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Study of the effect of recent and future earthquakes on the current building inventory of San Juan, Argentina

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ABSTRACT

Information about an earthquake's extent and severity shortly after its occurrence is an important input for organizing response and planning efforts. However, direct damages information is rarely available due to the constraints of the situation. Rapid damage estimates developed with simulations provide approximate estimates which are helpful aids to rapid decision making. San Juan city, located in the most seismic-prone region of Argentina, has experienced severe earthquakes over the years. On January 19, 2021, a moderate M6.4 earthquake occurred near the city and, according to post-event official estimates, damaged 30,000 buildings and destroyed 3,000 others. This study refers the simulation and results of a rapid assessment of the effects of this earthquake. Ground motions and the number of damaged buildings were simulated probabilistically with a finer spatial resolution than is usual for similar assessments. The simulated ground motions were validated with few data point available and indirectly simulating and validating the Caucete 1977, M7.4 earthquake for which there are measurements available. The modeled damages look reasonable in view of the data available. The study also identified several input information problems, including lack of adequate information of local site effects, lack of an attenuation function that reflects the geological and seismological characteristics of the San Juan metropolitan region, and of fragility functions for the local residential building inventory. These knowledge gaps could cause that future assessments underestimate the extent of damages in the region. Areas of future research are listed and discussed. Improvements in these aspects are beneficial for better forecasting the effects of future earthquakes in the region.

Keywords: rapid assessment, earthquakes in Argentina, GMPEs

INTRODUCTION

Estimates of the extent and severity of earthquakes provide essential information for allocating and mobilizing resources, among other operations. Yet, direct reconnaissance operations are rarely feasible due to constraints imposed by the disaster and the impossibility of mobilizing enough resources and staff in a timely fashion. To overcome this difficulty, computer simulations conduct rapid damage estimates using the scattered information available about the hazard, building inventory, and vulnerabilities. Moreover, the simulation may afford insights into the actual extent of damages not revealed by reconnaissance.

The metro area of San Juan city, located in the most seismic-prone region of Argentina (Figure 1), has experienced several severe earthquakes: 1894 (M8.0), 1944 (M7.4), and in 1977 (M7.4), the latter causing 10,000 deaths. Recently, on January 19, 2021, an M6.4 earthquake occurred near Pocitos in the San Juan province. Initial estimates indicated that around 30,000 buildings were damaged and 3,000 were destroyed, but no information existed on the spatial distribution of damage, or the number of people affected.

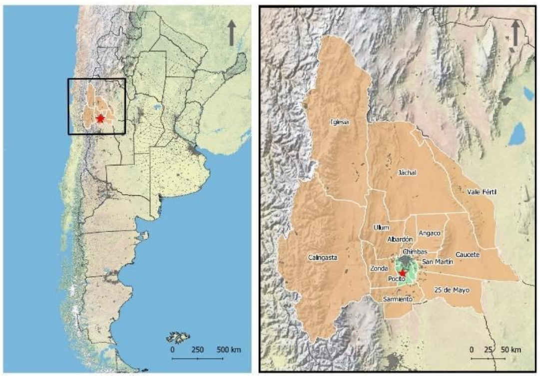

Figure 1: *Area of study in San Juan, Argentina*

The goals of this study were (with limited information about the residential building array, fragility functions, and ground motion prediction equations): (1) provide a rapid assessment of effects of the earthquake – extent and severity of ground motion, number of buildings damaged, and percentage of population affected with a level of detail equal or superior to that of existing products; (2) identify and evaluate information gaps and explore how they affect simulation results; and (3) provide recommendations about future steps to improve earthquake risk estimates in the region.

The remainder of this paper is organized as follows. First, a discussion of the available sources of information for the simulation components is provided. Next, the characterization of the residential building inventory is discussed, followed by the description, and limitations, of the fragility functions and ground motion prediction equations (GMPEs) adopted. In the last section the results of the simulation as well as the potential effects of the gaps of information are presented and discussed.

METHODOLOGY

A standard simulation approach was adopted to characterize probabilistically the ground motion of the Pocito earthquake (M_w 6.4). General GMPEs and fragility functions were incorporated. At the time of this study, no detailed characterization of the inventory was available, and so a thorough survey was conducted. Validations of the earthquake model and of the damage output were limited as limited data was available. Consequently, a scenario for which there was more information – the 1977 San Juan Earthquake, an M_w 7.4 – was simulated in order to conduct an indirect validation of sorts (Figure 2). The details about these are discussed below.

