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INTEGRATED ASSESSMENT OF EARTHQUAKE RISK IN QUITO, ECUADOR USING OPENQUAKE

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Abstract
The city of Quito (Ecuador) reflects the complexity of earthquake risk in capital cities of South America: a substantial sized population, a considerable seismic hazard (e.g., peak ground acceleration above 0.4 g for a return period of 475 years) and low-income settlements that increase the potential for adverse impacts. In this sense, a holistic assessment of the scale and consequences of earthquake impacts in cities such as Quito has become a focal point of the South America Risk Assessment (SARA) project. This paper presents an assessment of the potential adverse impacts from earthquakes within Quito in an integrated manner by moving beyond the simple estimation of physical damage, to the assessment of direct losses coupled the social vulnerability of the city’s communities.

For the integrated analysis of earthquake risk, direct damages were estimated accomplished via: (i) the selection of earthquake ruptures and assessment of ground motion fields considering recent and publicly available seismic hazard studies; (ii) the development of exposure models using information from recent national census and cadastral databases; (iii) the generation of fragility functions of common residential building types; and (iv) the calculation of collapse maps for the selected scenarios.

The social vulnerability of Quito was measured using composite indicators in order to identify factors that may contribute to the potential for loss within communities such as the habitation of fragile settlements. To derive an estimate of risk from a comprehensive perspective, a priority index was evaluated via the combination of the social vulnerability index with the direct risk estimates. These evaluations were conducted at census subdivisions in order to prioritize areas where the potential for damage is highest and where populations are least likely to recover. The results indicate a differential pattern of integrated risk within the city that is the result of geography and location, the physical vulnerability of dwellings, and the pre-existing social conditions of the people living there.

Keywords: Integrated risk assessment, Earthquake scenarios, Social vulnerability

1 Introduction

Quito (the capital city of Ecuador) is located in the Andean Cordillera where shallow and potentially destructive earthquakes can occur [1]. Historically, various earthquakes of considerable magnitude have affected the city. The damaging events that occurred along the Quito Fault System in 1990 (M_w 5.3) and 2014 (M_w 5.1) provides one example [2]. In addition, the city experiences the effects of damaging earthquakes that occur at considerable distances. Examples of the latter include the 1797 earthquake that occurred about 150 km to the south of Quito [3] and the recent event of Muisne (April 16th, 2016; M_w 7.8) with an epicenter about 190 km to the north-west of the city that caused minor landslides, power shutdowns and structural collapses [4].

Quito, as other capital cities of the Andean Region, faces a complex earthquake risk problem with a large population (2,239,191 inhabitants according to the 2010 census) that is exposed to a high seismic hazard (peak ground acceleration above 0.4 g for a return period of 475 years). A multitude of areas within the city contain low-income settlements characterized by informal buildings and deteriorated tenements. Regarding vulnerable groups within these settlements, the percentage of the elderly (>65 years) and the young (<18 years) is around 41% of the total population; the unemployment rate is considered low (near 3.6%) and more than a third of the population (36.4%) is below the poverty line [5]. Increases in vulnerable populations have resulted in the increase of high-density developments of non-engineered buildings that are located in steep mountain slopes [3]. This complex problem has propelled the development of comprehensive studies concerning the seismic risk of Quito.

In 1995, “The Quito Earthquake Risk Management Project” was developed with the lead of the local government and the participation of various national and international institutions. In this study, damages to buildings, roads, elements of the water supply system, power network and sewers were estimated for three selected earthquakes (i) an inland earthquake of magnitude 7.3 and epicentral distance of 80 km from Quito; (ii) a coastal earthquake of magnitude 8.4 and epicentral distance of 200 km and (iii) a local earthquake of magnitude 6.5 and epicentral distance of 25 km [3,6,7]. In recent studies [8], an exceedance probability curve was calculated considering seismic events for residential, commercial and industrial buildings in Quito.

As a contribution to the evaluation of earthquake risk in the city, the GEM Foundation led the South America integrated Risk Assessment (SARA) project, which promoted the analysis of damages of residential buildings for specific scenarios. This paper presents the results of an end-to-end scenario damage calculation for Quito that was conducted as just one SARA deliverable. Here, a high-resolution evaluation of physical risk for the city was combined with indicators of social vulnerability (defined here as characteristics within social systems that create the potential for loss) in order to evaluate the city’s risk from an integrated perspective. To this end, this analysis is relevant to locate and prioritize communities where high damages are expected to occur coupled with populations that have limited capacities for conducting earthquake risk mitigation and recovery activities.

2 Estimation of earthquake damage for the residential building stock

An integrated assessment of earthquake risk requires a number of steps. As a first step, the number of collapsed dwellings in urban areas of Quito was calculated using the Scenario Damage Calculator of the OpenQuake-engine [9]. This calculator requires the definition of a finite rupture model, an exposure model, and a fragility model. According to the rupture model, realizations of ground motion fields (GMFs) are generated, taking into consideration variability from ground motion prediction equations (GMPE). For each realization, damage fractions were estimated for every asset in the exposure model in a manner in which each asset is characterized by a building class and corresponding fragility function. A description of the inputs used for the damage assessment is presented in the following sections. For additional details concerning the calculation workflow readers are referred to [10].

