https://doi.org/10.5194/nhess-2022-73
Preprint. Discussion started: 9 March 2022


Natural Hazards and Earth System Sciences
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# Seismic risk scenarios for the residential buildings in the Sabana Centro province in Colombia

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**Abstract.** Colombia is in one of the most active seismic zones on Earth, where the Nazca, Caribbean, and South American plates converge. Approximately 83% of the national population lives in intermediate to high seismic hazard zones, and a significant part of the country's building inventory dates from before the nation's first seismic design code (1984). At present, seismic risk scenarios are available for the major cities of the country, but there is still a need to undertake such studies in other regions. This paper presents a seismic risk scenario for the "Sabana Centro" province, an intermediate hazard zone located close to the country's capital. An exposure model was created combining information from the Global Earthquake Model (GEM) Foundation, surveys, and the national census. Fragility and vulnerability curves were assigned to the building types of the region. A hazard model was developed for the region and eighteen earthquake scenarios with a return period of 475 years were simulated using the OpenQuake (OQ) hazard and risk assessment tool to estimate damage and economic losses. In addition, a social vulnerability index (SVI) based on demographic information was used to assess the direct economic loss in terms of replacement costs. The results show that 18% of all buildings considered in the region would experience collapse, and 7% would suffer severe damage. Losses account for 18% of the total replacement cost of the buildings and represent 15% of the annual Gross Domestic Product (GDP) of the region.

## 1. Introduction

Colombia is in one of the most active seismic zones on Earth, where the Nazca and Caribbean tectonic plates converge against the South American plate (Paris et al., 2000). The seismicity of the country is associated with the activity of the South American subduction zone along the Colombian Pacific, the Bucaramanga Seismic Nest (BSN), and several other active faults (Arcila et al., 2020). According to the Colombian Geological Service (SGC, by its acronym in Spanish), approximately 83% of the national population lives in areas with intermediate to high seismic hazard levels (AIS, 2010; Arcila et al., 2020).

In addition to the hazard levels mentioned above, more than 10 million Colombians live in houses vulnerable to seismic events (BuildChange, 2021). This situation stems from non-engineered buildings and informal constructions that account for between 60 to 90% of the country's residential building stock (Bonet et al., 2016; Yepes-Estrada et al., 2017). Due to these conditions, earthquakes have resulted in considerable economic and human losses in recent history. Examples include the $M_w$ 5.5 Popayan earthquake in 1983 (Contreras, 2018) and the Mw 6.2 Armenia earthquake in 1999. In the first case, the earthquake caused 287 deaths, 7248 injured, and 150 thousand people affected (Cardona et al., 2004; Lomnitz and Hashizume, 1985). This earthquake represented an estimated loss of 0.98% of the gross domestic product (GDP) for that year (Cardona et al., 2004; AIS, 2009). In the second case, this event left 1185 casualties, 8523 injured people (Naciones Unidas | CEPAL, 1999), and 35000 buildings that collapsed or experienced severe damage (Chávez et al., 2021). The estimated losses from this earthquake amounted to 1.9% of that year's national GDP (AIS, 2009; Cardona et al., 2004). In such cases, field observations showed that the resulting damage was concentrated in old and historical buildings, and in those built from low-quality materials and using inadequate construction techniques (Villar-Vega and Silva, 2017; Cardona et al., 2004; Macdonald et al., 2000; PAHO, 1983).

To help formulate mitigation strategies for earthquakes, risk management agencies and researchers have developed earthquake risk scenarios for different countries at the local, national, and global levels (Chaulagain et al., 2014, 2015; Silva et al., 2014a; Erdik et al., 2003; Nievas et al., 2022). Recently, a seismic risk assessment and a set of earthquake scenarios were developed for the residential building stock of Colombia's three largest metropolitan centers: Bogotá, Medellín, and Cali (Acevedo et al., 2020). In addition, probabilistic seismic risk assessments have been conducted in cities such as Medellín (Salgado et al., 2014) and Manizales (Salgado et al., 2017; Carreño et al., 2017). Despite these efforts, there is still a need to assess the expected consequences of potential earthquake events in other parts of the country. Therefore, this study presents the methodology and results of a seismic risk scenario for the "Sabana Centro" region, a zone made up of 11 municipalities located in the Department of Cundinamarca, north of Bogotá, the capital of the country. Historical earthquakes have occurred and affected this region. In 1644, a Mw 5.5 earthquake mainly affected churches and houses in Bogotá, and in 1743 a Mw 6.2 earthquake caused severe damage to the churches of Cota and Chía, two of the region's municipalities (JICA, 2002; Salcedo and Gómez, 2013), which saw intensities of VII being experienced (Mercalli scale) (SGC, 2021a).

The development of seismic risk scenarios involves three main components: 1) a set of ground motion fields estimated for a given earthquake rupture (seismic hazard model), 2) an exposure model defining the types of buildings in the study zone

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and their spatial distribution, and 3) a set of fragility and vulnerability functions that describe the seismic vulnerability of the buildings. The seismic vulnerability of a structure is a quantity associated with the likelihood of it suffering damage in the event of ground motion of a given level (Calvi et al., 2006). To simulate this vulnerability, fragility curves are associated with the type of construction employed for the buildings in the study area. This association allows the estimation of the probability of a building suffering different damage levels due to earthquake-induced ground motion, i.e., light, moderate, extensive, and collapse.

For the first component (i.e., the hazard), a national probabilistic seismic hazard model developed by the SGC was used to select the events of interest to estimate potential damage and expected losses. In addition, a model developed by the SGC that describes the spatial distribution of $Vs_{30}$ values was considered as a proxy to account for ground motion amplification due to soil conditions (Choi and Stewart, 2005). A study undertaken by the Global Earthquake Model Foundation (GEM) in 2016 (Yepes-Estrada et al., 2017) was used as the basis for creating the exposure model. The data presented in that study was updated with information collected from the 2018 national census of Colombia (DANE, 2018) and the inclusion of on-site surveys. Regarding the structural vulnerability of the building stock, a database of fragility functions (Yepes-Estrada et al., 2016) is publicly available in the GEM Physical Vulnerability Suite (OpenQuake Platform - Vulnerability, 2021). Some of the fragility functions developed for global seismic risk analysis (Martins and Silva, 2021) were taken as a basis. The curves for thin reinforced concrete walls from Arroyo et al., (2021) and Cabrera et al. (2021) for wooden houses were also used. Seismic risk scenarios were simulated using these three components as input for the OpenQuake (OQ) hazard and risk assessment engine (Silva et al., 2014b), from which the number of damaged buildings and associated economic losses was calculated.

One aspect of risk assessment frequently neglected is social vulnerability (SV). Post-disaster assessments have demonstrated that the extent of losses from disasters depends not only on the magnitude and duration of extreme natural events but also on the resilience of the population to build-back their lives, livelihoods, and property (Chen et al., 2013; Schmidtlein et al., 2011; Contreras, 2016). The most vulnerable segments of a population are usually the most severely affected by extreme natural phenomena (Contreras et al., 2020b). Experiences from past earthquakes, such as the 2010 Haiti earthquake which resulted in 200,000 deaths (Boot et al., 2010) and 1.5 million homeless (Contreras et al., 2020a) have shown that casualties and building damages are higher among people who live in poorly constructed non-engineered buildings (Boot et al., 2010). In some cases, less-favored families may be forced to sell their income-providing assets to fulfill their immediate basic needs, even though they are less able to replace them. Moreover, the impact of natural phenomena may span for generations, as parents may need to withdraw children from schools to help generate family income, thus limiting their future opportunities. Consequently, earthquake preparedness plans should consider that the consequences of these events have a greater impact on more vulnerable members of a community. According to data from the World Bank (WB), Colombia has a Gini index of 0.517, making it a country with a substantial level of income inequality (World Bank, 2022). In fact, the same study showed that Colombia's economy has the second most uneven distribution of income within Latin America, with only Brazil being higher. In Colombia, inequality goes beyond income level, as it is also present in aspects related to the quality of life, such as social security, access to basic services, education, and so forth (Joumard and Londoño Vélez, 2013). These differences are visible throughout the country, and the Sabana Centro province is an example of

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this. This study, therefore, also considers social vulnerability (Cutter et al., 2003), which is represented as an index to adjust the economic losses due to structural damage.

## 2. Description of the study area

Sabana Centro is a region of Cundinamarca, Colombia, to the north of Bogotá, the country's capital. It comprises 11 municipalities (Figure 1) and according to the 2018 National Population and Housing Census (CNPV, by its acronym in Spanish), the number of inhabitants of the region is 539,295 (DANE, 2018). Table 1 presents the area and the number of inhabitants of the 11 municipalities that make up this region that hosts several economic and industrial activities due to its proximity to Bogotá. The majority of the building stock of the region is comprised of one- and two-story houses.

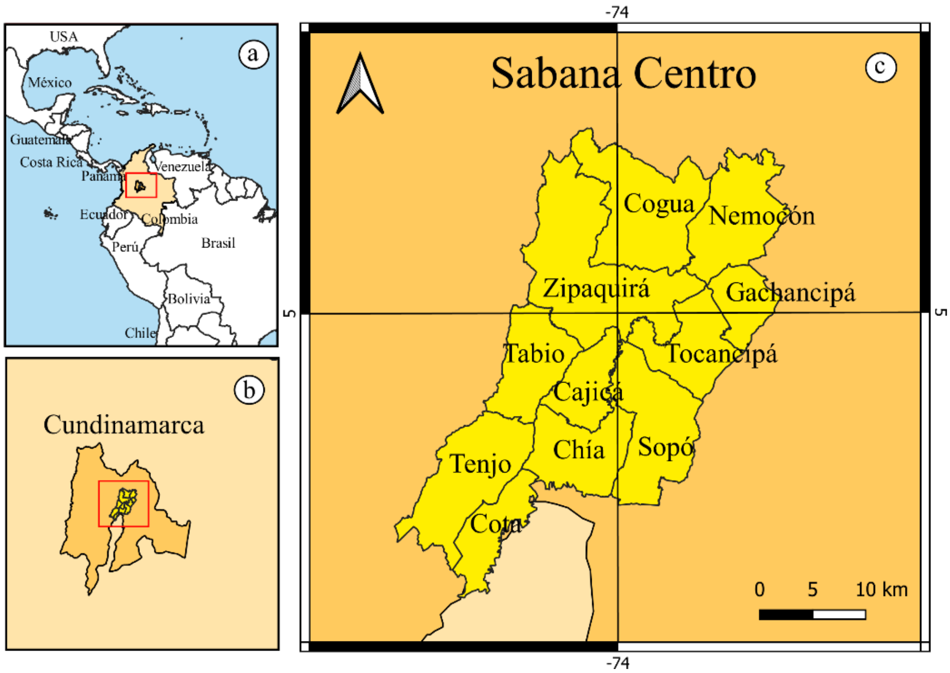


**Figure 1.** a) Location of the study area within Colombia. b) The region within the department of Cundinamarca ("department" is the first administrative division in Colombia). c) The municipalities which make up the Sabana Centro province.