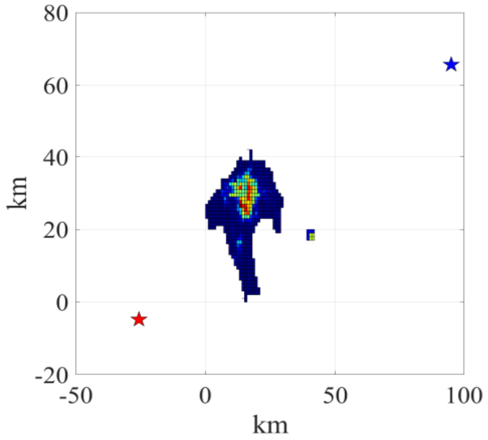

Figure 2: *Location of earthquake epicenters for Pocito 2021 (31.833°S 68.799°W) (red star), and Caucete 1977 (31.842°S 68.822°W) (blue star), and the exposure grid*

Characterization of the building inventory

The building inventory of San Juan was surveyed from both, a top-down and bottom-up approach, to achieve more accuracy. An orthogonal grid of a 1km x 1km was arranged over the study area. Sources of information for built-up areas and construction quality came from the Statistics and Census National Institute of Argentina (INDEC Census 2010). The number of buildings per grid cell was estimated from census data by tracts and collated visually inspecting footprint polygons from OpenStreetMap (OSM 2017), and information from the Spatial Data Infrastructure of San Juan Province (UIDE 2021) (Figure 3).

The building typologies were characterized, also with information from the Census, which has typologies INMAT I, II, III, or IV types in each census district. Five-building typologies were defined: Confined Masonry (CM), Masonry Infilled Reinforced Concrete Frames (C3), Unreinforced Masonry (URM), Adobe (A), and Informal (INF).

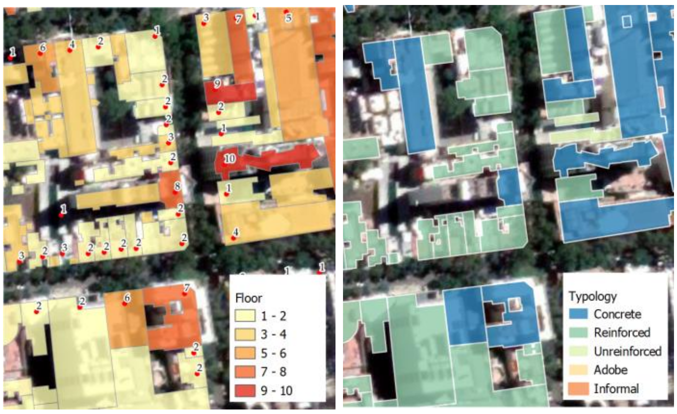

Figure 3: *Sample of the survey of number of buildings and typologies.*

Building areas were estimated examining the OSM polygon dataset. Two predominant average built areas were identified: 50 and 100 m^2, which could tentatively be assumed to describe a group of URM and A (50%), and another group of URM and RM (100 m^2) (Figure 4). The smaller areas may represent appurtenant constructions.

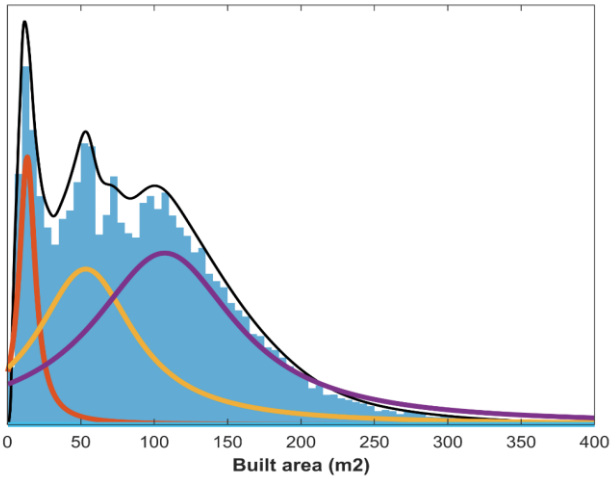

Figure 4: *Estimation of built-up areas from OSM (2017) data.*

The determination of building costs is difficult and was not pursued, due to building quality variations, taxes changes after a disaster, and demand surge. Information about constructions costs exists – the monthly construction index, CIRCOT, which robustly tracks the construction costs (CIRCOT 2021). However, there are other complicating factors, such conversion from peso to dollars, and high inflation which distorts any estimates quickly.

A summary of the building inventory characteristics is presented in Table 1 and in Figure 5. Information is approximate due to time limitation and information gaps.

Table 1: *Summary of the building inventory characteristics.*

Typology	Built area (m^2)	Number of buildings	Total built area	Repl. Value (USD/m^2)	Avg. Repl. Cost per typology	Total value (M-USD, rounded)
CM	100	101,780	10,178,000	300	$30,000	$3,050
C3	200	851	170,200	400	$80,000	$70
URM3	80	22,957	1,836,560	200	$16,000	$370
A	50	5,212	260,600	150	$7,500	$40
INF	30	703	21,090	100	$3,000	$2

