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URBAN SEISMIC RISK INDEX FOR MEDELLÍN, COLOMBIA: A PROBABILISTIC AND HOLISTIC APPROACH

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ABSTRACT

A fully probabilistic seismic risk assessment of Medellín, Colombia, was conducted using a building by building resolution level database with more than 240,000 dwellings. An updated seismic hazard assessment was used in the analysis and a set of stochastic seismic scenarios was generated. Because the city has a seismic microzonation study, the dynamic soil response was taken into account. A set of building classes was identified and vulnerability functions were developed to calculate the seismic risk in terms of probabilistic metrics using several modules of the CAPRA Platform. Risk premiums by sectors, as well as casualties and other direct effects were calculated on a building by building basis and then aggregated at county level. Furthermore, a holistic approach, using the holistic evaluation module of CAPRA, was used to take into account social fragility and lack of resilience conditions in each county that could increase the second order effects in case a strong earthquake strikes the city. These conditions were inferred from a set of indicators that are meant to capture the aggravating conditions of the direct physical impact, the second order effects and the intangible impact of future seismic events. A comprehensive Urban Seismic Risk Index was obtained at county level in order to communicate risk to stakeholders and decision-makers, helping identify areas that would be particularly problematic in terms of vulnerability, both in physical and socioeconomic dimensions. This study constitutes a complete example of how an integrated research on disaster risk reduction has been performed with the aim to decrease the gap between the risk analysis and its relevance for disaster risk management decision-making processes.

INTRODUCTION

Quantifying risk from a physical point of view is a key but it is only the first step in a comprehensive disaster risk management scheme (Cardona, 2009). It is clear that it 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).

This paper presents the seismic risk results obtained for the city of Medellín, Colombia from a probabilistic and holistic approach. Medellín is the second largest city in Colombia with more than 2.3 million inhabitants and where many industries and financial facilities have their head offices. The city is located on a valley on the east side of the western cordillera of the North Andean zone and is placed

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on an intermediate seismic hazard zone where earthquakes associated to different active seismic faults can generate important damage and disruption on its infrastructure (AIS, 2010; Salgado et al., 2010; Salgado et al., 2013). The city is divided into 16 counties (*comunas*) for administrative purposes, each of them with approximately the same area but with important differences from a social, economic and infrastructure point of view. In past years, the city has experienced a rapid urban growth and transformation, and different areas of the city have changed in terms of building classes, number of inhabitants and availability of public spaces since low rise houses have been demolished to build high-rise structures to accommodate a larger amount of citizens. This process has mainly occurred in the medium-high income zones of the city.

The risk identification process is the first of the disaster risk management steps (Cardona 2009) that may lead to the identification of the order of magnitude of the required budget to proceed to the following steps regarding mitigation strategies such as structural intervention or retrofitting of existing structures, urban planning regulations, long-term financial protection strategies (Freeman et al., 2003, Andersen, 2002) and emergency planning. Holistic risk assessment at urban level requires a combination of the physical risk with aspects that reflect social fragility and lack of resilience. All these aspects are captured by means of sets of indicators. The physical risk indicators are obtained starting from damage and loss scenarios that can be calculated by using fully probabilistic methodologies, such as the one of the CAPRA[7] platform by convoluting hazard and vulnerability for the exposed elements (Cardona et al., 2010; 2012). For this study, the probabilistic physical risk results obtained by Salgado et al. (2013) using CAPRA are complemented by estimating injured, casualties, homeless and unemployed on a building by building basis and grouping the results by counties.

The urban seismic risk index, *USRi*, is defined as a combination between a physical risk index, R_F, and an aggravating coefficient, F, in the following way: $USRi = R_F\ (1+F)$ where R_F and F are composite indicators (Carreño et al., 2007; Carreño, 2006). 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).

