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MULTI-HAZARD RISK URBAN ASSESSMENT: THE CASE OF LA ESTRELLA, COLOMBIA

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Abstract

A multi-hazard risk urban assessment including earthquake and flood hazards and earthquake secondary effects was developed for the residential buildings in the municipality of La Estrella, a 65 thousand inhabitants city of the metropolitan area of Medellin, Colombia. These two hazards are of interest for the municipality as it is located at a high seismic hazard zone, with a relevant number of dwellings near streams. The multi-hazard risk approach used in this work evaluates the potential physical damage and economic losses, and it has been carried out in close collaboration with local institutions and city planners, that can use the results to enhance the disaster risk reduction and mitigation strategies of the city. The level of detail and refinement used in this work is the first of this kind in the country, and has been tailored as a pilot case that can be further replicated in other urban centers.

The state-of-the-art probabilistic earthquake hazard model recently developed by the Colombian Geological Survey (SGC) in collaboration with the GEM Foundation was used in the assessment. The flood hazard model was developed by the Early Warning System of the Metropolitan Area of Medellin (SIATA) based on the historical knowledge of the rainfall duration and distribution. Scenarios with different intensity levels were examined for both perils, as well as secondary effects due to earthquake-triggered landslides. A detailed exposure model was developed for the residential buildings of La Estrella, where more than five thousand structures were individually surveyed to accurately characterize their capacity to withstand seismic and flood actions. Available building vulnerability functions for both considered hazards were used in the risk assessment. Probabilistic and deterministic risk metrics are presented, such as the average annual loss, loss exceedance curves, economic losses and number of building for different damage states. Results indicate an average annual loss for the municipality of 0.24‰ of the exposed value (residential building stock). The comparison of the loss exceedance curves for both hazards indicate that losses for return period smaller than 20 years are dominated by floods. The assessment of flood risk showed a high influence of the depth-damage vulnerability functions.

Keywords: multi-risk urban assessment; flood; earthquakes, seismic risk, disaster risk reduction.

1. Introduction

The assessment of risk due to natural hazards at urban centres has become a relevant topic for policy makers. The Sendai Framework for Disaster Risk Reduction[1] emphasizes the importance of quantifying the risk, aiming to provide metrics that can be effectively inform preparedness, mitigation and reduction strategies. Colombia, as many other countries, is exposed to several natural hazards, that are generally assessed independently. Although it is highly important to study individually the effects of each hazard in a given location, it becomes necessary to use methodologies, as unified as possible, that allow multi-hazard risk analysis. In this paper we selected the municipality of La Estrella, a 65 thousand inhabitants city of the metropolitan area of Medellín (Colombia). La Estrella has an area of 35 km^2 and it is located at the *Aburra Valley* (a steep valley that is the natural basin of the Medellin River). The municipality is exposed to different hazards such as earthquakes, floods, forest fires, landslides, air pollution and technological hazard [1]. Two hazards were chosen for the multi-hazard risk assessment presented herein: earthquakes, as the municipality is located at a high seismic hazard zone according to the Colombian seismic design code [2]; and floods caused by excessive rainfall, considering that the average annual precipitation of La Estrella varied between 1,100 mm and 2,900 mm in the last nine years (as recorded by the monitoring stations of the Early Warning System of the Metropolitan Area of Medellin, *SIATA)*. One key factor in the selection of La Estrella as the area under study is the high commitment of the disaster management municipality leaders. The interaction between the authors and the municipality leaders, made possible to gather useful and up-to-date data, and to take joined decisions in order to produce results that can be used in future risk management actions. Fig. 1 presents the geographical location of La Estrella as well as the buildings and streams considered in the analysis.

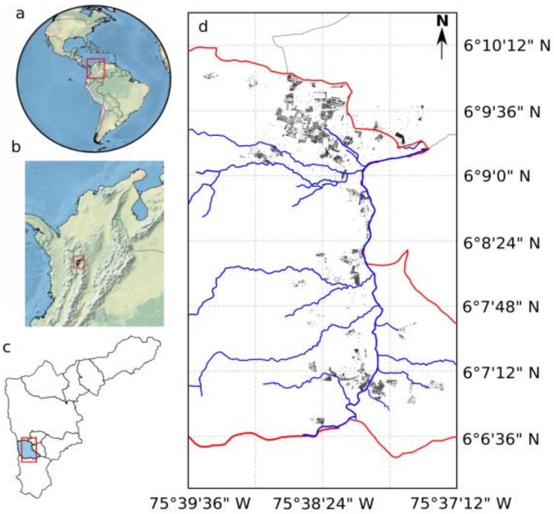

Fig. 1 – Location of study area. a) South America continent, b) Colombia, located in the north-west of South America, c) Municipalities of the Aburra Valley, d) Municipality of La Estrella. Blue lines are the streams included in flood scenarios; black squares are building footprints in the exposure model

