaluation. J. of earthq. eng. 12(S2):60-70.
721
722 Carreño M.L. (2006). Técnicas innovadoras para la evaluación del riesgo sísmico y su gestión en
723 centros urbanos: Acciones ex ante y ex post. Doctoral Thesis. Universidad Politécnica de
724 Cataluña, Barcelona, Spain.
725
726 Carreño M.L., Cardona O.D. and Barbat A.H. (2007). Urban seismic risk evaluation: a holistic
727 approach. Nat. Hazards. 40(1):137-172.
728
729 Carreño M.L., Cardona O.D. and Barbat A.H. (2012). New methodology for urban seismic risk
730 assessment from a holistic perspective. Bull. of earthq. eng. 10(2):547-565.
731
732 Carreño M.L., Cardona O.D. and Barbat A.H. (2014). Método numérico para la evaluación holística
733 del riesgo sísmico utilizando la teoría de conjuntos difusos. Revista int. de métodos numér. para
734 calc. y diseño en ing. 30(1):24-34.
735
736 CIMNE-RAG (2014). Holistic risk evaluation tool *EvHo* V1.0. Program for computing holistic risk at
737 urban level. Centro Internacional de Métodos Numéricos en Ingeniería, CIMNE, Risk Assessment
738 Group, RAG, Barcelona, Spain.
739
740 Crowley H., Stafford P.J. and Bommer J.J. (2008). Can earthquake loss models be validated using
741 field observations? j.of earthq. Eng. 12:1078-1104.
742

743 Cutter S., Boruff B. and Shirley W. (2003). Social vulnerability to environmental hazards. *Social*
744 *Science*. 84:242-261.
745

746 Daniell J.E, Daniell K.A., Daniell T.M. and Khazai B. (2010). A country level physical and
747 community risk index in the Asia-Pacific region for earthquakes and floods. *Proceedings of the 5th*
748 *Internacional Civil Engineering Conference in the Asian Region (CECAR)*. Sydney, Australia.
749

750 Davis I. (2003). The effectiveness of current tools for the identification, measurement, analysis and
751 synthesis of vulnerability and disaster risk. Universidad Nacional de Colombia. Manizales.
752

753 Departamento Administrativo de Planeación - DAP, (2012). *Pobreza y condiciones de vida de los*
754 *habitantes de Medellín, 2011*. Observatorio de Políticas Públicas.
755

756 Evaluación de Riesgos Naturales América Latina-ERN-AL, (2011). CAPRA-GIS v2.0. Program for
757 the probabilistic risk assessment. Available on: www.ecapra.org. Accessed May 15th 2013.
758

759 International Bank for Reconstruction and Development – IBRD, The World Bank (2013). *Pacific*
760 *Catastrophe Risk Assessment and Financing Initiative*. Better risk information for smarter
761 investments. Summary report.
762

763 Jaiswal K.S., Wald D.J., Earle P.S., Porter K.A. and Hearne M. (2011). Earthquake Casualty Models
764 Within the USGS Prompt Assessment of Global Earthquakes for Response (PAGER) System. In:
765 *Human Casualties in Earthquakes*. Eds: Spence R., So E. and Scawthorn C. Springer.
766

767 Jaramillo N. (2014). Evaluación holística del riesgo sísmico en zonas urbanas y estrategias para su
768 mitigación. Aplicación a la ciudad de Mérida-Venezuela. Doctoral Thesis. Universidad
769 Politécnica de Cataluña. Barcelona, Spain.
770

771 Khazai B., Bendimerad F., Cardona O.D., Carreño M.L., Barbat A.H. and Burton C.G. (2015). A
772 guide to measuring urban risk resilience. Principles, tools and practice of urban indicators.
773 *Earthquake Megacities Initiative*.
774

775 Khazai B., Burton C.G., Tormene P., Power C., Bernasocchi M., Daniell J.E., Wyss B. and Henshaw
776 P. (2014). Integrated risk modelling toolkit and database for earthquake risk assessment.
777 *Proceedings of the Second European Conference on Earthquake Engineering and Seismology*.
778 Istanbul, Turkey.
779

