Training and Communication for
Earthquake Risk Assessment

TREQ Project

Scenario selection for representative earthquakes in Quito, Cali and Santiago de los Caballeros

Deliverable 2.4.2 – Version 1.0.0

Global Earthquake Model (GEM) Foundation

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Scenario selection for representative earthquakes in the TREQ cities

Scenario selection for representative earthquakes in Quito, Cali and Santiago de los Caballeros

Deliverable D2.4.2

Technical report produced in the context of the TREQ project

Version 1.0.0 – October, 2021

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Collaborators

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The TREQ Project is designed to demonstrate how earthquake hazard and risk assessment can inform decision makers in the development of risk reduction policies, as well as how earthquake risk can be properly communicated to stakeholders and the public in general. Specifically, the project aims to develop capacity for urban earthquake risk assessment in Latin America, Quito (Ecuador), Cali (Colombia), and Santiago de los Caballeros (Dominican Republic), while the second part will produce training, educational and communication materials that will enhance the understanding of earthquake risk worldwide. This program targets a wide spectrum of stakeholders, categorized into four main groups: governance (decision-makers/public authorities), industry (practitioners and professionals), academia (researchers and professors), and the community.

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CONTENTS

1 City Earthquake Scenarios

Seismic scenarios support the creation of a common understanding of the consequences that an earthquake can cause in a region. Stakeholders can visualise the most affected areas within the region of influence, the number and spatial distribution of damaged and collapsed buildings, casualties and economic losses. Thus, earthquake scenarios allow the identification of weaknesses and strengths in the management system, evaluation of the required measures for reducing the risk, and improving preparedness and recovery in future events.

The consequences from single seismic events can change significantly depending on the earthquake rupture characteristics, such as magnitude, hypocentral depth, and distance to the exposed assets. As part of TREQ, a number of earthquake ruptures are selected considering two approaches:

i) Identification of relevant historical events whose magnitude, faulting style and rupture geometry are well-known.
ii) Using the probabilistic seismic hazard analysis (PSHA), in particular the results of the hazard disaggregation (i.e., identification of the combination of distance, magnitude and seismogenic sources that contribute the most to the seismic hazard at each urban centre). This approach is referred herein as the hazard-based approach.

A selection of relevant earthquakes scenarios has been performed jointly among GEM, the United States Geological Survey (USGS) and the risk management offices of Quito, Cali and Santiago de los Caballeros. The selection includes historical scenarios of interest to the stakeholders and plausible scenarios identified through the disaggregation of seismic hazard that are relevant for disaster preparedness. This document provides a summary of the methodology and the selected events for each city.

Scenario risk assessment has been carried out for the three cities. The models and results are openly available in the repository https://github.com/gem/treq-riesgo-urbano. The TREQ project website also host other deliverables relevant to the seismic hazard assessment, consideration of site-conditions, and risk estimates. The deliverable ***"D2.4.1 Database with ruptures selected for scenario analysis"*** includes the details of each earthquake scenario and rupture parameters used for the estimation of scenarios damage and risk. Additional details on the methodology for rupture selection was provided by the United States Geological Survey (USGS).

2 Methodology for Scenario Selection

2.1 Historical based scenarios

Quito, Cali and Santiago de los Caballeros have a long history of destructive earthquakes. Several events have caused significant damage in the city. Finding detailed information regarding seismic characterization of historical events and their impact in the infrastructure and inhabitants has revealed to be a challenging task. Given the number of events, it was decided to narrow the selection to few events that are relatively frequent, or that at least have been sufficiently documented in order to simulate the fault rupture. When available, the USGS ShakeMap information was used as the reference material.

2.2 Hazard based scenarios

Hazard based scenarios were identified based on the results of disaggregation of the seismic hazard using the corresponding PSHA models for each city. The hazard disaggregation results identify the combination of distance, magnitude and seismogenic sources that contribute the most to the seismic hazard at each urban centre. Special importance has been given to active faults close to the cities, that have historically generated damaging events.

The objective of a selection based on hazard is to identify events with destructive potential based on their contribution to the seismic hazard. In turn such events can be modelled to inform the risk management offices about their potential impact and support in disaster preparedness. For example, Figure 1 presents the disaggregation of the seismic hazard for Cali corresponding to the 475-year return period, where shallow crustal events generating in the nearby faults have a significant contribution to the hazard of the city.