**Table 1.** Area, distribution of population and population density of the eleven municipalities that make up Sabana Centro (DANE, 2018).

| Municipality | Area (km²) | Inhabitants | Population density (Inhabitants/km²) |
|---|---|---|---|
| Cajicá | 51 | 82,244 | 1613 |
| Chía | 79 | 132,181 | 1673 |
| Cogua | 136 | 22,067 | 162 |
| Cota | 55 | 32,691 | 594 |
| Gachancipá | 44 | 17,026 | 387 |
| Nemocón | 94 | 13,171 | 140 |
| Sopó | 111.5 | 25,782 | 231 |
| Tabio | 74.5 | 21,665 | 291 |
| Tenjo | 108 | 21,935 | 203 |
| Tocancipá | 73.51 | 39,996 | 544 |
| Zipaquirá | 197 | 130,537 | 663 |

In addition to natural population growth in Colombia, the country's capital and several municipalities have experienced a greater increase in population partly due to the constant migration from neighboring Venezuela since 2015. The region of Sabana Centro has not been immune to this process, wherein recent years, it has seen a significant demographic change in most municipalities (Sabana Centro Cómo Vamos, 2019). In 2015, the population density was 460 inhabitants per km², and in 2018, this had risen to 527 inhabitants per km². This increase in population density means that there was a growth rate of 14.6%, higher than the national average of 5.9%. Among the municipalities, Chía, Cajicá, and Zipaquirá had the highest population growth. This gro counts for 64% of the total population of the region. The number of inhabitants in the region represents 18% of the department of Cundinamarca (67% in urban areas and 33% in rural).

## 3. Description of input parameters

### 3.1. Seismic hazard

The SGC, in collaboration with researchers from the Geological and Mining Institute of Spain and the GEM Foundation, developed a national seismic hazard model (Arcila et al., 2020). Overall, this national seismic hazard model comprises a set of tectonic environments and seismogenic sources. In that study, the seismicity of the Colombian territory was classified into four tectonic environments. Superficial events (cortical) correspond to events in the national territory down to depths limited by the upper crust-mantle boundary. Interplate earthquakes of the Colombian Pacific subduction zone correspond to earthquakes that occur in the area of contact between the Nazca and South American Plates along the country's Pacific coast. Earthquakes in the Benioff area correspond to earthquakes inside the plate, which is subducting towards the east from the

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Preprint. Discussion started: 9 March 2022

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Colombian Pacific towards the country's interior. The Bucaramanga's seismic nest corresponds to an area where earthquakes with magnitudes between Mw 4.0 and 5.0 frequently occur at depths between 140 and 200 km.

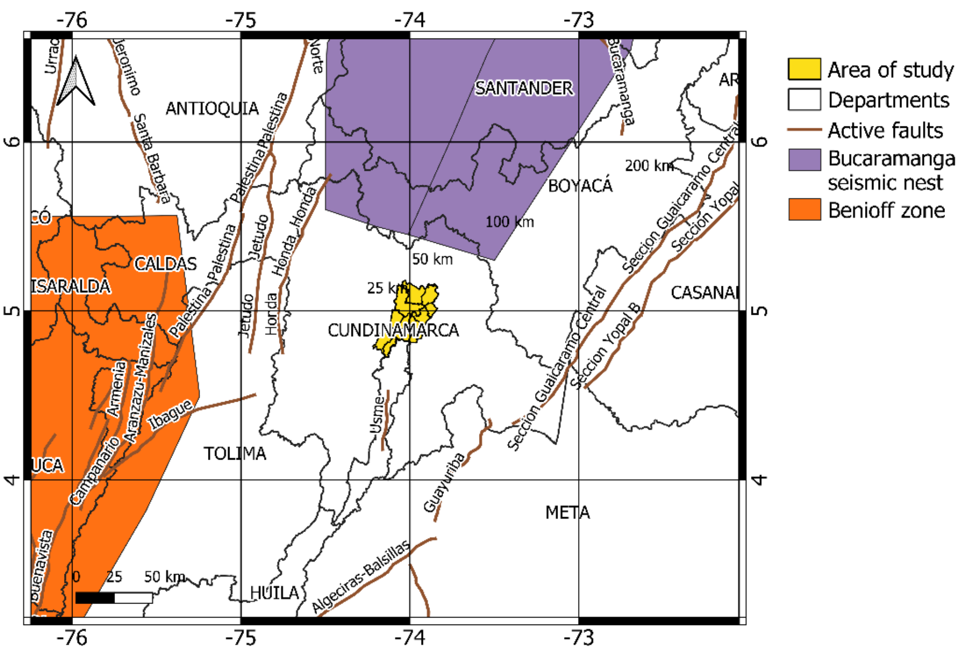


**Figure 2.** Seismic hazard sources close to the Sabana Centro province (Arcila et al., 2020): The active faults are presented in brown lines. The Usme fault is located less than 50 km from the municipality of Tenjo. The Benioff zone and the Bucaramanga seismic nest are located less than 120 km and 150 km approximately from Tenjo.

### 3.1.1. Definition of the earthquake scenarios

The Sabana Centro province is located close to seismic hazard sources of different tectonic regional types, as shown in Figure 2. According to the national seismic hazard model developed by the SGC and the GEM Foundation, the Sabana Centro province is close to active shallow seismic sources (such as the Usme Fault), intraplate events from the Benioff zone, as well as deep events from the Bucaramanga's seismic nest (Arcila et al., 2020).

In this study, earthquake events are defined in terms of the magnitude, location, and geometric characteristics of their ruptures. For the determination of the magnitude and location of the events to be considered in the estimation of damage, events from the unified earthquake catalogue developed by the SGC (SGC, 2021b) within a radius of 200 km were considered. Figure 3 shows the near shallow events with depths less than 70 km listed in the catalogue at distances less than 75 km from the center of Tenjo, a municipality of the province, and moment magnitudes ranging between Mw 6.0 and 6.5. In addition, it shows events with depths ranging between 70 and 300 km with magnitudes greater than 6.5 Mw, located at distances varying between 150 and 200 km from study area.

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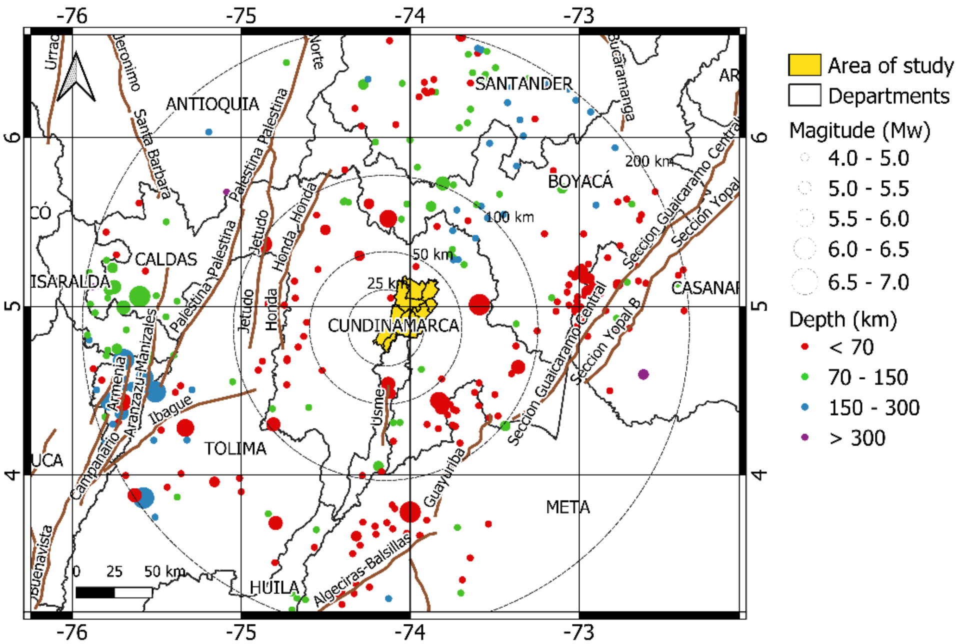


**Figure 3.** Geographic distribution of events occurring within 200 km of the study area selected from the Unified Earthquake Catalogue of the SGC (SGC, 2021b). The size of the circle represents the magnitude of the event, and color indicates depth.

To identify the type of events that contributes the most to the seismic hazard of the Sabana Centro province, a hazard disaggregation analysis (Bazzurro and Cornell, 1999) was conducted using the OQ Engine, considering the national seismic hazard of Colombia (Arcila et al., 2020). Details of the seismic hazard disaggregation procedure are described in Pagani et al. (2014). The disaggregation was developed for the population centroid within the region of analysis (longitude: -74.144, latitude: 4.872) located in the municipality of Tenjo. The annual rate is 0.0021 (10% probability of exceedance over 50 years, or 475 years return period). Regarding the geometry of the earthquake ruptures, in the case of shallow events, the dip, strike, and rake angles were defined using available information from the seismic hazard model (Arcila et al., 2020), as well as the focal mechanism of the Quetame earthquake of magnitude Mw 5.9, which occurred in May 2008 (Páez et al., 2015).

The results obtained given the distance and magnitude of the earthquakes are presented in Figure 4. In the case of the Peak Ground Acceleration (PGA), crustal events make a higher contribution to the seismic hazard, located at distances less than 35 km, with magnitudes ranging between Mw 5.0 to 7.0. These events correspond to seismic sources of the crustal tectonic region type. A lower contribution is observed from events of the Benioff zone with magnitudes between Mw 6.5 and 7.0 at distances between 125 and 150 km. In the case of spectral acceleration with a period of 1.0 second (Sa (1.0s)), the most significant contribution also comes from crustal events.However, there is an important contribution of events of magnitude greater than Mw 8.0 at distances ranging between 275 and 300 km, whose origins are in the subduction-interplate tectonic region.

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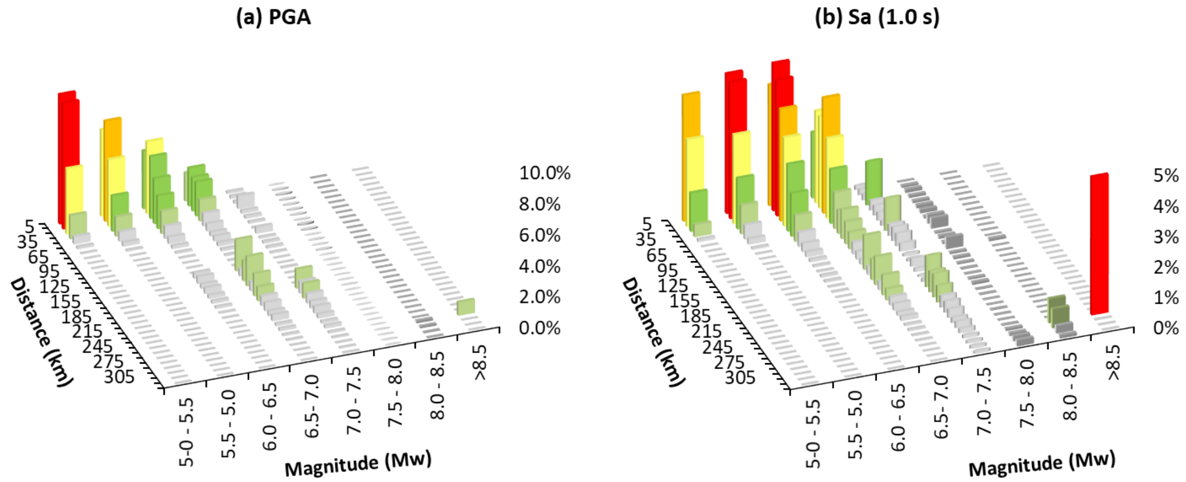


**Figure 4.** Contribution to the seismic hazard of earthquakes by distance and magnitude (a) PGA; (b) Sa (1.0 s). The color scale represents the percentage contribution of seismic events to the seismic hazard, with gray representing the lowest contribution and red the highest.