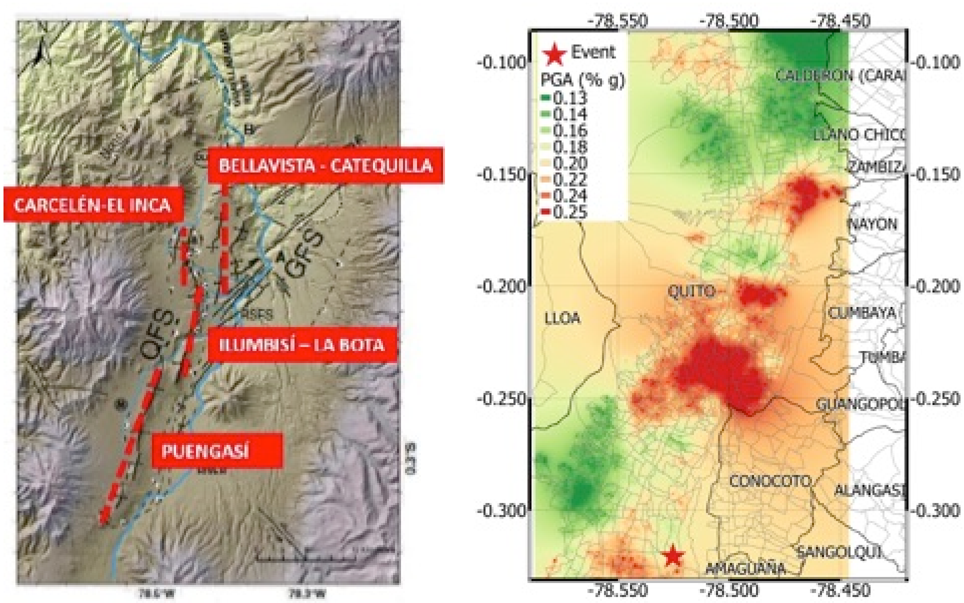
2.1 Rupture model

In order to define the rupture model, the type of events and magnitudes that could affect the city were considered. As described in [11], Quito can be affected by three types of earthquakes: events of the subduction zone, events from the Andes Cordillera and events occurring on faults close to the city. Table 1 delineates zones, distances and magnitudes of such events:

Table 1 – Types of earthquakes that can affect the city of Quito

Zone	Distance	Magnitude M_w
Subduction	> 200 km.	>8
Andes Cordillera	~ 80 km	7.0 – 7.5
Quito Fault System	< 20 km	6.0 -7.0

As discussed in [12], a considerable portion of Quito was constructed over active blind reverse faults. In [13] recurrence time, rupture area and maximum magnitude of events of segments of the Quito Fault System (QFS) were calculated. The maximum magnitudes obtained varies between 6.4 M_w, for the segment of Puengasí and 5.7 M_w for the segment of Carcelén El Inca (see Fig 1a). In order to contribute to the assessment of damages due to earthquakes occurring on the QFS, a rupture in the segment of Puengasí was selected and defined as follows: hypocenter at latitude = -0.3206 longitude = -78.5254, depth 18 km, rupture length of 22 km and Magnitude 6.4 M_w. Using the OpenQuake-engine, realizations of GMFs were generated. An example of one realization is presented in Fig 1.b. For this realization, it is observable locations with PGA around 0.25g.



(a) Source: [12,14] (b)

Fig. 1 – (a) Segments of the Quito Fault System; (b) Example of one realization of the ground motion field for the rupture selected for the analysis

2.2 Exposure model of residential buildings

An exposure model of residential buildings in urban areas of Quito was developed and includes estimates of number of dwellings by building classes for each census subdivision (4039 sectors). This model was derived using dwelling counts by type of housing unit, material of roof and material of walls from the Ecuador National Census of 2010. In order to classify dwellings into building classes, 4 zones were established from the urban regulation plan of the city: (i) low density; (ii) medium density; (iii) high density and (iv) rural areas. For each zone a mapping scheme (i.e. relation between the attributes in the national census data and a set of building classes) was established taking into account the aforementioned variables of dwellings, general distributions of building classes presented in [7] and the urban mapping scheme used in the SARA project for the creation of a national exposure model for Ecuador [15].

In addition, using cadastral databases provided by the Metropolitan Directorate of Risk Management of Quito, percentages of buildings by ranges of stories were calculated for each census subdivision. Such percentages were applied in order to distribute dwellings by number of stories. Table 2 presents the number and percentage of dwellings for the most representative structural types in Quito. From Table 2 it is possible to observe that the most frequent building classes are confined masonry buildings and those that are reinforced concrete infilled flat slab. Fig. 2 presents examples of the spatial distribution of dwellings of adobe and reinforced concrete flat slabs.

Table 2 – Number and percentage of dwellings by building types

Building type	Dwellings	
	Number	%
Adobe walls/ 1-2 stories	12,790	3%
Adobe walls/ 3-5 stories	8,549	2%
Wooden structures	8	0%
Unreinforced masonry/ 1-2 stories	22,944	5%
Unreinforced masonry/ 3-5 stories	10,835	2%
Confined masonry/ 1-2 stories non ductile	59,732	13%
Confined masonry/ 3-5 stories non ductile	38,080	8%
Confined masonry/ 1-2 stories/ductile	13,933	3%
Confined masonry/ 3-5 stories/ductile	11,251	2%
Reinforced concrete frames/ 1-2 stories/ non ductile	19,026	4%
Reinforced concrete frames/ 3-5 stories/ non ductile	11,190	2%
Reinforced concrete infilled flat slab/ 1-2 stories/ non ductile	97,367	21%
Reinforced concrete infilled flat slab/ 3-5 stories/ non ductile	63,215	14%
Reinforced concrete infilled flat slab/ 6-10 stories/ non ductile	4,703	1%
Reinforced concrete infilled flat slab/ 1-2 stories/ ductile	5,950	1%
Reinforced concrete infilled flat slab/ 3-5 stories/ ductile	4,060	1%
Reinforced concrete infilled frame/1-2 stories	41,442	9%
Reinforced concrete infilled frame/3-5 stories	27,387	6%

