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BACKGROUND PAPER

Prepared for the Global Assessment Report on Disaster Risk Reduction 2015

SELECTION OF LOCAL CASE STUDIES WITH FULLY PROBABILISTIC HAZARD AND RISK ASSESSMENTS

International Centre for Numerical Methods in Engineering and INGENIAR Ltda.

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Compilation of Local Fully Probabilistic Hazard and Risk Assessment Cases

Overview

For the Global Risk Assessment of the UNISDR's Global Assessment Report on Disaster Risk Reduction 2015 (GAR15), a coarse grain fully probabilistic risk assessment has been conducted at country level, obtaining in this version the full loss exceedance curve (LEC) from where relevant risk metrics such as the average annual loss (AAL) and probable maximum loss (PML), among others, can be derived. What is also important to highlight, is that following the exact same arithmetic, physical risk can be also assessed at higher resolution levels such as sub-national level using a proxy exposure database and even at city level using detailed building by building information. The selection of the resolution level lies, besides the available information, on if the question that is to be answered requires a detailed approach (e.g. for insurance, cost-benefit of retrofitting and land-use planning).

Since physical risk is being calculated as the convolution of the hazard and vulnerability the selection of a higher resolution level may have influence in the way the exposure and in some cases the hazard are modelled. That may imply an abrupt change in scope, approach and resources associated to the risk assessment, especially in countries and regions where there is little information.

By increasing the resolution level, it is also possible to consider other hazards such as floods and landslides that have a more relative punctual affection whilst also allowing considering more details that are relevant such as the site effects (due to the dynamic soil response) in the seismic hazard and risk analysis.

This background paper presents a selection of fully probabilistic hazard and risk assessments conducted at local (city) level where the same methodology and model used for the GAR13 and GAR15 have been followed; that is, hazard is represented through a set of stochastic scenarios and physical vulnerability is quantified by means of probabilistic vulnerability functions. Even more, all the cases have been calculated using the CAPRA Platform (Cardona et al. 2010; 2012) the same used for the Global Risk Model of UNISDR's GAR from 2013. The information presented in each case is a summary of the complete studies and/or reports. Many of them have also been associated with peer-reviewed papers and proceedings of international conferences and all the relevant references are given in case the reader wants to know more details about any of them.

For all the cases, physical risk, in terms of the same metrics obtained for the 216 countries, is assessed, but in some cases, in addition, those physical risk results have been used as the input data for holistic risk assessments to include risk and resilience drivers. These local cases have been calculated in the framework of both, consultancy activities and academic research. For each case a brief description of the area under analysis and the question that is attempting to answer is presented. Each of these studies constitutes a base for future updates and recalculation since many of the aspects considered in this kind of modelling, especially those related to the exposure and the socioeconomic conditions are dynamic and should be evaluated on a regular basis. Therefore, all these results may be different if evaluated later, for example in 5 or 10 years.

Medellín, Colombia

Introduction

Medellín is the second largest city of Colombia with more than 2 million inhabitants; it is an important trading center and it is highly relevant for the country's economy (DANE, 2014). It lies on an intermediate seismic hazard zone according to the Colombian earthquake resistant building code as shown in Figure 1 and has not been affected by earthquakes in the recent times; anyhow, it does not mean that this is a negligible risk though its perception is low for most of its citizens.

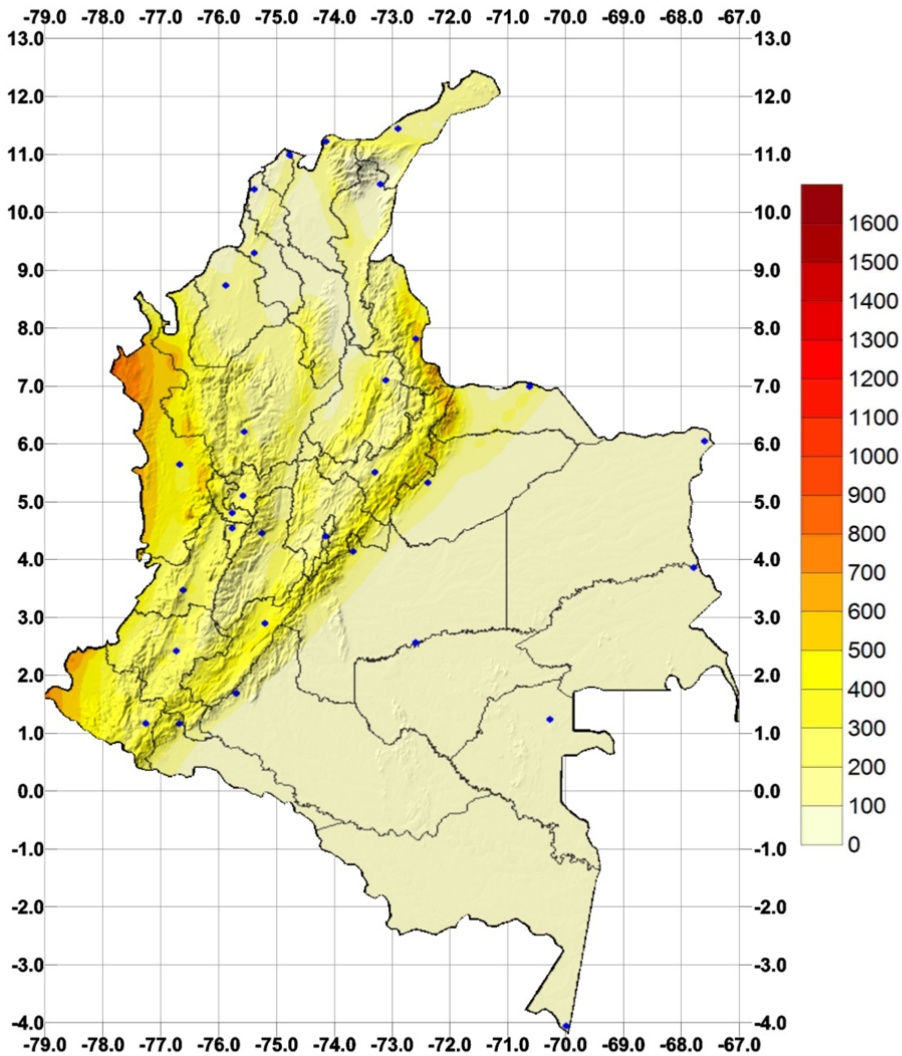

Figure 1. Seismic hazard map of Colombia. PGA, 1000 years – cm/s^2 (From AIS, 2010)

The city has suffered important changes in terms of the building stock characteristics driven by the socio economic conditions, more reflected in the middle and high income areas where low rise houses have been demolished to give space to high rise buildings, generating important challenges not only in terms of the structural engineering but in urban planning.

The city is divided, for administrative purposes, into 16 counties (*comunas*), each of them with approximately area but with important differences not only from the building stock point of view but for the socioeconomic one. Physical risk has been assessed in this study in a building by building resolution but the results have been later aggregated by county.

From a socioeconomic perspective the city has become a prosperous business center but social inequalities still exist among the inhabitants. Violence and its associated consequences still play an important role in the performance of the city and, acknowledging many improvements have occurred in the past years, there is still a long road to transit. The past local governments have invested remarkable resources into education and that is something which results are expected to be observable in the long-medium term.

Purpose of the Risk Assessment and Resolution Level

The purpose of this fully probabilistic seismic risk assessment, conducted in 2013, was to calculate the expected damage and losses in terms of probabilistic risk metrics such as the LEC, the AAL and the PML. On the other hand, because the available information for socio economic data is of high quality, complete and disaggregated by county, the possibility to adopt a holistic risk assessment approach was feasible and then, taking into account social fragility and lack of resilience conditions an aggravating factor was obtained to calculate what is known as the Urban Seismic Risk Index (USRi) (Carreño et al., 2007; 2012).

The assessment was intended to be performed only in the portfolio of buildings, both public and private and account for the direct damages and losses that they are subjected to in case earthquakes strike the city. Though calculation of indirect losses can be performed using as input data some of the results obtained in this assessment, they are out of the scope of this analysis.

An added value of this assessment was the calculation of the casualties in terms of injured and death that the city could face in case that an earthquake occurs. This analysis was performed for a single scenario where a deterministic approach was selected for the occurrence of it but a fully probabilistic approach was followed to estimate damages in the buildings and their correspondent consequences to the occupants.

A holistic risk approach admits disaggregating the results by descriptor and then it is possible to identify which of them are most contributing to the overall results allowing highlighting the most critical risk drivers that should be intervened in a comprehensive disaster risk management scheme. More details of this analysis can be found in Salgado et al., (2014a; 2014b).

The resolution level of the analysis in terms of exposure can be classified as high since a building by building database is being used for the analysis; from the hazard perspective it is also classified as detailed since local site effects have included in the hazard assessment and also, local faults and their correspondent feasible stochastic scenarios, have been considered and generated respectively. USRi has been calculated at county level since, according to the available socioeconomic it was the unit of analysis for which the descriptors were compiled and also, because that kind of risk index is useful at said scale both, for comparative purposes and to plan strategies that aim to reduce risk not on an individual dwelling but on a community basis.

Hazard Assessment

A fully probabilistic seismic hazard assessment has been conducted for the city using as a base the latest national seismic hazard study (AIS, 2010). The calculations were performed in the software CRISIS 2007 V7.6 (Ordaz et al., 2007) and then, in this case hazard is represented through stochastic scenarios, associated to all the seismogenetic sources that contribute to the overall seismic hazard at bedrock level whilst also considering the effects of the dynamic soil response through spectral transfer functions since the city has a seismic microzonation study (SIMPAD et al., 1999). Figure 2 presents the hazard, considering the site effects for peak ground acceleration (PGA) and 475 years return period; polygons denote the 16 counties of the city.

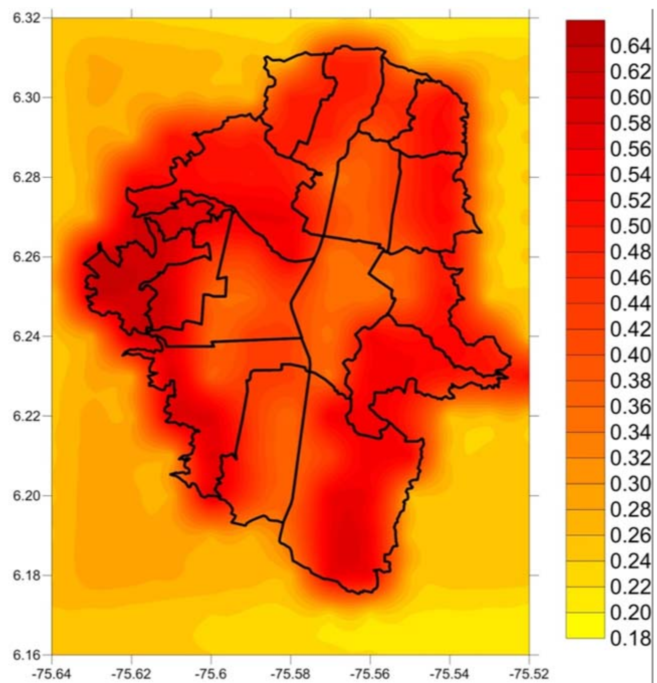

Figure 2. Seismic hazard map considering site effects for Medellín. PGA, 475 years (g)

Exposed Assets

For this local assessment the exposed assets in Medellín consist in the public and private buildings that all together account for more than 240,000 dwellings. The information is based on cadastral databases (Alcaldía de Medellín, 2010) from where information related to the plan area, number of stories, building class, construction year and main used can be derived, allowing a building by building characterization.

Figures 3 and 4 present the characterization of the dwellings in terms of building class and main use respectively. Annex 1 presents more details in terms of other relevant attributes from the exposure perspective.

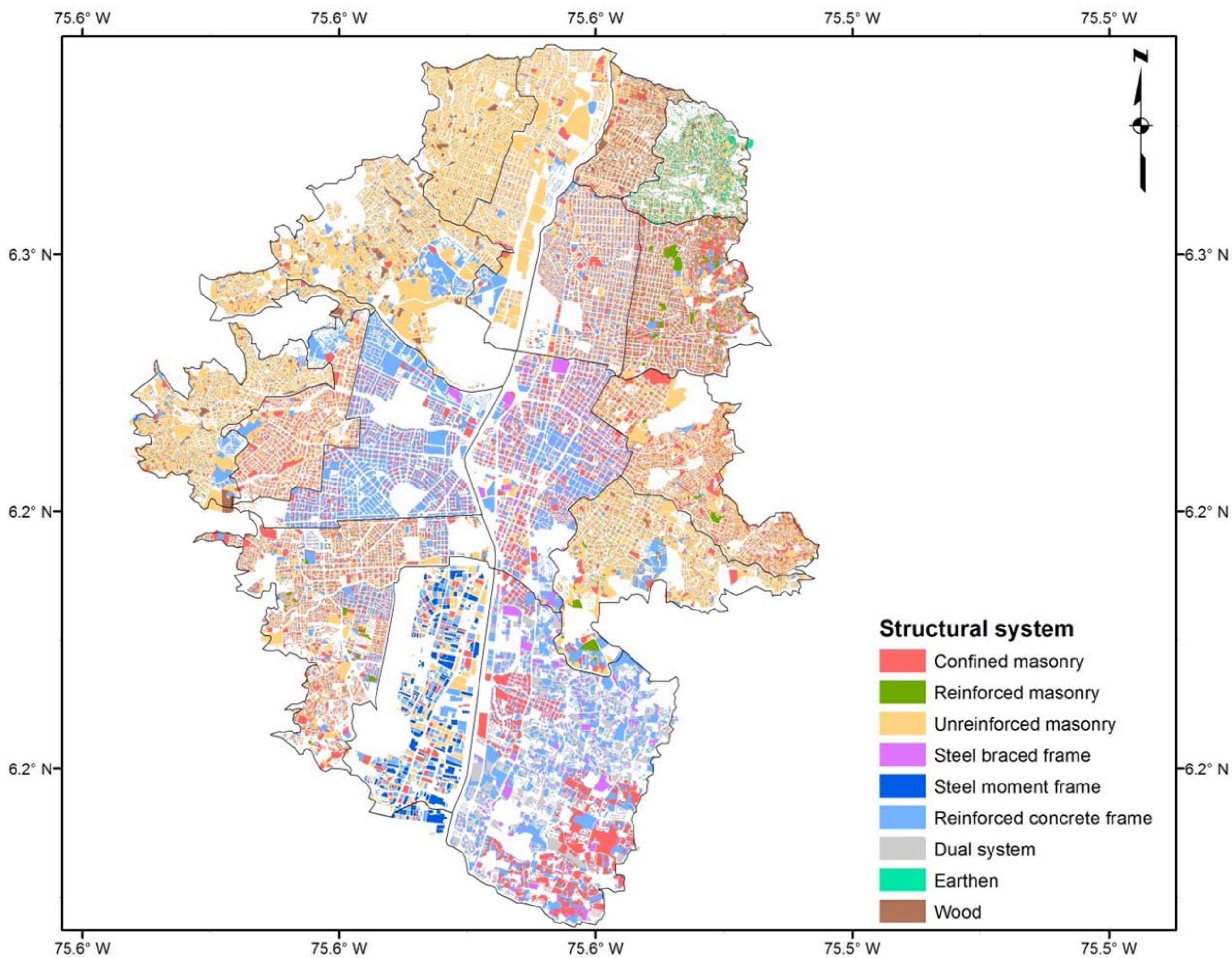

Figure 3. Building class distribution for Medellín

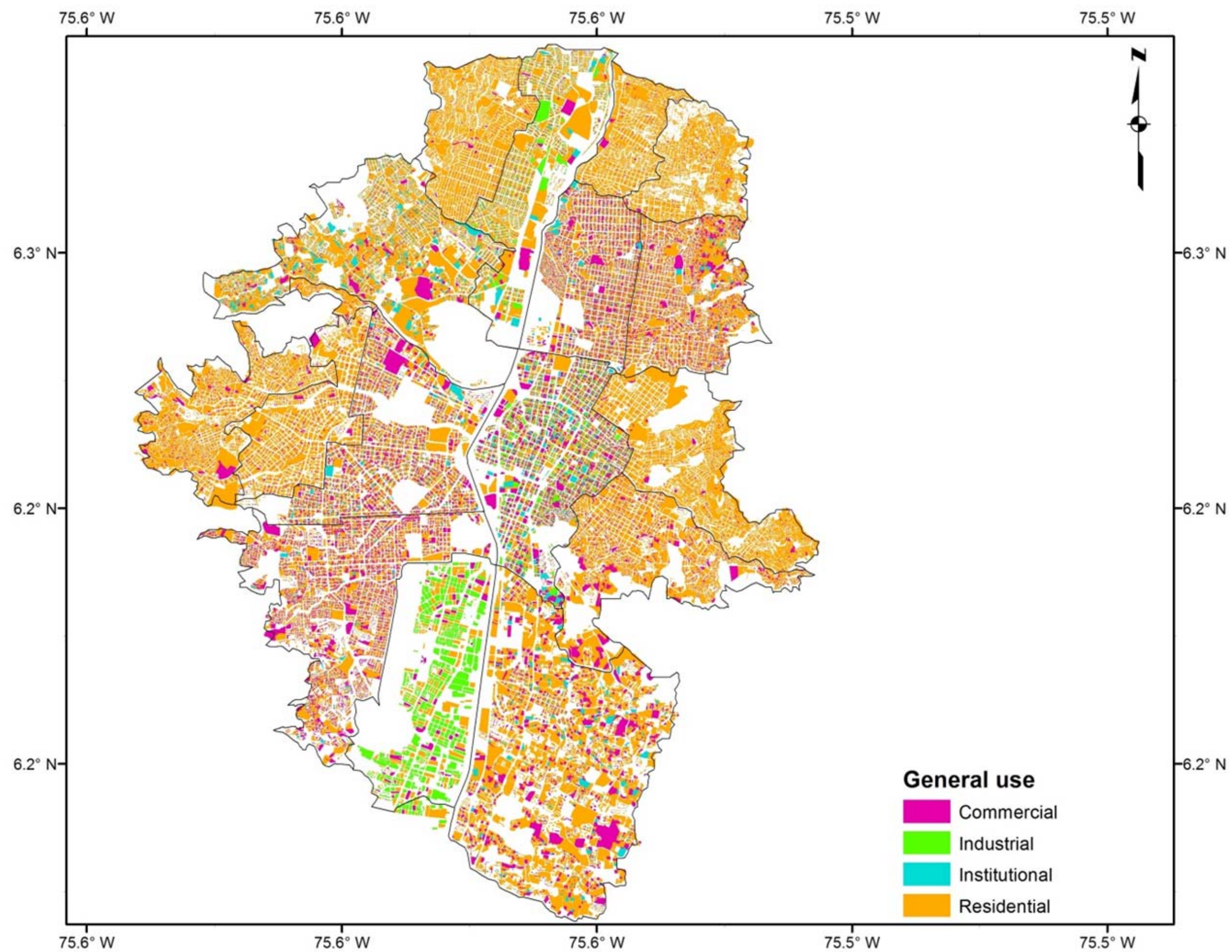

Figure 4. Main use distribution for Medellín

Vulnerability of the Exposed Assets

Given that a fully probabilistic risk assessment was to be performed for Medellín, the representation of the seismic physical vulnerability was done through vulnerability functions that besides allowing a continuous representation of the damages and losses account for the associated uncertainties. The set of vulnerability functions in this case were calculated using the ERNAL-Vulnerability module (ERN-AL, 2009) having in mind that in this case they are only intended to capture the direct physical damage of the dwellings due to seismic forces. Dwellings have been grouped according to building classes (typologies) and for each of them a unique vulnerability function has been assigned. Also, since the hazard representation considers different spectral ordinates and acknowledging that different structures respond differently even when subjected to the same event, a fundamental vibration period has been calculated for each typology and then, the hazard intensities have been associated to them. Figure 5 presents the vulnerability functions for unreinforced masonry units in Medellín. More details about the vulnerability functions for other building classes can be found in Salgado et al. 2014a.

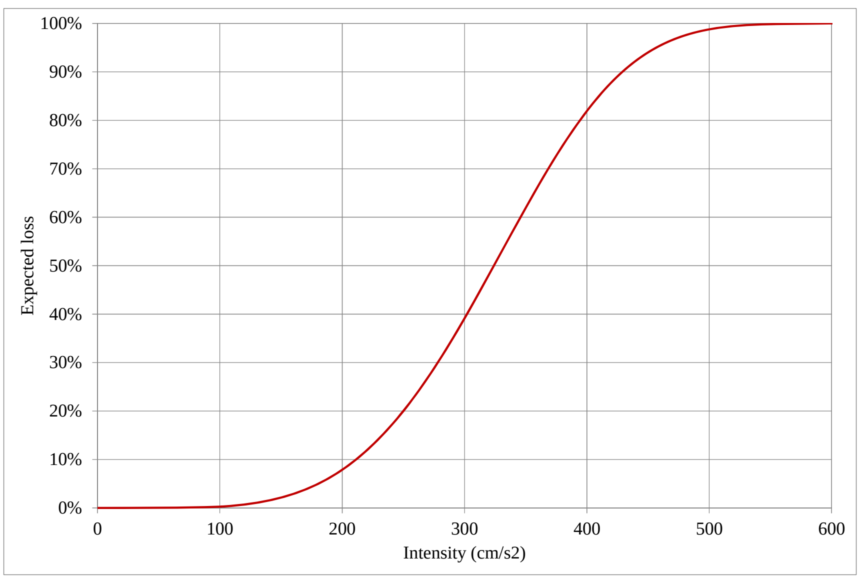

Figure 5. Vulnerability function for unreinforced masonry dwellings

Physical Risk Results

Physical risk results were calculated using CAPRA-GIS (ERN-AL, 2010) and have been obtained after convoluting hazard and vulnerability of the exposed assets and also, since hazard has been represented through a set of stochastic scenarios, then the feasible losses can be quantified in terms of exceedance rates for different levels. This risk results representation is known as the loss exceedance curve (LEC) from where other relevant probabilistic risk metrics such as the average annual loss and probable maximum losses can be derived. Figure 6 presents the LEC whilst Table 1 presents a summary of the risk results in terms of AAL and PML.

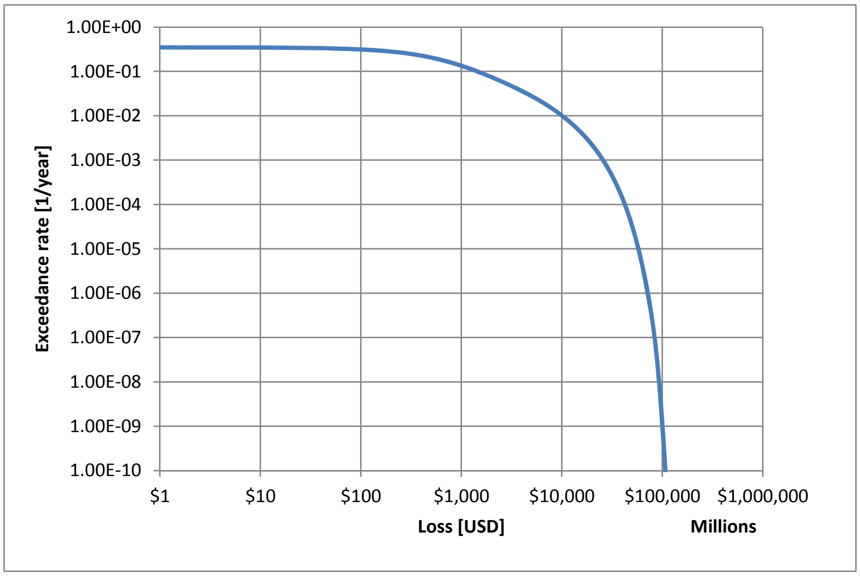

Figure 6. Earthquake loss exceedance curve for Medellín

Table 1. Summary of physical seismic risk results for Medellín

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

Seismic risk results for Medellín display a medium-high category and can be understood that, a loss that occurs on average each 500 years corresponds to almost 14% of the total exposed value. Since the exposed assets database is geo-referenced it is also possible to display in a graphical way the physical risk results. Having in mind that there are several possibilities to choose the risk metric to do so, it has been seen that it is more convenient in terms of relative (to the exposed asset of each dwelling) AAL since it gives the possibility of directly comparing the results and identify which are the elements that are concentrating the most the seismic risk. It is interesting to note that the areas with the higher expected damages and losses are the ones where masonry units constitute the majority of the building stock; its vulnerability, combined with the dynamic soil response. Figure 7 presents the geographical distribution by dwelling of the AAL in Medellín. Annex 1 presents the AAL results in terms of absolute monetary values that are not that representative of the overall risk levels and therefore may not be that useful for comparison purposes.

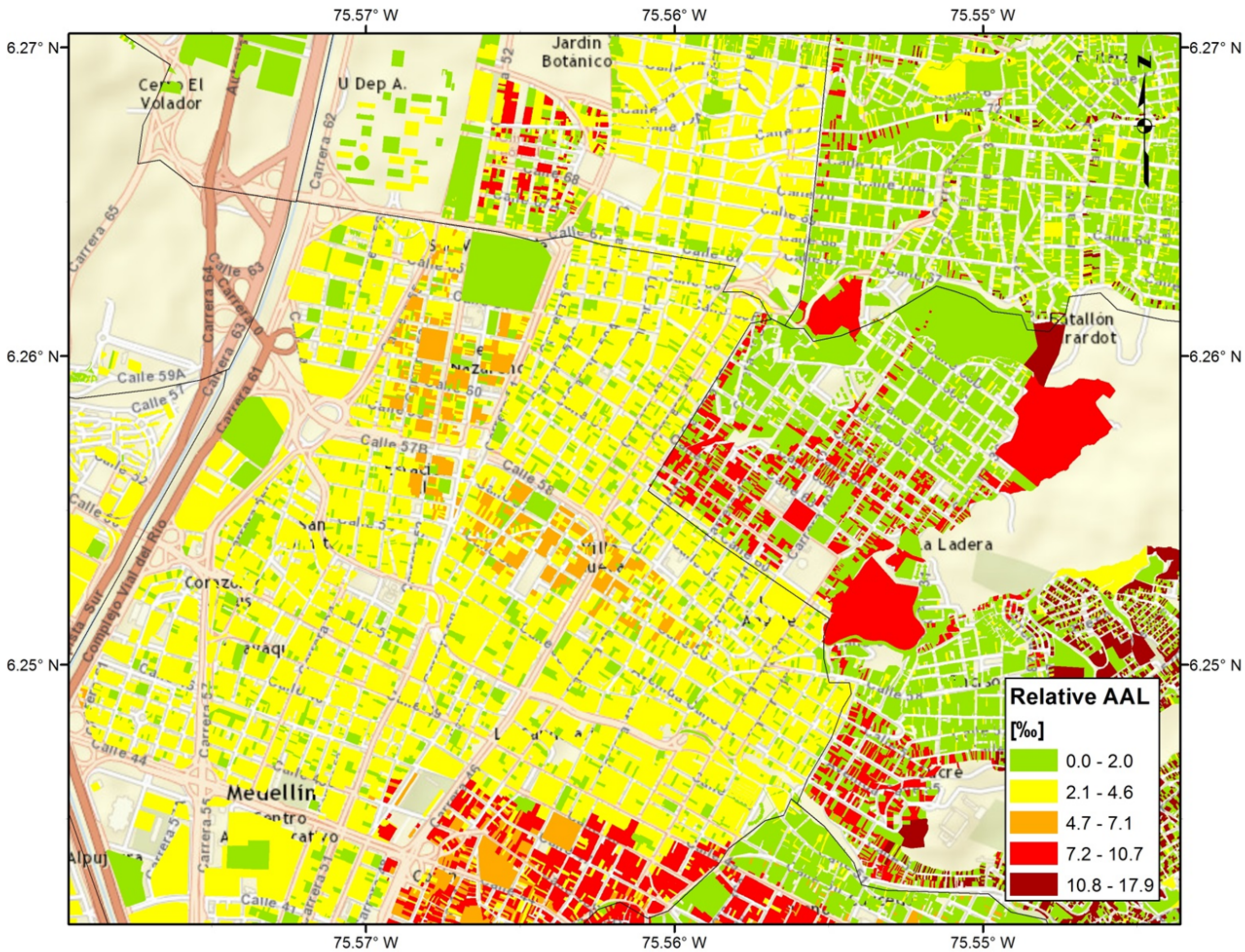

Figure 7. Relative (‰) AAL loss distribution by dwelling in Downtown Medellín (From Salgado et al., 2014a)

Casualties Estimation

By selecting a scenario that generated losses with order of magnitude as the 500 years PML, a casualties' estimation was performed in Medellín. In this case, injured and death vulnerability functions were defined (Coburn and Spence, 2002) according the building classes and an extra attribute, related to the occupancy of the buildings was included in the exposure database. Figures 8 and 9 present the maps, grouped by county, of the number of injured and deaths respectively. These figures are later used as descriptors for the calculation of the physical risk index in the holistic seismic risk assessment.

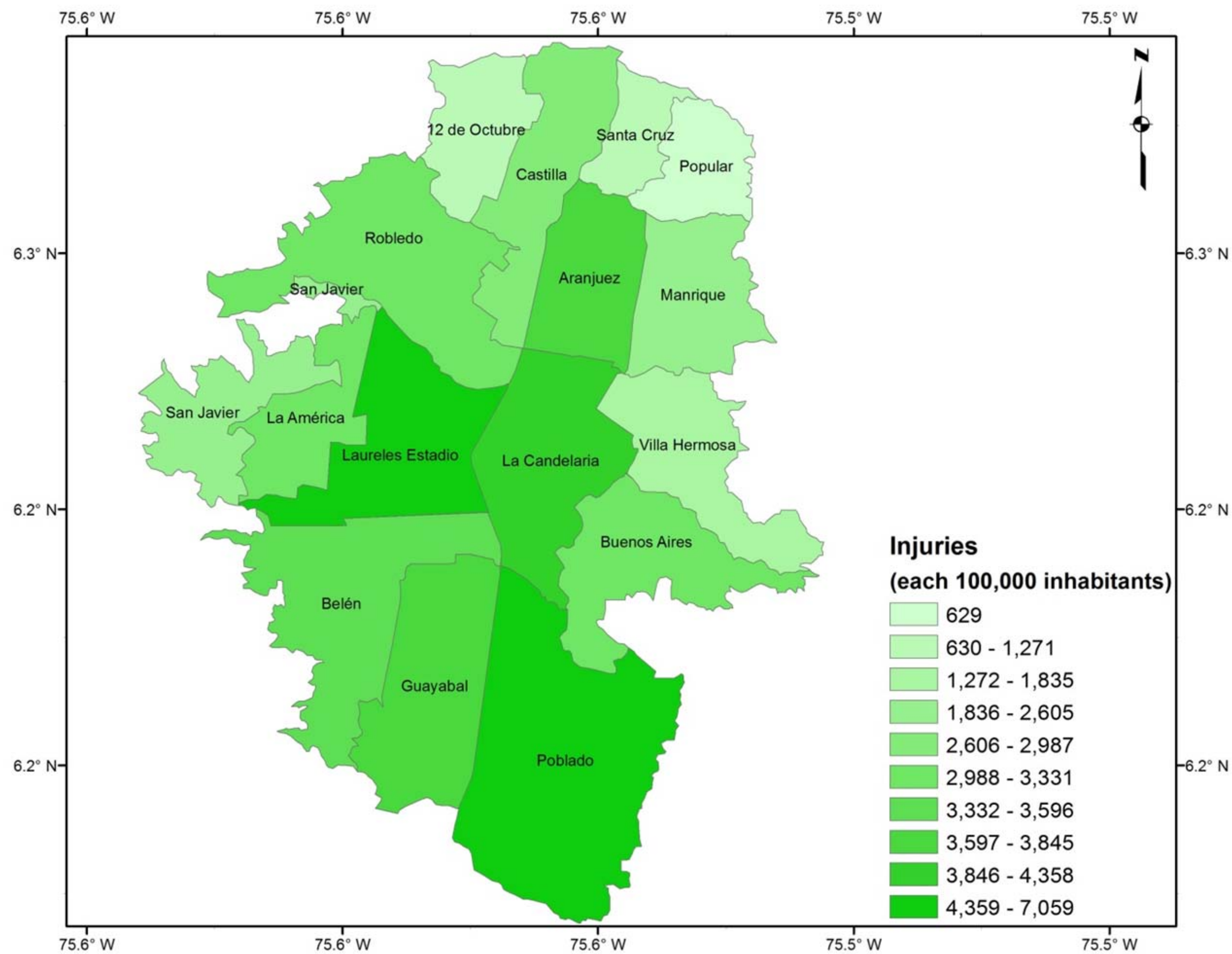

Figure 8. Injuries estimation by county

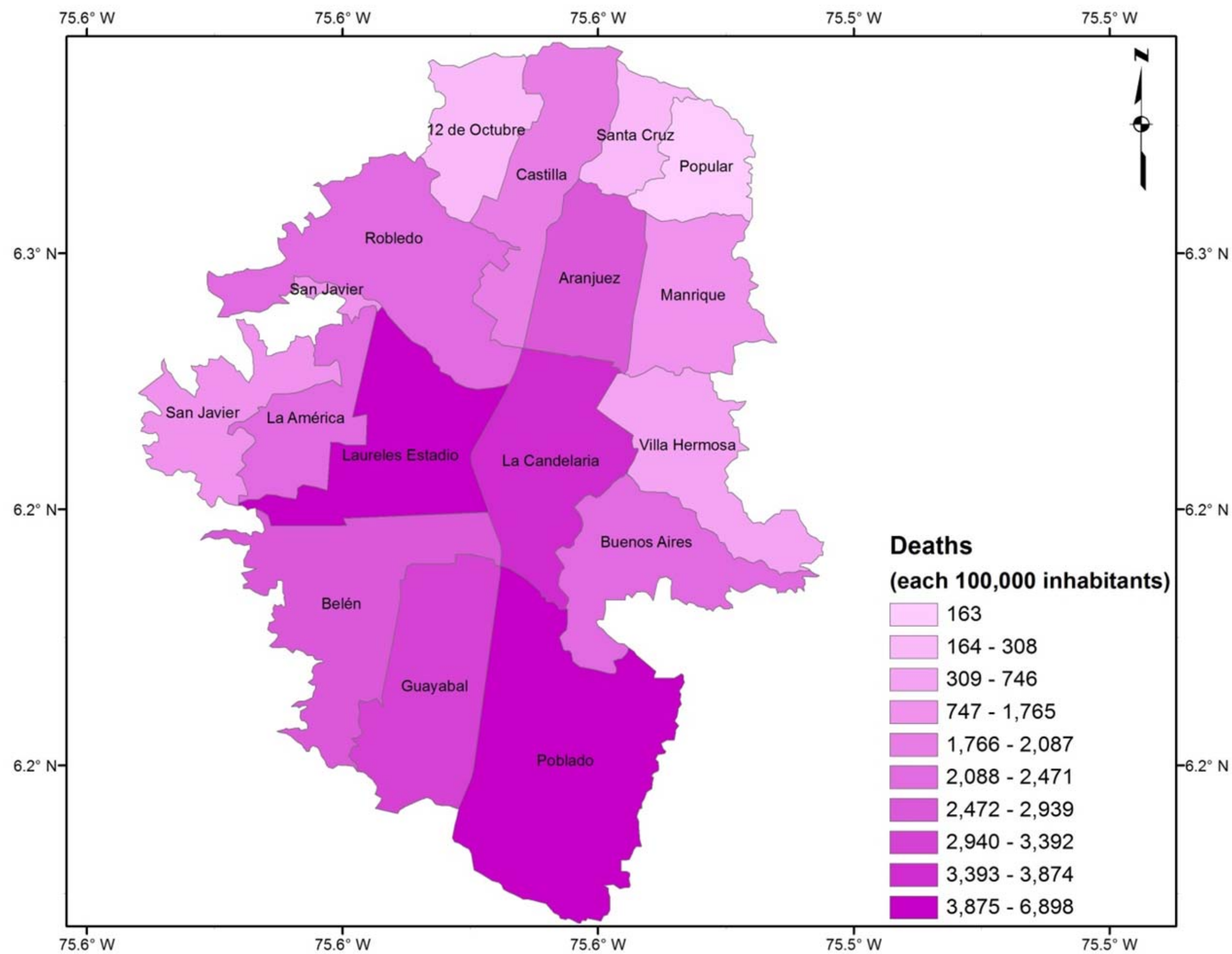

Figure 9. Deaths estimation by county

Holistic Risk Assessment

Though quantifying physical risk constitutes an unavoidable step into the risk identification process, it is not the only dimension that may be of interest in a comprehensive disaster risk management scheme and because of that, approaches to include socioeconomic aspects, such as the one presented in this chapter are relevant. This assessment is based on the approach proposed by Cardona (2001) and later improved by Carreño et al. (2007; 2012) that uses as an input the physical losses and aggravate them by a coefficient that accounts for social fragility and lack of resilience issues. Physical risk, social fragility and lack of resilience indexes are obtained by selecting a set of descriptors that are then aggregated using a weighting procedure. The full list of descriptors and their associated categories can be found in Annex 1. This requires a multidisciplinary approach of the risk assessment that ends in a set of results that constitute a common language for stakeholders and decision-makers. This assessment also allows quantifying both vulnerability and resilience at different dimensions. The robustness of this holistic risk approach has been assessed using Monte Carlo techniques for the definition of the weighting values (Marulanda et al., 2009).

Part of the physical risk index calculation needed the estimation of homeless and jobless. For this case, using the same scenario as for the injured and deaths estimation, calculation of the mean damage ratio (MDR) by dwelling was performed. Given that the use of each element was included, defining a threshold damage level, the unit was considered habitable or not. Annex 1 presents the estimation of said values by county. The holistic risk analysis was performed using the tool EvHo (CIMNE-RAG, 2014) that is the module for said evaluations in the CAPRA Platform.

Figure 10 presents the map in terms of USRi by county in Medellín whilst Table 2 presents a disaggregation, again by county not only in terms of the USRi but in terms of the physical risk index and the aggravating coefficient. In Annex 1 the physical risk index and aggravating coefficient distribution by county can be found.

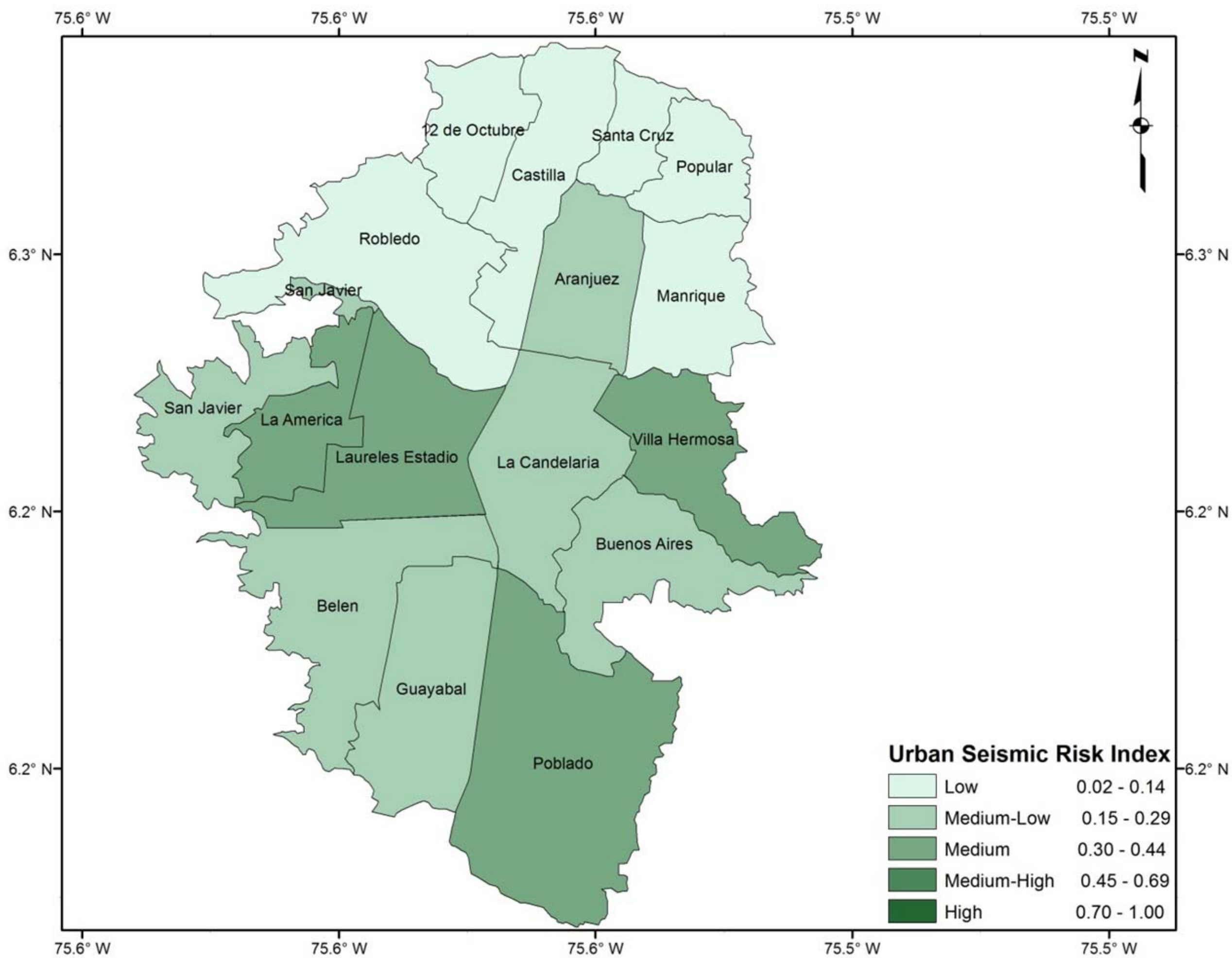

Figure 10. Urban Seismic Risk Index of Medellín at county level (from Salgado et al., 2014b)

Table 2. USRi results by county for Medellín

County	R_F	*F*	*USRi*
8 - Villa Hermosa	0.31	0.28	0.39
12 - La América	0.28	0.32	0.37
14 - Poblado	0.28	0.20	0.34
11 - Laureles Estadio	0.24	0.27	0.31
10 - La Candelaria	0.22	0.33	0.29
9 - Buenos Aires	0.22	0.28	0.28
15 - Guayabal	0.18	0.29	0.23
16 - Belén	0.17	0.20	0.21
4- Aranjuez	0.12	0.32	0.16
13 - San Javier	0.10	0.41	0.15
5 - Castilla	0.10	0.30	0.13
7 - Robledo	0.09	0.31	0.12
3 - Manrique	0.08	0.33	0.10
6 - Doce de Octubre	0.07	0.28	0.08
1- Popular	0.06	0.34	0.08
2 - Santa Cruz	0.02	0.29	0.02

An interesting finding in this assessment is that two of the counties with the higher income levels (Poblado and Laureles Estadio) have a high USRi that is related both to physical risk conditions in terms of expected injured and death since high-rise buildings such as the ones that exist in said areas are far more vulnerable in that dimension if compared with masonry units and to urban planning characteristics such as the availability of public space. In other counties such as Popular and San Javier, the aggravating coefficient is controlled by high violence rates. In Popular, the low physical risk index can be explained by the characteristics of the non-engineered dwellings that in overall terms, do not have large vulnerability when subjected to earthquakes and, generally speaking, do not cause important harm to its occupants. From this can be concluded that being poor does not necessarily mean being vulnerable, notwithstanding that poverty is a very important risk driver.

This holistic approach of risk has been useful not only to identify the concentration of physical risk but also the social and resilience conditions that aggravate the physical risk in the different counties of the city. Distinct stakeholders and actors from different sectorial and institutional point of views, both from public than private sector, have the underlying information that reflects socioeconomic causes, governance absences, drivers of vulnerability that should be intervened to reduce risk from a multidisciplinary and comprehensive perspective. This approach is a key technique to facilitate both to prospective and corrective disaster risk management taking into account the risk reduction as a component of the socio-economic development planning.

Barcelona, Spain

Introduction

Barcelona is the second largest city of Spain lying on the Mediterranean with almost 2 million inhabitants. Although located in a low-to-moderate seismic hazard area, the study of seismic risk constitutes an interesting case since, associated to the low seismic risk awareness, the building stock of the city can be classified, in general terms, as highly vulnerable. Most of the buildings belong to the pre-code period and, if combined with high population density values, the potential effects both in the elements and their occupants are not negligible. There have been several seismic hazard assessments of the Iberian Peninsula and using that base information for the definition of seismogenetic sources and seismicity parameters a probabilistic seismic hazard assessment was performed using CRISIS 2007 V7.6 (Ordaz et al., 2007) from where integrated hazard maps for a selected return period can be obtained, such as the one shown in Figure 11.

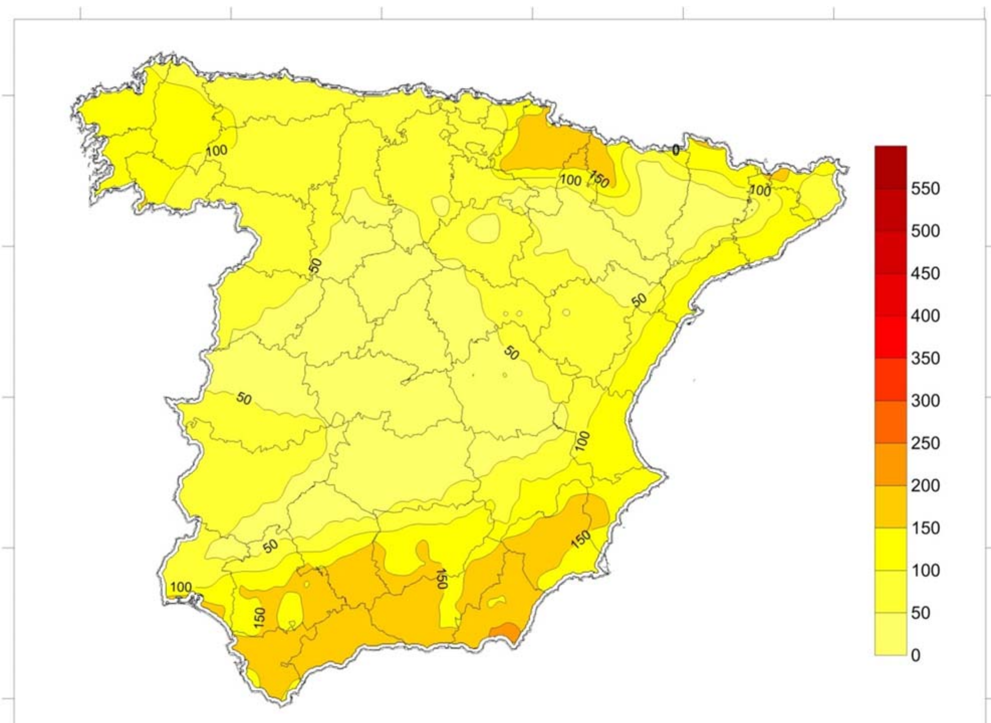

Figure 11. Seismic hazard map of Spain. PGA, 475 years (cm/s^2)

Mainly for taxing purposes, the city has very detailed and high quality information about the buildings, both public and private and relevant characteristics from the structural point of view such as age, number of stories and building classes are available.

This study did not constitute the first seismic risk assessment of the city, but, in fact, this was the first time that it was assessed in a fully probabilistic manner, accounting for a fully probabilistic representation of the hazard in terms of stochastic scenarios and considering the physical vulnerability of the buildings and its occupants through vulnerability functions.

This led to obtaining the risk results in terms of probabilistic risk metrics such as the LEC from, as was explained before, other indicators such as the AAL or the PML can be derived.

Finally, keeping in mind that vulnerability has different dimensions, besides obtaining only the physical one, accounting for issues related to social fragility and lack of resilience, a holistic risk assessment, following the methodology proposed by Carreño et al. (2007) was performed. For administrative purposes, Barcelona is divided into 10 districts that subsequently are divided into 233 Basic Statistical Areas (*Áreas Estadísticas Básicas* – AEB).

Purpose of the Risk Assessment and Resolution Level

The purpose of this study, finished in 2012, was to conduct the first fully probabilistic risk assessment using the CAPRA Platform in Europe. Barcelona constituted a very interesting case since, located in an area of low seismic activity (though not negligible or nonexistent) and having a building stock with high vulnerability since many of the dwellings were constructed before the existence of any building code, rose the interest of quantifying, in a probabilistic way, the losses that may occur in the city.

Also, accounting that physical risk results could be low if compared with other major cities in the world located in more active seismic environments, the interest to calculate an USRi that also considered socioeconomic affairs that consequently could aggravate the conditions in case earthquakes strike the city.

The availability and quality of the data to model all the aspects of seismic risk in Barcelona was high and even allowed selecting a detailed resolution level in terms of hazard and exposure. For the first, different seismogenetic sources were identified and modelled to generate a set of stochastic scenarios, accounting not only for a historical approach in the hazard assessment and, in the other hand, local site effects were considered by identifying homogeneous soil zones and assigning to them unique spectral transfer functions. For the exposure, based on cadastral information a building by building database was assembled with detailed information in all the relevant aspects from a structural, economic and social perspective. Given that USRi is calculated for comparative purposes but also to identify which are the aspects to be intervened in a community basis, socioeconomic information was derived from basic statistical areas and districts; therefore, the results for this aspect are presented at said resolution level.

Hazard Assessment

A fully probabilistic hazard assessment was performed using the software CRISIS 2007 V7.6 (Ordaz et al. 2007). For this case, 10 seismogenetic sources that cover the Mediterranean area as well as the north of Spain were defined. Each of them was modelled as area-sources accounting for a full description of them in terms of geometry. Besides obtaining results in terms of hazard maps such as the one presented in Figure 11, a set of stochastic scenarios was generated to conduct later the fully probabilistic risk assessment. A total of 15 spectral ordinates were considered to account that, buildings with different structural characteristics, respond in a different manner even when subjected to the same earthquake.

Based on a study of Cid et al. (2001), four homogeneous soil zones were identified in the urban area of the city to account for the dynamic soil response. For each of those zones, a mean Vs30 speed was defined and also, the zones were classified in terms of soil classes according to the Eurocode-8. Figure 12 presents the homogeneous soil zones of Barcelona.

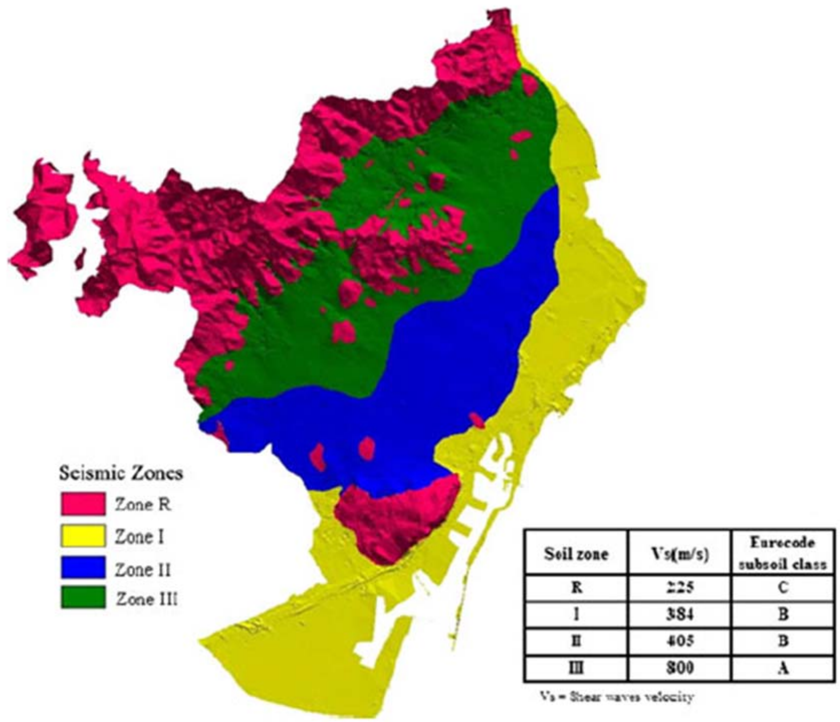

Figure 12. Homogeneous soil zone areas for Barcelona (from Cid et al., 2001)

Exposed Assets

A building by building exposure database with more than 70,000 dwellings was developed for Barcelona. Based on cadastral information, all the relevant parameters in terms of constructed area, number of stories and replacement values were derived. For information about structural characteristics and building classes, information about previous studies of CIMNE in the city was used. More details can be found in Marulanda et al. (2013).

Figures 13 and 14 present the characterization of the dwellings in terms of building class and replacement cost respectively. Annex 2 presents more details in terms of other relevant attributes from the exposure perspective.