170 Based on this disaggregation and the fact that Sabana Centro has a significant number of low-rise stiff buildings that have small fundamental periods, eighteen crustal events were selected from the catalogue to be used in this study to calculate the expected damages and economic losses. The magnitude, location and geometry of ruptures are shown in Table 2.

**Table 2.** Information describing the seismic events selected as scenarios in this work to estimate potential damage and impact.

| Municipality | Magnitude (Mw) | Longitude | Latitude | Depth (km) | Strike (°) | Dip (°) | Rake (°) |
|---|---|---|---|---|---|---|---|
| Cajicá | 6.35 | -74 | 4.96 | 5 | 0 | 90 | 0 |
| Chía | 5.95 | -74 | 4.87 | 5 | 0 | 90 | 0 |
| Cogua | 6.45 | -74 | 5.05 | 5.51 | 0 | 90 | 0 |
| | 6.35 | -74 | 5.09 | 5 | 0 | 90 | 0 |
| Cota | 6.95 | -74.1 | 4.8 | 9.27 | 39 | 76 | -6.5 |
| | 5.55 | -74.1 | 4.82 | 5 | 0 | 90 | 0 |
| Gachancipá | 5.95 | -73.9 | 5.02 | 7.5 | 39 | 76 | -6.5 |
| Nemocón | 6.65 | -73.9 | 5.05 | 6.78 | 0 | 90 | 0 |
| | 6.25 | -73.9 | 5.09 | 5 | 0 | 90 | 0 |
| Sopó | 6.55 | -74 | 4.91 | 6.11 | 0 | 90 | 0 |
| | 6.25 | -74 | 4.91 | 5 | 0 | 90 | 0 |
| Tabio | 6.65 | -74.1 | 4.91 | 6.78 | 0 | 90 | 0 |
| | 6.25 | -74.1 | 5 | 5 | 0 | 90 | 0 |
| Tenjo | 5.95 | -74.2 | 4.80 | 7.5 | 81 | 38 | -76 |
| | 5.35 | -74.1 | 4.87 | 5 | 0 | 90 | 0 |
| Tocancipá | 6.85 | -73.9 | 4.98 | 25 | 81 | 38 | -76 |
| | 6.15 | -73.9 | 4.96 | 5 | 0 | 90 | 0 |
| Zipaquirá | 5.65 | -74 | 5 | 5 | 0 | 90 | 0 |

### 3.1.2. Soil-site conditions

To the best authors' knowledge, there are no specific studies of the seismic response of soil deposits within the region of Sabana Centro reported in the scientific literature. Therefore, the average shear wave velocity in the top 30 m ($Vs_{30}$) has been considered a proxy to address the contribution of soil-site conditions on the calculated ground motions at this regional scale (Derras et al., 2017). For designing the foundations of new buildings, the current Colombian seismic design code, NSR-10 (AIS, 2010), classifies soils based on the $Vs_{30}$ values of the site of interest and proposes a set of coefficients to account for soil effects in the calculation of the seismic demand. Therefore, such ranges of Vs30 are considered for the Sabana Centro province. A map of $Vs_{30}$ values within the Sabana Centro province is presented in Figure 5, , according to a map developed by Eraso and Montejo (2020), with a 7.5 arc second resolution (~250 m$^2$) based on digital elevation models. It shows the presence of different conditions, from soft soils with values of $Vs_{30}$ under 200 m/s to stiff soils with $Vs_{30}$ > 1000 m/s. The figure also shows that most urban blocks are in sites with $Vs_{30}$ values less than 450 m/s. In particular, the municipalities of Tenjo, Tocancipá, Nemocón, Gachancipá, Cajicá, and Chía are in areas with $Vs_{30}$ less than 180 m/s, corresponding to soft soils.

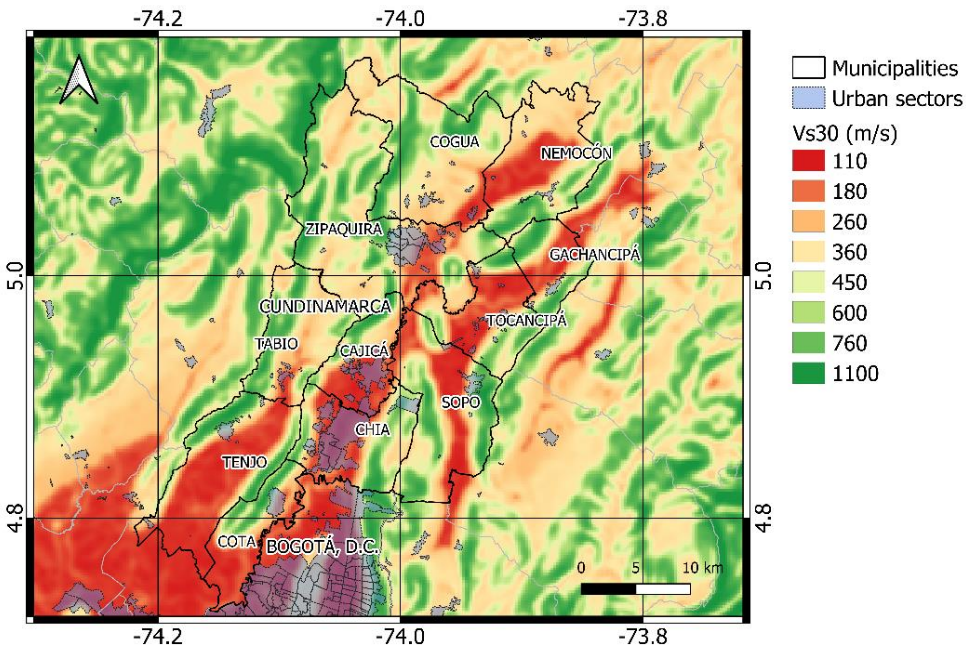


**Figure 5.** Spatial distribution of $Vs_{30}$ values in the Sabana Centro province according to Eraso and Montejo, (2020). The urban areas of the municipalities in the region are also shown.

### 3.1.3. Selection of ground motion prediction equations

Ground motion prediction equations (GMPE) allow one to forecast the expected intensity of ground motion at a given site due to an earthquake event in terms of some measure, for example, spectral accelerations (Stewart et al., 2015). Several equations have been proposed worldwide for different tectonic environments, with different functional forms and input parameters. In

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Colombia, two sets of equations were developed to define the seismic hazard maps of the national building design code (NSR-10) (Gallego Silva, 2000) and the bridge design code (CCP-14) (Bernal Granados, 2014). More recently, Arcila et al. (2020) defined logic trees of GMPEs for the different tectonic regions of the country as a way to address epistemic uncertainty in the selection of other GMPEs, following the criteria proposed by Scherbaum et al. (2005) and Cotton et al. (2006), as shown in Table 3.

As introduced above, this study uses $Vs_{30}$ to account for ground motion amplification due to soil conditions (Choi and Stewart, 2005). The values in this region range between 112 m/s and 1100 m/s. This study considered crustal earthquakes and among the three GMPE proposed by Arcila et al. (2020), for shallow crustal regions in Colombia, the Idriss. (2014) GMPE is not defined for $Vs_{30}$ < 450 m/s, therefore, it was not considered for the scenarios. The weight assigned to this model (0.399) was distributed proportionally between the Cauzzi et al. (2015) and Abrahamson et al. (2014) GMPE, whose final weights used in this study are 0.65 and 0.35, respectively.

Table 3. Logic tree of GMPEs for crustal events as defined by Arcila et al. (2020) for the National Model and the actual weights used for the earthquake's scenarios.

| Tectonic region type | GMPE | Weight | |
|---|---|---|---|
| | | Defined in the national model | Used for the scenarios |
| Shallow crustal | Idriss (2014) | 0.399 | 0 |
| | Cauzzi et al. (2014) | 0.390 | 0.65 |
| | Abrahamson et al. (2014) | 0.211 | 0.35 |

Using the GMPE logic tree shown in Table 3, the mean expected PGA values for the Chía Mw 5.95 scenario of Table 2 may range between 0.12g (Cogua) and 0.49g (Cajicá).

### 3.2. Exposure model for the residential building stock

The building exposure model for the region has information about the building classes, the number of buildings, inhabitants, and the buildings' replacement costs. To develop this model for Sabana Centro, the exposure model for Colombia published by the South America Risk Assessment (SARA) project was taken as a basis (Yepes-Estrada et al., 2017). Then, this information was updated using the national census data from 2018 (DANE, 2018), and from information collected during remote surveys carried out by students from the Universidad de La Sabana in the municipality of Chía. The SARA exposure model used 2005 census information considering a population of 381,202 inhabitants and 57,110 buildings. The South America Risk Assessment obtained the number of residential buildings from the average nighttime inhabitants per inferred building class using this outdated population data. For this reason, to update the exposure model, this study considered the most recent census (DANE, 2018), wherein the Sabana Centro province has a total population of 539,925. Thereby, the number of buildings per municipality was updated based upon this population assuming that the dwellings of each building class increase proportionally to the population of each municipality. The building replacement cost refers to the cost of structural and non-structural components of a building and it is a value associated with the building's rehabilitation. This study has only considered the structural cost per building given in the SARA exposure model for Colombia, where the replacement cost was considered as a function of the socio-economic levels of the country[1]. Figure 6 shows the results of inhabitants, buildings, and their total replacement cost for the region. The bold numbers indicate the percentages for each municipality.

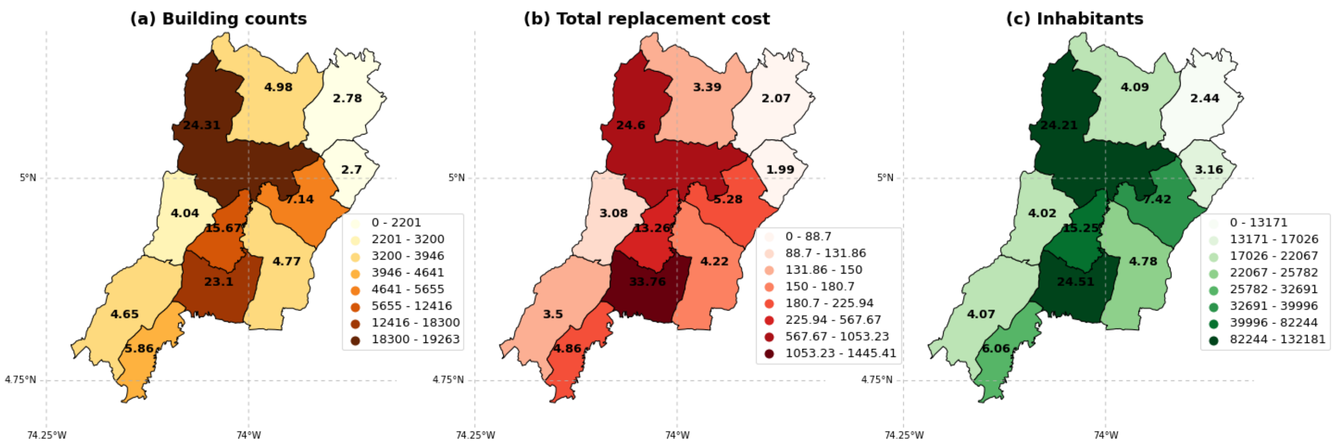


**Figure 6.** Summary of the exposure model for the Sabana Centro province. a) Building counts, b) total replacement cost in million USD, and c) inhabitants per municipality.

