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San José, Costa Rica



MINISTERIO DE  
MEDIO AMBIENTE  
Y RECURSOS  
NATURALES



Universidad de El Salvador  
*Hacia la libertad por la cultura*



# ASSESSING SEISMIC RISK FOR EFFECTIVE DISASTER MANAGEMENT AT AN URBAN SCALE IN EL SALVADOR

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Affiliations:

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<sup>2</sup>University of El Salvador

<sup>3</sup>Global Earthquake Model Foundation (GEM)



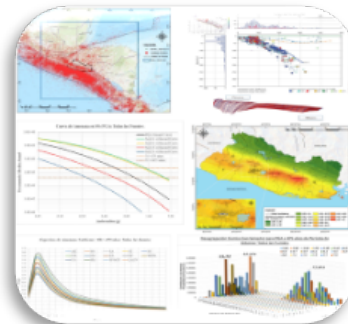
# INTRODUCTION

➤ This study presents the first results of the collaborative effort between Ministry of the Environment and Natural Resources of El Salvador (MARN), the University of El Salvador and the Global Earthquake Model Foundation under the Forecasting and Communicating Earthquake Hazard and Risk (FORCE) project framework, to estimate probabilistic seismic risk for the national building stock.

## FORCE

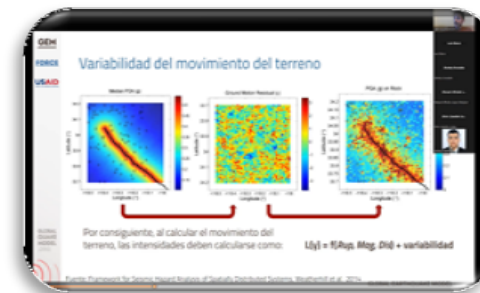
### Knowledge

State-of-the-art on seismic hazard and risk modelling to forecast future risk



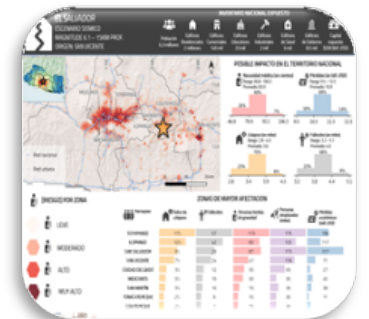
### Training

Strengthening local capacities and consolidating a technical community network



### Communication

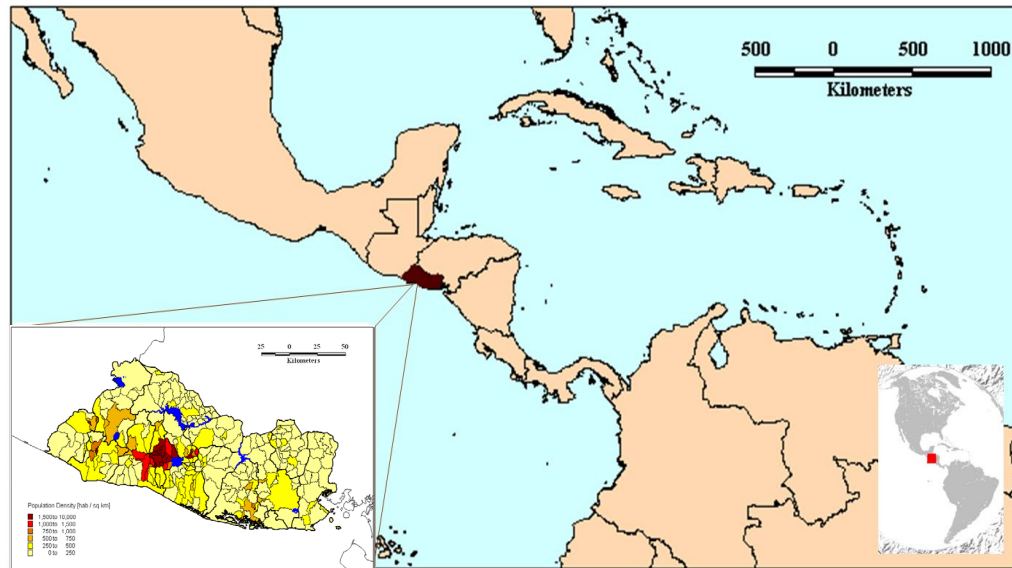
Usable information for stakeholders and decision-making authorities





# EL SALVADOR: A Multi-hazard territory - The Valley of The Hammocks

- Smallest and most densely populated country in Central America.
- According World Risk Report 2023, El Salvador has very high World Risk Index, ranking it 34th worldwide.
- National Exposure Model presents more than 2 million assets and approx. 6.2 million occupants.



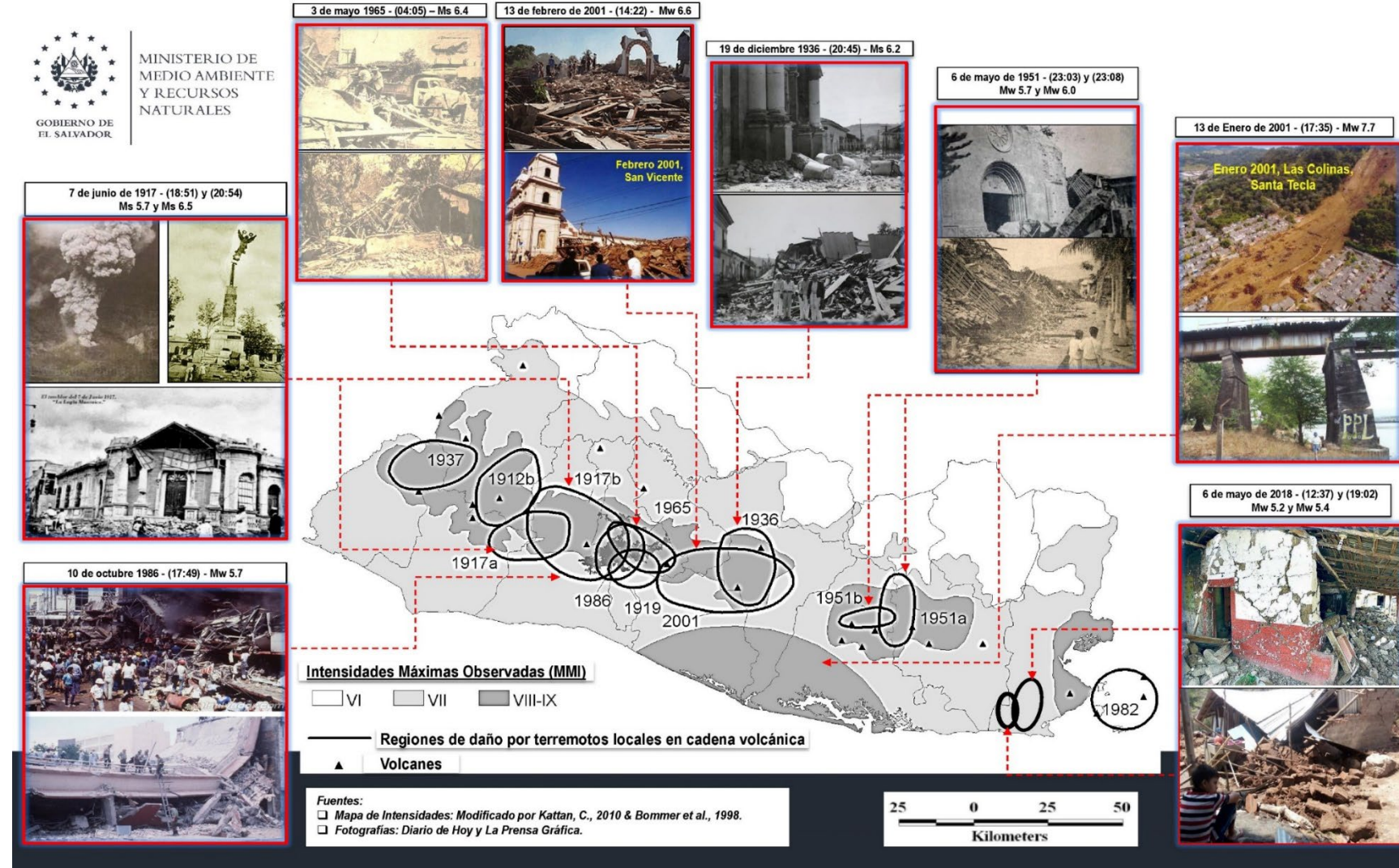
Source:  
<https://snet.gob.sv/informacion/?area=sismologia>





# EL SALVADOR: Has suffered significant earthquakes in the past

- The seismic source that most contributes to the country's seismic hazard is the **Active Shallow Crust**
- It matches with the axis of the volcanic chain and where the Geological Fault Zone of El Salvador is located.

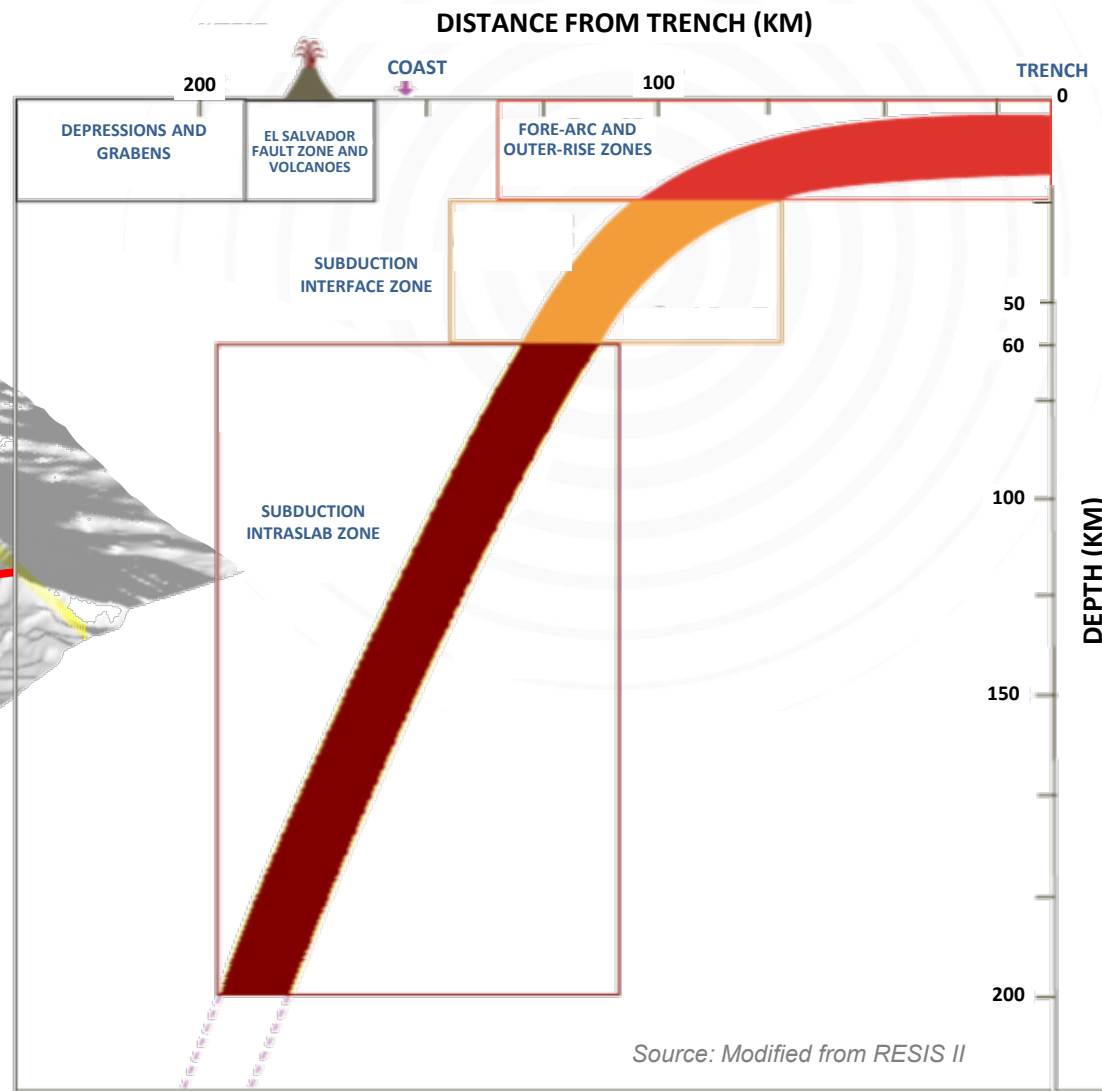
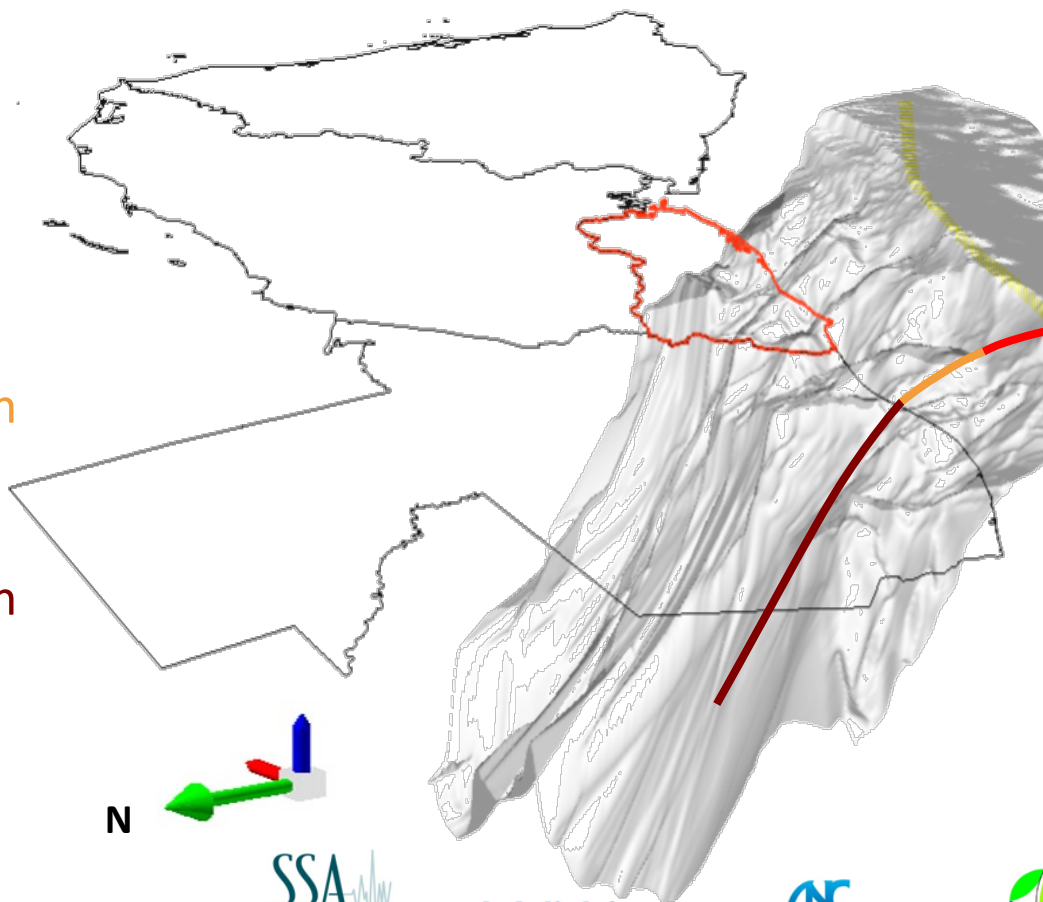