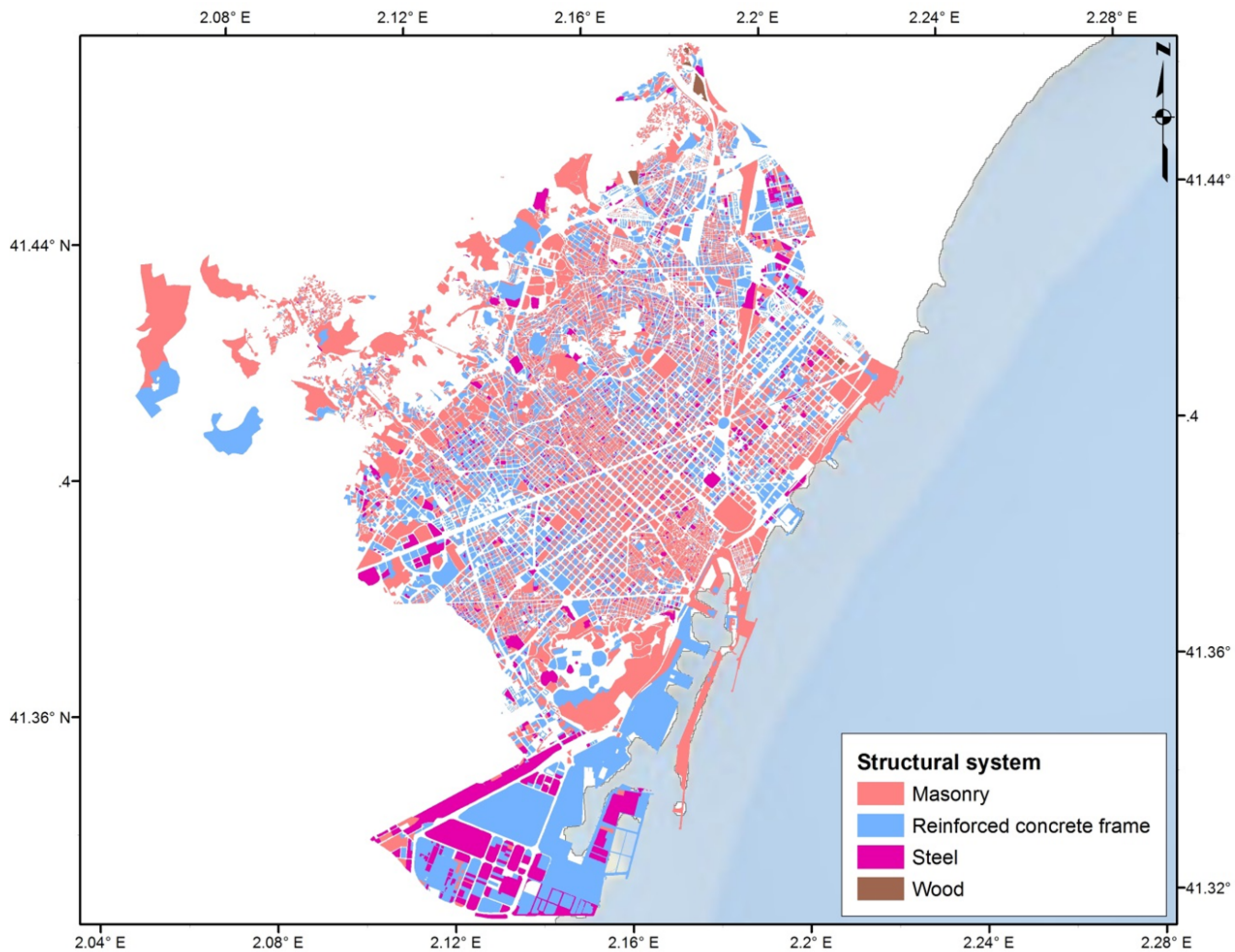

Figure 13. Building class distribution for Barcelona

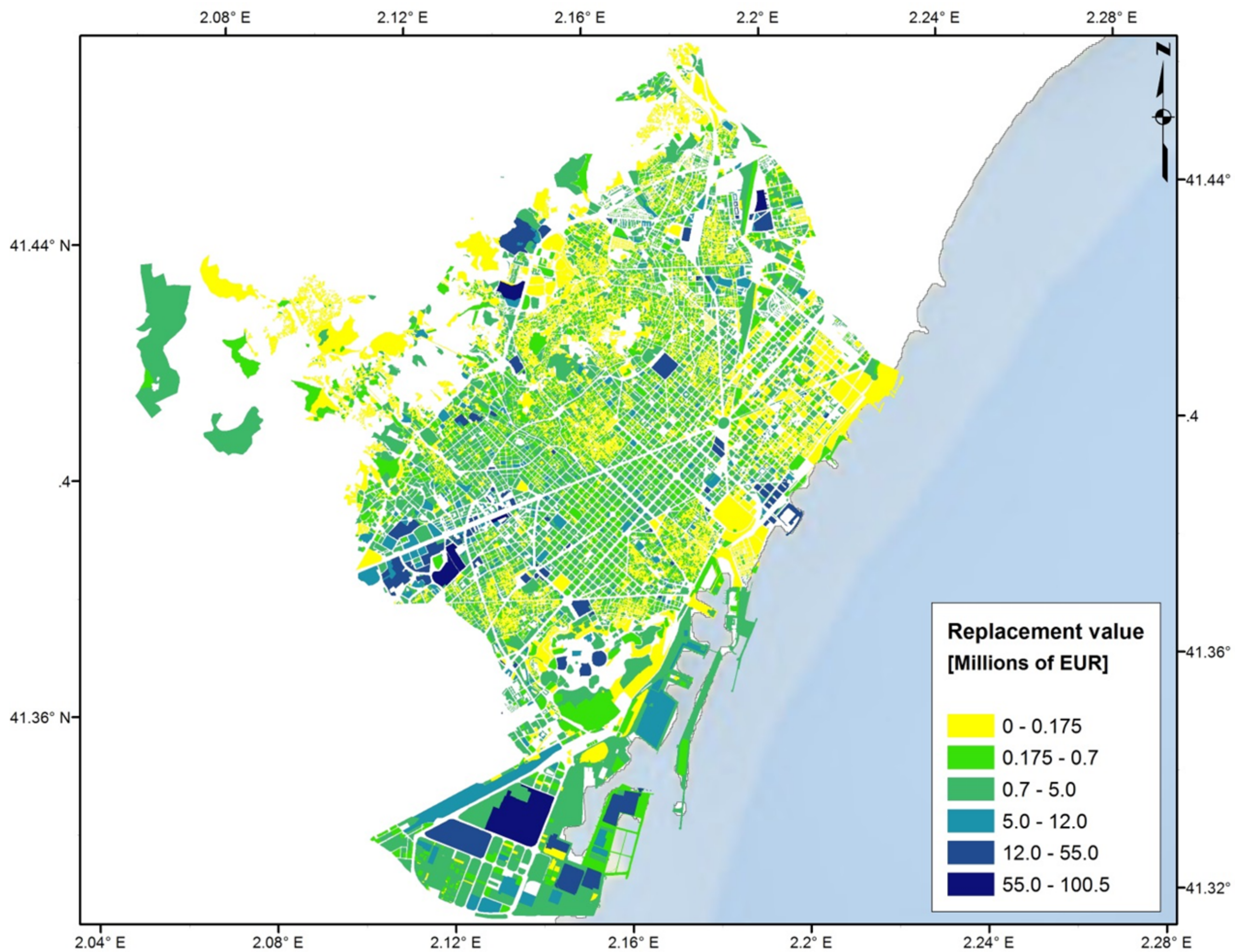

Figure 14. Replacement value by dwelling in Barcelona

Vulnerability of the Exposed Assets

A set of vulnerability functions for the building stock of Barcelona was developed. In general terms, it can be said the building stock is comprised by masonry and wooden dwellings, reinforced concrete frames and steel (moment resistant and braced) frames. Figure 15 presents a vulnerability function for the wooden dwellings. Details about the rest of vulnerability functions used in this analysis can be found in Marulanda et al. (2013) and Annex 2.

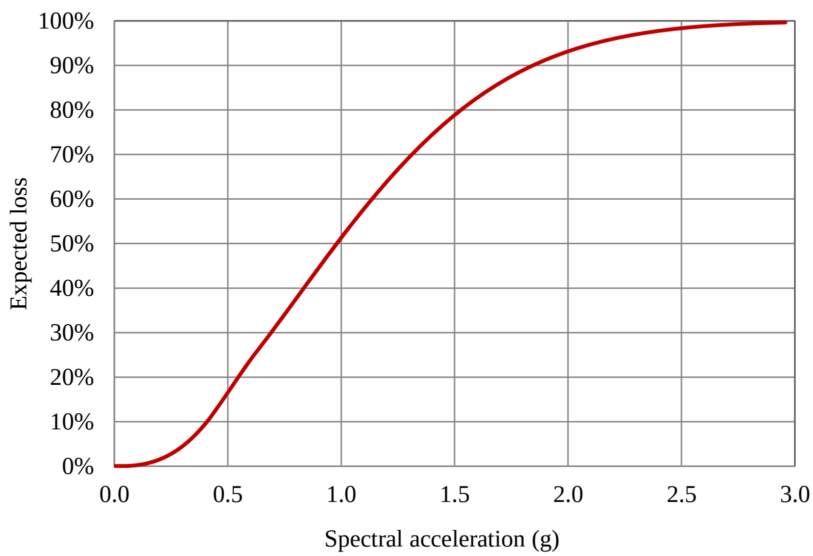

Figure 15. Vulnerability function for unreinforced masonry dwellings

Physical Risk Results

Since a fully probabilistic risk analysis approach was followed, risk results were obtained in terms of probabilistic risk metrics such as the LEC, AAL and PML. The latest can be represented through a plot where in the horizontal axis the return period is included whilst in the vertical, the monetary losses are shown. As can be seen, that is exactly the same information included in the LEC with the difference that, instead of exceedance rates being presented in number of times per year, they were presented in terms of return periods which are its inverse values. Figure 16 presents the PML plot for Barcelona.

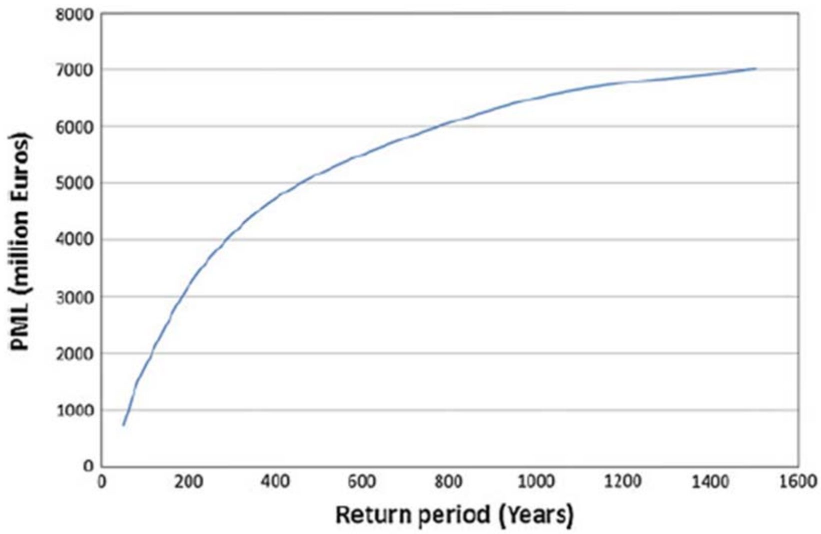

Figure 16. Earthquake PML plot for Barcelona

Table 3 presents the summary of the physical risk results in terms of AAL and PML for selected return periods.

Table 3. Summary of physical seismic risk results for Barcelona

Results		
Exposed value	€ x10^6	31,522
Average annual loss	€ x10^6	72.1
	‰	2.3
PML		
Return period	Loss	
years	€ x10^6	%
100	$1,770	5.6
250	$3,699	11.7
500	$5,172	16.4
1000	$6,510	20.6

From the results it can be concluded that seismic risk in Barcelona is not negligible at all and that, even if the seismic hazard can be classified as low and even more, perceived as not relevant by many of its citizens, the high vulnerability of the portfolio of buildings constitute an important risk driver. On average, it can be seen from the results, that each 1000 years, a loss equivalent to the 20% of the exposed value is likely to occur.

As in the case of Medellín, the cadastral database has been arranged in a GIS platform that allows a geographical representation of the expected damage and losses. For this case, the relative AAL has been selected for said representation and Figure 17 presents the results. From it, is evident that the higher expected losses are located in the oldest areas of the city, that is Ciutat Vella and Eixample districts. Newer areas of the city such as Les Corts and Sant Marti have a considerable lower seismic vulnerability and consequently, lower seismic risk.

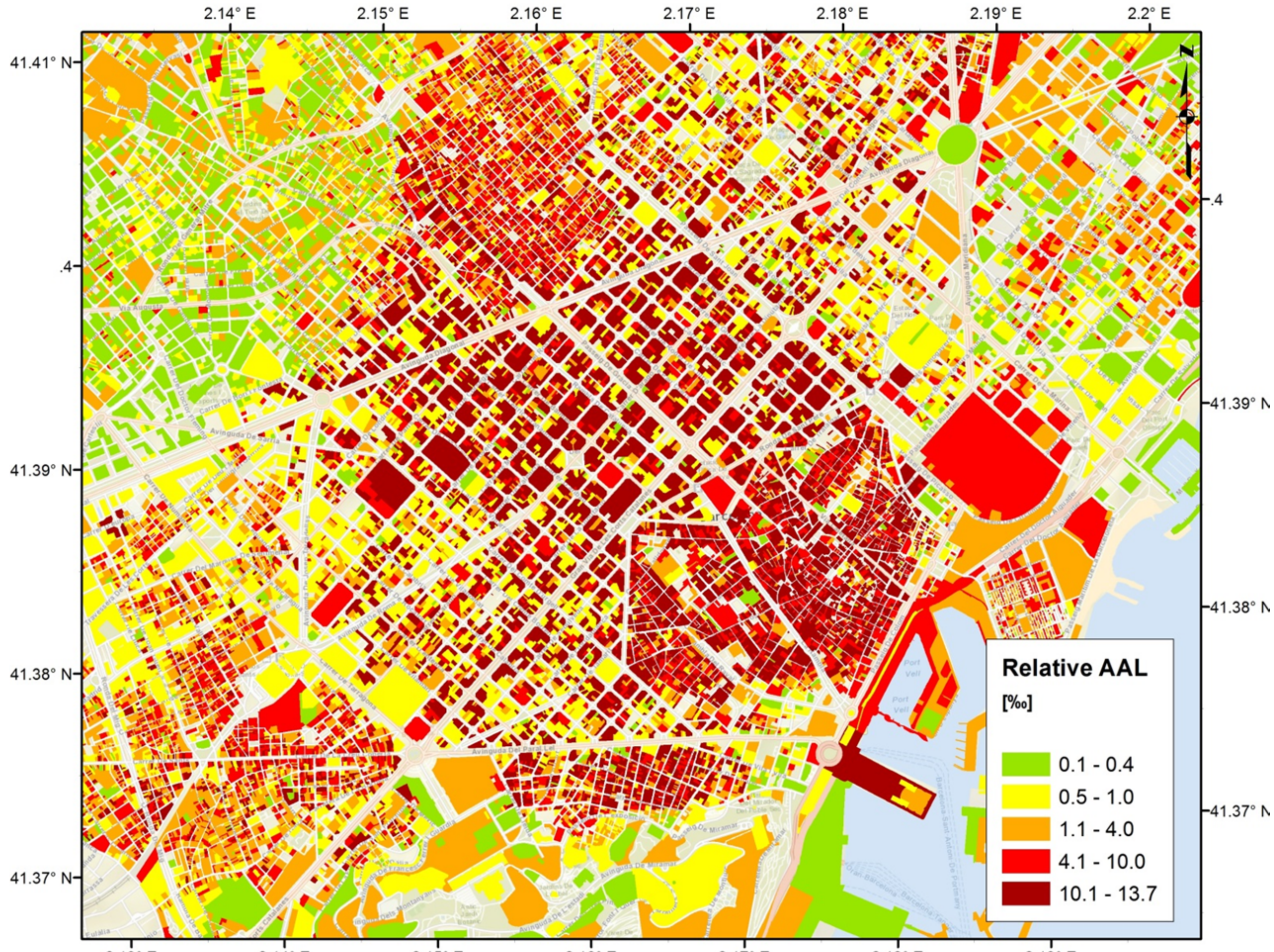

Figure 17. Relative (‰) AAL loss distribution by dwelling in downtown Barcelona (From Marulanda et al., 2013)

Casualties Estimation

Given that casualties in terms both of injured and death are important physical risk descriptors in a holistic seismic risk assessment framework, they were estimated for Barcelona. In this case the results were obtained in terms of annual average values such as the ones presented in Tables 4 and 5.

Table 4. Average annual deaths by earthquakes in Barcelona

Dead people		
Exposed value	Inhabitants	1,639,880
Average annual loss	Inhabitants	28.3
	‰	0.017

Table 5. Average annual injured by earthquakes in Barcelona

Injured people		
Exposed value	Inhabitants	1,639,880
Average annual loss	Inhabitants	113.6
	‰	0.07

Holistic Risk Assessment

For the reasons presented before, Barcelona constitutes a very interesting case of urban areas where seismic risk can be evaluated considering not only the physical dimension but the socioeconomic one. Following the methodology proposed by Carreño et al. (2007), an Urban Seismic Risk index was calculated both at AEB and district level. Several descriptors were considered for the calculation of aggravating coefficient and a full description of them is presented in Annex 2.

Figure 18 presents the USRi by district from where it can be seen that those areas that have higher AAL correspond also to the ones with higher USRi after a holistic risk assessment.

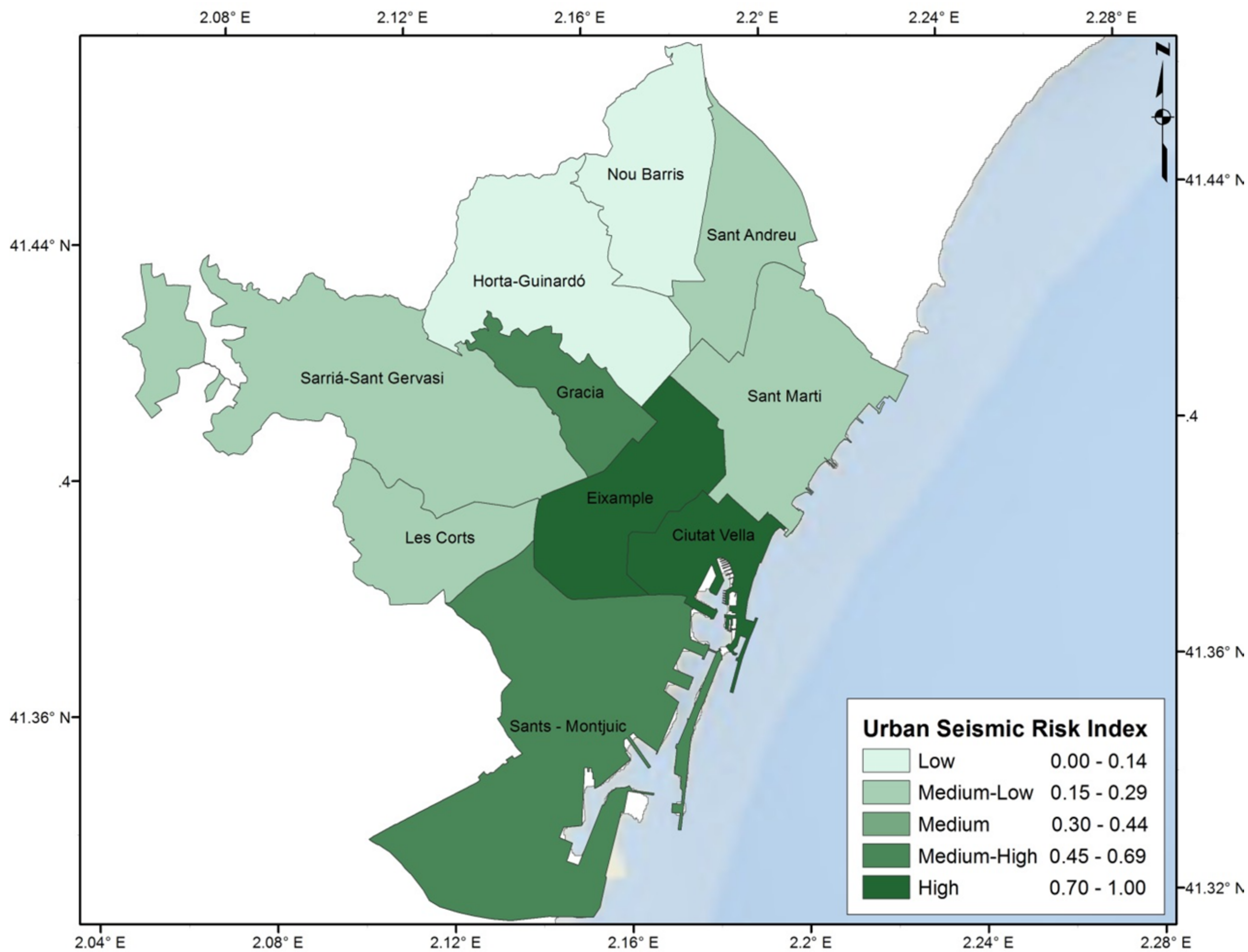

Figure 18. Urban Seismic Risk Index of Barcelona at district level (from Marulanda et al., 2013)

Table 6 presents the USRi results by district for Barcelona from where it is possible to see how the combination of both, physical risk index and aggravating coefficient lead to a more comprehensive overview of the overall results.

Table 6. USRi results by district for Barcelona

District	R_F	F	*USRi*
Ciutat Vella	0.68	0.44	0.99
Eixample	0.55	0.28	0.70
Gracia	0.39	0.29	0.50
Sants-Montjuic	0.37	0.25	0.46
Sant Martí	0.11	0.66	0.19
Sarriá - Sant Gervasi	0.14	0.17	0.17
Sant Andreu	0.10	0.50	0.15
Les Corts	0.11	0.23	0.14
Horta-Guinardó	0.09	0.39	0.13
Nou Barris	0.03	0.62	0.05

This assessment constitutes another example where integrated and multidisciplinary research on disaster risk reduction has helped to reduce the gap between the risk assessments per se and the decision-making process to be carried on by different stakeholders (Carreño et al., 2014).

Bogotá, Colombia

Introduction

Bogotá is the main city in Colombia with more than seven million inhabitants according to the latest census (DANE, 2005) holding also the main business district in the country comprised by industries of different sectors that altogether have the largest urban participation in terms of GDP (DANE, 2014). The city is located in an intermediate seismic hazard zone according to the Colombian earthquake resistant building code as shown in Figure 1 and also, because some zones lie on what used to be lakes, soft soil characteristics are predominant in many areas.

The building stock of the city is, as any other Latin American urban center, mainly comprised by masonry dwellings with another characteristic that is that more than 60% of the dwellings were built following informal and non-engineered building practices, even when building codes exist and are mandatory in the country since 1984.

The city is divided for administrative purposes into 20 localities and covers a vast area of more than 308 km^2 in the urban area. From south to north, the extension of the city is of more than 40km.

Purpose of the Risk Assessment and Resolution Level

Having in mind that different probabilistic risk assessments had been previously performed in Bogotá following similar methodologies (CEDERI, 2004; 2005; Acevedo, 2005; ODCA-ITEC, 2008; ODCA-INGENIAR-ITEC, 2008), given that updates on the cadastral database in terms of dwellings' values were available in 2011, a seismic risk assessment, now using different modules of the CAPRA Platform was performed. The base hazard model corresponded to the one developed in the framework of the update of the national building code (AIS, 2010; Salgado et al., 2010).

Also, in 2011 after a meeting of the American Geological Society in Manizales, the proposal of a new lithospheric interpretation that modified the seismic hazard in the city (Salgado et al., 2011; 2013) lead to a new hazard model which effects wanted to be evaluated in terms of physical risk in the city.

The exposure database has a building by building resolution level with more than 800,000 elements; the most challenging in urban assessments so far in the CAPRA Platform that based on previous studies were characterized in terms of structural, social and economic characteristics.

This study was not intended to determine if the new tectonic proposal was right or not, but to assess in a counterfactual way, the effects in terms of physical risk through the appropriate metrics the variations due to the changes in the hazard model, that is, keeping exposure and vulnerability constant.

Finally, it is worth to stress that in cases when different interpretations exist about a factor that can determine several and important modifications in the risk results, in this case the base seismic hazard model, it is relevant to at least, assess the impact and make that information available to the public.

Hazard Assessment

Two separate probabilistic seismic hazard assessments were performed at national level accounting for more than 35 seismogenetic sources. The first one, as mentioned before, corresponded to the one developed by the Colombian Association for Earthquake Engineering (AIS) in the framework of the update of the national earthquake resistant building code (NSR-10), whilst the second one corresponds to the new lithospheric proposal (Vargas and Mann, 2013) that proposed the existence of a seismogenetic source denoted as *Caldas Tear*, that would modify the hazard levels in some main cities of Colombia (Salgado et al., 2013), in the case of Bogotá, decreasing it. The outputs of both hazard models correspond to separate sets of stochastic scenarios that were later used to calculate physical seismic risk in fully probabilistic terms.

Bogotá has had several microzonation studies (CEDERI, 2006) as well as other soil exploration projects that allow the identification of several homogeneous soil zones and then take them into account in the hazard and risk assessment as presented in Figure 19.

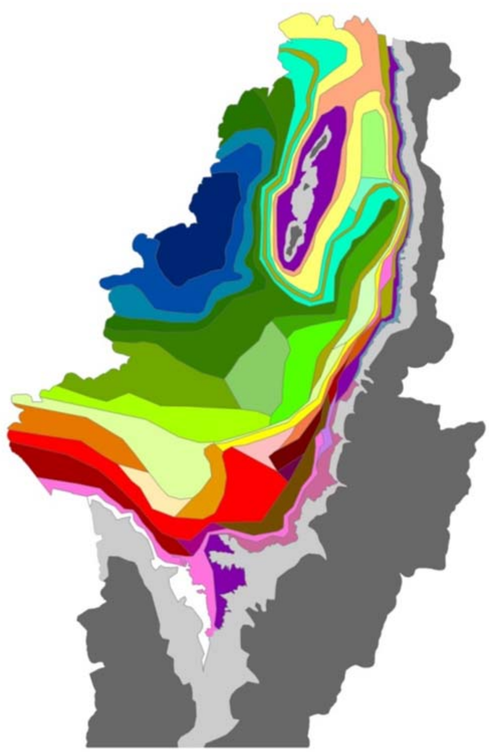

Figure 19. Homogeneous soil zones for Bogotá (From CEDERI, 2006)

Because many dwellings of the city lie on what used to be lakes 60 or 70 years ago, there is a strong presence of soft soils that may have strong influence on the hazard levels and also increase the expected damage and losses in the buildings according to their structural characteristics as can be seen in Figure 20 where spectral transfer functions for soft soil areas for different intensities at bedrock level to account for the non-linearity of the soil response.

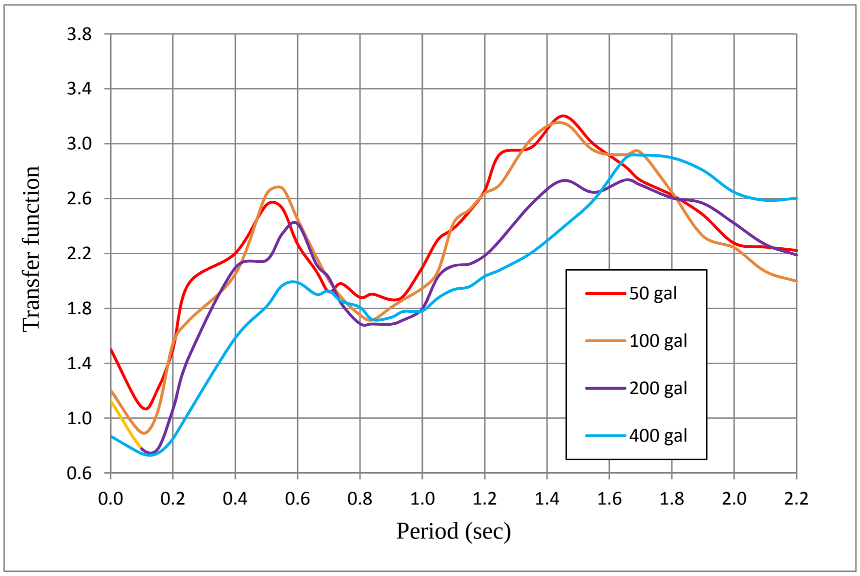

Figure 20. Soft soil spectral transfer functions

Figure 21 presents the hazard, considering the site effects for peak ground acceleration (PGA) and 475 years return period using the official seismic hazard model.

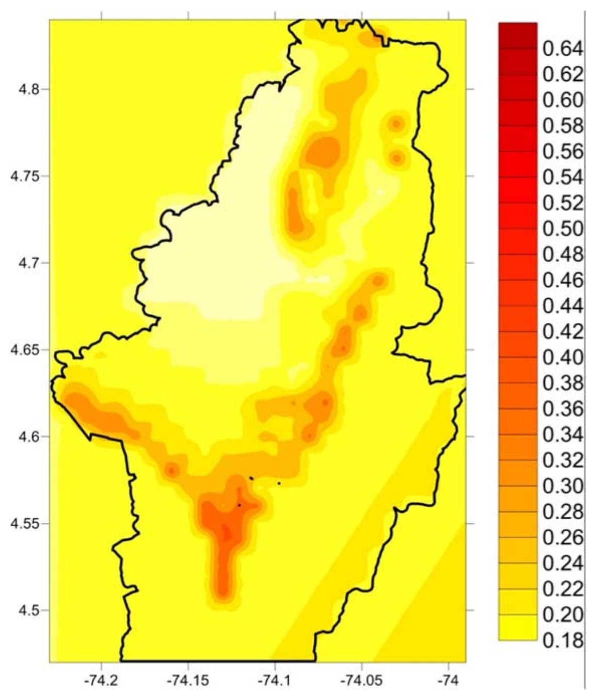

Figure 21. Seismic hazard map considering site effects for Bogotá. PGA, 475 years (g)

Exposed Assets

The building's exposure database of Bogotá has more than 860,000 dwellings that becomes a challenge not only in computational requirements but in the data needed to identify and characterize them in a proper manner to conduct a risk assessment. Based on the cadastral information the location and geometry of each element was captured and then, knowing also the number of stories the total constructed area was inferred.

In Colombia, for taxing purposes there are six socioeconomic levels being 1 the poorest and 6 the richest; for the case of Bogotá this information is associated to each element in the database and, combining said value with the main use of each element, a base index replacement cost per constructed square meter was derived. More details about this can be found in Zuloaga (2011).

The quality of completeness of the data can be classified as high since the existing information; all the relevant characteristic of the elements could be captured. Figure 22 presents the building class distribution along the city while Figure 23 presents the main use distribution. It can be seen that most of the elements have associated a masonry building class while the predominant use for many parts of the city is the residential.

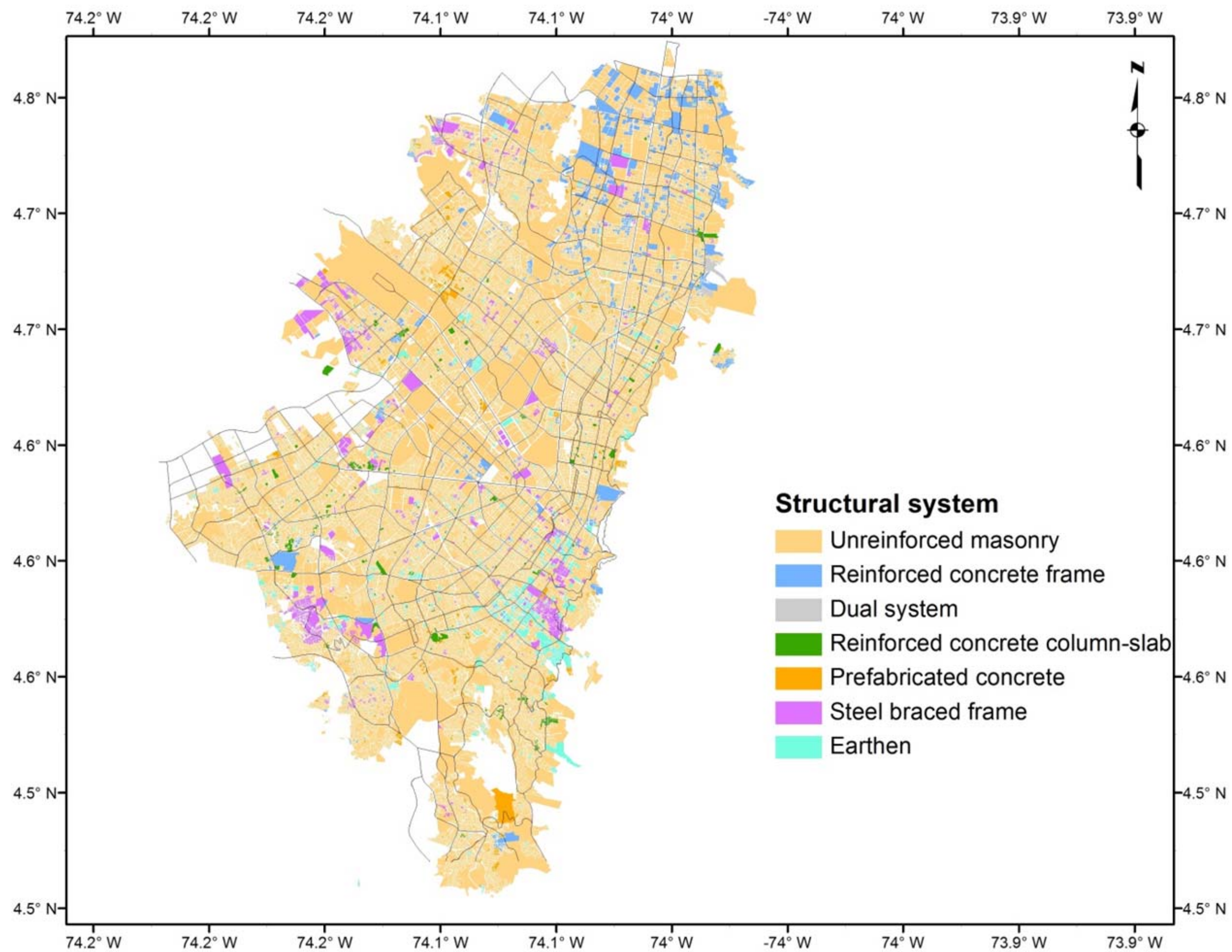

Figure 22. Building class distribution for Bogotá

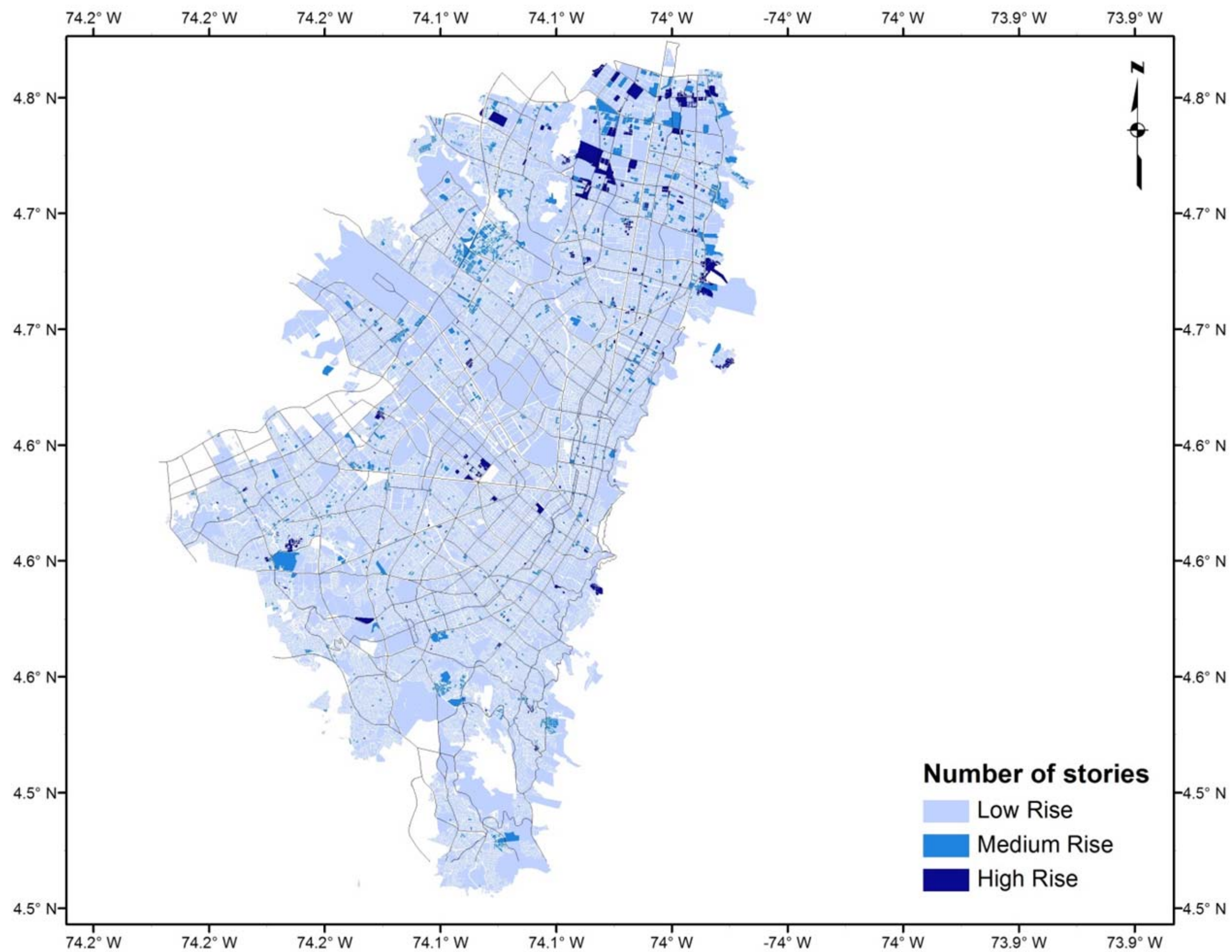

Figure 23. Number of stories distribution for Bogotá

Vulnerability of the Exposed Assets

Seismic physical vulnerability was characterized in terms of vulnerability functions that, as explained before accounts for both a continuous and probabilistic representation. Considering the characteristics of the dwellings and based in previous studies of the city and other Latin American cities with similar building stock characteristics (ERN-AL Consortium, 2009) a set of vulnerability functions was developed.

The vulnerability functions used in this study are intended only to capture the direct damage associated to the ground shaking and other indirect effects such as building interruption or fires ignited after the quake are not considered and are out of the scope of the assessment.

Figure 24 presents the vulnerability function assigned to the mid-rise reinforced concrete frames, very common in middle and high income areas of the city. More details about the vulnerability functions for the rest of building classes can be found in Annex 3 and Zuloaga (2011).

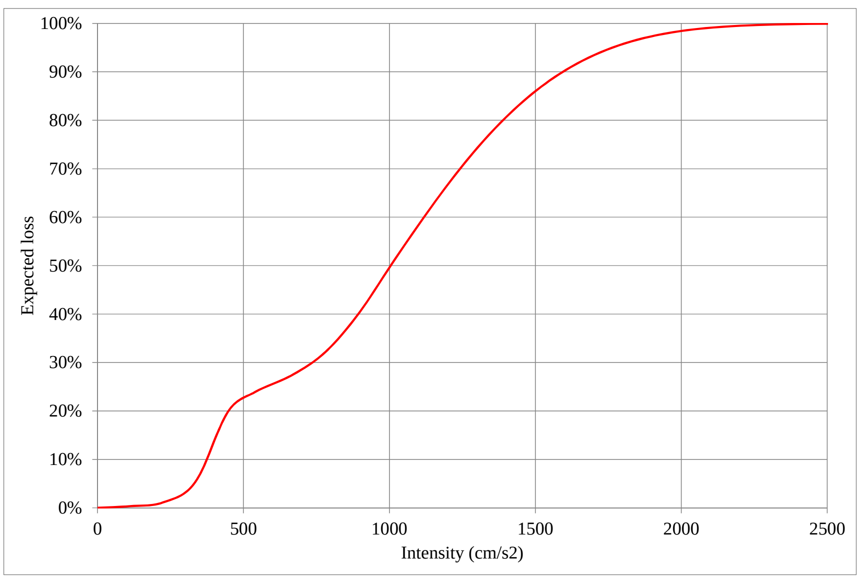

Figure 24. Vulnerability function for unreinforced masonry dwellings

Physical Risk Results

After convoluting hazard and vulnerability of the exposed elements in Bogotá following a fully probabilistic approach such as the one adopted by the CAPRA Platform, results in terms of LEC for both hazard models were obtained. Though slight, there are relevant changes in terms of AAL and PML for certain return periods when considering the hazard model that includes the *Caldas Tear* seismogenetic source. Figure 25 presents the comparison risk results using both hazard models in terms of LEC.

To have a better understanding of the relevance and implications of changing the hazard model, Table 7 compares the risk results as a summary from where it can be seen that a decrease of around 23% exists in terms of AAL. That can have several implications in the definition of risk premiums and is of high relevance among the insurance and reinsurance sector.

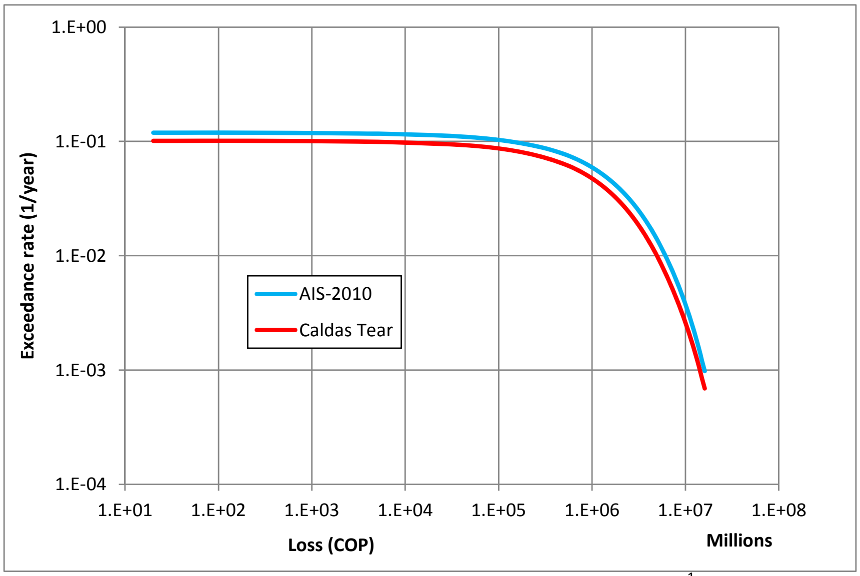

Figure 25. Earthquake loss exceedance curves for Bogotá[1]

Table 7. Summary and comparison of physical seismic risk results for Bogotá

Hazard model	AIS-2010		Caldas Tear	
Exposed value	COP$ x10^6	100,316,000	COP$ x10^6	100,316,000
AAL	COP$ x10^6	252,350	COP$ x10^6	194,006
	‰	2.516	‰	1.934
PML				
Return period	Loss		Loss	
years	COP$ x10^6	%	COP$ x10^6	%
100	$6,041,078	6.02	$4,921,600	4.91
250	$9,617,823	9.59	$8,102,422	8.08
500	$12,623,801	12.58	$10,958,366	10.92
1000	$15,970,367	15.92	$13,973,154	13.93

As in the previous cases, since the exposure database has been developed on a GIS environment, it is possible to develop and generate risk maps to observe the geographical distribution of the expected damages and losses such as the one presented for the AIS-2010 model in Figure 26 and for the Caldas Tear model in Figure 27. When interpreting these maps, the reader should be careful of understanding that they have been developed under a probabilistic framework, and, therefore, results should be seen in aggregated terms and so the values. That is that, for example, reading the AAL of a single element is not adequate but to read the AAL of the building class that element belongs to (Salgado et al., 2014c). Risk maps in absolute terms for both hazard models are presented in Annex 3.

[1] 1USD is approximately 1,950 COP

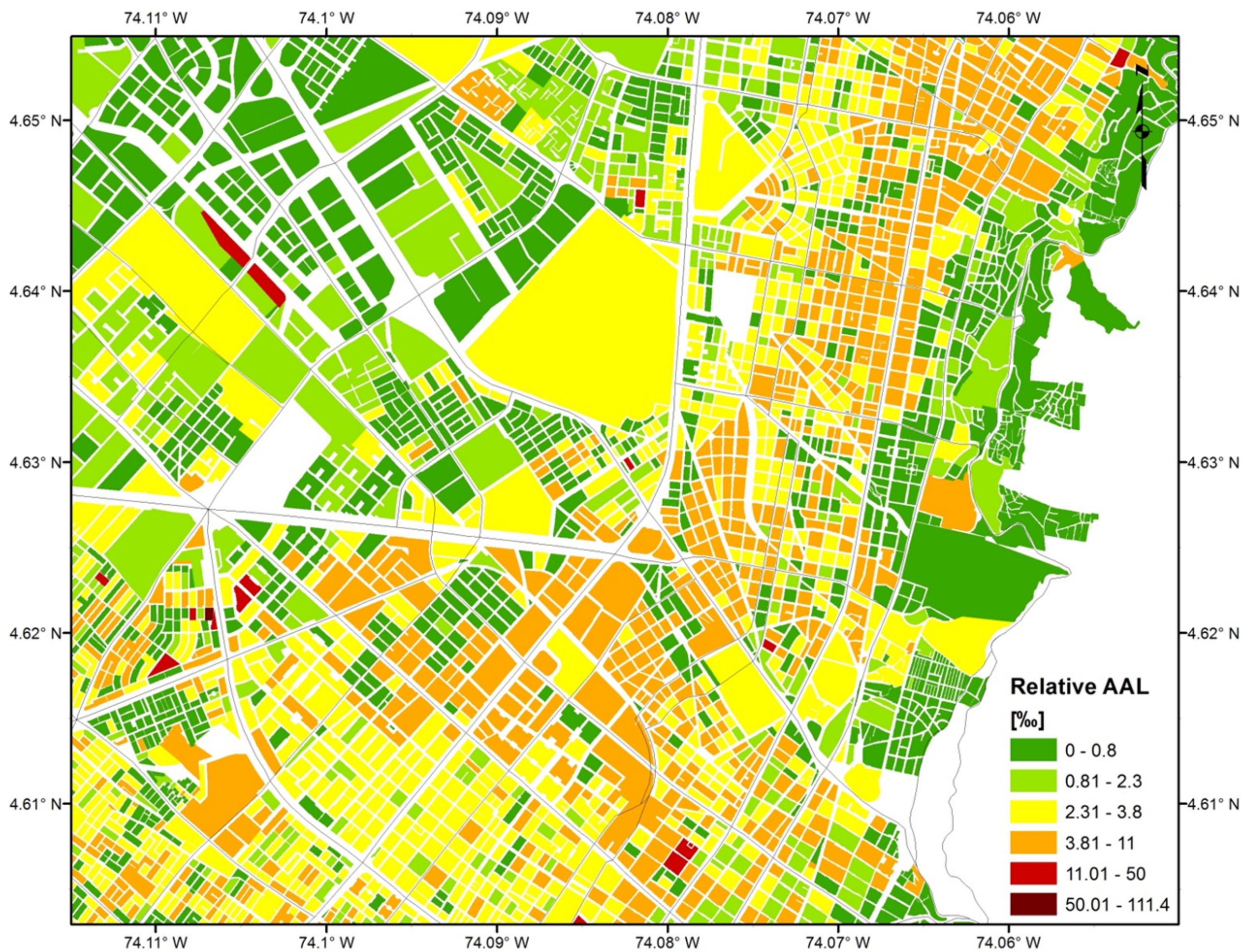

Figure 26. Relative (‰) AAL loss distribution by block in Bogotá with AIS-2010 Model (From Zuloaga, 2011)

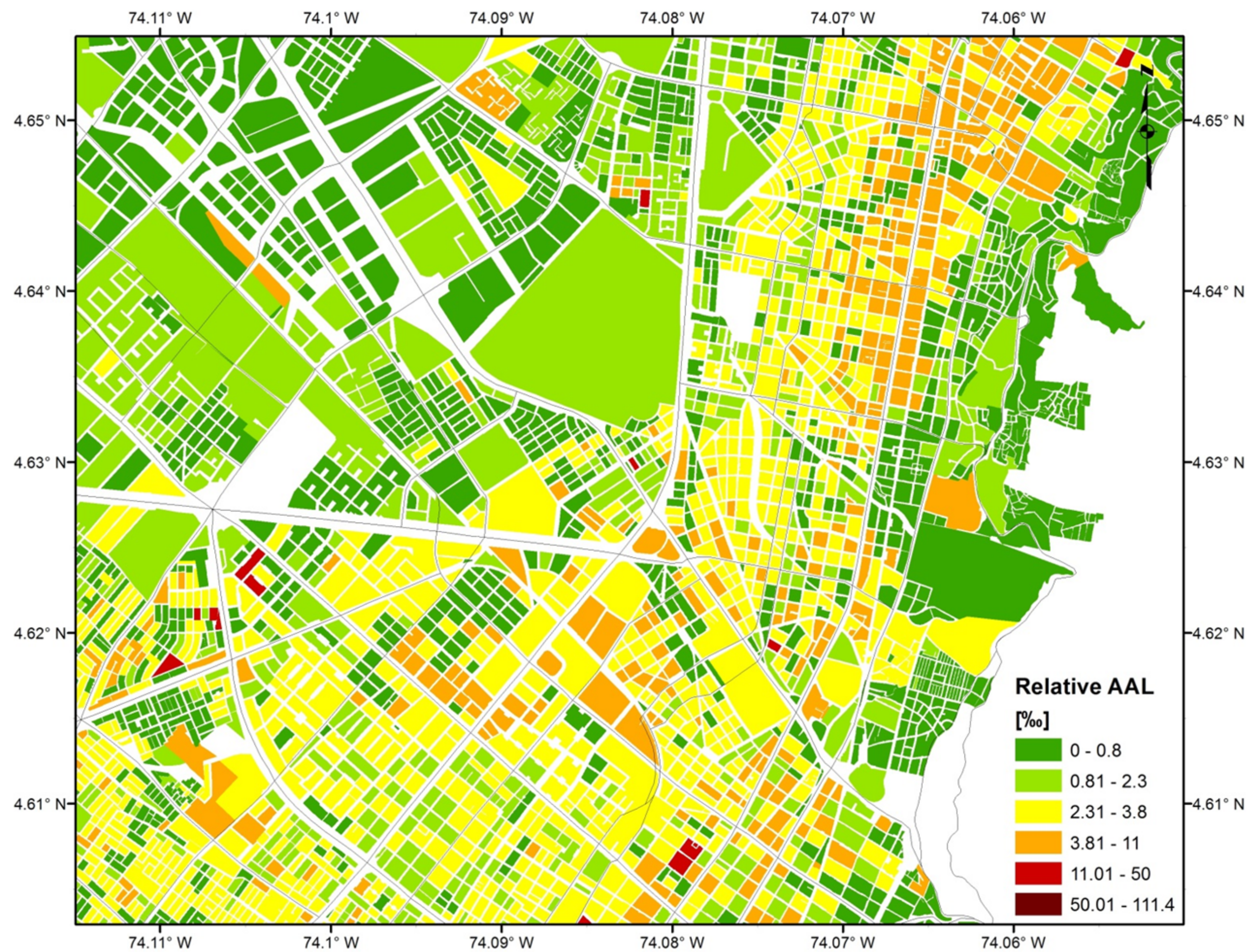

Figure 27. Relative (‰) AAL loss distribution by block in Bogotá with Caldas Tear Model (From Zuloaga, 2011)

Belize City, Belize

Introduction

Belize City is the largest city of Belize and used to be the administrative center until 1970 when, after different political events and being severely affected by different tropical cyclones, the National Government made the decision of locating the offices in Belmopan, approximately 50 kilometers inland to the west.

The city is located on the Caribbean Coast as presented in Figure 28 and most of its economic activity largely depends on tourism and commercial activities, for example from cruises that frequently stop there. Because its location, Belize City may be affected by tropical cyclones occurring in the North Atlantic Basin that, as is well known, is one of the most active worldwide in terms of this hazard.