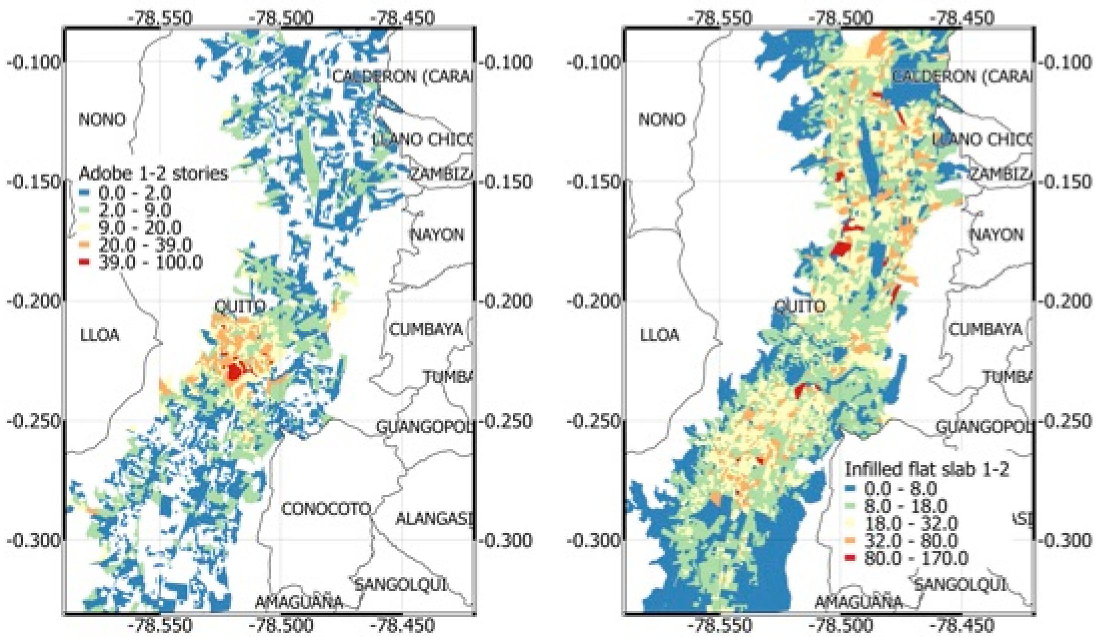
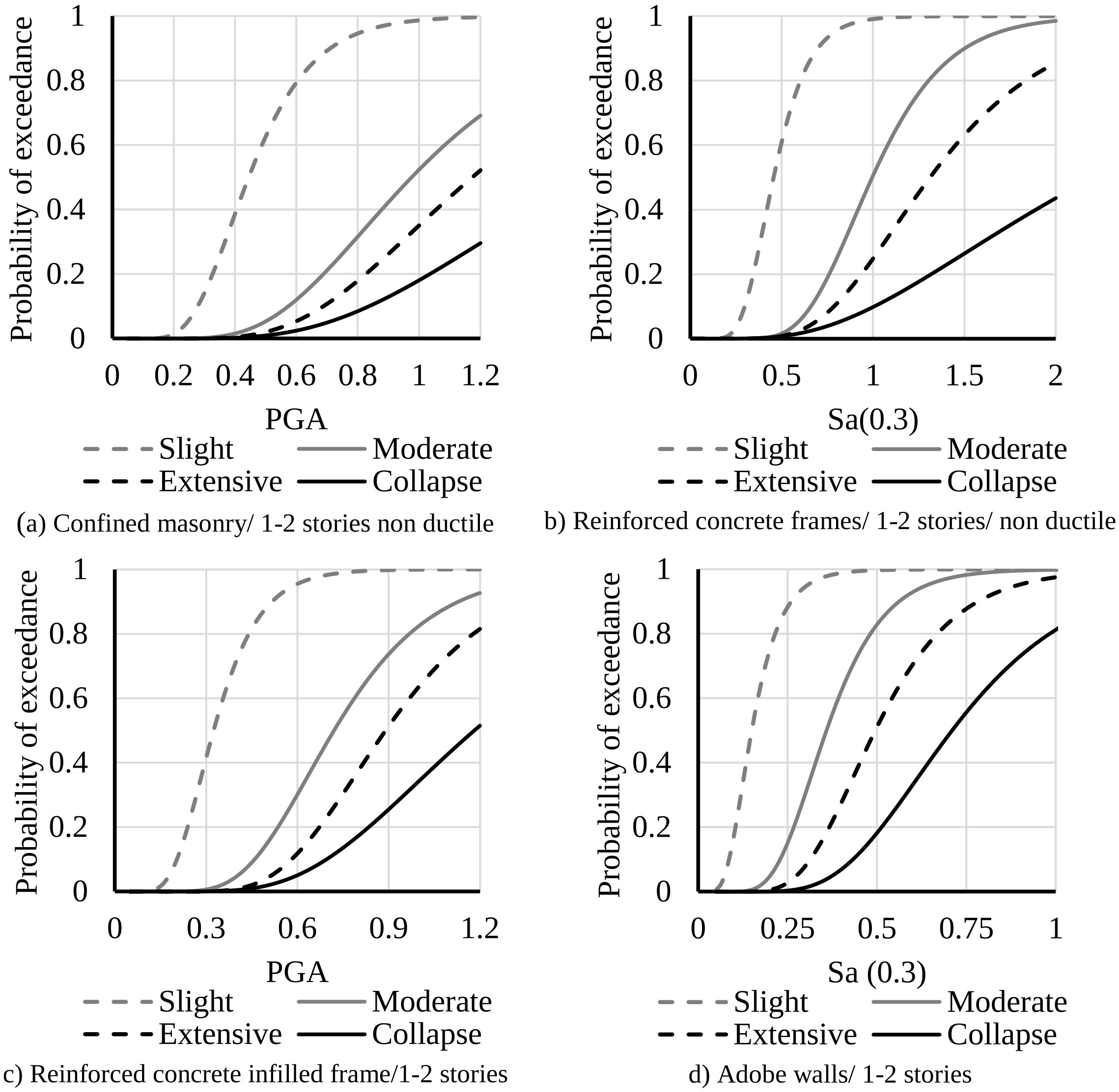