Both earthquake and flood risk are evaluated following the framework in which risk is the result of the interaction of three components: hazard, exposure and vulnerability [3, 4]. *Hazard* refers to the probability of occurrence of the natural phenomenon (earthquake or flooding) in terms of its frequency and magnitude; the *exposure* is a compendium of the assets in the region under study; and *vulnerability* refers to the capacity of the exposed elements to sustain the forces induced by the hazard. For the earthquake assessment we used the

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[1] Sendai Framework for Disaster Risk Reduction 2015 – 2030. United Nations Office for Disaster Risk Reduction (UNISDR). Available at https://www.unisdr.org/we/coordinate/sendai-framework.

latest seismic hazard model for Colombia [5] developed by the Colombian Geological Survey (SGC) in collaboration with the Global Earthquake Model (GEM) Foundation. The flood hazard model that we used was specificaly developed for this work by SIATA. A building-to-building exposure model developed by the authors of this work was used for the multi-hazard risk assessment. Finally, we selected earthquake and flood building vulnerability functions from those publicly available. The probabilistic assessment of both seismic and flood risk is presented in this paper in terms of average annual losses and loss exceedance curves. Scenarios for different intensity levels were selected in collaboration with the municipality and metrics such as expected economic losses and damage are presented. The secondary effects of earthquake-induced landslides were considered in the seismic scenarios.

2. Previous earthquake and flood risk assessments for La Estrella

One of the latest multi-hazard risk assessments developed for Colombia is the *Colombian Risk Atlas* [6], in which earthquakes, floods, tsunamis, tropical cyclones, forest fires, droughts and landslides were considered. National hazard maps are presented for each peril, while risk results are given at departmental level for earthquakes and floods, and tsunami and tropical cyclone risk is presented for specific areas (which do not include La Estrella). The exposure dataset included buildings (public and private) on urban and rural areas. It is stated by the authors of the work that non-detailed input data was used for the analysis; therefore, it is expected that more detailed studies should be carried out to produce reliable risk metrics that can be used for the disaster risk management. Information of the Colombian Risk Atlas [6] for La Estrella is found in the Antioquia Department Risk Profile, in which risk due to earthquakes and floods is presented. For La Estrella, a multi-hazard risk average annual loss of 7.53 ‰ of the exposed value was estimated. As detailed information is only given at departmental level it is not possible to differentiate the fraction of the loss corresponding to each hazard.

A significant seismic event has not yet been recorded at La Estrella; nonetheless the assessment of its seismic risk has been a concern in the last decades, as the municipality is located in a high seismic hazard zone according to the Colombian seismic code [2]. Two official seismic risk assessment studies for Medellin and its metropolitan area (which includes La Estrella) have been developed in the past decades: the microzonation study in 2007 [7] and the updated seismic risk study in 2018 [8]. On the other hand, flood risk assessment following the methodology proposed in this work (i.e., convolution of hazard, exposure and physical vulnerability) have not—to the knowledge of the authors—been developed for La Estrella. Nonetheless, two valuable studies have been developed for the municipality [9, 10] that include landslides and flood hazards, as well as definition of zones with different risk levels for each hazard.

3. Input models for risk assessment: hazard, exposure and vulnerability

The quality of a risk assessment is closely related to the quality of the input models. The following sections briefly present the models used for earthquake and flood hazards, the selected vulnerability models, and the exposure model that was developed for both hazards.

3.1 Hazard models

A hazard model indicates the probability of occurrence of a given hazard intensity, i.e., its frequency and magnitude in a given period of time. In this work we used a probabilistic seismic hazard model recently developed for Colombia [5]. On the other hand, a flood hazard model was specifically developed for this study.

3.1.1 Seismic hazard

Colombian seismic hazard has been evaluated over the last decades [11, 12, 13]. In this study we used an up-to-date probabilistic seismic hazard assessment recently developed by the Colombian Geological Survey (SGC) with the collaboration of the GEM Foundation [5] that assess La Estrella peak ground acceleration (PGA) at rock sites as 0.15g for a 10% probability of exceedance in 50 years. This PGA value is in accordance with the estimated of the current seismic design code [2]. The model includes seismic areas sources, and active faults, covering four tectonic environments: subduction interface (SI), subduction in-slab (SIS), active shallow crust (ASC) and deep seismicity (DS). Two source models are considered for the hazard analysis, with three ground motion prediction equations (GMPEs) for each tectonic environment. As the hazard at La Estrella is influenced by three tectonic regimens (SI, SIS and ASC), a total of 54 logic-tree branches are considered in the analysis ($54 = 2*3^3$). Weights on source models and GMPEs are given in [5].