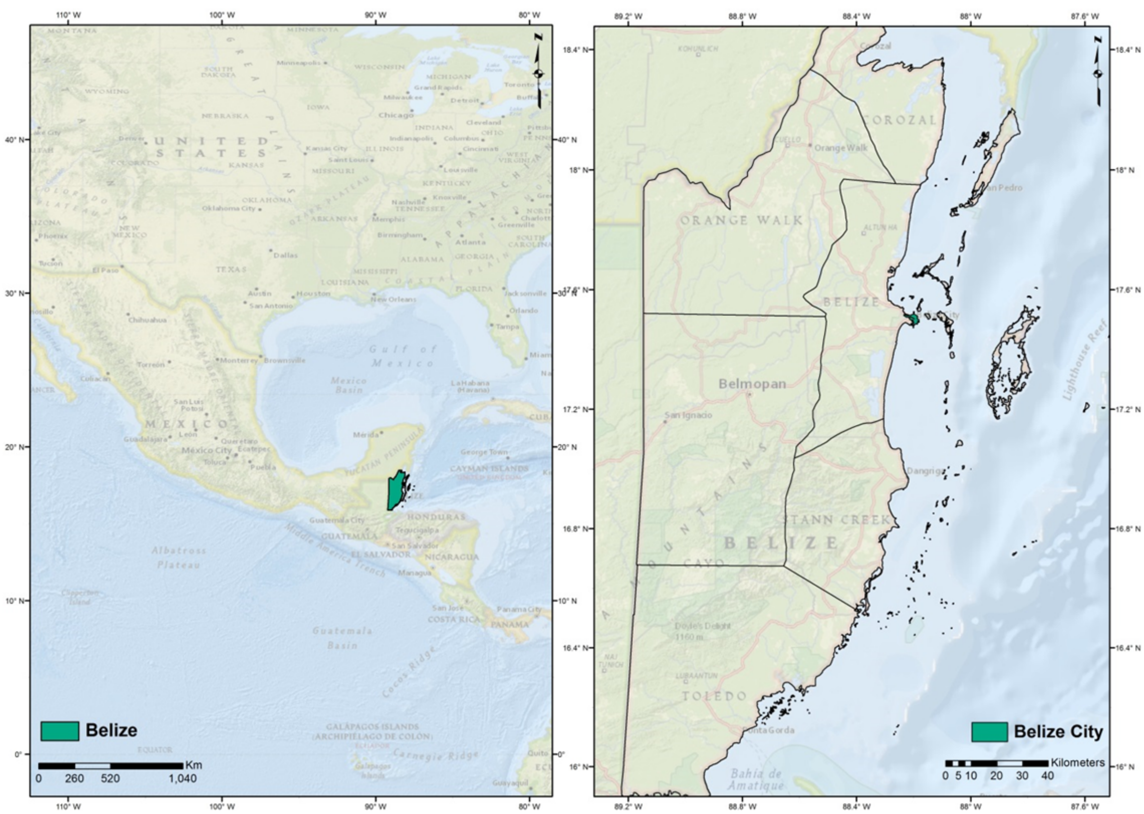

Figure 28. Geographical location of Belize City

This example shows how, when having detailed information not only in terms of the exposed assets but on the topographical and bathymetry data, hazards such as the storm surge can be modelled with a higher resolution than in the Global Risk Model, leading then to more accurate results.

This assessment also constitutes an interesting case since as it is well known, associated to the occurrence of a tropical cyclone there can be different intensities occurring, approximately, at the same time, such as strong winds and storm surge. A detailed tropical cyclonic hazard and risk assessment should account for both of them especially in cases like Belize City when, because of the location of the elements, can all be affected by any of the above mentioned ways that the hazard may manifest.

Purpose of the Risk Assessment and Resolution Level

The purpose of this risk assessment was to quantify in probabilistic terms and metrics the feasible losses in the building stock of Belize City for the tropical cyclonic hazard. This, considering all three intensities that may damage the elements being them strong winds, storm surge and flood associated with the hurricane rainfall.

The analysis was conducted under the framework of the Project "Country *risk evaluations and indicators of disaster risk and risk management for Belize, El Salvador and Guatemala – RME2039/C0031-08*" funded by the Inter-American Development Bank (IDB) which comprised besides a national hazard assessment, the development of local studies considering the most relevant natural hazards for each case in Belize. Besides being an example of how a local assessment could be conducted on a building by building resolution level, this study generated interest among the institutions related to the topic (i.e. NEMO) that led to a capacity building process where specialists in meteorological data and modelling participated in a set of trainings aimed to make them able to replicate and update this kind of analysis when new information in terms of hazard, exposure and/or vulnerability is available.

The resolution level in terms of hazard and exposure can be classified as high because detailed information relevant for the calculation of the first and the identification and characterization of the second. For the hazard mainly the use of detailed bathymetric information as well as de definition of closely spaced points along the shore to calculate that intensities constitute a major improvement if compared with other resolution level analyses.

Hazard Assessment

As mentioned in the introduction of this case study, when detailed information in terms of the base data for the hazard modelling is available, it is possible to conduct said analysis at a higher resolution level, increasing the accuracy of the results both in terms of the expected hazard intensities in each calculation point and in the definition of the areas that may be affected given the occurrence of a tropical cyclone, this latest, especially related to the storm surge. An update on the hazard model, using the tropical cyclonic model developed for GAR15 was used, making use of detailed information mostly in terms of bathymetry and land roughness; the first one with direct effect in the quantification of the hazard for the storm surge and the second one with direct effect in the wind speed estimation using the CAPRA Team TCHM suite (Bernal, 2014). Details about that methodology can be found in Chapter 3 of the report of the Global Risk Model by CIMNE-INGENIAR (2014).

As in the previous cases, given that the aim of the study is related to a probabilistic risk assessment, a set of stochastic scenarios, in this case, storms, was generated, complying with the exact same requirements as before:

- Mutually exclusive
- Collectively exhaustive

- Admit a probabilistic representation

Since each scenario is characterized in terms of its frequency of occurrence and on the other hand, intensities are calculated through the first two probabilistic moments, it is possible to integrate the hazard and obtain intensity exceedance curves for any point of interest. When those point of interest constitute a grid (each then, being a node), by selecting the same return period for each of them, it is possible to generate hazard maps. Figures 29 and 30 present the intensity exceedance plots for strong winds and storm surge in Belize City

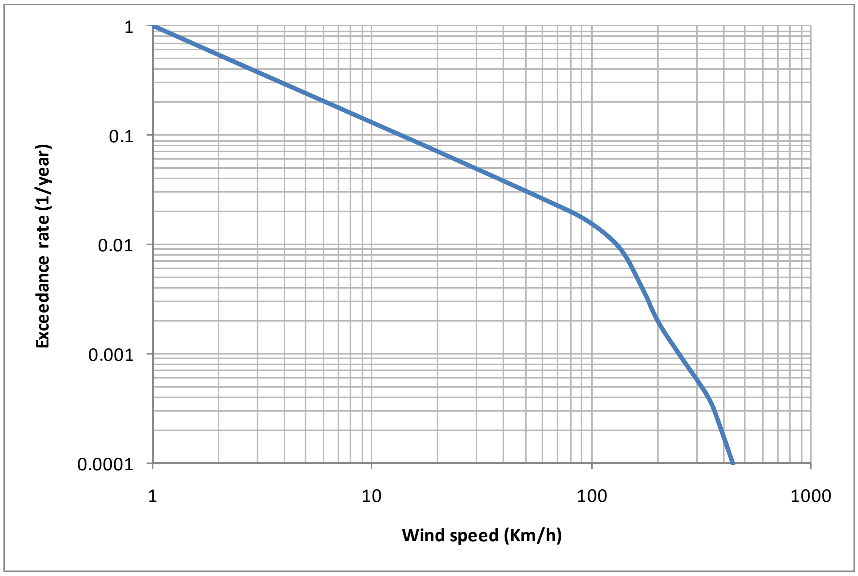

Figure 29. Strong wind exceedance rates for Belize City

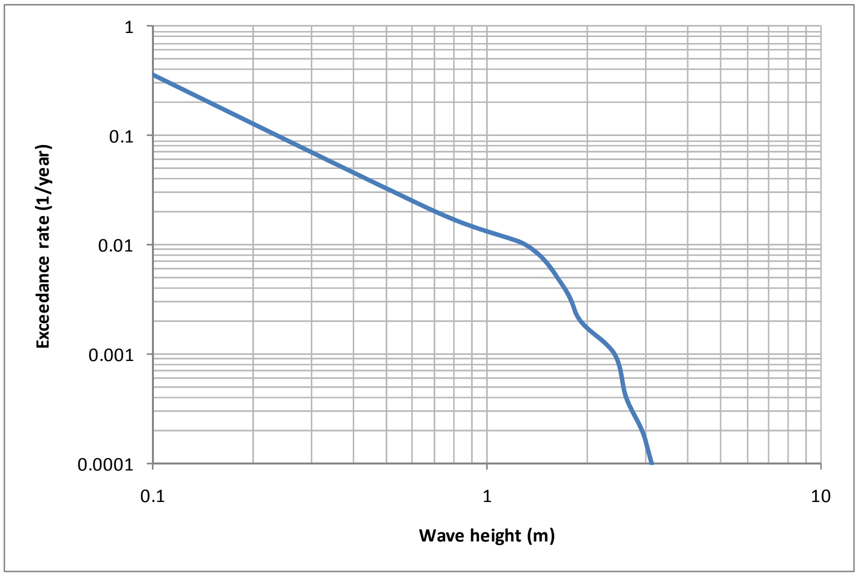

Figure 30. Storm surge exceedance rates for Belize City

Whilst small variations occur for the wind speed estimation in the urban area of Belize City, for the case of the storm surge it is evident that the geographical dependency for it is important; that is, only elements located within certain distance from the shore may be affected by said hazard and it explains why a detailed approach in the exposure in hazard and exposure is needed.

Though quantified at a global level for GAR15, it is clear that for a better understanding of this hazard and its relevance in the risk results, a more detailed approach should be selected and therefore, that kind of assessments should be promoted to derive in comprehensive disaster risk management schemes.

Exposed Assets

For this local assessment the exposed assets in Belize City consist in the building stock on an element by element resolution level based on official information (BGOP, 2011; SIB, 2011; MHUD, 2011) that besides location and geometry data has characteristics in terms of age, main use, number of stories and building class.

Most of the dwellings in Belize City are made out of wood which is a very common building class in the Caribbean region. Though located in Central America, Belize has more common characteristics with the Caribbean countries than with neighboring ones such as Guatemala or Mexico.

Figures 31 and 32 present the characterization of the dwellings in terms of building class and main use respectively. Annex 4 presents more details in terms of other relevant attributes from the exposure perspective.

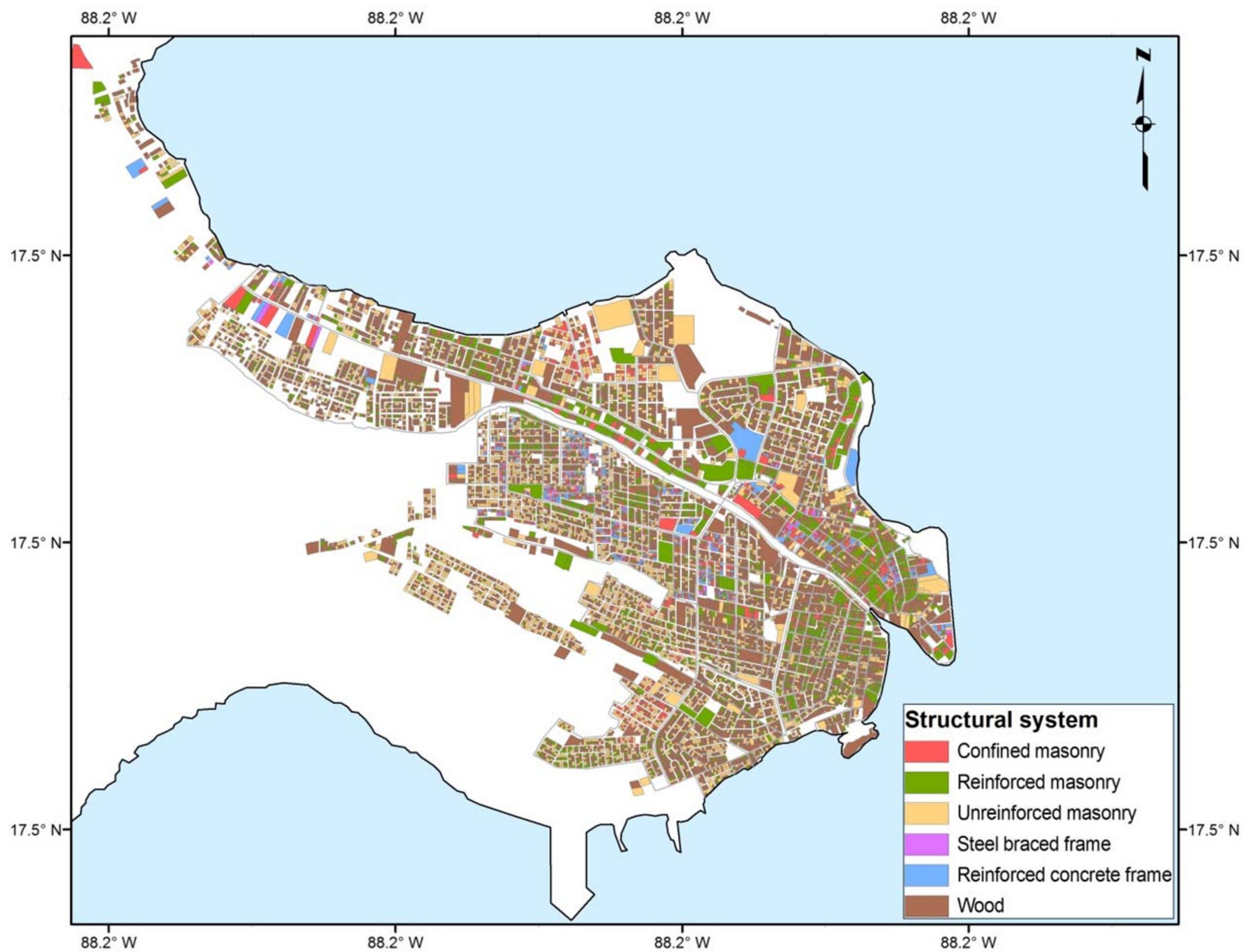

Figure 31. Building class distribution for Belize City

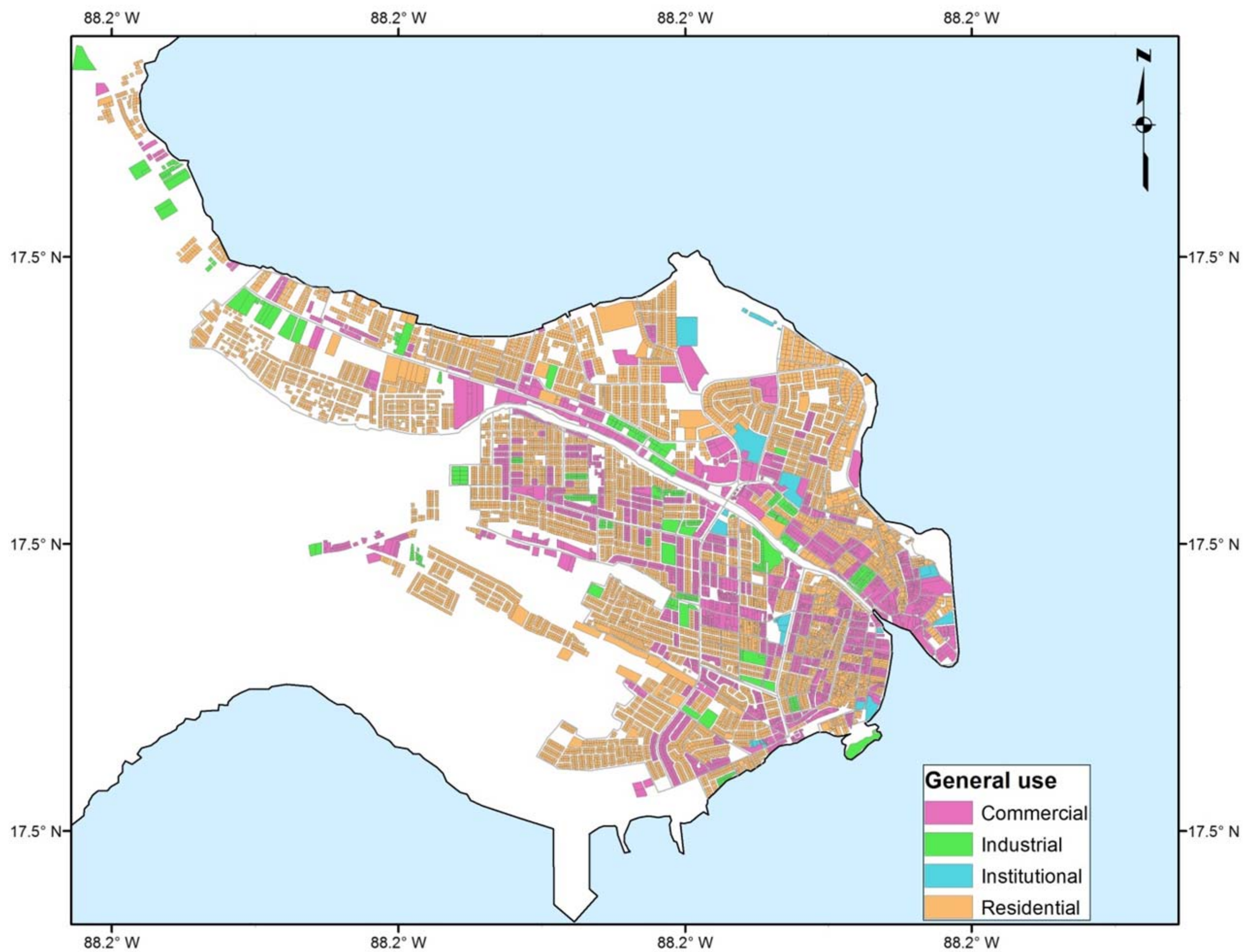

Figure 32. Main use distribution for Belize City

Vulnerability of the Exposed Assets

For this assessment two different sets of vulnerability functions were developed. The first one corresponded to vulnerability functions in terms of wind speed and the second one in terms of water depth, used for the storm surge assessment. As in previous cases, for each building class, a unique vulnerability function is assigned for each intensity. Figure 33 presents the vulnerability function wooden structures for wind speed, while Figure 34 presents the vulnerability function for steel frame buildings for flood and storm surge.

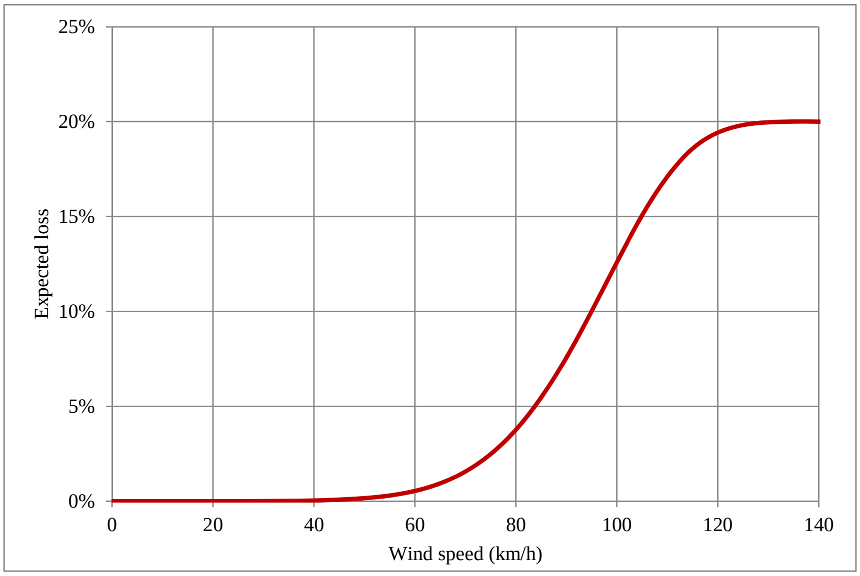

Figure 33. Wind vulnerability function for wooden dwellings

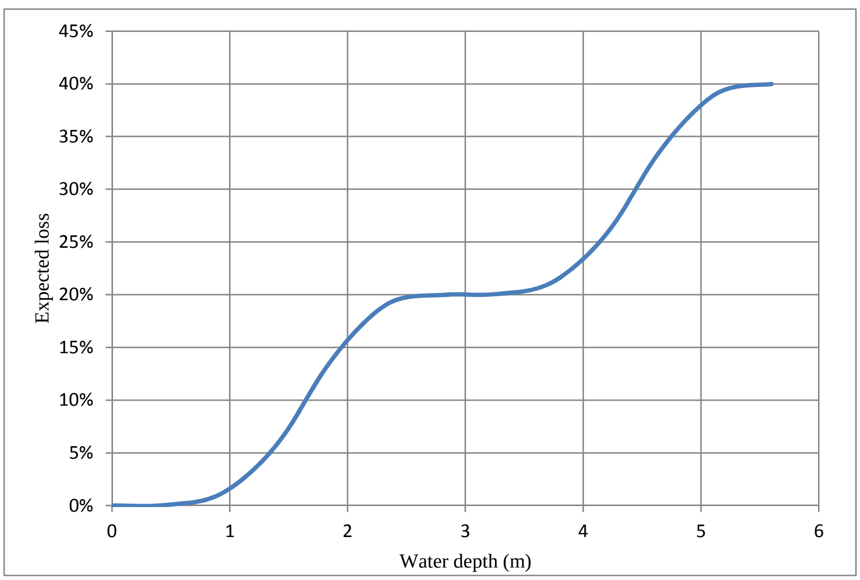

Figure 34. Flood vulnerability function for reinforced concrete framed dwellings

More details about the vulnerability functions for the rest of building classes for strong winds, and storm surge can be found in ERN-AL Consortium (2009) and Annex 4.

Physical Risk Results

Physical risk results in Belize City consider the effects of strong winds, storm surge and floods associated to hurricane rainfall at the same time. To consider that, all the intensities are considered in the same temporality for which in this case the same number of scenarios are required for the hazard representation in each case. The loss calculation follows a cascade process and therefore, the results can be obtained in terms of the same probabilistic risk metrics as presented before, that is the LEC from where AAL and PML can be derived.

Figure 35 presents the PML plot for Belize City that considers the influence of all the intensities, which is the appropriate way to represent them since the effects are not independent among them.

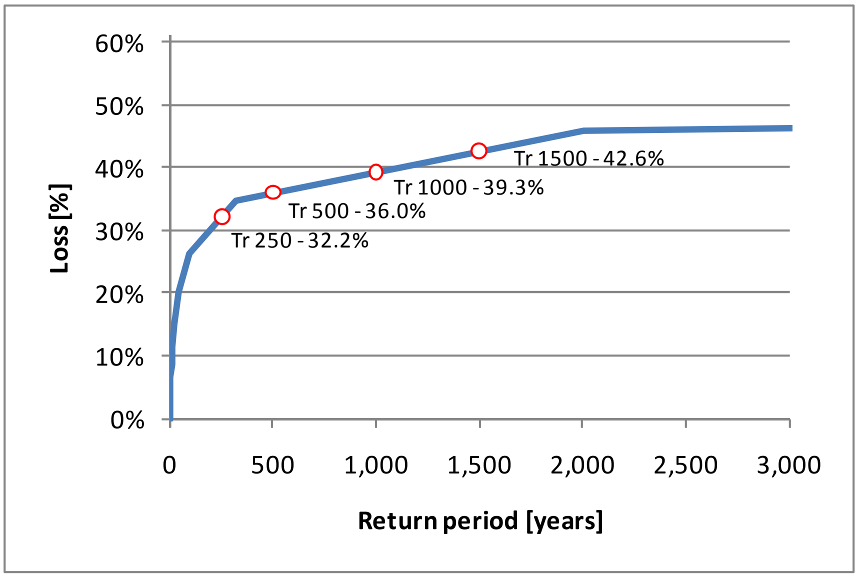

Figure 35. PML plot for tropical cyclones (wind and storm surge) for Belize City

On the other hand, Table 8 presents the summary of the risk results now in terms of AAL and PML for selected return periods from where it can be seen that the risk level can be considered as high since for a return period of 250 years, a loss equivalent to more than 30% of the total exposed value is expected.

Table 8. Summary of tropical cyclonic risk in Belize City

Results		
Exposed value	US$ x10^6	1,280.48
Average annual loss	US$ x10^6	37.36
	‰	29.18 ‰
PML		
Return period	**Loss**	
Years	**US$ x10^6**	**%**
250	412.59	32.22%
500	461.10	36.01%
1,000	503.18	39.30%
1,500	545.25	42.58%

When conducting risk analysis considering different hazard intensities, it is possible to disaggregate the results by intensity; that is in this case, checking if the strong winds, storm surge or flood are most contributing to the overall risk. The best indicator to make this verification is the AAL since it accounts for all the events, ranging from small and frequent to intense and extreme.

Finally, Figure 36 presents the geographical distribution of the expected damage and losses in terms of relative AAL for strong winds. On the other hand, Figure 37 presents the geographical distribution of the expected losses, again in terms of AAL for storm surge. For the latest, as mentioned in the hazard section, it is evident that only places located within certain distance from the shore or lying in lowlands, may be affected by those effects and this could only be determined by having detailed hazard and exposure information.

These results have been very useful for the emergency response plan lead by the National Emergency Management Organization, NEMO. In addition, training activities have been implemented with many institutions to evaluate the separated hazards and the multi-hazard risk assessment using CAPRA. They have been evaluated taking into account the current level of hazard and also future scenarios of climate change.

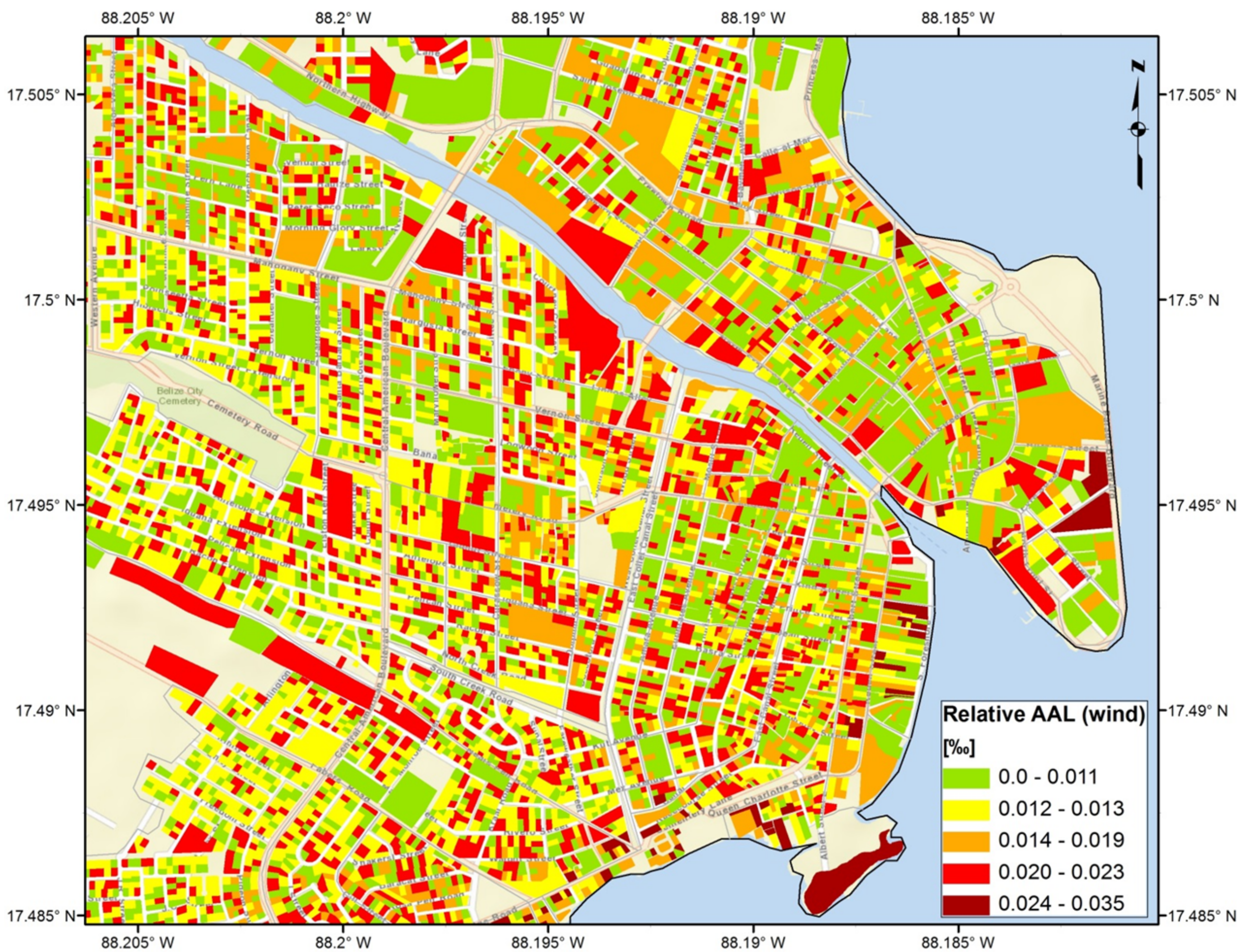

Figure 36. Tropical cyclone relative AAL by dwelling in Belize City due to strong winds

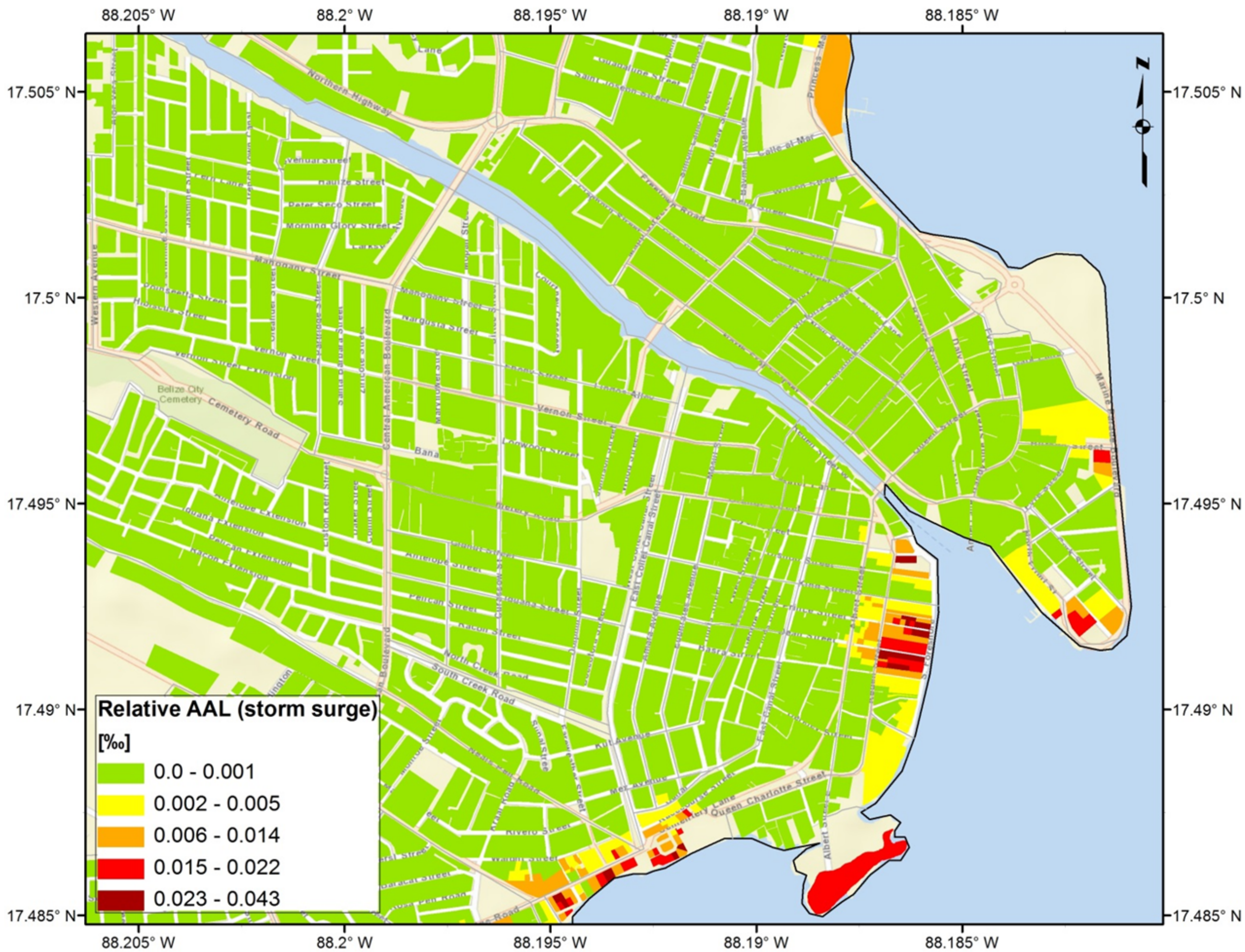

Figure 37. Tropical cyclone relative AAL by dwelling in Belize City due to storm surge

Galeras Volcano, Colombia

Introduction

Galeras Volcano is located at approximately 10 kilometers west from the urban area of Pasto, the capital city of Nariño Department in Colombia. It is one of the most active volcanoes in the area and has been studied in different opportunities by national and international researches. The volcano has an observatory with permanent personnel and state of the art equipment with real time and telemetric data to feed the warning systems.

This assessment was part of a technical assistance project (TAP) funded by The World Bank where the main objective was to involve local experts in the volcanic hazard assessment into the probabilistic risk assessment to complement, integrate and further develop applications related to disaster risk management and reduction.

Purpose of the Risk Assessment and Resolution Level

The main objective of this probabilistic volcanic risk assessment was not to determine the possible damages and losses but to make the CAPRA tool and methodology known and available to local experts in the volcanic hazard modelling and, based on previous studies for the hazard side, and existent information in terms of exposure and vulnerability (mainly due to ash fall), have a case study where the capacity on risk assessment was to be built and that knowledge applicable to be replicated in future studies. The institution involved in the assessment was the Colombian Geological Survey.

The volcanic hazard was quantified in terms of three intensities; ash fall, pyroclastic and lava flows. The last two require detailed topographical information in terms of a digital elevation model. The risk assessment was performed on the municipalities that lie around the volcano which are the ones that could result heavily damaged in case an eruption takes place.

Hazard Assessment

Whilst not being the objective of this TAP to develop a methodology to assess the volcanic hazard, an innovative scenario based approach with the aim of obtaining physical risk results through a fully probabilistic methodology was followed. The hazard assessment was performed using existing information and studies that were used as input to obtain this probabilistic representation. A challenge existed in defining the frequency of occurrence of the eruption events that were classified according to the volcanic explosivity index (VEI). Figure 38 presents the hazard map in terms of pyroclastic flows for the Galeras Volcano obtained through this hazard assessment methodology in VHAST (Bernal, 2012).

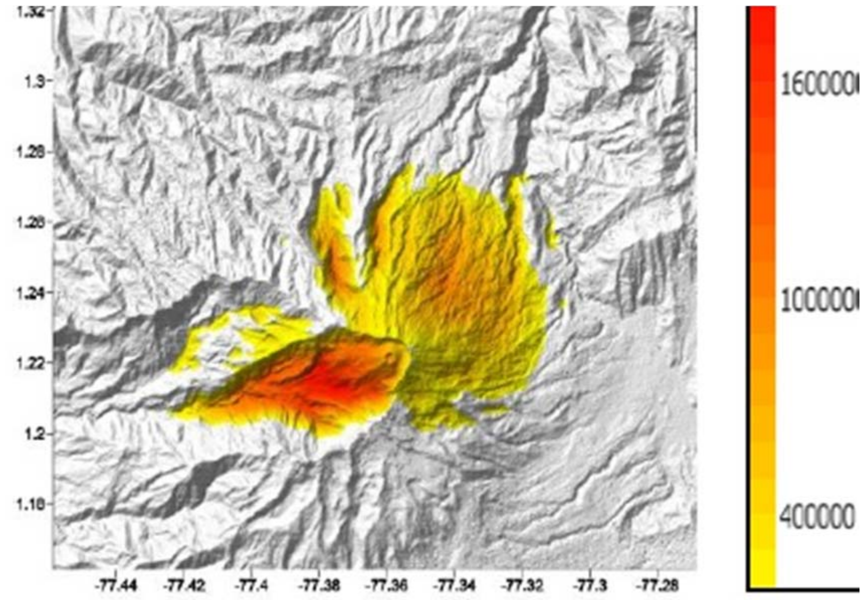

Figure 38. Pyroclastic flows hazard map for Galeras Volcano

Exposed Assets

Figures 39 and 40 present the characterization of the assets in terms of actual condition and roof type; this last a very relevant parameter when assessing risk associated to ash fall. Annex 5 presents more details about the characteristics of the exposed assets in the region.

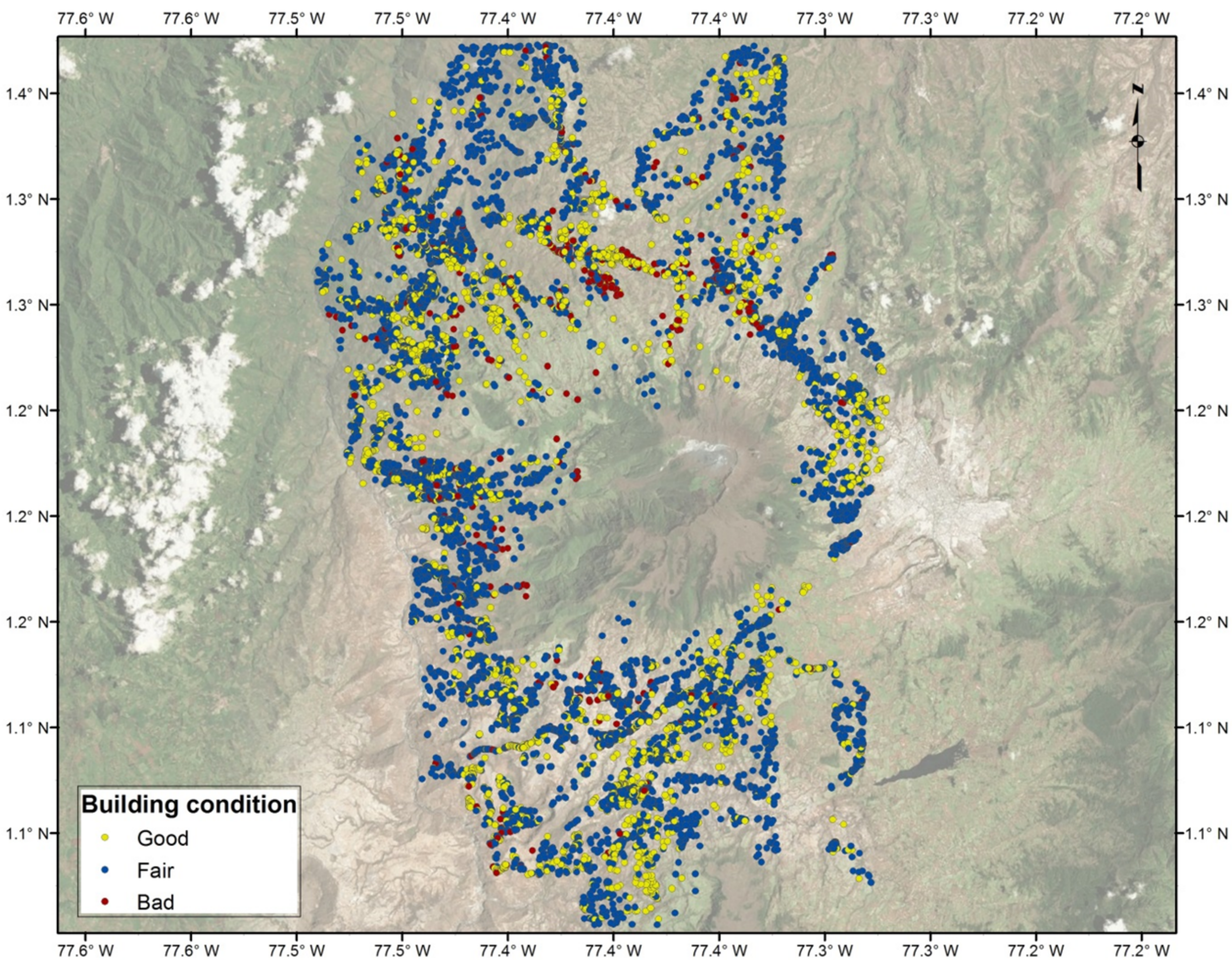

Figure 39. Building condition

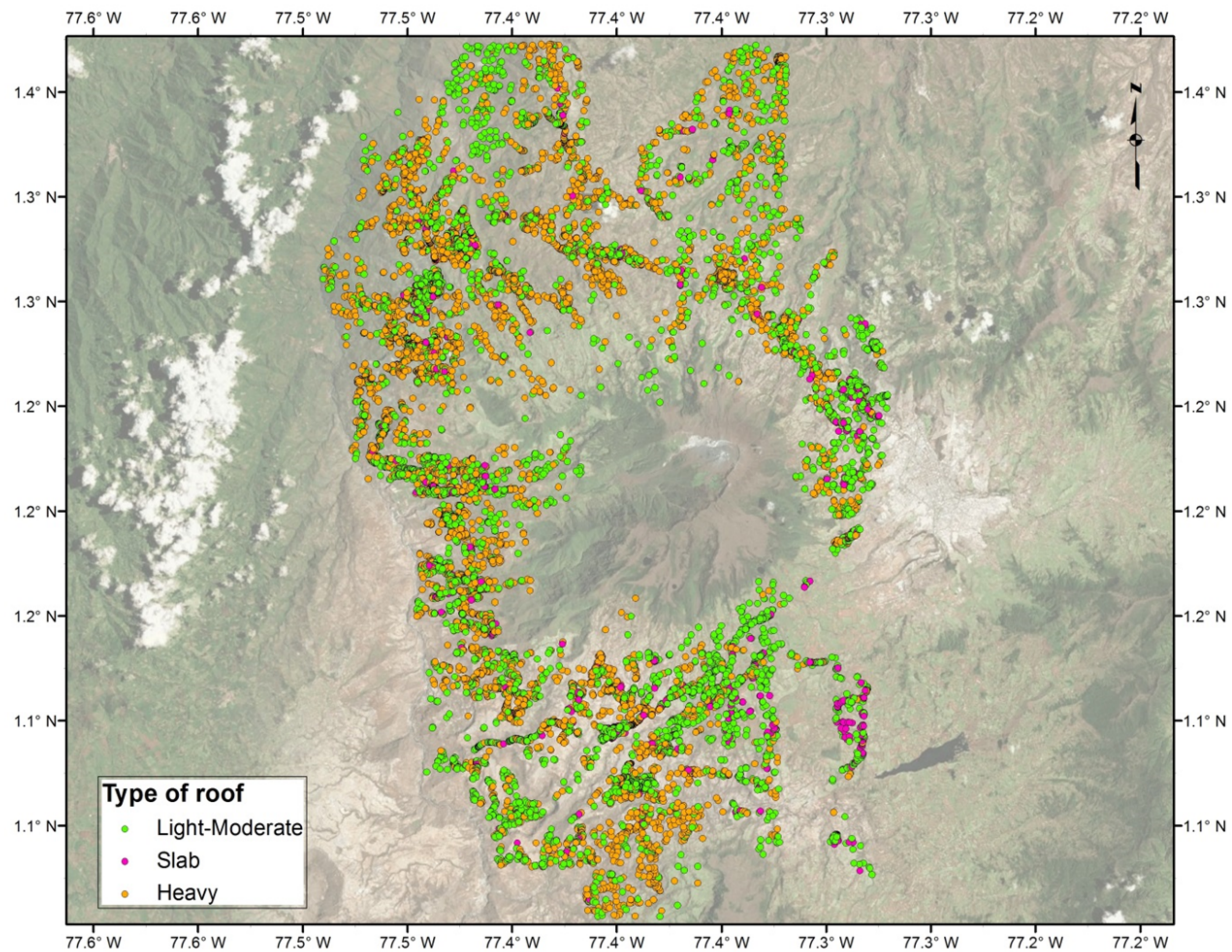

Figure 40. Roof type

Vulnerability of the Exposed Assets

Vulnerability functions for pyroclastic and lava flows have a unique characteristic and it is that they can be classified as binary; that is, if the element is affected, at any level by the hazardous event, the associated loss is complete. The opposite occurs with the ash fall since the affection on the surrounding elements depends heavily on the accumulated thickness on the roofs and its characteristics. Figure 41 presents the vulnerability function in terms of ash thickness for light roofs.

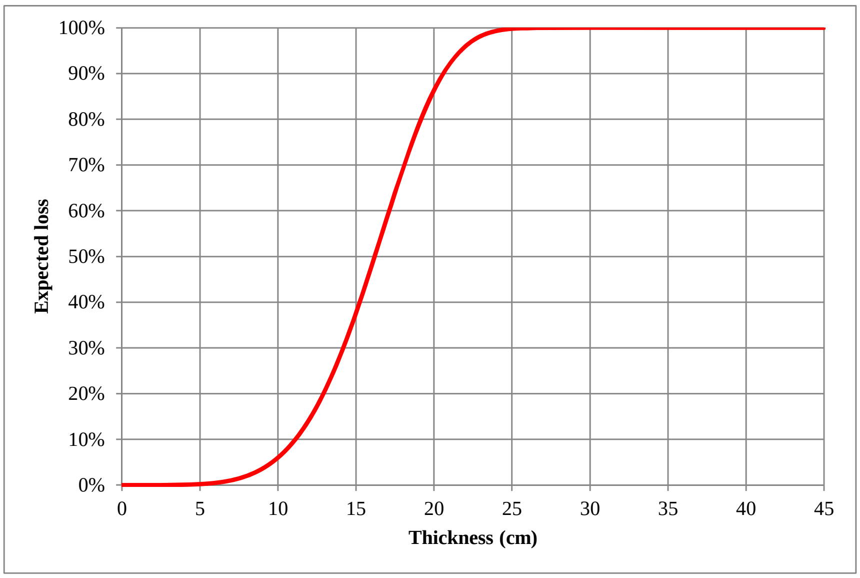

Figure 41. Vulnerability function for light roof structures

Physical Risk Results

Risk results have been obtained in terms of a loss exceedance curve since a scenario representation was selected for the hazard. Figure 42 presents the LEC for the portfolio of exposed dwellings around the Galeras Volcano.

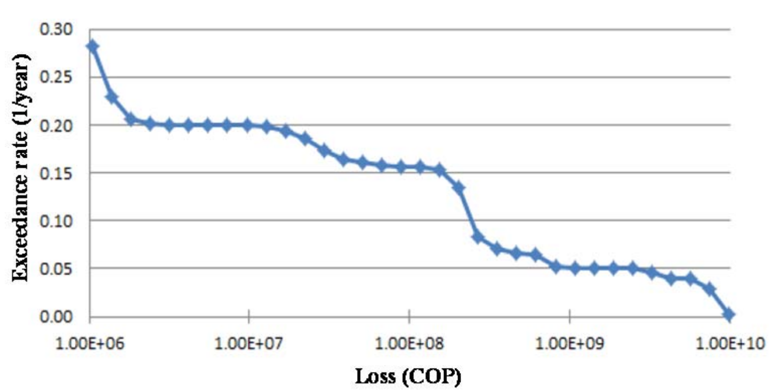

Figure 42. Volcanic loss exceedance curves for Galeras Volcano surrounding buildings[2]

[2] 1USD is approximately 1,950 COP

Finally, Figure 43 presents the risk results through a map in terms of relative AAL due to ash fall in the portfolio of exposed elements. Absolute AAL distribution can be found in Annex 5.

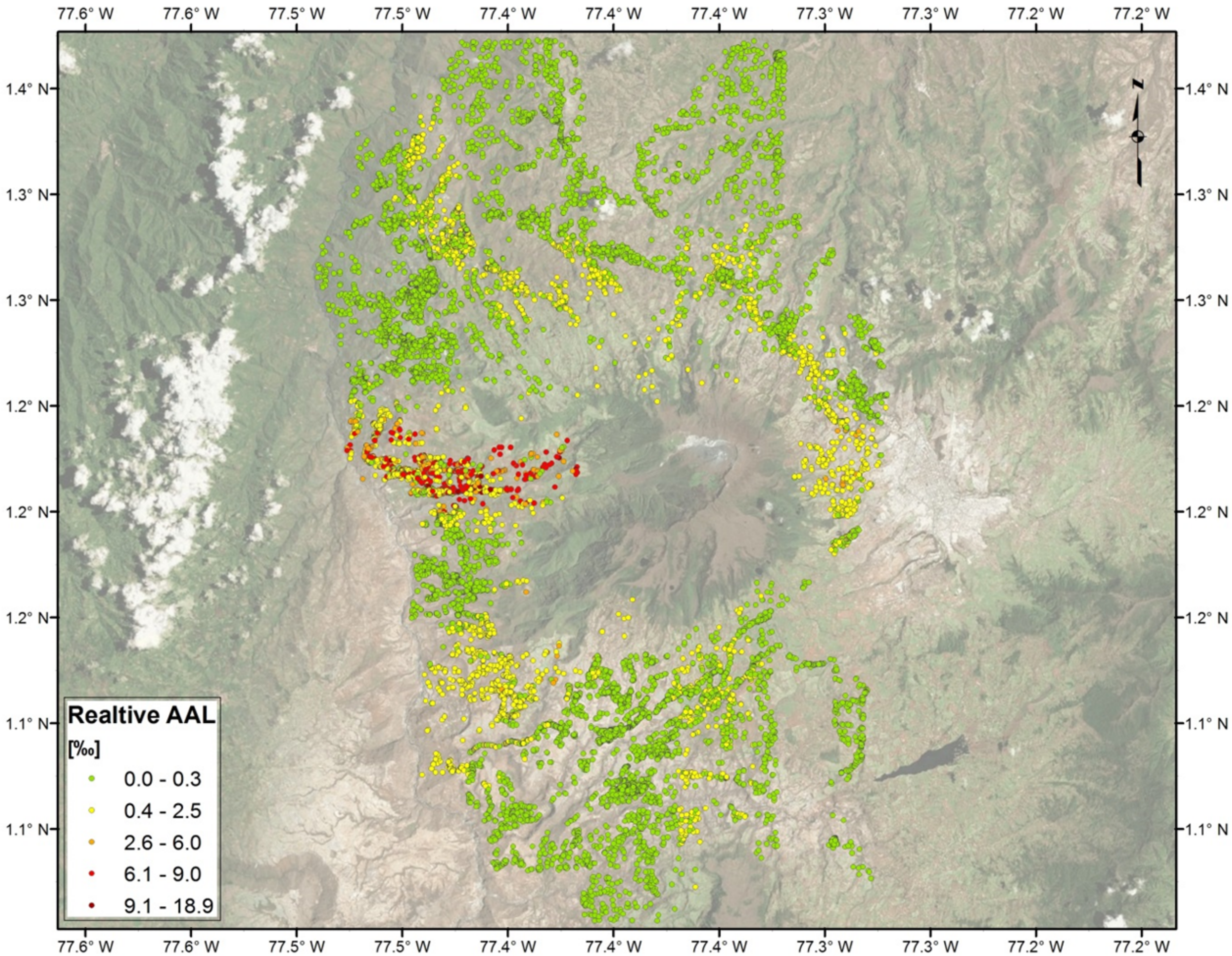

Figure 43. Relative (‰) AAL loss distribution by element in the Galeras Volcano surrounding buildings

Lorca, Spain

Introduction

On May 11th 2011 a 5.1 (M_W) earthquake stroke the Murcia region in south-eastern Spain, where the city of Lorca, with almost 60,000 inhabitants, was the most affected and damaged place. The epicentre was located 5 km north of Lorca and the depth of the event was estimated at 5 km. In spite of the moderate magnitude of the event, 9 casualties occurred, more than 300 people were injured and around 10,000 people could not return to their houses after the event due the damage to their homes. Two health centres suffered severe structural damage that endangered the security of the patients and medical staff, and were therefore evacuated. According to the damage surveys, around 80% of the inspected buildings presented some degree of damage, though it was generally classified as slight. The damage generated a chaotic situation in the post-disaster phase since there was no prior experience in implementing an emergency plan, and many of the response actions took longer than what was expected by the community (Barbat et al., 2011).

According to the post-earthquake damage assessment made by the local municipality, 19% of the existing 7,852 buildings were not inspected given that they suffered only very slight damage, 52% of the buildings were inspected and classified as habitable because of the lack of significant damage, 16% had no significant structural damage but limited access because of non-structural damage, 9% had forbidden access because of high structural damage, and for 4% of the buildings a mandatory demolition order was given (Ayuntamiento de Lorca, 2012).