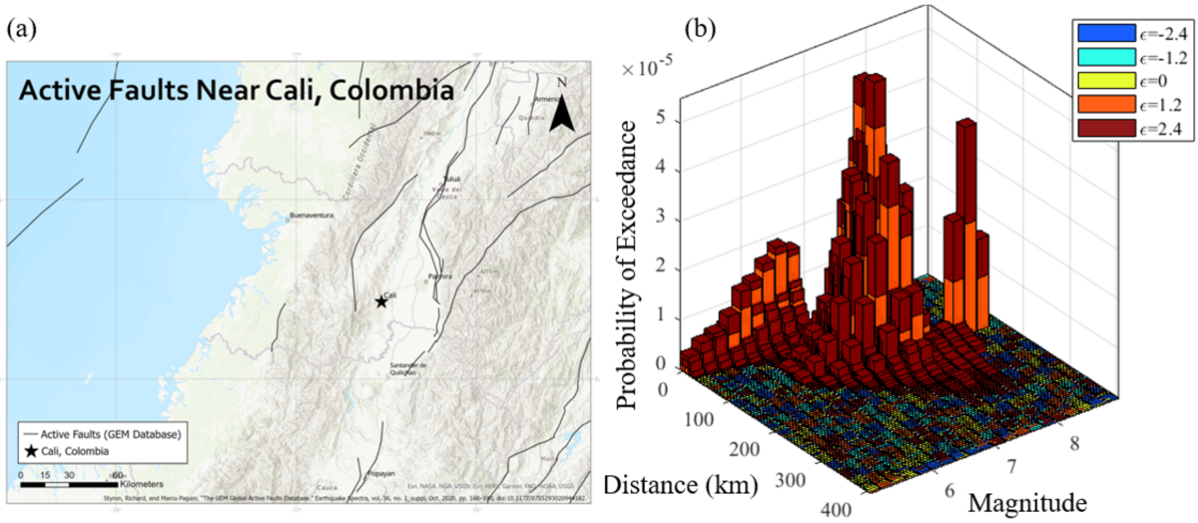

Figure 1. (a) Map of nearby faults in Valle del Cauca which are sources of potentially damaging events for Cali. (b) Disaggregation of the seismic hazard for Cali corresponding to the 475-year return period.

In addition to the losses estimated from the physical vulnerability, the USGS is also compounding risk metrics with social vulnerability indicators to create a composite score of risk. The score is presented in bivariate maps, that combine the physical consequences of the scenario in each part of the city (e.g. building collapse, economic loss, fatalities), with socioeconomic indicators about its inhabitants. Among the indicators being considered are:

1. Population of minors and elderly
2. Disabled population
3. Population not affiliated to social welfare or private medical care programs

4. Population without household tenure
5. Population that cannot read or write

The composite score is estimated at the same administrate level available for the social indicators. Figure 2 presents two maps, one with the illiterate population social indicator, together with the composite risk map with the consequences from a Mw6.5 rupture occurring north of the city of Quito.