A new CAPRA holistic risk assessment module (CIMNE-RAG, 2014) has been developed and used in this work. It is a tool that incorporates directly the output files of the physical risk estimation made using CAPRA-GIS (ERN-AL, 2011) which is the probabilistic risk calculator module of the CAPRA platform. The module defines factors and their corresponding weights to calculate R_F and F; it 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. All these computations are made possible by the modular, open source and open architecture characteristics of the CAPRA platform.

Obtaining risk results from a holistic perspective highlights the socioeconomic factors that contribute mostly 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 comparison of the obtained results and it can help in prioritizing the areas for developing disaster risk reduction and management strategies.

PROBABILISTIC PHYSICAL SEISMIC RISK AND IMPACT ANALYSIS

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 scenarios 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 average annual loss by sector, where four different

[7] Comprehensive Approach to Probabilistic Risk Assessment (www.ecapra.org)

categories are included (residential, commercial, institutional and industrial). The other factors are related to the expected number of casualties, injuries, homeless and unemployed. This section presents the methodology followed for the calculation of said factors.

For a fully probabilistic seismic risk analysis, a set of input data for the hazard, exposure and vulnerability representation is required. Hazard is represented through a set of stochastic scenarios generated by CRISIS 2007 (Ordaz et al., 2007), which is the seismic hazard module of CAPRA, associated to the different seismogenetic sources identified at country level (AIS, 2010; Salgado et al., 2010); for each scenario, 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 to a building class. Vulnerability is represented by means of vulnerability functions that allow both a continuous and probabilistic representation of the loss associated to different hazard intensities, in this case corresponding to the spectral acceleration for 5% damping.

Since all input data has been represented using a probabilistic approach, the risk 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 this analysis is the loss exceedance curve (LEC) that relates loss values, in monetary units with their annual loss frequencies. The LEC is calculated using Eq. 1:

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

where $v(l)$ is the rate of exceedance of loss l, N is the total number of earthquake scenarios that comprise the stochastic set, $F_A\ (Event_{\mathrm{i}})$ is the annual frequency of occurrence of the i^{th} earthquake event, while $\Pr(L>l|Event_{\mathrm{i}})$ is the probability of exceeding l, given that the i^{th} event occurred. The sum of the equation includes all potentially damaging events. The inverse of $v(l)$ is the return period of loss l, identified as Tr. Once the LEC is known, 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 analysis. AAL can also be directly computed, leading to exactly the same value using Eq. 2:

$$AAL = \sum_{i=1}^{N} \mathrm{E}(L \,|\, Event_{i}) \cdot F_A(Event_{i}) \qquad (2)$$

where $\mathrm{E}(L|Event_{i})$ is the mean loss value given the occurrence of the i^{th} event and $F_A(Event_{i})$ 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 global risk of the small and frequent events as well as the large and low frequency events. Table 1 summarizes the obtained probabilistic risk results. Average annual losses were obtained and grouped at county level for the residential, commercial, industrial and institutional sectors.

Table 1. Summary of the results

Results		
Exposed value	USD$ x10^6	146,608
Average annual loss	USD$ x10^6	604.6
	‰	4.1
PML		
Return period	Loss	
years	USD$ x10^6	%
100	$10,033	6.8
250	$15,716	10.7
500	$20,356	13.9
1000	$24,930	17.0

The estimation of the casualties, injuries, homeless and unemployed is performed using a single scenario approach that has been selected by choosing a single event out of the more than 2,500 included in the stochastic set. A scenario that is expected to generate a direct economic loss of similar order of magnitude of that of a 500 years return period loss is selected by reading the LEC shown in Figure 1. It is important to remember 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 (Salgado et al., 2013). The expected loss for the selected return period obtained from the LEC is estimated in around 20 million USD[8] which represents 13.9% of the total exposed value. Though the annual frequency of occurrence of the scenario 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. For the estimation of casualties and injuries a workday scenario is assumed. Given that occupation is a dynamic parameter and the day and time of the earthquake cannot be established, a rate of 60% occupancy, which corresponds to an average occupation according to Liel and Deierlein (2012), was used for the calculation.