A total of 79,222 residential buildings in the region were classified into fifteen building classes. Table 4 provides a description of these typologies along with the number of buildings within each category and their percentages. Among them, 6249 randomly distributed buildings in Chía were inspected in 2020 by civil engineering students of the Universidad de La Sabana. Their attributes were collected, making use of the Rapid Remote Visual Screening -RRVS web-platform (Haas et al., 2016), which allowed the use of the GEM V.2.0 taxonomy (Brzev et al., 2013) as a checklist while observing the buildings' façades through Google Street View. The resulting dataset is available in Arroyo et al. (2022). Five attributes of the GEM v.2.0 taxonomy were used for classifying these inspected buildings: the main construction material type, material technology, lateral load-resisting system, the expected level of ductility, and the number of stories. During the elaboration of the surveys, instead of "labelling" buildings as certain typologies, the collected attributes were used to classify them in a probabilistic manner. For such a purpose, the method proposed in Pittore et al. (2018) was used to evaluate the level of compatibility between the observed building attributes and each predefined building typology. This procedure served to update the percentages of the typologies of the SARA exposure model. Details of this process can be consulted in Arroyo et al. (2022).

[1] https://platform.openquake.org/documents/236

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From Table 4 it is noticeable that 68.86% of the buildings are constructed of non-ductile unreinforced masonry walls, including adobe blocks and dressed and semi-dressed stone. Figure 7 shows the number of buildings for the three types of construction materials identified in the exposure model: concrete, masonry, and wood. This figure shows that the predominant construction material is masonry (70,195 buildings), mainly in Chía and Zipaquirá, with more than ten thousand buildings for each one. Then, there are those buildings made of wood (6528), with more than one thousand in Zipaquirá. Last, there are those structures made of concrete (2500), especially in Zipaquirá with more than 432 units. The number of masonry buildings represents the 88.61% of the total buildings in Sabana Centro, whereas those of concrete and wood represent 3.16% and 8.24%, respectively, with. The number of buildings for each of the 15 typologies is depicted in Figure 8. In the case of concrete, the predominant building class is non-ductile reinforced concrete moment frames, whilst for the masonry buildings, the non-ductile unreinforced masonry walls class is predominant.

**Table 4.** Summary of the building typologies in the exposure model defined for the study area. The building classes are defined based on the GEM v.2.0 taxonomy while including medium ductility (DUM), which is presented in Martins and Silva. (2021).

| Building class | Description | Number of buildings | Proportion (%) | Replace-ment cost (M. USD) |
|---|---|---|---|---|
| CR/LDUAL/DUM/H4 | Medium-ductile reinforced concrete dual frame-wall system, 4 stories | 54 | 0.07 | 33.74 |
| CR/LFINF/DNO/H1 | Non-ductile reinforced concrete infilled frames, 1 story | 859 | 1.08 | 58.83 |
| CR/LFINF/DUM/H4 | Medium-ductile reinforced concrete infilled frames, 4 stories | 145 | 0.18 | 185.49 |
| CR/LFM/DNO/H1 | Non-ductile reinforced concrete moment frames, 1 story | 878 | 1.11 | 156.53 |
| CR/LFM/DUM/H4 | Medium-ductile reinforced concrete moment frames, 4 stories | 287 | 0.36 | 189.59 |
| CR/LWAL/DUM/H1 | Medium-ductile reinforced concrete walls, 1 story | 125 | 0.16 | 309.94 |
| CR/LWAL/DUM/H4 | Medium-ductile reinforced concrete walls, 4 stories | 152 | 0.19 | 163.88 |
| MCF/DNO/H:1 | Non-ductile confined masonry, 1 story | 10,854 | 13.70 | 946.58 |
| MCF/LWAL/DUM/H1 | Medium-ductile confined masonry walls, 1 story | 3551 | 4.48 | 401.61 |
| MR/LWAL/DUM/H1 | Medium-ductile reinforced masonry walls, 1 story | 1233 | 1.56 | 767.06 |
| MUR/LWAL/DNO/H1 | Non-ductile unreinforced masonry walls, 1 story | 37,863 | 47.79 | 443.88 |
| MUR+ADO/LWAL/DNO/H1 | Non-ductile unreinforced masonry with adobe blocks walls, 1 story | 14,959 | 18.88 | 336.57 |
| MUR+STDRE/LWAL/DNO/H1 | Non-ductile unreinforced masonry with dressed stone walls, 1 story | 996 | 1.26 | 24.89 |
| MUR+STRUB/LWAL/DNO/H1 | Non-ductile Unreinforced masonry with semi-dressed stone, 1 story | 739 | 0.93 | 18.47 |
| W/H1 | Wood, 1 story | 6528 | 8.24 | 244.79 |

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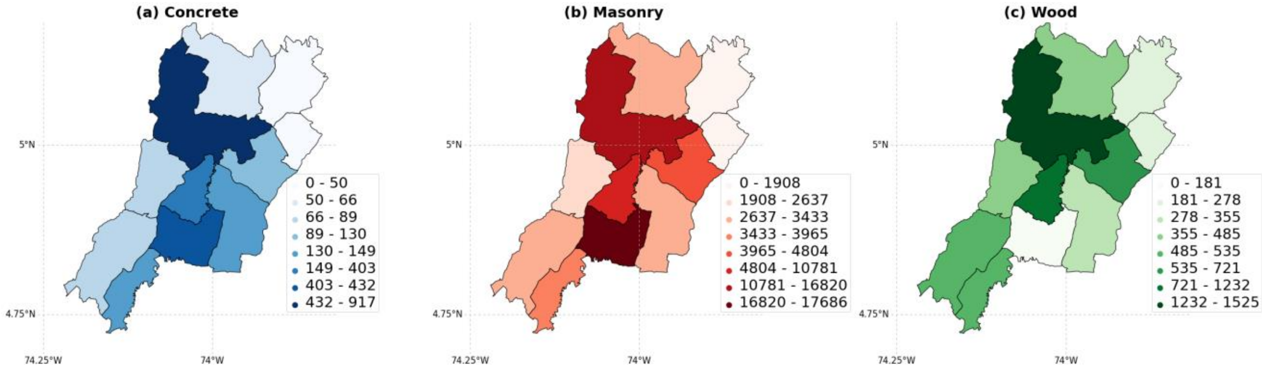


**Figure 7.** Spatial distribution of buildings whose construction materials are (a) concrete, (b) masonry, and (c) wood within each municipality.

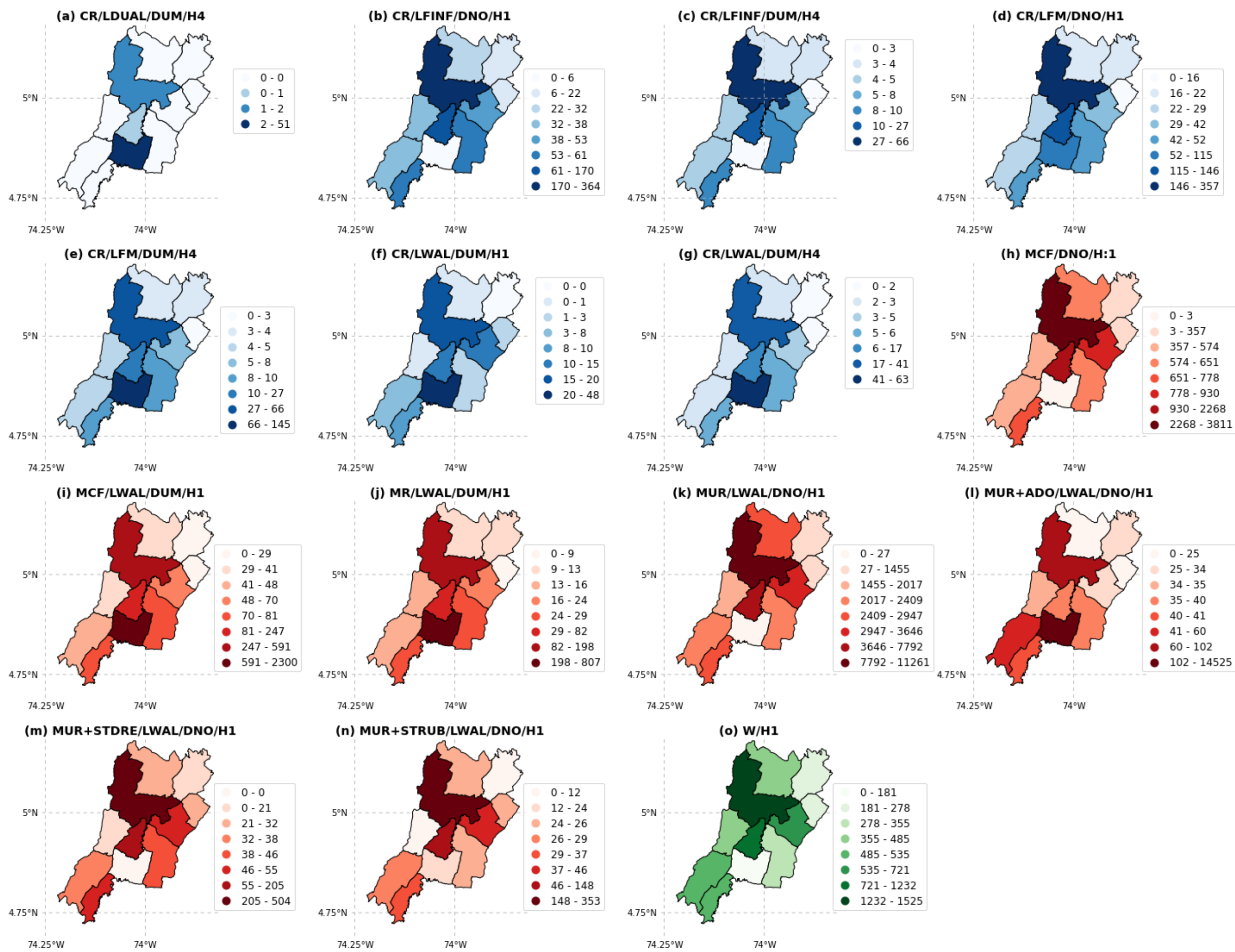


**Figure 8.** Spatial distribution of the building counts per class within each municipality.

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### 3.3. Physical vulnerability of residential building stock to seismic ground shaking

A large part of the building inventory was constructed using unreinforced masonry and with characteristics that make them non-ductile or with low ductility. Therefore, it is necessary to make an appropriate assignation of the fragility curves to evaluate their physical vulnerability to ground-shaking. In the absence of specific curves locally developed for the Sabana Centro province, fragility curves were selected to to represent these structures. Thereafter, a literature review was undertaken to select the fragility functions that most closely resemble the characteristics of the Sabana Centro building inventory. The Physical Vulnerability Suite of the GEM Foundation was taken as the main source for the review (OpenQuake Platform - Vulnerability, 2021). A set of 15 fragility functions was used to represent the probability of exceeding a level of damage conditioned to ground shaking intensity.