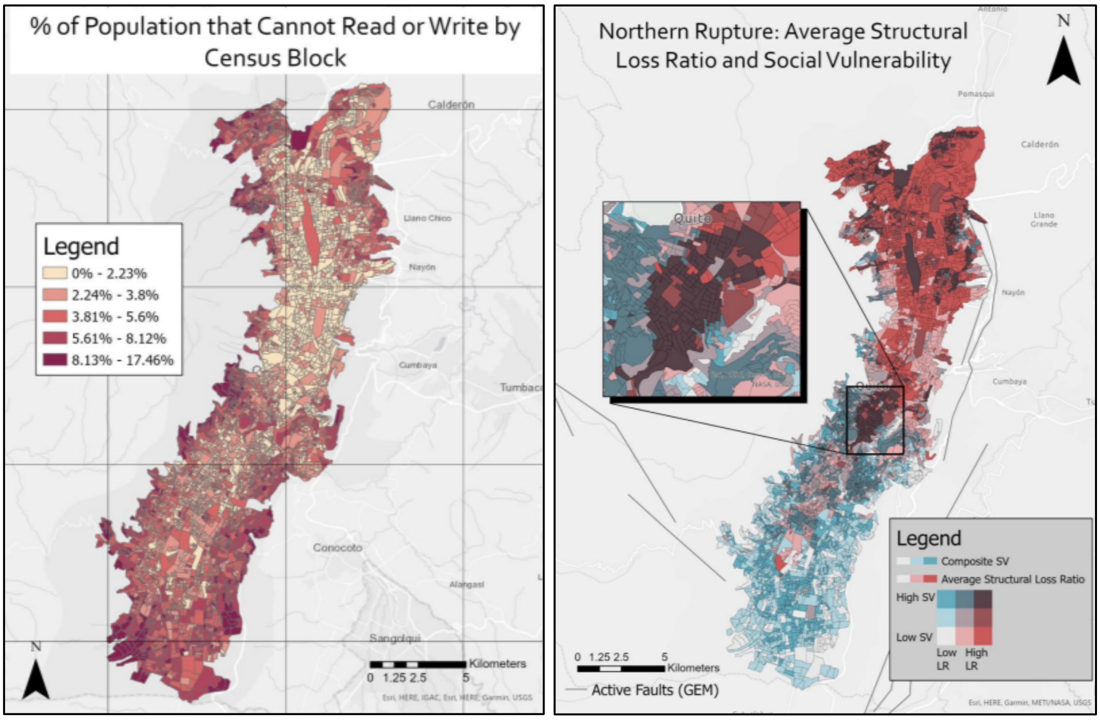

Figure 2. (Left) Social indictor of illiterate population per neighbourhood within the urban center of Quito. (Right) composite risk map displaying the economic losses per neighbourhood in scale of white to red, together with the composite social vulnerability in scale of white to blue. Brown resulting colours highlight regions where recovery from the disaster might be challenging to the population.

2.3 Scenario Risk Assessment

Seismic ruptures were modelled using the OpenQuake engine[1] scenario calculator developed by the GEM Foundation. For the selected scenarios, ground shaking was estimated at the surface considering site-specific characteristics and using the ShakeMap tool developed by the USGS (Wald et al., 1999). In this process, ground shaking intensities are estimated considering the characteristics of each rupture, at the location of the exposed buildings of the city. For each site, the maximum shaking intensity of the event is estimated using the ground motion models present in the hazard model. First ground shaking is estimated on rock conditions and subsequently, the intensity at each location is amplified using the amplification functions of the city in accordance to the corresponding seismic zone, thus taking into account the local site characteristics. To incorporate the associated uncertainty in the

[1] https://github.com/gem/oq-engine

ground shaking estimation (i.e., the ground shaking from any given rupture can be felt in various ways on the surface, called inter-event variability), we considered 2,000 simulations. In the case of historical scenarios, when recording stations values where available, the uncertainty in the vicinity of the recording station was reduced following the proposal by Silva and Horspool (2019). For each resulting simulation, impact estimates were estimated, such as number of damaged buildings, injuries, affected population, number of fatalities, or economic losses, among others. By considering the consequences from 2,000 simulations, it is possible to identify what is the most likely impact (estimates close to the average of all simulations), the most favourable impact (estimates close to the minimum impact obtained) and the most adverse impact (estimates close to the maximum impact obtained). To present in a concise but yet detailed manner the resulting impact from every event, scenario profiles were created, considering the preferences and needs of each city. Consequences are presented per neighbourhood and total values per city, showing in histograms the results of the scenario in a single figure for each risk metric obtained.

3 EARTHQUAKE SCENARIOS FOR QUITO

The catalogue of selected event for the city is presented in *Table 1*, where seven events have been listed, ranging from magnitude 6.5Mw to 8.8Mw and considering crustal and subduction events. The list includes details of the type of event (historical or hazard based), the magnitude and depth, the USGS ShakeMap identification code (useful to look on the online ShakeMap library[2]) and a short description of the event.

Table 1. List of earthquake scenarios for urban risk assessment for the city of Quito.

	Type	Mw	Depth (km)	ShakeMap ID	Description
1	Historical	8.8	20	official19060131153610_30	Nazca Subduction event of 1906
2	Historical	7.8	20.6	us20005j32	Quito Muisne event of 2016
3	Hazard based	6.5	8.0	quito_mfr	Shallow crustal event below the city
4	Hazard based	6.5	8.0	quito_n65	Near shallow event north of the city
5	Hazard based	7.0	8.0	quito_qf7.0	Strong shallow event below the city
6	Hazard based	6.5	8.0	quito_s65	Near shallow event south of the city
7	Hazard based	6.5	8.0	quito_w65_se	Near shallow event southeast of the city

[2] Access the USGS ShakeMap for each event by adding the appropriate *ShakeMap_ID* in the following link: https://earthquake.usgs.gov/earthquakes/eventpage/*ShakeMap_ID*/

3.1 Historical scenarios

Historical scenarios were selected based on their relevance for risk management offices in each city. For Quito, two historical earthquakes are being considered. The 1906 Nazca event, a large magnitude event (Mw 8.8) was selected to estimate the level of damage to the city at present, given the occurrence of an event in the Pacific subduction zone. The second event is the recent 2016 earthquake (Mw 7.8) in Muisne. This event was selected to serve as a benchmark for the performance of the earthquake loss model for Quito, as the risk management offices have reports of the impact in the city, which can be compared to the simulations using the urban risk model.