Fig. 2 – Geographical distribution of: (a) Number of 1-2 stories adobe dwellings; (b) 1-2 stories reinforced concrete infilled flat slabs

2.3 Physical fragility of building types

Within the SARA project, fragility functions of common residential building types in South America were developed using nonlinear dynamic analyses that consider a wide spectrum of sources of uncertainty such as the building-to-building or the record-to record variability. The methodology and main results from these activities are thoroughly described in [16]. Fig. 3 presents examples of the fragility functions used for the calculation of damages.

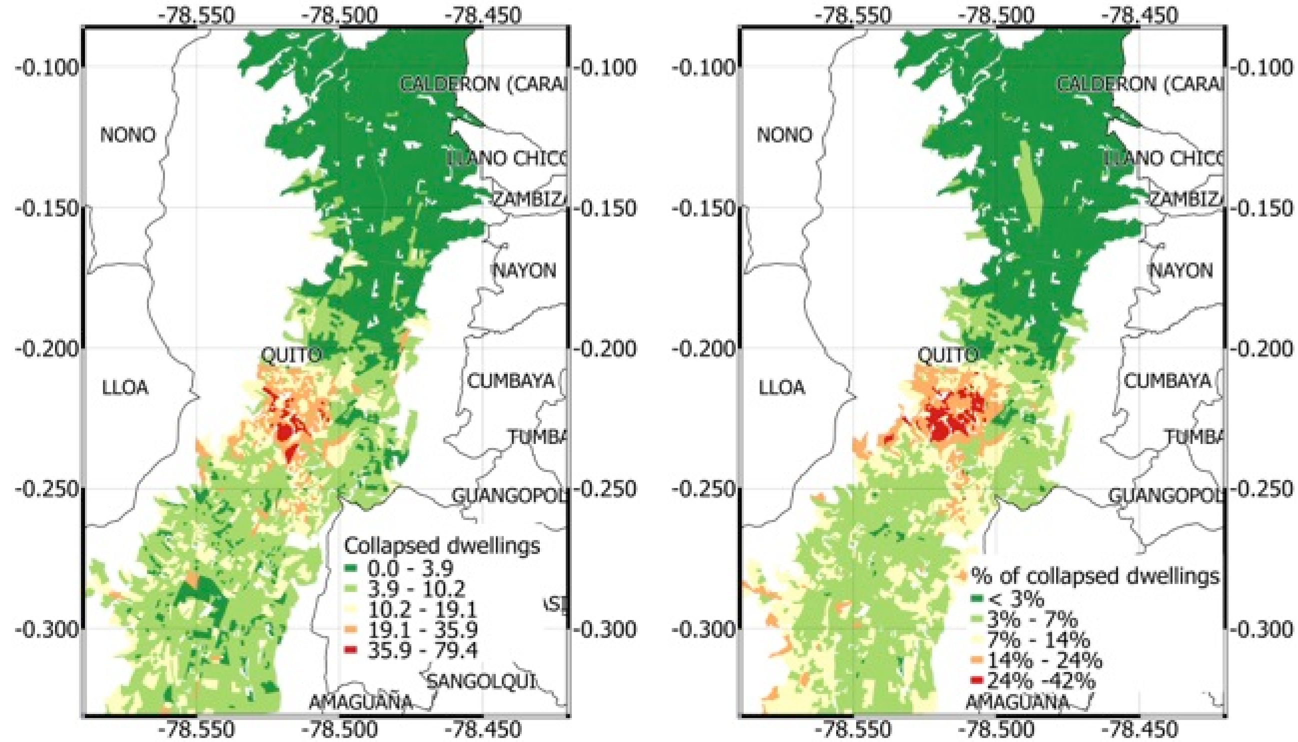


(a) Confined masonry/ 1-2 stories non ductile
b) Reinforced concrete frames/ 1-2 stories/ non ductile
c) Reinforced concrete infilled frame/1-2 stories
d) Adobe walls/ 1-2 stories

Fig. 3 – Example of fragility functions used for the analysis

2.4 Damage assessment

Considering the seismic rupture, exposure and fragility models described in the previous sections, aggregated damage distribution statistics per building taxonomy, aggregated damage distribution statistics for the city and collapse maps were computed using the Scenario Damage Calculator from the OpenQuake-engine. Fig.4 (a) presents the number of collapsed dwellings per census subdivision, and Fig. 4(b) presents the fraction between the collapsed dwellings and the total number of dwellings per sector. From this figure, it is observable that the majority of the collapsed dwellings are located in the center of the city, in areas with a large density of adobe structures (see Fig. 2).