These functions are comprised of three sets of curves reported by FEMA (2003), four sets reported by Liao et al. (2006) for Taiwanese building types similar to ones that can be found in the study area, two sets developed by Villar-Vega et al. (2017) for the residential building stock in South America, and a set of fragility curves for reinforced concrete buildings in countries such as Turkey, Italy, and Greece (Pitilakis et al., 2013). In addition, three sets of functions developed by Martins and Silva (2021), and one set developed for wooden Chilean houses were selected (Cabrera et al., 2022). For buildings classified as CR/LWAL/DUM/H4, which are constructed using thin RC walls, the fragility functions developed by Arroyo et al. (2021) were used. These fragility functions are described by a cumulative probability curve with a lognormal distribution, whose statistical parameters are listed in Table 5 for their four damage levels. This set of fragility curves was used to calculate the damage to the buildings included in the exposure model. Based on these curves, vulnerability functions were developed to evaluate the losses in the region.

**Table 5.** Statistical parameters of the fragility curves considered in the study: logarithmic mean (λ) and logarithmic standard deviation (ζ) for four damage levels. The intensity measure (IM) for which each model was developed is listed. The source name represents the authors who developed the functions that were selected in this study to represent the vulnerability of each building type. The loss ratios per used in this study are 2%, 10%, 50%, and 100% for the slight, moderate, extensive and collapse damage respectively.

| Building type | IM | Statistical parameter | Damage level | | | | Source name |
|---|---|---|---|---|---|---|---|
| | | | Slight | Moderate | Extensive | Collapse | |
| CR/LWAL/DUM/H1 | PGA | λ | 0.221 | 0.368 | 0.601 | 1.068 | C2L-Moderate code (FEMA, 2003) |
| | | ζ | 0.157 | 0.262 | 0.428 | 0.759 | |
| CR/LWAL/DUM/H4 | PGA | λ | 0.3 | 0.565 | 0.647 | 0.694 | (Arroyo et al., 2021) |
| | | ζ | 0.087 | 0.376 | 0.468 | 0.506 | |
| CR/LDUAL/DUM/H4 | PGA | λ | 0.184 | 0.258 | 0.552 | 1.056 | PC2M - Moderate code (FEMA, 2003) |
| | | ζ | 0.131 | 0.183 | 0.393 | 0.751 | |
| CR/LFINF/DNO/H1 | PGA | λ | 0.147 | 0.209 | 0.319 | 0.54 | HAZUS C3L-Low code (FEMA, 2003) |
| | | ζ | 0.105 | 0.148 | 0.227 | 0.384 | |
| CR/LFINF/DUM/H4 | PGA | λ | 0.135 | 0.209 | 0.393 | 0.626 | C3M - Low code (FEMA, 2003) |
| | | ζ | 0.096 | 0.148 | 0.279 | 0.445 | |
| CR/LFM/DNO/H1 | PGA | λ | 0.249 | 0.398 | 0.477 | 0.563 | CL |

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| Building type | IM | Statistical parameter | Damage level | | | | Source name |
|---|---|---|---|---|---|---|---|
| | | | Slight | Moderate | Extensive | Collapse | |
| | | ζ | 0.133 | 0.189 | 0.199 | 0.235 | (Liao et al., 2006) |
| CR/LFM/DUM/H4 | PGA | λ | 0.085 | 0.125 | 0.196 | 0.355 | (Pitilakis et al., 2013) |
| | | ζ | 0.028 | 0.058 | 0.084 | 0.139 | |
| MCF/DNO/H1 | PGA | λ | 0.469 | 1.005 | 1.192 | 1.574 | MCF/H:1/DNO (Villar-Vega et al., 2017) |
| | | ζ | 0.148 | 0.33 | 0.384 | 0.597 | |
| MCF/LWAL/DUM/H1 | PGA | λ | 0.638 | 1.39 | 1.546 | 1.917 | MCF/H:1 (Villar-Vega et al., 2017) |
| | | ζ | 0.271 | 0.57 | 0.604 | 0.76 | |
| MR/LWAL/DUM/H1 | PGA | λ | 0.283 | 0.387 | 0.487 | 0.596 | RML (Liao et al., 2006) |
| | | ζ | 0.151 | 0.183 | 0.203 | 0.248 | |
| MUR+ADO/LWAL/DNO/H1 | PGA | λ | 0.193 | 0.288 | 0.368 | 0.466 | URML (Liao et al., 2006) |
| | | ζ | 0.103 | 0.136 | 0.153 | 0.194 | |
| MUR+STDRE/LWAL/DNO/H1 | Sa at 0.3 s | λ | 0.5 | 0.923 | 1.285 | 1.612 | (Martins and Silva, 2021) |
| | | ζ | 0.6 | 0.6 | 0.6 | 0.6 | |
| MUR+STRUB/LWAL/DNO/H1 | Sa at 0.3 s | λ | 0.373 | 0.805 | 1.159 | 1.476 | (Martins and Silva, 2021) |
| | | ζ | 0.595 | 0.595 | 0.595 | 0.595 | |
| MUR/LWAL/DNO/H1 | PGA | λ | 0.193 | 0.288 | 0.368 | 0.466 | URML (Liao et al., 2006) |
| | | ζ | 0.103 | 0.136 | 0.153 | 0.194 | |
| W/H1 | PGA | λ | 0.442 | 1.023 | 1.245 | 1.595 | (Cabrera et al., 2022) |
| | | ζ | 0.338 | 0.268 | 0.239 | 0.194 | |

### 3.4. Social Vulnerability (SV)

To determine the level of social vulnerability (SV) of the municipalities of the Sabana Centro province, this paper estimated a social vulnerability index (SVI) based on the methodology proposed by Cutter et al. (2003). The SVI index aims to identify those municipalities in Sabana Centro whose inhabitants are more vulnerable to an earthquake based on a selection of specific indicators. To define the indicators, five general categories were selected based on the SV component of SARA project[2]: population, economy, infrastructure, education, and health. The population category accounts the female and native population and considers the distribution of people in each municipality (Schmidtlein et al., 2011). Poverty is an important aspect to consider because of its direct association with access to resources, which affects coping with the impacts of disasters (Fatemi et al., 2017). The economy category considered the labor market of the population and the total number of people in poverty. As limited access to public resources makes a population more socially vulnerable to the effects of hazardous events (Cutter et al., 2010), the infrastructure category describes the households that do not have access to basic services (Contreras et al., 2020b). In the case of the education category, it considers the educational level about the ability to understand emergencies and how to recover (Cutter et al., 2003). Not having good access to health facilities and health care increases people's susceptibility to the potential impact of disasters (Fatemi et al., 2017; Contreras et al., 2020b), therefore, this is considered in the health category. Due to the worldwide population consequences of coronavirus disease (COVID-19), a sixth category is

[2] https://sara.openquake.org/development_of_indicators_of_social_vulnerability

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included. This category counts confirmed, active, recovered, and deceased persons in each municipality until December 2021. The number of these COVID-19 cases was taken from Colombia's national institute of health[3]. Based on these categories and the availability of information for the region, a total of 26 indicators were defined and are shown in Table 6. Much of the information used for the indicators is from the national census (DANE, 2018) database, studies such as the multipurpose survey (EM2017), which examined the quality of life of households in Bogotá and surrounding areas[4], and the analysis of the characteristics of the population in Sabana Centro (Sabana Centro Cómo Vamos, 2019).

The min-max normalization was used to standardize the SV indicators from zero to one to estimate the SVI per municipality. Higher scores indicate more socially vulnerable municipalities and lower scores reflect less vulnerable ones. Then, the indicators were integrated by summing them with equal weight, as followed in Contreras et al. (2020c). The resulting SVI index is therefore used to adjust the percentage of economic losses with respect to the costs presented by the building inventory, i.e., multiplying them by (1+SVI) (Carreño et al., 2007).

**Table 6.** Categories and indicators considered to calculate the SVI for each of the municipalities of the study region.

| Categories | Indicators |
|---|---|
| Population | Female population |
| | Native Indigenous population |
| | Age dependence |
| | Total population |
| | Population density (inhabitants/km2) |
| | Number of households |
| | Number of people per household |
| Economy | Population unemployed |
| | Population looking for employment |
| | Population with unsatisfied basic needs |
| | Total population in poverty |
| Infrastructure | Household with no computer and internet |
| | Households with no access to improved water source |
| | Households with no electric energy access |
| | No sewage system |
| Education | Illiteracy rate |
| | Education level completed primary |
| | Education level secondary |
| | Population enrolled in education institution |
| Health | Number of hospital or clinics |
| | Population with no healthcare |
| | Population no registered to national healthcare |
| COVID-19 | Confirmed |
| | Active |
| | Recovered |
| | Deceased |

[3] https://www.ins.gov.co/Noticias/Paginas/coronavirus-filtro.aspx
[4] https://sdpbogota.maps.arcgis.com/apps/MapJournal/index.html?appid=c984e588b0764efbb424ffc2207b5cf6

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## 4. Results

This section presents the results of this study in terms of median building damage and median economic losses for each municipality. First, the Mw 5.95 earthquake scenario results in Chía are introduced to illustrate the methodology. Then, the mean results of the eighteen seismic risk scenarios for Sabana Centro are presented. These eighteen scenarios are defined based on the earthquake events presented in Table 2. The economic losses are adjusted based on the SVI discussed in section 3.4 and are also presented. For this purpose, before presenting the economic losses, the SVI calculation will be presented.

### 4.1. Damage forecast

The predicted damage for the Mw 5.95 earthquake scenario in Chía considered for the region is presented in Table 7.

**Table 7.** Number and percentage of buildings expected to suffer damage in the region after the Mw 5.95 earthquake scenario in Chía.

| Damage state | Number of Buildings | Percentage of buildings |
|---|---|---|
| No damage | 41,262 | 52.08 |
| Slight | 13,370 | 16.88 |
| Moderate | 6335 | 8.00 |
| Extensive | 4747 | 5.99 |
| Collapse | 13,509 | 17.05 |
| Total | 79,222 | 100 |

In the region, 47.92% of the buildings considered in the exposure model are expected to suffer some degree of damage. This result represents 37,961 out of the 79,223 analyzed buildings. Table 7 shows that the type of damage with the highest occurrence is collapse (17.05%), followed by slight (16.88%); moderate (8.00%) and extensive damage (5.99%). Overall, 23.04% might suffer extensive or collapse damage, hence they will not fulfil their life safety functionality. The highest concentration of building collapses in the region is expected for houses constructed of unreinforced masonry (Table 8), mostly involving non-ductile unreinforced masonry walls (49.76%) and non-ductile unreinforced masonry with adobe blocks walls (41.08%). Notably, these two types of buildings account for 90.84% of collapses.