3.2 Hazard based scenarios

For Quito, five scenarios were selected through disaggregation. These are moderate magnitude events occurring on nearby faults surrounding the city, rupturing in locations that would cause the adverse effects given their depth and location.

The most damaging event is the Mw7.0 rupture occurring below the city that results in intense ground motion acceleration, where 90% of the exposure is located. Figure 3 presents a ShakeMap with the estimated ground shaking intensities for this scenario, where most of the city is in a zone with a PGA above 0.50g.

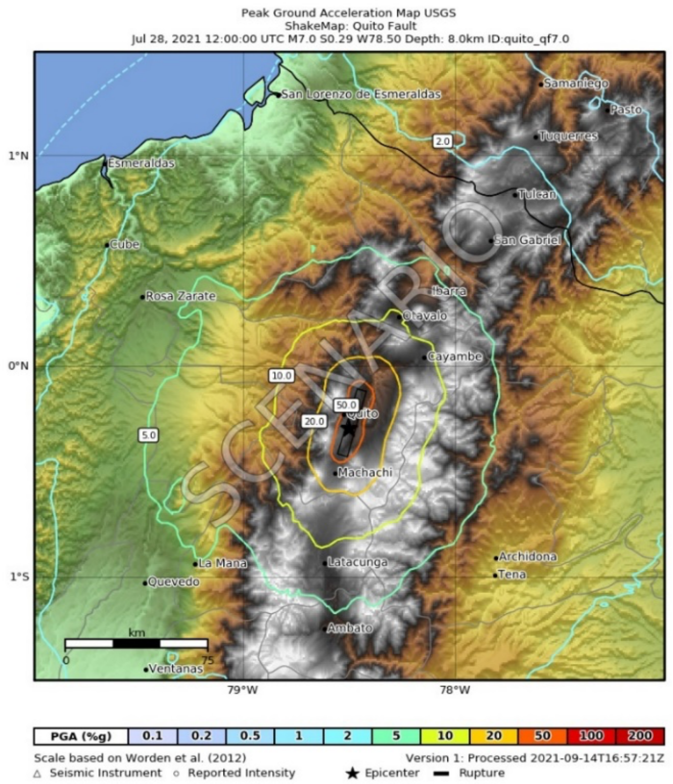

Figure 3. ShakeMap for the hypothetical scenario of Mw 7.0 rupturing right below the city of Quito, causing mean ground shaking intensities of 0.50g across in areas holding 90% of the exposed assets and occupants. Source: U.S. Geological Survey.

3.3 Scenario risk assessment

For every event proposed in the city, we estimated the potential impact on the city, regarding damage to the buildings and population affected (fatalities, injuries and homeless). Direct economic losses coming from ground shaking was also considered. The results for each scenario are presented in a series of emergency preparedness and response risk profiles. These profiles were developed in collaboration with the city's technical group and professionals in the areas of disaster response and humanitarian aid. The figure below presents an example of a scenario profile for the city.