(a) (b)

Fig. 4 – (a) estimated number of collapsed dwellings; (b) Percentage of collapsed dwellings

From a total of 460,665 dwellings considered in the exposure model, the following damage distribution was estimated: 24% are projected to sustain slight damage, 5% moderate, 4% extensive and 6 % collapsed. The remaining dwellings (61%) are projected to sustain no damage. Fig. 5(a) presents a summary of the total damage distribution for the scenario selected. In addition, the number of collapsed buildings by building classes was calculated. These results were used in order to identify the contribution of building classes to the total collapsed buildings. From Fig. 5 (b) it is observable that adobe, reinforced concrete flat slab structures, and unreinforced masonry walls makes up a large portion of collapsed dwellings (around 69% of the total collapsed dwellings).

Such results can also be described by the damage fractions obtained per structural type (see Fig 5. c). In the case of adobe structures-(MUR+ADO), the percentage of collapsed dwellings varies between 40% and 50%. For unreinforced masonry structures (MUR/LWAL) of 3-5 stories such percentages are close to 20%. Those results are quite different to the damage fractions obtained for infilled frames (LFINF) with 1-2 stories. For those structures, the number of collapsed dwellings is close to zero.

For the development of emergency plans in Quito, this study provides useful information in terms of the location of the number of dwellings affected, their geographical distribution and their structural types. Such values could be valuable inputs in order to estimate (for example) the demand of potential emergency houses, as well as the force tasks and personnel for the analysis of damages and needs.

3 Evaluation of indices of social vulnerability and integrated risk

In order to be effective and promote feasible interventions within risk mitigation programs and recovery plans, it is required that governments, disaster planners and managers identify the social and economic conditions of the population that could be benefited/affected. In this sense, besides the assessment of physical losses, the analysis of the social vulnerability of communities offers additional insight for the design of risk management strategies. In this regard, the following sections briefly presents the results of the evaluation of indices of social vulnerability for the urban areas of Quito.