Purpose of the Risk Assessment and Resolution Level

The purpose of this study was to compare the observed losses, based on the official post-earthquake survey conducted by the local authorities with the modeled ones using the CAPRA Platform where a hazard scenario with similar characteristics in terms of magnitude, location, depth and ground accelerations and a building by building resolution level exposure database were available. To quantify the physical vulnerability of buildings, vulnerability functions that take into account the uncertainties related to the accuracy of building data and seismic structural behaviour were used. A unique vulnerability function was assigned to each building class identified in Lorca. The convolution between the hazard and the vulnerability provides the expected losses. Only direct physical losses were accounted for in the analysis by calculating the mean damage ratio (MDR) of each building of the exposure database. More details about this study can be found in Salgado et al. (2014c).

Hazard Assessment

To represent the seismic hazard in this way, the best approach was to conduct a probabilistic and spectral seismic hazard analysis in the Iberian Peninsula and its neighbouring regions. Accordingly, a seismic hazard assessment is performed considering different seismogenetic sources that were characterized by a Gutenberg-Richter (G-R) (1944) model. The employed tectonic zonation corresponds to the one proposed in the framework of the SHARE project (GRCG, 2010) where 51 seismogenetic sources were defined. An additional source was located in northern Africa to account for the seismicity occurring in that area which may affect the Peninsula. Since the occurrence of earthquakes over the time cannot be predicted, and a complete time window is an unknown quantity, a set of 1,991 stochastic events was generated using the CRISIS 2007 software (Ordaz et al., 2007). To characterize the seismicity occurrence process at each source, a Poisson model was selected. Seismic activity is determined based on the magnitude recurrence rates, relating the frequencies with which earthquakes with a given magnitude occur at each seismogenetic source.

Once the set of stochastic scenarios was generated, an event with similar characteristics in terms of location and magnitude was selected to conduct the damage analysis on the buildings of Lorca. Figure 44 shows the shakemap of the selected event which is associated to the *ESAS250* seismogenetic source (GRCG, 2010) which is located beneath the city of Lorca. Intensities are computed at bedrock level and no local site-effects are taken into account in the analysis since no information to generate spectral transfer functions was available for the city.

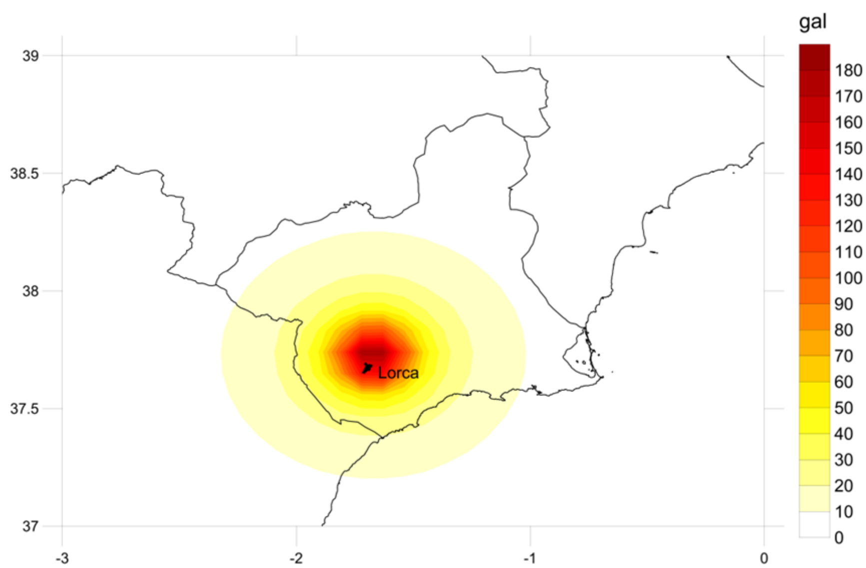

Figure 44. PGA (cm/s2) for the selected scenario

Exposed Assets

Updated cadastral information is available for Lorca (MHAP, 2013) with a building by building resolution level. Since the information was generated for cadastral and tax purposes, several properties other than buildings such as terraces, squares and balconies are originally included. Initially, a total of 42,062 elements were included in the database. After a depuration process, intended to include only the buildings, only 17,017 elements remained; in this process, the buildings classified as ruins (before the 2011 earthquake) by the cadastral office were also removed. The cadastral information contains data about the geographical location and number of stories of each building. Building footprints were compared with an aerial image and 599 additional elements were included in the database for a total of 17,616 buildings. Most of the buildings in Lorca are classified as low-rise from a structural point of view; i.e., buildings of 1 to 3 stories. Figure 45 presents the geographical distribution of the number of stories attribute while Figure 46 presents the building classes. More maps with information related to exposure characteristics are presented in Annex 6.

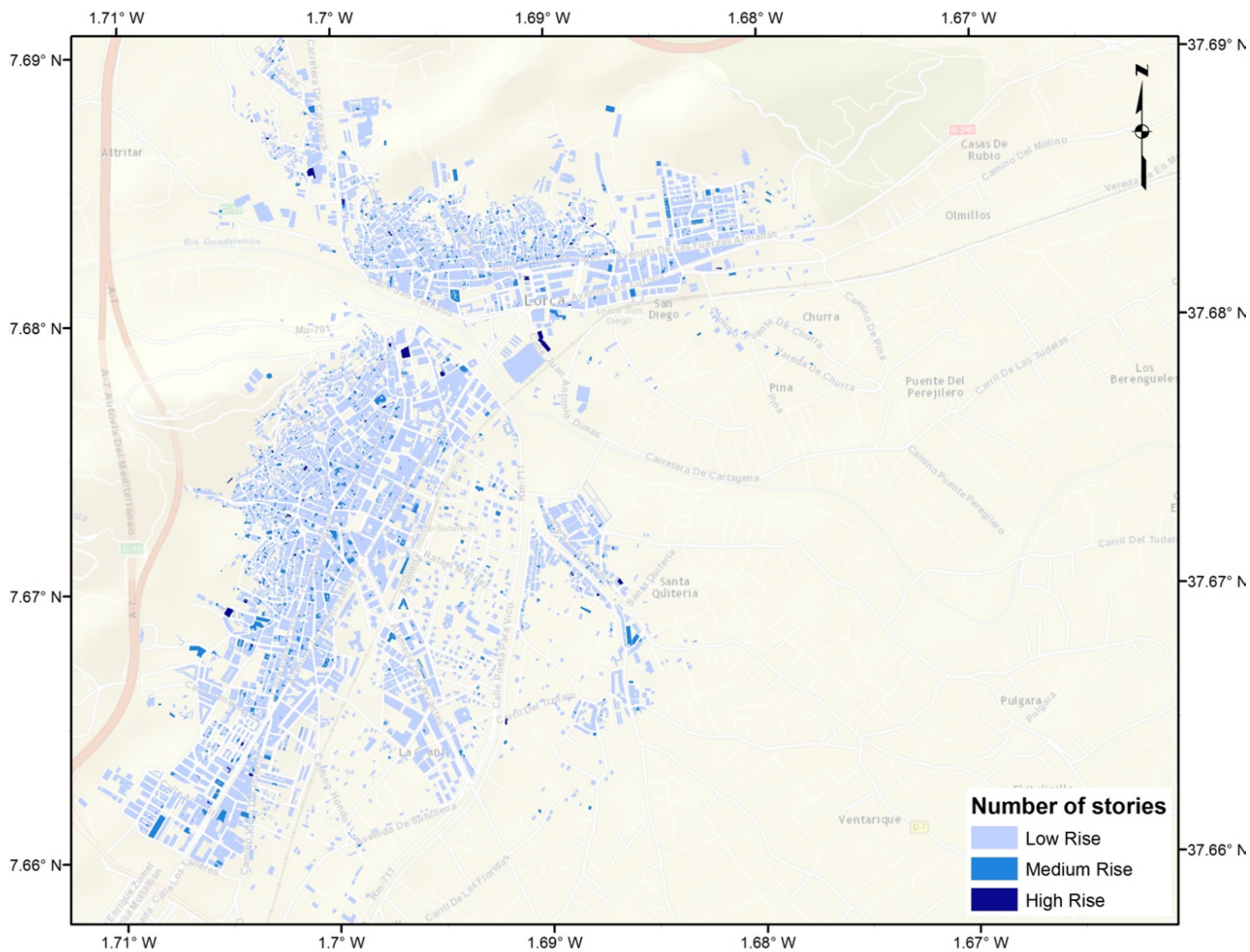

Figure 45. Number of stories distribution for Lorca

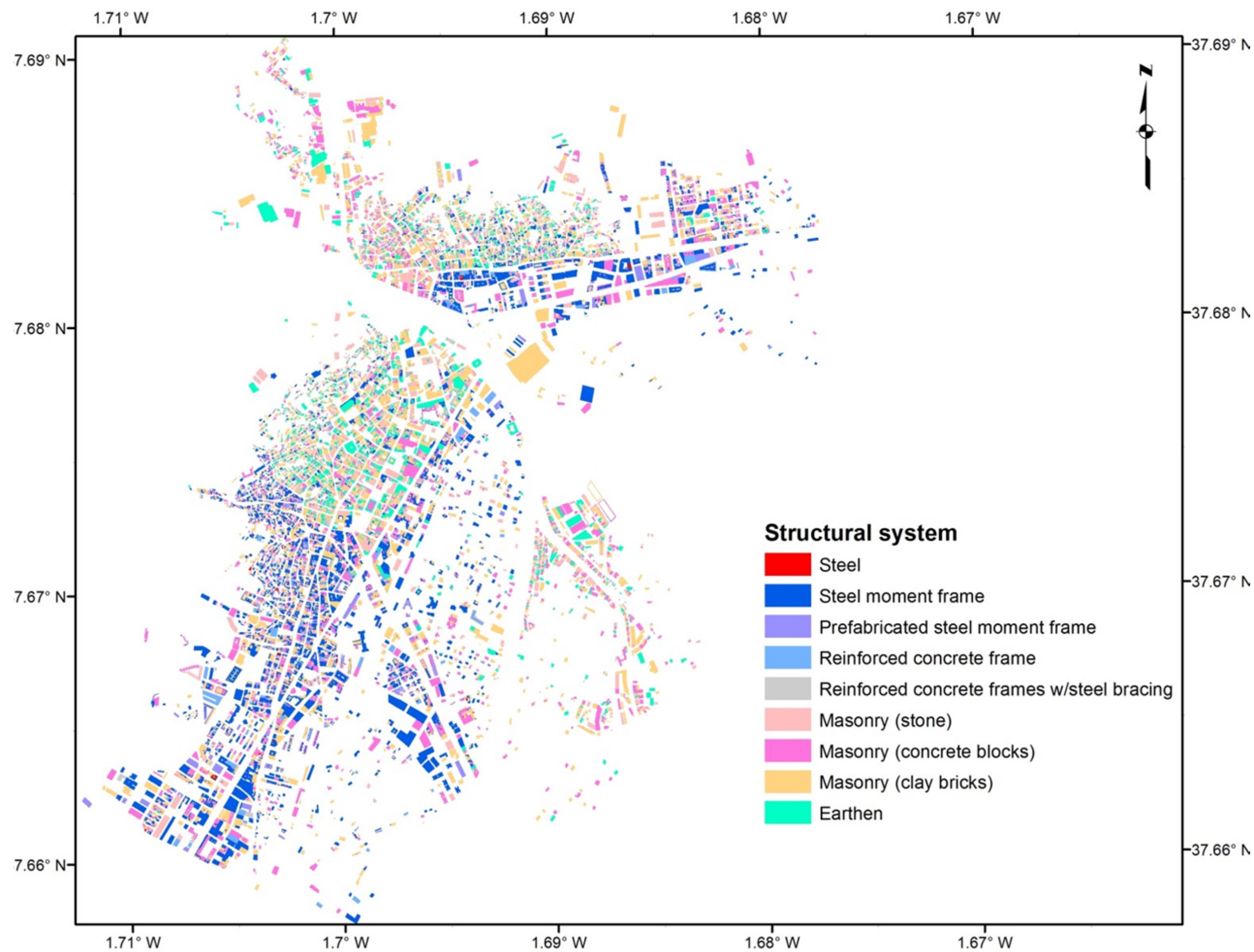

Figure 46. Building class distribution for Lorca

From Table 9 it can be seen that most of the buildings in Lorca are made of masonry, concentrating more than 60% of the total both in number and in exposed value. Moreover, waffle slab buildings constitute the majority of the R/C structures in the city (more than 20% of the buildings in the city).

Table 9. Summary of exposed assets statistics for Lorca, Spain

Building class	Number of elements	% of dwellings	Exposed value	% of exposed value
Earthen	1,972	11.19	774.1 €	11.63
Stone masonry	1,777	10.09	620.1 €	9.31
Brick masonry	3,757	21.33	1,347.1 €	20.23
Masonry walls and R/C slabs	3,514	19.95	1,352.1 €	20.31
Stone and brick blocks	1,953	11.09	739.7 €	11.11
Steel buildings	177	1.00	103.0 €	1.55
R/C frames with steel braces	170	0.97	86.9 €	1.30
Pre 1995 R/C frames	2,346	13.32	846.4 €	12.71
Prefabricated R/C structures	703	3.99	255.5 €	3.84
Post 1995 R/C frames	1,247	7.08	533.5 €	8.01
TOTAL	**17,616**	**100**	**6,658.2 €**	**100**

Vulnerability of the Exposed Assets

Vulnerability functions are a description of the variation of the first two statistical moments of loss with respect to the hazard intensity. A Beta probability distribution function is assigned and, in this case, the mean value and the standard deviation correspond to the mentioned statistical moments. Once this distribution function is computed, all the parameters required to compute risk in a probabilistic way are available (Ordaz, 2000). This approach is compatible with the probabilistic risk assessment approach selected for the study. Each of the building classes has an associated vulnerability function. The replacement cost of each asset is needed to quantify the expected losses in monetary units since what it is obtained at each intensity level is the ratio of the repair cost relative to the total value of the building. A total of 22 vulnerability functions were used in the analysis, which have been developed for the Global Risk Model by CIMNE et al. (2013) and included in the Global Assessment Report on Disaster Risk Reduction 2013 (UNISDR, 2013).

Figure 47 shows the different vulnerability functions from where it is clear that some building classes, especially those made of unreinforced masonry, are far more vulnerable in seismic terms than others, having for the same intensity level a higher associated MDR. The height of the structures is included in the analysis through three different categories: low-rise (L) for buildings between 1 and 3 stories, medium-rise (M) for those that have 4 to 7 stories and high-rise (H) for 8 and more.

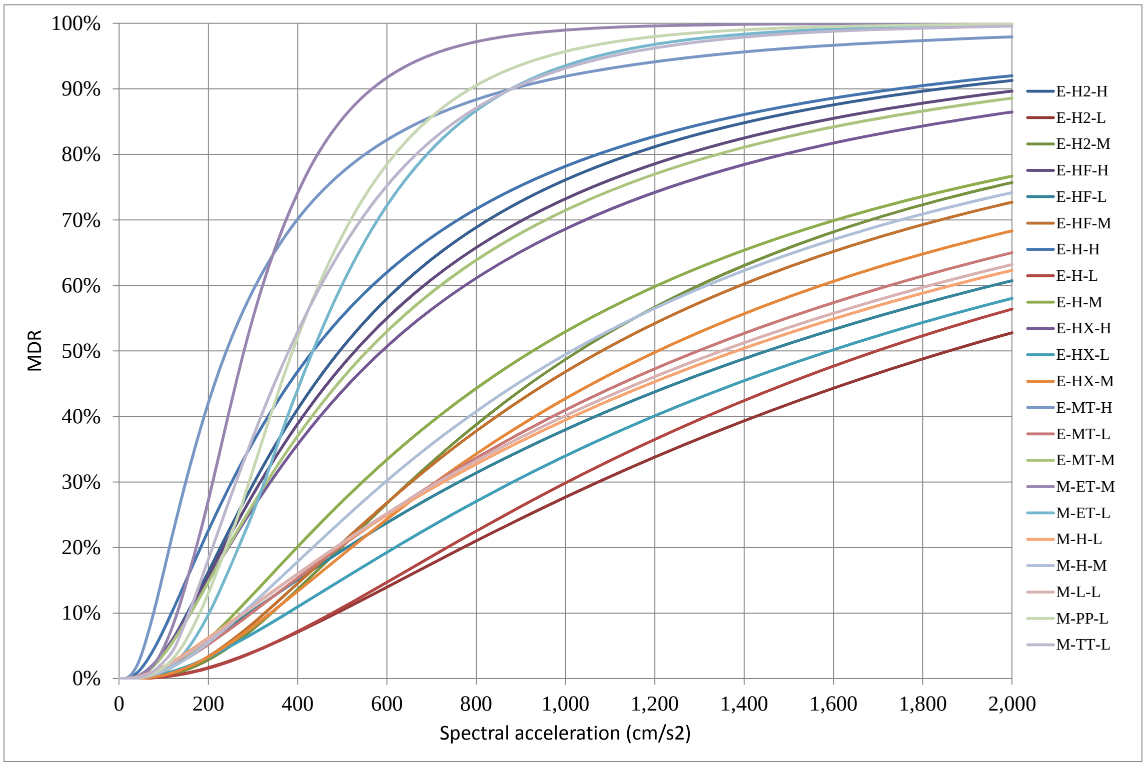

Figure 47. Seismic vulnerability functions used in Lorca

Physical Risk Results

In the case of a single scenario approach, the mean damage ratio (MDR) for each building is obtained and aggregated for all the buildings of the city. Results can be disaggregated in terms of building classes to see which classes concentrate higher risk levels.

Table 10 shows the risk results in terms of the aggregated MDR for all the building classes of Lorca considered in this study; from this it is clear that the masonry building classes concentrate the higher physical risk values. Furthermore, it can be seen that the building class with higher MDR corresponds to earthen structures, which have proven to have poor performance under the seismic demand due to the poor construction practices and materials. Masonry structures have the highest MDR values, showing the fact that the stone masonry buildings present the highest risk. R/C slabs also have an important contribution to the modeled losses due to their high seismic vulnerability. According to the simulated scenario, a global MDR equal to 8.2% is expected for the buildings of Lorca, which in monetary units and using the replacement cost approach selected for this study corresponds to a total 546.5 million of euros of direct losses.

Table 10. MDR by building class in Lorca

Building class	Damage cost (millions €)	MDR
Earthen	172.8	22.3%
Stone masonry	79.4	12.8%
Brick masonry	75.0	5.6%
Masonry walls and R/C slabs	94.7	7.0%
Toledo masonry	73.8	10.0%
Steel buildings	3.2	3.1%
R/C frames with steel braces	3.2	3.6%
Pre 1995 R/C frames	21.7	2.6%
Prefabricated R/C structures	13.2	5.2%
Post 1995 R/C frames	9.4	1.8%
TOTAL	**546.5**	**8.2%**

According to the official post-earthquake survey, the damaged buildings were classified in four categories: 1) habitable, without significant damage; 2) with restricted access due to non-structural damage endangering the safety of the occupants; 3) with forbidden access because retrofitting actions were required; and 4) buildings with mandatory demolition orders. A total of 7,852 buildings were inspected, accounting for 44.5% of the buildings in Lorca, and it was observed that 19% of those did not suffer any significant damage.

In order to compare the observed with the simulated damage, MDR levels were set for the different damage categories. It is assumed that buildings need a demolition order if MDR is higher than 40%; have forbidden access if MDR is between 20 and 39.9%; have restricted access if MDR is between 10 and 19.9%; are habitable if MDR is between 6 and 9.9%; and have no damage if MDR is lower than 6%. According to these levels, the statistics for all buildings in Lorca is presented in Table 11. Figure 48 presents the geographical distribution of the MDR along Lorca.

Table 11. Damage categories statistics from the simulated scenario

Damage category	MDR (%)	Number of buildings	% of buildings
No damage	0.0 - 5.9	3,206	18.2
Habitable	6.0 - 9.9	8,904	50.5
Non-structural damage	10.0 - 19.9	3,606	20.5
Structural damage - forbidden access	20.0 - 39.9	1,897	10.8
Demolition order	>40.0	3	0.0
TOTAL		**17,617**	**100**

Figure 48. MDR distribution in Lorca's historical center

The percentage values of the simulated scenario are similar in all damage categories with the exception of the buildings with demolition order. In Lorca many buildings were not demolished because they presented a high level of damage but due to social, institutional and insurance reasons. This is important to bear in mind since after a disaster event there are decisions made not necessarily following technical reasons but economic and urban planning ones. Disaster events may trigger economic boost initiatives. generate new open public space areas and/or stock replacement (even more when resources are available through an insurance consortium). Those actions are not predictable since they depend in each case on the economic circumstances of the event's occurrence.

Finally, earthquake risk models at urban level provide overall estimations that can be useful for decision-makers in terms of required resources and expected damage of the portfolio even if the exact location cannot be established. Therefore, if the results are mapped, a building by building resolution level risk assessment can be misleading since the simulated results could be interpreted as an exact prediction for each building, whilst they only represent mean values. Therefore, results in the best case should be grouped by categories, such as building classes, neighborhoods, counties, etc.

Manizales, Colombia

Introduction

This final case study constitutes the most complete and updated local case that has been calculated using the CAPRA Platform. Located in the Central Cordillera, Manizales has high level hazard not only in terms of seismic hazard but in terms of floods, volcanoes and landslides where a comprehensive and detailed approach was selected.

This section presents a summary of a set of studies developed under the framework of an Inter-institutional project where also, the Universidad Nacional de Colombia in Manizales has been a center of excellence of the Integrated Research of Disaster Risk, IRDR program. The aim of the project was to quantify in probabilistic terms, the physical risk not only to know the value of AAL or PML but to develop tasks associated to the hazard and risk assessment. For example, a local seismic hazard assessment has been conducted at bedrock level to update and harmonize the seismic microzonation of Manizales to the national earthquake resistant building code (NSR-10), but, besides this, both inputs (hazard at bedrock level and the seismic microzonation) were later used for a fully probabilistic risk analysis in both, the building stock and the water and sewage network with the purpose of financial risk transfer through insurance or another risk mechanisms (Cardona, 2009; Marulanda et al., 2008; SELA, 2010). Another interesting and innovative application has been the developing of land use planning measures that directly and implicitly account for the risk level, in this case for the case of landslides.

Purpose of the Risk Assessment and Resolution Level

As mentioned in the introduction, all the results presented in this section are part of a detailed study in terms of hazard, exposure and risk conducted in Manizales, Colombia. The city can be seen as a worldwide example in disaster risk management because, since 2.5% of property tax paid by its citizens is destined to disaster risk mitigation studies or works. Though it has not been easy to achieve, it presents a clear example of political will, gained only by making understandable the risk that the city faces. This constitutes a very interesting case when the expected outputs of the project in terms both of selected methodology and expected results were defined before starting it; that is, the question to be answered by the risk analysis was previously asked and understood, one of the key aspects of successful risk assessments (GFDRR, 2014).

Topography in Manizales is a challenge and most of the buildings and infrastructure is either located in or exposed to high slope areas; to account for this in a proper manner in the hazard and subsequent risk studies, a high resolution level is needed to be chosen which, of course, requires detailed base information.

Urban planning had a very relevant role in this project and the landslide hazard and risk assessment was directly related to the topic. The results obtained in the framework of this project were used in the land use planning through the Territorial Ordering Plan (POT) of Manizales and constitutes the first known case where, risk, has been directly addressed and quantified while implicitly regulated through a mandatory document with the aim of reduce future risk by addressing which areas can be used and more interesting, which ones need to be intervened and improved for allowing it future use.

The purpose of part of study consists on the detailed evaluation of natural risk in the city for developing a comprehensive disaster risk reduction strategy covering topics such as retrofitting of existing structures, update of the current subsidized earthquake insurance scheme (Marulanda et al., 2014), probabilistic benefit/cost analysis of structural interventions and land use planning.

Additional to this, through a set of training sessions in the different modules related to the hazards, exposure, vulnerability and risk of the CAPRA Platform, a group of both experts and students became familiarized with the concepts and tools related to probabilistic risk analysis; this with the aim of having a center of excellence in the topic within the University and expand the experts' community on the topic so that future assessments and updates can be easily conducted in the short and medium term.

Hazard Assessment

Seismic Hazard

A probabilistic seismic hazard assessment at bedrock level to be later used as part of the input data for the seismic microzonation of the city has been conducted at local level in Manizales following the requirements included in the national earthquake resistant building code NSR-10 (MAVDT, 2010). For this case, local calibrated ground motion prediction equations (GMPE) were used in the analysis (Bernal et al., 2014a) and the output results consisted on a set of stochastic scenarios from where besides being later used in the risk analysis, hazard maps for different return periods, such as the one shown in Figure 49 were obtained.

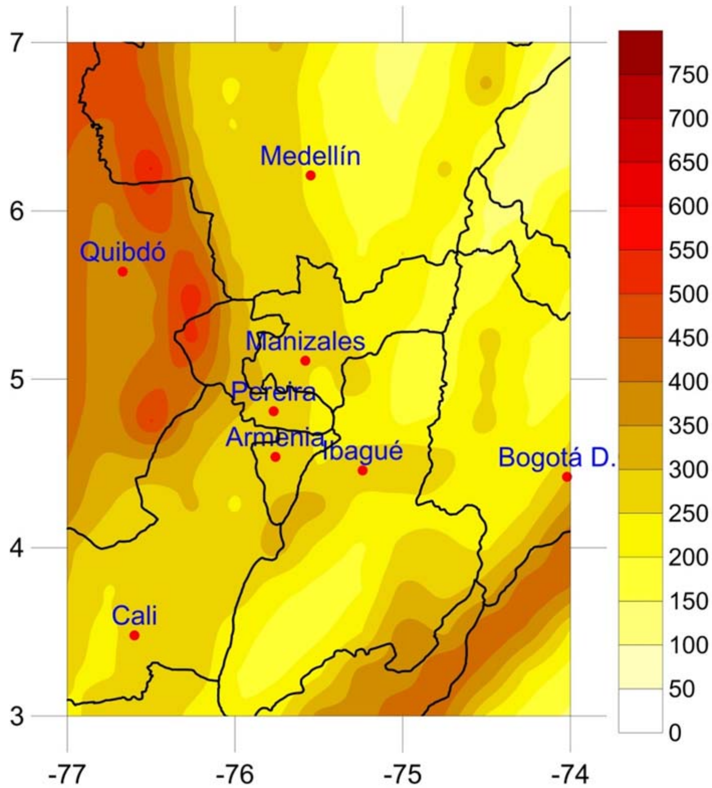

Figure 49. Seismic hazard map for Manizales; RT: 975 years, PGA (cm/s^2)

Following the procedure proposed by Bernal et al. (2014b), different homogeneous soil zones were identified and for each of them a unique spectral transfer function was defined. Figure 50 presents the fundamental vibration period of each soil zone in Manizales.

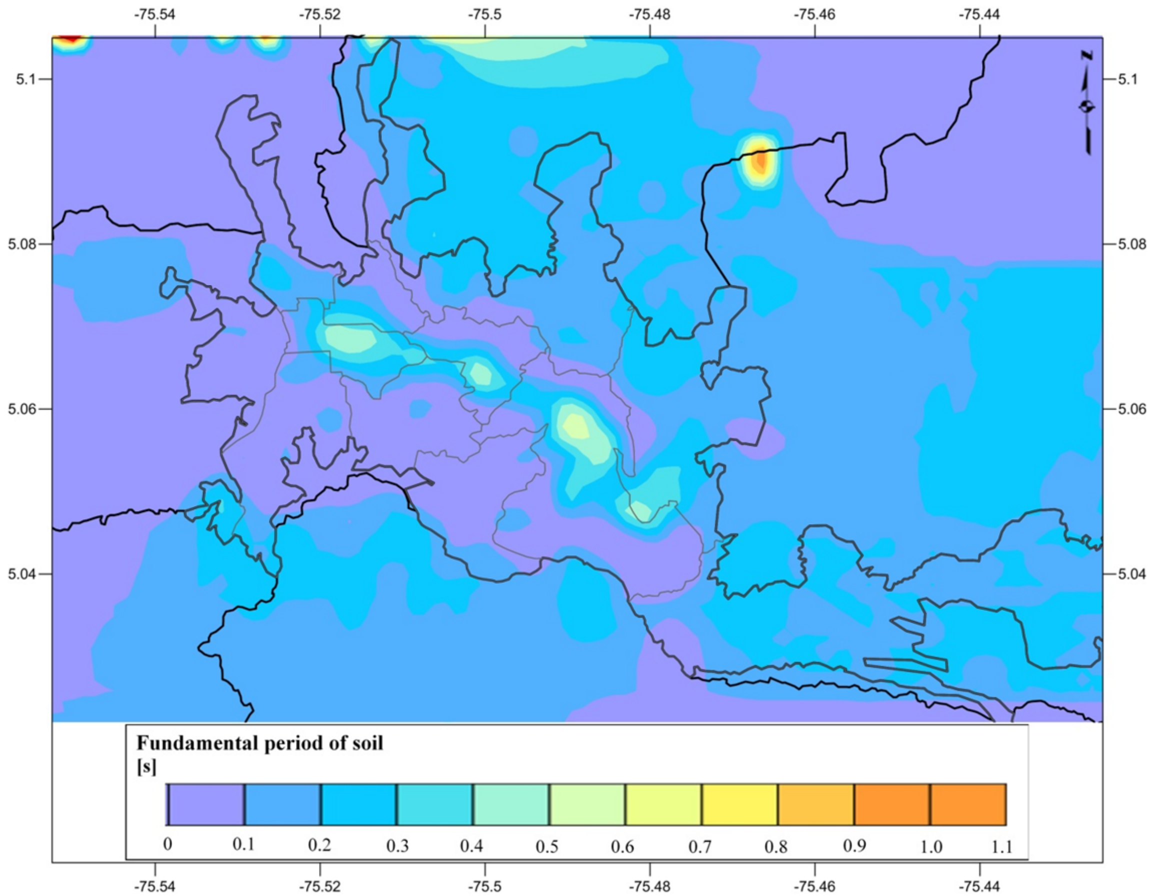

Figure 50. Fundamental vibration period of the soil zones in Manizales (sec)

Rainfall and Flood Hazard

A detailed rainfall analysis was performed for the Chinchiná basin where, from rain gauge records for more than 30 years in several meteorological stations, precipitation-area-duration-frequency (PADF) curves were generated. From them, a set of stochastic rainfall scenarios was generated such as the ones presented in Figure 51.

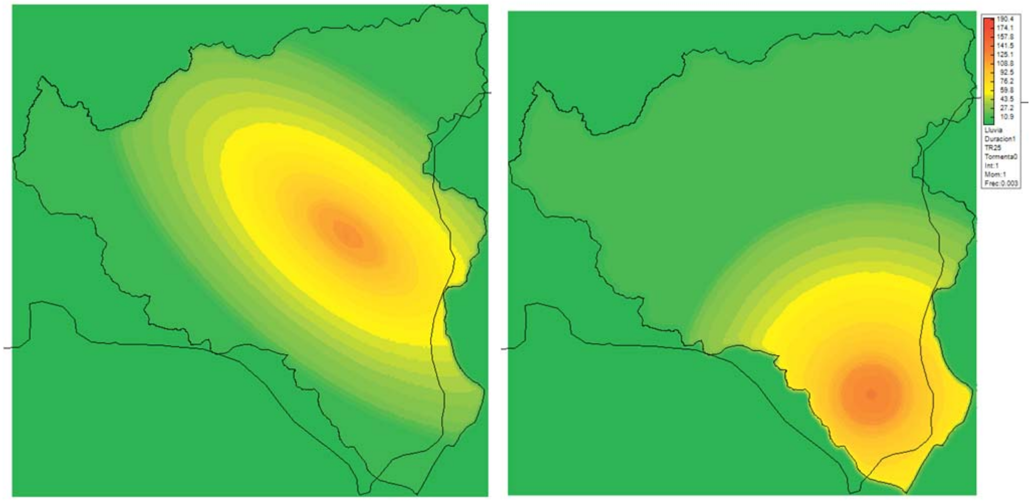

Figure 51. Stochastic rainfall scenarios (mm)

Using the rainfall scenarios, hazard maps for any return period and for selected rainfall duration were generated such as the one presented in Figure 52.

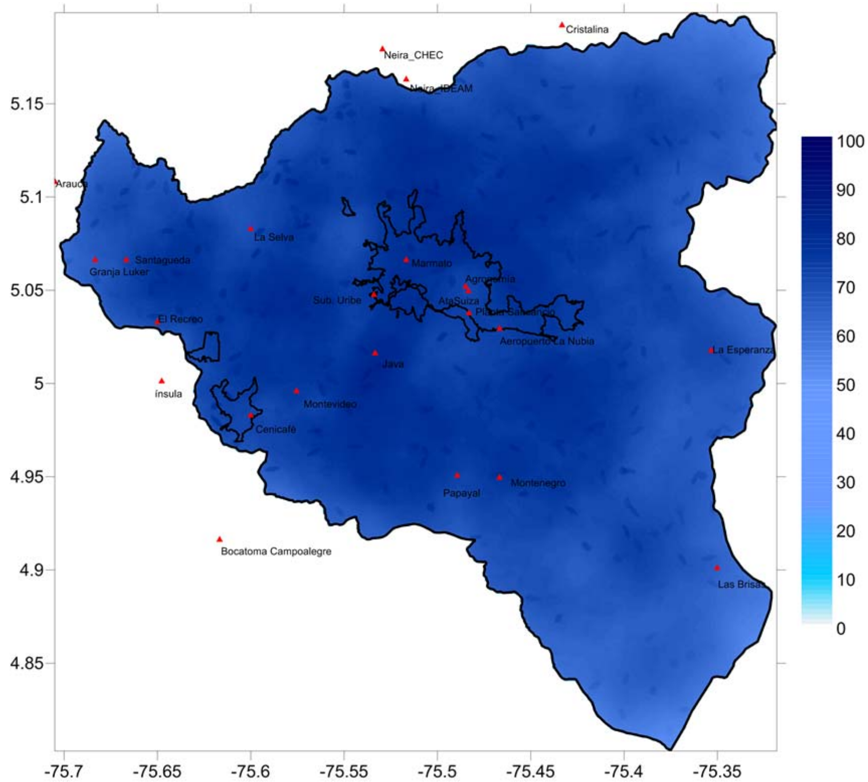

Figure 52. Rainfall hazard map. TR: 75 years; 1 day (mm)

Volcanic Hazard

Ruiz Volcano is located 30 kilometers south east away from Manizales and several historical eruptions have affected and reflected through disruptions in the city. Because of the characteristics of the volcano, the effects that may affect Manizales are mostly related to the ash fall. Following an innovative probabilistic volcano hazard analysis, a set of stochastic scenarios for ash fall was generated based on historical information and activity indexes. The geographical coverage, pitch and extent of each scenario, considers in a comprehensive manner the wind effects that, together with the eruption magnitude, has to do with the way this hazard intensity manifests.

Figure 53 presents a ash hazard map for Manizales where can be seen, that the expected ash thickness in the city is between 10 and 1 centimeters, that in terms of vulnerability can be translated in moderate-high risk for light cover/roof buildings and have consequences in public health issues.

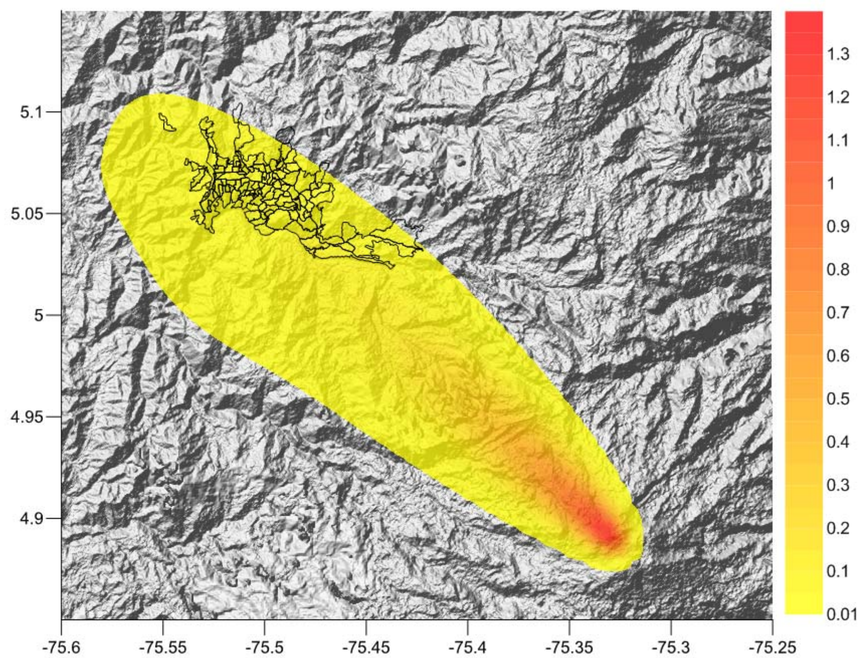

Figure 53. Volcanic ash thickness hazard map (m)

Landslide Hazard

A landslide hazard and risk analysis was performed using detailed information in terms of input data such as land use, topography and geological information for the city. Hazard was quantified in terms of susceptibility both at geographical (polygons) and exposed dwellings that can be mapped with purposes of urban planning. Hazard has been also quantified in terms of probability of occurrence in 100 years. On the other hand, risk in terms of economic losses due to direct damages was quantified with a detailed resolution of 5 by 5 meters as presented in Figure 54.

The concept of implicit and explicit risk was addressed in this study and, because of the characteristics of the hazard and its level of affection it can be classified in the first category. Figure 55 shows this classification.

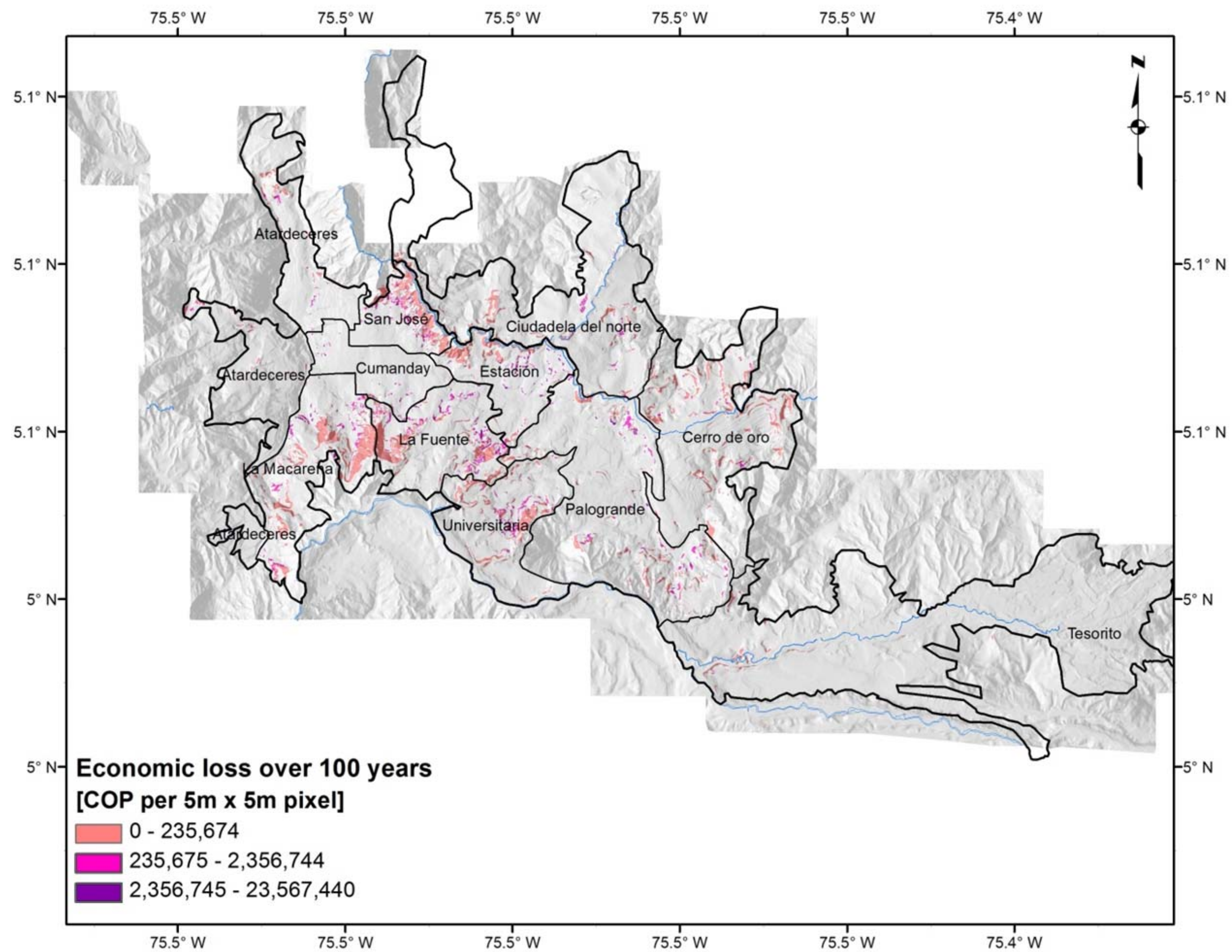

Figure 54. Expected losses due to landslides in Manizales

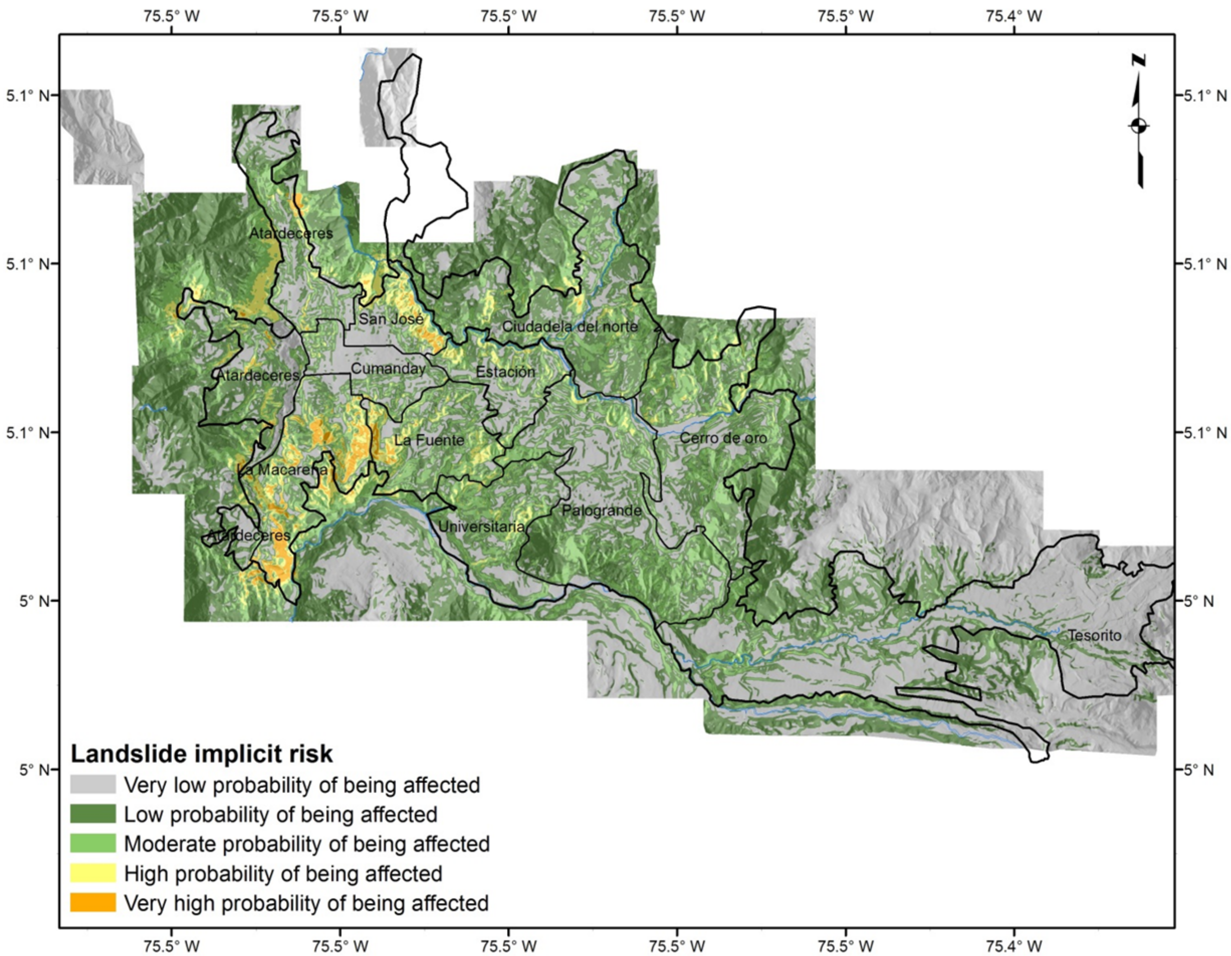

Figure 55. Landslide implicit risk level for Manizales

From the results it is clear that this is a very relevant hazard and its consideration through planning measures is important for Manizales in terms of risk reduction. More results of this landslide hazard and risk assessment for Manizales can be found in Annex 7.

Exposed Assets

Building stock

The building stock in the urban area of Manizales is comprised by around 85,000 dwellings. Cadastral information is up to date both in terms of economic appraisal of each element and in terms of relevant structural characteristics. Most of the elements in the database have residential use, not ignoring an important participation of the commercial elements in some important areas of the city. Figure 56 presents the geographical distribution of the exposed elements classified by main use while Figure 57 presents the same information in terms of number of stories.

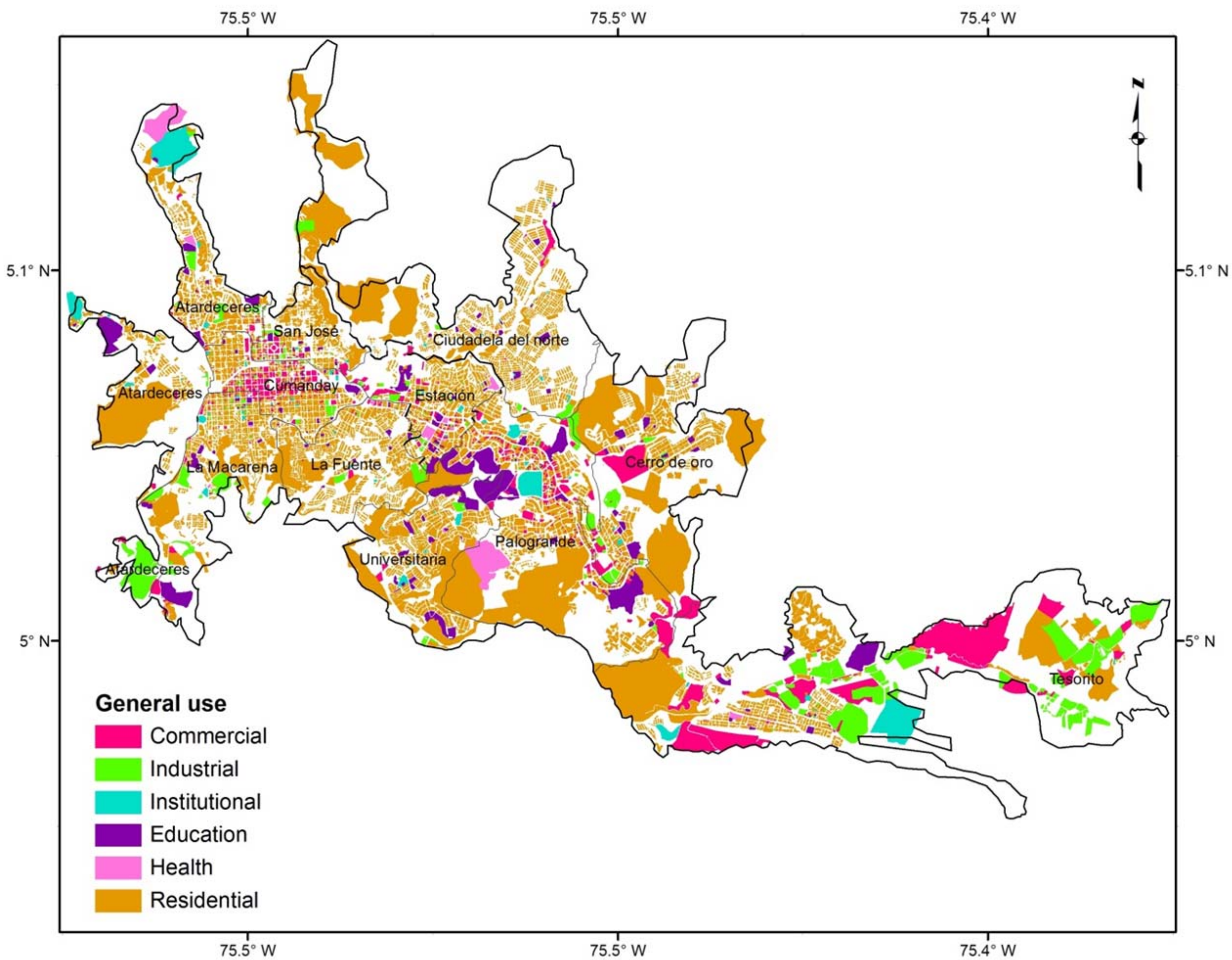

Figure 56. Main use of the building stock of Manizales

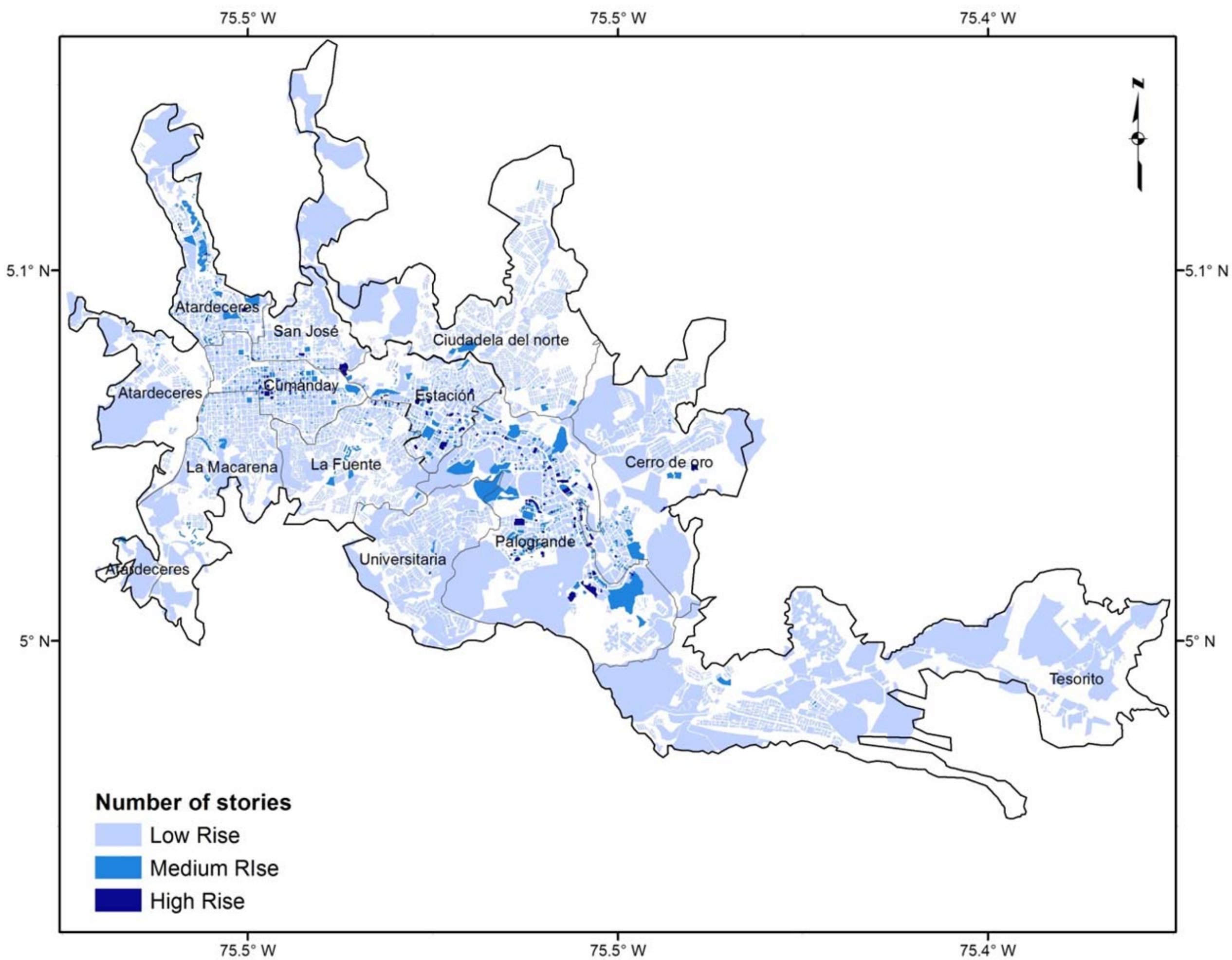

Figure 57. Number of stories category for the building stock of Manizales

Water and sewage network

For the probabilistic seismic risk assessment of the water and sewage network of Manizales, a database of exposed assets was developed using the information of *Aguas de Manizales* which allowed an identification and characterization of the elements through information related to their material, diameter and age among others. This was later used for the assignation of a unique vulnerability function, defined in terms of peak ground velocity which has been observed to be the physical parameter that best correlates the seismic damage for this kind of elements. Figure 58 presents the geographical distribution for the main water network in terms of material.