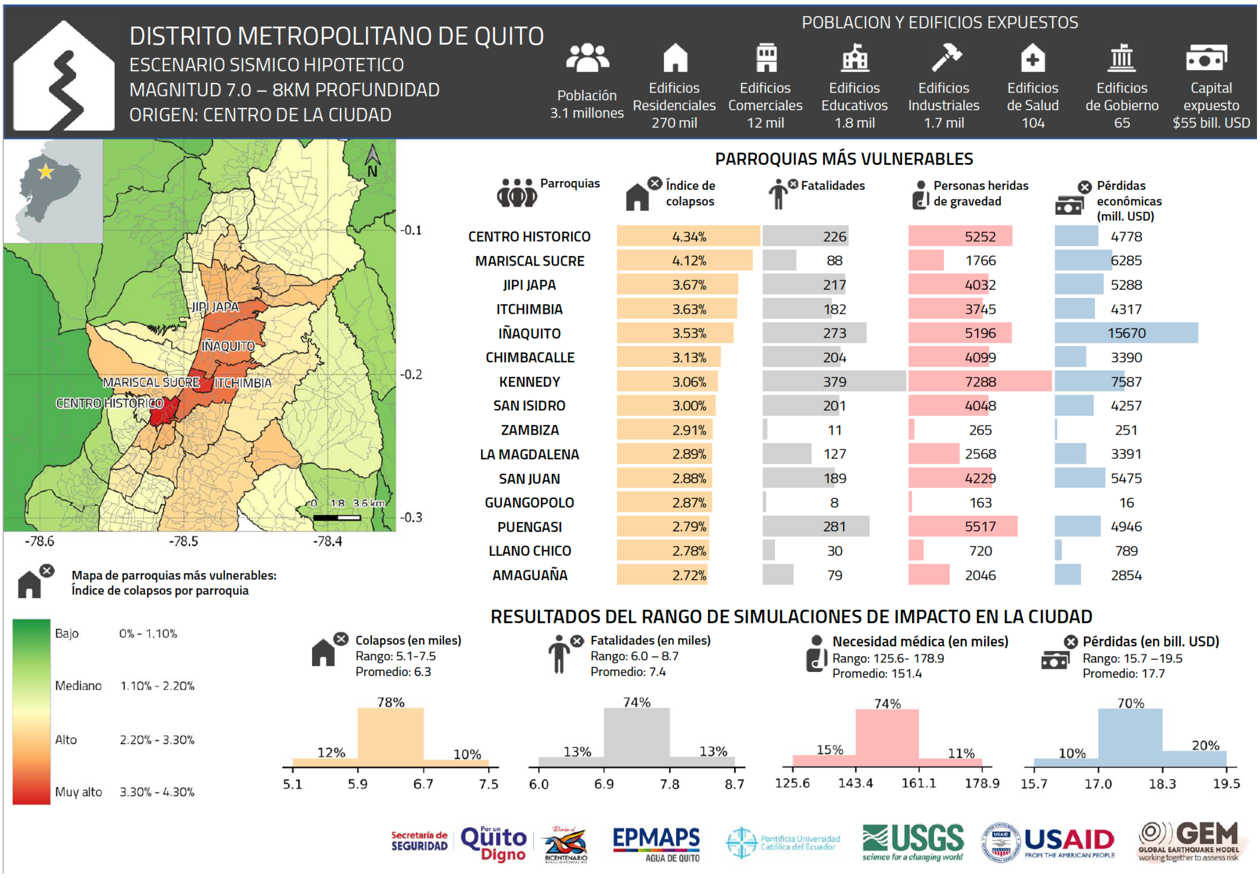

Figure 4. Example of scenario risk assessment results for a specific event in Quito.

4 EARTHQUAKE SCENARIOS FOR CALI

The catalogue of selected event for the city is presented in Table 2, where thirteen events have been listed, ranging from magnitude 6.1Mw to 8.8Mw and considering crustal and subduction events. The list includes details of the type of event (historical or hazard based), the magnitude and depth, the USGS ShakeMap identification code (useful to look on the online ShakeMap library[3]) and a short description of the event.

Table 2. List of earthquake scenarios for urban risk assessment for the city of Cali.

	Type	Mw	Depth (km)	ShakeMap ID	Description
1	Historical	8.8	20	official19060131153610_30	Nazca Subduction
2	Historical	6.3	15	iscgem910531	1925 EQ
3	Historical	7.2	15	usp000d8gx	Twin EQ - 2004
4	Historical	6.8	12.1	usp0006dv8	1994 EQ
5	Historical	7.2	21.3	usp0004zbt	Twin EQ - 1991
6	Historical	6.1	17	usp00091q3	1999 EQ
7	Historical	6.1	52.3	iscgem886586	1957 EQ
8	Historical	6.4	73.5	usp0006skc	1995 EQ
9	Hazard based	6.5	10	South East	Cucuana Dextral
10	Hazard based	6.5	10	West	Dagua Calima Normal
11	Hazard based	6.5	10	North East	Saliente de Buga 1 Reverse
12	Hazard based	6.5	10	East	Saliente de Buga 2 Reverse
13	Hazard based	8.8	22.9	big_north_nazcasuduction_se	Nazca Subdution event

4.1 Historical based scenarios

For Cali, most the historical events selected are subduction interface earthquakes that did not produce strong ground motion in the city due to the great depths and distances to Cali. However, many of them generate some level of damage. This is the case of the events of 1906, 1957 and 1991, 1995 and 2004. These events have been relatively frequent, and the risk management office has collected information about their impact and expressed its interest in estimating the potential impact of these events, given the actual conditions of the city. For example, the twin earthquakes of 1991 and 2004 (both Mw 7.2), caused different levels of damage in the city despite having similar magnitude and origin.