3.1.2 Flood hazard

A flood hazard model was developed by SIATA. The model is based on the historical knowledge of rainfall duration and distribution. A 2D hydraulic model was used to transform rainfall to inundation depths along the municipality streams. Rainfall intensity was estimated for different return periods; assuming that the resulting simulated discharge in the 2D hydraulic modelling has the same return period as the rainfall (as commonly reported in flood hazard assessment [14]). Inundation depth was the parameter selected to represent the flood hazard, as the flood fragility functions are related to this parameter. Nonetheless, the output of the 2D model included other parameters, such as water velocity that can be implemented if required by future models. A brief description of the flood hazard model is described below.

Rainfall intensity:

For this study the spatiotemporal analysis of radar-derived precipitation of [15] was used to generate three scenarios from 99, 99.5 and 99.9 percentiles of historical hourly rainfall data (Fig. 2). These scenarios were standardized and subsequently scaled to reach the maximum intensity that was estimated from an analysis of Intensity-Duration-Frequency (IDF) of data recorded from periods greater than 50 years at land-based stations located near La Estrella.

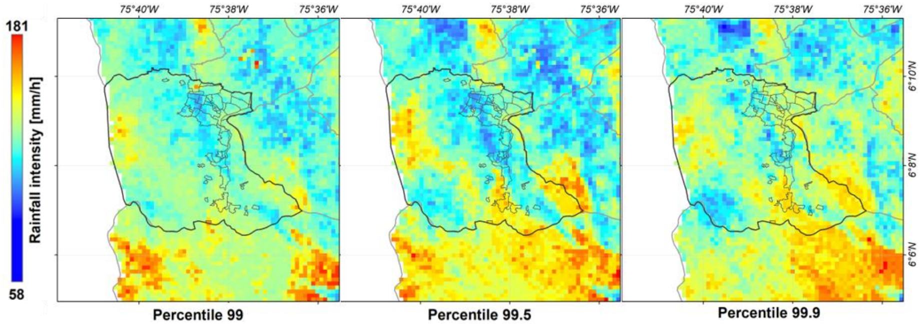


Fig. 2 – Precipitation scenarios calculated from historical radar information

To define the temporality of the events, a statistical analysis of precipitations with duration between 1.5 and 2.5 hours was carried out, and the 99.9 percentile was used for the definition of the histogram behaviour. Combinations of the maps that spatially correspond to the 99, 99.5 and 99.9 percentiles with intensities associated to return periods of 2, 5, 10, 25, 100, 200, 500 and 1000 years were obtained.

The runoff at each point of interest and for each return period was defined by the calibration of the distributed hydrological model for the Medellin River basin [16], using data from the level sensor register by SIATA since the year 2017, at the height of the *Inmaculada* stream stage station (75.62W, 6.17 N). Based on this information, the 24 most severe events were selected. A summary of the performance of the hydrological model is shown in Fig. 3, in terms of the Nash-Sutcliffe (NSE) and Kling-Gupta (KGE) efficiency coefficients, displaying an adequate performance in terms of direct runoff [17].

Fig. 3 – Performance of precipitation scenarios calculated from historical radar information. Left: Nash-Sutcliffe efficiency (NSE); right: Kling-Gupta efficiency (KGE)

2D hydraulic modelling and inundation depth:

The IBER free software [18] was used to estimate the heights of the water sheet, since the hydrological model only provides the water flow in the analyzed areas. In this case, the full depth-averaged shallow water equations are solved in order to compute the water depth and the two horizontal components of the depth-averaged velocity. These equations are solved with an unstructured finite volume solver explicit in time. The algorithms implemented in the model have been extensively validated and applied in previous studies related to river inundations [18, 19]. An inundation depth map was generated for each scenario with a cell resolution of 2 m. The selected number of return periods is in accordance with the recommendation of previous authors [20], where it is advised to use, at least, three flood return periods—and preferably six—if the average annual loss (AAL) is to be computed (see Section 4). Flood risk assessment of Jakarta (Indonesia) [21] and Saxony (Germany) [22], among others, have used between five and seven return periods to assess the AAL.