# SEISMIC HAZARD: Seismic source characterization for modeling

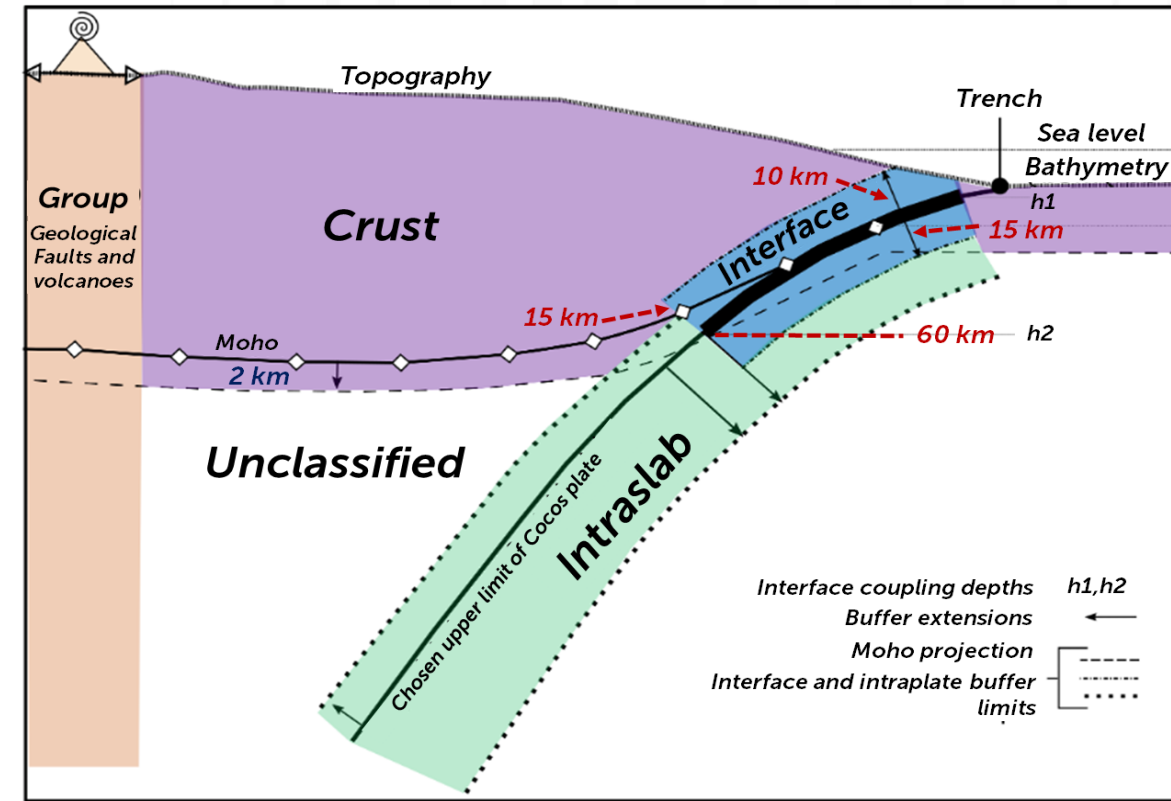
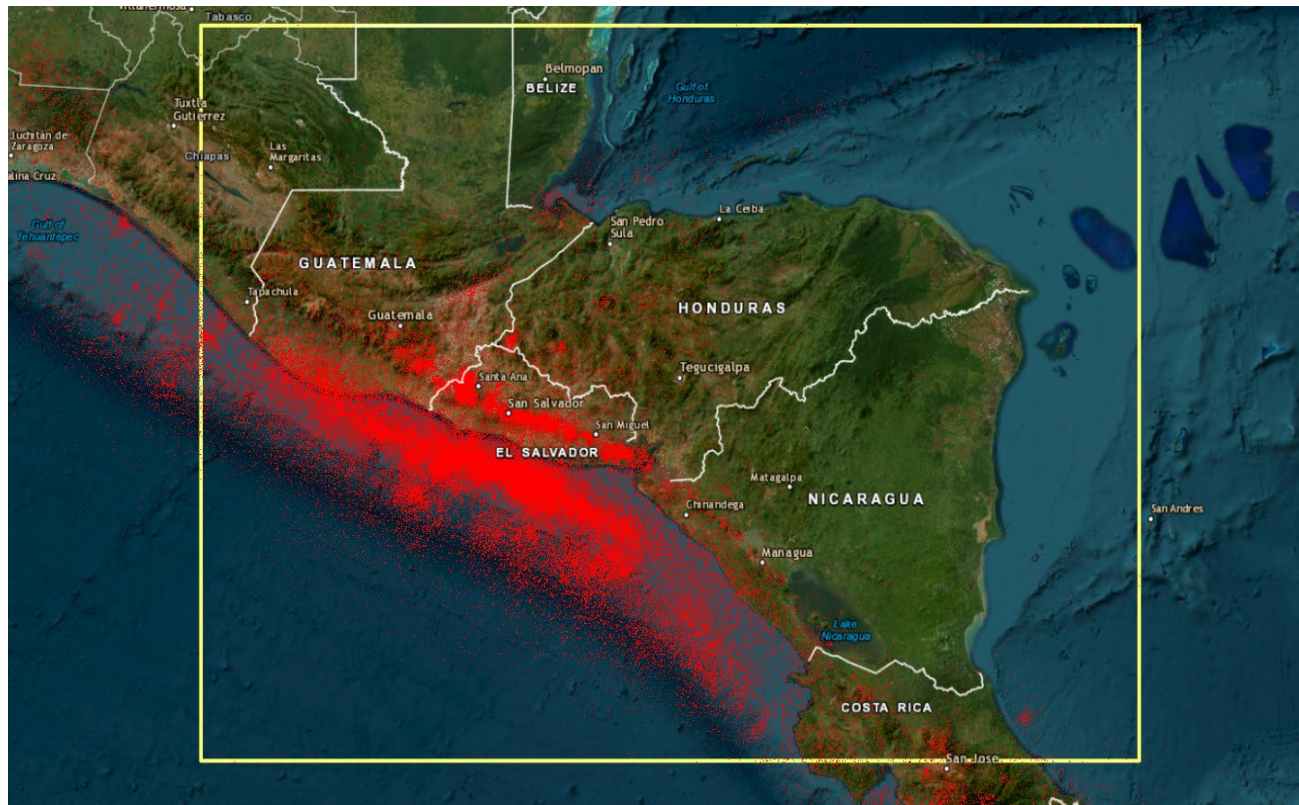
➤ Due to the tectonic environment in El Salvador, the main seismic sources are subdivided in three:

- ➡ Active shallow Crust
- ➡ Subduction Interface
- ➡ Subduction Intraslab

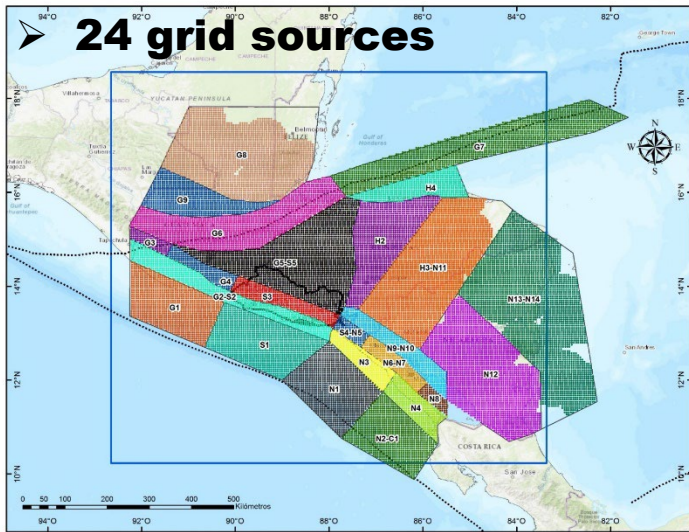


# SEISMIC HAZARD: Regionalization of seismic catalogue according tectonic and rupture mechanisms

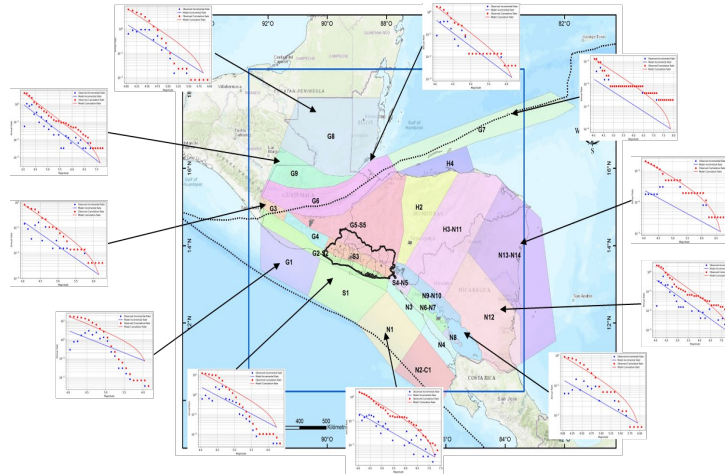
- Compilation of homogenized seismic catalog from different agencies
- Criteria definition for regionalizing the catalog by tectonic environments



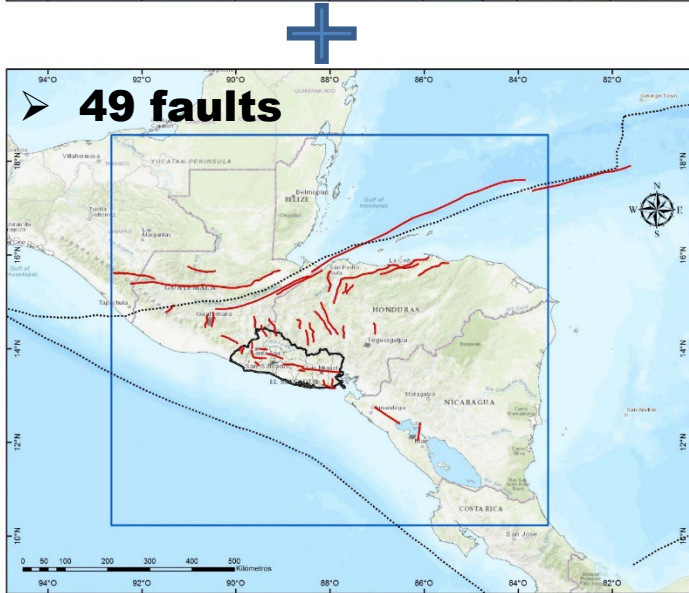
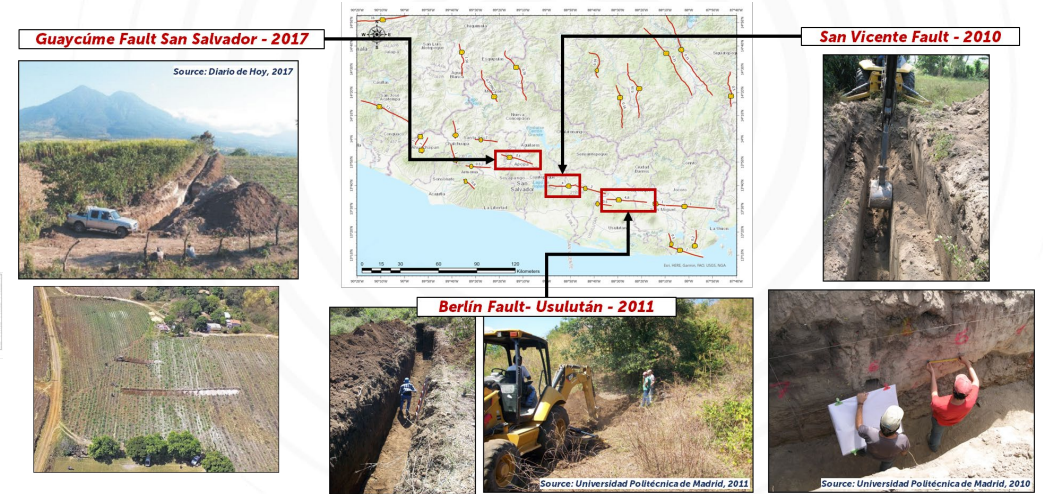
# SEISMIC HAZARD: Seismic source characterization for modeling: geological faults + grid sources



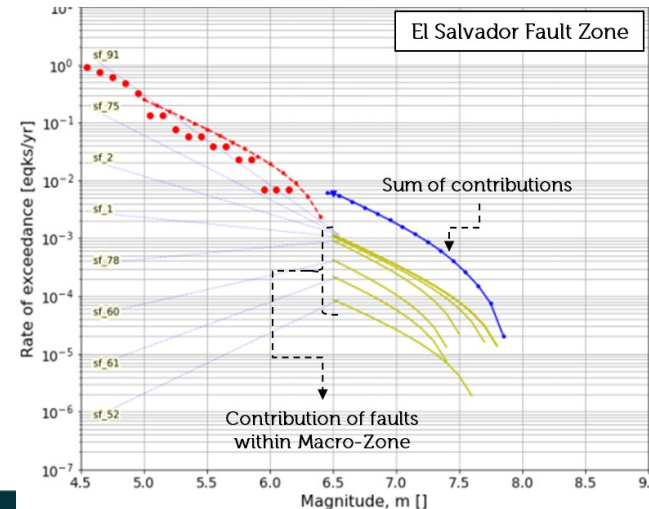
➤ Recurrence rates in sources



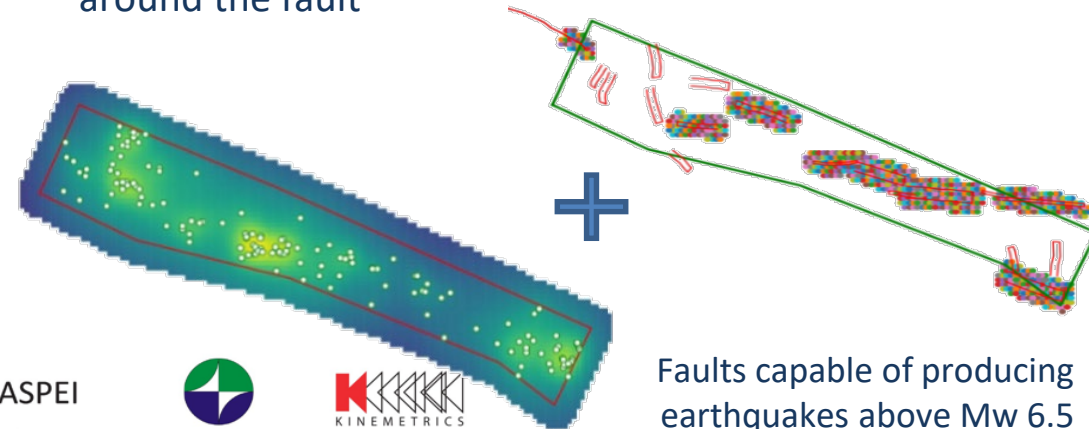
➤ Activity rates derived from Paleo-studies



➤ MFD for El Salvador Fault Zone



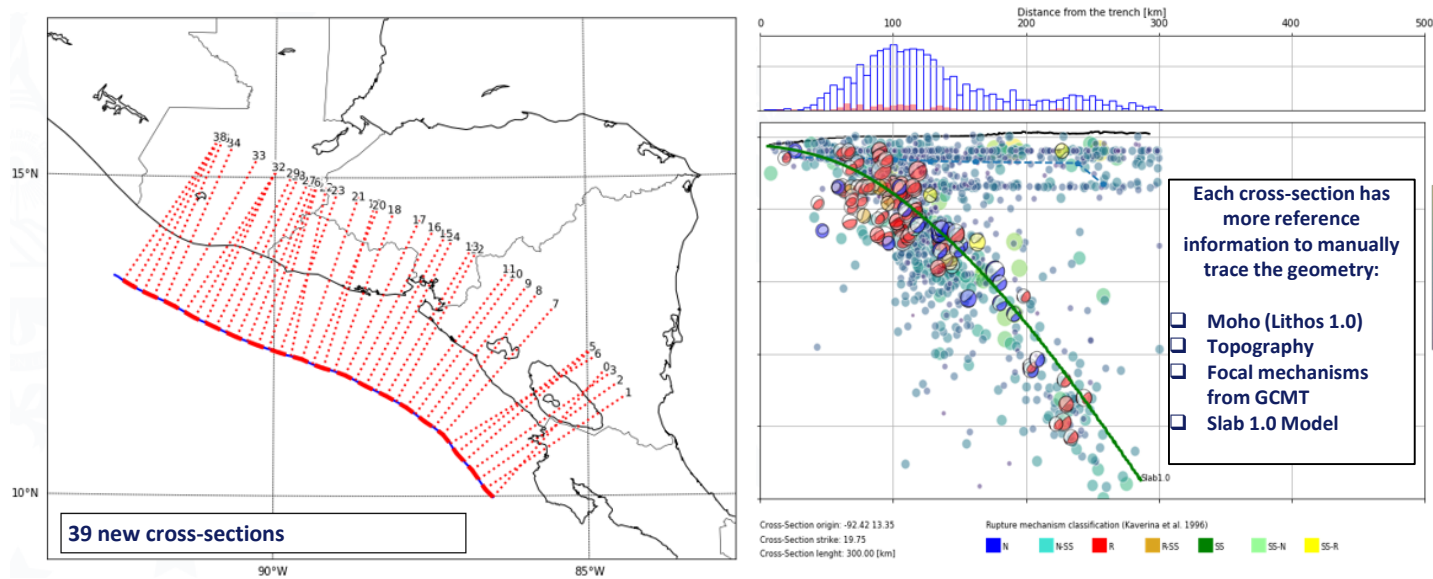
➤ Avoid duplicity in the calculus using 10 km buffers around the fault



Faults capable of producing earthquakes above Mw 6.5

# SEISMIC HAZARD: Seismic source characterization for modeling: subduction zone

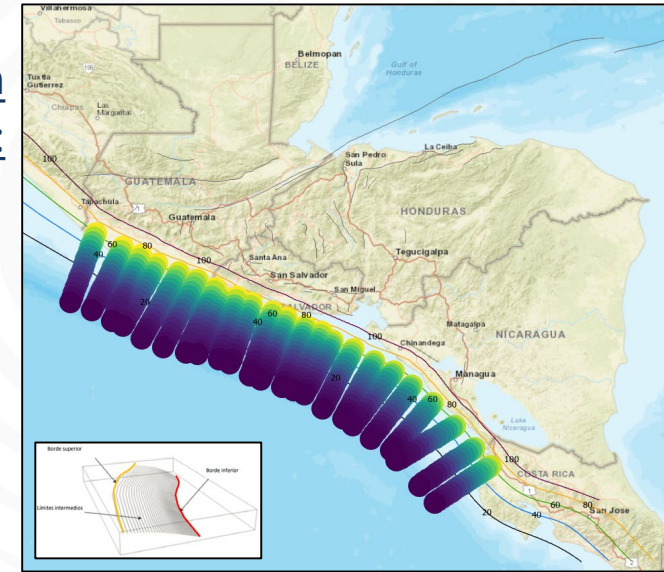
➤ Definition of Cocos Plate geometry off the coast of El Salvador



Source: CCARA-GEM, 2017

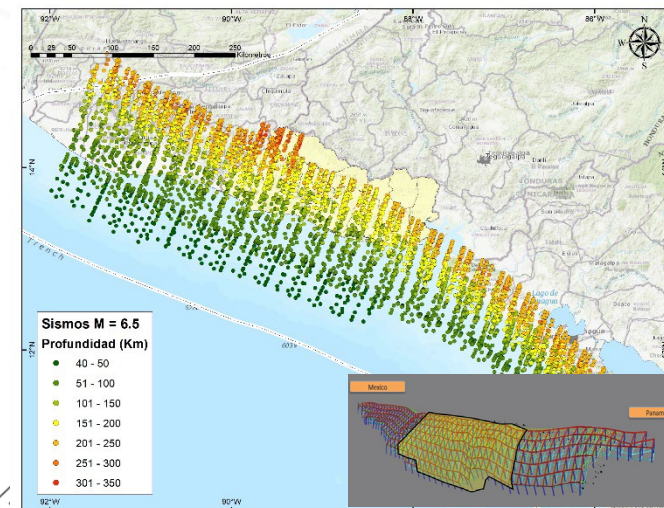
➤ Subduction Interface:

Modeled as complex surfaces, since their geometry can vary in depth



➤ Subduction IntraSlab:

Modeled as a collection of ruptures, where each one has its probability of occurring.