[3] Access the USGS ShakeMap for each event by adding the appropriate *ShakeMap_ID* in the following link: https://earthquake.usgs.gov/earthquakes/eventpage/*ShakeMap_ID*/

4.2 Hazard based scenarios

For Cali, a series of ruptures generated in the surrounding faults were taken as plausible scenarios of critical importance to the city. Previously strong shallow events occurring in these structures happened far enough from the city to cause significant damage. Therefore, 5 ruptures of Mw 6.5 were located in adverse locations in the Cucuana Dextral, Dagua Calima and the Saliente de Buga faults, selected in accordance with the hazard contribution from these sources. In addition, a large rupture occurring in the subduction zone in the Nazca Plate, with a Mw 8.8 has also been modelled as part of the city scenarios.

4.3 Scenario risk assessment

For every event proposed in the city, we estimated the potential impact on the city, regarding damage to the buildings and population affected (fatalities, injuries and homeless). Direct economic losses coming from ground shaking were also considered. The results for each scenario are presented in a series of emergency preparedness and response risk profiles. These profiles were developed in collaboration with the city's technical group and professionals in the areas of disaster response and humanitarian aid. The figure below presents an example of a scenario profile for the city.

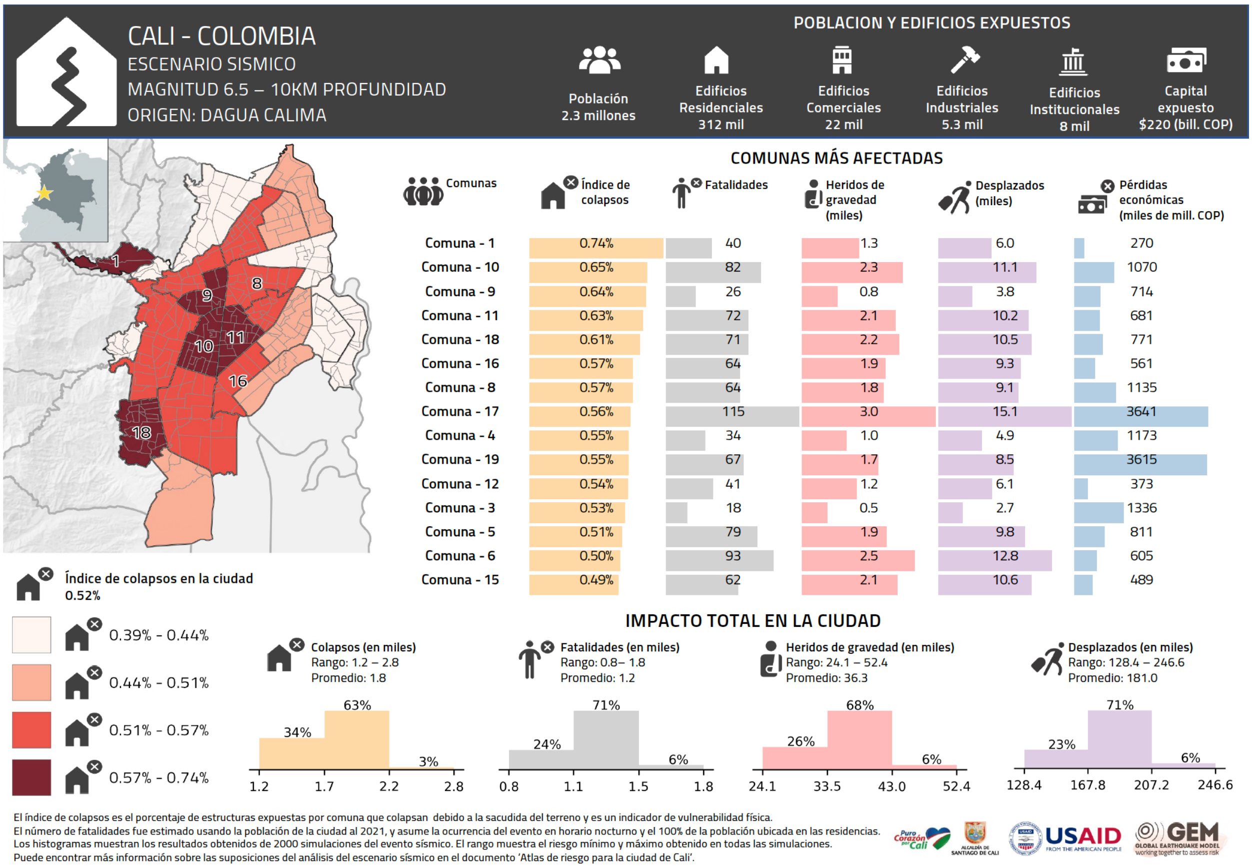

Figure 5. Example of scenario risk assessment results for a specific event in Cali.

5 EARTHQUAKE SCENARIOS FOR SANTIAGO DE LOS CABALLEROS

The catalogue of selected event for the city is presented in *Table 3*, where eight events have been listed, ranging from magnitude 6.0Mw to 7.5Mw for crustal events The list includes details of the type of event (historical or hazard based), the magnitude and depth, the USGS ShakeMap identification code (useful to look on the online ShakeMap library[4]) and a short description of the event.

Table 3. List of earthquake scenarios for urban risk assessment for the city of Santiago de los Caballeros

	Type	Mw	Depth (km)	ShakeMap ID	Description
1	Historical	6.4	10	usp000c89d	Puerto Plata earthquake of 2003