3.2 Exposure model

The exposure model is an inventory of the buildings in the region under study that must be classified based on their capacity to sustain the loads applied by the analyzed hazards. In this study we only considered residential buildings in the urban area of La Estrella. A building-to building exposure model was developed, in which characteristics of each asset were collected by remote surveys. Additional information, such as the plan building area, building use and the number of stories was retrieved from a cadastral map provided by the municipality. Another valuable input data used was the exposure model developed in the risk study of the metropolitan area of Medellín [8]. Even though the model indicated building by building characteristics, the building typologies were inferred from several assumptions and not from individual building surveys. For the present exposure model, we only used the building typology assigned by [8], when a virtual survey was not available. Buildings were classified based on the GEM building taxonomy [23] by the use of four parameters: material of the lateral load-resisting system, lateral load-resisting system (LLRS), ductility level, and number of stories. For each building typology, a corresponding earthquake fragility function was assigned (see next section). Building capacity for flood assessment is a function of the material of the LLRS, and the building use (in this case all of the buildings are residential). As the later parameter is included in the building typology classification, a unique exposure model for both hazards can be used. The exposure model comprises 6,283 buildings, classified into 48 typologies, and with a total exposed value of 4,929,170 million of COP (1,450 million USD). The replacement cost was computed based on a fixed cost per square meter square of 1,650,000 COP (485 USD/m^2), according to [24] and validated by the city planners. Unreinforced masonry (MUR) is the most common building typology representing 77% of the residential building stock (from which 35%, 39% and 24% are one-, two- and three-story buildings, respectively), followed by non-ductile reinforced concrete buildings (9% of the total stock).

3.3 Vulnerability model

Each building typology indicated in the exposure model must be associated to a given fragility/vulnerability function. The vulnerability model associates a given intensity parameter to a loss measure: damage through the use of fragility functions or economic loss by the use of vulnerability functions. In this study we used fragility and vulnerability functions for the earthquake risk assessment and vulnerability functions for the flood risk assessment.

3.3.1 Seismic vulnerability model

In this study we used the fragility functions developed as part of the GEM's Global Seismic Risk Model [25]. The model considered four damage stages: slight, moderate, extensive and complete. The functions were defined for different intensity measures, to consider the dynamic properties of various building classes. Seismic fragility functions can be transformed into seismic vulnerability functions by the use of a consequence model, that relates loss ratios for each damage state. Loss ratios of 5%, 25%, 60% and 100% were considered for slight, moderate, extensive and complete damage, respectively.

3.1.2 Flood vulnerability model

The number of available flood vulnerability functions is minimal when compared to the number of available functions for earthquakes. As a result, it is common practice to use functions from other countries, if functions have not yet been developed for the region under study [21]. The majority of the vulnerability functions available for flood risk assessments use water depth as the intensity measure. It has been recognized by several authors [21, 26] that the vulnerability function selection is a crucial factor on flood risk assessment. In order to consider the epistemic uncertainty on the vulnerability functions, the flood risk assessment included two sets of existing vulnerability functions, as presented below. Both functions include damage of contents, structural and non-structural elements.

Vulnerability functions previously used in Colombia [27]:

The first set of functions [27] have been used in Colombia for the assessment of residential buildings [28, 29]. These functions were derived for different building materials (earth, masonry, or concrete), and number of stories (one to three), as shown in the dashed lines of Fig. 4.

Global flood depth-damage vulnerability functions [30]:

The second set of functions [30] were derived for five continents including South America. A unique function is defined for residential buildings, which can be modified for different building materials. For earth buildings the original function was used, while for for masonry and concrete buildings, the functions were modified, as suggested by the authors, assuming that 40% of those buildings are never damaged under excessive rainfall floods. The global vulnerability functions were defined considering that contents damage is 50% of the structural cost; as this value is smaller for buildings in La Estrella, a further modification was applied to the function by considering a ratio between contents and structural cost of 20%. The adapted functions are shown in Fig. 4 (continuous lines). A minimum water depth damage threshold of 0.2 m, presented as a grey shadow in the Figure, is included to consider the relative ground floor level, as suggested by [31].