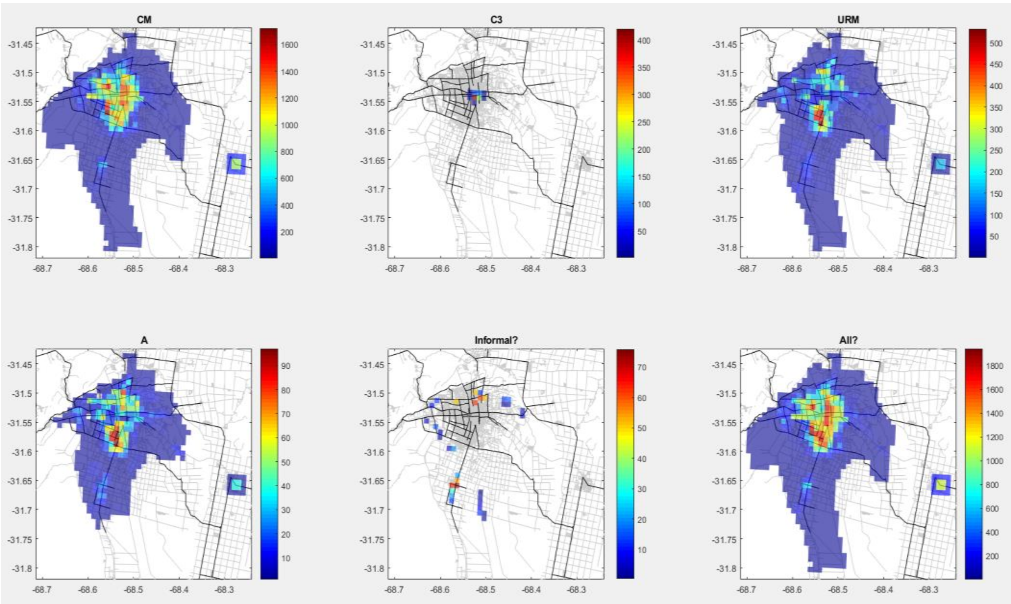

Figure 5: *Number of buildings typologies per cell.*

An estimation of the population was also projected on the grid using information from Landscan (2019) (Figure 6).

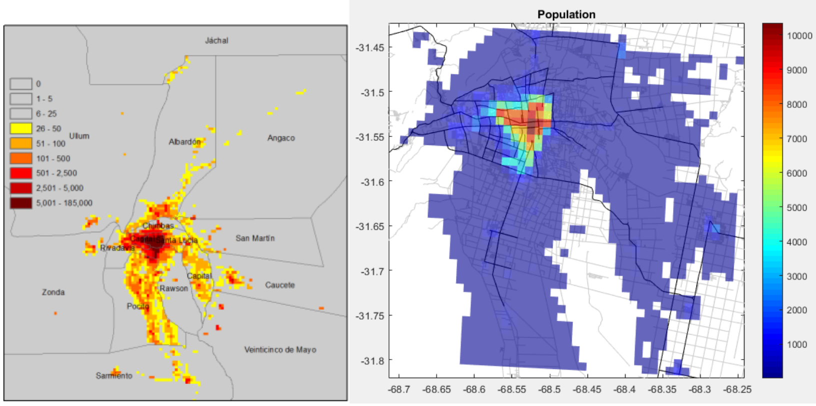

Figure 6: *Population distribution (left, from: Landscan 2019 ORNL ## S032W069); (right) population density in the study area.*

Fragility functions

Fragility functions to model the damageability of San Juan buildings did not exist at the time of the study. Hence, a set of fragility functions designed for similar typologies was adopted (GPSS 2019) (Figure 7 and Table 2). A number of other simplifications were made such as using same functions for adobe and informal typologies. It must be noted, however, that this selection should be considered provisional for this study, and adequate fragilities should be developed in the future.

Table 2: *Summary of the fragility function parameters for the building typologies. Only slight and complete damage parameters are presented for brevity.*

Typology	**Slight Damage**		**Complete Damage**	
	Mean (μ)	**Dispersion (β)**	**Mean (μ)**	**Dispersion (β)**
CM	0,72	0,35	3,79	0,49
C3	0,50	0,12	3,47	0,75
URM3	0,12	0,27	0,51	0,64
A	0,01	0,45	0,85	0,55
INF	0,01	0,45	0,85	0,55

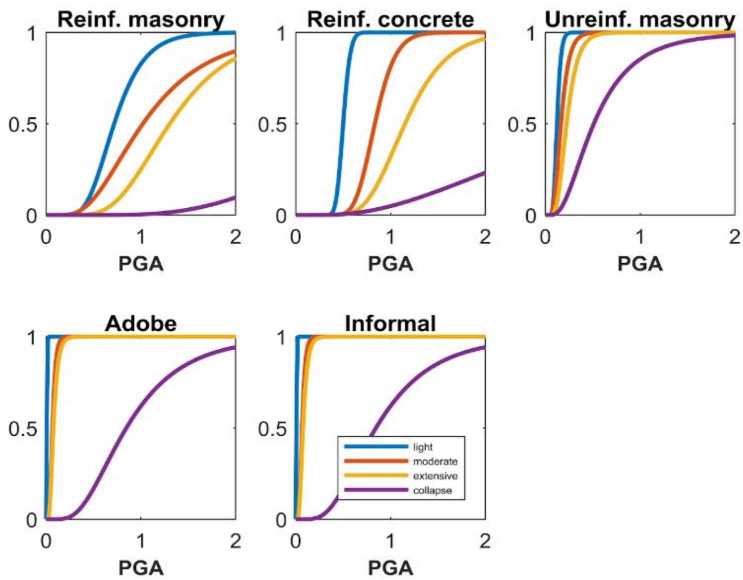

Figure 7: *Representation of the fragility functions adopted for this study (GPSS, 2019).*

Earthquake source model and ground motion prediction equations

The seismic source was modeled on the earthquake's epicenter as a point source, in accordance to the seismic records of the earthquake (La Laja Fault in particular or the thrust front of the Eastern Precordillera in general), although some doubts remain about the hypocentral location (INPRES 1977; Alvarado and Beck 2006; Meigs and Nabelek 2010).