780 Khazai B., Burton C.G., Power C. and Daniell J. (2013). Socio economic vulnerability and integrated
781 risk project. Technical report Nr. 2. Karlsruhe Institute of Technology, Willis Research Network,
782 The Center for Disaster Management and Risk Reduction Technology, Global Earthquake Model.
783

784 Lantada N., Irrizari J., Barbat A.H., Goula X., Roca A., Susagna T. and Pujades L.G. (2010). Seismic
785 hazard and risk scenarios for Barcelona, Spain, using the Risk-UE vulnerability index method.
786 *Bull. of earthq. eng.* 8:201-229.
787

788 Liel A.B. and Deierlein G.C. (2012). Using collapse risk assessments to inform seismic safety policy
789 for older concrete buildings. *Earthq. spectra*. 28(4):1495-1521. DOI:10.1198/1.4000090.
790

791 López J. (2010). Índice de gestión de riesgo (IGR). Programa de información e indicadores de gestión
792 del riesgo BID-IDEA. Departamento Administrativo de Planeación y Atención de Desastres.
793 Medellín, Colombia.
794

795 Luco N. and Cornell C.A. (2007). Structure-specific scalar intensity measures for near-source and
796 ordinary earthquake motions. *Earthq. spectra*. 23(2):357-392.
797

798 Marulanda M.C., Cardona O.D., Mora M.G. and Barbat A.H. (2014). Design and implementation of a
799 voluntary collective earthquake insurance policy to cover low-income homeowners in a
800 developing country. *Nat. Hazards*. 74:2071-2088.
801

802 Marulanda M.C., Carreño M.L., Cardona O.D., Ordaz M. and Barbat A.H. (2013). Probabilistic
803 earthquake risk assessment using CAPRA: application to the city of Barcelona, Spain. *Nat.*
804 *Hazards*. 69:59-84. DOI: 10.1007/s11069-013-0685-z.
805

806 Marulanda M.C., Cardona O.D. and Barbat A.H. (2009). Robustness of the holistic seismic risk
807 evaluation in urban centers using the USRi. *Nat. Hazards*. 49(3):501-516.
808

809 Ordaz M. (2000) Metodología para la evaluación del riesgo sísmico enfocada a la gerencia de seguros
810 por terremoto. Universidad Nacional Autónoma de México, México D.F.
811

812 Ordaz M., Aguilar A. and Arboleda J. (2007). CRISIS 2007 V7.6, Program for computing seismic
813 hazard. Instituto de Ingeniería. Universidad Nacional Autónoma de México.
814

815 Ordaz M., Miranda E., Reinoso E. and Pérez-Rocha L.E. (2000). Seismic loss estimation model for
816 Mexico City. Proceedings of the 12th World Conference on Earthquake Engineering.
817

818 Paris G., Machete M, Dart R. and Haller K. (2000). Map and Database of Quaternary Faults and Folds
819 in Colombia and Offshore Regions, USGS Open-File Report.
820

821 Park J., Bazzurro P. and Baker J.W. (2007). Modeling spatial correlation of ground motion Intensity
822 Measures for regional seismic hazard and portfolio loss estimation. Applications of Statistics and
823 Probability in Civil Engineering. ISBN 978-0-415-45211-3.
824

825 Proantioquia, Universidad EAFIT, Fundación Corona, Comfama, Comfenalco, Cámara de Comercio
826 de Medellín, El Colombiano, Cámara de Comercio de Bogotá and El Tiempo (2012). Medellín
827 cómo vamos?
828

829 Pulido N. (2003). Seismotectonics of the Northern Andes (Colombia) and the Development of Seismic
830 Networks. *Bull. of the int. inst. of seismol. and earthq. eng.* Special Edition:69-76.
831

832 Renn O. (2008). Concepts of risk: An interdisciplinary review. Proceedings of the ISA Conference,
833 Barcelona, Spain.
834

835 Saaty T. and Vargas L. (1991). Prediction, projection and forecasting: applications of the analytic
836 hierarchy process in economics, finance, politics, games and sports. Kluwer Academic Publishers,
837 Dordrecht.
838

839 Salgado-Gálvez M.A., Carreño M.L., Barbat A.H. and Cardona O.D. (2015a). Evaluación probabilista
840 del riesgo sísmico en Lorca mediante simulaciones de escenarios. *Revista int. de métodos numér.*
841 *para calc. y diseño en ing.* DOI: 10.1016/j.rimni.2014.12.001. In press.
842