**Table 8.** Expected number and percentage of buildings by class that might collapse as a result of the Mw 5.95 earthquake scenario in Chía.

| Building classes | Number of collapsed buildings | Percentage of collapsed buildings (%) | Direct economic losses (M. USD) | Percentage out of the economic losses (%) |
|---|---|---|---|---|
| CR/LWAL/DUM/H1 | 14 | 0.11 | 5.10 | 0.68 |

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| Building classes | Number of collapsed buildings | Percentage of collapsed buildings (%) | Direct economic losses (M. USD) | Percentage out of the economic losses (%) |
|---|---|---|---|---|
| CR/LDUAL/DUM/H4 | 9 | 0.07 | 14.40 | 1.91 |
| CR/LFINF/DNO/H1 | 168 | 1.24 | 37.68 | 5.00 |
| CR/LFINF/DUM/H4 | 23 | 0.17 | 26.36 | 3.50 |
| CR/LFM/DNO/H1 | 130 | 0.96 | 27.28 | 3.62 |
| CR/LFM/DUM/H4 | 105 | 0.77 | 147.62 | 19.58 |
| CR/LWAL/DUM/H4 | 32 | 0.23 | 25.27 | 3.35 |
| MUR/LWAL/DNO/H1 | 6722 | 49.76 | 174.15 | 23.10 |
| MCF/DNO/H:1 | 189 | 1.40 | 11.34 | 1.50 |
| MCF/LWAL/DUM/H1 | 93 | 0.69 | 40.45 | 5.37 |
| MR/LWAL/DUM/H1 | 277 | 2.05 | 102.75 | 13.63 |
| MUR+ADO/LWAL/DNO/H1 | 5549 | 41.08 | 131.77 | 17.48 |
| MUR+STDRE/LWAL/DNO/H1 | 65 | 0.48 | 2.44 | 0.32 |
| MUR+STRUB/LWAL/DNO/H1 | 62 | 0.46 | 2.18 | 0.29 |
| W/H1 | 71 | 0.52 | 5.08 | 0.67 |
| Total | 13,509 | 100 | 753.87 | 100 |

The number of expected damaged buildings for each municipality due to the Chía Mw 5.95 scenario is presented in Figure 9. It also shows their percentages for each damage state relative to the province's total. These results show that Chía, Cajicá, and Sopó have the highest percentage of collapsed buildings, with 44.12%, 25.95%, and 7.65%, respectively. In this scenario, the least affected municipalities are Cogua and Nemocón, with less than 1% collapse percentages.

The damage calculations were then conducted for all the seismic events presented in Table 2. Table 9 shows the resulting number and percentage of buildings that suffer damage considering the mean of the eighteen seismic risk scenarios. The results show that 49.80% of the province’s buildings are expected to suffer some type of damage. This percentage is concentrated in collapses (17.98%) and slight damage (17.34%). The other 8.18% of buildings suffer moderate damage and 6.29% experience extensive damage. Notably, collapse and extensive damage might be experienced by one out of four buildings in the province. Figure 10 shows that for all the damage states, the highest contribution comes from Chía and Zipaquirá, with collapse percentages higher than 20% and the smallest contribution comes from Gachancipá with 2.15%.

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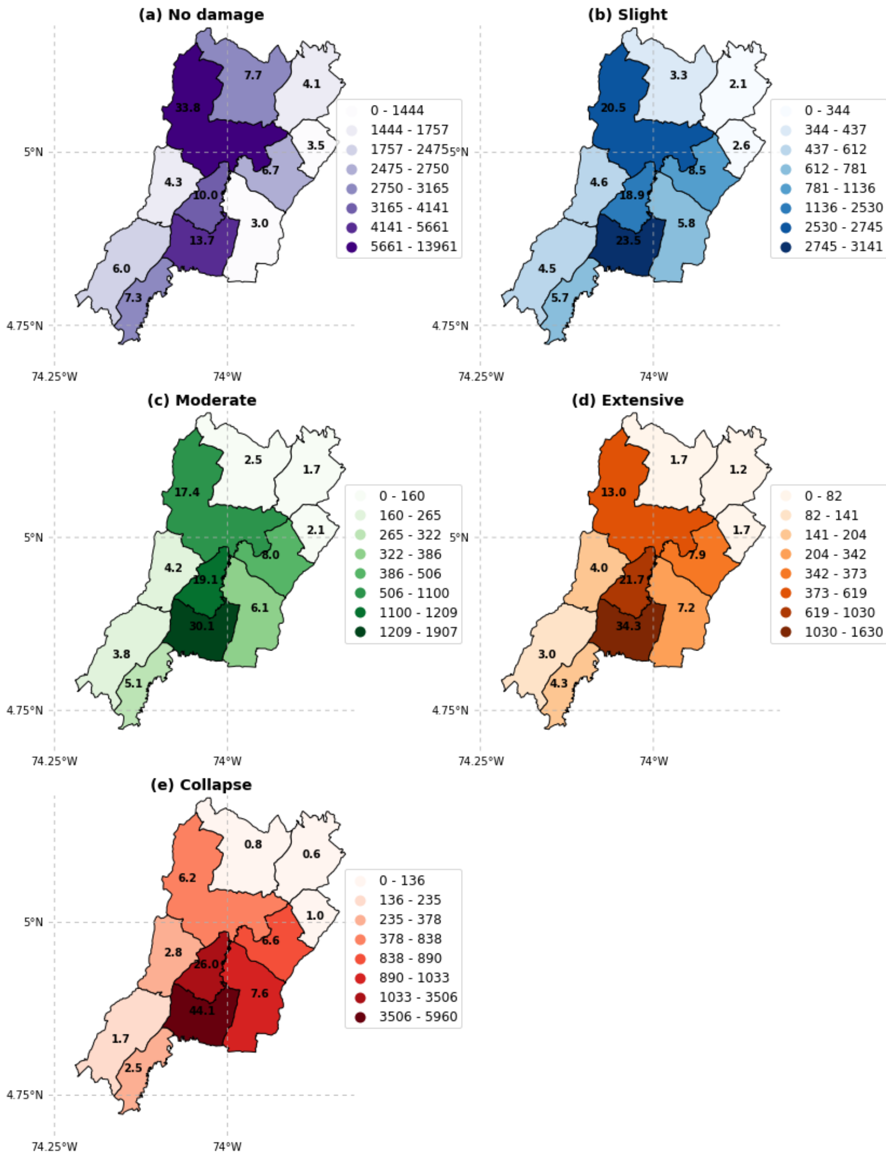


**Figure 9.** Number of buildings expected to experience: (a) no damage, (b) slight, (c) moderate, (d) extensive damage, or (e) collapse as a result of the Mw 5.95 earthquake scenario in Chía. The corresponding percentage values of buildings are presented within each municipality.

**Table 9.** Expected damage in the region considering the average results of the eighteen seismic events presented in Table 2.

| | No damage | Slight | Moderate | Extensive | Collapse |
|---|---|---|---|---|---|
| Number of buildings | 39,774 | 13,738 | 6,484 | 4,981 | 14,247 |
| Percentage (%) | 50.21 | 17.34 | 8.18 | 6.29 | 17.98 |

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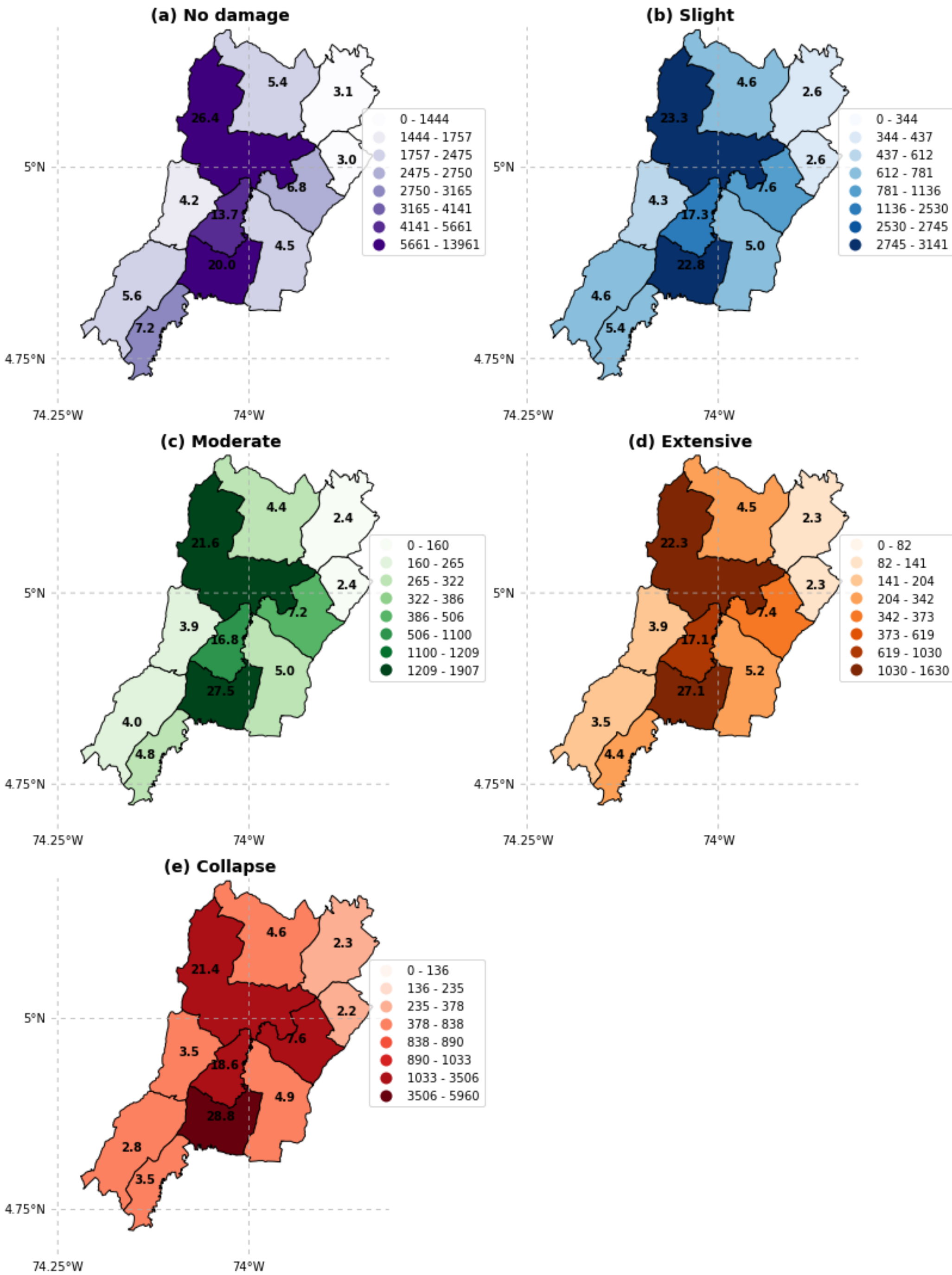


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**Figure 10.** Mean number of buildings expected to experience either (a) no damage, (b) slight, (c) moderate, (d) extensive damage, or (e) collapse as a result of the 18 earthquakes scenarios presented in Table 2. The percentage values of buildings experiencing this level of damage are presented within each municipality.