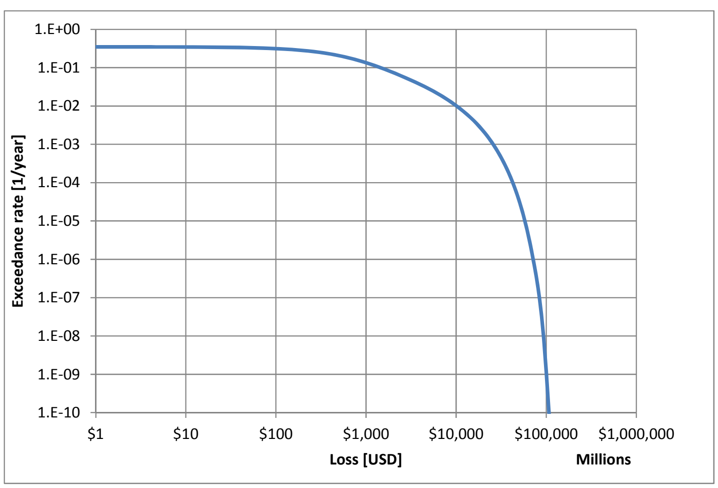


Figure 1. Seismic LEC for Medellin

Table 2 shows the estimated direct impact results of the selected scenario in terms of economic loss, casualties, and injuries as well as homeless and unemployed, while Figure 2 shows the AAL and MDR distribution for Medellín; the first considers all scenarios included in the stochastic set while the second one shows the results for the single scenario approach. From the obtained results it can be seen that the highest MDR exists in *Villa Hermosa* County which is located on the eastern part of the city

[8] An Exchange rate of 1USD=1,800COP has been used in this study

where high structural vulnerability exist due to the large number of unreinforced masonry units. Homelessness and unemployment estimations are highest for *Villa Hermosa*, *La América*, *Belén*, *Guayabal* and *Manrique* counties, while higher casualty 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 casualty and injury point of view if compared with low-rise masonry units.

Table 2. Result of the direct losses for the selected scenario

Seismogenetir source	Romeral Fault System
Expected loss (Million USD)	18,272
Relative loss (%)	12.5
Casualties	51,780
Injuries	68,165
Homeless	177,671
Unemployed	37,547