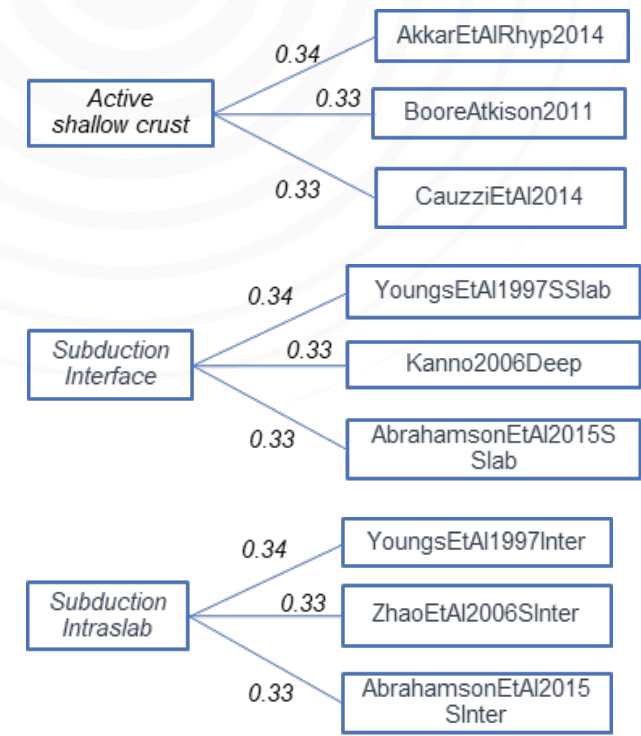
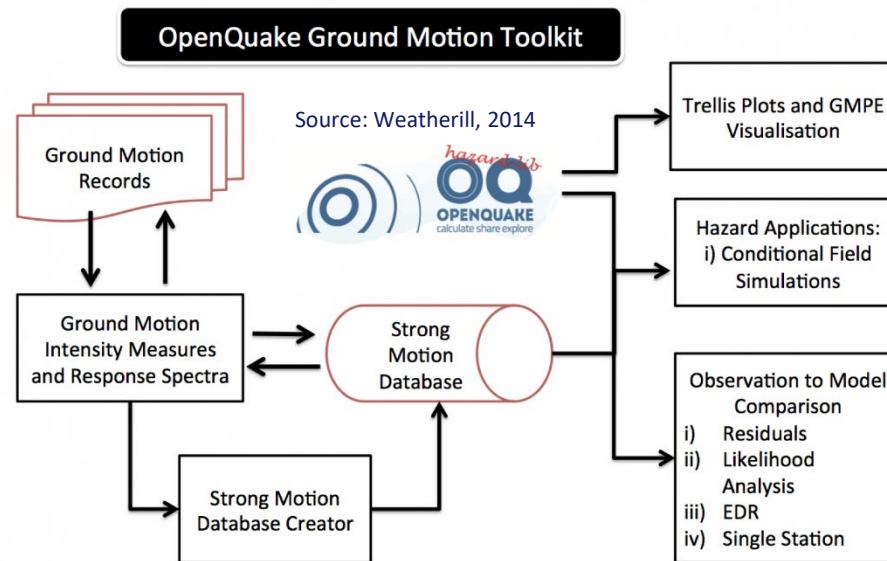
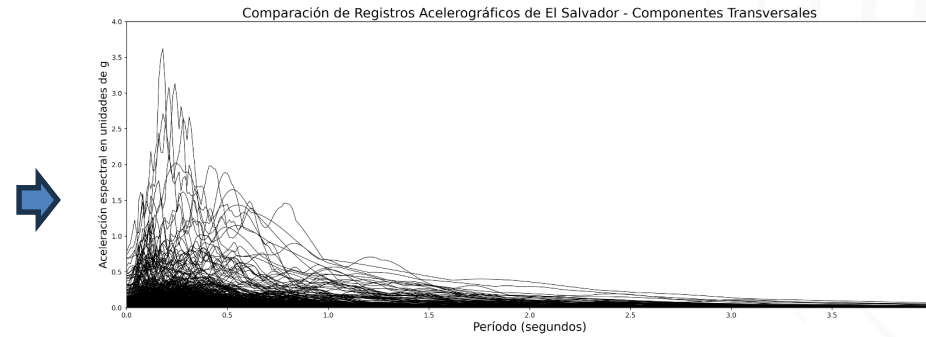
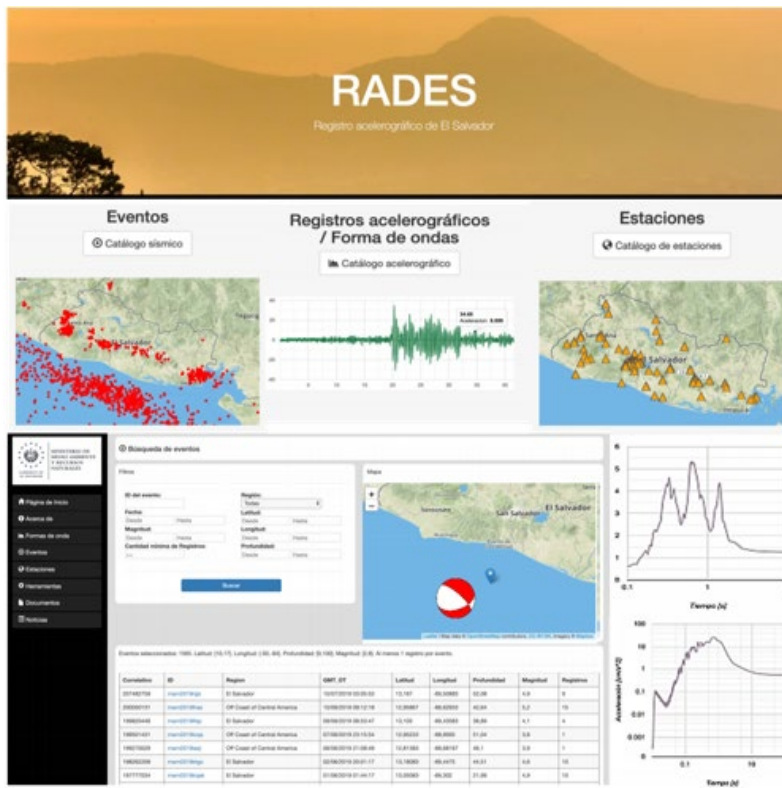
Source: CCARA-GEM, 2017





# SEISMIC HAZARD: Ground motion characterization using local records

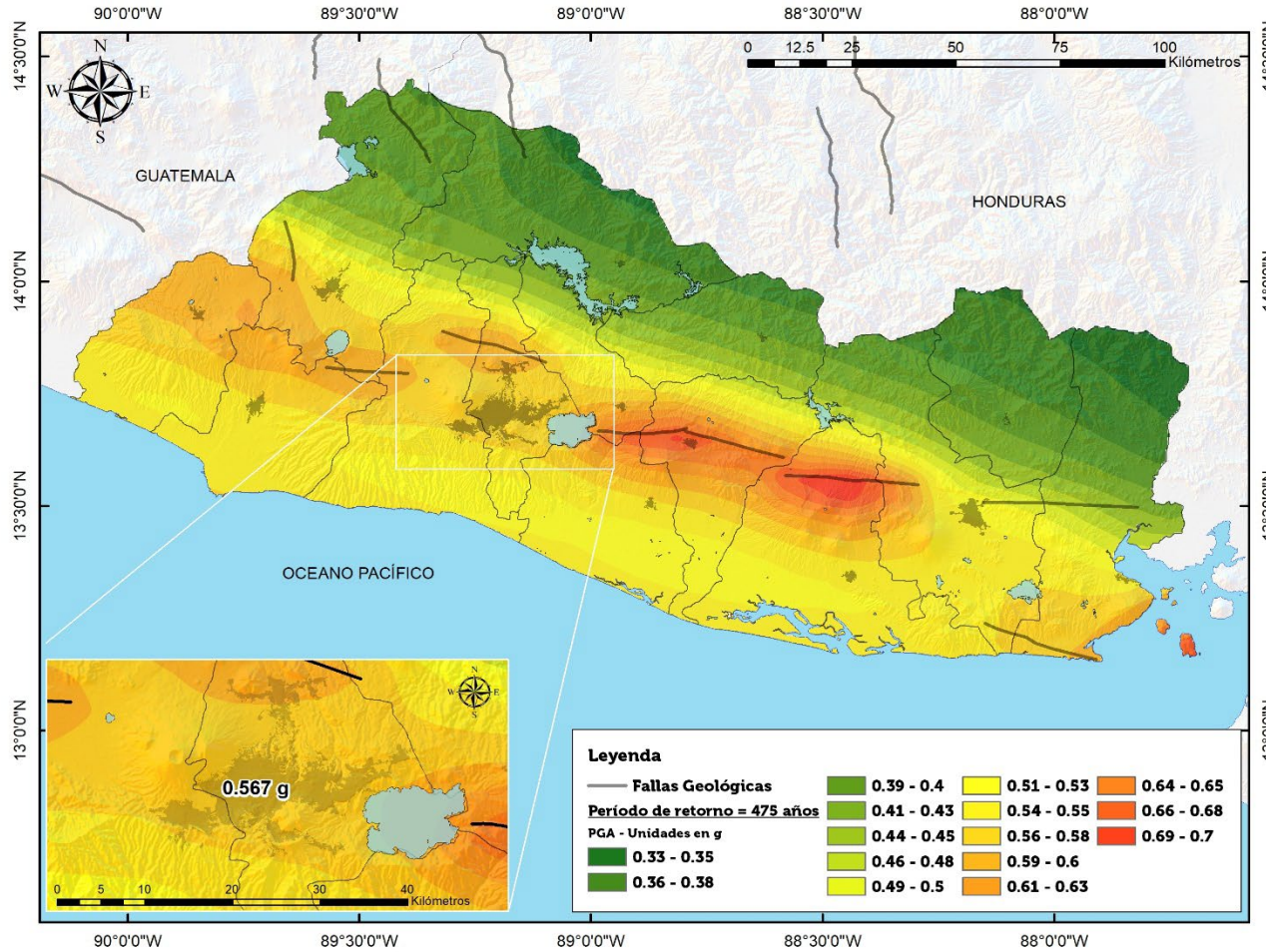
- Use of GEM's Strong Motion Toolkit and El Salvador Strong Motion Database (RADES) to evaluate models and statistical criteria to analyze the fit between observed data and those predicted by GMPEs according to the tectonic environment of the seismic sources.





# SEISMIC HAZARD: Seismic hazard map on rock and disaggregation charts for some return periods

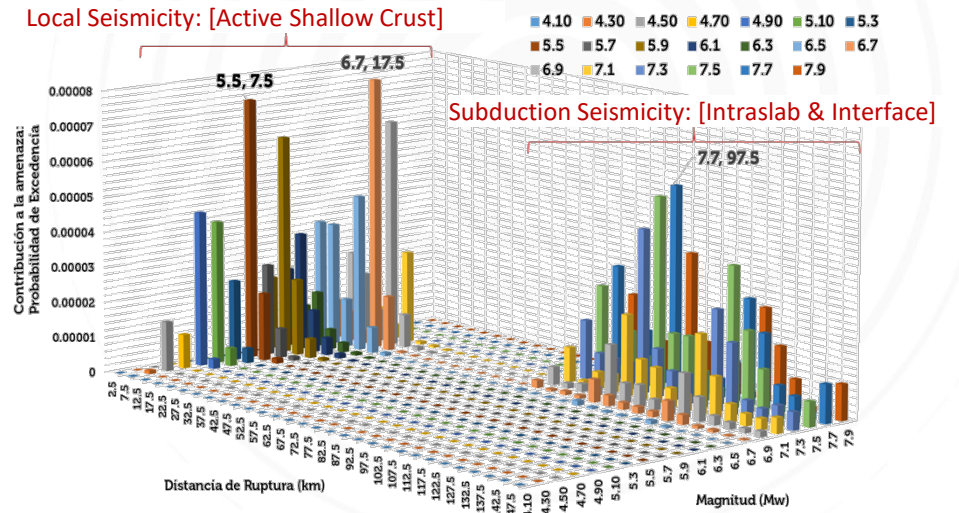
➤ PGA - Return Period: 475 years



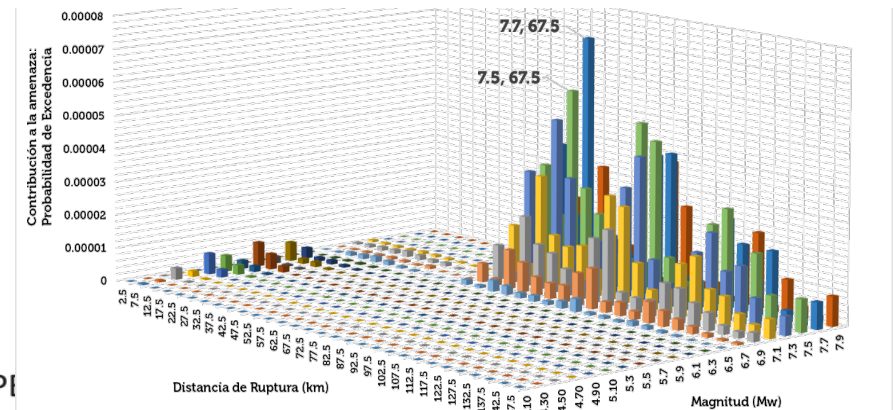
**Leyenda**

— Fallas Geológicas	0.39 - 0.4	0.51 - 0.53	0.64 - 0.65
Período de retorno = 475 años	0.41 - 0.43	0.54 - 0.55	0.66 - 0.68
PGA - Unidades en g	0.44 - 0.45	0.56 - 0.58	0.69 - 0.7
	0.46 - 0.48	0.59 - 0.6	
	0.36 - 0.38	0.49 - 0.5	0.61 - 0.63