In the absence of GMPEs developed specifically for Argentina (Gregori and Christiansen, 2018), equations developed for other regions worldwide are adopted. More than one GMPE is assumed to reflect the epistemic uncertainty involved in seismic hazard assessments and provide a range of possible results (Silva 2016). Functions from five studies (the first for Europe, the rest for western United States in the NGA-West2 project) were evaluated (Akkar and Bommer 2010, Abrahamson, Silva & Kamai (ASK14) et al. 2014, Campbell and Bozorgnia 2014, Boore et al. 2014, Chiou and Youngs 2014). All are for active crustal regions, San Juan's tectonic environment (see Bommer et al., 2010).

These GMPEs, or their predecessors, have been applied in previous hazard assessment studies for the region (Frau, 2009; Gregori and Christiansen, 2018; Petersen et al., 2018), for other countries in South America (Petersen et al., 2018, Acevedo et al., 2020), and in global seismic risk studies (Stewart et al., 2015).

GMPEs coming from the NGA-West2 project require several fault-related input parameters that are unknown for the region. These unknown sources, path, and site parameters were estimated from relevant literature (Kaklamanos et al. 2011 and Kaklamaons et al., 2010). The earthquake source was characterized according to Frau (2009) and Costa et al. (2020), including shear wave velocity, style-of-faulting, and dip angle of active faults near San Juan. The shear wave velocity in the upper 30 meters of soil (Vs30) was taken as 287 m/s (Alvarado et al. 2020), which is consistent with the Vs30 value found in another study (Imhof et al., 2016).

The model simulated 1,000 random ground motion fields in peak ground acceleration (PGA) sampled from the GMPEs considering both the intra-event and inter-event variabilities. A spatial correlation between these random numbers is applied with the methodology in Goda and Atkinson (2010).

For each random ground motion field, the number of damaged buildings was computed at each cell of the inventory grid, with the standard methodology (e.g. Elnashai and Di Sarno 2008).

RESULTS

Available damage information at the time of the study

The preliminary estimates indicated approximately 3,000 destroyed dwellings and 30,000 buildings exhibiting some level of damage (see appendix for sources) (Figure 8).

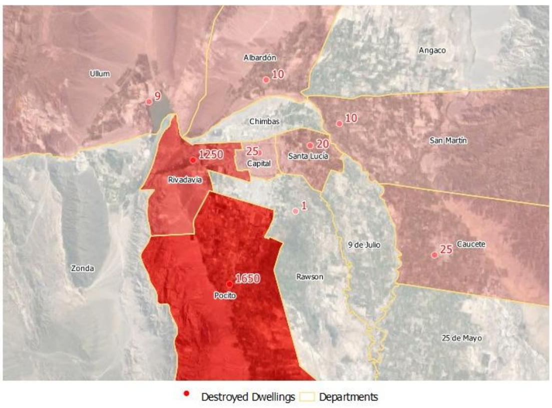

Figure 8: *Distribution of damages reported in the national and provincial media.*

Simulated ground motion of the Pocito Earthquake (6.4M_W)

The distribution of peak ground accelerations in the San Juan/Rawson area was estimated probabilistically with 10,000 realizations. However, the initial mean estimates significantly underestimated the few available PGA measurements, shown in the dashed box of Figure 9. This mismatch appears to indicate that the selected GMPEs from ASK14, arguably the best choice available, are a poor descriptor of the law of attenuation in San Juan. Other simplifications in the process also contribute to the mismatch: adopting a unique VS_{30} across the entire area. This finding indicates the need to develop a GMPE which is adequate for the local conditions of San Juan.

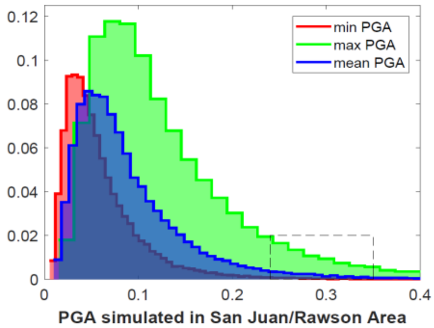

Figure 9: *PGA distribution simulated by the adopted GMPEs (maximum, minimum, and mean). The dashed rectangle shows the bounds of PGA registered (0.24g - 0.35g) in the San Juan/Rawson area.*

Consequently, a smaller subset of the 10,000 realizations was retained so that the mean PGA were consistent with the observed accelerations. The resulting simulated mean ground motion is displayed in Figure 10 and Figure 12. Conversion of the PGA into the Mercalli Modified Intensity (MMI), following Wald et al. (1999), is shown in (Figure 10). There are other approaches to perform this conversion (e.g. Petersen et al. 2018, Worden 2012) which did not output similar results.