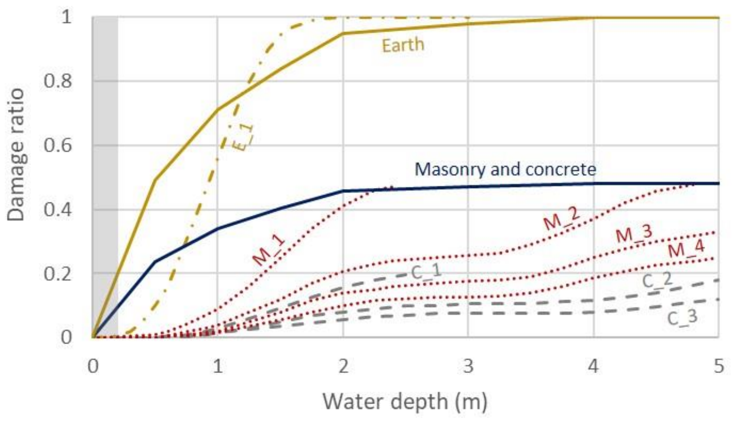


Fig. 4 – Flood vulnerability functions for residential buildings of earth (E), masonry (M) and concrete (C). Continuous lines: Functions for South America (adapted from [30]); dashed lines: functions previously used for Colombia for one-, two- and three-story buildings (adapted from [27]). Shadowed area indicates water depth threshold

4. Methodology for the probabilistic multi-hazard risk assessment

The multi-hazard risk assessment of La Estrella includes two natural hazards: earthquakes and floods. Hazard, exposure and vulnerability models presented in previous sections were combined using the OpenQuake-engine [32], to obtain loss exceedance curves and average annual losses. In addition, earthquake and flood scenarios were considered and are presented in Section 5.

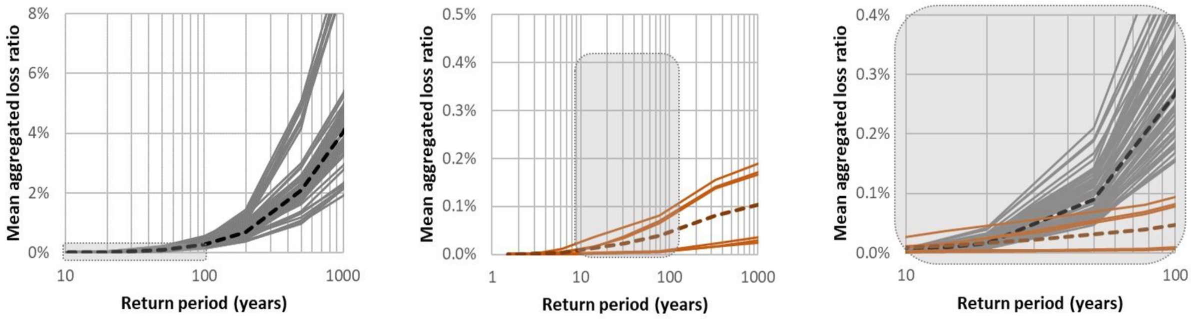
4.1 Seismic risk assessment

100,000 stochastic event sets, with a 1-year time span, were generated using Monte Carlo simulation, based on the seismic hazard model described in Section 3. Site effects were considered by the use of the shear wave velocity in the upper 30 meters (Vs30) in the GMPEs of the hazard model. The effects of each event on the building stock were assessed by the combination of the exposure and vulnerability models. Loss exceedance curves and average annual losses (AAL) were computed, based on the total aggregated losses of each event, and the associated return period. Fig. 5a presents the aggregated loss ratio for each seismic hazard logic-tree branch (continuous lines) and the mean weighted aggregated loss ratio (dashed line), with weights according to the logic-tree branches (see Section 3.1.1). The seismic AAL of the municipality was calculated as 1,012 million COP (0.20‰ of the exposed value).

4.2 Flood risk assessment

The complexity of the 2D hydraulic modelling used for the calculation of flood depths does not allow generation of stochastic event sets. Therefore, risk metrics (loss exceedance curve AAL) were computed based on flood scenarios as suggested and used by other authors [20, 21, 22]. Flood hazard (section 3.1.2) was represented by scenarios with eight rainfall return periods (2, 5, 10, 25, 50, 100, 500 and 1000 years). Inundation depths were computed for each scenario and later combined with the exposure and vulnerability functions. Economic losses associated to each scenario were estimated for the two sets of vulnerability functions, with a total of six loss exceedance curves. Fig. 5b presents the aggregated loss ratio for each curve (continuous lines). Notice that values significantly differ for each set of vulnerability functions, being much higher for the South America functions [30]. Equally weights were considered for the calculation of the mean value presented in Fig. 5b (dashed line). It is acknowledged by the authors of this work that further work is needed in the selection of the vulnerability curves, as the risk estimation is highly sensitive to such selection, as reported by [22]. The flood AAL was computed by finding the expected value of the loss across all return periods, as suggested by [14], and was calculated as 175 million COP (0.04‰ of the exposed value).