➤ San Salvador city



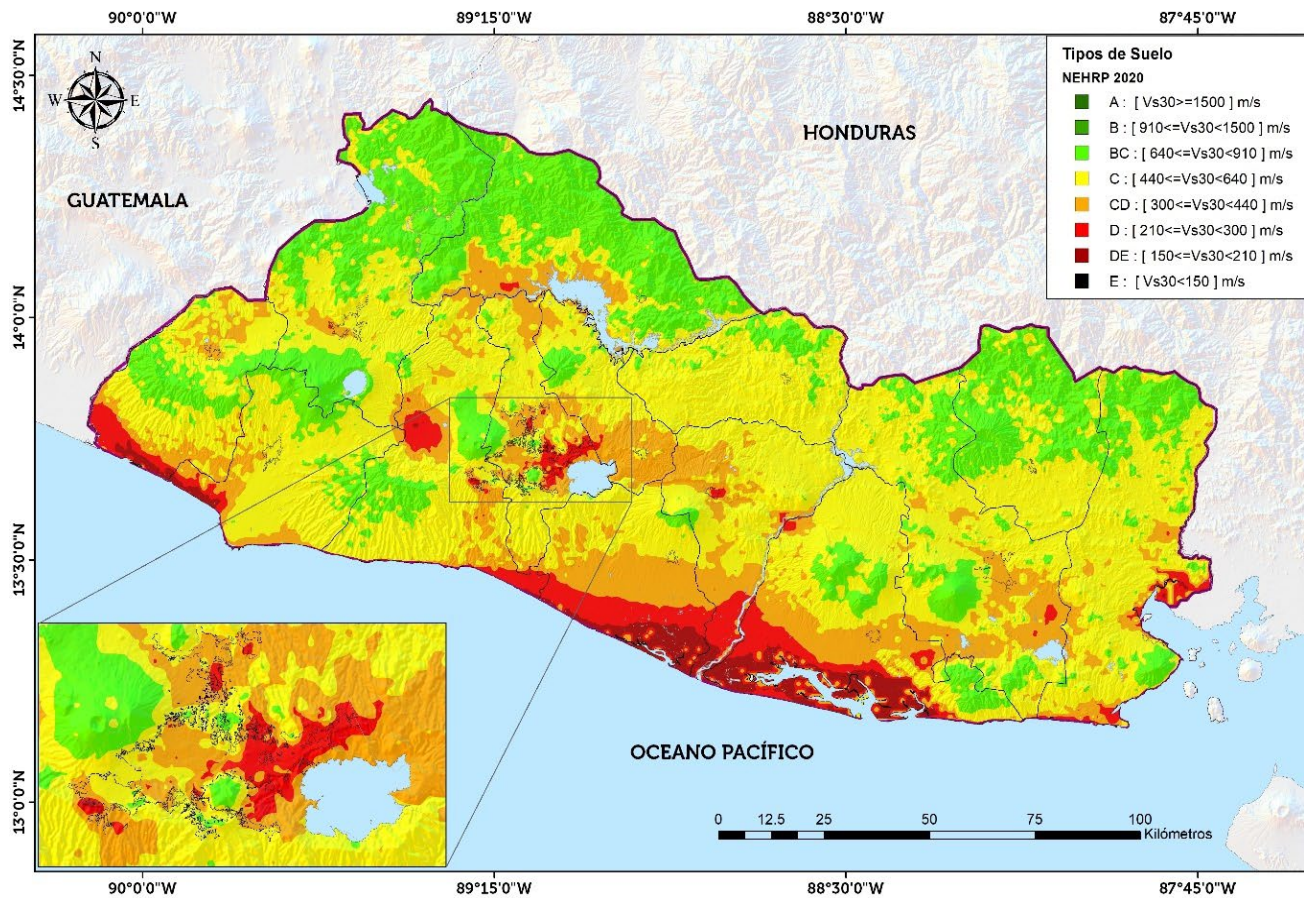
➤ Acajutla city



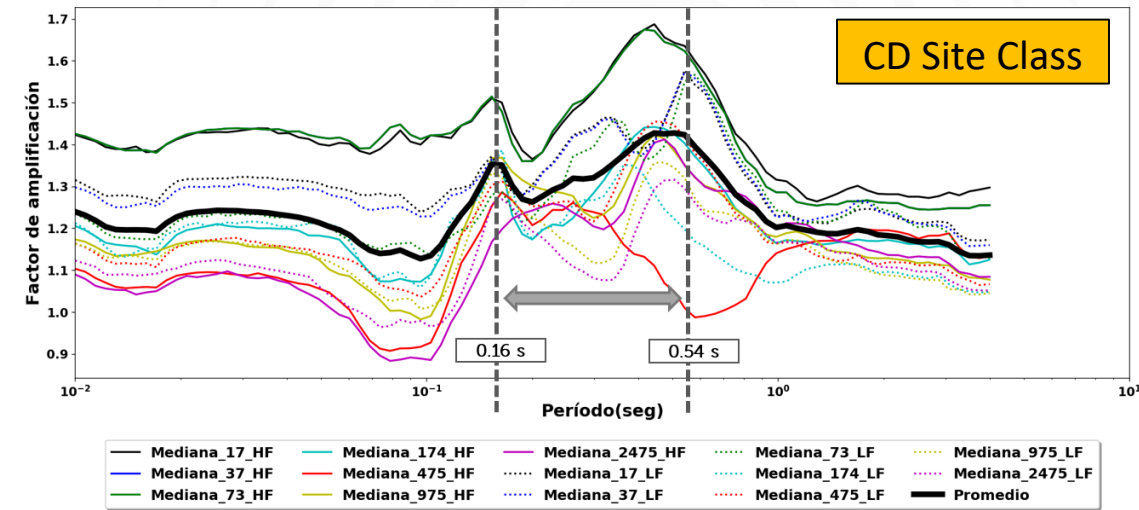


# SITE CHARACTERIZATION: Using proxy Vs30 map and amplification functions for site classes

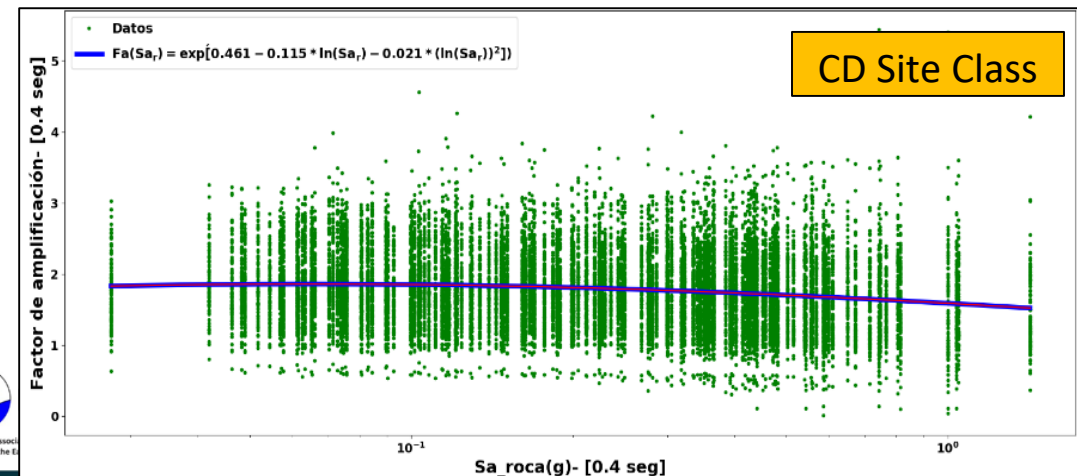
➤ Vs30 Map classified by site classes, using geological and downhole data through machine learning



➤ Average transfer functions for 6 site classes



➤ Amplification functions for 6 site classes





# EXPOSURE MODEL FOR EL SALVADOR: Creation of infrastructure exposure

## ➤ Basic data in the Exposure Model

Building's number with spatial and structural attributes

Occupants at morning



Value of exposed assets

Structural Typology that resists lateral loads

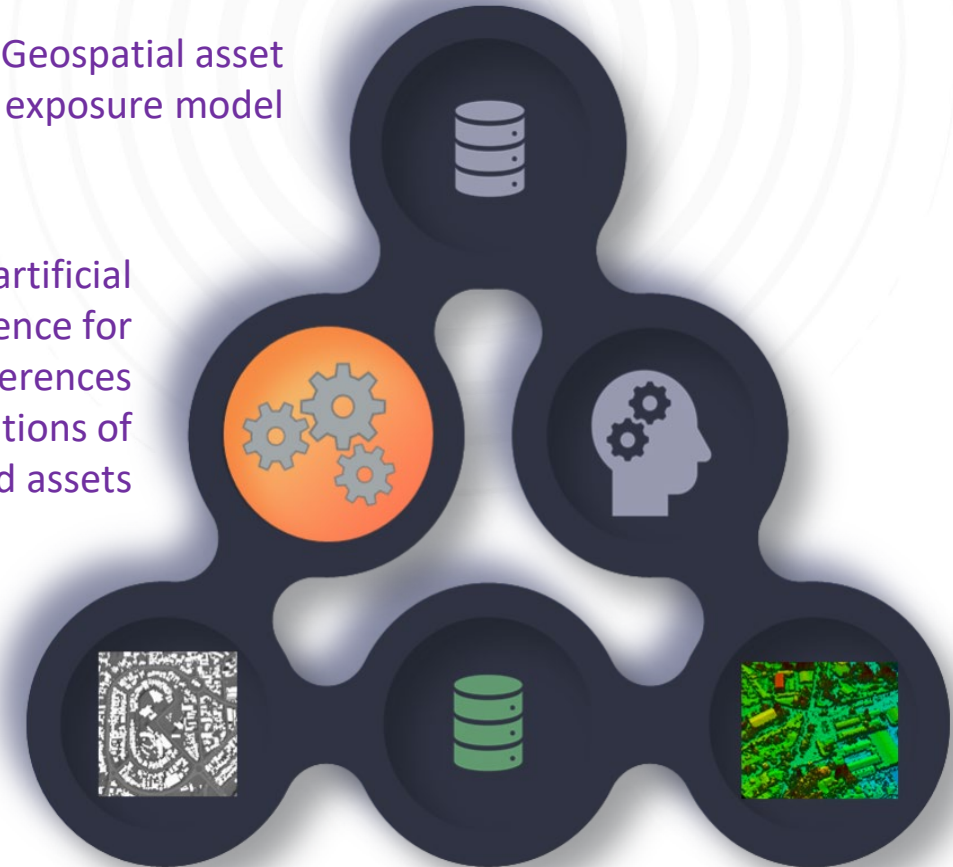
Occupants at night

## ➤ Exposure model construction

Geospatial asset exposure model

Using artificial intelligence for attribute inferences and cost calculations of exposed assets

Digitization, collection and data analysis from cartographic studies, censuses, etc.

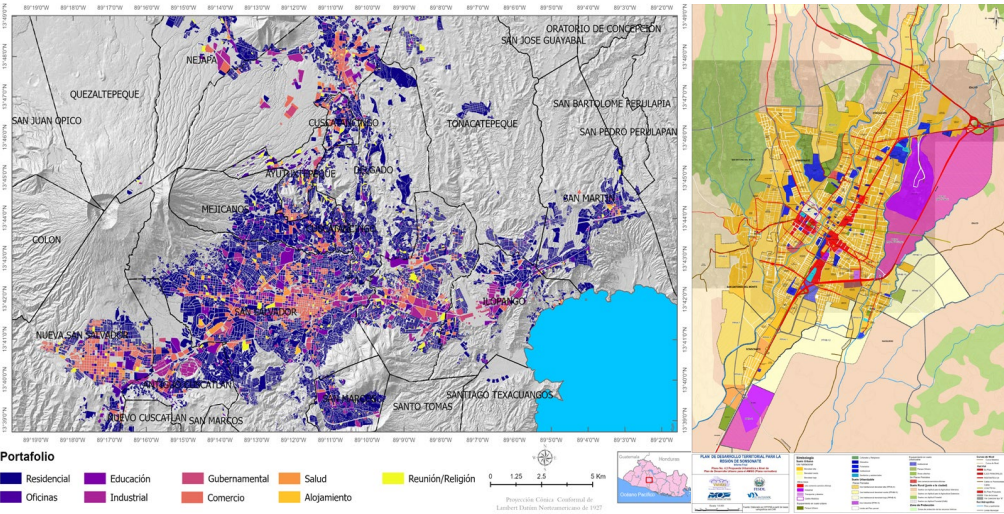




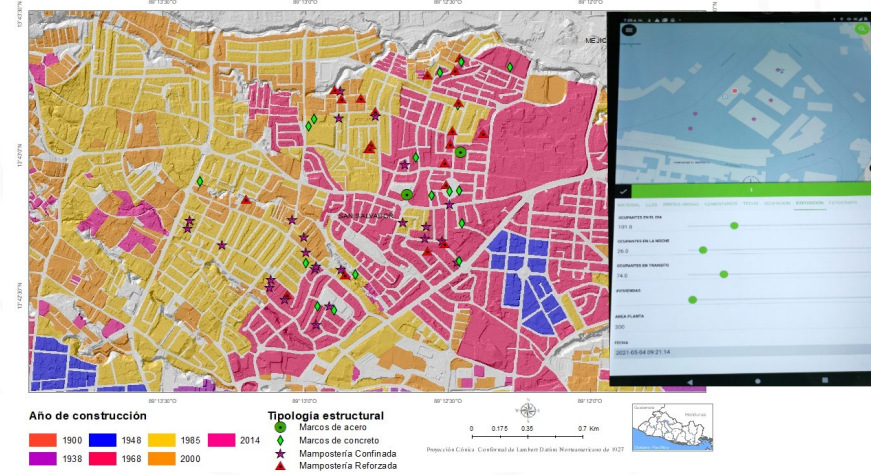
# EXPOSURE MODEL FOR EL SALVADOR: Data used as input for the exposure characterization

➤ Field surveys to estimate construction year and structural typologies

➤ Territorial Planning Maps to estimate land use



Tipología Estructural  
Miramonte, San Luis, Universitaria



➤ Open Building footprints from Google



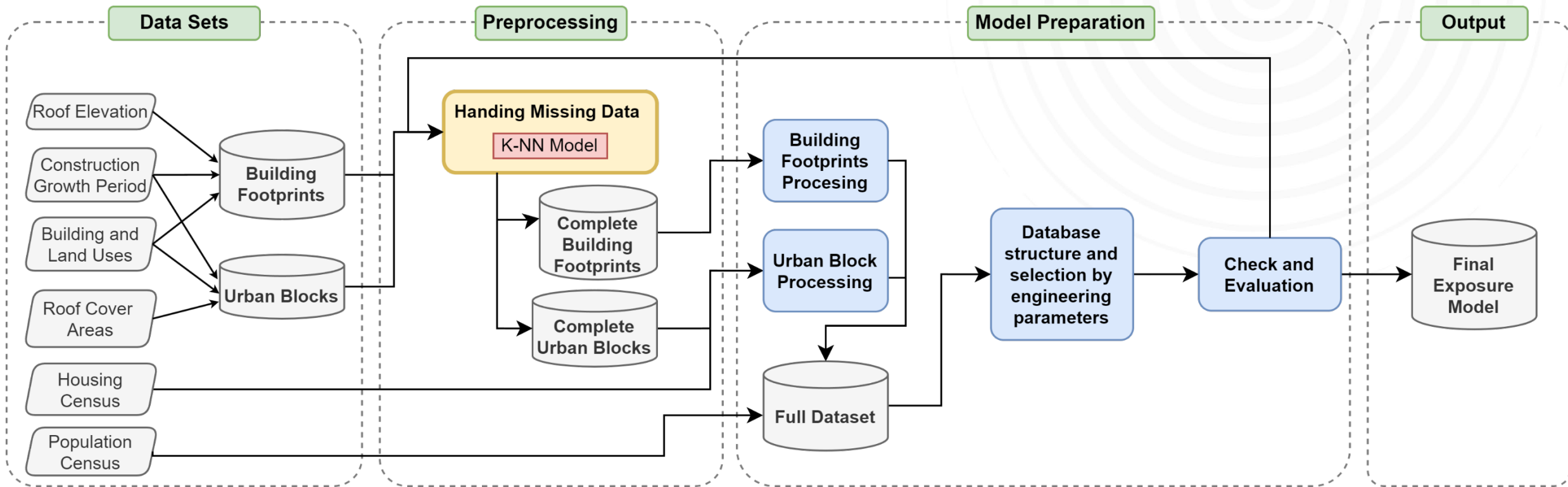
➤ LIDAR data to estimate roof elevation





# EXPOSURE MODEL FOR EL SALVADOR: Flowchart for data collection

- Flowchart presenting the process of data collection, processing and preparation performed to obtain a national exposure model for El Salvador.