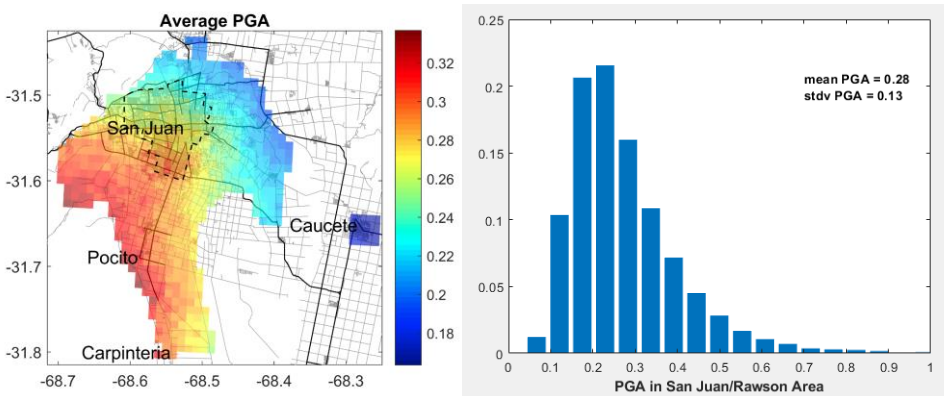

Figure 10: *(Left) simulated mean PGAs for the M6.4 earthquakes, (right) distribution of the simulated PGA*

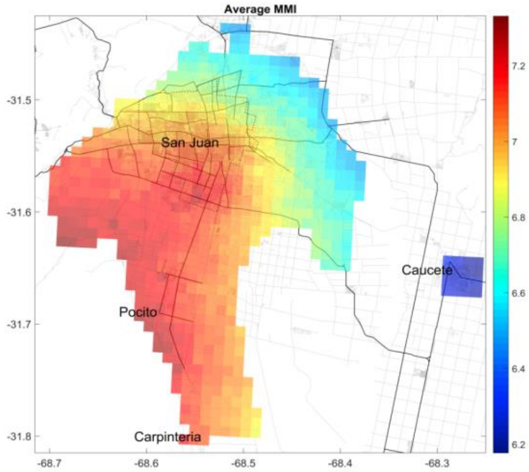

Figure 11: *MMI distribution in the study area (dashed rectangle covers San Juan and Rawson approximately). Relationship from Wald et al. (1999:558) with a σ ≈ 1. The model in Worden et al. (2012) seems to overestimate MMI.*

The agreement between the simulated PGA and MMI with the data available looks reasonable (Figure 12).

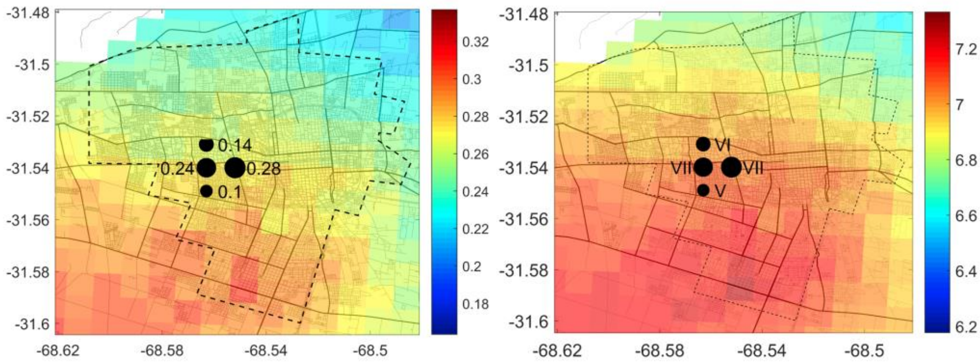

Figure 12: *Simulated mean ground motion in (left) PGA, and (right) MMI. Dots indicate reported data.*

The spatial distribution of damaged buildings (Figure 13), by department (Figure 14 and Table 3) are shown below. The variability of the damage estimates are shown in Figure 15, the distribution of damaged and collapsed buildings by typology is depicted in Figure 15 and reported in Table 3.

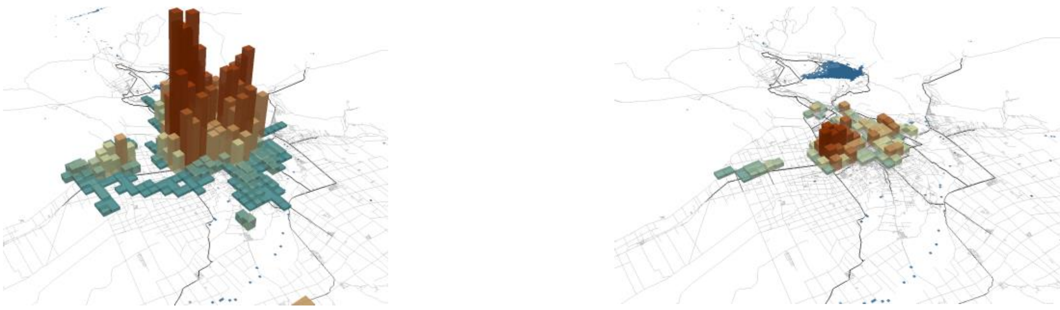

Figure 13: *(Left) Damaged buildings and (right) collapsed buildings (9 or less per pixel not shown)*