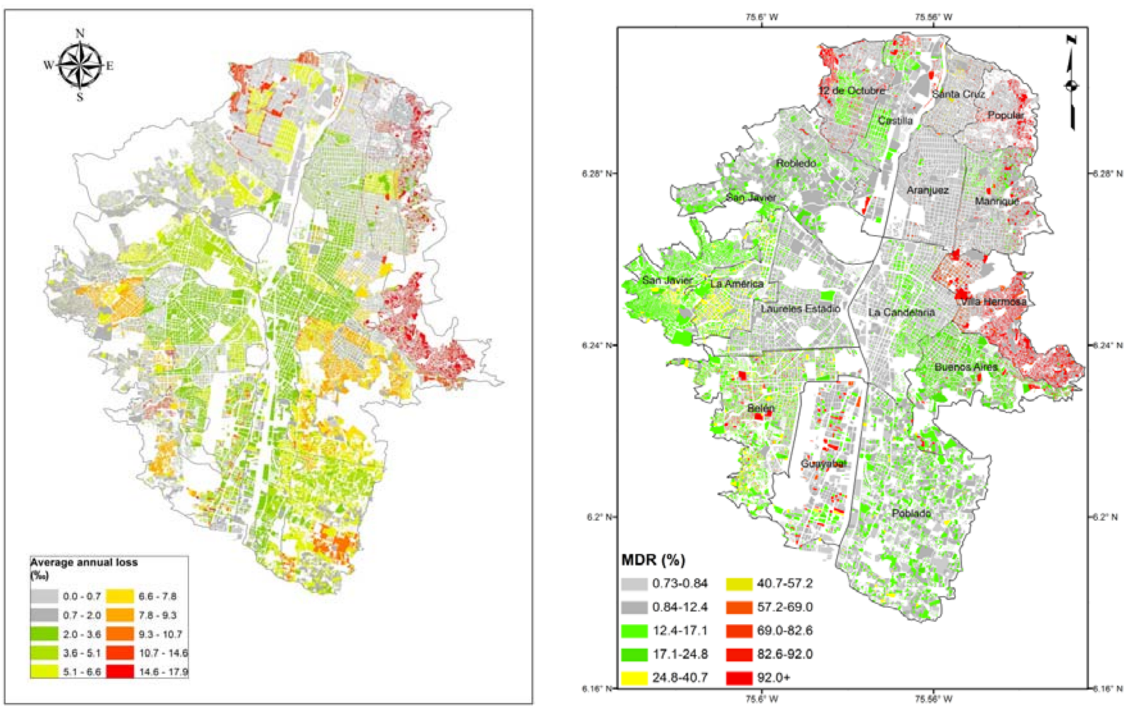


Figure 2. AAL (left) and MDR (right) for Medellín

HOLISTIC SEISMIC RISK ASSSESSMENT 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; Carreño et al., 2007). This can be achieved by using a holistic seismic risk 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 assessment, in terms of number of descriptors, as long as the characteristics to be captured are well reflected by the considered descriptors. This is possible since 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 section 2, which is considered to have a higher robustness if compared with previous holistic seismic risk evaluations performed before (Carreño et al., 2007).

Holistic seismic risk analysis can be performed at different scales and even for a multi-hazard approach. For this study, the resolution level has been set to counties and the hazard limited to earthquakes since this is the only catastrophic threat expected for the city.

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 Eq. 3:

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

known in the literature as *Moncho's Equation*. The physical risk index, R_F, is calculated considering a set of factors as well as their associated weights by means of Eq. 4:

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

where F_{RFi} are the p physical risk factors and w_{RFi} their corresponding weights. In this case we used 8 factors to obtain R_F which were calculated from the results of the probabilistic seismic risk analysis of the buildings in Medellín described in section 2, in which we considered both their structural characteristics and their mean occupation values. The aggravating coefficient, F, is calculated with Eq. 5:

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

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; 2012b; Proantioquia, et al. 2012; DAP, 2012) with the exception of the calculation of public areas and distances to the closest hospitals and health centres, where geographical information system (GIS) tools were used. Figure 3 shows the summary of the descriptors used in this analysis.