843 Salgado-Gálvez M.A., Bernal G.A. and Cardona O.D. (2015b). Evaluación probabilista de la amenaza
844 sísmica de Colombia con fines de actualización de la Norma Colombiana de Diseño de Puentes
845 CCP-14. *Revista int. de métodos numér. para calc. y diseño en ing.* In press.
846

847 Salgado-Gálvez M.A., Bernal G.A., Barbat A.H., Carreño M.L. and Cardona O.D. (2015c).
848 Probabilistic estimation of annual lost economic production due to premature deaths because of
849 earthquakes. *Hum. ecol. Risk assess.* DOI: 10.1080/10807039.2015.1095072. In press.
850

851 Salgado-Gálvez M.A., Zuloaga D., Bernal G.A., Mora M.G. and Cardona O.D. (2014a). Fully
852 probabilistic seismic risk assessment considering local site effects for the portfolio of buildings in
853 Medellín, Colombia. *Bull. of earthq. Eng.* 12:671-695. DOI: 10.1007/s10518-013-9550-4.
854

855 Salgado-Gálvez M.A., Barbat A.H., Cardona O.D., Carreño M.L., Velásquez C.A. and Zuloaga D.
856 (2014b). Urban seismic risk index for Medellín: a probabilistic and holistic approach. *Proceedings*
857 *of the Second IRDR Conference. Beijing, China.*
858

859 Salgado-Gálvez M.A., Zuloaga D., Bernal G.A. and Cardona O.D. (2014c). Comparación de los
860 resultados de riesgo sísmico en dos ciudades con los mismos coeficientes de diseño sismo
861 resistente. *Rev. De Ing.* 41:8-14. Universidad de Los Andes, Bogotá, Colombia.
862

863 Salgado-Gálvez M.A., Zuloaga D. and Cardona O.D. (2013). Evaluación probabilista del riesgo
864 sísmico de Bogotá y Manizales con y sin la influencia de la Caldas Tear. *Rev. De Ing.* 38:6-13.
865 Universidad de Los Andes, Bogotá, Colombia.
866

867 Salgado-Gálvez M.A., Bernal G.A., Yamín L.E. and Cardona O.D. (2010). Evaluación de la amenaza
868 sísmica de Colombia. Actualización y uso en las nuevas normas colombianas de diseño sismo
869 resistente NSR-10. *Rev. de Ing.* 32:28-37. Universidad de Los Andes, Bogotá, Colombia.
870

871 Silva V., Crowley H., Varum H. and Pinho R. (2014). Seismic risk assessment for mainland Portugal.
872 *Bull. of earthq. Eng.* DOI: 10.1007/s10518-014-9630-0.
873

874 Sistema Distrital de Prevención y Atención de Emergencias – SDPAE (2002). Plan de respuesta a
875 emergencias por terremoto en Bogotá D.C. Alcaldía de Bogotá D.C. Colombia.
876

877 Sistema Municipal Para la Atención de Desastres - SIMPAD, Universidad EAFIT, Integral,
878 INGEOMINAS and Universidad Nacional de Colombia Sede Medellín, (1999). Instrumentación y
879 microzonificación sísmica del área urbana de Medellín.
880

881 Taboada A., Rivera A., Fuenzalida A., Cisternas A., Philip H., Bijwaard H., Olaya J. and Rivera C.
882 (2000). Geodynamics of the northern Andes. Subductions and intracontinental deformation
883 (Colombia). *Tecton.* 19(5): 787-813.
884

885 Velásquez C.A., Cardona O.D., Mora M.G., Yamín L.E., Carreño M.L. and Barbat A.H. (2014).
886 Hybrid loss exceedance curve (HLEC) for disaster risk assessment. *Nat Hazards.* 72: 455-479.
887

888 Zuloaga D., Salgado-Gálvez M.A., Cardona O.D. and Yamín L.E. (2013). Implicaciones en la
889 estimación del riesgo sísmico de Bogotá como resultado de una nueva interpretación sismo-
890 tectónica. *Proceedings of the VI Congreso Nacional de Ingeniería Sísmica. Bucaramanga,*
891 *Colombia.*