The same identification and characterization of other elements of the network ranging from storage tanks to administrative buildings is also available and was considered in the analysis. Seismic risks results for the water and sewage network of Manizales besides quantifying risk in a rigorous manner, gave important information to the company in the framework of exploring other alternative risk transfer mechanisms to be able to put into consideration, other available options different to the traditional insurance policies.

Finally, knowing not only the risk results in terms of monetary losses but in terms of repair rates per kilometer for the pipeline network, helped to design maintenance and expanding plans of the company by deciding which are the more convenient material and construction practices in terms of seismic risk; this, not only to have lower monetary losses but to guarantee that the service is available to the citizens in case an strong earthquake strikes the city.

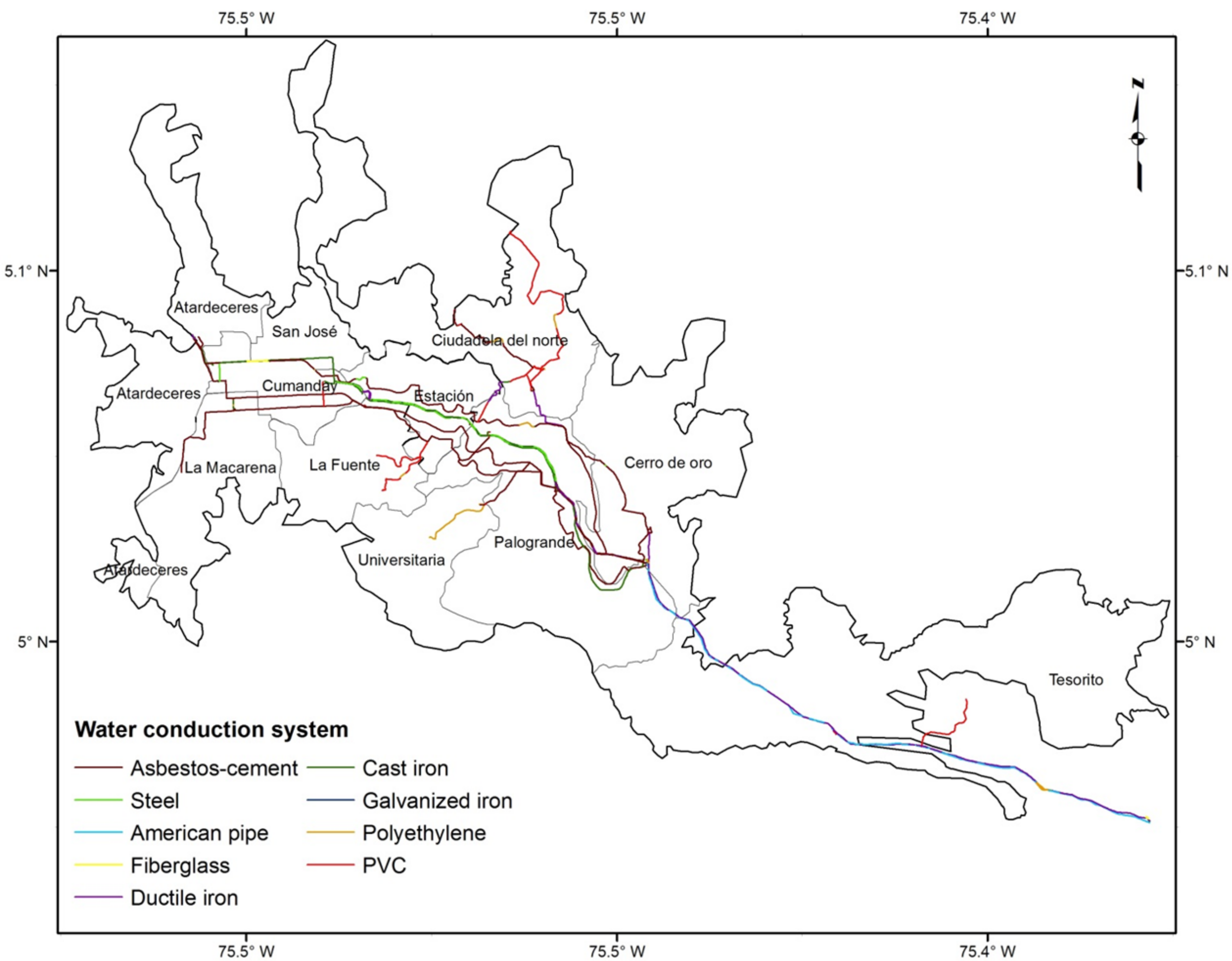

Figure 58. Pipe material for the main water network of Manizales

Vulnerability of the Exposed Assets

The development of vulnerability functions in Manizales represented a big challenge since they needed to be associated to different hazards in order to correctly make estimations of the possible future losses in the city due to the occurrence of natural events. Even more, since different infrastructure elements were considered at different stages of the analysis, for example buildings, tanks and pipelines, specific functions were required.

It is important to mention that depending the kind of element for which the physical vulnerability is being assessed, even when dealing with the same hazard, the physical measure (intensity) that better correlates the expected damage. An example of this can be shown through the seismic vulnerability functions of reinforced concrete frames, which damage is better correlated through the spectral acceleration as presented in Figure 59 while for the pipelines, the seismic vulnerability functions are defined in terms of the peak ground velocity as presented in Figure 60. It is evident that, of course, the hazard needs to be quantified in terms of the relevant and better correlating physical measures of each hazard.

Vulnerability functions for the pipelines of the water and sewage network take into account different characteristics in terms of age, material, diameter and soil conditions where the pipe lie; Annex 7 presents example of this changes in the parameters for concrete pipelines. All this information was possible to gather due to the excellent and updated database of exposed elements collected and continuously updated by *Aguas de Manizales*. This is a clear example of how, data gathering and update constitute a first and very important step in risk assessment. Even more, in this case where the information was not gathered specifically for this study but for the normal operating conditions of the Company.

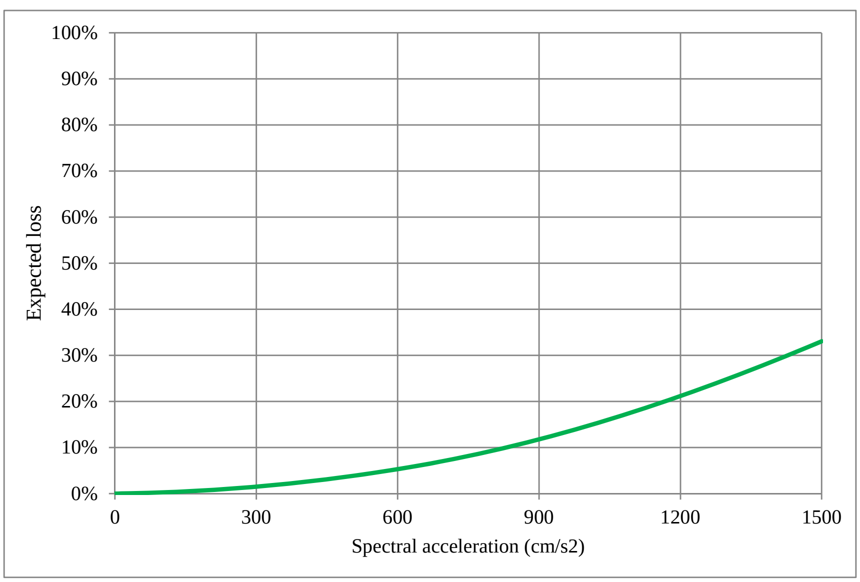

Figure 59. Vulnerability function for 5 stories reinforce concrete buildings

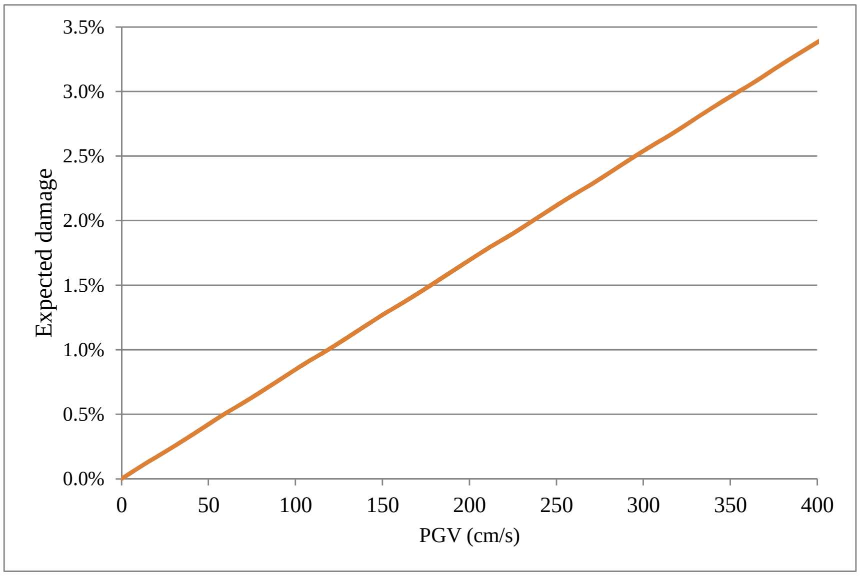

Figure 60. Seismic vulnerability function for concrete pipelines

Physical Risk Results

Figure 61 presents the LEC for seismic risk considering the building stock of Manizales, while Table 12 presents a summary of the results showing also the AAL and PML for selected return periods.

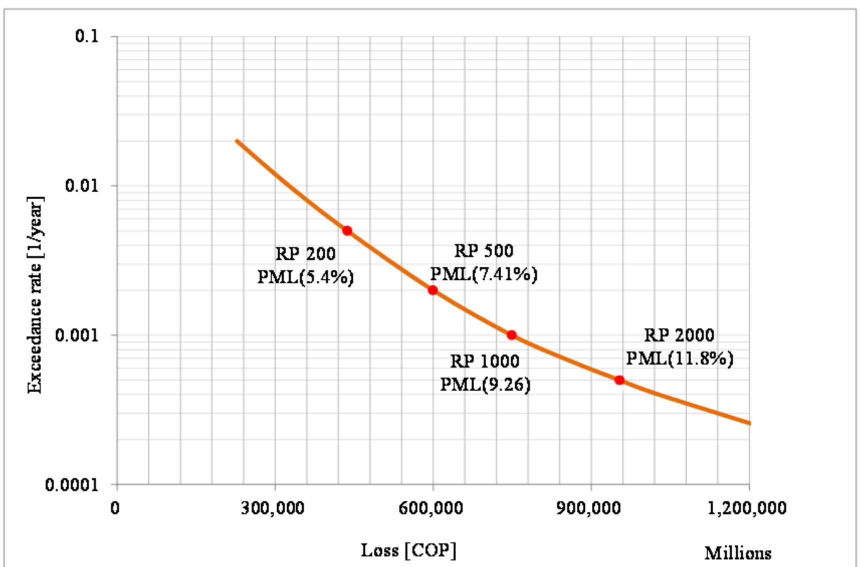

Figure 61. Earthquake loss exceedance curves for Manizales[3]

[3] 1USD is approximately 1,950 COP

Table 12. Summary of physical seismic risk results for Manizales

Results		
Replacement value	COP x10^6	8,090,792.54
Average annual loss	COP x10^6	19,479.87
	‰	2.408
PML		
Return period	Loss	
years	COP x10^6	%
200	$436,872.23	5.40
500	$599,641.24	7.41
1000	$749,084.37	9.26
2000	$953,506.42	11.79

On the other hand, Figures 62 and 63 present the geographical distribution of the expected damages and losses in the building stock and main sewage pipeline system in the city center. For the first, results are presented in terms of relative AAL as in the previous cases while for the second one, results are presented in terms of repair rate by kilometer (RR/Km) that is a useful metric in said field.

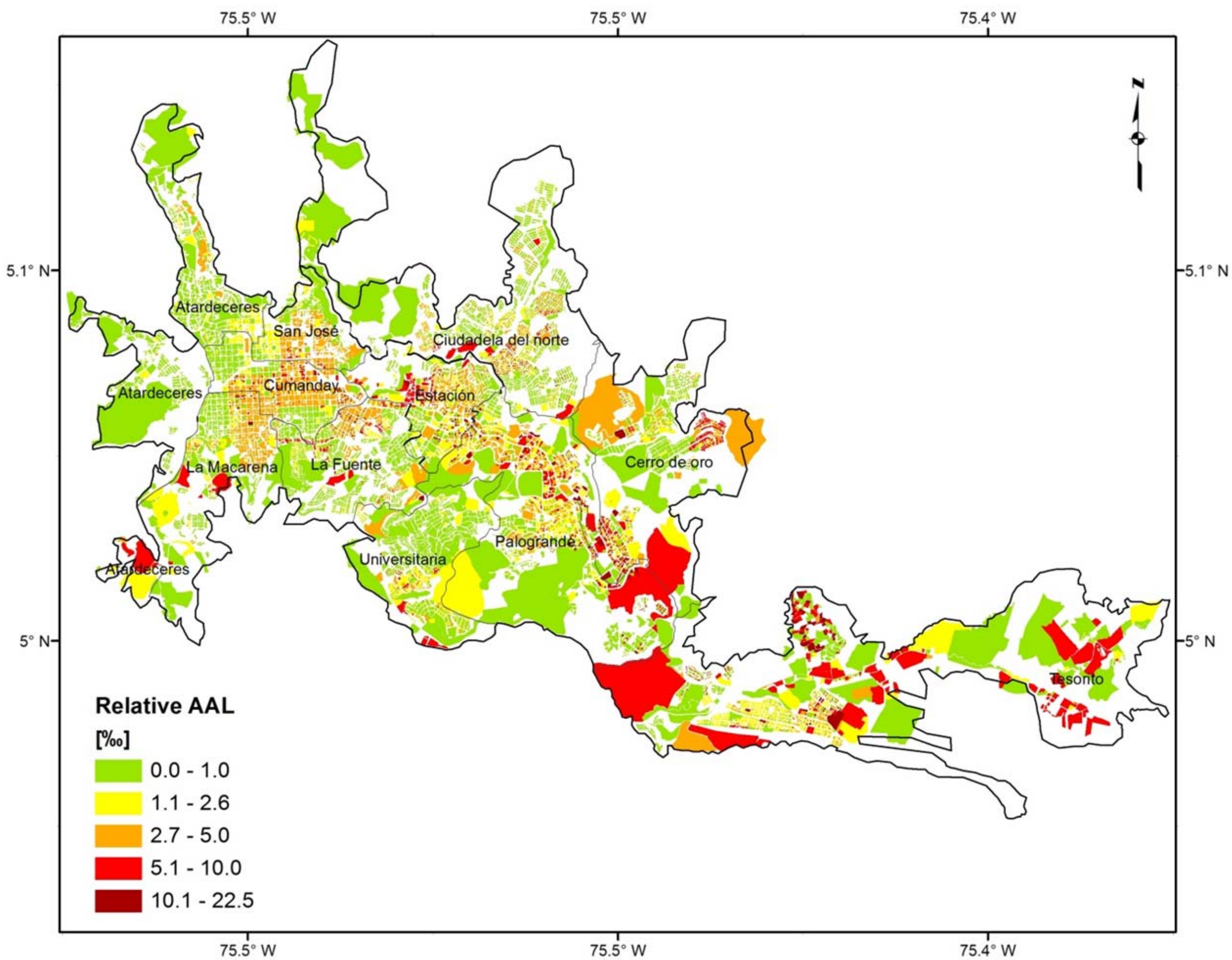

Figure 62. Relative (‰) AAL loss distribution for the building stock of Manizales

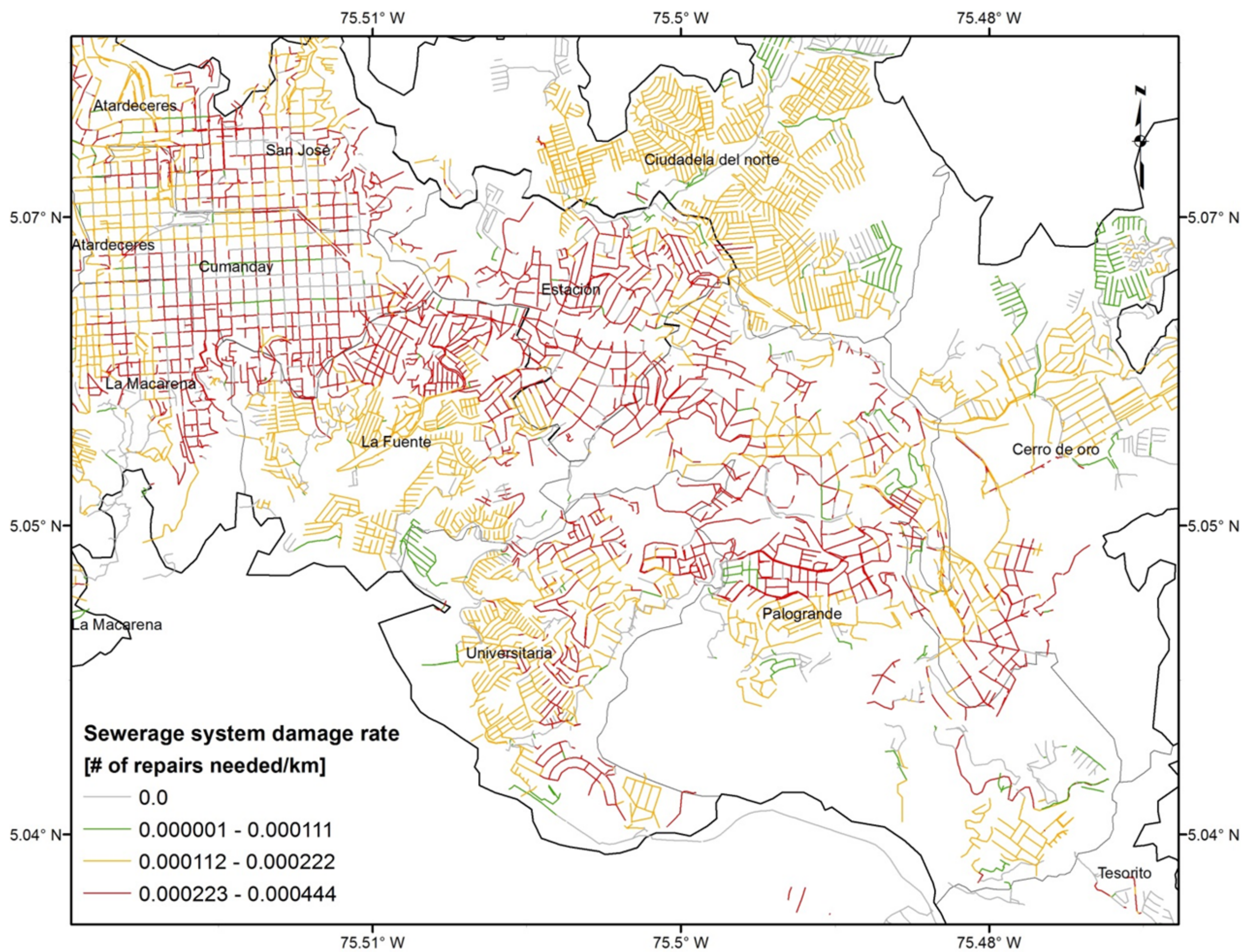

Figure 63. Average annual repair rate by kilometer distribution for the sewage network in downtown Manizales

Cross insurance scheme

Manizales has one of the real application and results' use from probabilistic risk assessment that has been used and promoted from over 5 years. This case is related to the insurance of the private buildings where, using the results of a fully probabilistic risk assessment an subsidized scheme exists where, owners that voluntarily underwrite policies to cover their assets, also pay for the insurance of those owners who, because of their economic conditions, are not in the position to pay for it. Insurance premiums are charged together with the property taxes in the city, which are charged on an annual basis and, of course, are related to its cadastral value. If a homeowner wants to buy the insurance, has to acquire also the portion that covers the poorest socio-economic layers.

In this case, the local government is not insuring the citizens but serving as an intermediate in the acquisition of said instrument. Of course, the local government is a beneficiary of this scheme by knowing that a good part of the possible losses in case of an earthquake occurring in the city are covered. On the other hand, this scheme constitutes an interesting case from the homeowner perspective since when insurance is underwritten in this form the premiums are lower if compared with the traditional individual basis. As was explained in the case of Bogotá, zones and assets in Colombia are classified for socioeconomic purposes in 6 layers; 1 being the poorest and 6 being the richest. In general terms, 1 and 2 layers correspond to the low income group, 3 and 4 layers correspond to the middle income group and 5 and 6 layers correspond to the high income group. The subsidize scheme is intended to cover the future losses of the low income group by the participation of the middle and high income ones. Figure 64 presents a summary of the insurance scheme from where it can be seen that in all cases exist a retention level captured trough a deductible that for the low income group is to be covered by the Municipality (local government); then, from that deductible level to a defined PML, risk is transferred in a classical insurance scheme with the only difference that, even by not underwriting any policy, the low income layer transferred losses are covered. For this scheme to work, a minimum participation (having again in mind that is a voluntary insurance) of the medium and high income level is required, and also, the higher the participation, the lower the overall risk premium. More details about this scheme can be found in Marulanda et al. (2014).

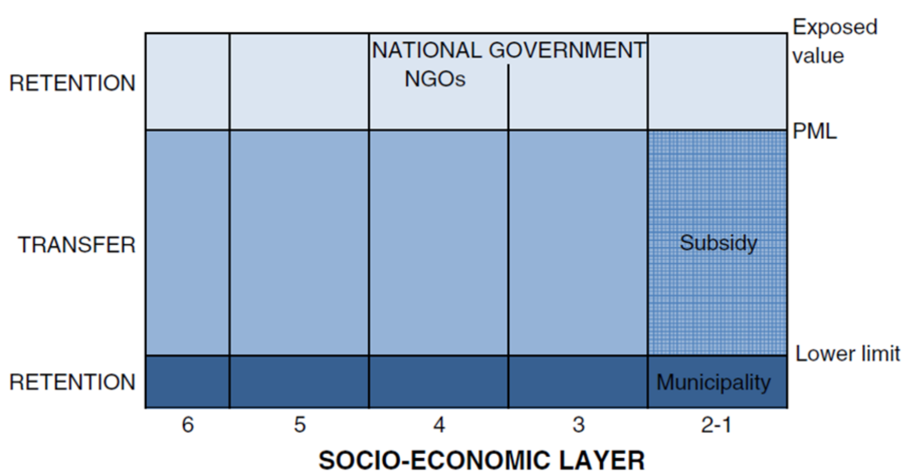

Figure 64. Subsidized insurance financial scheme for Manizales (From Marulanda et al. 2014)

Because building stock suffers changes with the time and the overall characteristics of the exposed elements and of course its characteristics are dynamic, it is important to update these studies on a regular basis when new information in terms either of hazard, exposure and/or vulnerability becomes available. In this case it is clear those important changes in terms of the hazard are mostly related to the inclusion of a new, updated and harmonized microzonation study not leaving aside, the improvements and refinements in the exposure database that consider more than 5 more extra years if compared with the original one used to develop and implement for the first time this subsidized insurance scheme.

Conclusions

This background paper has presented a set of local case studies where, following the exact same methodology and arithmetic than the one used in the Global Risk Assessment for the Global Assessment Report 2013 and 2015, direct physical risk has been assessed and quantified. As has been highlighted over this paper, detailed approaches are the solution when the question to be answered requires that resolution. Also, as has been shown, modification in the level of resolution has implications in how hazard, exposure and even vulnerability are modelled.

The global risk assessment conducted in the last two versions of GAR has had the unique objective to raise awareness, at a high administrative and political level, about the potential catastrophic risks than more than 200 countries face. Now, that those results have been shared and made available to the interested ones, efforts focused on conducted more refined risk assessments should be developed.

These detailed assessments will allow developing specific activities and policies related to disaster risk reduction, they may range from retrofitting of existing buildings after conducting probabilistic benefit-cost analysis up to land use planning to decrease the chance that future risks are created by increasing today’s vulnerability.

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Annex 1: Exposure, Vulnerability and Risk Data for Medellín

Exposure Information

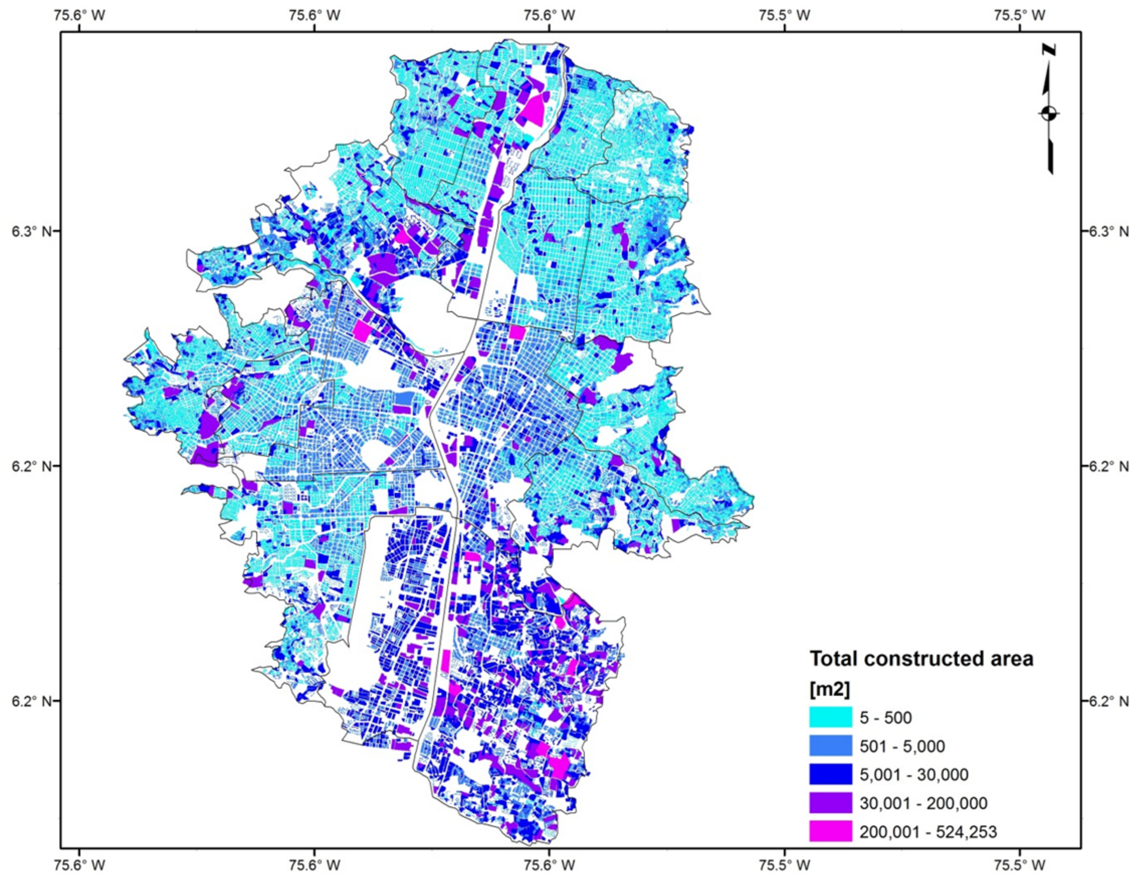


Figure 65. Total constructed area by dwelling

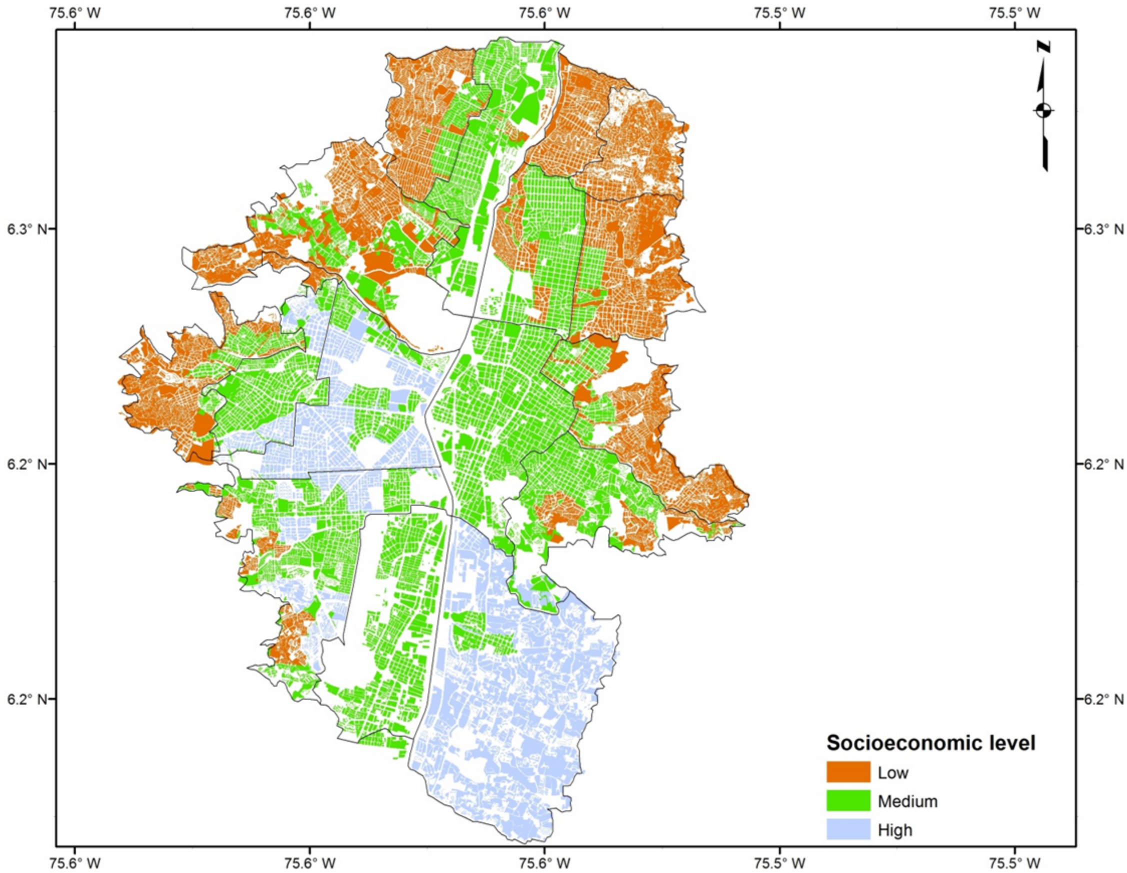


Figure 66. Predominant socioeconomic dwelling by county

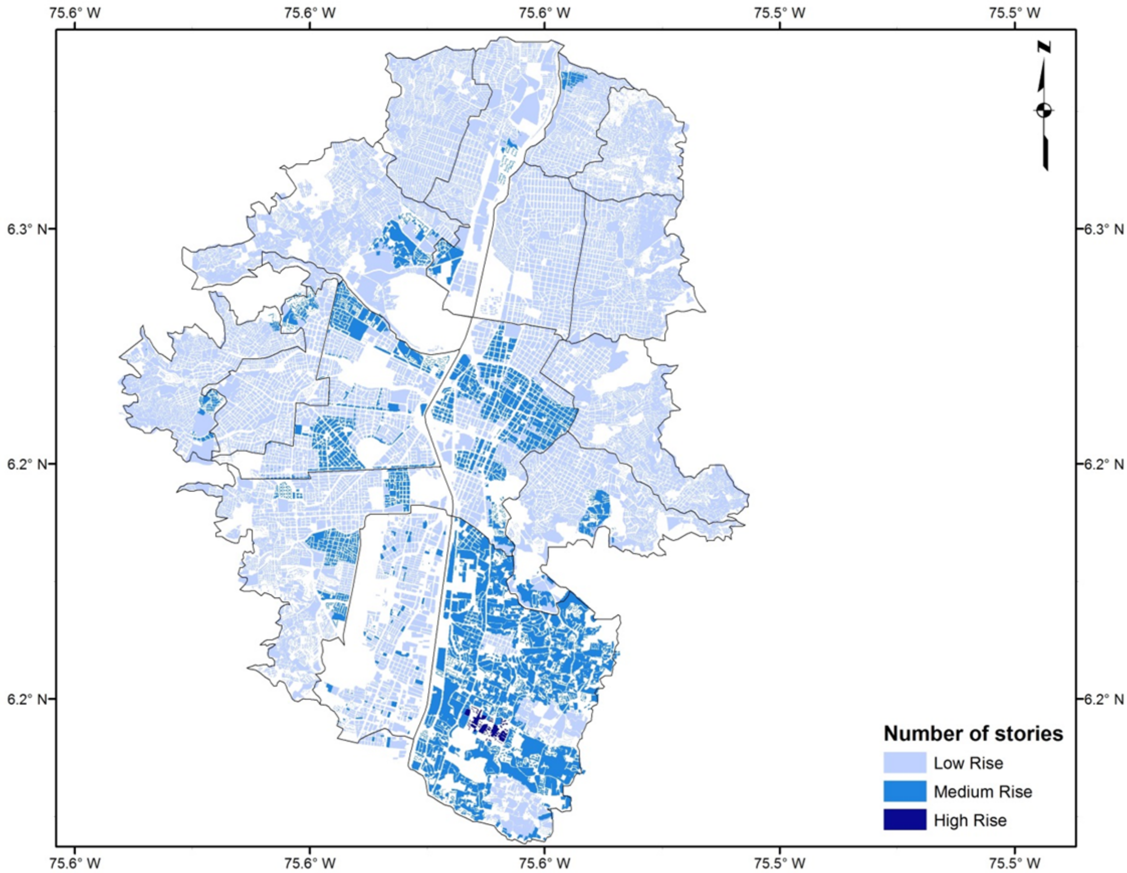


Figure 67. Number of stories category by dwelling

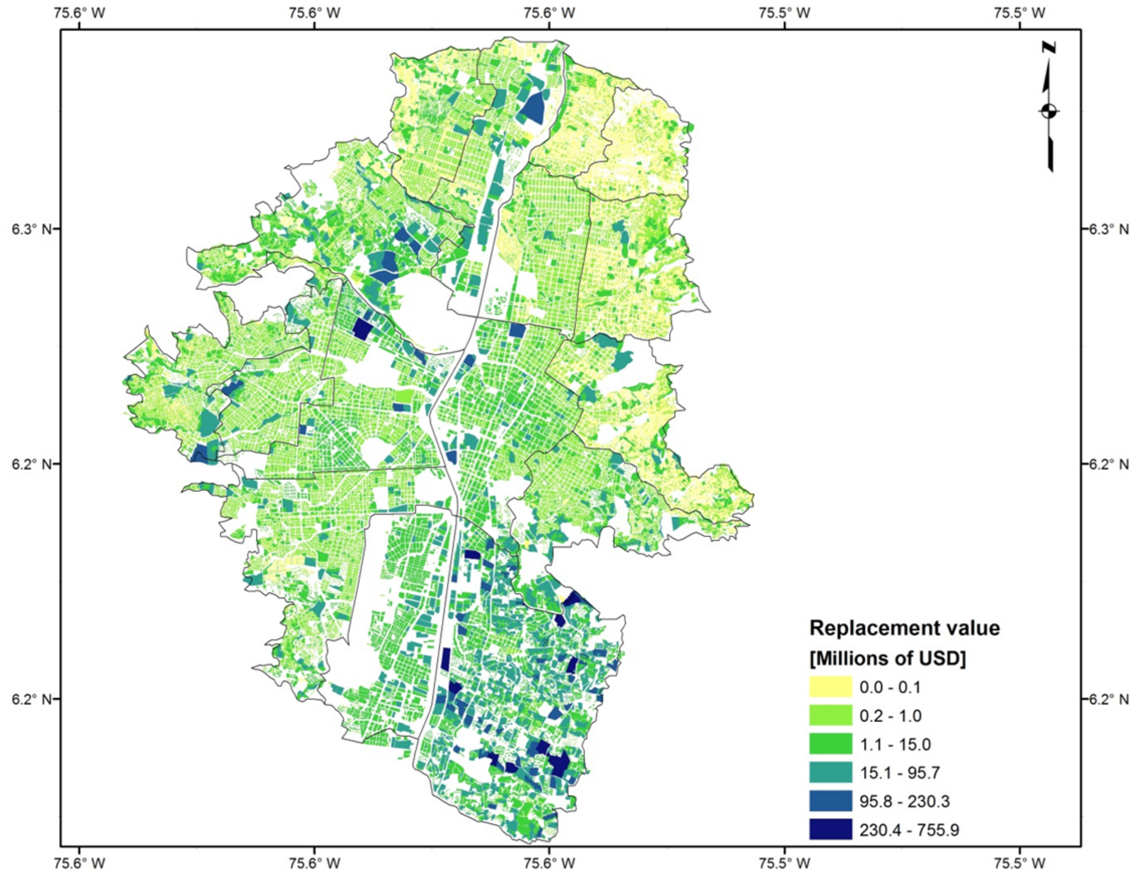


Figure 68. Replacement value by dwelling

Vulnerability Functions

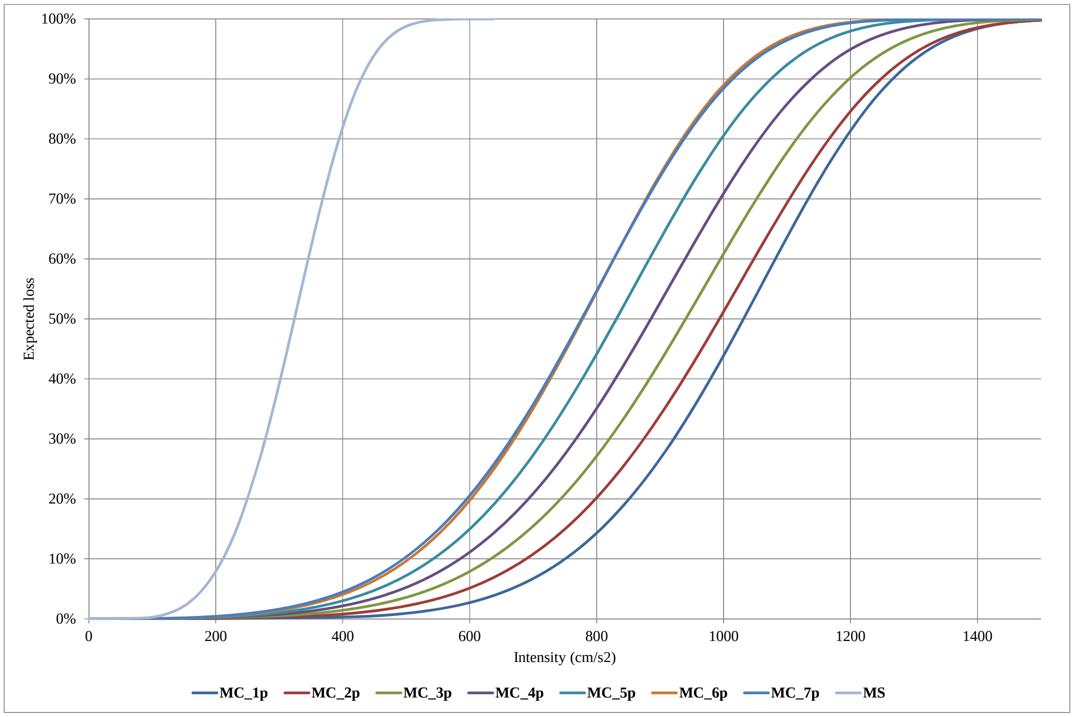


Figure 69. Vulnerability functions for masonry dwellings (unreinforced and confined)

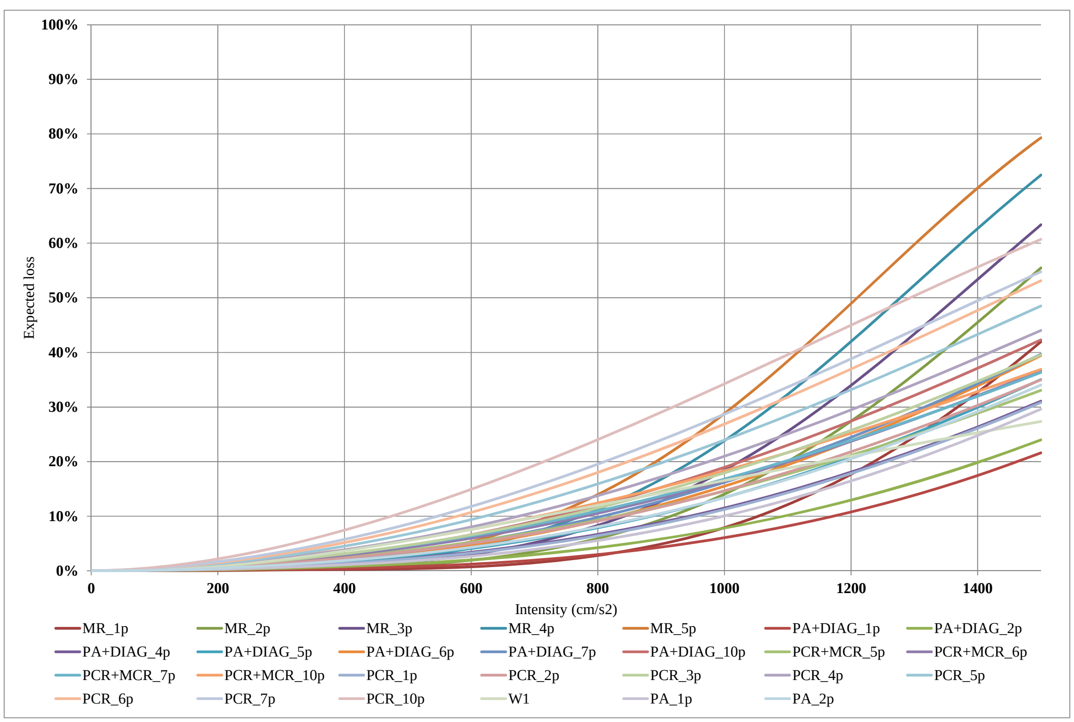


Figure 70. Vulnerability functions for reinforced concrete and braced steel frames

Seismic Risk

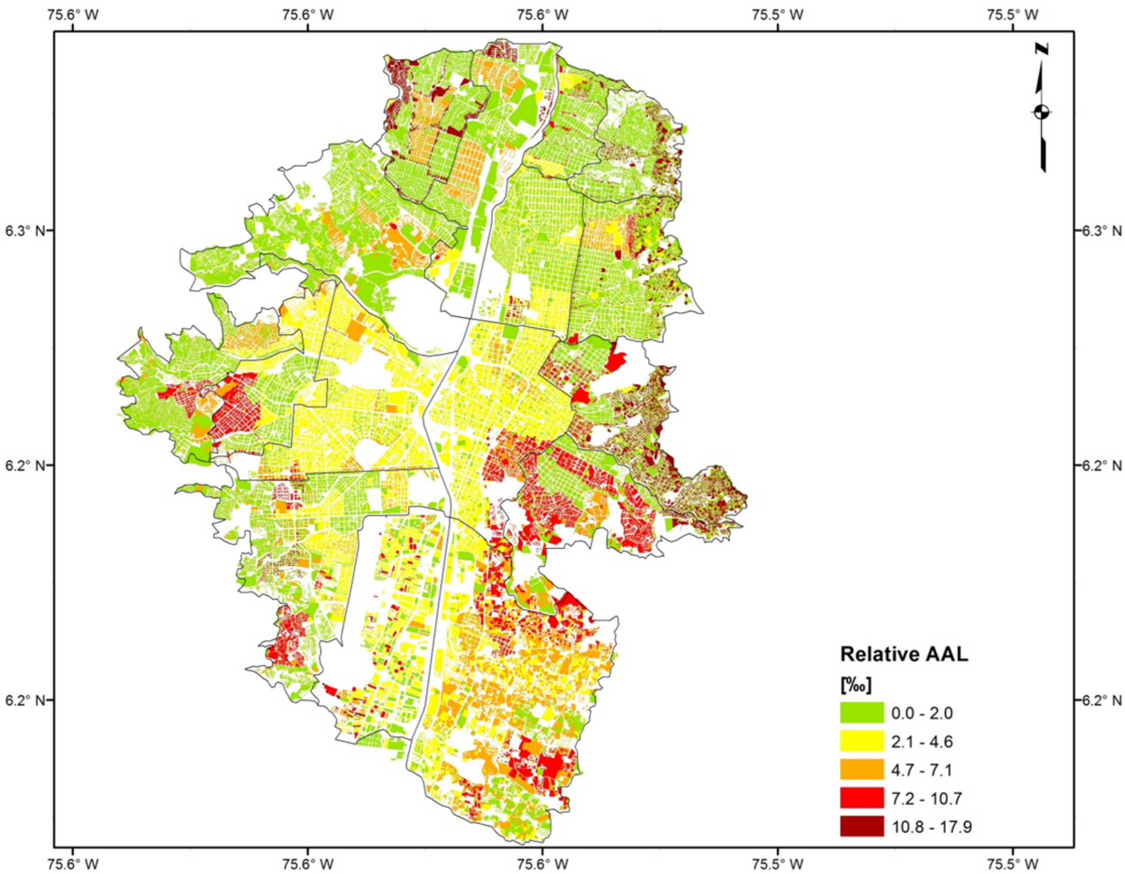


Figure 71. Relative AAL by dwelling

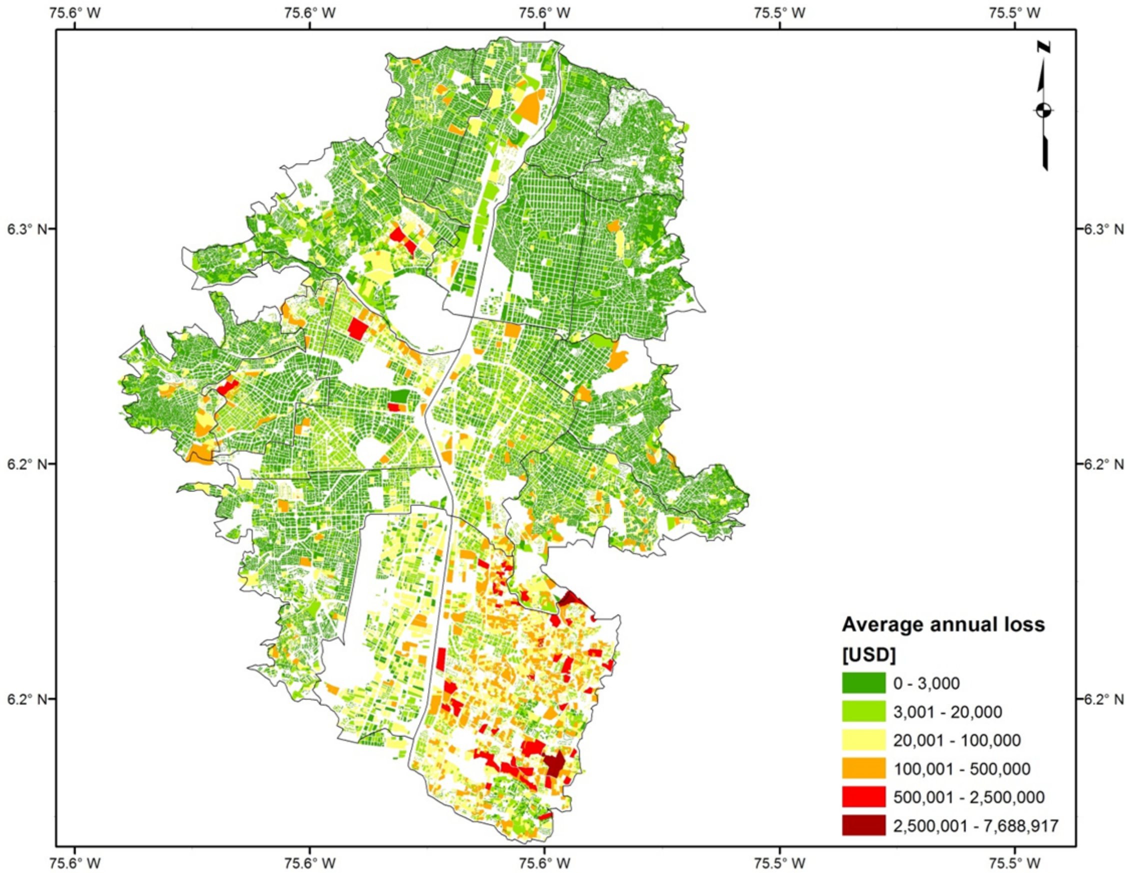


Figure 72. Absolute AAL by dwelling

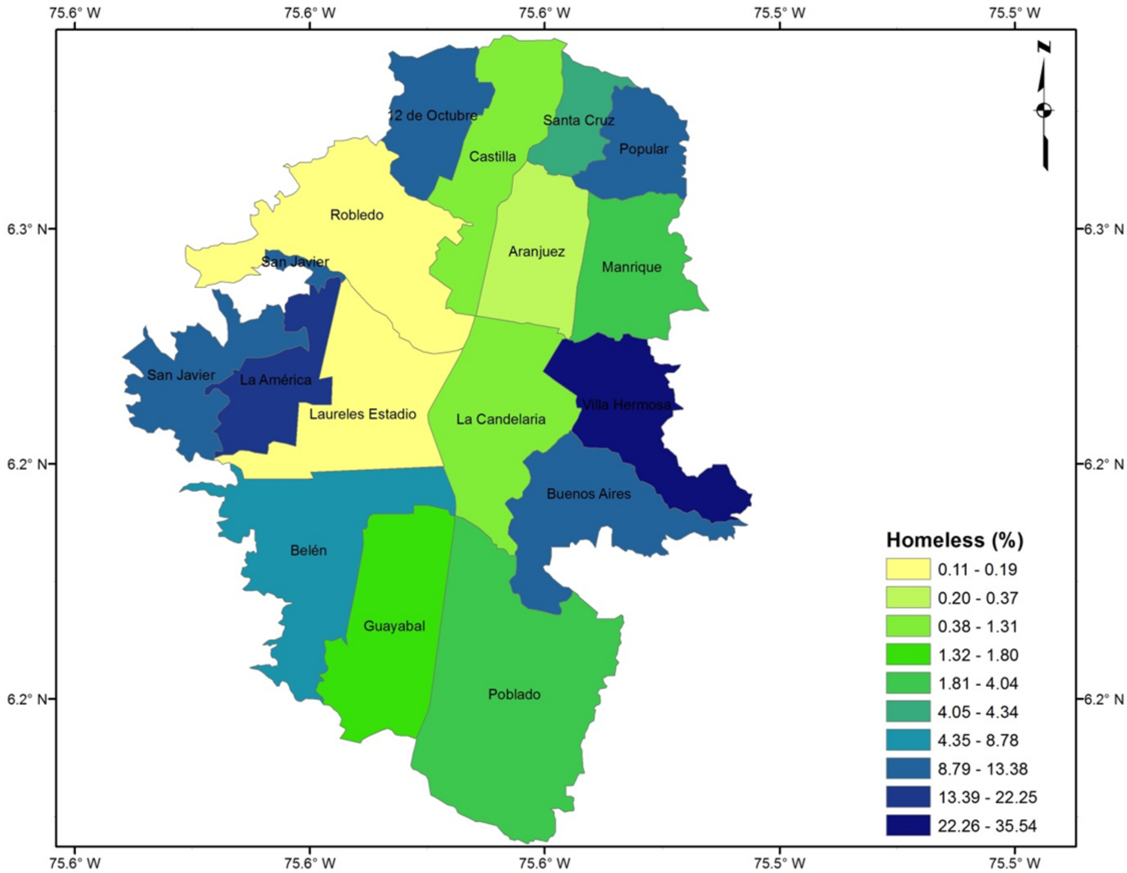


Figure 73. Homeless estimation (due to dwelling damage) for Medellín

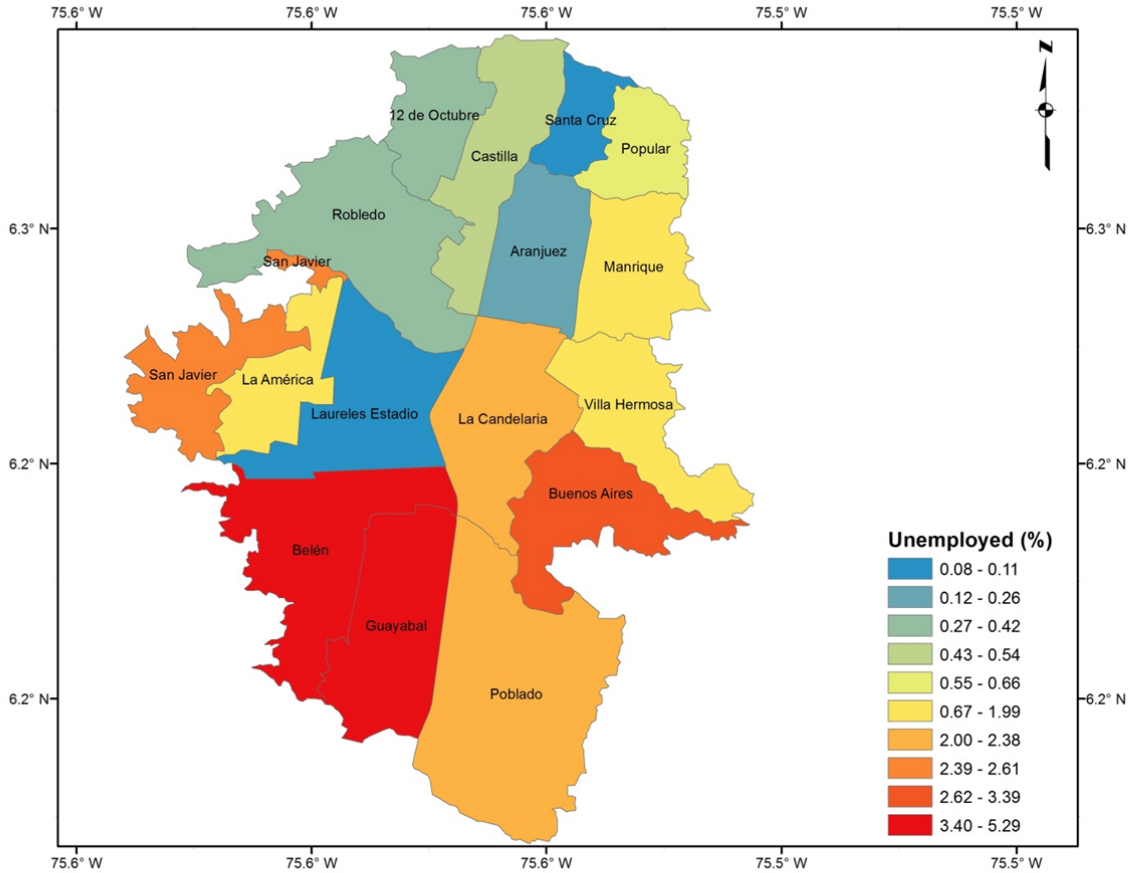


Figure 74. Unemployed estimation (due to dwelling damage) for Medellín

Holistic Risk Analysis

F_{RF1}	AAL commercial sector	w_{RF1}
F_{RF2}	AAL industrial sector	w_{RF2}
F_{RF3}	AAL institutional sector	w_{RF3}
F_{RF4}	AAL residential sector	w_{RF4}
F_{RF5}	Expected injured	w_{RF5}
F_{RF6}	Expected deaths	w_{RF6}
F_{RF7}	Expected unemployed	w_{RF7}
F_{RF8}	Expected homeless	w_{RF8}