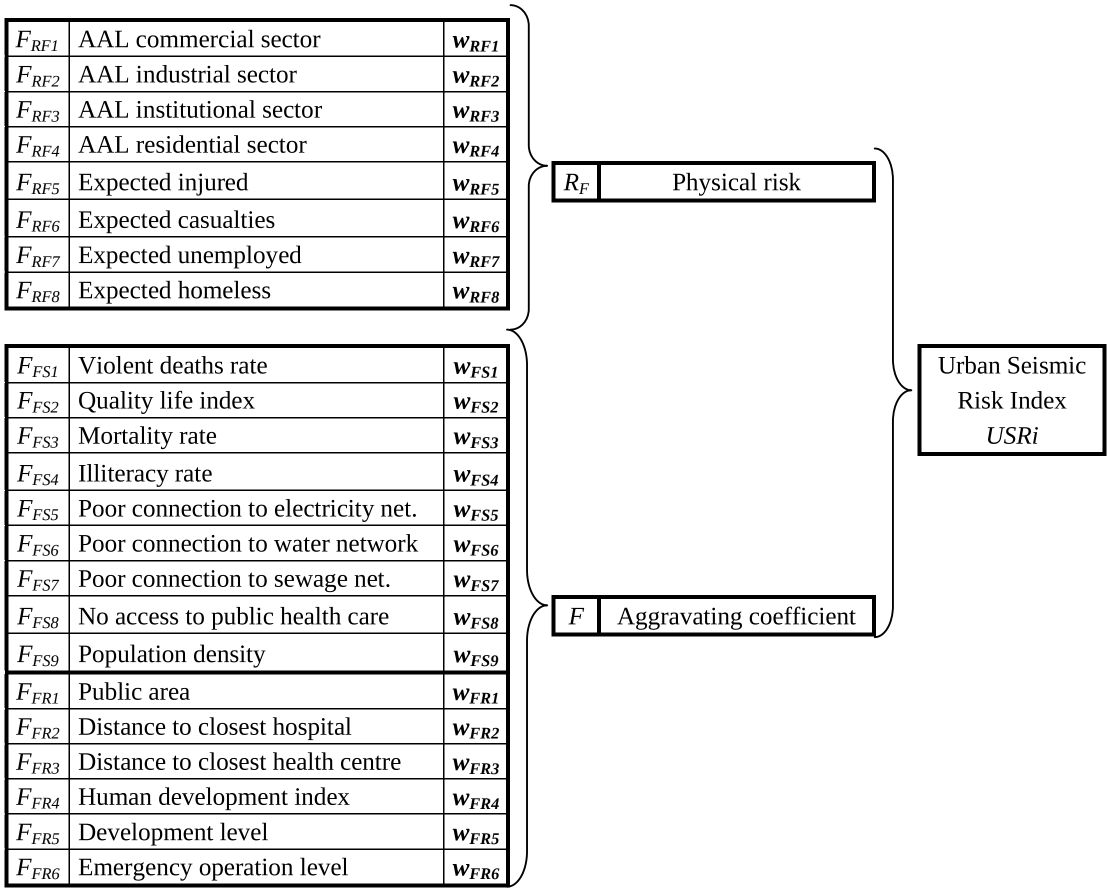


Figure 3. Descriptors used in the analysis

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 we used the transformation functions as the one shown in Figure 4 that standardize the physical risk, social fragility and lack of resilience factors used in this study. Depending on the nature of the descriptor, the shape and characteristics of the functions vary and because of that, functions related to descriptors of the physical risk have an increasing shape while those related to the lack of resilience have a decreasing one; that is, the higher the value of the factors, the lower their aggravation.

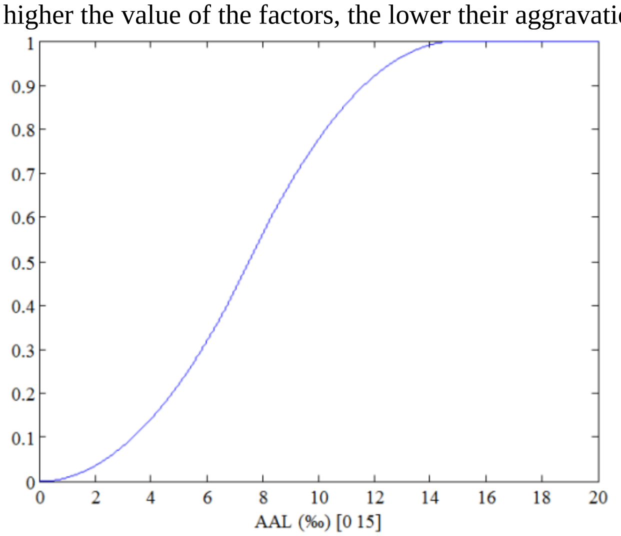
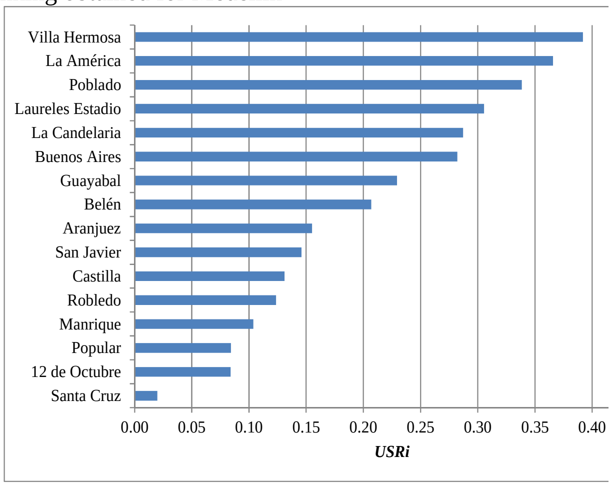


Figure 4. Example of a transformation function

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 opinions and information about previous disasters. 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. 2007). Table 3 presents the results of this study for the 16 counties of Medellín.