2	Historical	6.6	16.7	iscgem891713	Puerto Plata earthquake of 1953
3	Historical	7	13	usp000h60h	Haiti earthquake of 2010
4	Historical	7.5	15	iscgem898498	Hispaniola Earthquake of 1946
5	Hazard based	6	9	dr_60_septentrional_western_se	Moderate shallow crustal event west segment of SF
6	Hazard based	6.5	9	dr_65_septentrional_central_se	Moderate shallow crustal central segment of SF
7	Hazard based	7.5	9	dr_75_septentrional_central_se	Strong shallow crustal central segment of SF
8	Hazard based	7.5	9	dr_75_septentrional_western_se	Strong shallow crustal west segment of SF

5.1 Historical based scenarios

For Santiago de los Caballeros, two of the historical scenarios selected caused significant destruction in the old city and similar events are a major concern for the municipality. These are the Mw7.5 1946 Hispaniola and Mw7.0 1953 Puerto Plata earthquakes, both of which caused significant damage and loss of life in the north of the country. The other two earthquakes are more recent and were selected for benchmarks and testing of the earthquake loss model. These are the 2010 Haiti earthquake and the 2003 Puerto Plata event.

5.2 Hazard based scenarios

For Santiago four different ruptures were defined based on hazard disaggregation. These are located in two segments of the Septentrional Fault, which is the structure that contributes most to the seismic hazard of the city. Two were located in the west segment of the fault with Mw 6.0 and Mw 7.5. The other two are ruptures occurring in the central segment of the fault, with the same magnitudes. The central segment rupture of Mw 7.5 is the most adverse of all the scenarios modelled for Santiago, as the length of the rupture crosses below the city centre (see Figure 6).

[4] Access the USGS ShakeMap for each event by adding the appropriate *ShakeMap_ID* in the following link: https://earthquake.usgs.gov/earthquakes/eventpage/*ShakeMap_ID*/

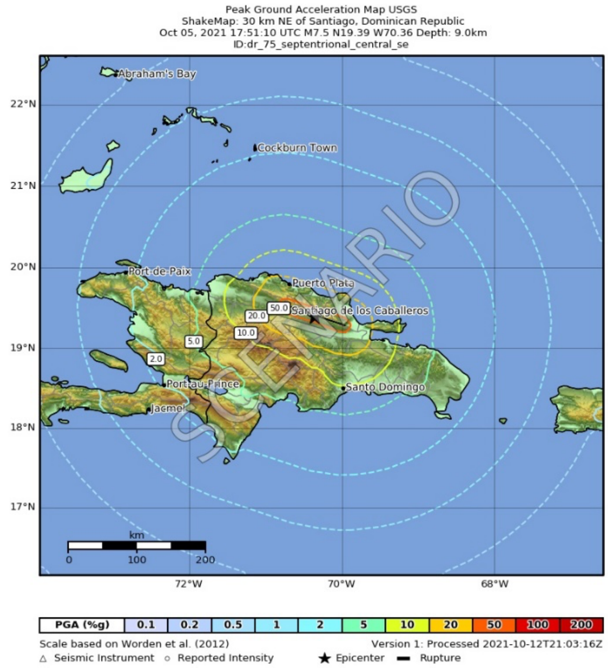

Figure 6. ShakeMap for the hypothetical scenario of Mw 7.5 rupturing along the central segment of the Septentrional Fault. This is one of the most adverse scenarios for the cities given that most of the city present shaking intensities above 0.50g. Source: U.S. Geological Survey.