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### 4.2. **Social Vulnerability Index (SVI)**

According to the methodology presented in section 3.4, the SVI is calculated and shown in Table 10.

**Table 10.** SVI for the municipalities of the Sabana Centro province.

| | **Municipalities** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Categories | Cajicá | Chía | Cogua | Cota | Gachancipá | Nemocón | Sopó | Tabio | Tenjo | Tocancipá | Zipaquirá |
| Population | 0.46 | 0.51 | 0.47 | 0.42 | 0.35 | 0.39 | 0.29 | 0.32 | 0.14 | 0.24 | 0.66 |
| Economy | 0.42 | 0.37 | 0.39 | 0.44 | 0.66 | 0.61 | 0.32 | 0.22 | 0.59 | 0.75 | 0.39 |
| Infrastructure | 0.23 | 0.16 | 0.43 | 0.24 | 0.17 | 0.52 | 0.10 | 0.27 | 0.33 | 0.64 | 0.004 |
| Education | 0.07 | 0.08 | 0.91 | 0.26 | 0.48 | 0.76 | 0.25 | 0.22 | 0.37 | 0.47 | 0.24 |
| Health | 0.55 | 0.46 | 0.62 | 0.59 | 0.68 | 0.89 | 0.68 | 0.44 | 0.57 | 0.75 | 0.68 |
| COVID-19 | 0.36 | 0.23 | 0.76 | 0.09 | 0.00 | 0.26 | 0.13 | 0.64 | 0.25 | 0.81 | 0.27 |
| Index | 0.35 | 0.30 | 0.60 | 0.34 | 0.39 | 0.57 | 0.30 | 0.35 | 0.37 | 0.61 | 0.37 |

The results show that Tocancipá is the municipality with the highest SV, since it shows the highest values in three out of the six categories evaluated: economy, infrastructure, and COVID-19 cases, with indices of 0.75, 0.64, and 0.81, respectively. In the population category, the most vulnerable municipality is Zipaquirá, with an index of 0.66 and the least vulnerable is Tenjo, with 0.14. In terms of education, the municipality of Nemocón is the most vulnerable with an index of 0.76, unlike Cajicá and Chía which have indices of 0.07 and 0.08, respectively. The health category shows higher vulnerability indices than the other categories for most municipalities, varying between 0.46 for Chía and 0.89 for Nemocón. Evaluating all of the categories, it was found that Chía and Sopó are the least vulnerable, with each having an index of 0.30.

### 4.3. Economic losses from the Mw 5.95 Chía earthquake scenario

The direct total economic loss arising from the considered Mw 5.95 Chía scenario is US$753 million, which represents 17.61% of the total replacement cost of the building inventory. The municipalities that contribute the most to these losses are Chía, with 51.66% and Cajicá, with 22.18%, as shown in Figure 11a. This result was expected since these municipalities' urban growth is high compared to the other municipalities. The smallest contribution comes from Cogua and Nemocón, with 0.47% each. Overall, in the case of this Mw 5.95 earthquake scenario, the direct economic loss in terms of replacement costs would be approximately 15 % of the region's GDP.

The economic losses for each municipality are presented in Table 11. Cajicá is the one with the highest percentage of losses, with 29.46% of the replacement costs. Other municipalities for which high economic losses are expected are Sopó and Chía, with 28.95% and 26.94%, respectively. The municipalities with the lowest losses are Nemocón (3.97%) and Cogua (2.56%). The percentage of economic losses concerning the building types relative to the total losses in the region are shown in Table 8. Forty percent of losses come from unreinforced masonry buildings (MUR/LWAL/DNO/H1 and

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MUR+ADO/LWAL/DNO/H1). This result is expected because this building type has a high seismic vulnerability, while the lowest contribution would come from wooden houses, with less than 1%.

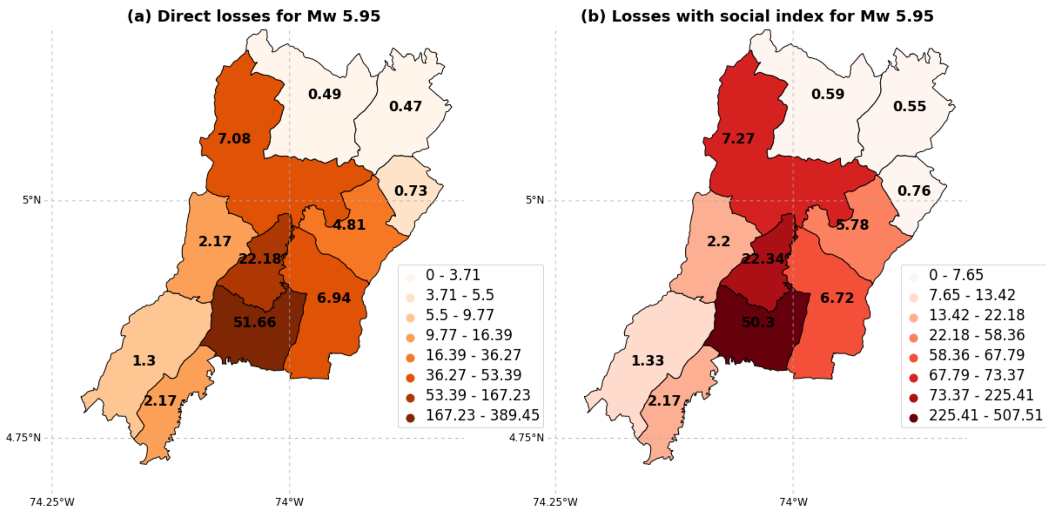


**Figure 11. (a)** Expected losses in millions of US dollars for the region as a result of the Mw 5.95 earthquake scenario and (b) the expected losses after considering the SVI. The percentage of losses with respect to the total is presented within the municipalities.

**Table 11.** Economic losses for the region as a result of the considered Mw 5.95 earthquake scenario. Economic losses with SV consider the percentage of losses with respect to the total losses per municipality and are adjusted using the SVI. Consequently, the losses in M.USD are adjusted.

| Municipality | Cost of building Inventory (USD) | Direct economic losses | | | Economic losses with social vulnerability | |
|---|---|---|---|---|---|---|
| | | Losses (USD Million) | Losses with respect of the total (%) | Percentage of losses (%) | Losses + SVI (%) | Losses after considering the SVI (M. USD) |
| Cajicá | 567.67 | 167.23 | 22.18 | 29.46 | 39.71 | 225.41 |
| Chía | 1445.41 | 389.45 | 51.66 | 26.94 | 35.11 | 507.51 |
| Cogua | 145.01 | 3.71 | 0.49 | 2.56 | 4.08 | 5.92 |
| Cota | 208.29 | 16.33 | 2.17 | 7.84 | 10.50 | 21.88 |
| Gachancipá | 85.03 | 5.50 | 0.73 | 6.47 | 8.99 | 7.65 |
| Nemocón | 88.70 | 3.52 | 0.47 | 3.97 | 6.24 | 5.53 |
| Sopó | 180.70 | 52.32 | 6.94 | 28.95 | 37.51 | 67.79 |
| Tabio | 131.86 | 16.39 | 2.17 | 12.43 | 16.82 | 22.18 |
| Tenjo | 150.00 | 9.77 | 1.30 | 6.51 | 8.95 | 13.42 |
| Tocancipá | 225.94 | 36.27 | 4.81 | 16.05 | 25.83 | 58.36 |
| Zipaquirá | 1053.23 | 53.39 | 7.08 | 5.07 | 6.97 | 73.37 |
| Total | 4281.85 | 753.87 | 100 | | | 1009.02 |

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Figure 11(b) shows the adjusted economic losses by municipality, and includes SV. After considering the SV in the region, the economic losses increase by 34%, from $753 to US$1009.02 million. The municipality that would have the highest economic losses is Cajicá (29.46% of the building replacement cost), with US$167.23 million. When the SV is included, its potential economic losses increase to US$225.41 million (39.71% of the building replacement cost). In the case of Tocancipá, the most socially vulnerable municipality, the losses were initially US$36.27 million, and increase to US$58.36 million when the SVI is accounted for.

### 4.4 Mean direct economic losses for the earthquake scenarios

The seismic ground motion fields expected for each earthquake scenario listed in Table 2 were simulated 1,000 times to account for their aleatoric uncertainty as advised by Silva (2016), making use of the OQ Engine. The physical vulnerability was calculated in a similar manner as for the Mw 5.95 earthquake scenario. Figure 12 shows the loss exceedance curves that describe the probability of exceeding a given percent of economic losses for each earthquake scenario.

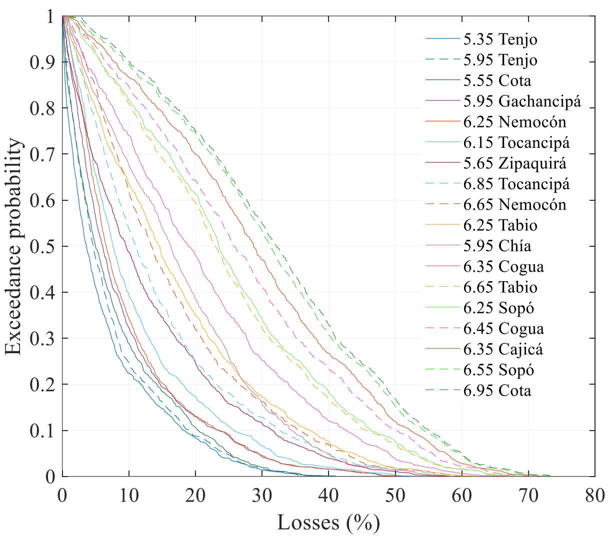


**Figure 12.** Loss-exceedance curves (LEC) as a function of percentage of economic losses in the region for the 18 earthquake scenarios considered (Table 2) whose ground motion fields were simulated 1000 times. The legend is sorted according to the line position in the figure from left to right.

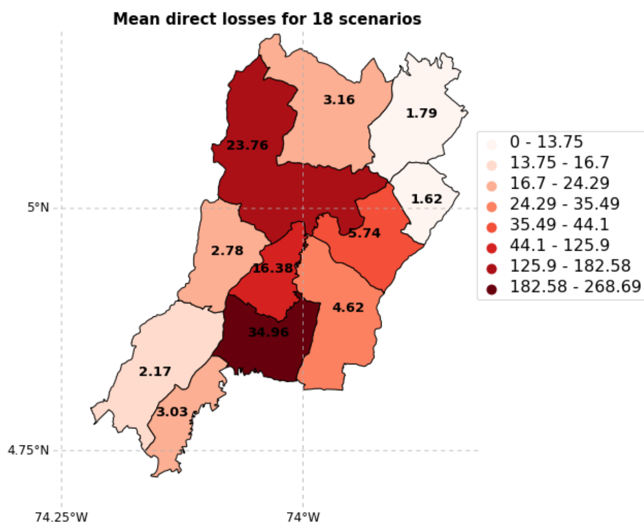


**Figure 13.** Mean direct losses after considering the 18 scenarios (Table 2). Within the municipalities, the mean percentage of losses is presented with respect to the total expected losses in the region.