# EXPOSURE MODEL FOR EL SALVADOR: Main building classes identified with their structural attributes

Material	LLRS	Description	Code levels	Storeys
CR	LFINF	Reinforced concrete frames with infills	CDN, CDL, CDM	H:3 to H:25
	LFM	Reinforced concrete moment resisting frames		
	LDUAL	Reinforced concrete with dual systems (frames and shear walls)		
MATO	LN	Waste and light materials	CDN	H:1
MCF+CBH	LWAL	Confined and reinforced concrete masonry shear walls	CDN, CDL, CDM	H:1 to H:3
MR+CBH	LWAL	Unconfined reinforced concrete masonry shear walls	CDN, CDL, CDM	H:1 to H:3
MUR+ADO	LWAL	Adobe masonry shear walls	CDN	H:1
S	LFM / LFBR	Hot-rolled steel moment resisting frames	CDL, CDM	H:1 to H:3
W+WLI	LN	Light wood moment resisting frames	CDN, CDL	H:1
W+WWD	LWAL	Bahareque shear walls	CDN	H:1



CDN: No Design Code  
 CDL: Low Design Code  
 CDM: Medium Design Code



# EXPOSURE MODEL FOR EL SALVADOR: Photographs of some buildings typologies found in the country

REINFORCED MASONRY



RC MOMENT FRAMES



RC WALLS



CONFINED MASONRY



RC INFILLS WALLS



STEEL FRAMES







# EXPOSURE MODEL FOR EL SALVADOR: Photographs of houses constructed with the most vulnerable materials

ADOBE



SHEET METAL



BAHAREQUE



STRAW



WOOD



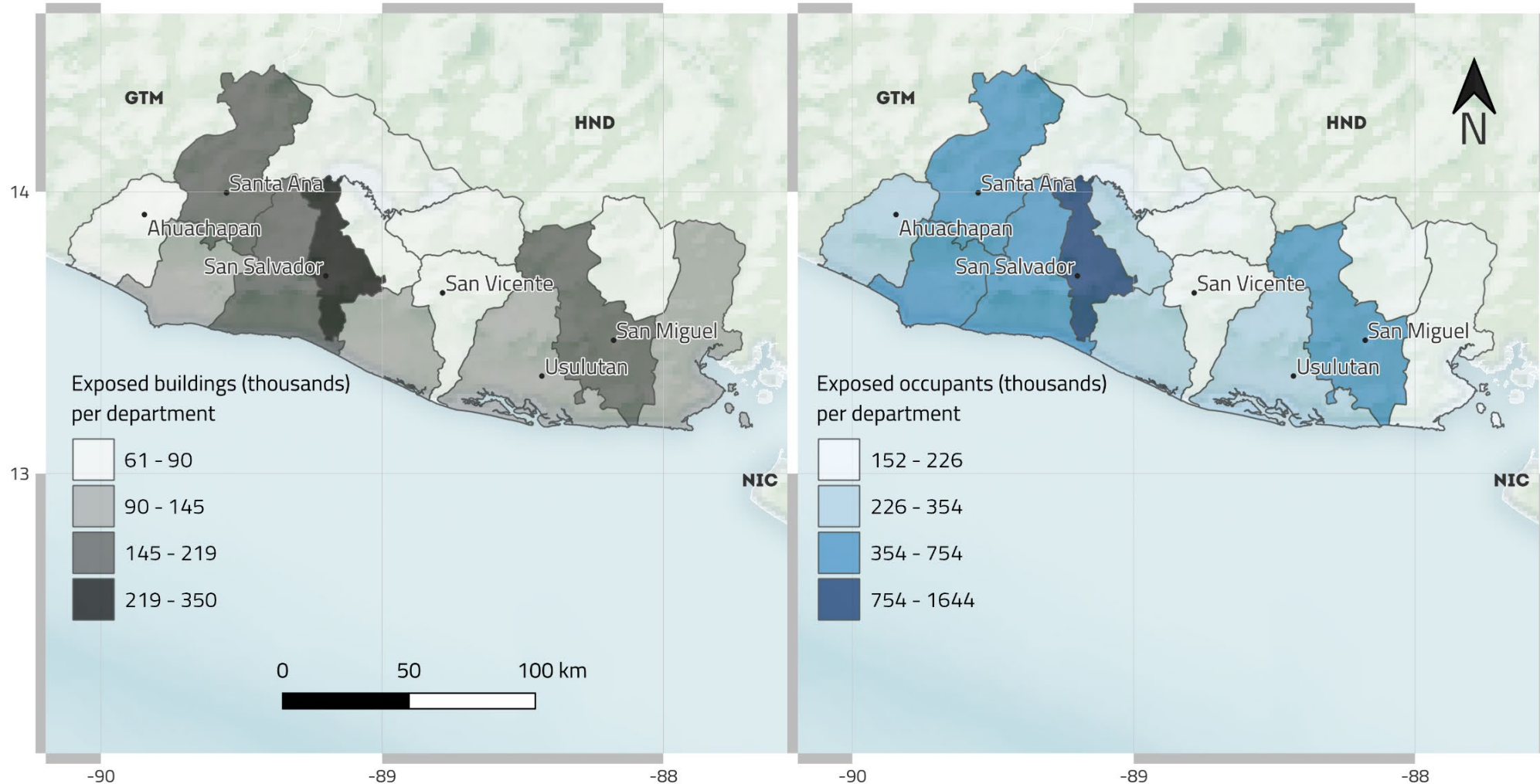
WASTE MATERIALS





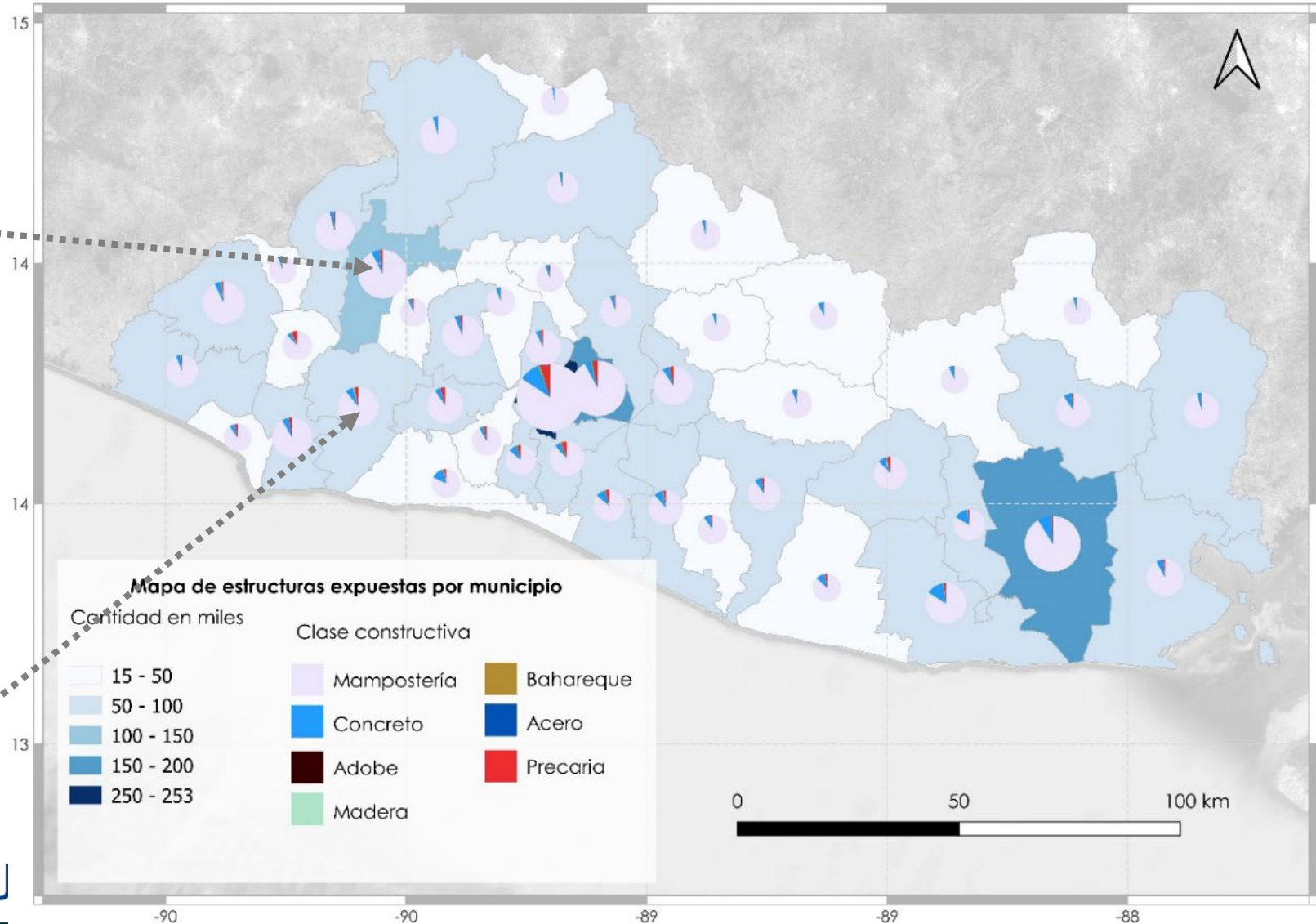
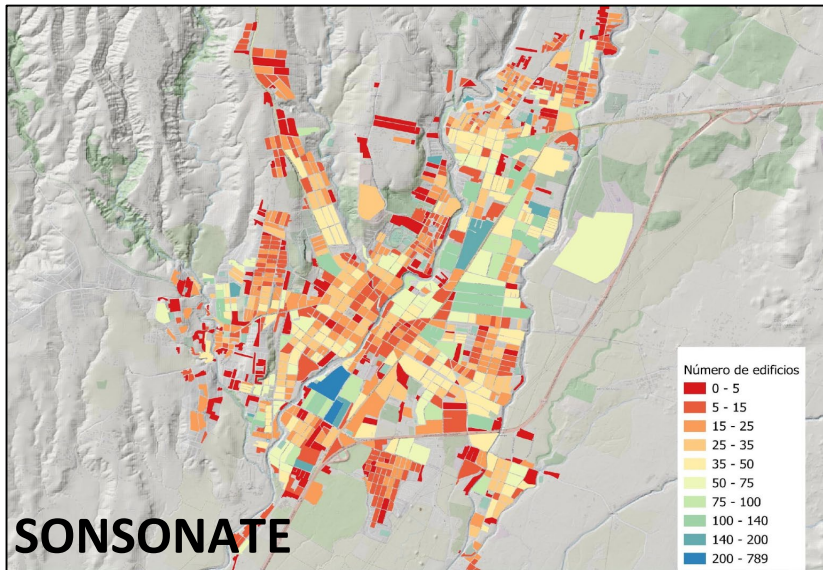
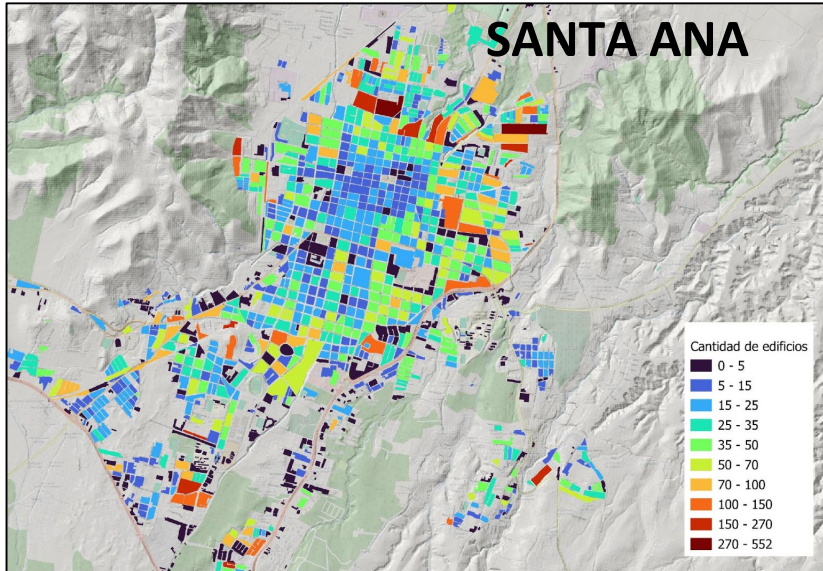
# EXPOSURE MODEL FOR EL SALVADOR: Summary of national exposure model at department level

➤ Spatial distribution of the national building stock and occupants per administrative department