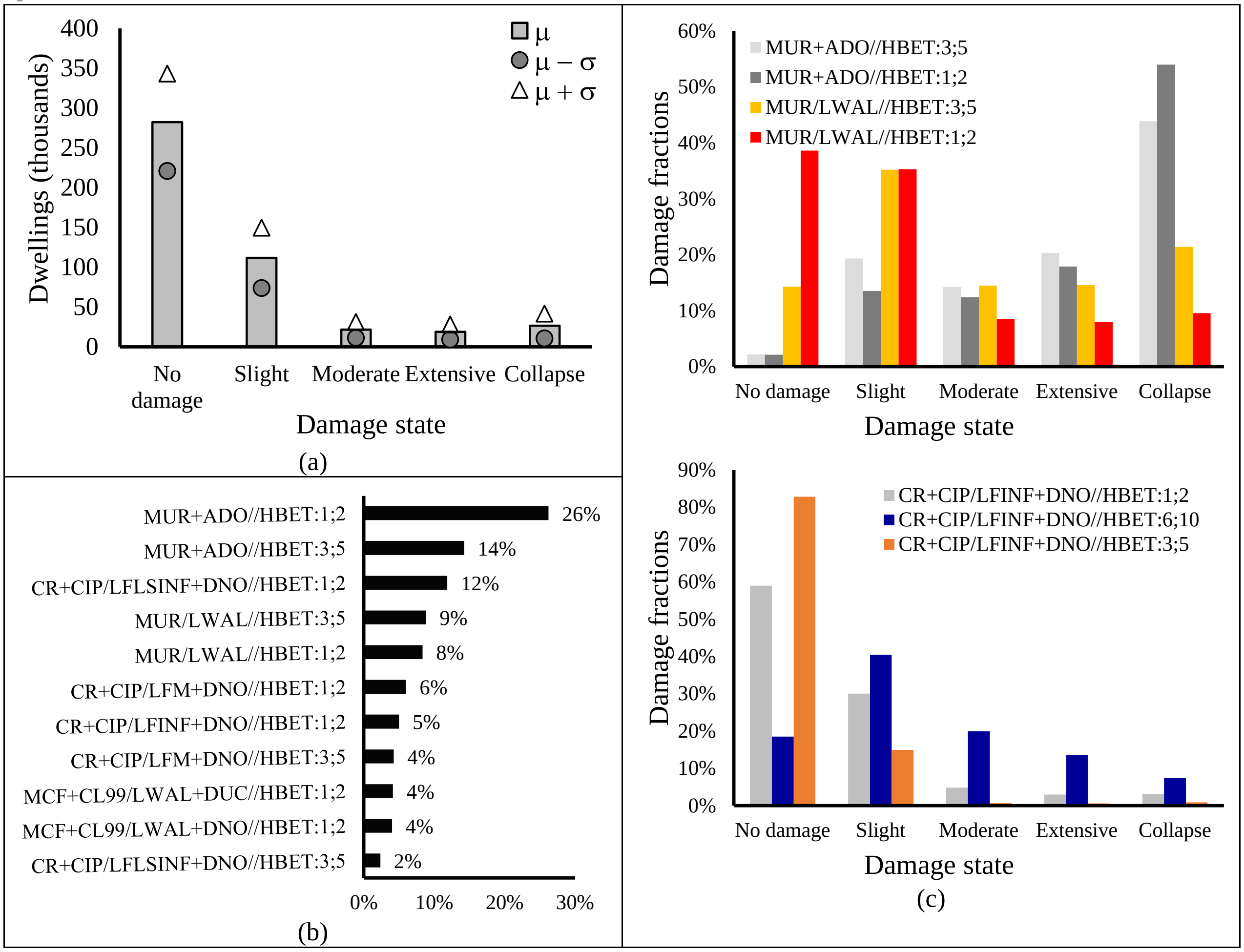


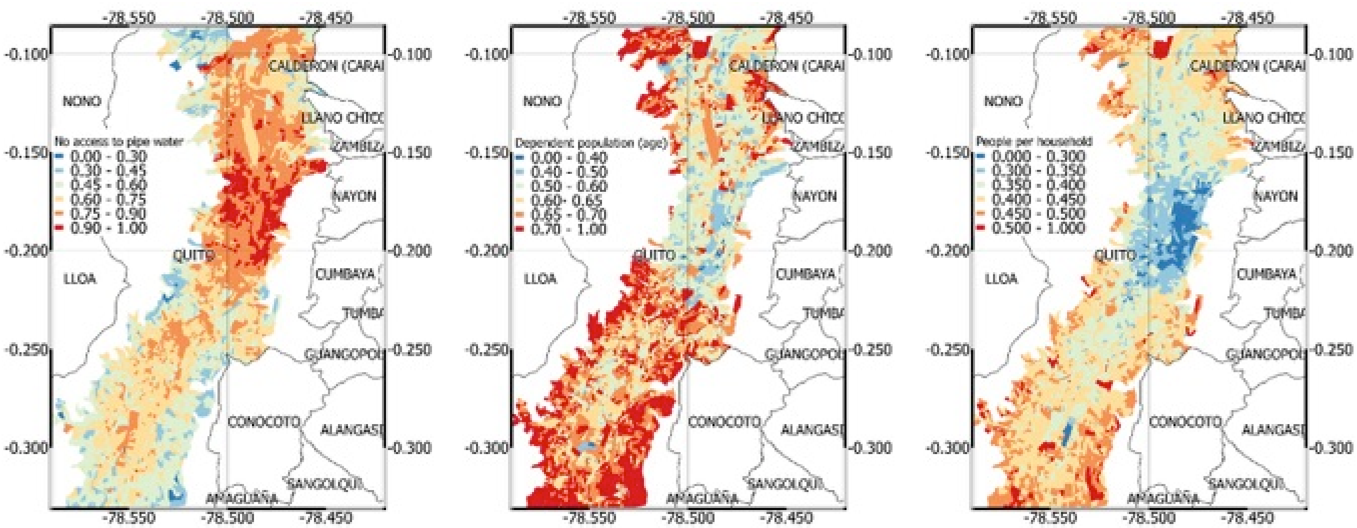
Fig. 5 – (a) Total distribution of damages; (b) contribution of building typologies to the total number of collapsed buildings; (c) damage fractions for various building types

3.1 Indices of social vulnerability

A composite index of the social vulnerability of Quito at the census subdivision level was developed using the methodology suggested in [17] as a starting point. Here, data was collected within population, health, education, infrastructure, and economic dimensions. Once data was collected and processed into indicators, a correlation analysis was conducted as a subsequent step to remove potential measurement redundancies where highly correlated variables (Spearman's Rho >0.800) were eliminated. To develop a parsimonious index that is straightforward and easy to understand, a Principal Component Analysis (PCA) was then applied to identify variables that potentially have a high influence on the social vulnerability of the study area. This was accomplished by selecting variables highly correlated with their respective factors (factor loadings >=0.500 and <-0.500). Herein, households that have no access to piped water, population over 65 and between 0-14 years, female population, population not in the labor force, people with disabilities, workers in the commercial/manufacturing industry, and the number of people per household largely influence the social vulnerability of the city's population. Fig.6 presents (min-max) normalized values of such social vulnerability drivers in urban sectors of Quito. From Fig.6 it is observable different distributions of these variables across the city: higher percentages of dwellings that have no access to piped water are located at the center and north while higher percentages of dependent population (the young and the old) are located at the center and south. On the other hand, higher numbers or people per household are found in peripheral areas.