R_F	Physical risk

F_{FS1}	Violent deaths rate	w_{FS1}
F_{FS2}	Quality life index	w_{FS2}
F_{FS3}	Mortality rate	w_{FS3}
F_{FS4}	Illiteracy rate	w_{FS4}
F_{FS5}	Poor connection to electricity net.	w_{FS5}
F_{FS6}	Poor connection to water network	w_{FS6}
F_{FS7}	Poor connection to sewage net.	w_{FS7}
F_{FS8}	No access to public health care	w_{FS8}
F_{FS9}	Population density	w_{FS9}
F_{FR1}	Public area	w_{FR1}
F_{FR2}	Distance to closest hospital	w_{FR2}
F_{FR3}	Distance to closest health centre	w_{FR3}
F_{FR4}	Human development index	w_{FR4}
F_{FR5}	Development level	w_{FR5}
F_{FR6}	Emergency operation level	w_{FR6}

F	Aggravating coefficient

Urban Seismic
Risk Index
USRi

Figure 75. Descriptors used for the physical risk and aggravating coefficient indexes

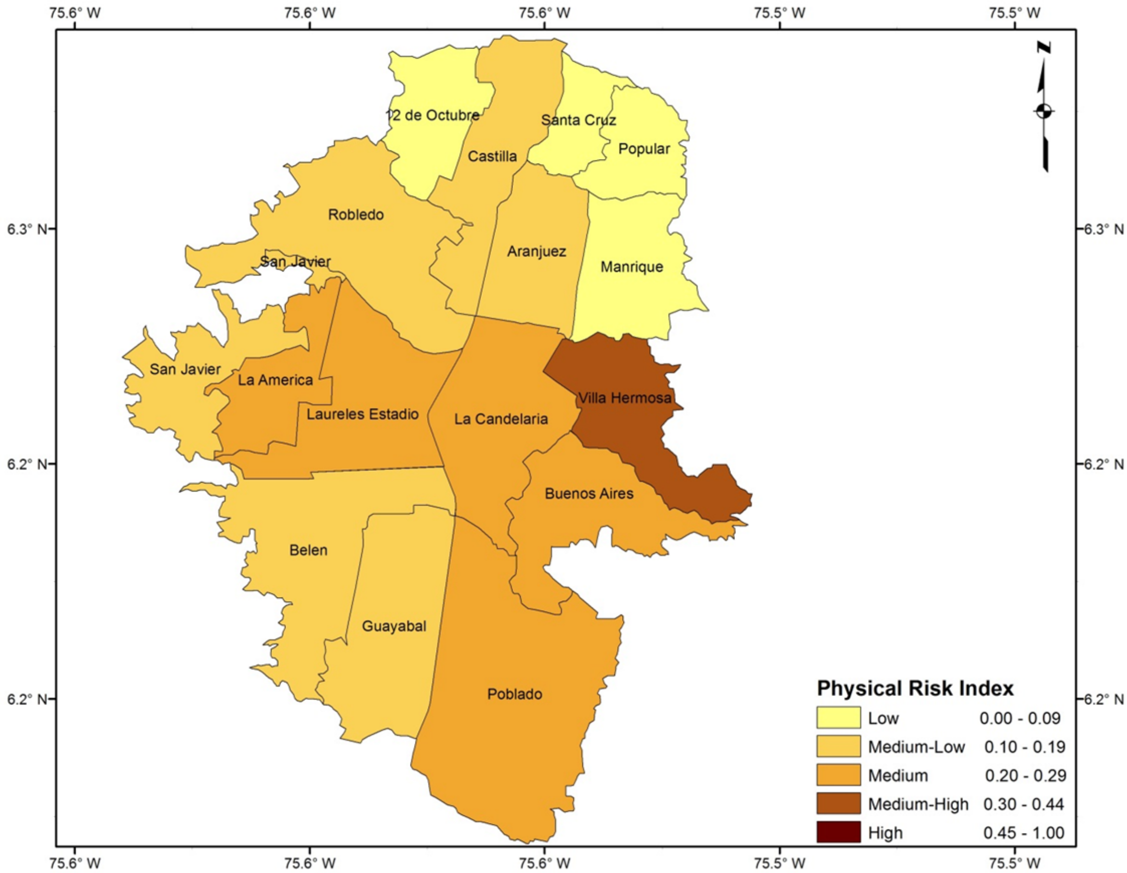


Figure 76. Physical risk index by county

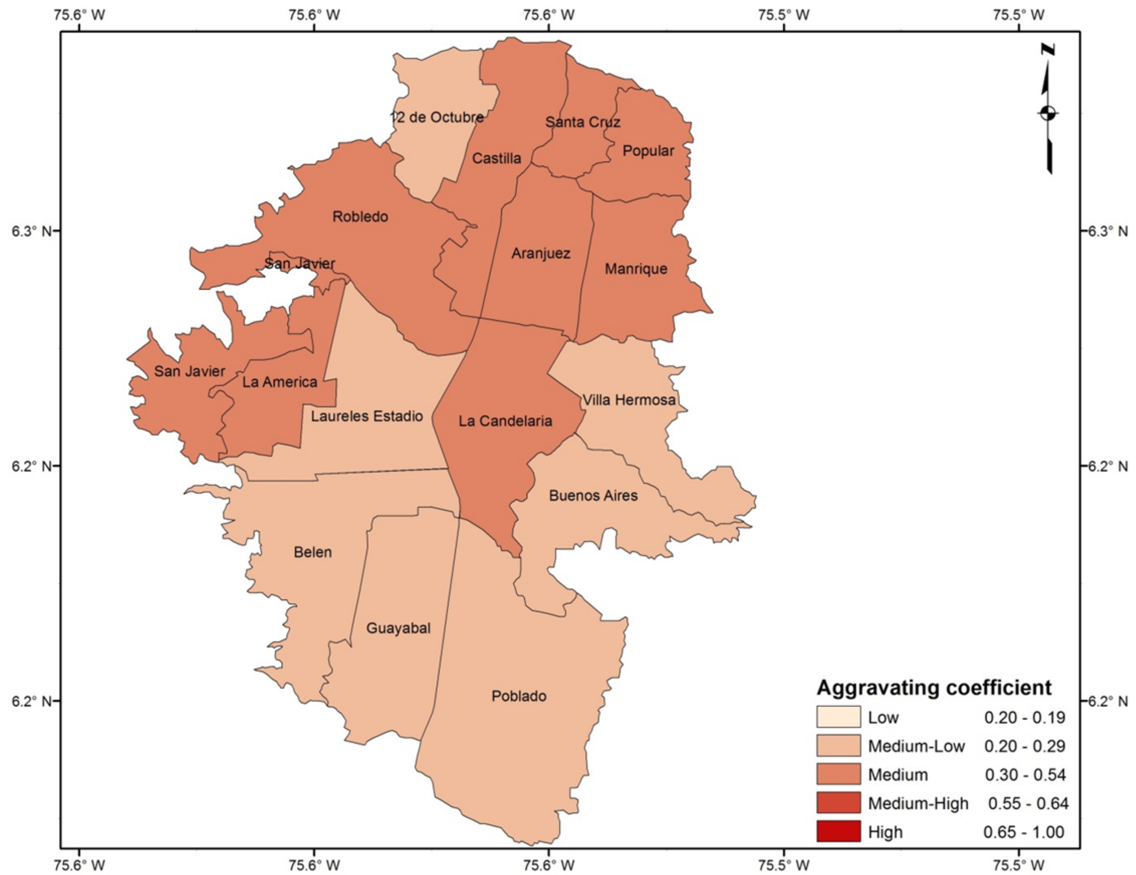


Figure 77. Aggravating coefficient by county

Annex 2: Exposure, Vulnerability and Risk Data for Barcelona

Exposure Information

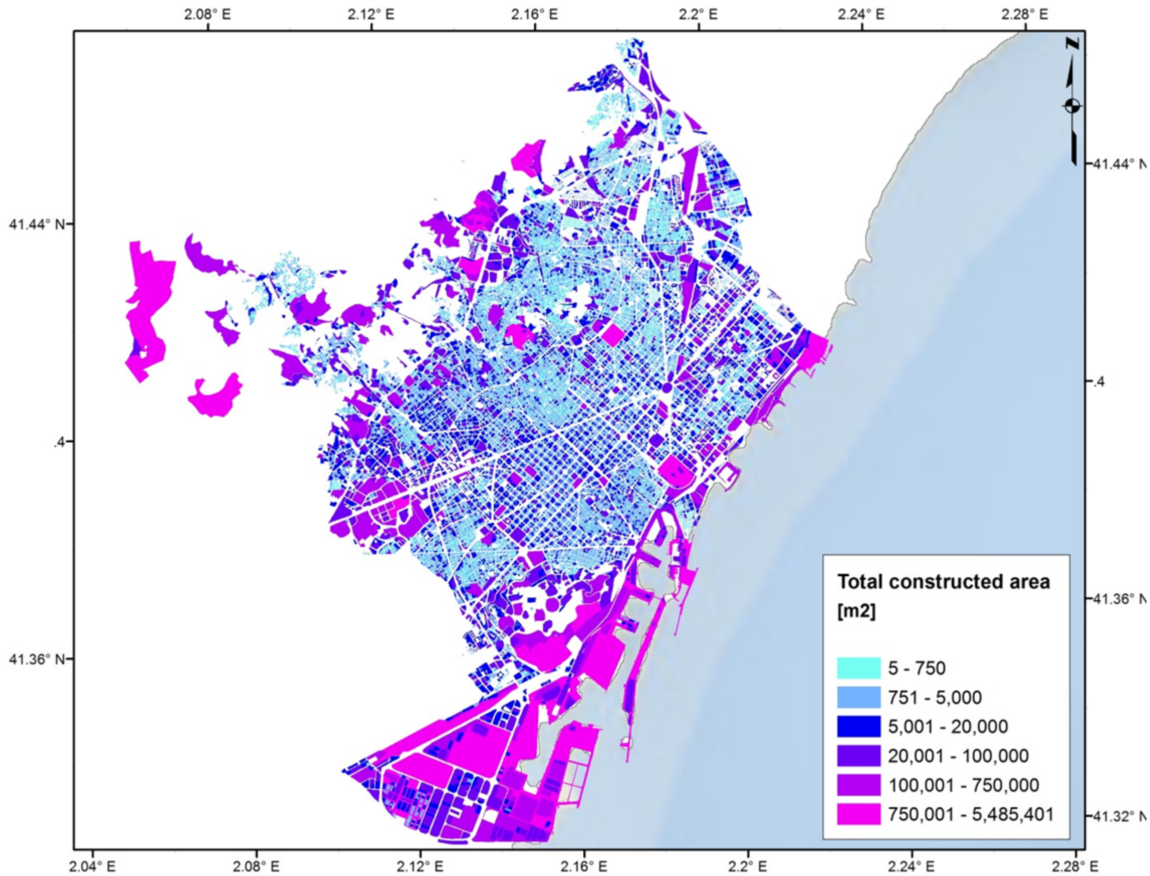


Figure 78. Total constructed area by dwelling

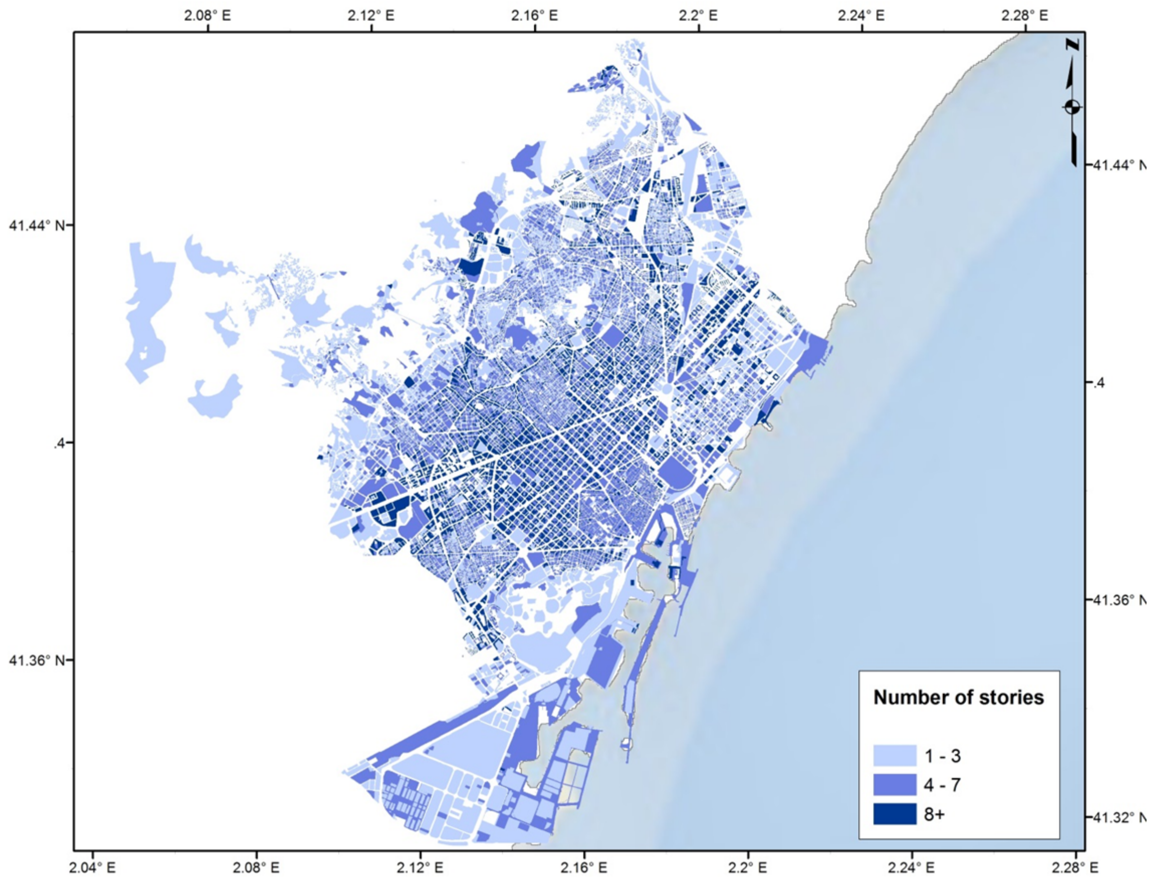


Figure 79. Number of stories category by dwelling

Vulnerability Functions

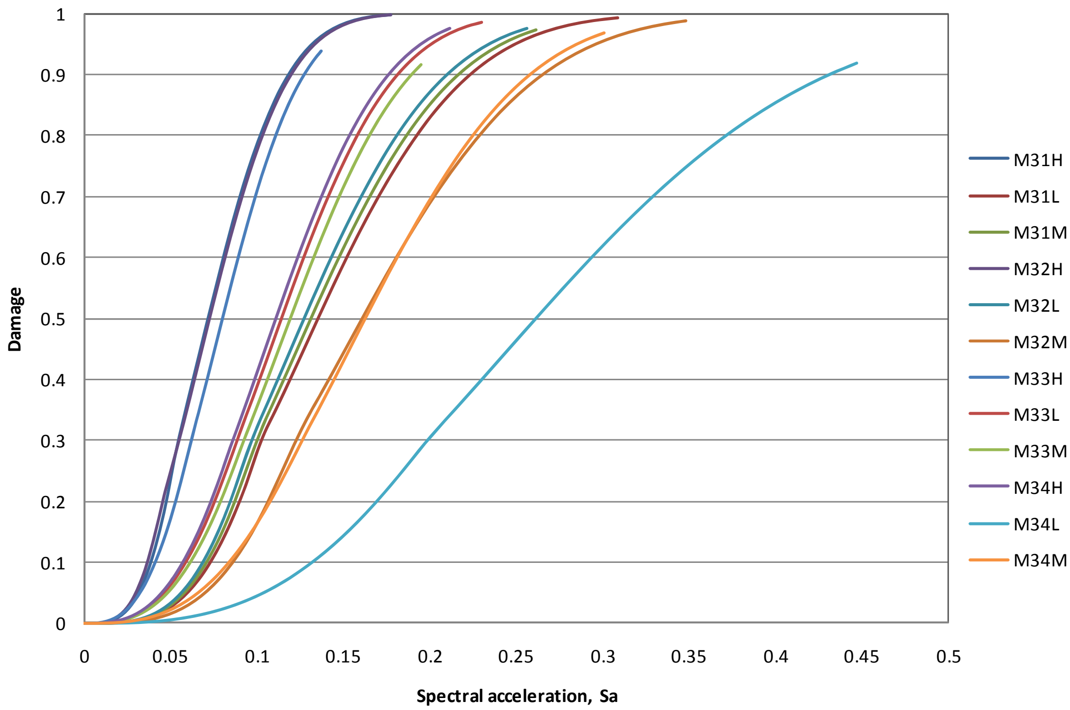


Figure 80. Vulnerability functions for masonry dwellings (unreinforced and confined)

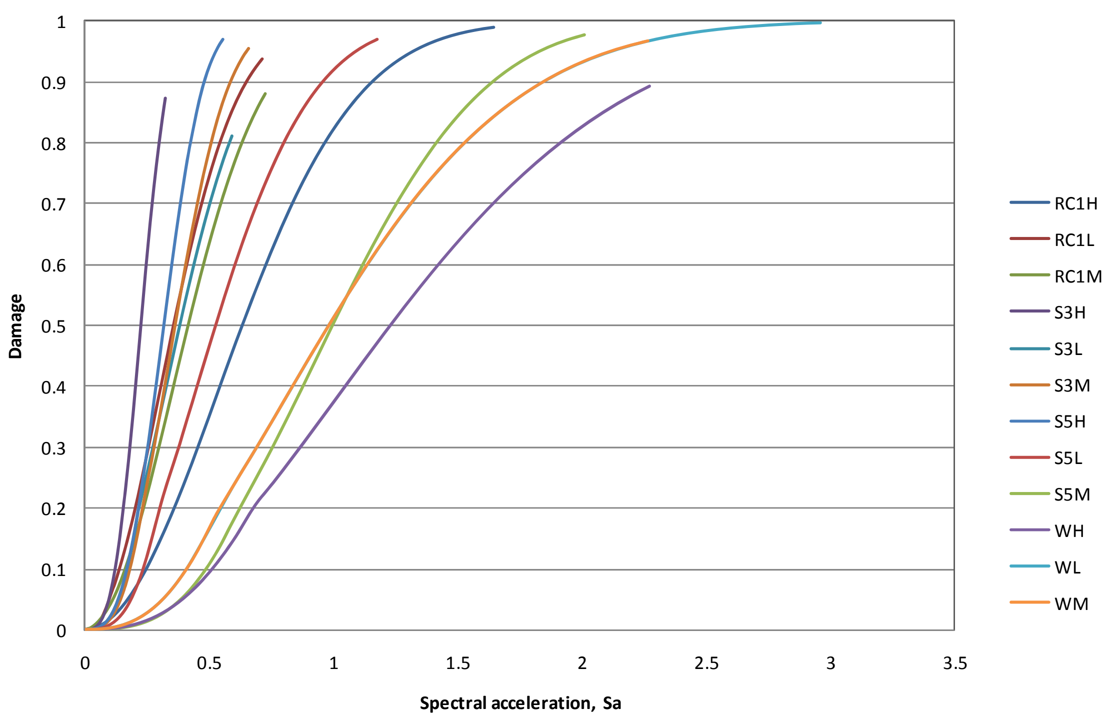


Figure 81. Vulnerability functions for reinforced concrete and braced steel frames and wooden dwellings

Seismic Risk

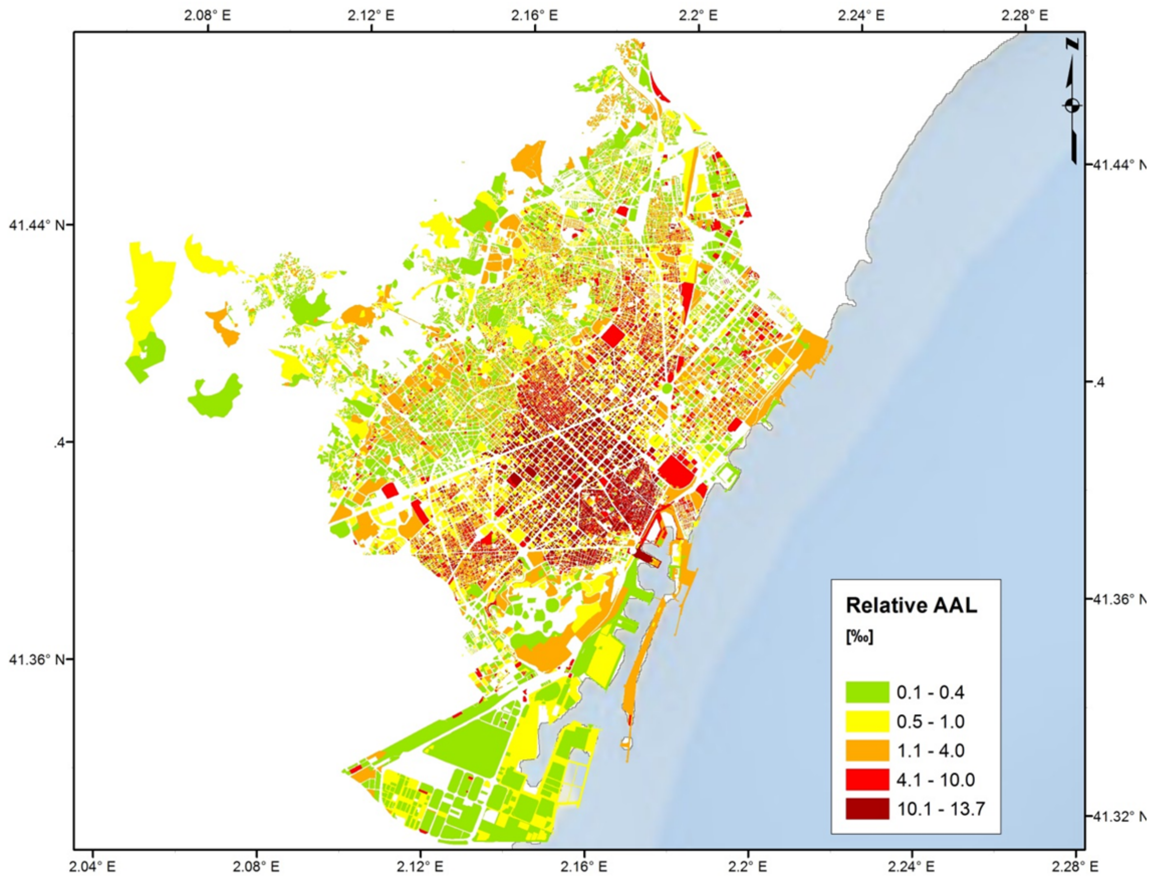


Figure 82. Relative AAL by dwelling

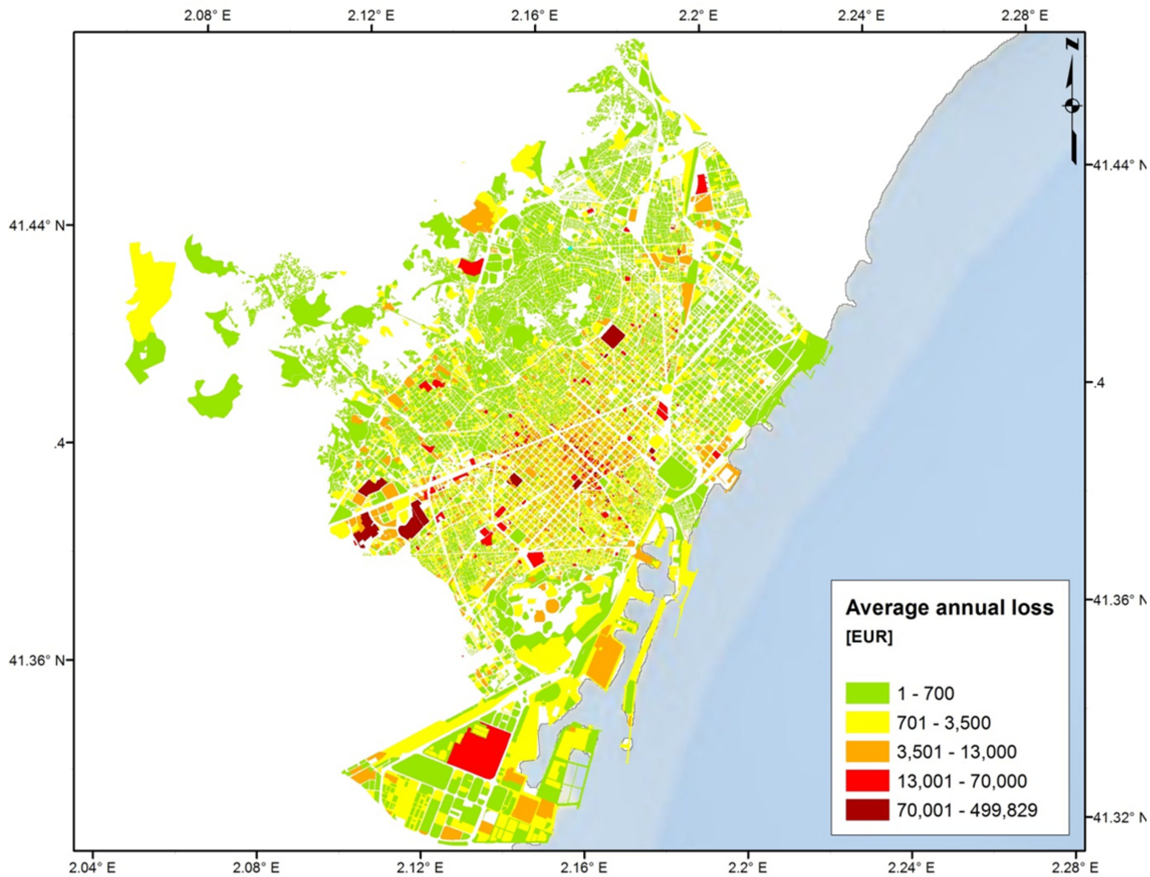


Figure 83. Absolute AAL by dwelling

Holistic Risk Analysis

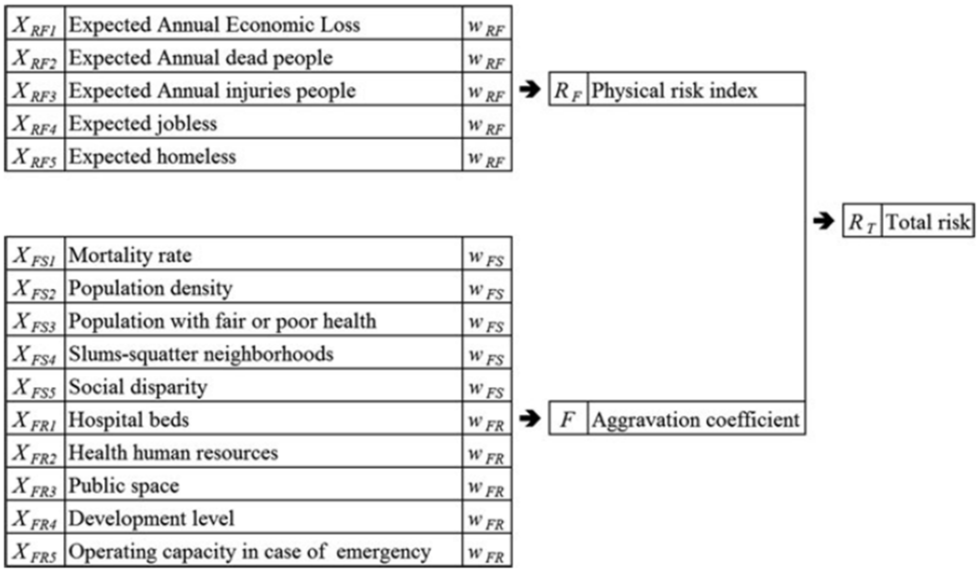


Figure 84. Descriptors used for the physical risk and aggravating coefficient indexes

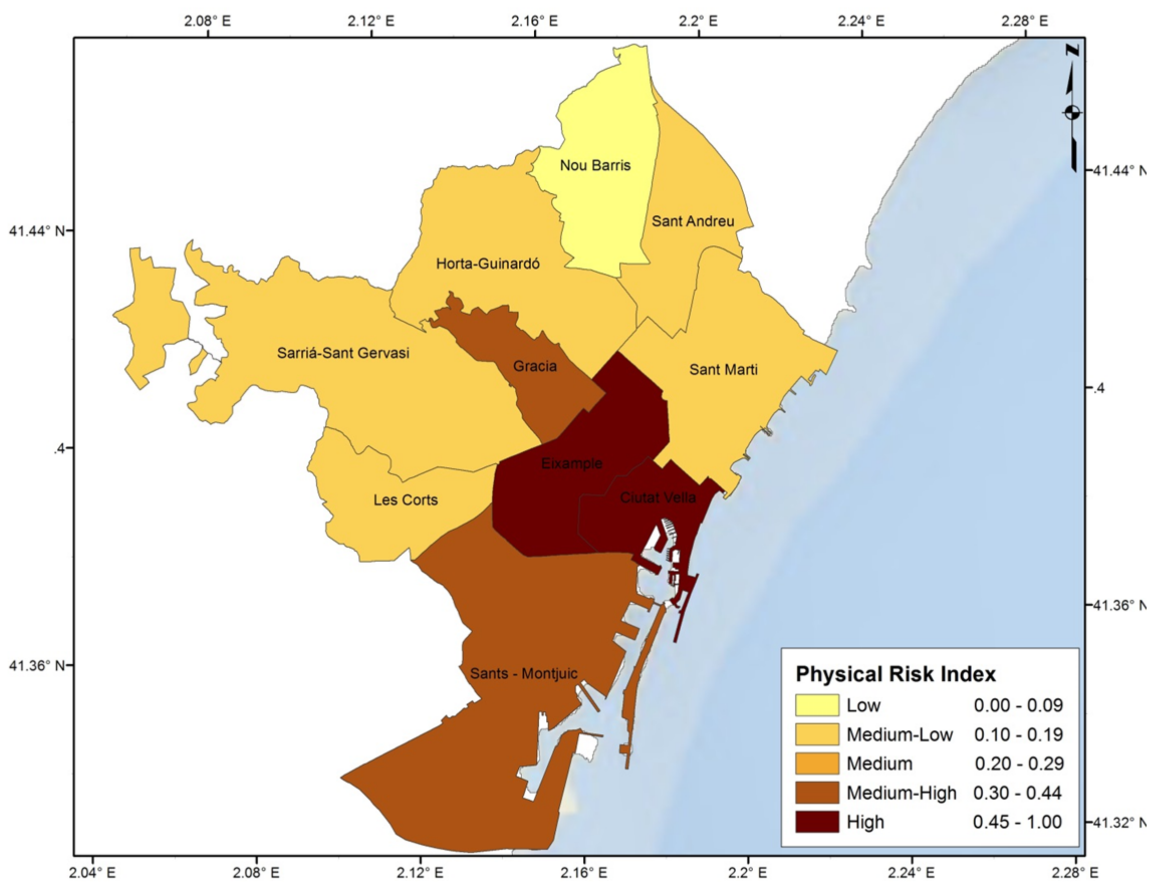


Figure 85. Physical risk index by district

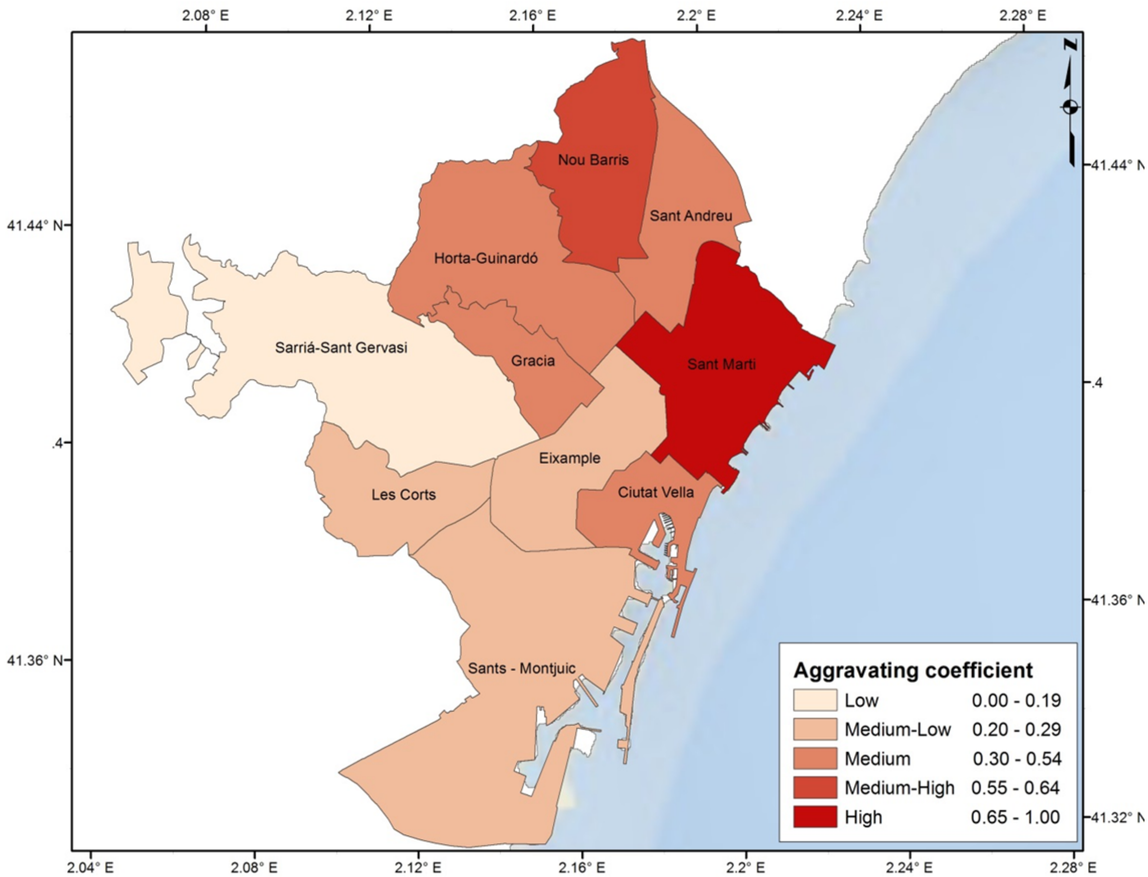


Figure 86. Aggravating coefficient by district

Annex 3: Exposure, Vulnerability and Risk Data for Bogotá

Exposure Information

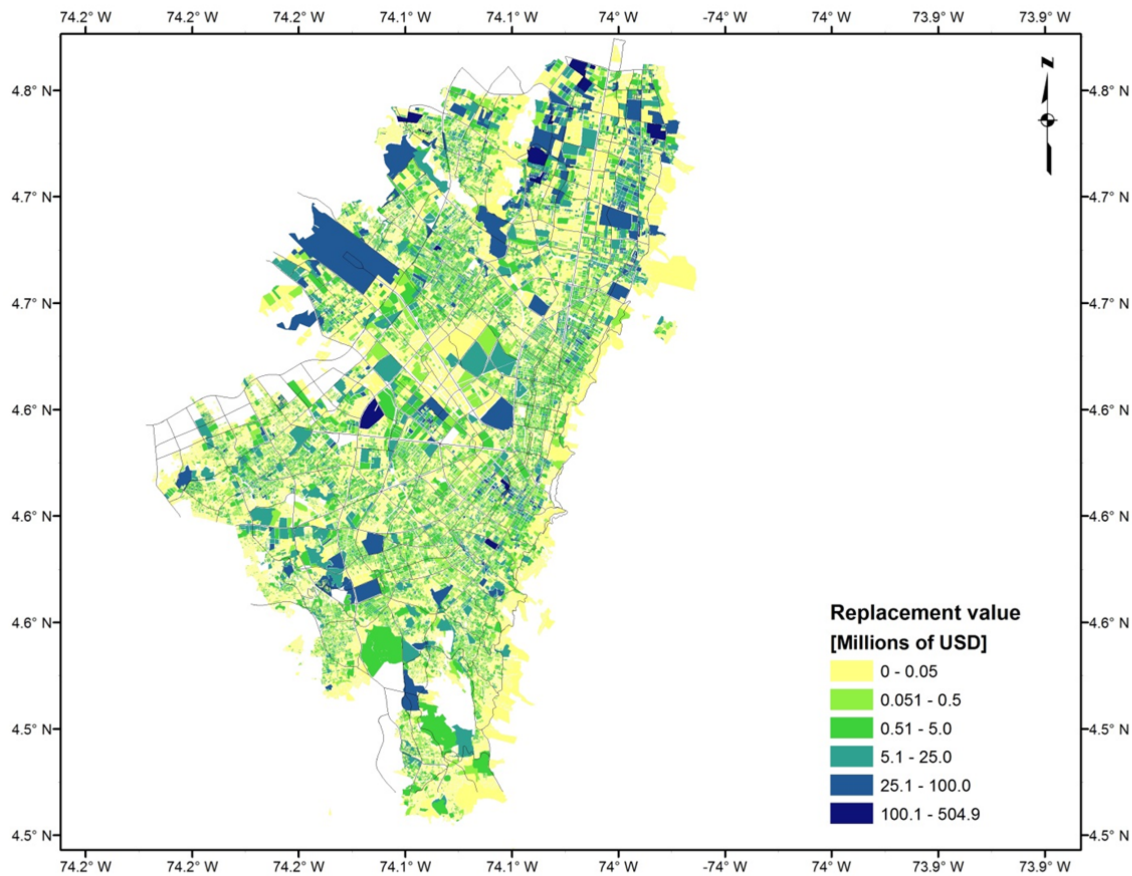


Figure 87. Total replacement cost by block in Bogotá

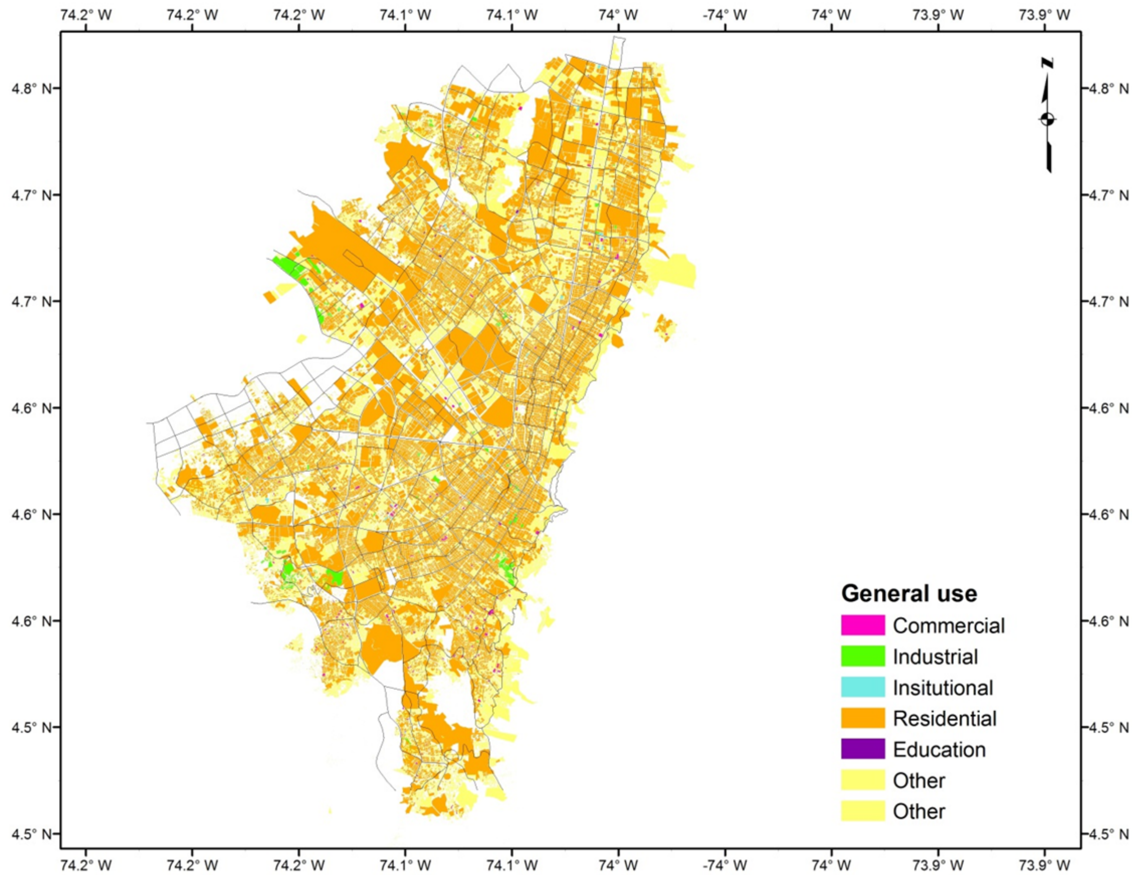


Figure 88. Main use by block in Bogotá

Vulnerability Functions

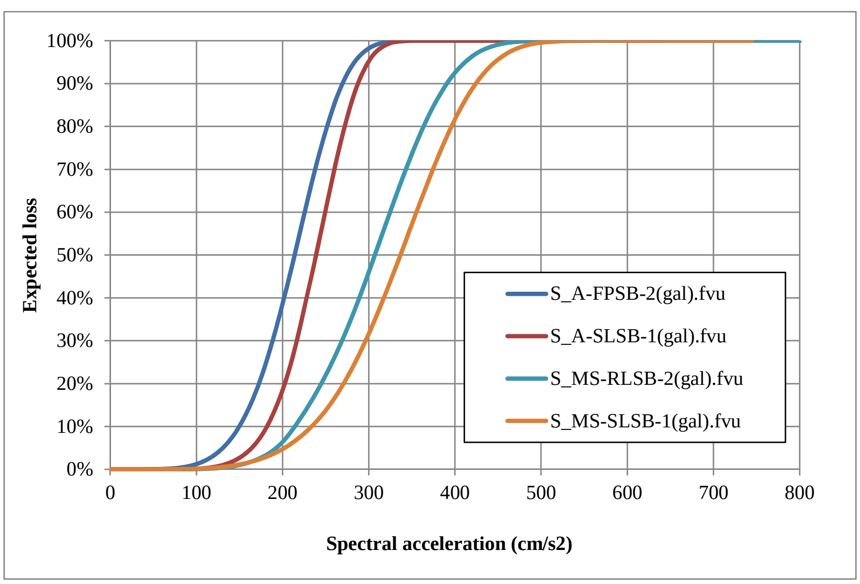


Figure 89. Vulnerability functions for adobe and masonry dwellings

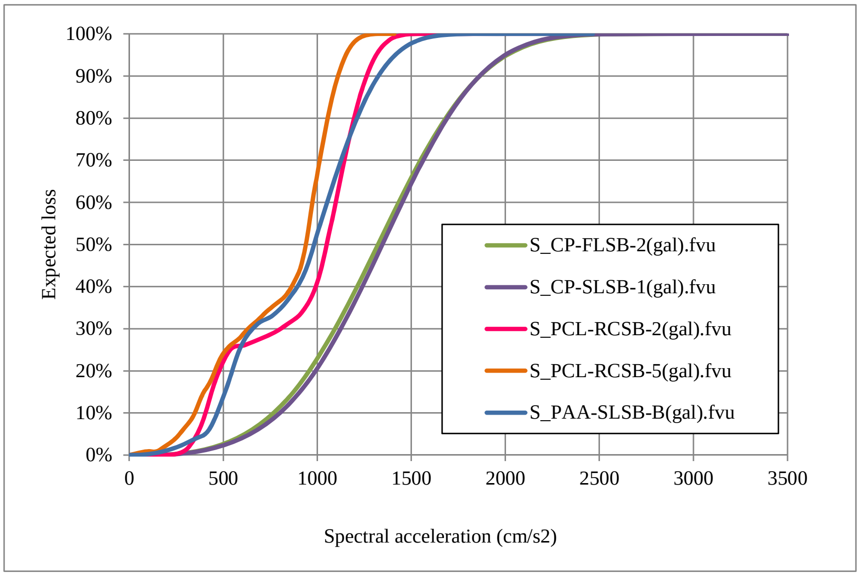


Figure 90. Vulnerability functions for precast reinforced concrete, reinforced concrete slabs and industrial facilities

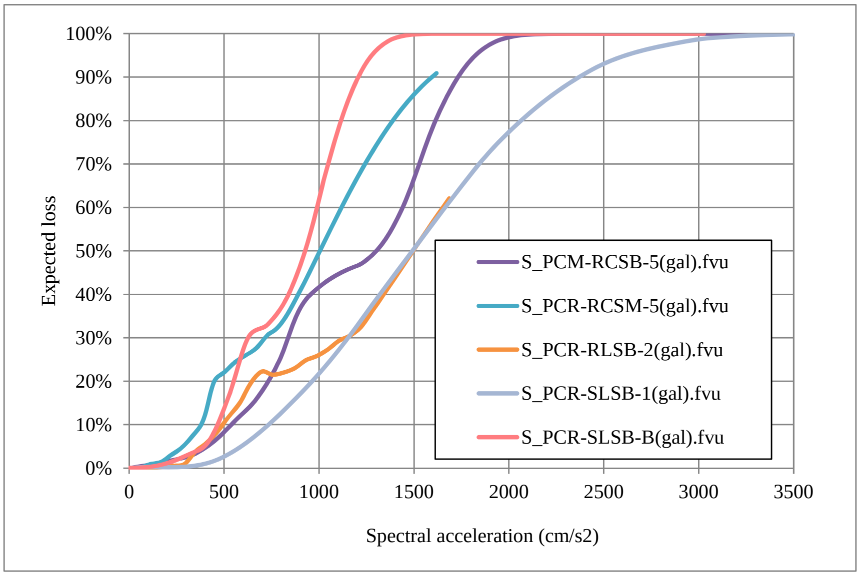


Figure 91. Vulnerability functions for reinforced concrete frames and dual systems