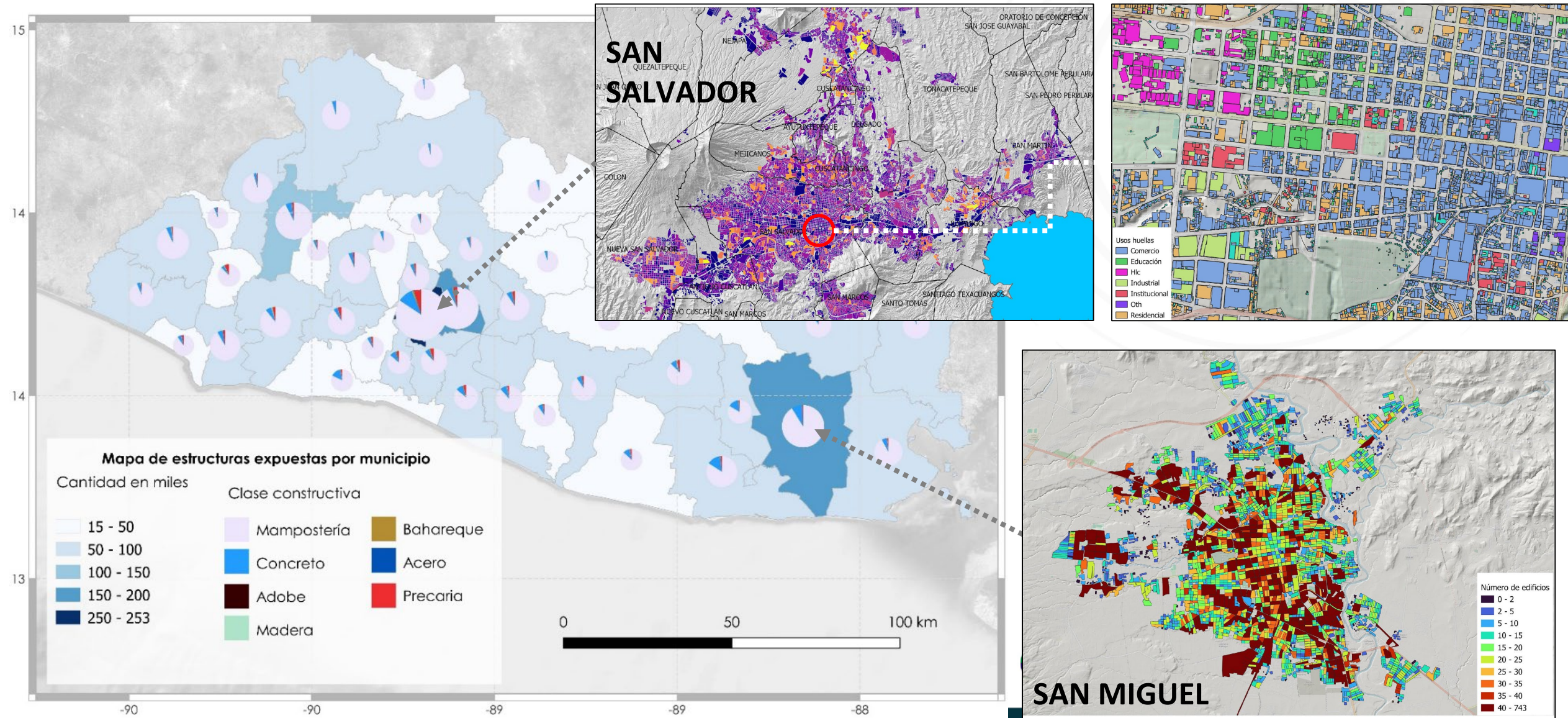


# EXPOSURE MODEL FOR EL SALVADOR: Summary of the national exposure model at municipal and city level (1)



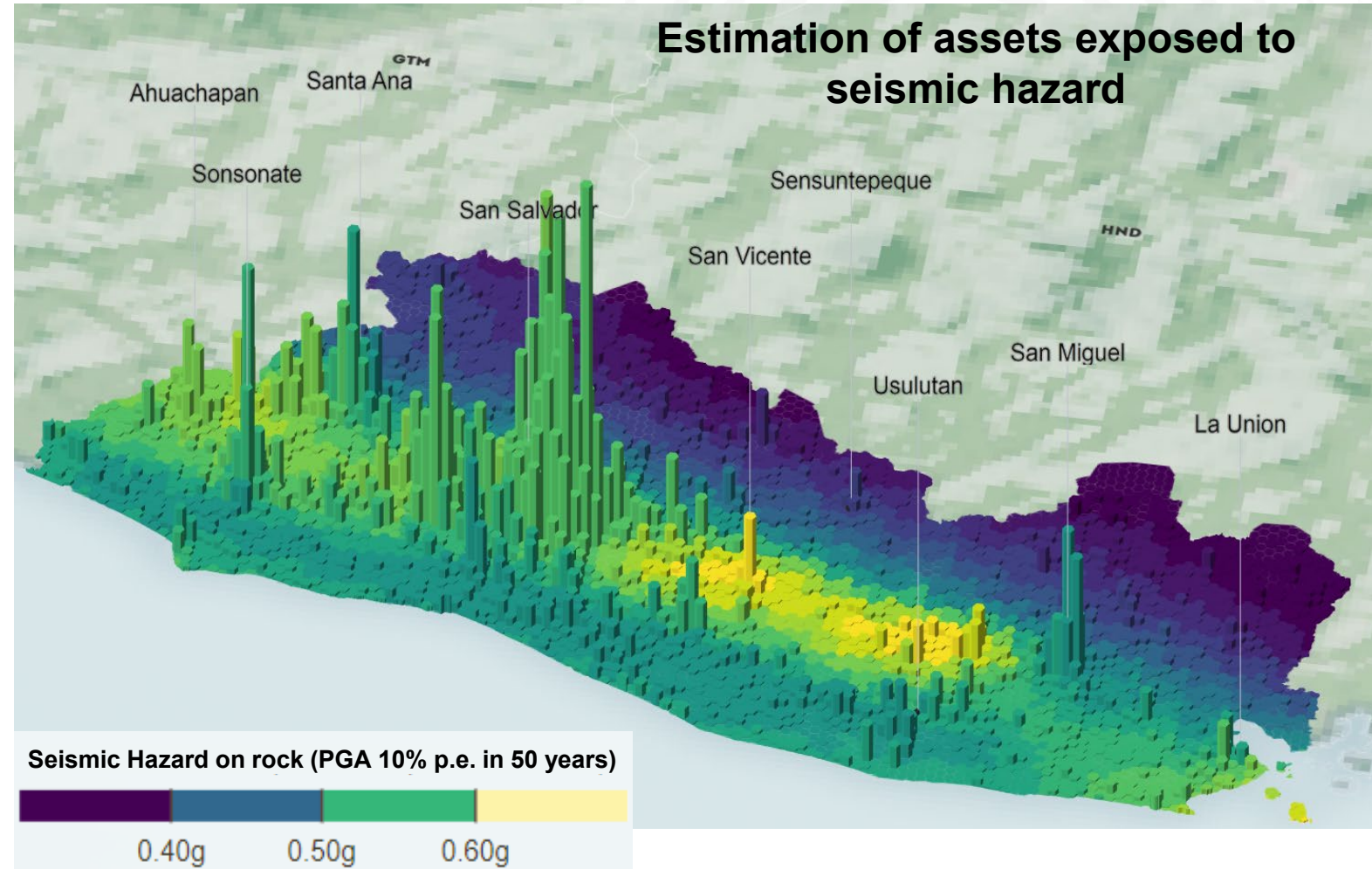
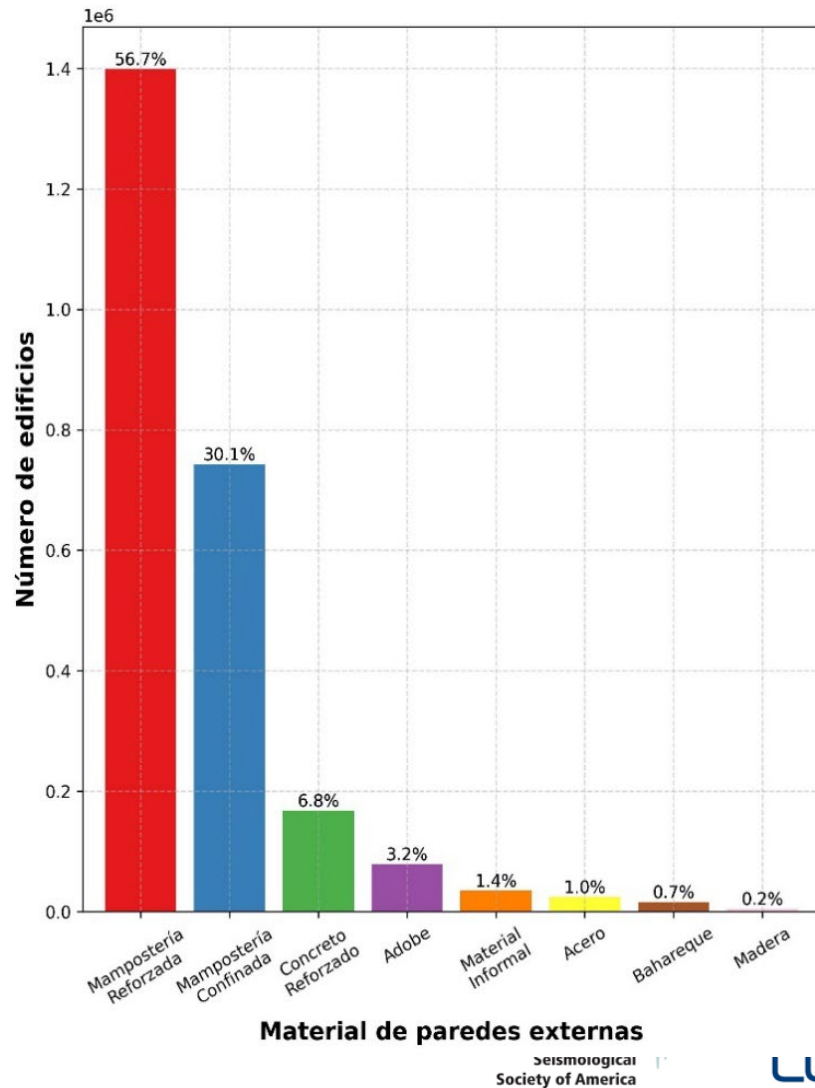


# EXPOSURE MODEL FOR EL SALVADOR: Summary of the national exposure model at municipal and city level (2)





# EXPOSURE MODEL FOR EL SALVADOR: Building classes distribution and Exposure to the seismic hazard





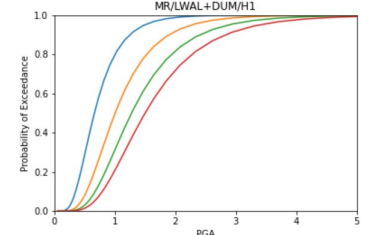
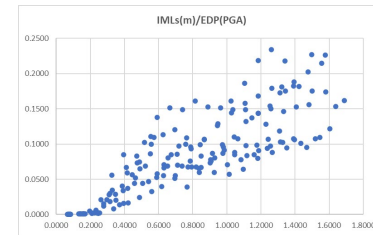
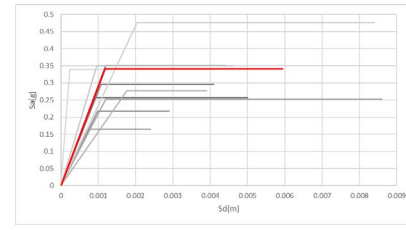
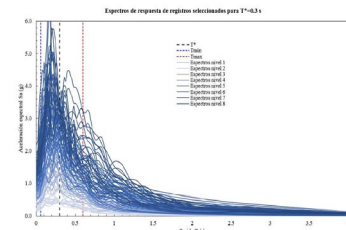
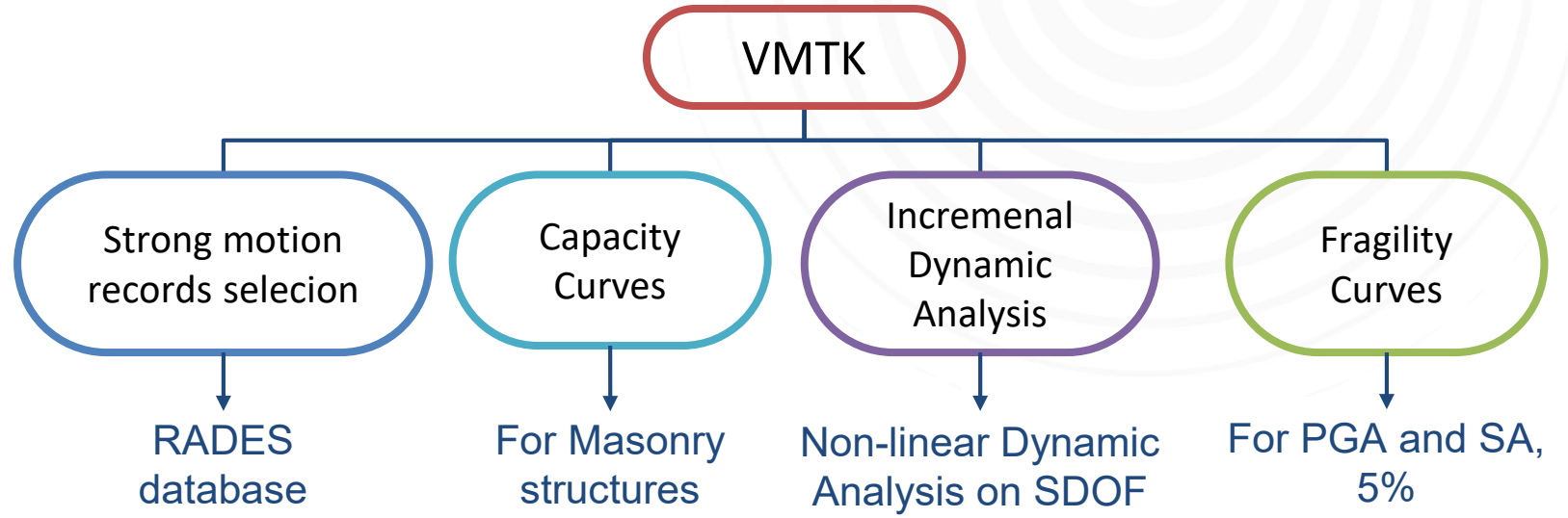
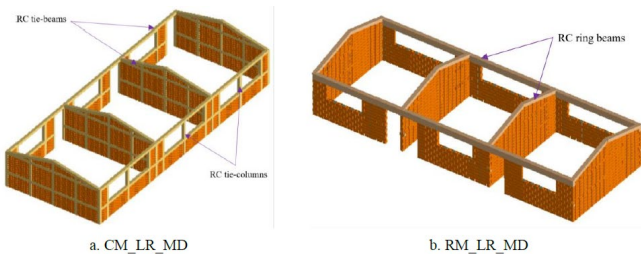
# VULNERABILITY MODEL: Global Earthquake Model vulnerability functions and local fragility curves

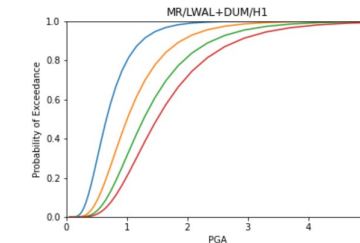
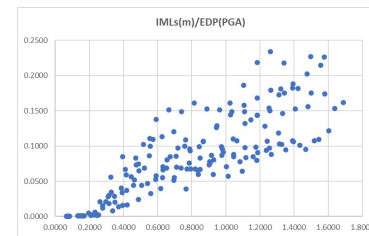
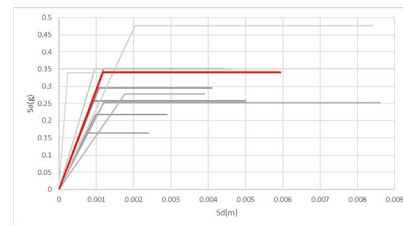
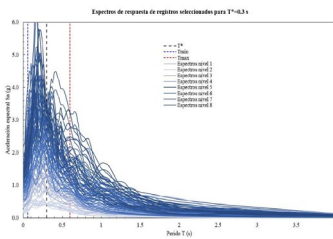
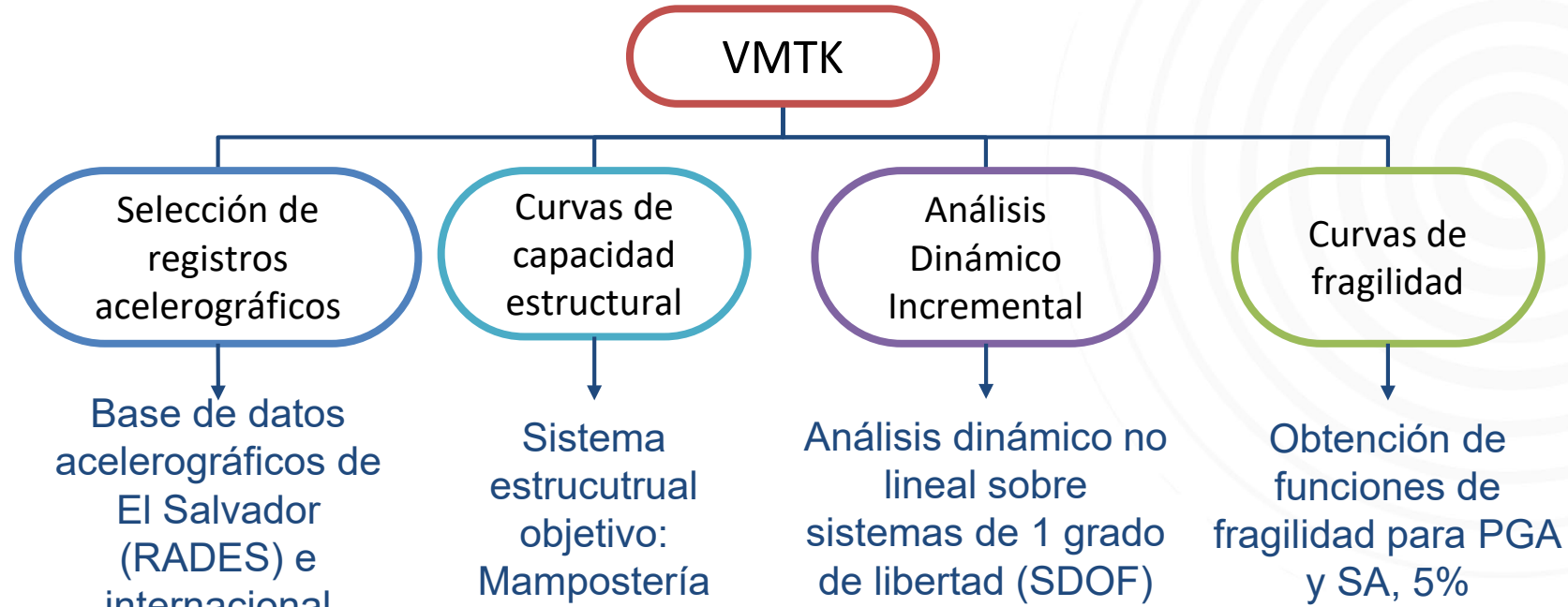
- GEM Foundation's vulnerability functions for global risk assessment were used, along with local fragility models for reinforced, confined, and adobe masonry, derived from local studies and using the Vulnerability Model ToolKit (VMTK-GEM).