Table 3 – Variables considered for the estimation of the Social Vulnerability Index

Vulnerability dimension	**Variable**
Health	Percentage of the total population with no private insurance
Education	Percentage of the population 15 and above that cannot read and write
Economy	Percentage of the total dwellings that is rented
	Percentage of the population between 15-64 that does not work
	Percentage of the population between 15-64 that works in manufacturing industries
	Percentage of the population between 15-64 that works in wholesale and retail
	Percentage of the population between 15-64 that works in accommodation and meals
Infrastructure	Percentage of the total dwellings that have shared toilet or do not have toilet at all
	Percentage of the total dwellings that do not cook
	Percentage of the total dwellings that have no access to pipe water
Population	Population Density (persons/km^2).
	Number of people per household
	Percentage of the population 15 years and above with NO national I.D
	Percentage of the total population that is between 0-14 and over 65 years
	Percentage of the total population that speaks indigenous language
	Percent of total population with disabilities (intellectual, mental, hearing, visual, permanent, disabilities-motion)
	Percentage of the total population that is female



(a) (b) (c)

Fig. 6 – Normalized values: (a) percentage of the total dwellings that have no access to pipe water; (b) percentage of the total population that is between 0-14 and over 65 years; (c) people per household

Individually, each one of the variables considered in Table 3 provides relevant inputs for defining specific aspects of risk management plans. For example, identifying sectors with larger concentration of population and higher percentages of dependent population could be useful for managing logistical requirements in order to respond to destructive earthquakes. Similarly, identifying urban sectors with deficit in infrastructure and public services could be useful for defining needs and opportunities in post-earthquake recovery projects.

On the other hand, the aggregation of the variables included in Table 3 provides a comprehensive and overarching view of the social vulnerability of the city and could be used for prioritization purposes. In this regard, a composite social vulnerability index was calculated by using the average of the normalized variables included in Table 3. Fig. 7(a) presents the results of the social vulnerability index at level of geography of census subdivisions. From this figure, it is possible to observe higher values of such index in the center of the city where deteriorated buildings are placed. Also, higher values were obtained in peripheral areas in the north and the south of the city, where informal settlements characterized by low-income households are located [18]. Such geographical distribution of the social vulnerability index is in agreement with the results shown in Fig. 6.

3.2 Integrated risk assessment: an alternative priority criterion

Physical damages can be expressed using objective measurements such as number/percentage of collapsed buildings and expected losses, amongst others. On the other hand, the assessment of indirect effects and impacts of earthquakes on communities depend not only on the magnitude of physical damages but also on the capacity of populations to absorb and recover from such events. In other words, the impacts from an earthquake will be expressed differentially across communities. For understanding such differences, prioritization methods [19] and integrated/holistic approaches have been suggested [20, 21, 22]. In practice, an integrated risk assessment is conceived as the combination of physical risk estimates with evaluations of the social vulnerability of communities [23].

One of the main goals of the present study is to provide a criterion to decision makers in order to prioritize sectors according to the expected collapse of dwellings and the social vulnerability of communities. In order to achieve this goal a priority index was calculated according to the following procedure:

i. **Selection of sectors with high expected damage**: sectors with a percentage of collapsed dwellings greater than the 85th percentile were selected for the analysis of the integrated risk.
ii. **Ranking**: the selected sectors were ordered first by the percentage of collapsed dwellings and then sectors were ordered by the results of the social vulnerability analysis. Such rankings were performed from highest to lowest values.
iii. **Making an ordered list**: Once the sectors are ranked, a number $\tau(i)$ indicating the position of the sector *i* in the ranking was assigned.
iv. **Evaluation of a priority index:** for each sector a Priority Index (PI) is obtained following Eq (1); this value corresponds to the normalization of the ordered list obtained in the previous step.

$$PI_i = 1 - \frac{\tau(i)-1}{|\tau|} \quad (1)$$

Where $|\tau|$ corresponds to the number of selected sectors in step i. Some advantages of the suggested procedure are described below:

- **Focus on critical areas:** This method is considered useful given the selection of sectors with physical damages higher than a certain value (for example, percentage of collapsed dwellings greater than the 85th percentile). Such selection allows decision makers to focus in critical zones. Depending on the type of risk calculation or risk estimates required, decision makers could define different thresholds for physical damages and risk.
- **A risk prioritization**: A given degree of damage is a prerequisite for this prioritization. In other words, it is necessary to be affected by a damaging event in order to be considered a priority. In case that two or more sectors are described by identical physical damage estimates (i.e. % of collapsed dwellings) a greater priority (a higher PI) will be assigned to the sector with the higher composite social vulnerability value. This approach reduces ambiguous results that could be derived when an integrated risk index is calculated as a composite index [21] and higher values of the social vulnerability index compensate lower values of physical risk estimates.
- **Meaning of the index:** The PI varies between 0 and 1, being 1 the highest value and priority. The PI reflects scores assigned to sectors with expected (physical) damages greater than a given threshold defined in the analysis (i.e. percentage of collapsed dwellings greater than the 85th percentile). It should be noted that scale of the PI denotes the priority of the sectors taking into account physical risk estimates and results of the social vulnerability index.

Fig. 7(b) presents the results of the application of the Priority Index in Quito. Results delineating areas with percentages of collapsed dwellings lower than 10% (that corresponds to the 85th percentile) were discarded (see Fig 4b). The highest values of the Priority Index were identified in the center of the city, in areas with the largest percentages of collapsed dwellings and highest values of the social vulnerability index where adobe buildings and low-income households are located.