5.3 Scenario risk assessment

For every event proposed in the city, we estimated the potential impact on the city, regarding damage to the buildings and population affected (fatalities, injuries and homeless). Direct economic losses coming from ground shaking were also considered. The results for each scenario are presented in a series of emergency preparedness and response risk profiles. These profiles were developed in collaboration with the city's technical group and professionals in the areas of disaster response and humanitarian aid. The figure below presents an example of a scenario profile for the city.

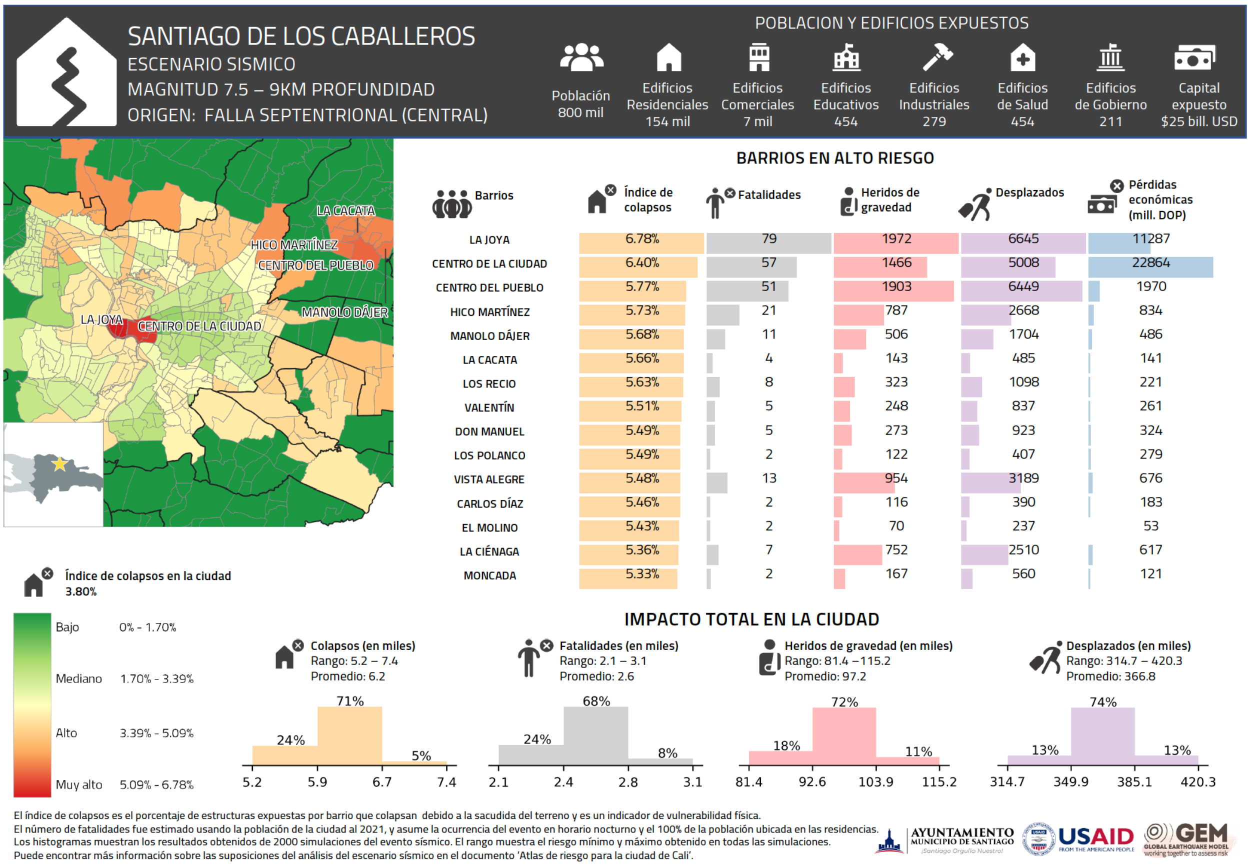

Figure 7. Example of scenario risk assessment results for a specific event in Santiago.