Experimental data



Analytical Models







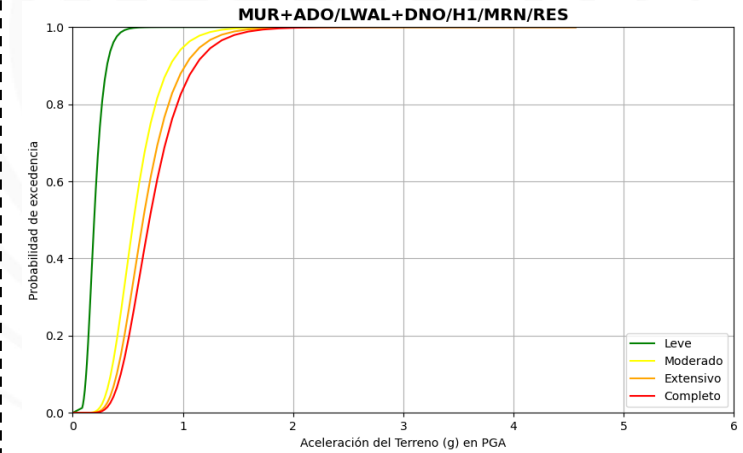
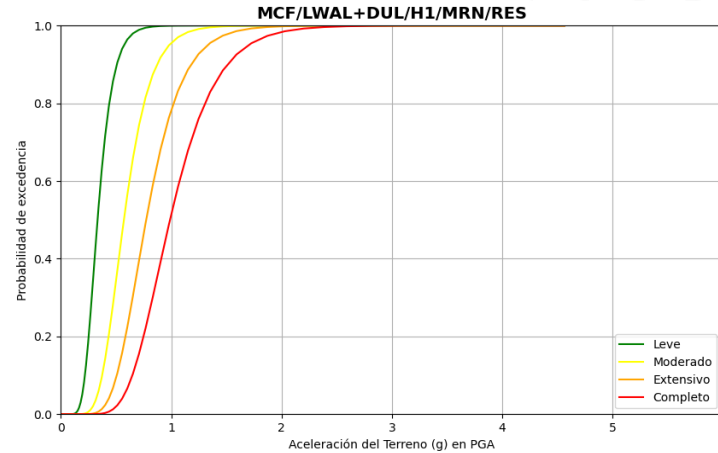
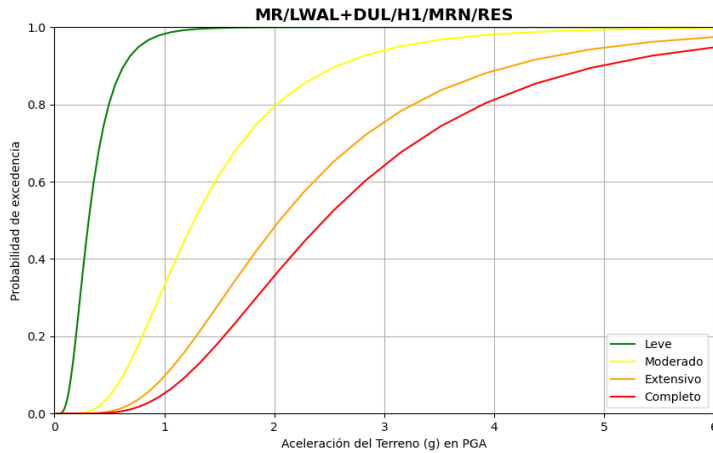
# VULNERABILITY MODEL: Some discrepancies were found. Assignment of weights to capture joint probability

1 Storey - Reinforced Masonry Fragility Curve, Low Code. Residential Portfolio

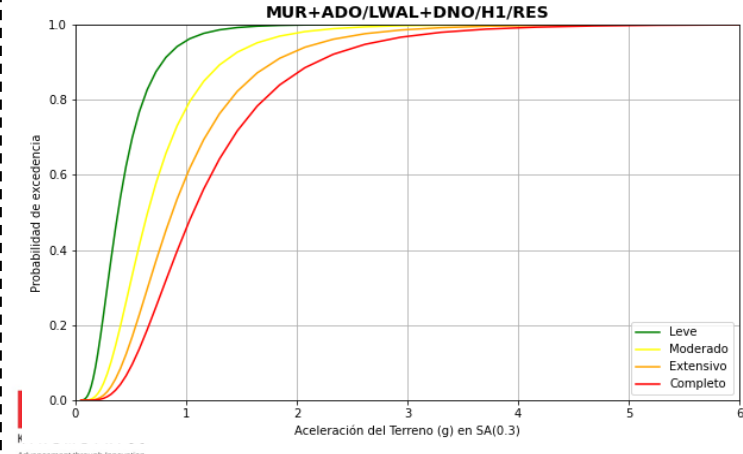
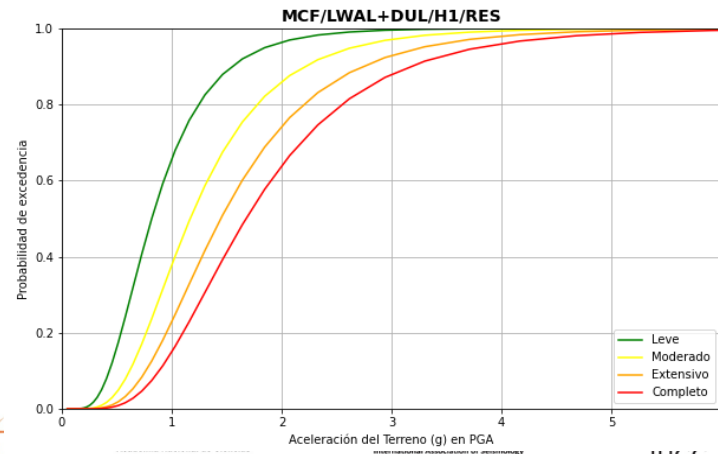
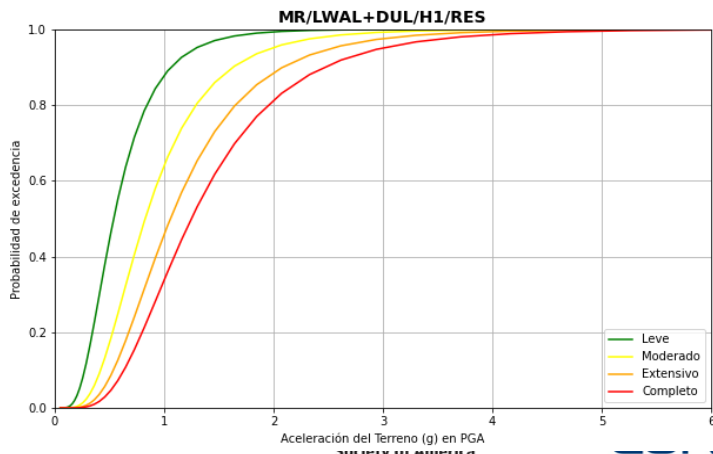
1 Storey - Confined Masonry Fragility Curve, Low Code. Residential Portfolio

1 Storey - Adobe Fragility Curve, Low Code. Residential Portfolio

MARN  
El Salvador



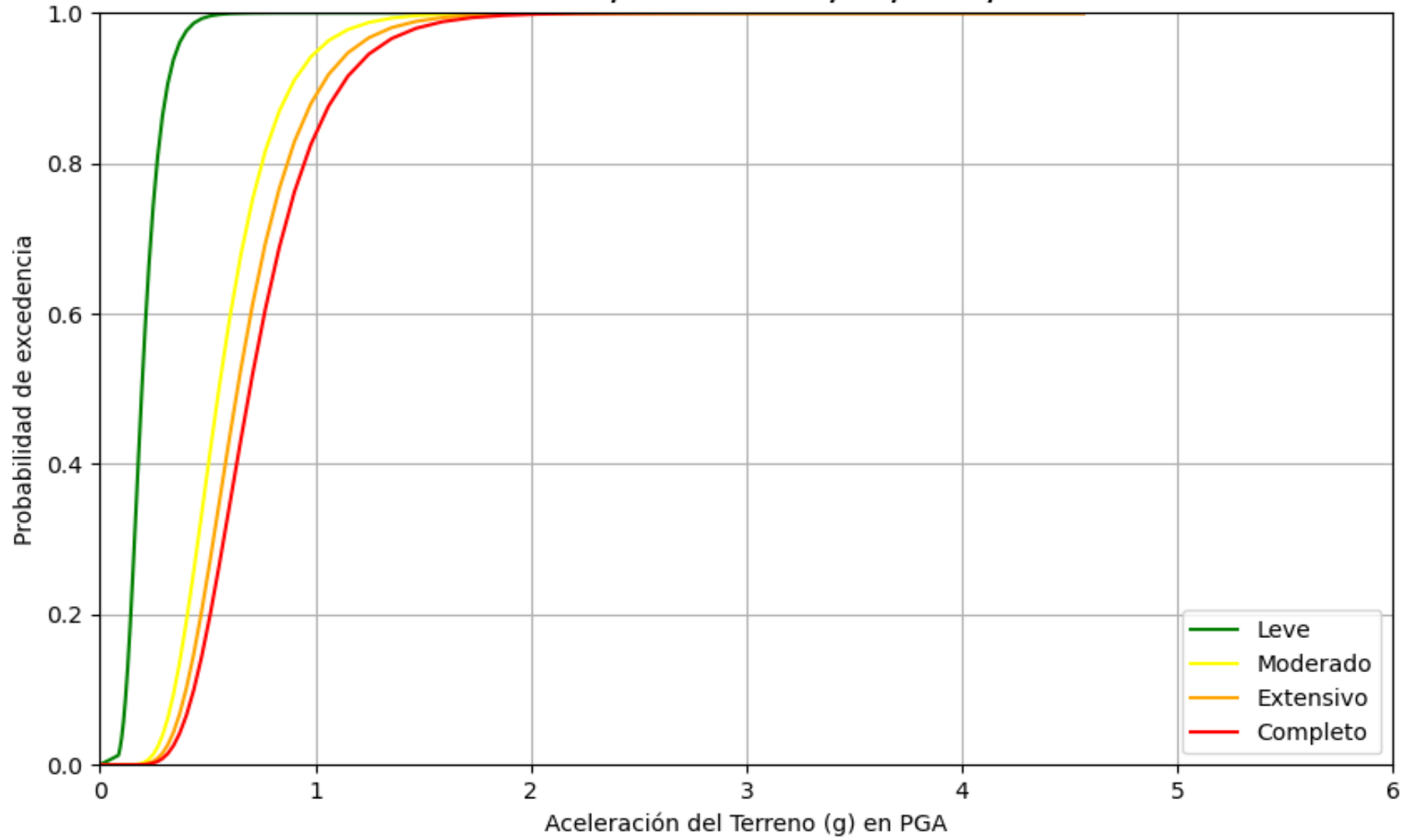
GEM  
Database

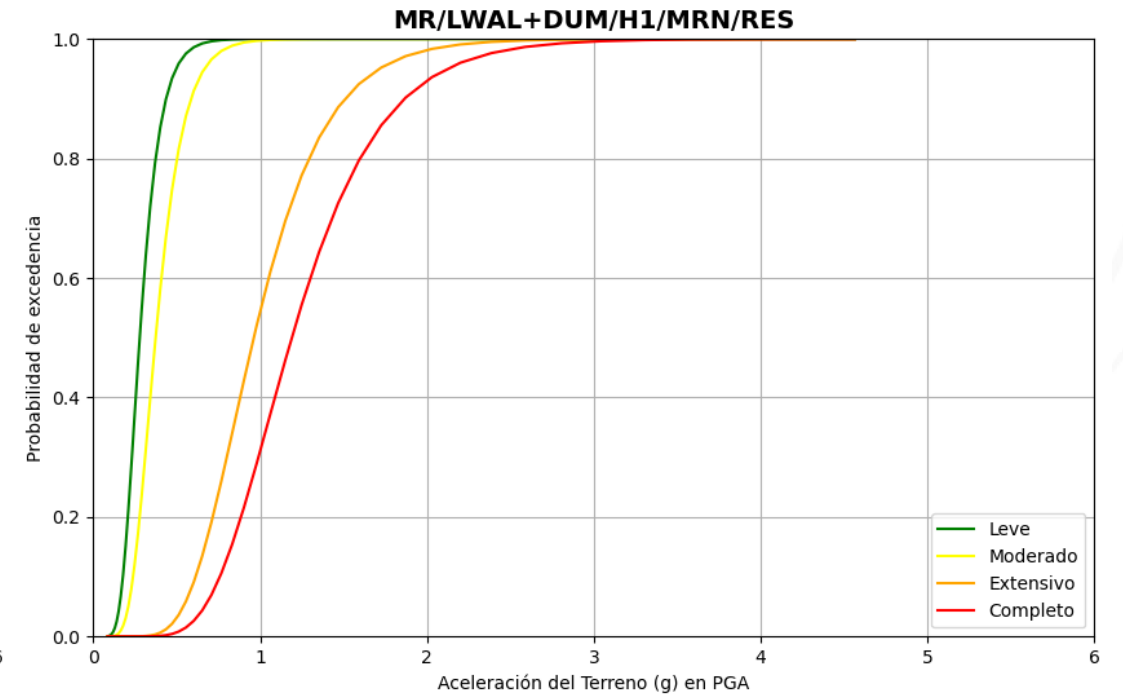
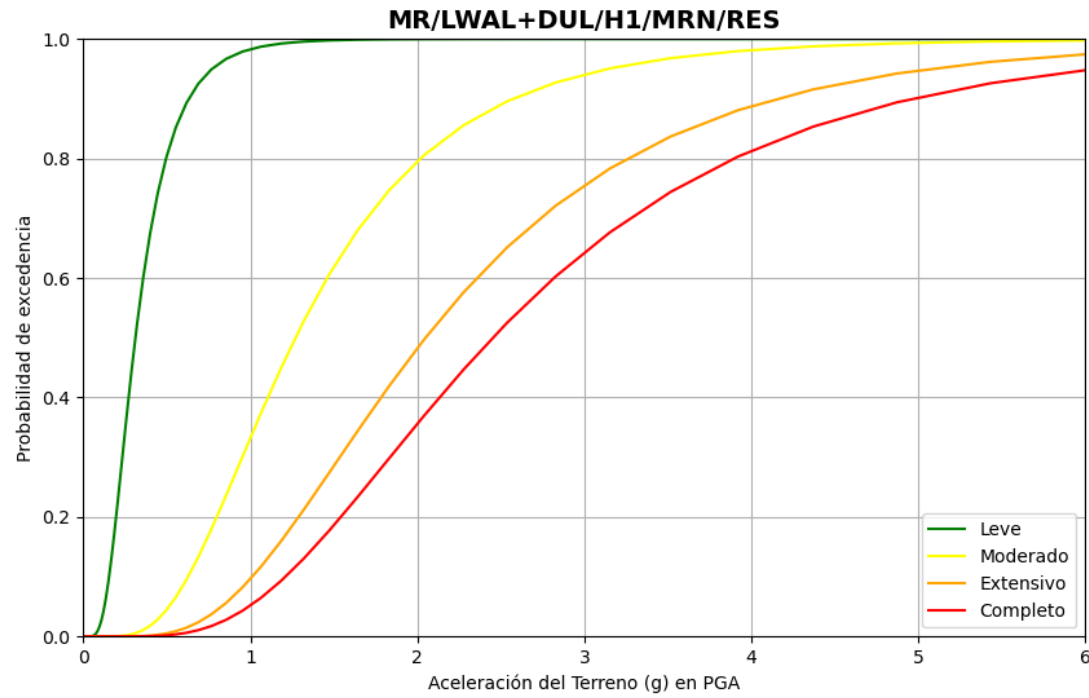


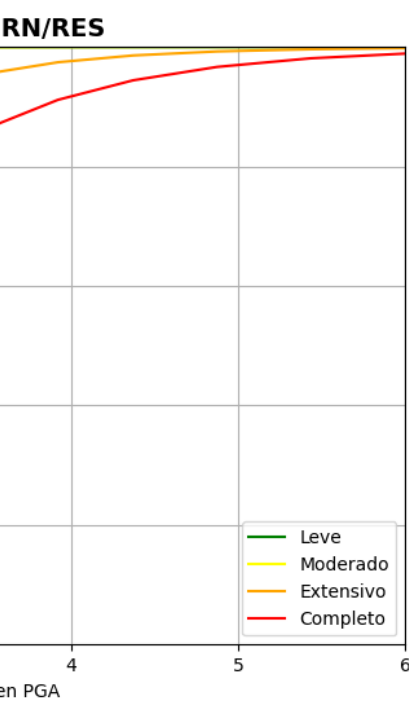
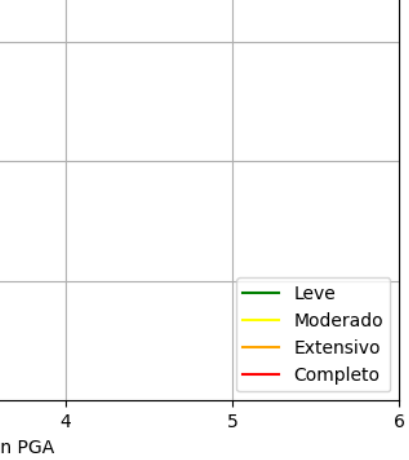