Seismic Risk

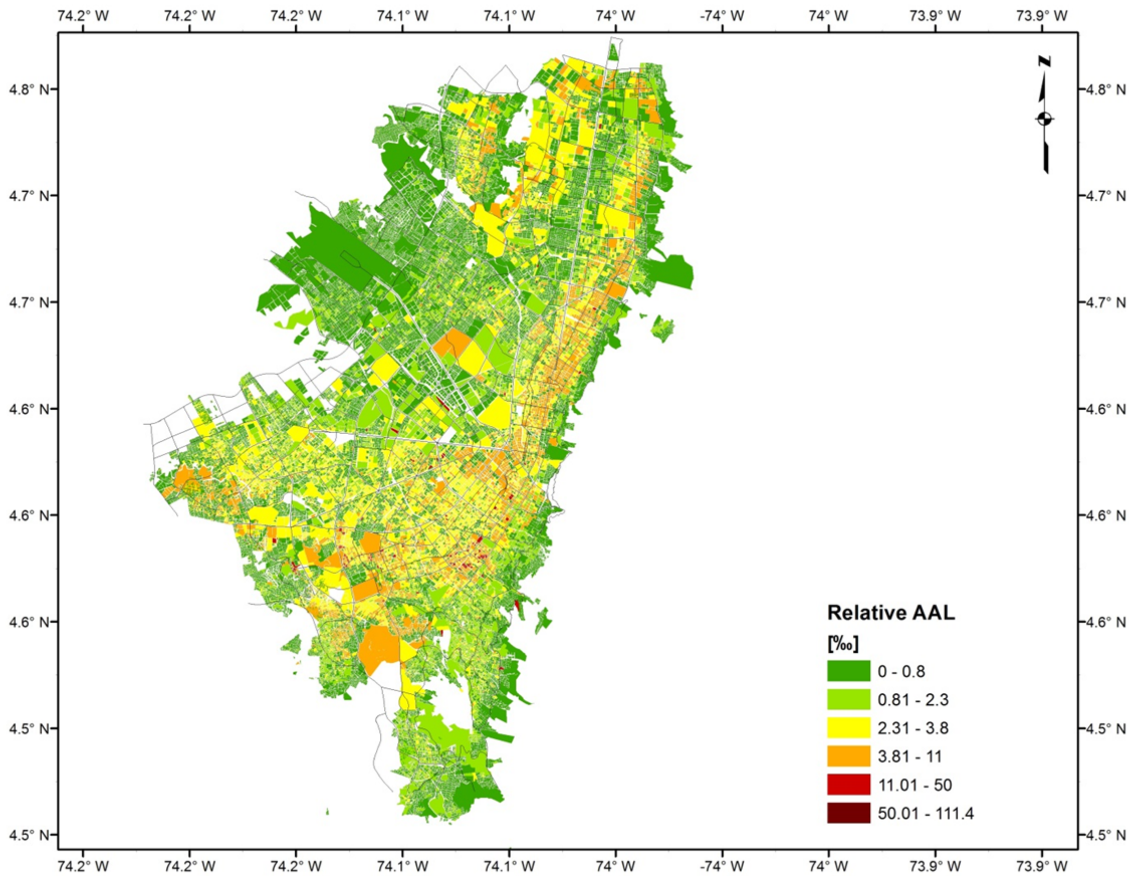


Figure 92. Relative AAL by dwelling with AIS-2010 hazard model

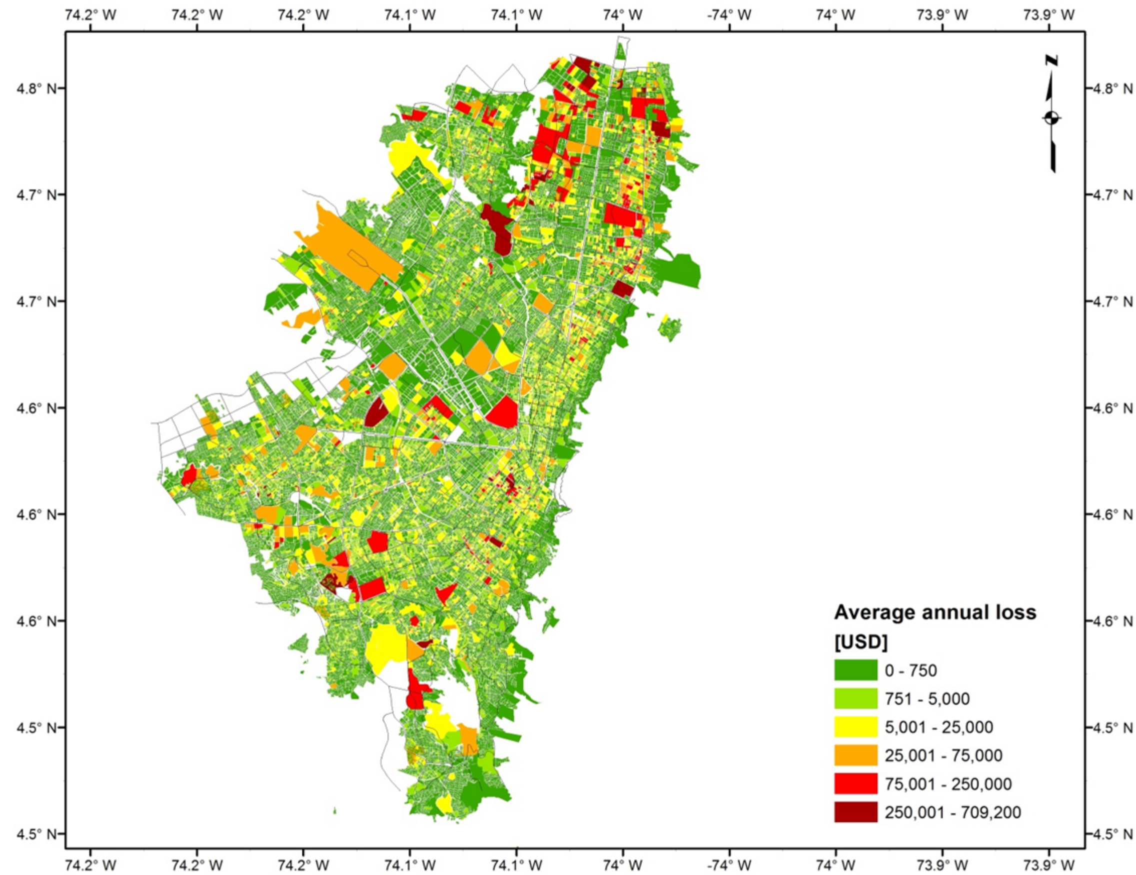


Figure 93. Absolute AAL by dwelling with AIS-2010 hazard model

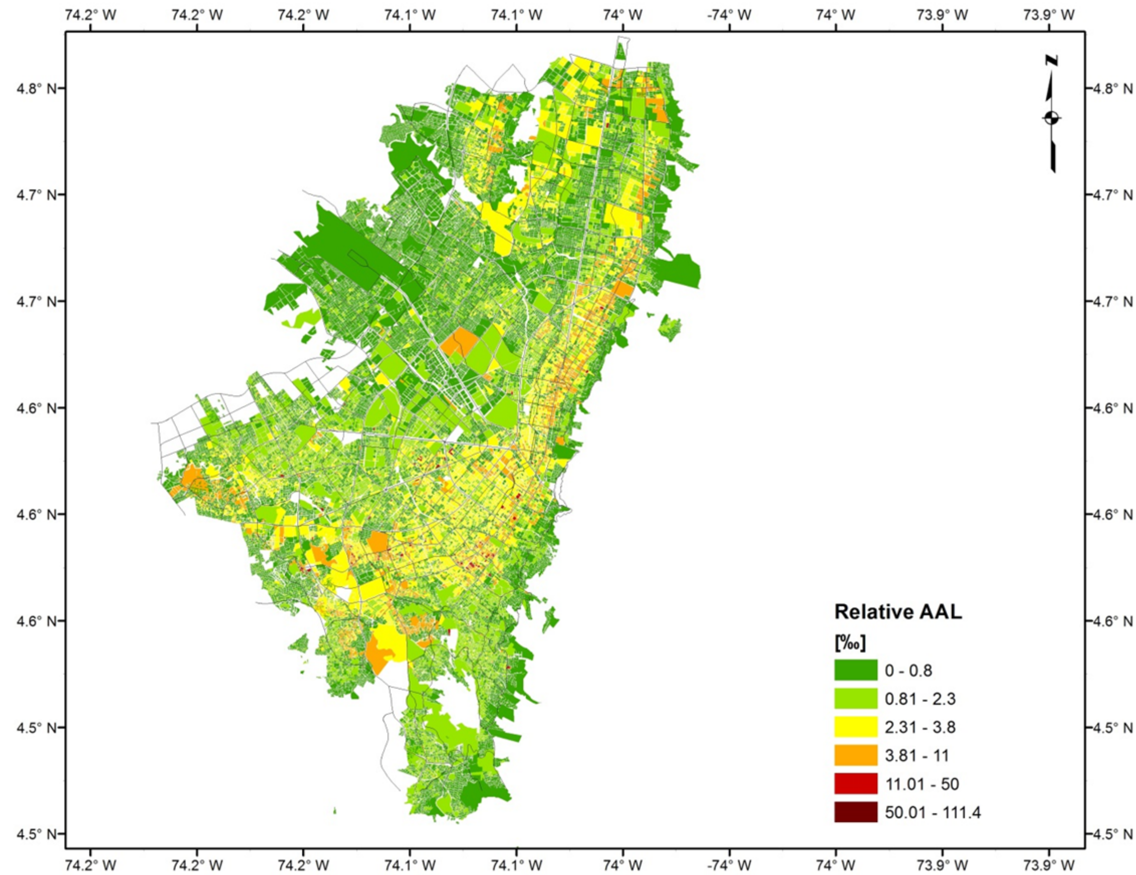


Figure 94. Relative AAL by dwelling with Caldas Tear hazard model

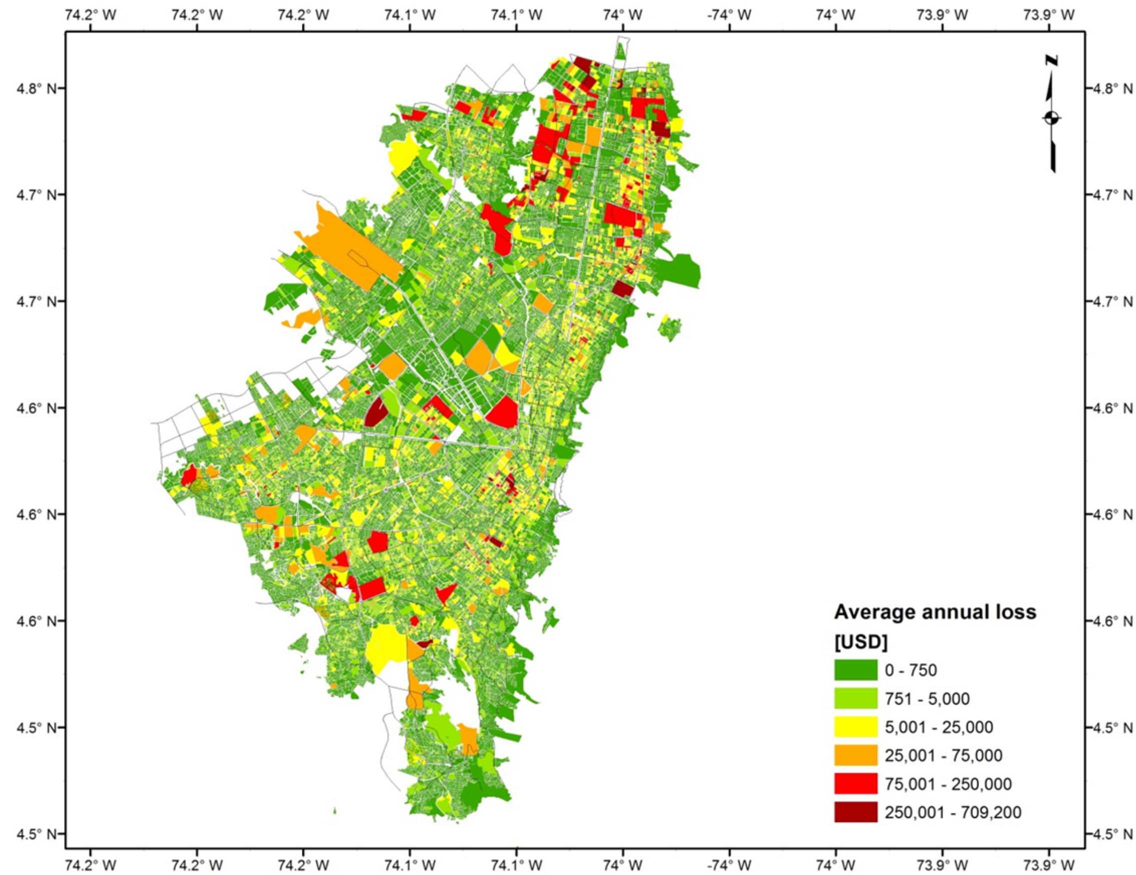


Figure 95. Absolute AAL by dwelling with Caldas Tear hazard model

Annex 4: Exposure, vulnerability and risk data for Belize City

Exposure Information

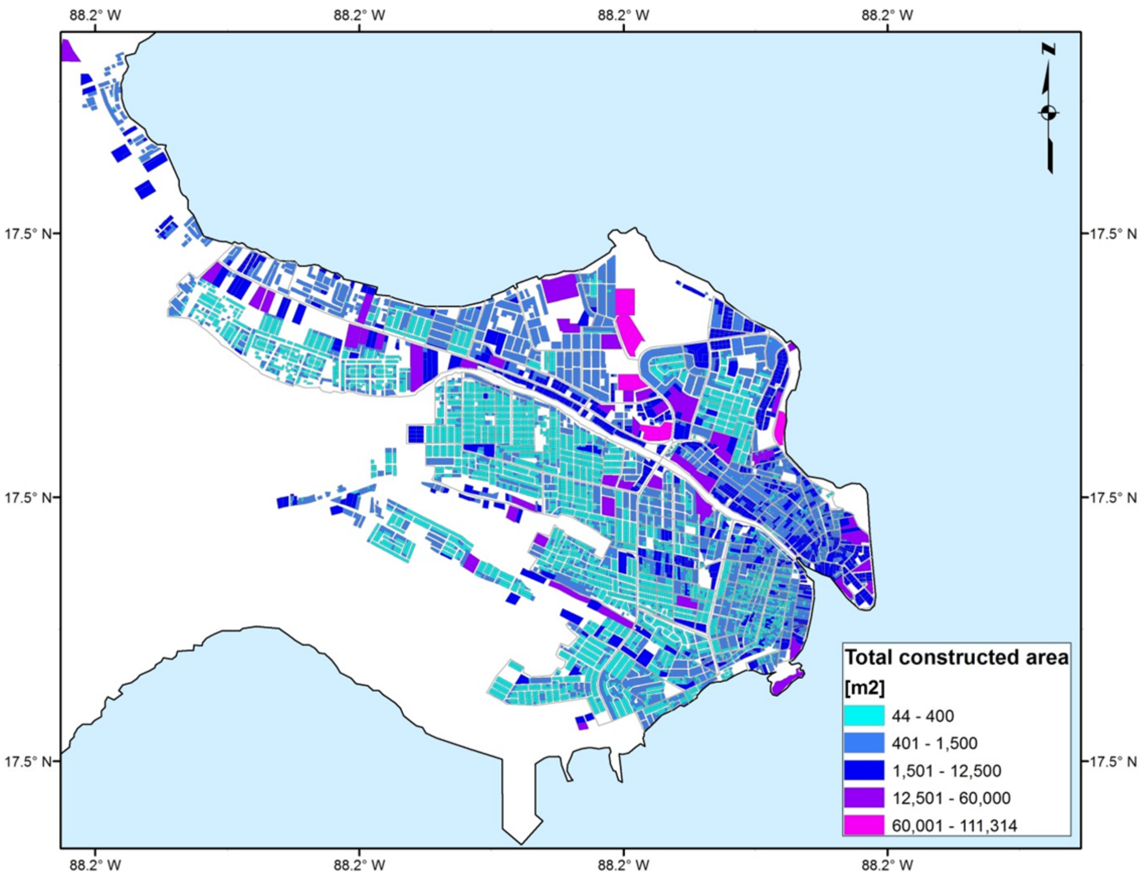


Figure 96. Total constructed area by dwelling in Belize City

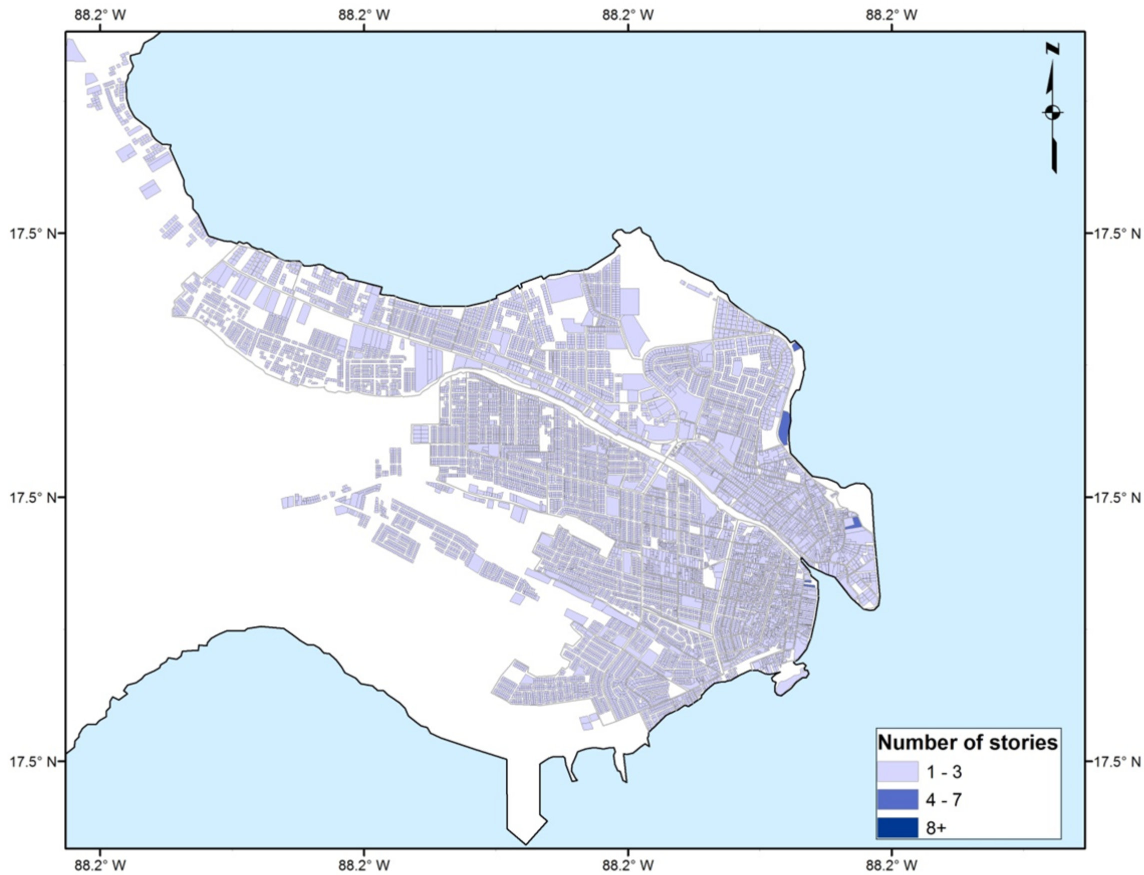


Figure 97. Number of stories by dwelling in Belize City

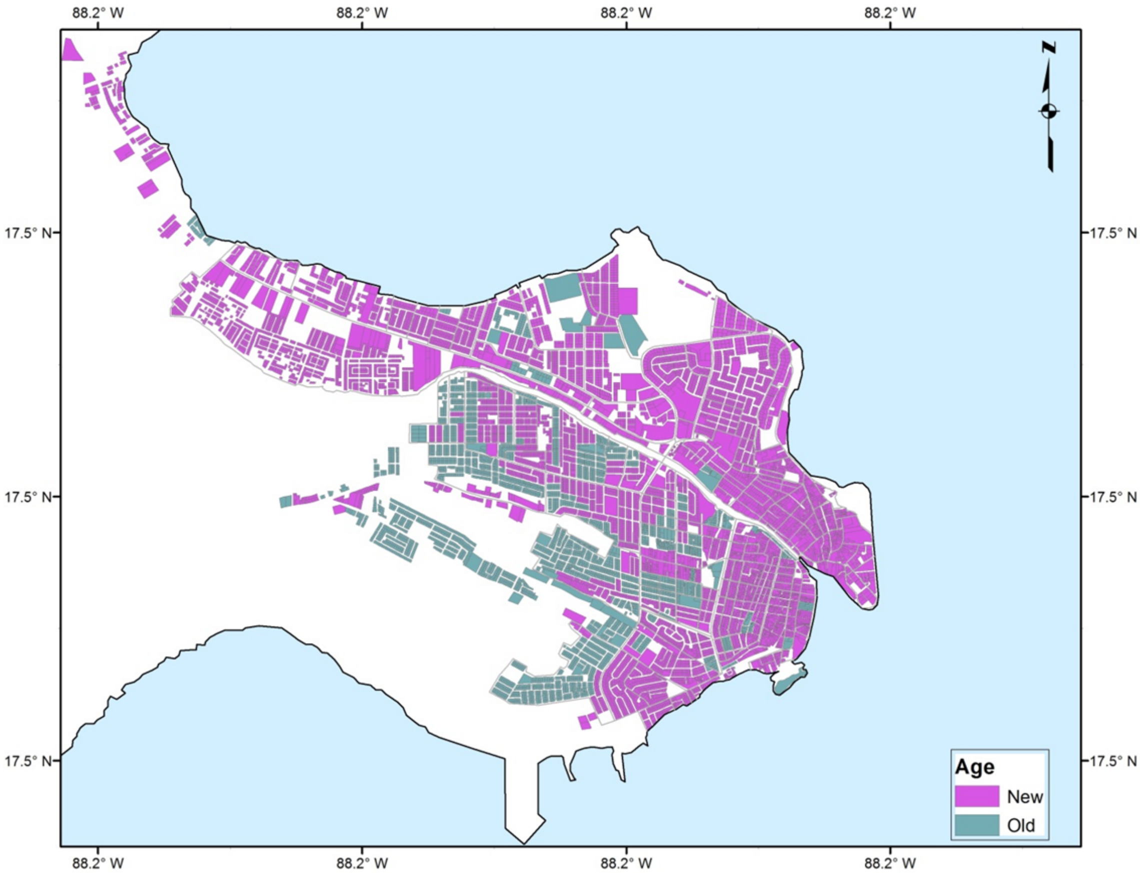


Figure 98. Age category by dwelling in Belize City

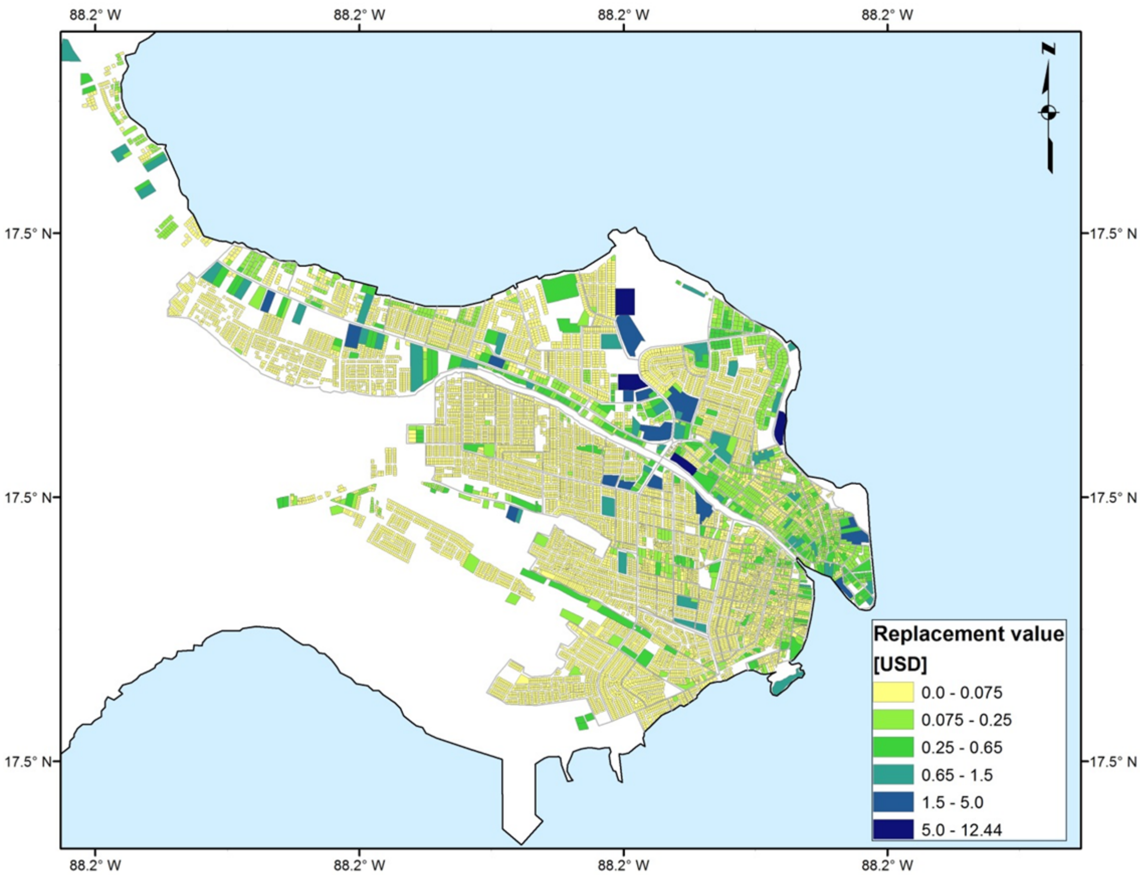


Figure 99. Replacement value by dwelling in Belize City

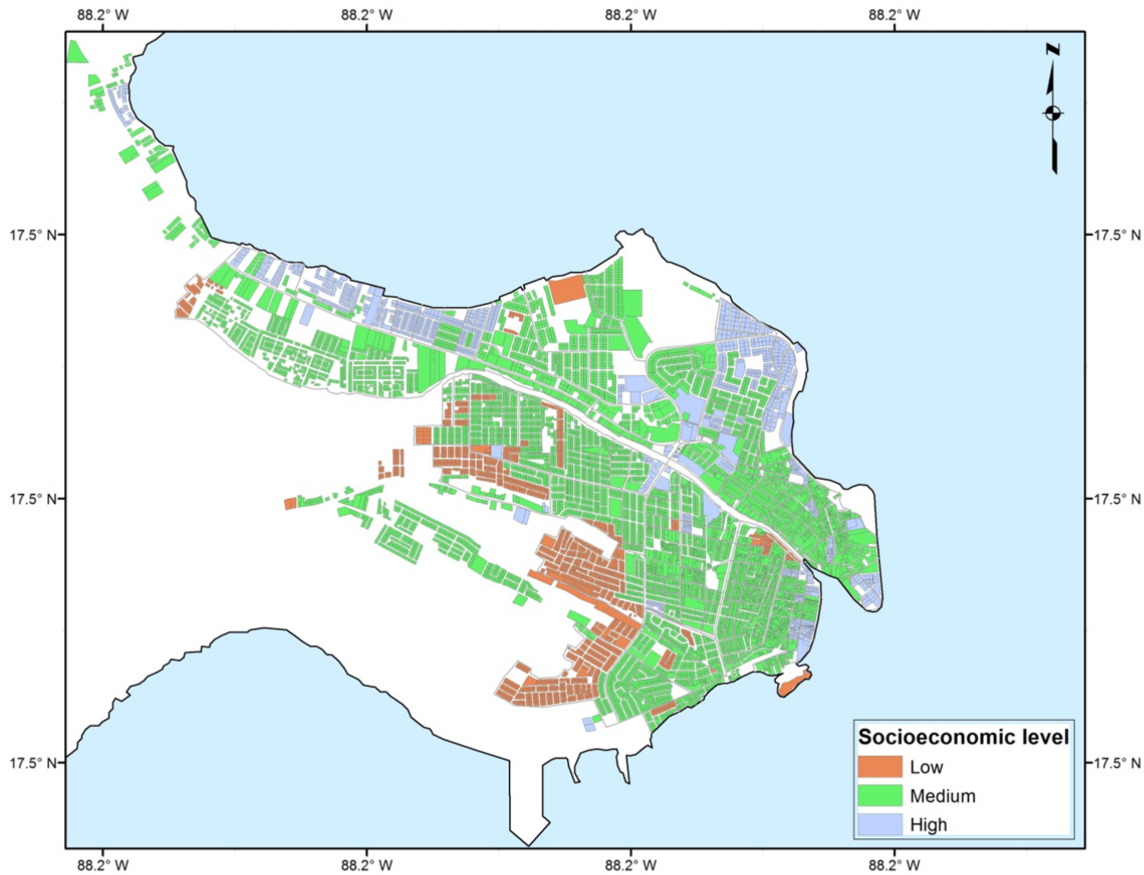


Figure 100. Socioeconomic category by dwelling in Belize City

Vulnerability Functions

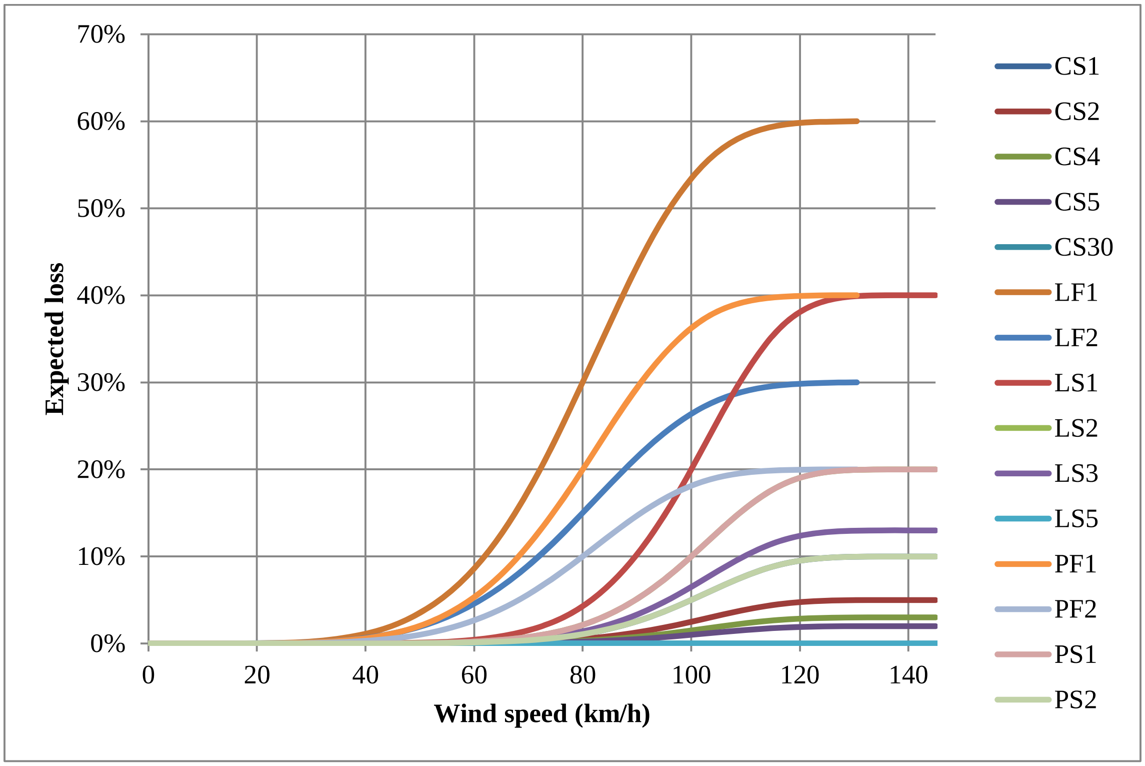


Figure 101. Wind vulnerability functions for the building stock of Belize City

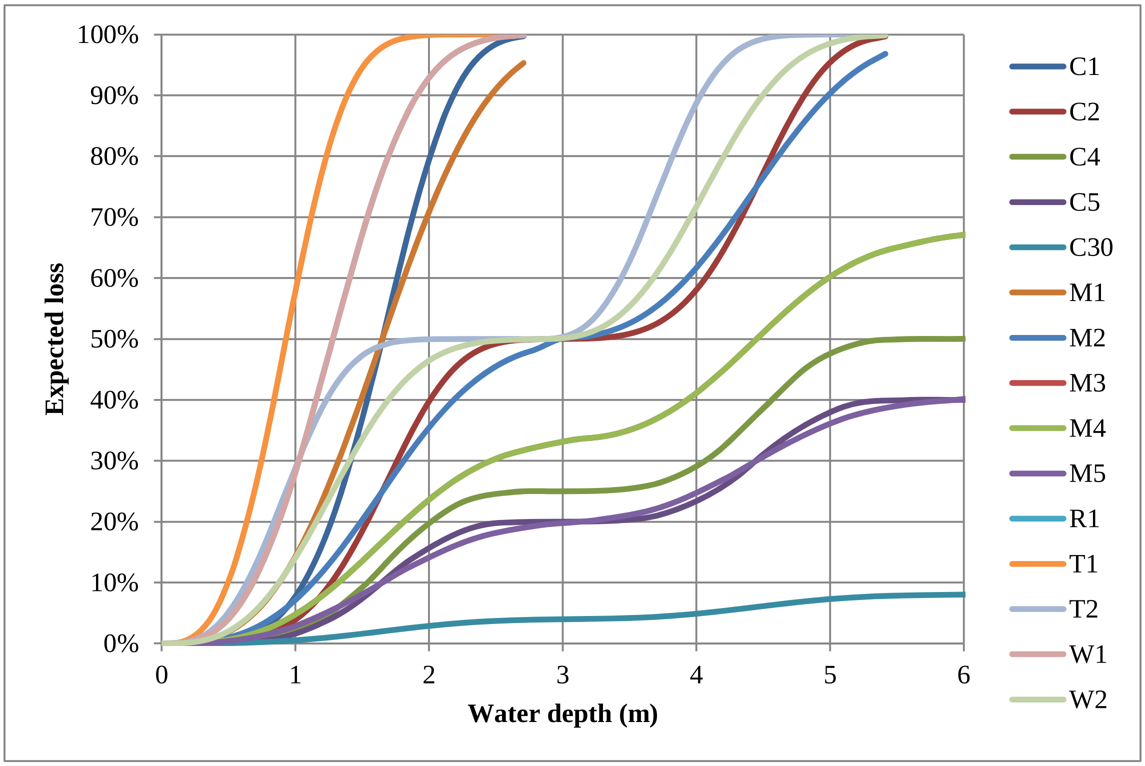


Figure 102. Storm surge vulnerability functions for the building stock of Belize City

Tropical Cyclonic Risk (Wind and Storm Surge)

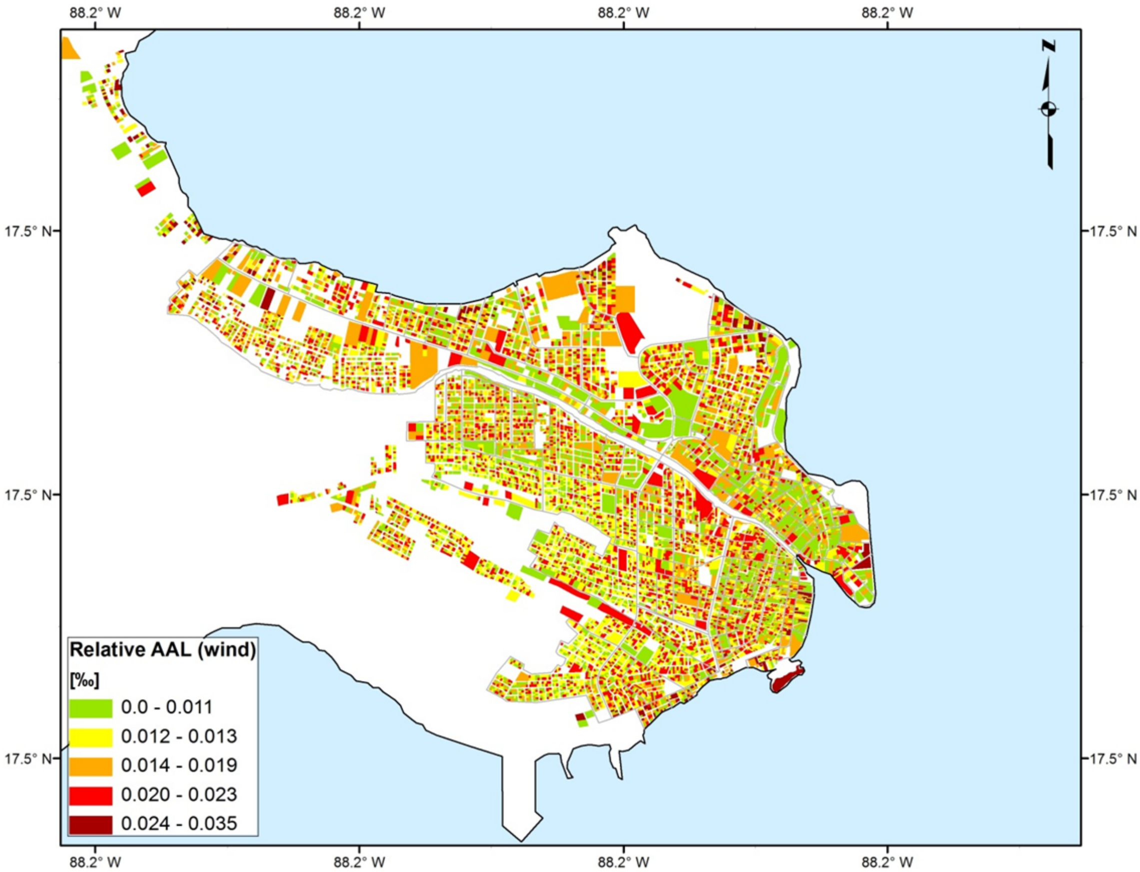


Figure 103. Relative AAL by dwelling in Belize City due to strong winds

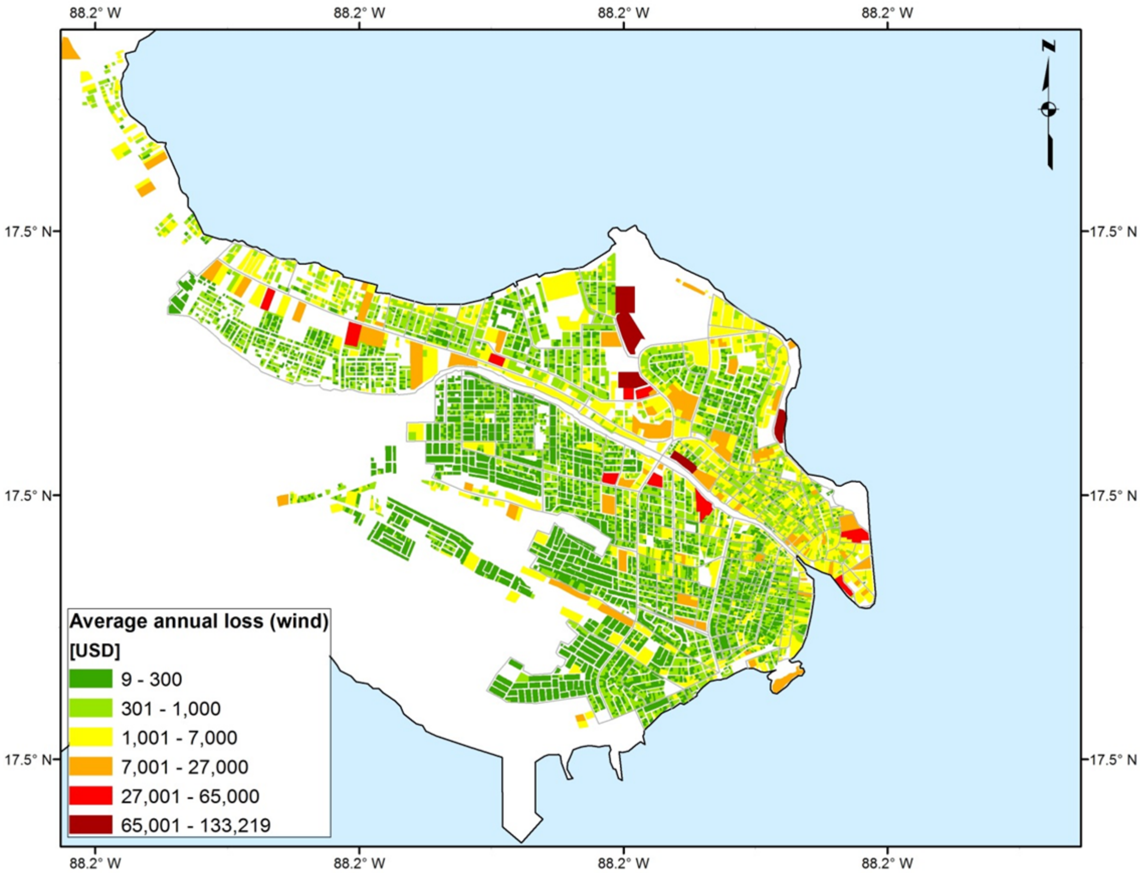


Figure 104. Absolute AAL by dwelling in Belize City due to strong winds

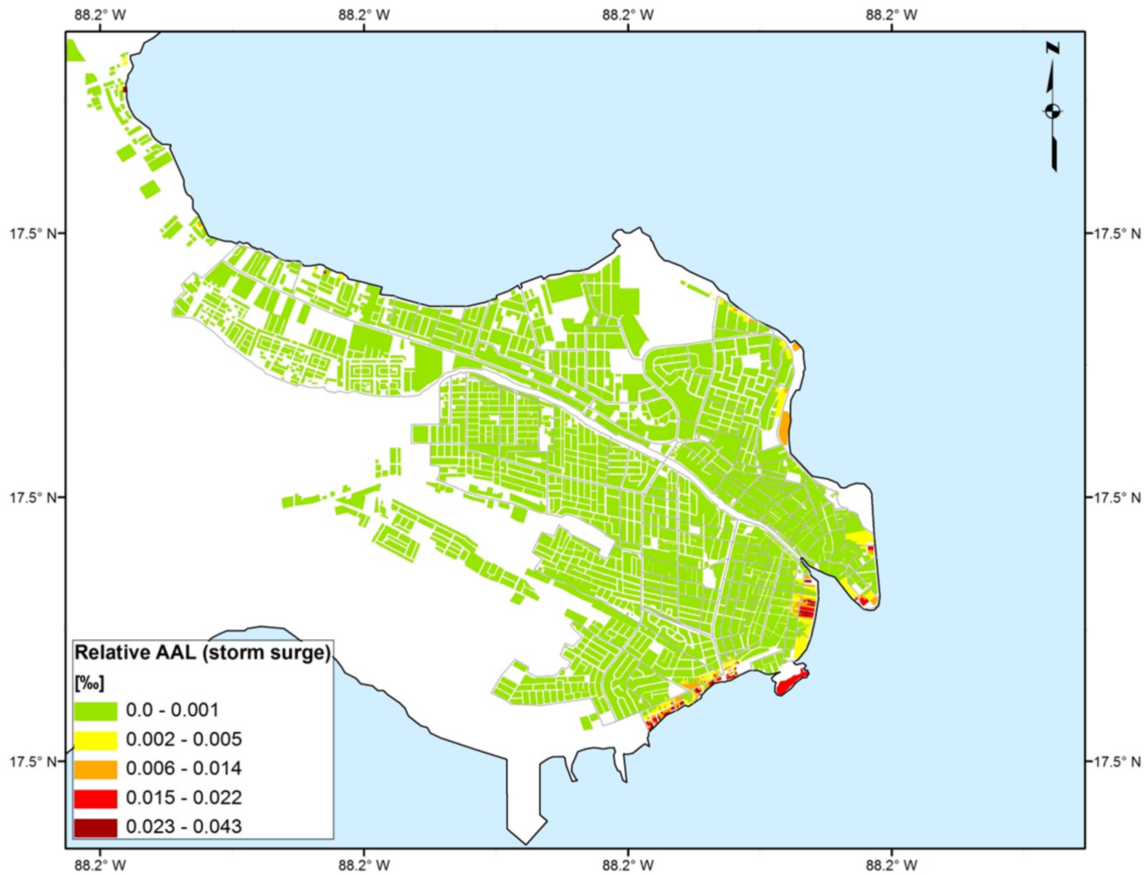


Figure 105. Relative AAL by dwelling in Belize City due to storm surge

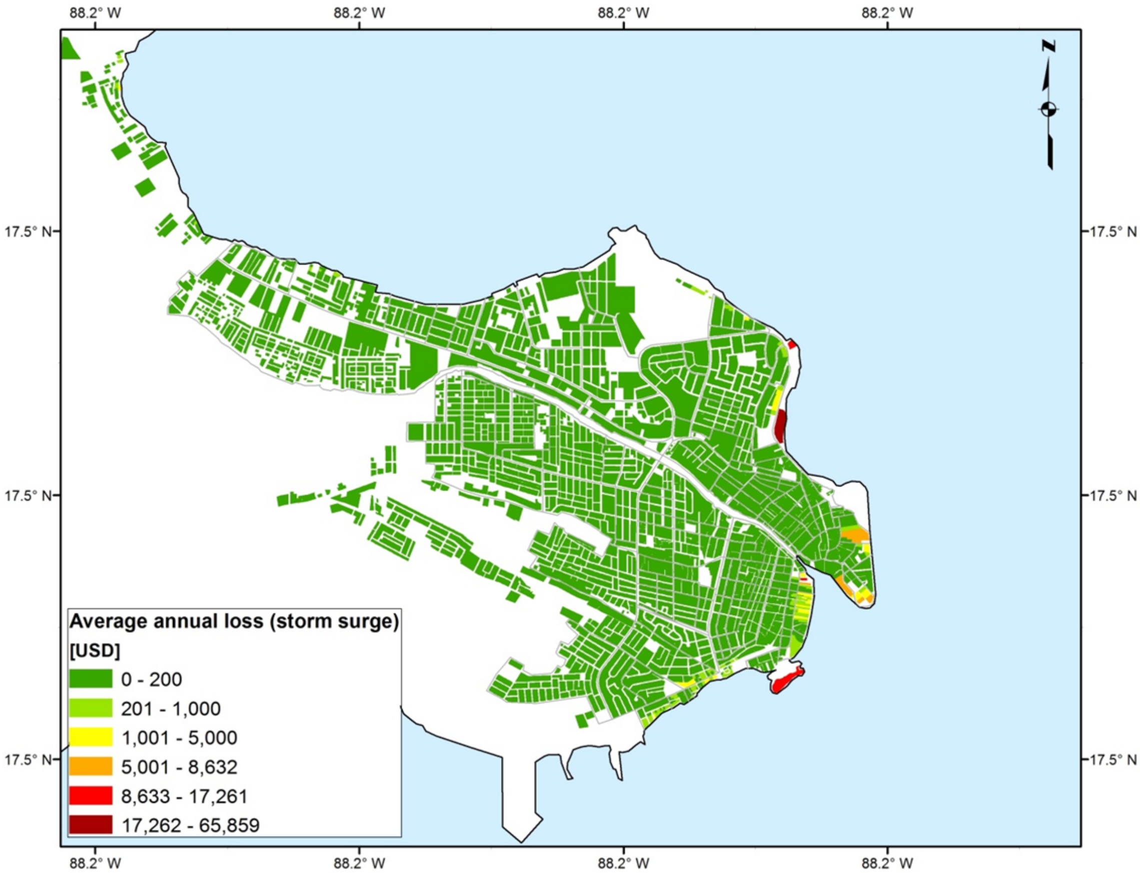


Figure 106. Absolute AAL by dwelling in Belize City due to storm surge

Annex 5: Exposure, Vulnerability and Risk Data for Galeras Volcano

Exposure Information

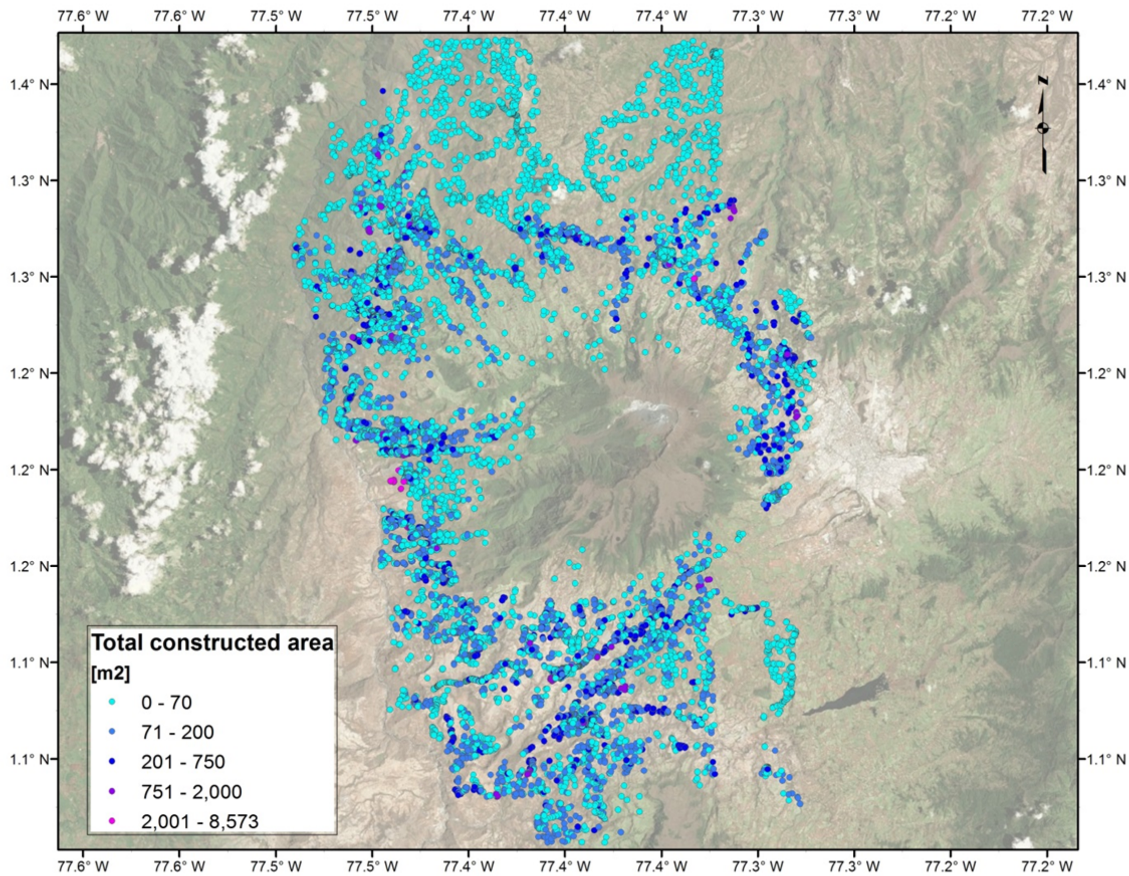


Figure 107. Total constructed area by dwelling

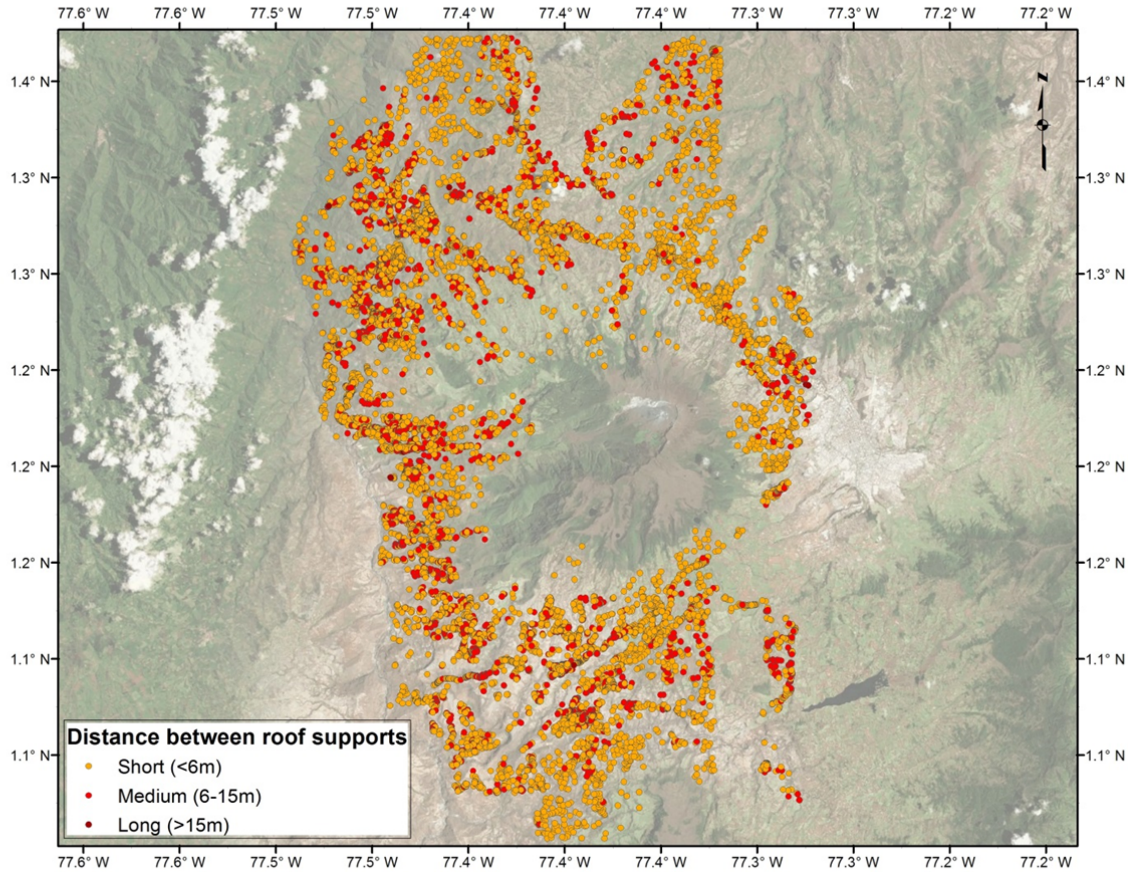
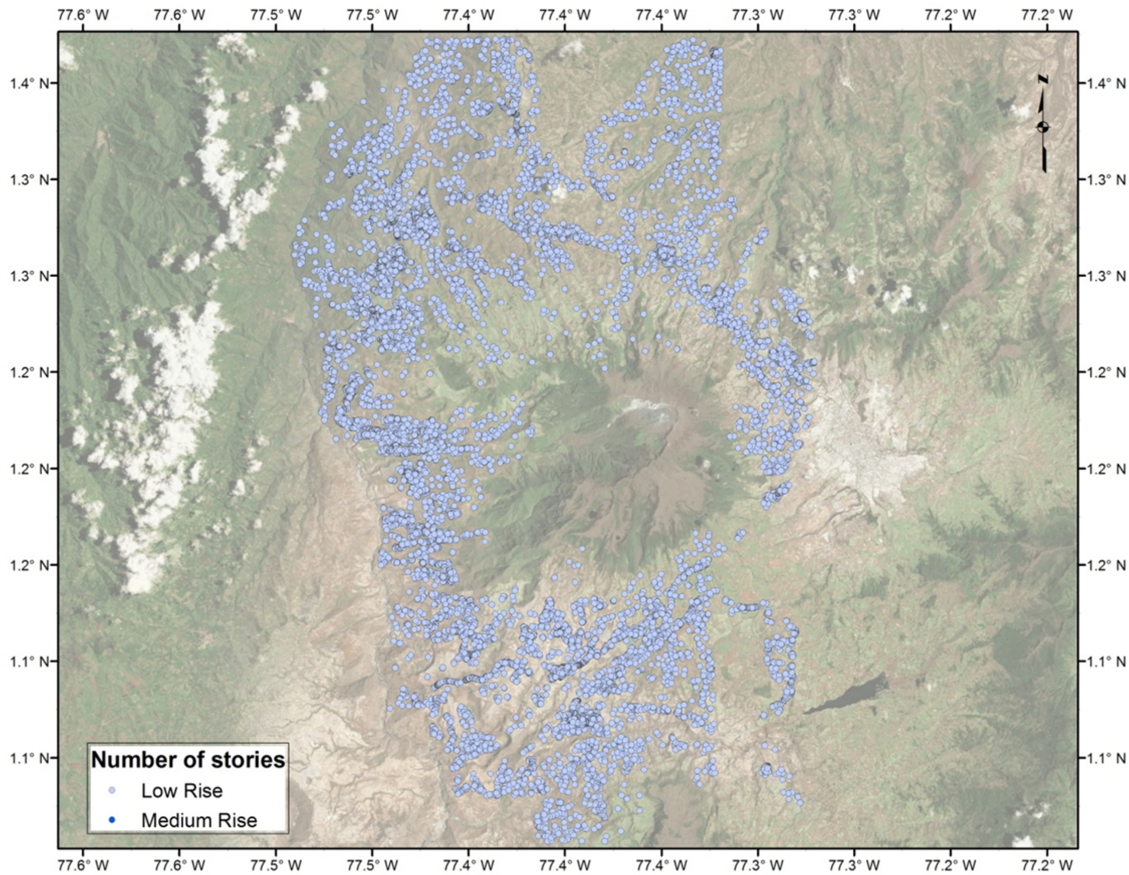
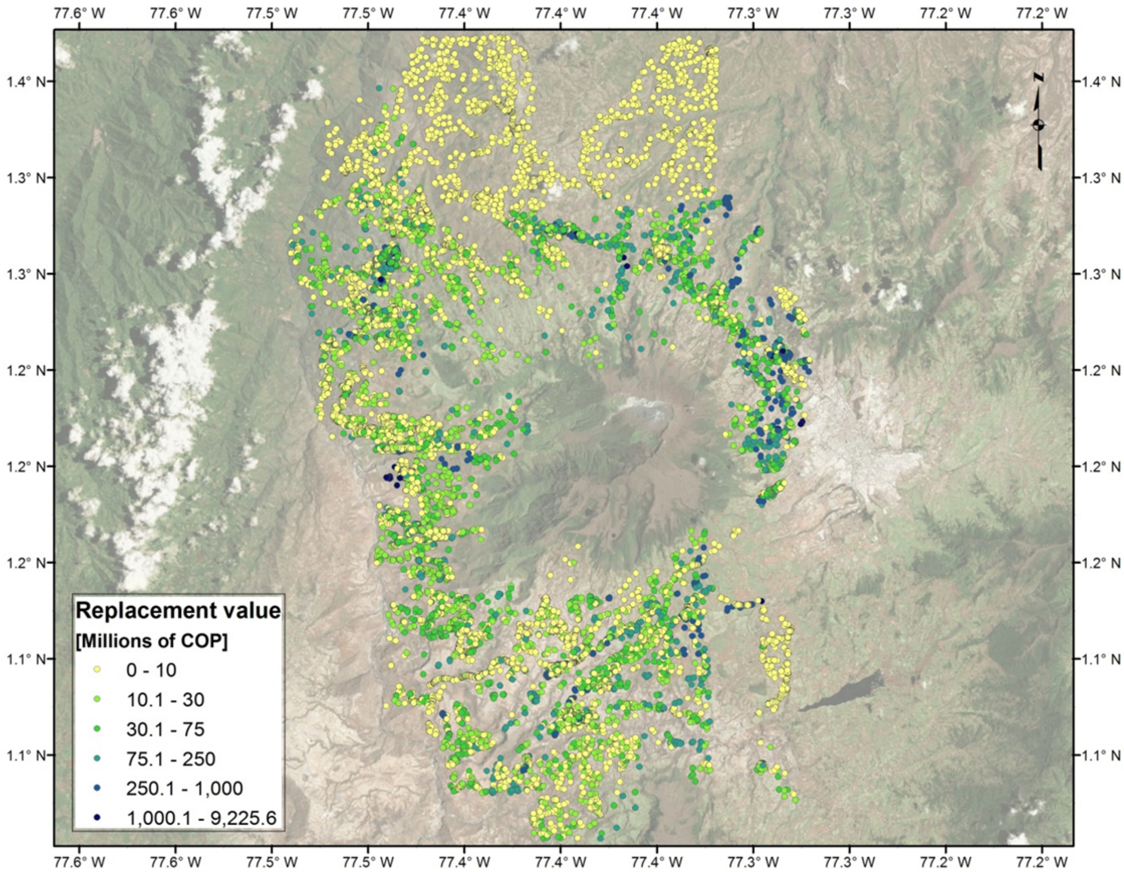