Table 3. Results and ranking obtained for Medellín

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



Since the results have been obtained using a GIS tool, maps with the distribution of the results can be built can be of help to decision-makers for communicative and comparison purposes among the decision-makers. For each index a ranking has been generated to classify each result into low, medium-low, medium-high, high and very high. Figure 5 (left) 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 both correspond to low-income areas; this can be explained by the low injury and casualty rates associated to the building classes in these areas even if they correspond to non-engineered systems. 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 is explained by the high physical vulnerability and the consequences in terms of expected casualties, 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 casualties 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 achieved through the development of retrofitting schemes of critical buildings such as hospitals and schools, while also decreasing the physical vulnerability of new infrastructure by enforcement on the use of the earthquake building 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. The highest *F* as can be seen in Figure 5 (right) 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.

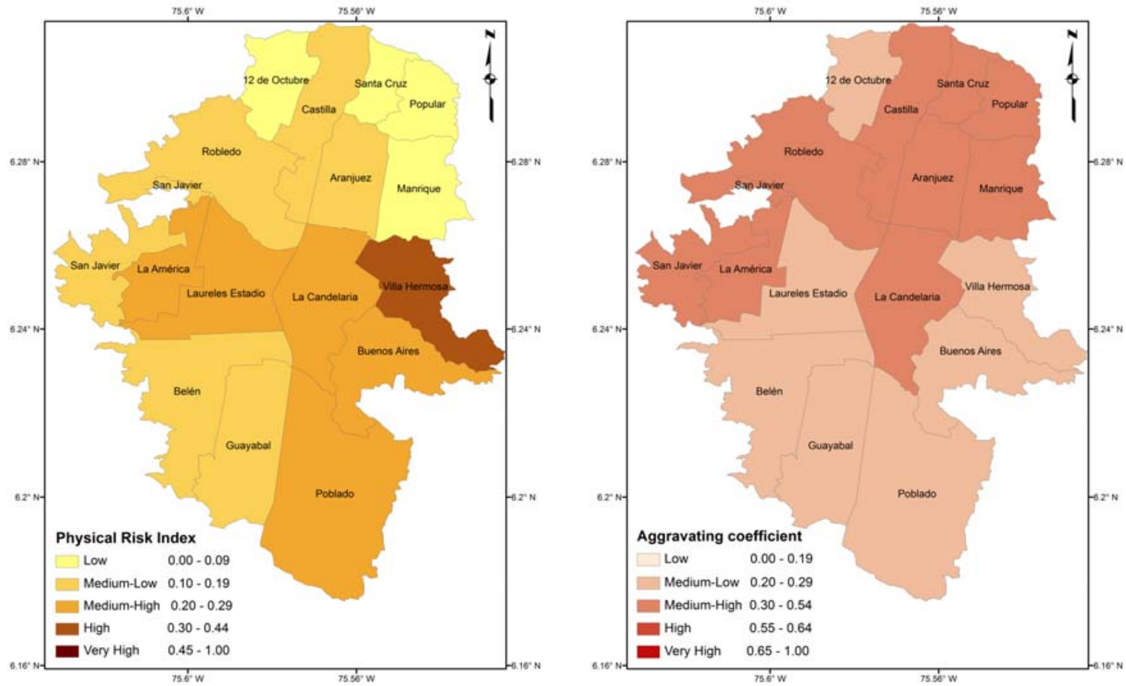


Figure 5. Physical risk index (left) and aggravating coefficient (right) at county level for Medellín

From the results, the descriptors for social fragility and lack of resilience that contribute the most to the aggravating coefficient, *F*, are population density and 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.

Figure 6 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 we can conclude 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.