Table 3: *Number of collapsed and damaged buildings by department.*

Department	Mean number of damaged buildings	Mean number of collapsed buildings	Total
Rawson	6018	1117	7135
Capital	3861	519	4380
Pocito	3864	776	4640
Chimbas	4403	610	5013
Rivadavia	3361	549	3910
Santa Lucia	2471	346	2817
9 de Julio	302	38	340
Caucete	600	50	650
Total	**24,917**	**3,915**	

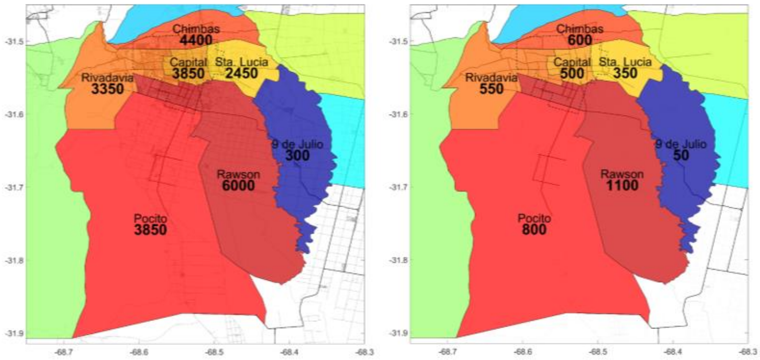

Figure 14: *Distribution of damaged buildings by the department. Rounded to nearest 50 (note: Caucete with 600 damaged and 50 collapsed doesn't appear in the pictures.*

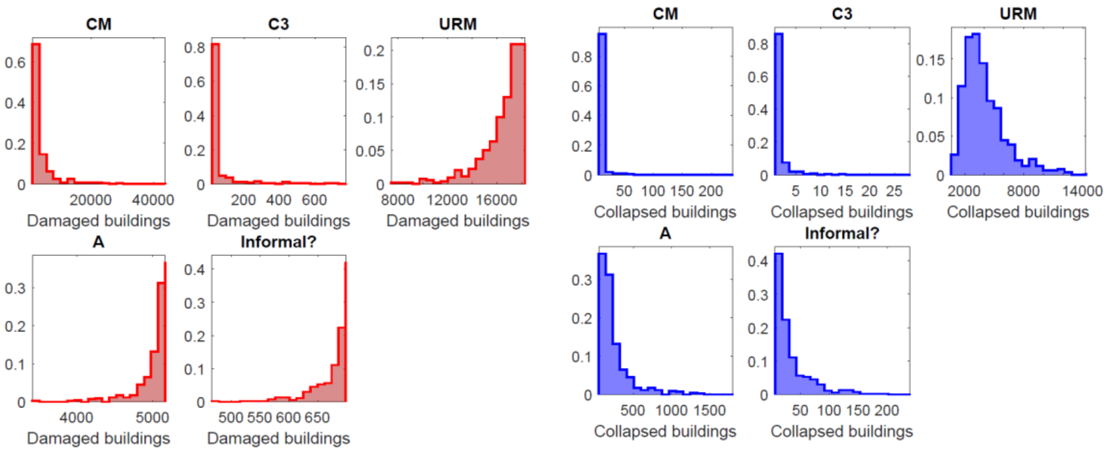

Figure 15: *(Left) number of damaged buildings, and (right) collapsed by typology.*

Table 4: *Mean number of damaged and collapsed buildings by typology from the simulation.*

Typology	Mean no. of buildings damaged	Mean no. of buildings collapsed
CM	3070	3
C3	44	1
URM	16422	3689
A	517	193
Informal	676	28
Total	**24,917**	**3,915**

The estimated affected population is approximately 20% of the people in the metropolitan area (Figure 16).

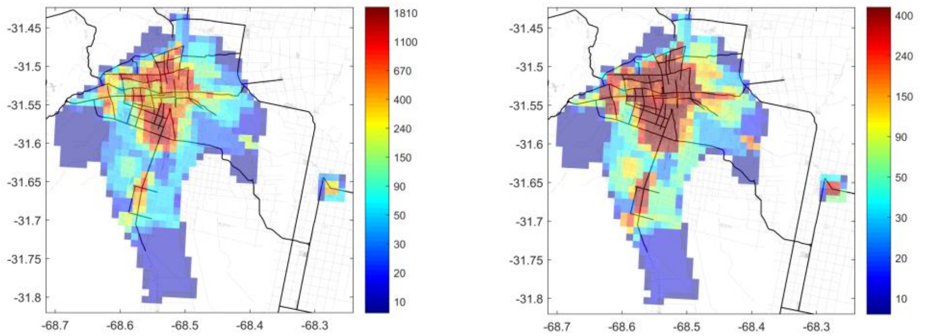

Figure 16: *(Left) affected population by damaged buildings (incl. collapsed).*

Simulated ground motion of the Caucete 1977 earthquake (7.4M_W)

Simulated accelerations (surface), using a smaller subset of the 10,000 realizations derived with the GMPE from ASK14, were consistent with information from the 1977 Caucete earthquake (USGS 2022) (Figure 17). This again lends some support to the possibility that ASK14 are not totally adequate to capture the situation in San Juan and the region. The impact of the recurrence of this earthquake on the current building inventory is indicated in Table 5.