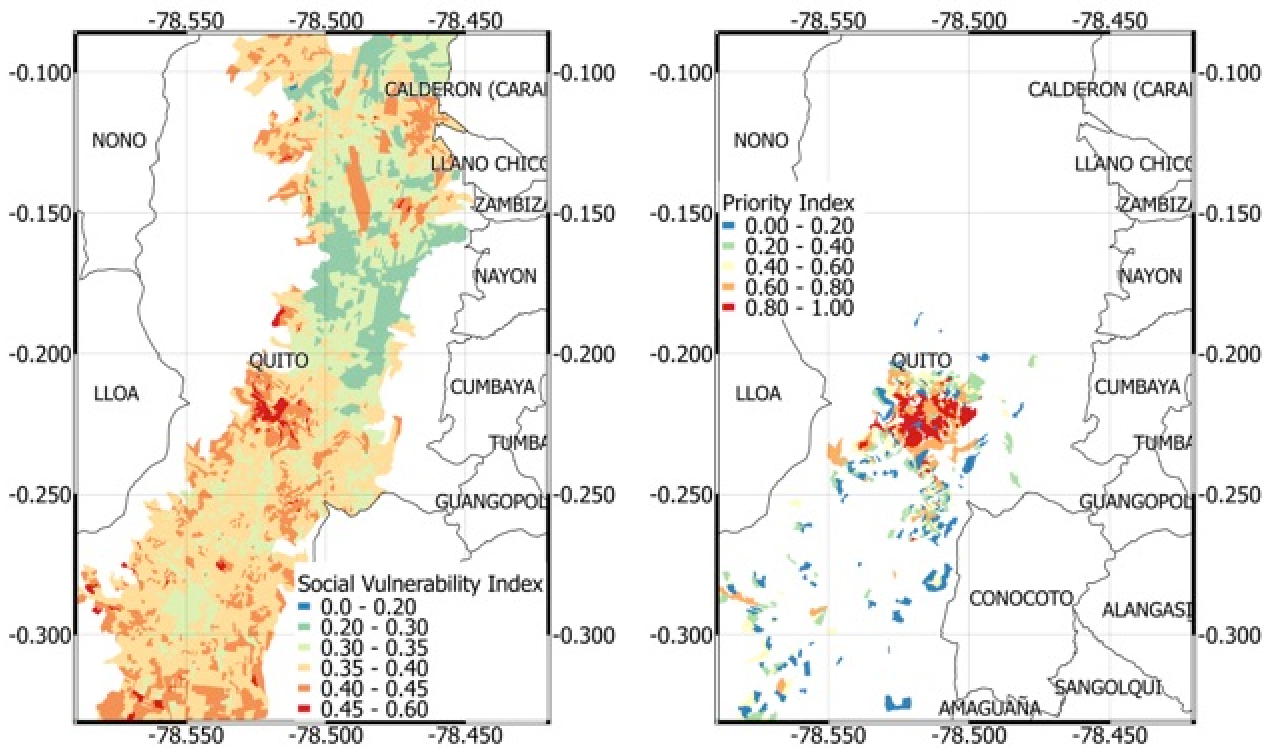


Fig. 7 – (a) Social Vulnerability Index; (b) Priority Index

From 4039 sectors included in the scenario damage calculation, 584 were selected given the percentage of collapsed buildings. From this group, 117 sectors were catalogued with a PI greater than 0.8. Such sectors could be considered as priority for defining risk reduction programs as well as emergency and recovery plans.

4 Conclusions

An integrated risk assessment of Quito was performed combining physical risk estimates with evaluations of the social vulnerability of communities. For the calculation of damages the following inputs were prepared: (i) ground motion fields for an earthquake rupture in the Quito Fault System of magnitude 6.4 M_w, (ii) an exposure model of residential buildings taking into account dwelling counts from recent census and building distributions by ranges of stories from cadastral databases, and iii) fragility functions derived in the framework of the SARA project. The Scenario Damage Calculator from the OpenQuake-engine was used to obtain the following results: from a total of 460665 dwellings, 24% are projected to sustain slight damage, 5% moderate, 4% extensive and 6% collapsed. The remaining dwellings (61%) are projected to sustain no damage. Nearly 69% of the collapsed dwellings correspond to adobe, unreinforced masonry and flat slab structures. In this regard, the geographical distribution of collapsed dwellings coincides with the location of such typologies, mainly placed in central areas of the city.

On the other hand, a social vulnerability index was obtained taking into account 17 variables that describe infrastructure, health, economy, education and population characteristics that affect social vulnerability. Higher values of the social vulnerability index were identified in the center of the city where deteriorated tenements are placed. Also, higher values were obtained in peripheral areas in the north and the south of the city.

In order to prioritize critical areas given the expected collapses of buildings and the social vulnerability of their inhabitants, a Priority Index was developed following a ranking procedure. Results indicate that the urban sectors that should be prioritized for the development of risk mitigation, emergency preparedness and recovery are located in central areas of the city where adobe buildings and low-income households are located. Such sectors are characterized by greater numbers of people per household, larger percentages households that have no access to pipe water and considerable percentages of population over 65 and between 0-14 years, female population, population not in the labor force, people with disabilities and workers in the commercial/manufacturing industry.

This study presents a scenario damage calculation in order to evaluate number of collapsed buildings considering a single rupture. Such results could be used for simulations and for the development of emergency plans. Additional efforts could be developed in order to assess the seismic risk of Quito considering all potential events that may affect the city, including not only residential buildings but also commercial, industrial, governmental, educational, healthcare facilities and lifelines. Currently, researchers at the National Polytechnic School of Ecuador are working in collaboration with the GEM Foundation and the Metropolitan Directorate of Risk Management of Quito in order to develop more detailed exposure datasets taking into account field surveys of buildings, as well as fragility functions of common residential buildings of the city. Such results will be an example of the collaborative effort promoted by the GEM Foundation within the framework of the SARA project.

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