HOLISTIC RISK ASSESSMENT TOOL

An automated tool has been created to incorporate the physical risk results obtained using the CAPRA-GIS (ERN-AL, 2011) into the holistic risk evaluation. 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 de desired unites. This tool, *Evaluación Holística del Riesgo – EvHo* (CIMNE-RAG, 2014) reads the physical risk files and calculates the different physical risk factors (F_{RFi}) while assigning their correspondent weights (w_{RFi}). Additionally, the tool gives flexibility to the user in order to select the shape of the transformation function for each factor and define their minimum and maximum limits. Figure 7 presents a flowchart of this process.

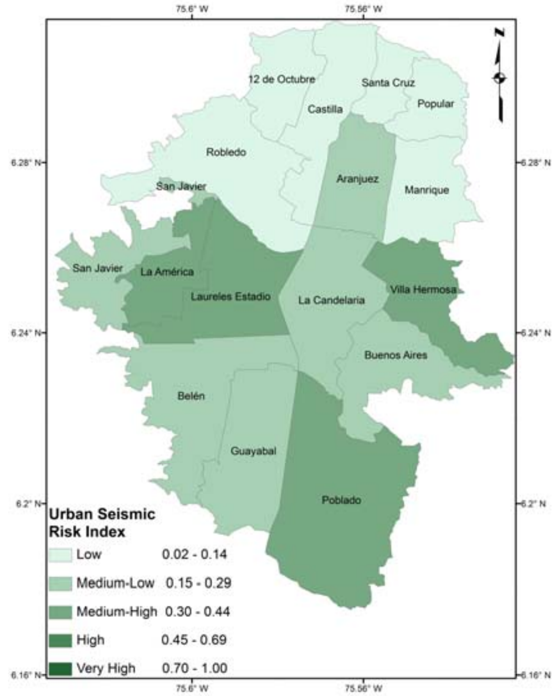


Figure 6. *USRi* results by county for Medellín

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 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 as can be seen in Figure 8. The development of this tool allows the use of physical risk assessment results into more complex and multidisciplinary applications such as the one presented in this study.