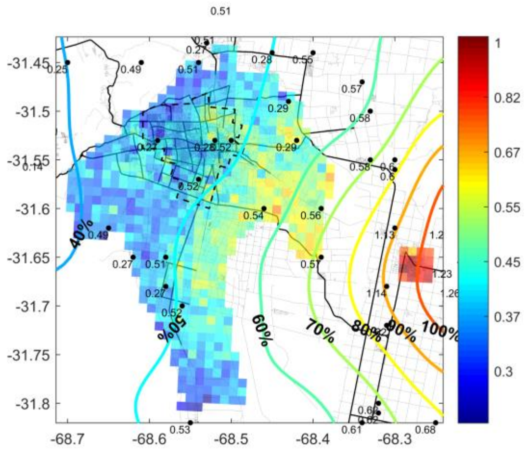

Figure 17: *Pseudo-accelerations (surface) of the Caucete 1977 earthquake. (USGS 2022).*

Table 5: *Number of damaged and collapsed buildings by typology.*

Typology	Mean number of damaged buildings	Mean number of collapsed buildings
CM	3768	0
C3	6	0
URM	24400	4762
A	5212	257
Informal	705	27
Total	**32068**	**5046**

SUMMARY AND DISCUSSION

A considerable difference between the damage obtained using different GMPEs. This reflects the importance of considering multiple GMPEs and developing GMPEs for the region. Nevertheless, the number of damaged and collapsed buildings was similar with the initial official estimates.

The typologies which sustained more damage were A and URM. Both comprise a large part of the inventory. Not much damage is expected from CM and C3 since such typologies are commonly constructed and designed according to seismic provisions.

In the simulation of the 2021 earthquake, adobe buildings exhibited most of the slight damage state, and most typologies with complete damage state were URM. In the case of the recurrence of the simulation of the Caucete 1977 earthquake, URM sustained most of the slight and complete damage states. Therefore, special attention must be directed to the retrofit efforts of URM and Adobe buildings.

In addition, the results for both earthquakes are compared side-by-side in Figure 18; note that medians are reported instead of mean values.

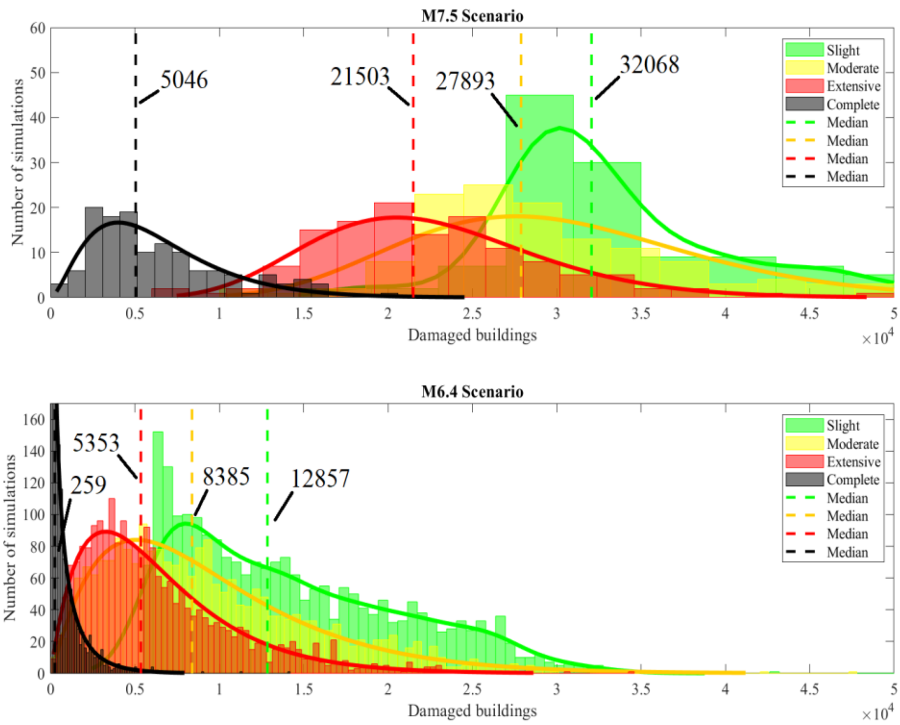

Figure 18: *Building damage distribution in (bottom) 2021 earthquake and (top) Caucete 1977 earthquake.*

CONCLUSIONS

The Pocitos earthquake (6.4M) appears to have damaged approximately 25,000 buildings and totally or partially destroyed more than 3,500 buildings, based on the computer simulation results conducted for this study. The damage is primarily concentrated in the Rawson departments, accounting for around 25% of the total number of damaged dwellings, followed by Chimbas, Pocito, Capital, and Rivadavia, which account for the remaining 60%. The population affected directly or indirectly can be around 20% of the people, where, fortunately, no casualties have been reported in this study. Loss estimates are not available for lack of unit cost information. All these parameters are mapped spatially with detailed maps.