The economic losses experienced by a province due to an earthquake depends on the event's epicenter as it is depicted in Figure 12 . This is due to the uneven distribution of the building stock, which is mostly concentrated in three municipalities. Among the simulated scenarios, the most significant economic losses might occur with the scenario that considers an

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earthquake of Mw 6.95 in Cota and the smallest with the simulation of the earthquake of Mw 5.35 in Tenjo. For example, the probability that economic losses exceed 20% in the "6.95 Cota" scenario is 75%, while for the scenario "5.35 Tenjo", the probability is 8%. The economic losses and their respective percentage in the region are presented in Figure 13. The economic losses in the region are US $768.59 million, representing 18% of the total replacement cost. In this case, the municipalities that contribute the most to this percentage of losses are Chía, Zipaquirá, and Cajicá, with 34.96%, 23.76%, and 16.38%, respectively. These municipalities have the highest number of buildings and inhabitants in the region. Including SV sees the total losses increasing by 6.5%. Given this increase, the total economic losses in the Sabana Centro province are US $1048.43 million. The specific direct economic losses and the effect of including SV for each municipality are shown in Table 12.

**Table 12.** Expected Economic Losses in the region considering the mean results of the eighteen seismic events. Economic losses when including SV consider the percentage of losses with respect to the total losses per municipality and are adjusted with the SVI.

| Municipality | Cost of building Inventory | Direct economic losses | | | Economic losses with SV | |
|---|---|---|---|---|---|---|
| | | Losses | Losses with respect of the total | Percentage of losses | Losses + SVI | Losses after considering the SVI |
| | USD | USD Million | % | % | % | M. USD |
| Cajicá | 567.67 | 125.90 | 16.38 | 22.18 | 29.89 | 169.69 |
| Chía | 1445.41 | 268.69 | 34.96 | 18.59 | 24.22 | 350.15 |
| Cogua | 145.01 | 24.29 | 3.16 | 16.75 | 26.74 | 38.77 |
| Cota | 208.29 | 23.31 | 3.03 | 11.19 | 14.99 | 31.22 |
| Gachancipá | 85.03 | 12.43 | 1.62 | 14.62 | 20.32 | 17.27 |
| Nemocón | 88.7 | 13.75 | 1.79 | 15.50 | 24.35 | 21.60 |
| Sopó | 180.7 | 35.49 | 4.62 | 19.64 | 25.45 | 45.99 |
| Tabio | 131.86 | 21.36 | 2.78 | 16.20 | 21.93 | 28.91 |
| Tenjo | 150 | 16.70 | 2.17 | 11.13 | 15.29 | 22.94 |
| Tocancipá | 225.94 | 44.10 | 5.74 | 19.52 | 31.41 | 70.97 |
| Zipaquirá | 1053.23 | 182.58 | 23.76 | 17.34 | 23.82 | 250.92 |
| Total | 4281.85 | 768.59 | 100.00 | | | 1048.43 |

## 5. Discussion

### 5.1. Damage and losses

The findings presented in this work show that the Sabana Centro province is exposed to a considerable level of seismic risk. The simulations of eighteen seismic scenarios with a return period of 475 years show that half of the building stock will experience some degree of damage. Worryingly, one out of four buildings will experience extensive damage or collapse. This situation stems from the fact that almost two-thirds of the houses in the province are constructed using unreinforced masonry, which is a structural system with a high level of seismic vulnerability.

In terms of economic losses, the mean expected cost of a design level earthquake in the province is 15% of its GDP, which accounts for US$ 768.59 million, almost 18% of the replacement cost of the building inventory. This result only accounts for the cost of physical damage of the building stock, however, and does not represent all of the potential impacts.

**5.2. Effects of social vulnerability (SV)**

Sabana Centro is a province with a significant level of SV representing many areas in Colombia and other countries in South America, with essential deficiencies in areas like health and education. The integration of SV with the economic losses increases them to 21% of the GDP, representing approximately 1 billion US-dollars. The results of this study show that including SV is important in risk analysis, as it allows one to go beyond only considering economic loss assessments with respect to physical damage. Despite the SVI being straightforward to quantify SV as an index, two refinements are needed for its improved integration within seismic risk analysis. First, as not all social aspects exert equal effect after an earthquake, it is necessary to develop a weighted approach to best estimate a more realistic SVI for earthquake events. A second improvement required is to devise a better way of estimating the economic impact of social vulnerability. One potential approach is to generate a database of past earthquakes with different consequences that include the economic costs. Developing a platform for cloud sourcing this information could significantly help this task (Contreras et al., 2021).

**5.3. Caveats and limitations**

There are several limitations that should be addressed in future studies. One of them involves the selection of the building's seismic fragility functions. Recent research has demonstrated that assumptions about several input parameters used in physical seismic vulnerability significantly influence risk assessment in urban areas (Hoyos and Hernández, 2021). Moreover, because we used various fragility functions that were developed adopting diverse damage criteria to define their limit states, we can encounter the situation where there might not be complete equivalences between the same damage states. For instance, Villar-Vega et al. (2017) followed the proposal by Lagomarsino and Giovinazzi (2006) as a function of the yielding and ultimate spectral displacements, whilst the HAZUS typologies proposed a building class-dependent parametrization based on inter-story drift ratios to define structural damage levels. Awareness of these differences is important, but the detailed study of their related uncertainties is beyond the scope of this study.

Furthermore, despite Colombia having a seismic design code with many similarities to the US code (Arroyo et al., 2019), most buildings in the region were designed and built without engineering supervision, hence, making them vulnerable to seismic events. For instance, in the case of masonry buildings, the fragility functions used in this study were developed for standard constructions, disregarding the presence of structural irregularities. Hence, they underestimate the physical vulnerability of these structures to ground shaking. Thus, the damage and losses estimates presented in this study should be considered as a lower bound. One way to improve this is by developing seismic fragility functions for non-engineered buildings that properly represent the peculiarities of this type of construction.

It is important to mention that the exposure model for residential buildings developed in this study considered two types of exposure modelling approaches. On the one hand, the census-based part is a top-down approach from aggregated data. In this step, the number of buildings increases proportionally to each municipality's population. This intuitive assumption would benefit from further study through more refined approaches (e.g., Calderón and Silva, 2021). On the other hand, the rapid remote surveys constitute a bottom-up approach. Although the latter allowed an assessment of the validity of the assumed building classes, both approaches were not fully integrated through a probabilistic approach (Pittore et al., 2020). Although this method requires more computational efforts, it is worth exploring in future studies.

Another aspect that was not explicitly addressed in this study was the consideration of spatial cross-correlation models in modelling the ground motion fields. Several studies (e.g., Weatherill et al., 2015) have demonstrated the relevance of such models in seismic risk assessment for building portfolios when sets of fragility functions that consider several IM are implemented. Although when such models are accommodated, the loss outcomes typically show a greater dispersion (and more likely to give extreme values), while when such models are disregarded, the mean loss values forecasted have been observed to be practically the same as for the cases when a spatial correlation model was used (e.g., Michel et al., 2017; Gomez Zapata et al, 2021). Therefore, the results presented in this study are still informative, but once again, we remark they should be treated as lower bounds for the considered risk scenarios.

Furthermore, due to the proximity of the study area to the Usme fault, near-fault effects might be expected. Hence, the study of possible directivity effects might be relevant for future studies. The evaluation of this feature has been shown to be relevant in both seismic ground motion (Türker et al., 2022) and earthquake loss models (Gentile and Galasso, 2021). Therefore, a better understanding of their role in risk scenarios will benefit the outlined results.

Another point is that this study did not consider human casualties. These were not included due to the lack of accurate information about housing occupation, since in this province, it is expected that more than one family share one dwelling. Notwithstanding, the results of physical damage assessment suggest that almost 25% of buildings will have a seismic performance below the life safety level. The limited number and quality conditions of hospitals and health care facilities in the province would further exacerbate the potential impact of an earthquake on the population.

## 6. Conclusions and future work

This paper presented the results of a seismic risk assessment for the Sabana Centro province in Colombia, which also accounted for the effects of SV. Eighteen earthquake scenarios with a return period of 475 years were selected from a hazard disaggregation study. Each scenario was simulated 1000 times using the OQ Engine to calculate the physical damage and economic losses. These were adjusted based on a SVI that included the effects of the ongoing COVID-19 pandemic. The key findings from the results of this study are as follows:

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- Sabana Centro is a region in a high seismic risk. Eighteen percent of the buildings would collapse and 6.29% would experience extensive damage considering the average of the eighteen scenarios. This scenario represents around one out of four buildings that will not perform at the life safety level and which will require replacement after the earthquake. The damage is concentrated on unreinforced masonry houses, which account for approximately two-thirds of the building stock.
- The mean expected economic losses are US$ 768.59 million, which represents 18% of the replacement cost of the building inventory and 15% of the region's GDP.
- Incorporating the SV plays an important role in loss estimation. The adjusted economic losses for the region are US$ 1048.43 million, a 36.4% increase compared to the losses from building damage. The most significant contribution (75.1%) comes from the municipalities of Chía, Zipaquirá, and Cajicá, in which are concentrated almost two thirds of the region's building stock and population.

Overall, these results show that a seismic event corresponding to the design earthquake (475 years return period) would cause significant damage to the infrastructure and severe economic and social losses. Given the prevalence of unreinforced masonry houses, an effective mitigation strategy for this region is to develop seismic retrofitting programs for these buildings, especially for municipalities with higher population growth, which contribute the most to damage and losses.

The development of this study revealed two prominent areas for future research. The first is developing a robust framework to incorporate SV into the loss estimations, with a strong basis on how each social category should be weighted. Second, despite a careful selection of the fragility functions based on literature reviews, the estimations of this study can be further refined by using a more complete dataset with fragility functions developed explicitly for Colombia, particularly for older masonry houses.

*Code and data availability.* The building surveys have been made available in the open repository: Arroyo et al. (2022).

*Competing interests.* The authors declare that they have no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

*Funding.* The first two authors received funding from the research division of the Universidad de La Sabana, internal grant ING-260-2020. Tamara Cabrera was funded by the Research Center for Integrated Disaster Risk Management (CIGIDEN), ANID/FONDAP/15110017. The contribution from Diana Contreras was funded by the Engineering and Physical Sciences Research Council (EPSRC) [Grant No.: EP/P025641/1]. Juan Camilo Gómez Zapata received financial support for the research from the RIESGOS 2.0 project, funded by the German Federal Ministry of Education and Research (BMBF) Grant No. 03G0905A-H, as part of the funding program CLIENT II – International Partnerships for Sustainable Innovations. This same project provided funds for its publication.

*Acknowledgements.* The authors would like to thank the Colombian Geological Survey for their support in the characterization of the hazard for the study area. We thank the Universidad de la Sabana, especially the work team of "Sabana Centro Cómo Vamos" for the data made available for the social vulnerability assessment. Our gratitude also goes to Fabrice Cotton for the advice during the elaboration of this study. We also thank Kevin Fleming for the careful proofreading.

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