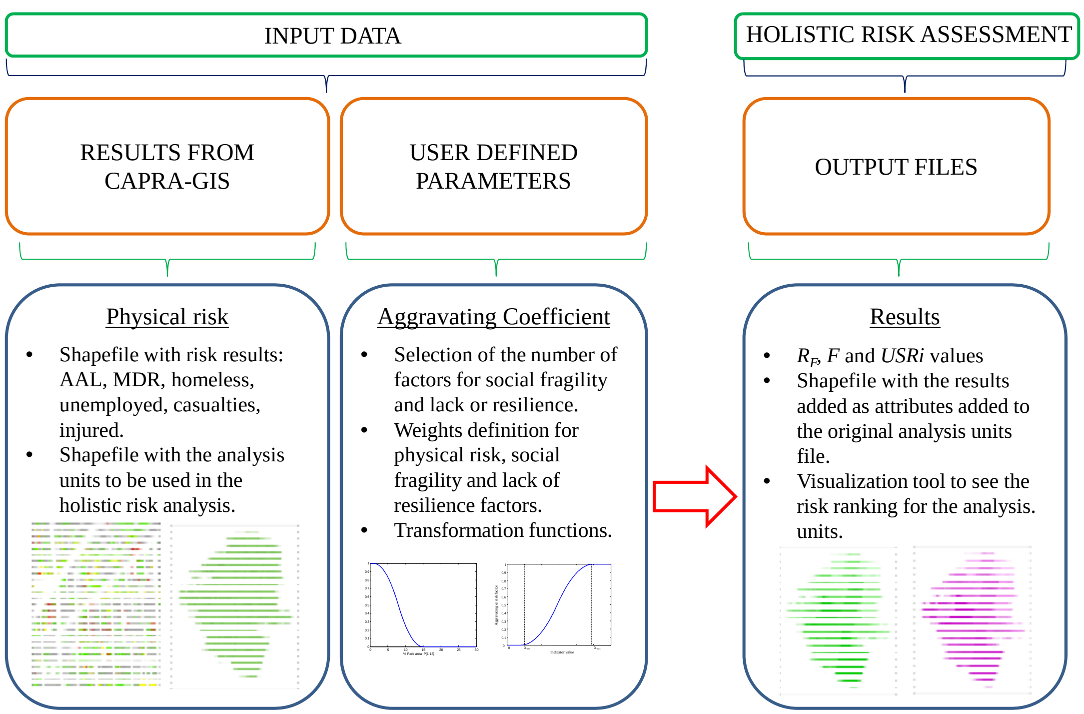


Figure 7. Holistic risk assessment module flowchart

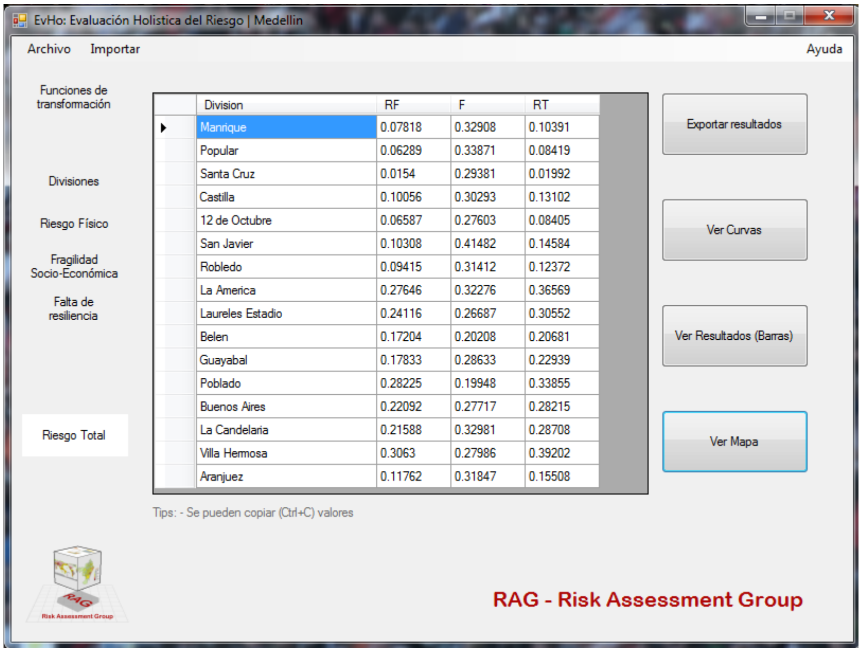


Figure 8. EvHo tool

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. A case study using the CAPRA platform has been developed in Medellín obtaining risk results in terms of different metrics such as the LEC, AAL and PML that constitute a common language to experts, policy makers and stakeholders. Direct physical losses on the private and public building portfolio of the city were quantified and the results obtained from this research can be used to group the risk results in terms of building classes, main use and number of stories; for instance, the building class that concentrates the highest risk is the unreinforced masonry, which is a common structural system in the poorest counties of the city, where some essential buildings such as schools and hospitals have this construction class, and hence a retrofitting scheme for these buildings could be planned.

The probabilistic risk results allow to generate risk maps with a building by building resolution that allow a visualization of the geographical distribution of the future losses; however, it must be clear that the risk should be preferably expressed in terms of loss exceedance rates and probabilities of exceedance. Somehow, the results can be updated every time new information related to the hazard, seismic microzonation zones and more detailed exposed assets database becomes available. 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 can 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. 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 casualties as well as important disruptions occurring at the same time in different zones within the city.

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 has a multidisciplinary approach that accounts not only for the physical damage but for social, institutional, economic and organizational issues related to development 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 on 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, this kind of evaluations can be periodically updated to evaluate the effectiveness of the prevention and mitigation strategies defined for the area of analysis whilst highlighting the more important measures to be taken that are needed to decrease either the physical vulnerability, the social fragility conditions and/or the lack of resilience.

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