Several necessary simplifications were made to conduct the study: modeling the extent and intensity of ground motion, distribution, and characteristics of building inventory. These assumptions influence the accuracy of the estimates and must be considered when reading results. At the same time, the simulated ground motion estimates were compared with recorded acceleration values from local accelerometers, and the match was found to be acceptable.

The study also singled out significant problems and information gaps by which future estimates may underestimate the extent of damages. Salient among these are lack of granularity in the information about local site effects and the absence of an attenuation function which reflects the geological and seismological characteristics of the San Juan metropolitan region. This study also indicates areas in which research is needed, and its results will be directly beneficial to better forecast the effects of the occurrence of a future earthquake.

The contributions of this study lay in it being a tool to inform decision-makers on research needs, provide data and a platform to planners and policymakers to improve system resilience (preparedness: evacuation, sheltering, first-care relief). The simulation also allows future scenarios to be used as input in raising awareness in communities, services, and emerging leaders, allows government officials to develop better response plans, and constitutes a tool for the government to foresee vulnerable spots and provide mitigation strategies.

In formulating and calibrating the simulation for this study, several information gaps were identified which have a direct bearing on the accuracy and reliability of the characterization of the earthquake and its effects in San Juan, and that require attention:

- There are not adequate attenuation functions to San Juan. The GMPEs adopted from other studies (ASK14) lower peak ground accelerations (PGA) ground motion values.
- More comprehensive and detailed microzonification studies are needed to better characterize the spatial variability of the shear velocity.
- Fragility functions of San Juan's building typologies must be derived. The adoption of functions derived for typologies in other countries (HAZUS, Peru, etc.) may not fully capture the response of the San Juan typologies.
- A more detailed inventory survey to develop better damage estimates. This includes data on year built, level of engineering design, building code (structural standards) enforcement, construction quality, inspection/permitting process, and replacement values.

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APPENDIX

Direct damages published in news outlets

San Juan Departments	Albardon	Caucete	Pocito	Capital	San Martín	Rivadavia	Rawson	Santa Lucía	Ullum
News-Data Compilation-House Damage									
In Albardón 10 uninhabitable houses, in Caucete 25 houses partially collapsed, in Pocito 50 houses collapsed and 2 adults and 2 children with serious injuries, in RIvadavia damage was verified in 6 adobe houses, San Juan Capital 25 houses with partial collapse and evacuated 2 buildings with cracks, San Martin damages in 10 adobe houses, Santa Lucia damages in 20 houses, Ullum damages in 9 adobe houses	**10 destroyed**	**25 damaged**	**50 destroyed**	**25 damaged**	**10 damaged**			**20 damaged**	**9 damaged**
The greatest damage was to the south of the province, in the departments of Rivadavia and Pocito, in addition, the RN40 route suffered cracks along 4km									
2000 to 3000 families have adobe houses and were affected by the earthquake	**2,000 to 3,000 families have adobe houses and were affected by the earthquake**								
47 days after the earthquake there are still, at least, 35 families living in the open in precarious nylon houses and wooden poles.	**35 homeless families after 2 months of the earthquake**								
60 schools are undergoing repairs (minor or reversible damage). In another 20 schools, the damage was greater (structural). Of those 20 schools with structural damage, at least 6 will be demolished.	**60 Schools with partial damage, 20 schools with structural damage and 6 schools destroyed**								
Damage to Juan Victoria Auditorium (an icon of San Juan culture): detachment of the ceiling in the south and north parts of the building, broken glass and damage to the organ (a valuable instrument acquired in 1967). The registered damage suffered by the organ was in some of its tubes (displaced and / or bent).	**Juan Victoria Auditorium damaged**								
500 houses destroyed and 900 houses damaged, in Pocito Department.			**500 destroyed 900 damaged**						
In the settlements of Pellegrini and La Paz, inhabited by more than 240 families, the earthquake caused the destruction of 40% of the homes.						**100 destroyed 140 damaged**			
Cracks in the routes, "In Colonia Fiscal and Media Agua, precarious homes collapsed and their occupants had to spend the night outside, on mattresses. In many shops and supermarkets roofs and gondolas fell and in dozens of houses there were objects and glass knocked down and shattered. At 1am Firefighters and the Police evacuated the	**Cracks in the roads, gas leaks, broken glass in houses and markets, precarious collapsed houses**								
100 houses with structural damage in Rawson Department. 1 house collapsed.							**100 damaged 1 destroyed**		

PGA information reported

Current info from USGS ("did you feel it" source) ~subjective

- VI MMI (31.531°S 68.563°W) ~0.14g
- VII MMI (31.540°S 68.563°W) ~0.24g
- VII MMI (31.540°S 68.552°W) ~0.28g
- V MMI (31.549°S 68.563°W) ~0.10g