Fig.5c presents a comparison of the mean aggregated loss ratio for both hazards, for return periods up to 100 years. It can be observed that losses for return periods smaller than 20 years are dominated by floods. The total AAL of the residential building stock of La Estrella is 1,187 million COP (0.24‰ of the exposed value), which corresponds to the sum of the AAL of both hazards.



a) Seismic risk b) Flood risk c) Comparison

Fig. 5 – Mean aggregated loss ratio for La Estrella due to: a) earthquakes, b) floods and c) comparison of both hazards. Continuous lines are curves for each analysis; dashed lines are for average mean

5. Earthquake and flood scenarios

Scenarios were selected in collaboration with the policy makers of the municipality in order to have a better insight of the expected damage due to earthquakes and floods. We briefly present consequences of two selected scenarios for each hazard. It is worth to mention that consequences vary according to the scenario characteristics. Expected building damage and economic loss distributions are shown for the earthquake scenarios, as well as the effects of earthquake-induced landslides.

5.1 Earthquake scenarios

Earthquake scenarios were selected based on a disaggregation of the hazard for return periods of 100 and 475 years. Fig. 6 presents the disaggregation for a structural period of 0.3s [Sa(0.3s)], which is representative of the period of the majority of the residential building stock, i.e., MUR buildings with one to three stories.

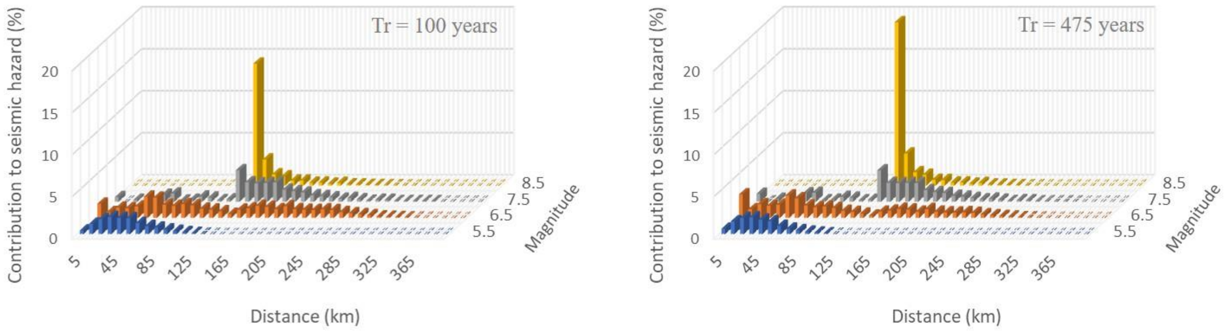


Fig. 6 – Seismic hazard disaggregation for Sa(0.3s) at return periods (Tr) of 100 and 475 years

It can be observed from the disaggregation that for both return periods hazard is dominated by large magnitude events at distances of about 160 km and close moderate magnitude events. This was the criteria used for the selection of the scenarios described in Table 1, in which events from subduction interface (SI) and active shallow crust (ASC) tectonic regimens were selected. Fig. 7 shows the associated damage distribution and its landslide probability for dry and wet seasons (as explained next).

Table 1 – Characteristics of earthquake scenarios

Magnitude (M_w)	**Distance (km)**	**Epicenter coordinates**	**Depth (km)**	**Tectonic regime**	**# of damaged buildings[1]**	**Economic loss (% of exposed value)**	**# of slopes with LP[2] ≥ 10%**	
							Dry	**Wet**
5.25	15.5	75.64 W, 6.01 N	7.5	ASC	44	1.0	12	23
8.45	172	77.07 W, 5.56 N	33.0	SI	139	2.9	16	26

[1] Weighted average of extensive and complete damage; [2] Landslide probability

Earthquake effects in 374 natural slopes were considered by the calculation of the induced landslides displacements. Slopes were selected using the Natural Slope Methodology (NSM) developed by [33], and the induced displacements were computed by the equations proposed by [34] for the active shallow event, and the equation of [35] for the subduction event. Both equations are function of the slope yield acceleration (k_y), the spectral acceleration at 1.5 degraded period and the earthquake moment magnitude. k_y was computed by a slope stability analysis with the Slide software [36]. Geotechnical soil parameters were assigned to each slope based on those reported by [9]. Dry and wet conditions were analyzed; for wet condition a piezometric level of 7 m was used, as considered by [9]. The slope probability of landslide (LP) was calculated based on the displacement level as suggested by [37].