Figure 108. Number of stories category by dwelling


77.6° W
77.6° W
77.5° W
77.5° W
77.4° W
77.4° W
77.4° W
77.3° W
77.3° W
77.2° W
77.2° W
1.4° N
1.3° N
1.3° N
1.2° N
1.2° N
1.2° N
1.1° N
1.1° N
N
Number of stories
Low Rise
Medium Rise


Replacement value
[Millions of COP]
0 - 10
10.1 - 30
30.1 - 75
75.1 - 250
250.1 - 1,000
1,000.1 - 9,225.6
77.6° W
77.5° W
77.4° W
77.3° W
77.2° W
1.4° N
1.3° N
1.2° N
1.1° N

Volcanic Risk

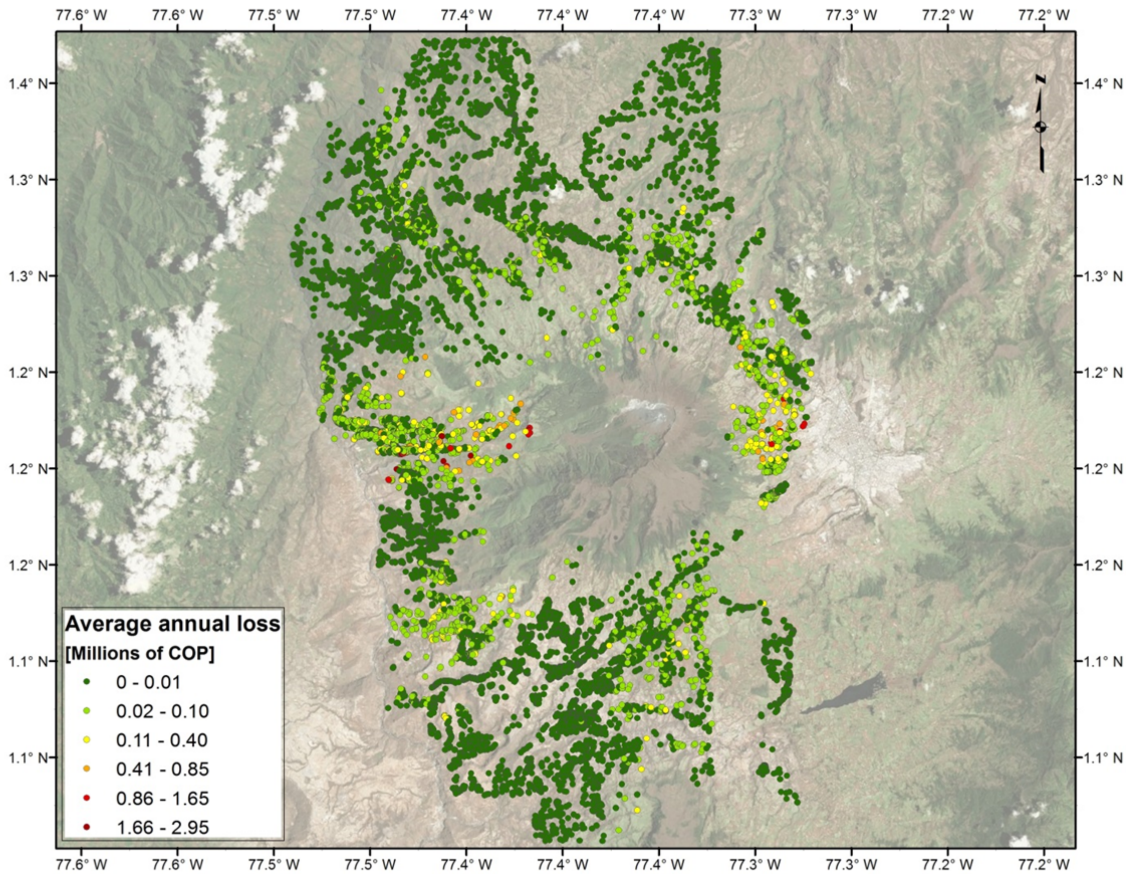


Figure 109. Absolute AAL by dwelling

Annex 6: Exposure and Risk Data for Lorca

Exposure Information

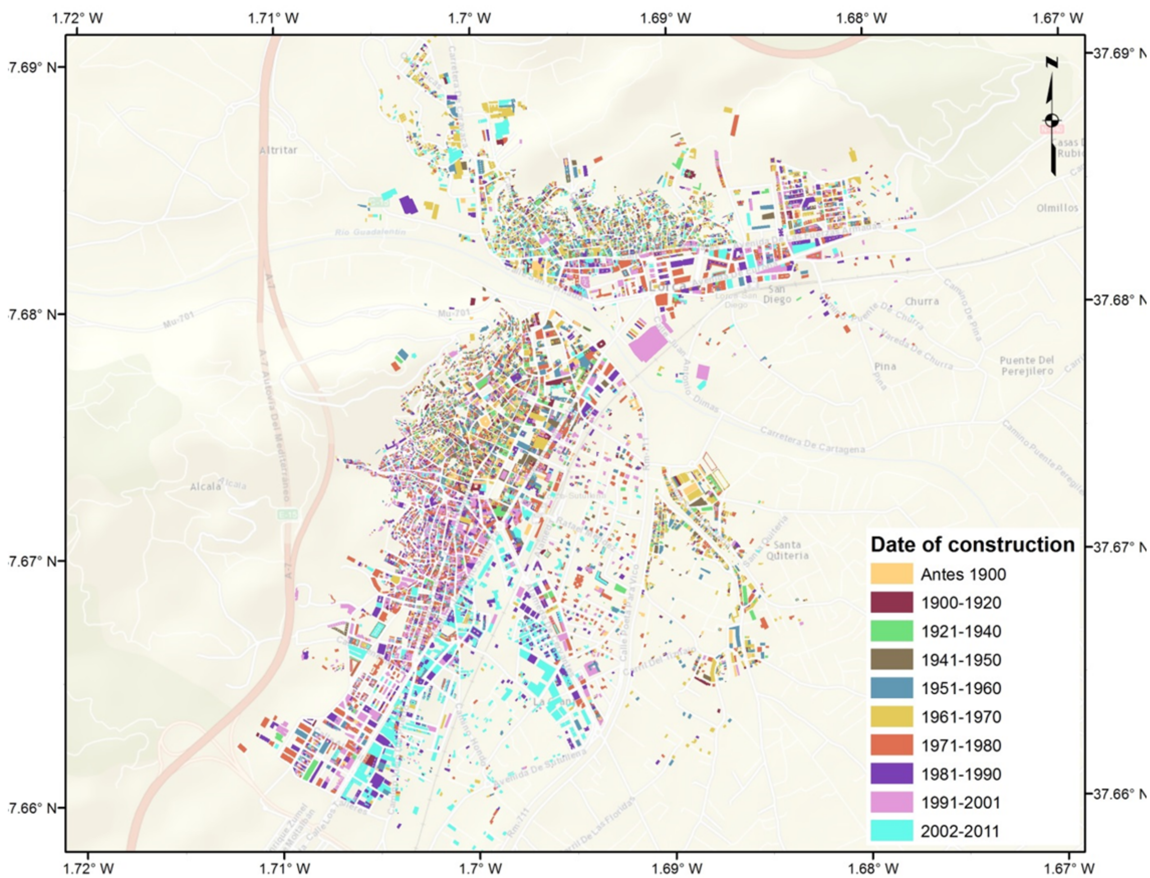


Figure 110. Age of construction by dwelling in Lorca

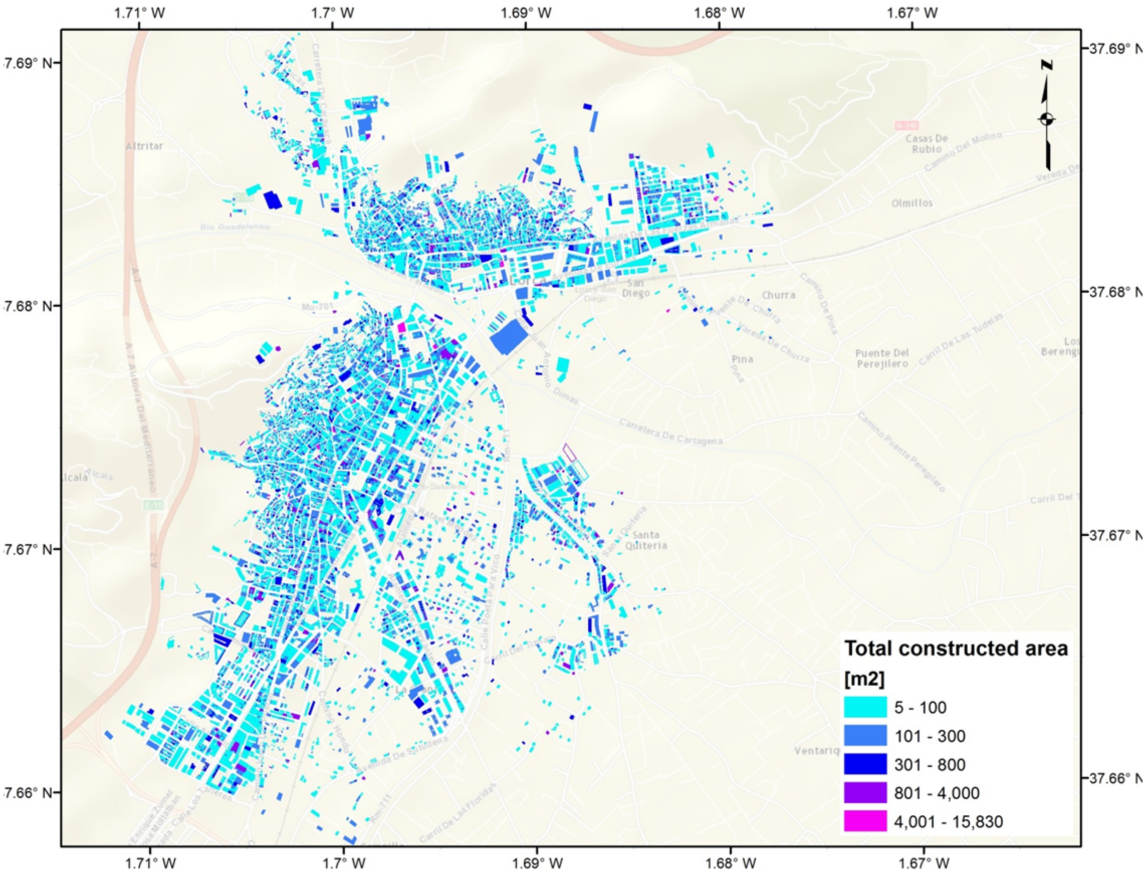


Figure 111. Total constructed area by dwelling in Lorca (m^2)

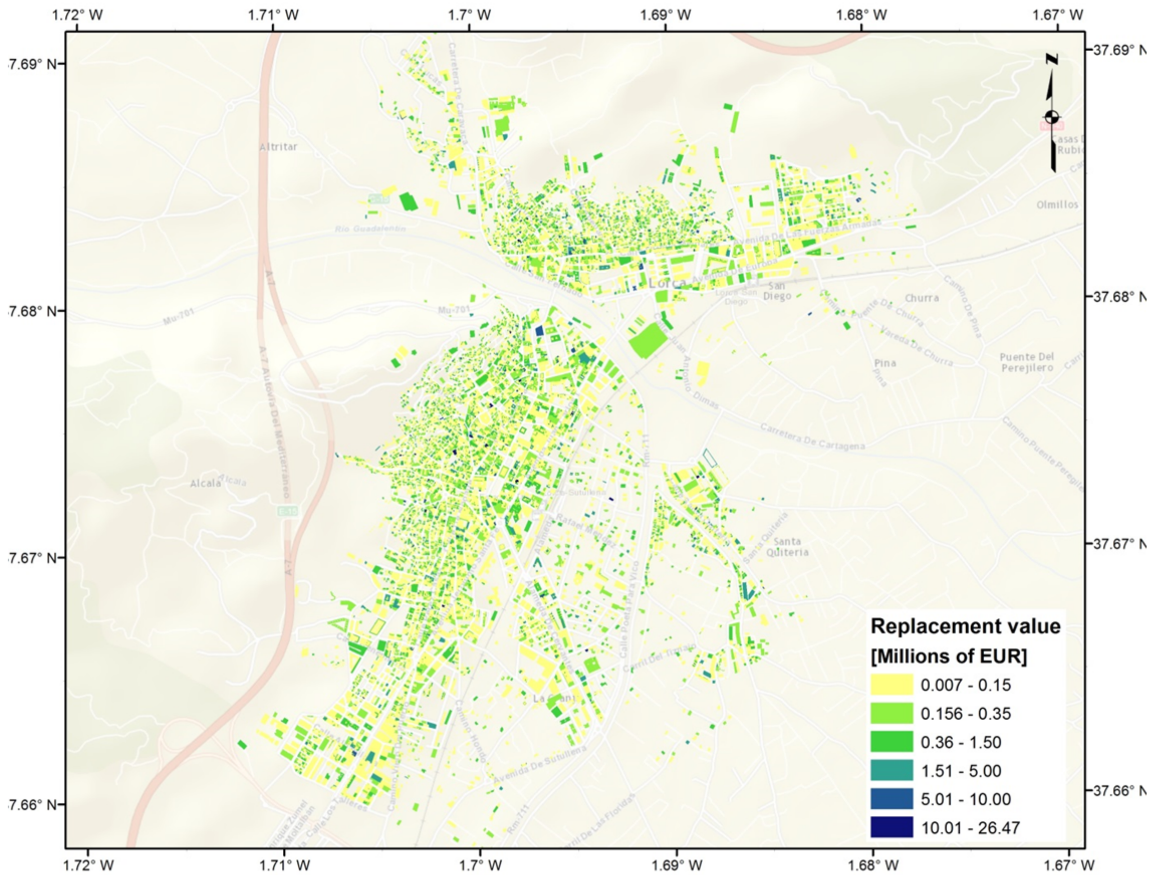


Figure 112. Replacement cost by dwelling in Lorca

Risk Results

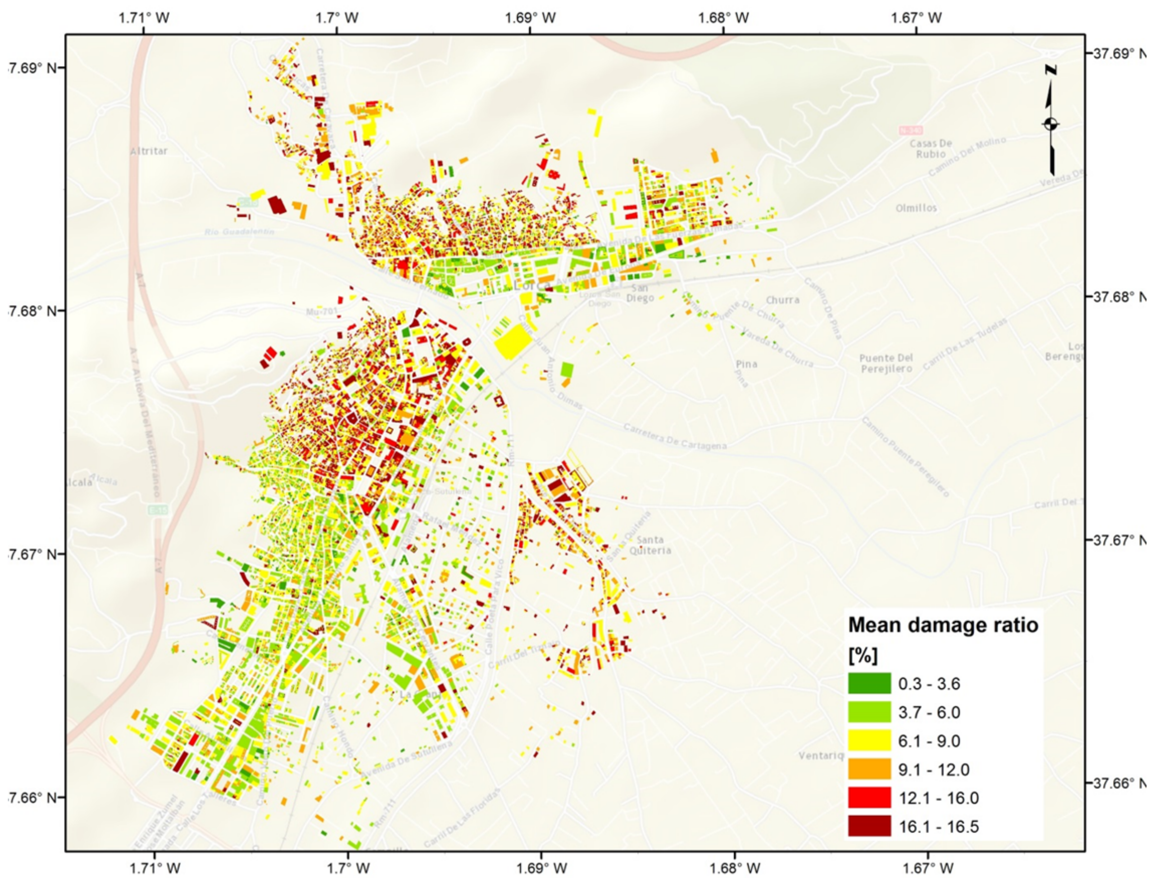


Figure 113. Mean Damage Ratio by dwelling in Lorca

Annex 7: Exposure, Vulnerability and Risk Data for Manizales

Landslide Hazard and Risk Assessment

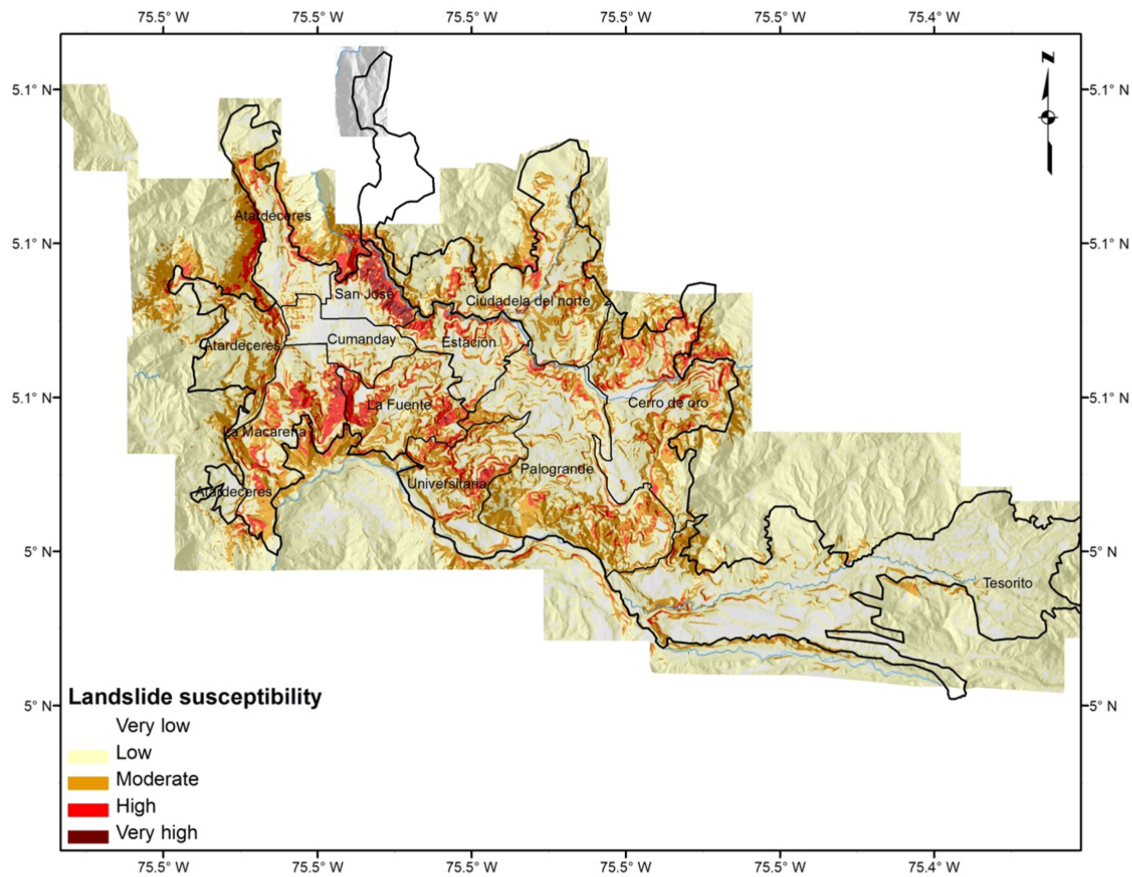


Figure 114. Landslide susceptibility in Manizales by dwelling

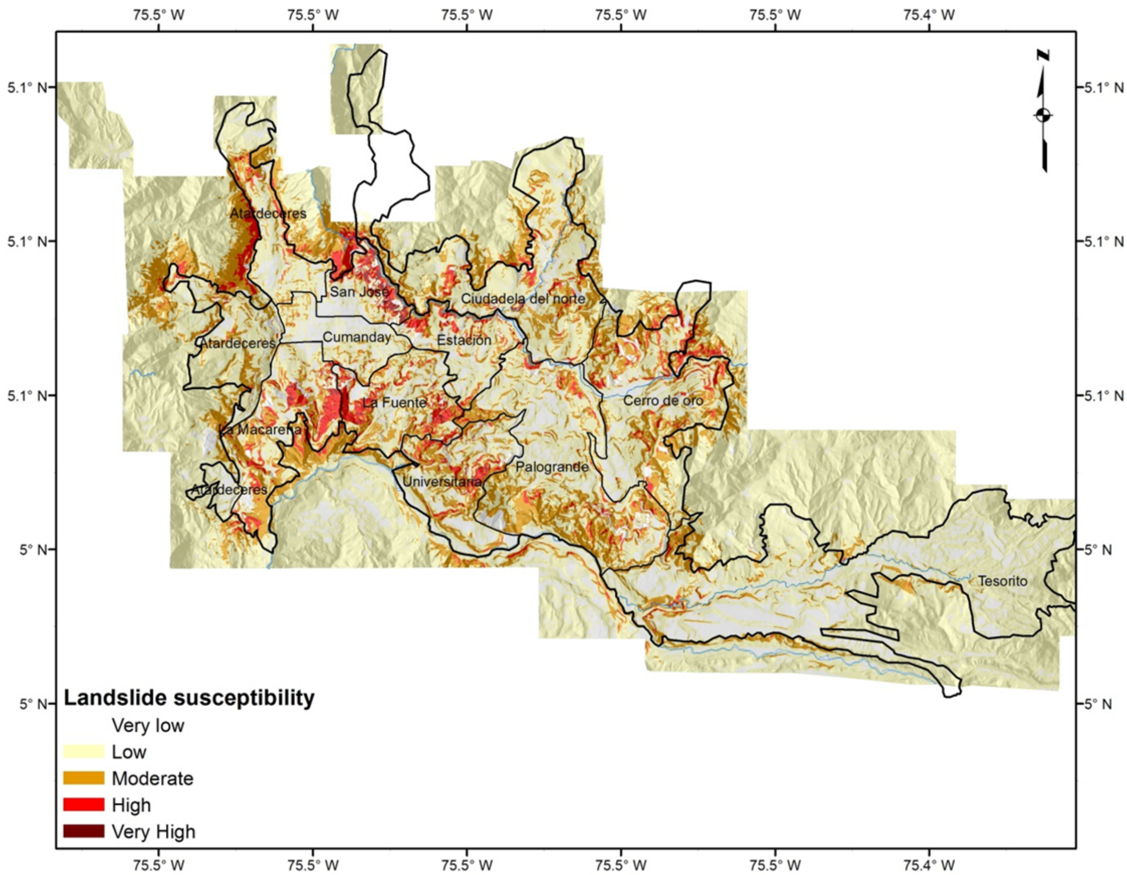


Figure 115. Landslide susceptibility in Manizales by polygon

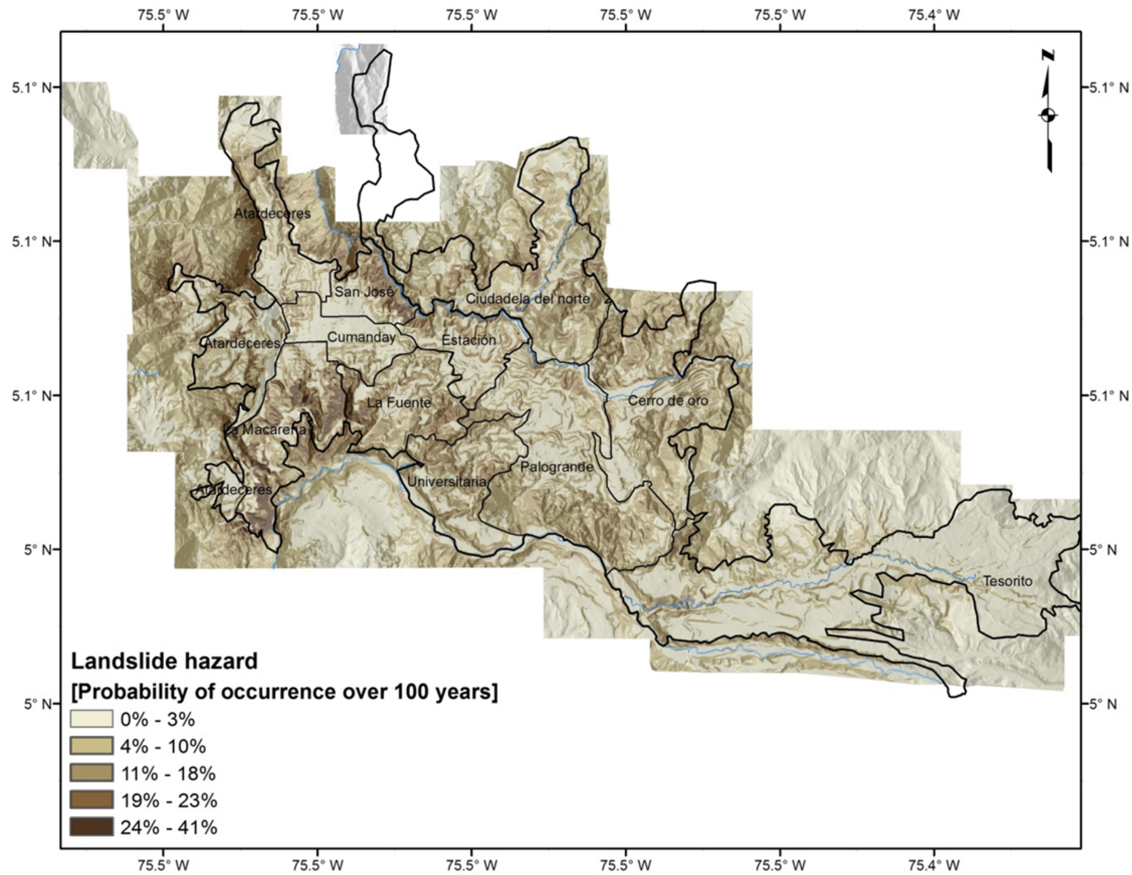


Figure 116. Landslide hazard map for Manizales

Exposure Information

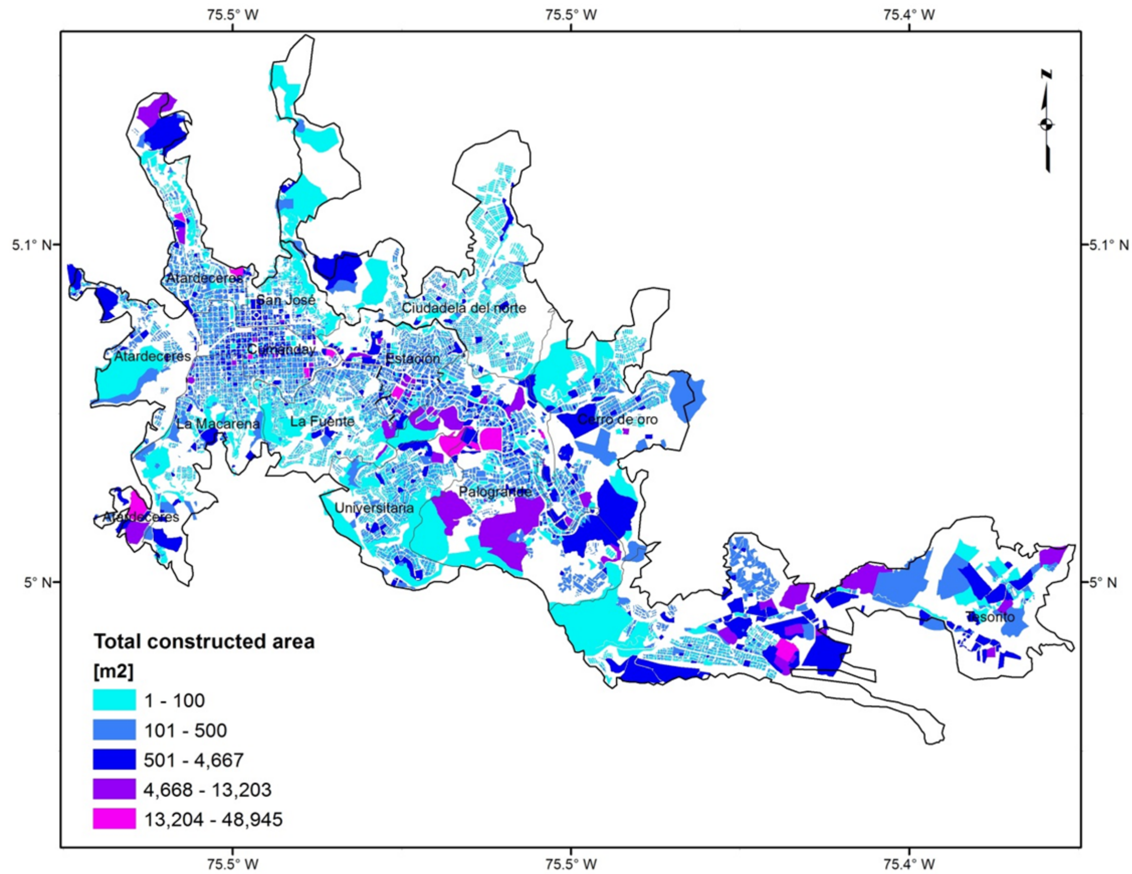


Figure 117. Total constructed area by dwelling

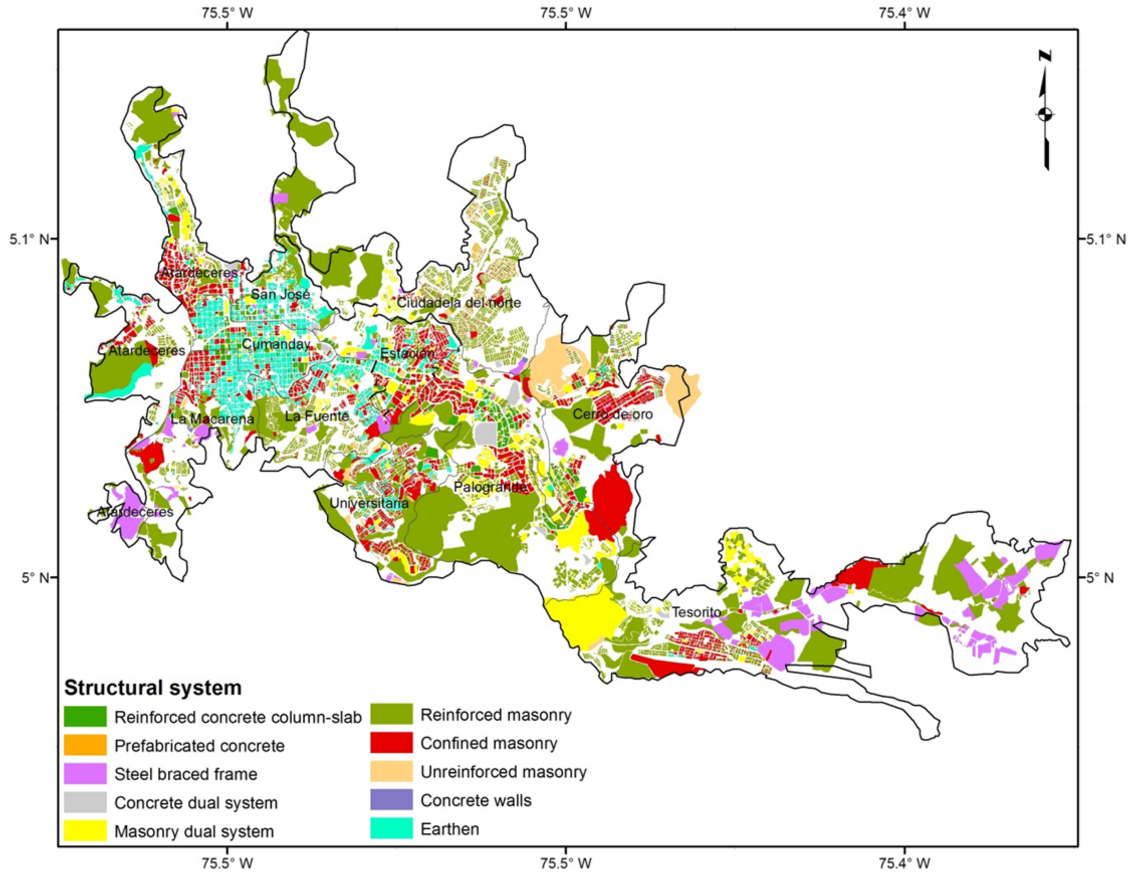


Figure 118. Building class by dwelling

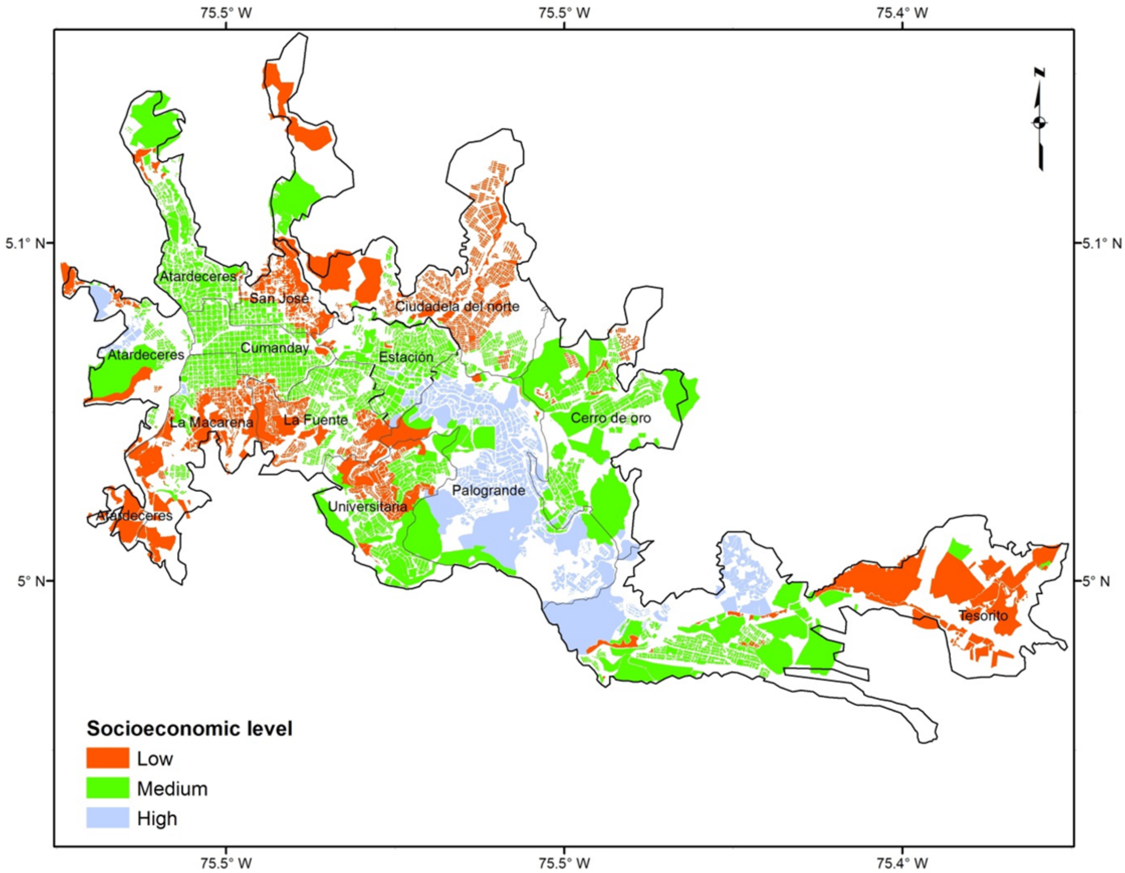


Figure 119. Socioeconomic level by dwelling

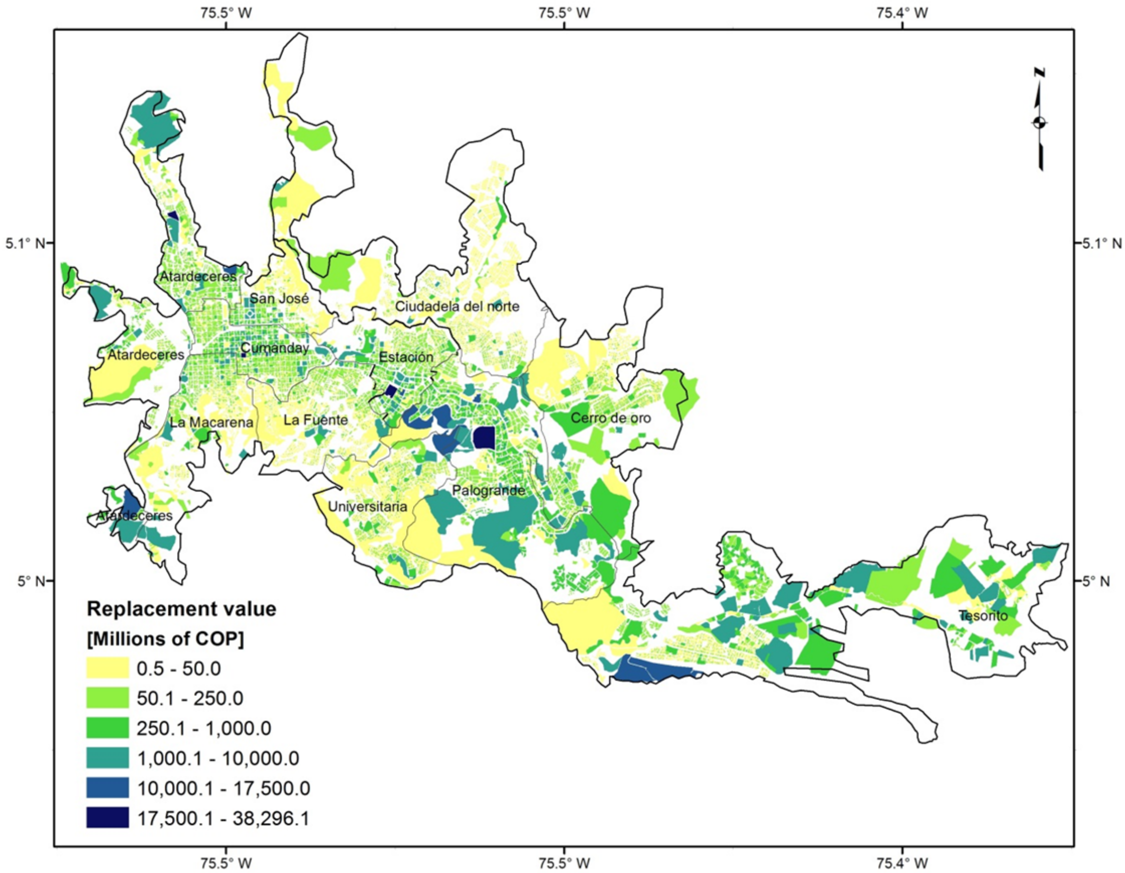


Figure 120. Exposed value by dwelling (COP)

Vulnerability Functions

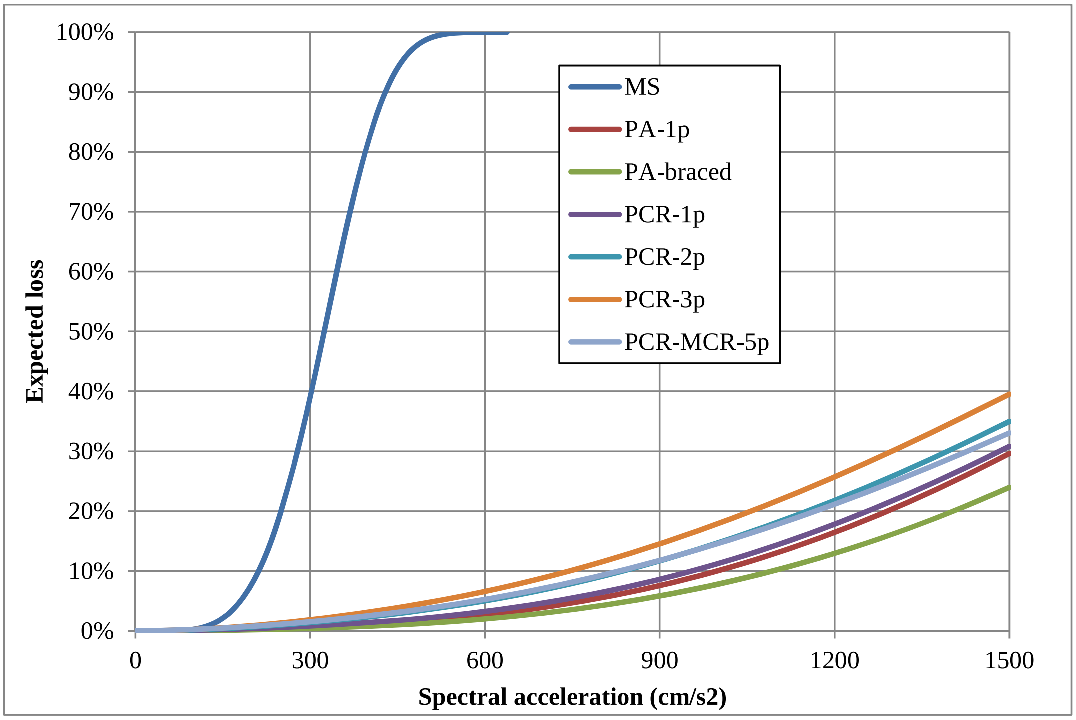


Figure 121. Vulnerability functions for buildings in Manizales

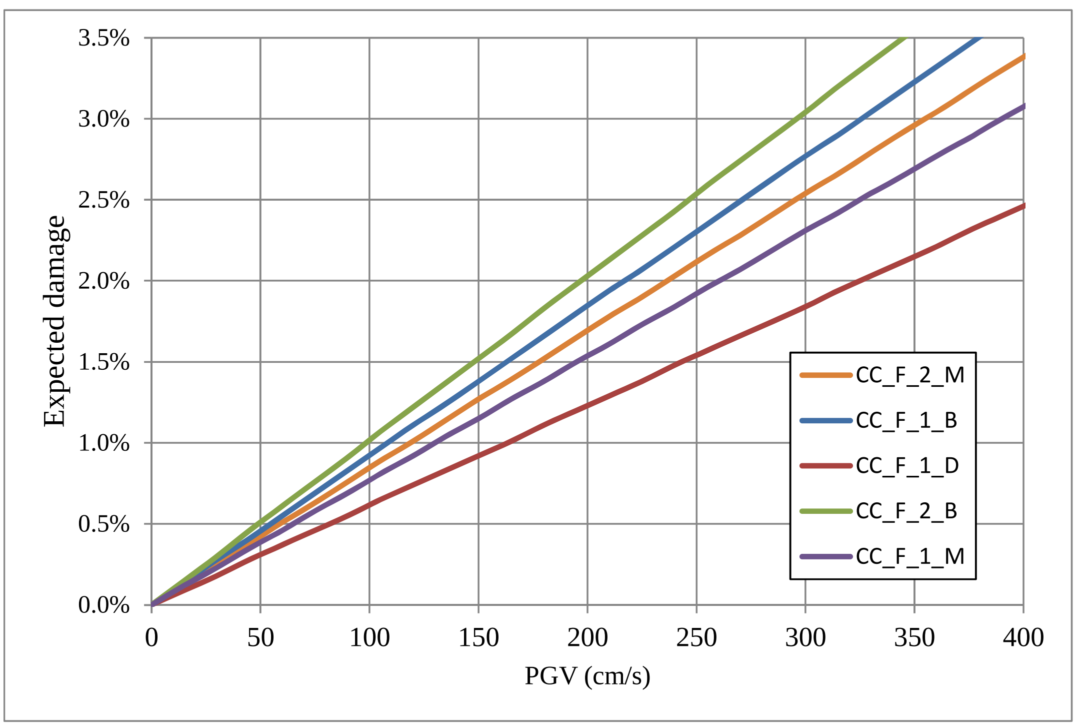


Figure 122. Vulnerability functions for concrete pipelines in Manizales considering different soil conditions

Seismic Risk Results

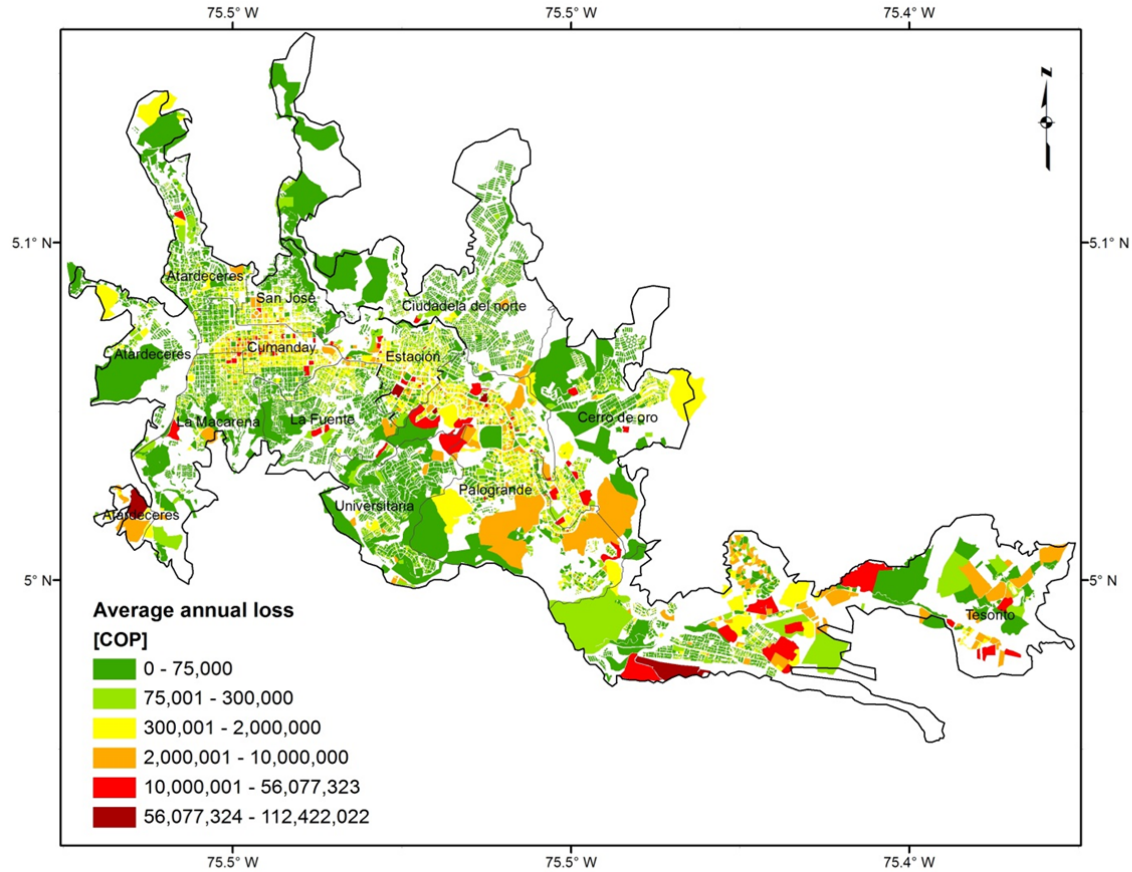


Figure 123. Absolute earthquake AAL by dwelling in Manizales