5.2 Flood scenarios

Return periods of 5 and 100 years were selected for the flood scenarios. Table 2 presents the main characteristics of the analyzed scenarios, as well as the mean number of affected buildings and economic losses. Values in Table 2 are shown independently for the two vulnerability functions (VF1: *Colombia* [27] and VF2: *South America* [30]) to emphasize the high dependence of results to the vulnerability model. Fig. 8 shows the geospatial distribution of the losses and, as expected, they agree with the zones of maximum water depth.

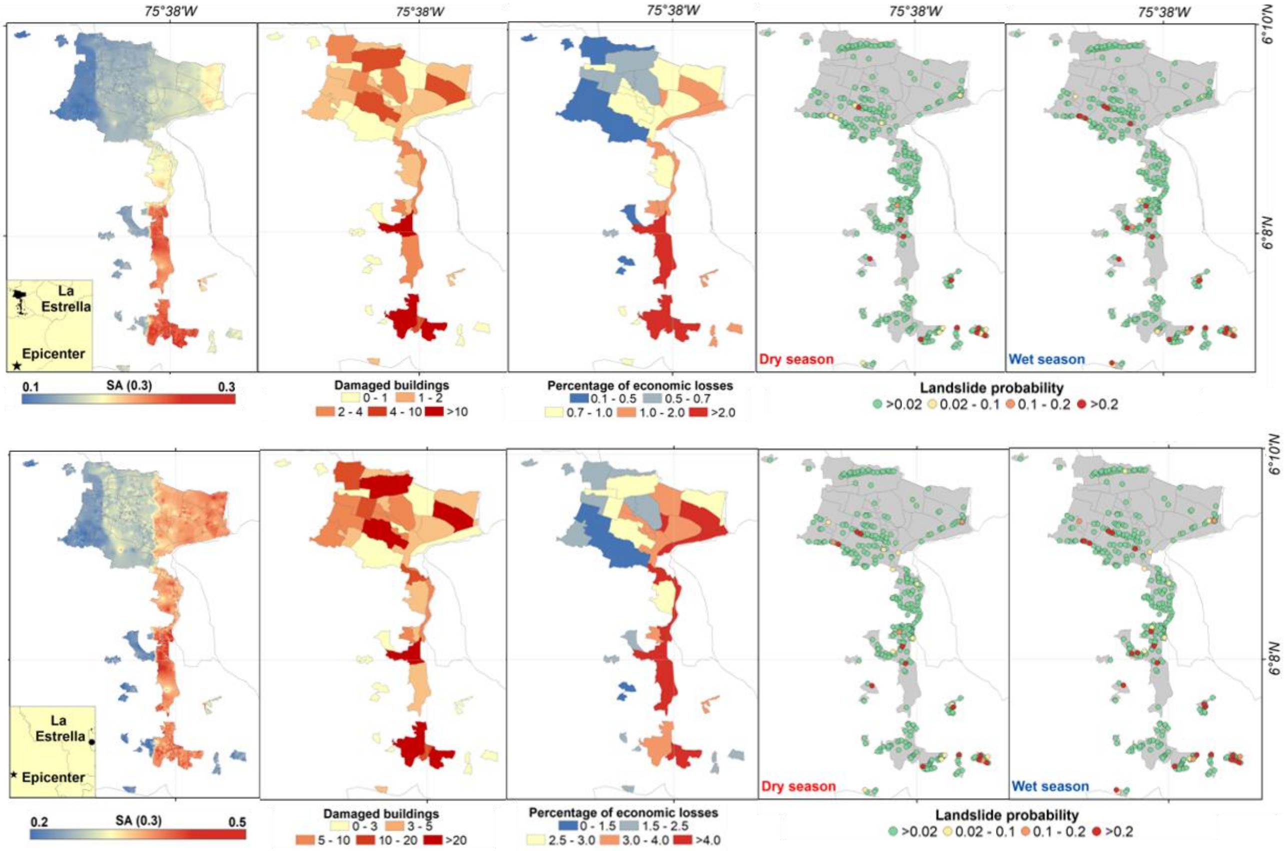


Fig. 7 – Mean values of spectral acceleration at 0.3s [SA(0.3)], distribution of building damage (moderate, extensive and complete) and economic loss per neighbourhood, and landslide probability for selected earthquake scenarios: ASC (above); SI (below)

Table 2 – Characteristics of flood scenarios

Return period (years)	Maximum water depth (m)	# of affected buildings		Economic loss (‰ of exposed value)	
		VF1(1)	VF2(2)	VF1(1)	VF2(21)
5	3.18	9	6	0.003	0.020
100	5.39	42	43	0.055	0.717

(1) VF1: *Colombia* vulnerability function [27]; (2) VF2: *South America* vulnerability function [30]

6. Conclusions and recommendations

A multi-hazard risk assessment for earthquakes and floods was developed for the residential building stock of La Estrella in closed collaboration with local institutions and city planners. Probabilistic risk metrics, such as the aggregated loss curves and the annual average loss (AAL), were generated for both hazards. Consequences for two seismic and two flood scenarios were presented. Results indicate a total AAL of 0.24‰ of the exposed value, and the aggregated loss curves show that losses with a return period smaller than 20 years are dominated by floods. The estimated AAL differs from the value reported by [6]. It must be kept in mind that: 1) in that study non-detail input data was used, 2) the study included public and private buildings, and 3) it included urban and rural areas. The lack of historical earthquakes recorded near La Estrella, challenges the validation of the results presented in this work.

On the other hand, floods events have been registered in La Estrella: from the period 2016 to 2019 five floods took place, whit four of them affecting, at least, one residential building. Unfortunately, detailed information about those events is not available. Further work will focus on collection of information that can be used to validate and improve the flood hazard and vulnerability models.

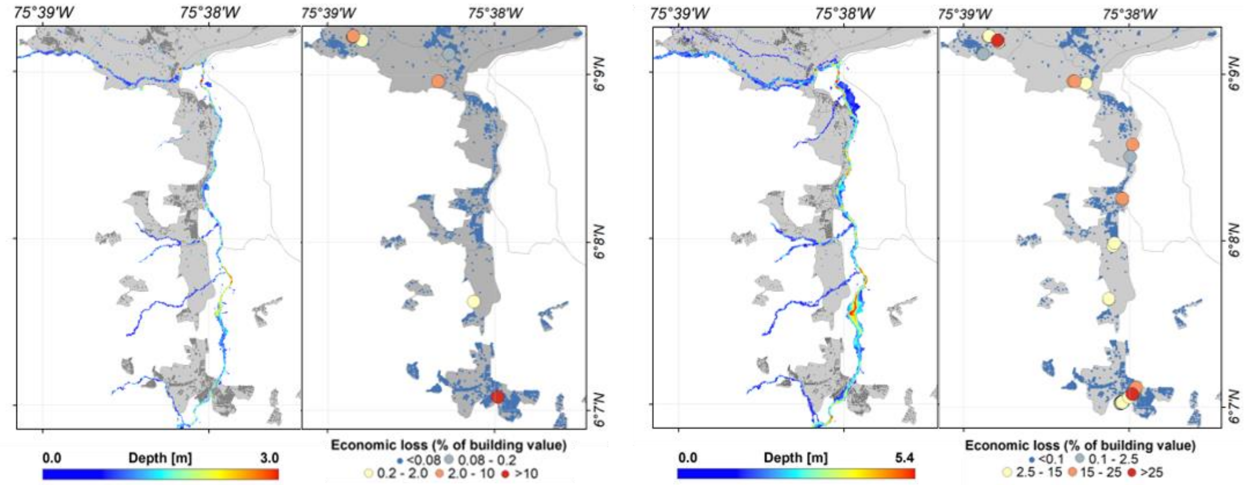


Fig. 8 – Mean water depth and distribution of mean economic loss for flood scenarios of return periods of 5 years (left) and 100 years (right)

Earthquake scenarios estimated economic losses of 1.0% and 2.9% of the exposed values, for the magnitude 5 and 8 events, respectively. The two considered earthquake scenarios suggest an average of 14 and 25 slopes, with landslide probability greater or equal than 10% for dry and wet conditions, respectively. On the other hand, flood scenarios for 5 and 100 years return period, estimated 8 and 43 buildings affected, with economic losses of 0.012‰ and 0.39‰ of the exposed value, respectively.

Considering the high dependence of the depth-damage vulnerability functions in flood risk assessment, it is recommended to concentrate efforts in the development (or improvement) of this model in the region. In particular, the function for South America can be improved by analyzing the damage to contents and the influence of the number of stories. For such analysis, data must be collected from previous events, a future work that will be developed in collaboration with the municipality risk managers.

The results of this work will be used by the municipality planners for the planification of disaster management strategies. Future work will include, in addition to improvements in the vulnerability models, the impact to population, and the consideration of critical and essential facilities, such a schools, hospitals, police and fire stations.

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