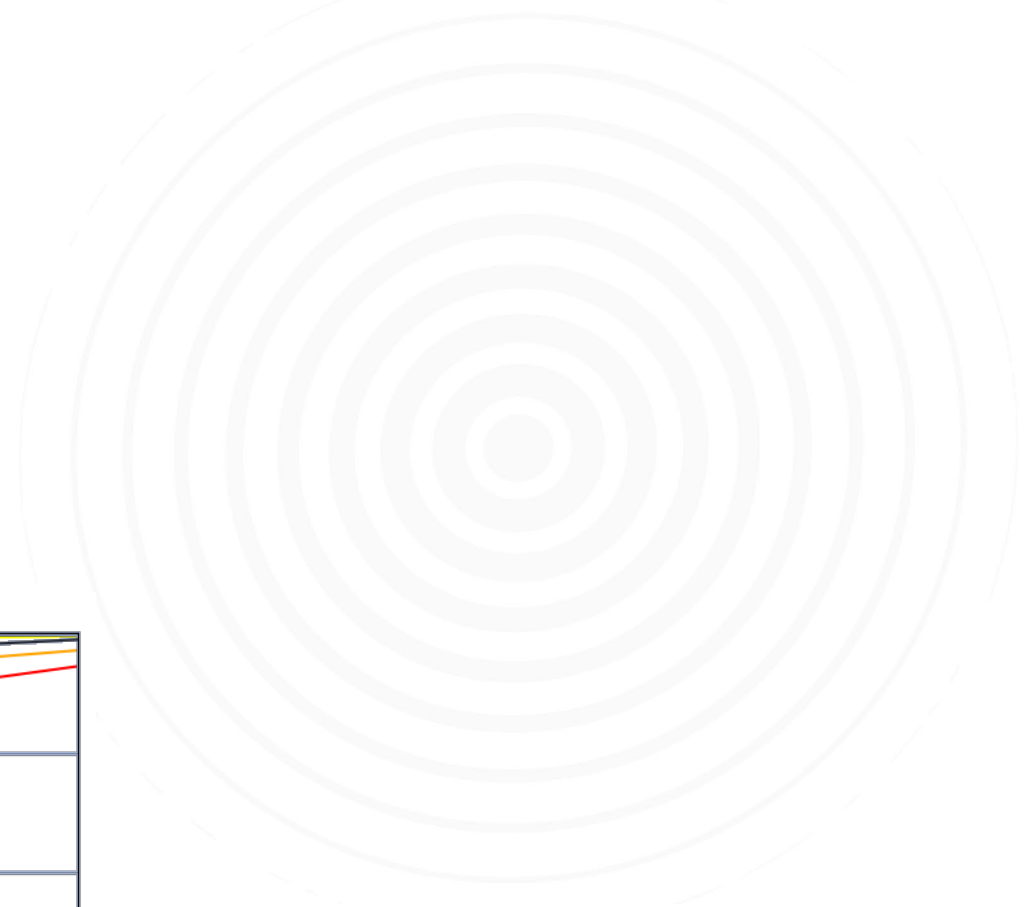
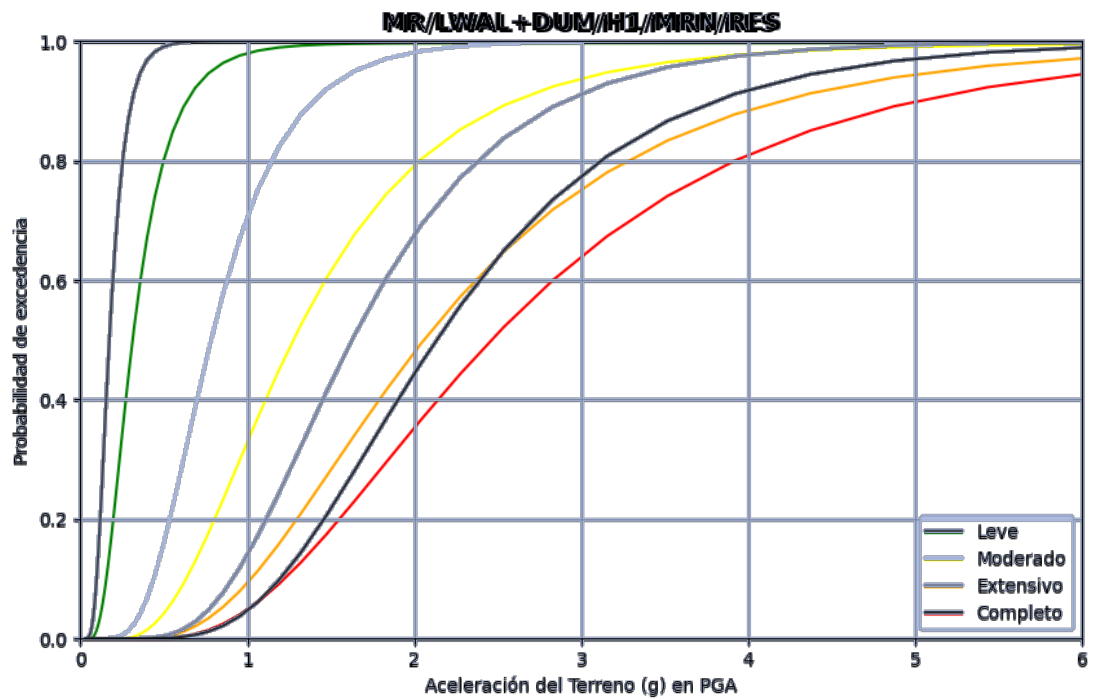
# MUR+ADO/LWAL+DNO/H1/MRN/RES







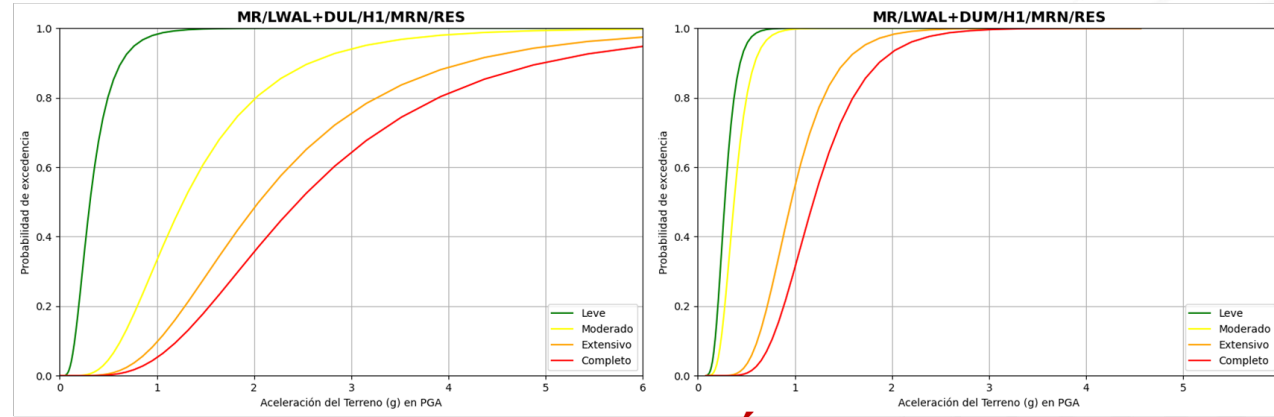
# DESPUÉS



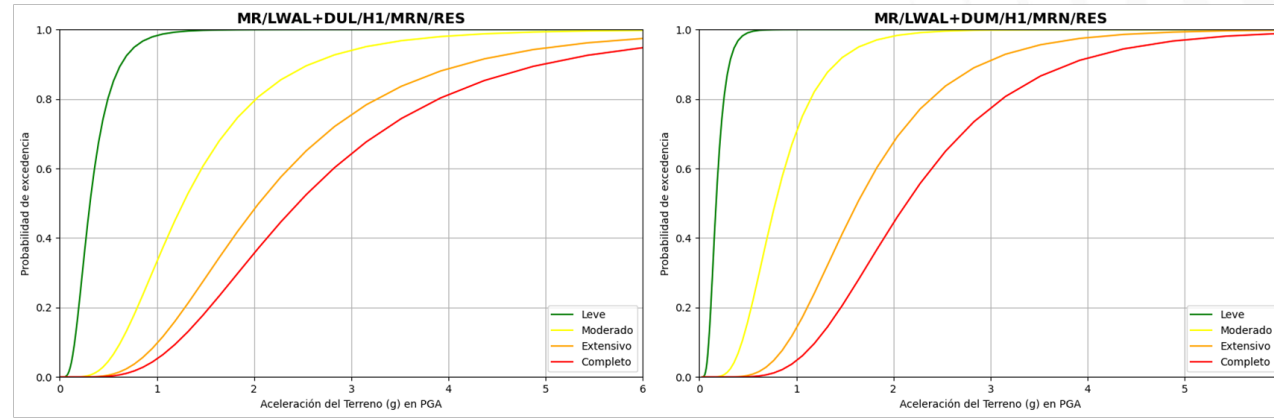
MR/LWAL+DUM/HI/CCA/RES



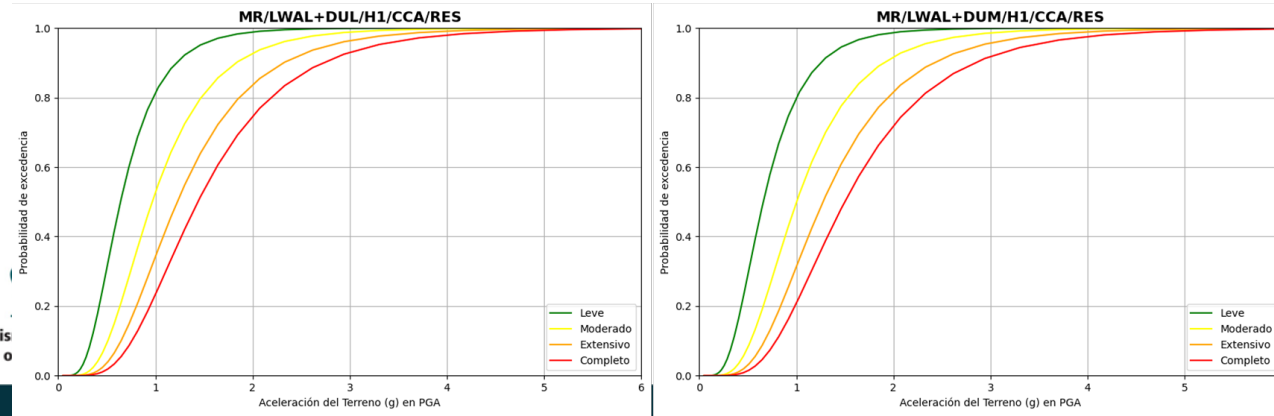
# ANTES



# DESPUÉS

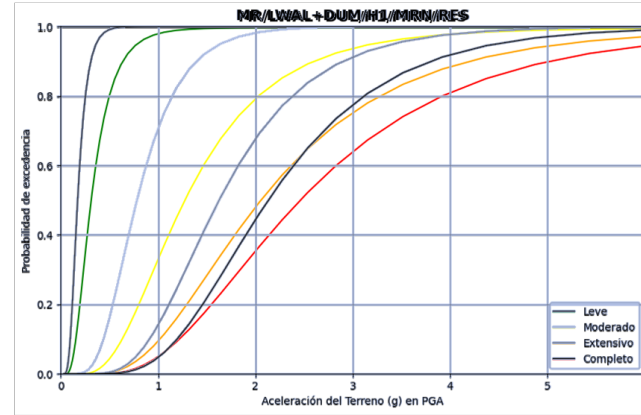


# GEM

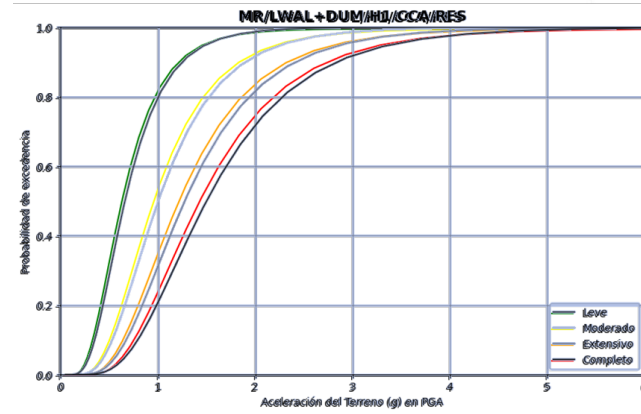




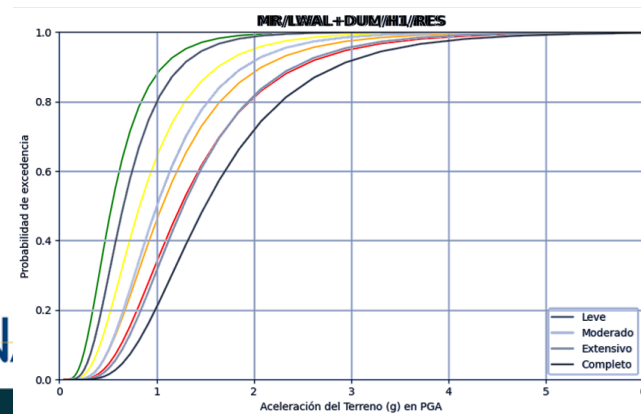
# DESPUÉS



# GEM/CCA



# GEM



### AMENAZA

La probabilidad, posibilidad o chance de ocurrencia de un fenómeno potencialmente destructivo



### EXPOSICIÓN

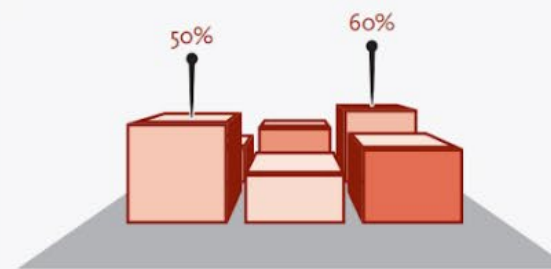
La ubicación, atributos y valores de los activos que son importantes para las comunidades



Tipología constructiva: Mampostería reforzada  
 Año de construcción: 1996  
 Altura: 2 niveles

### VULNERABILIDAD

La probabilidad de que los activos sean dañados o destruidos cuando están expuestos a un evento peligroso

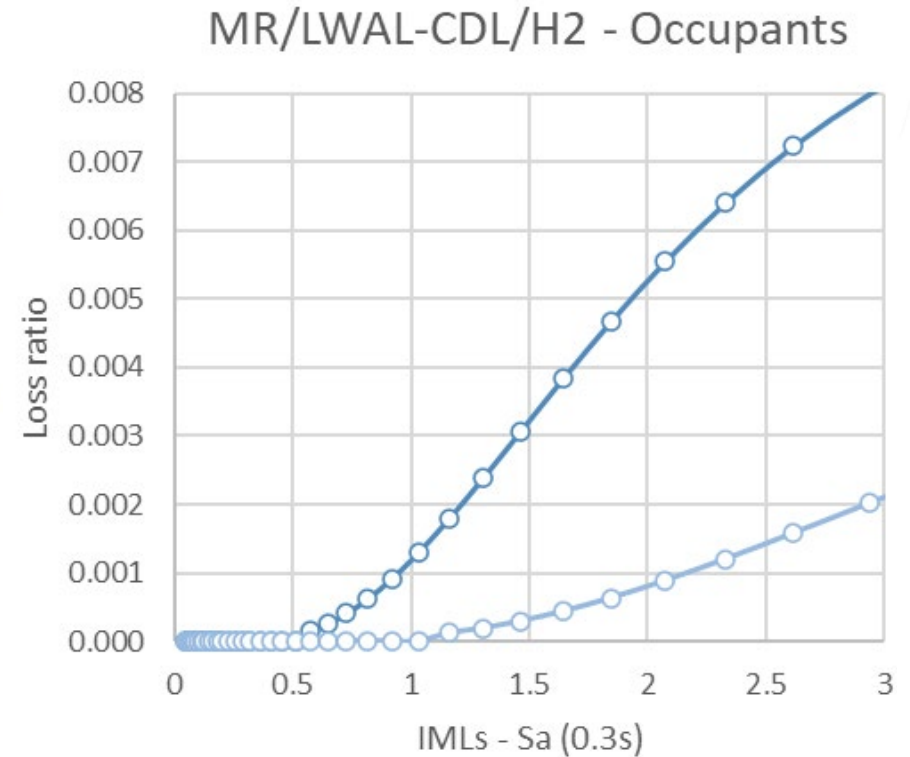
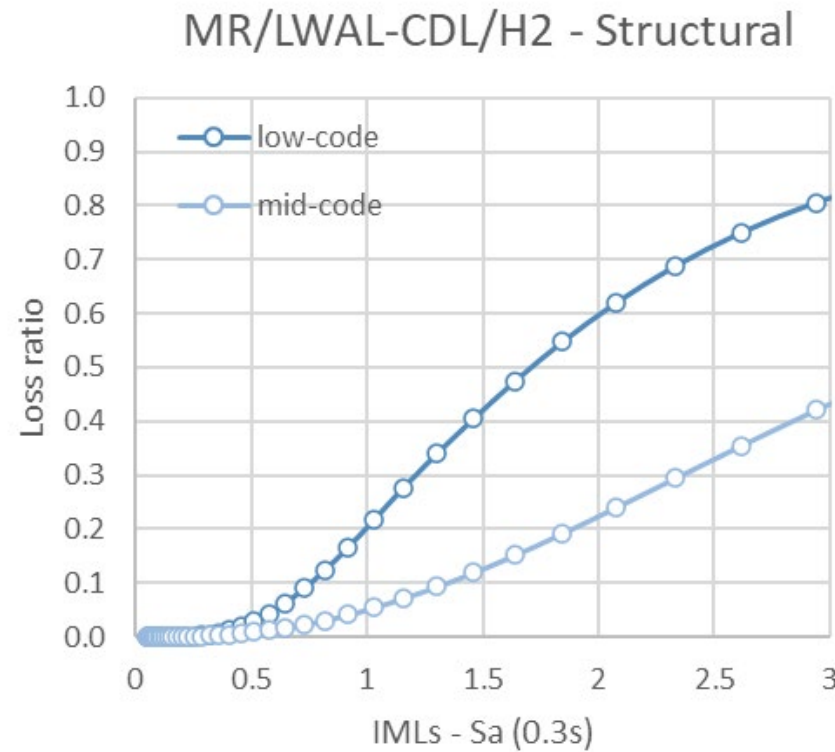




# VULNERABILITY MODEL: Vulnerability functions used for the estimation of economic and human loss ratios

Reinforced Masonry shear-wall (LWALL) structures, with low code (CDL) and mid-level seismic provisions (CDM) and two-storeys in height (H2).

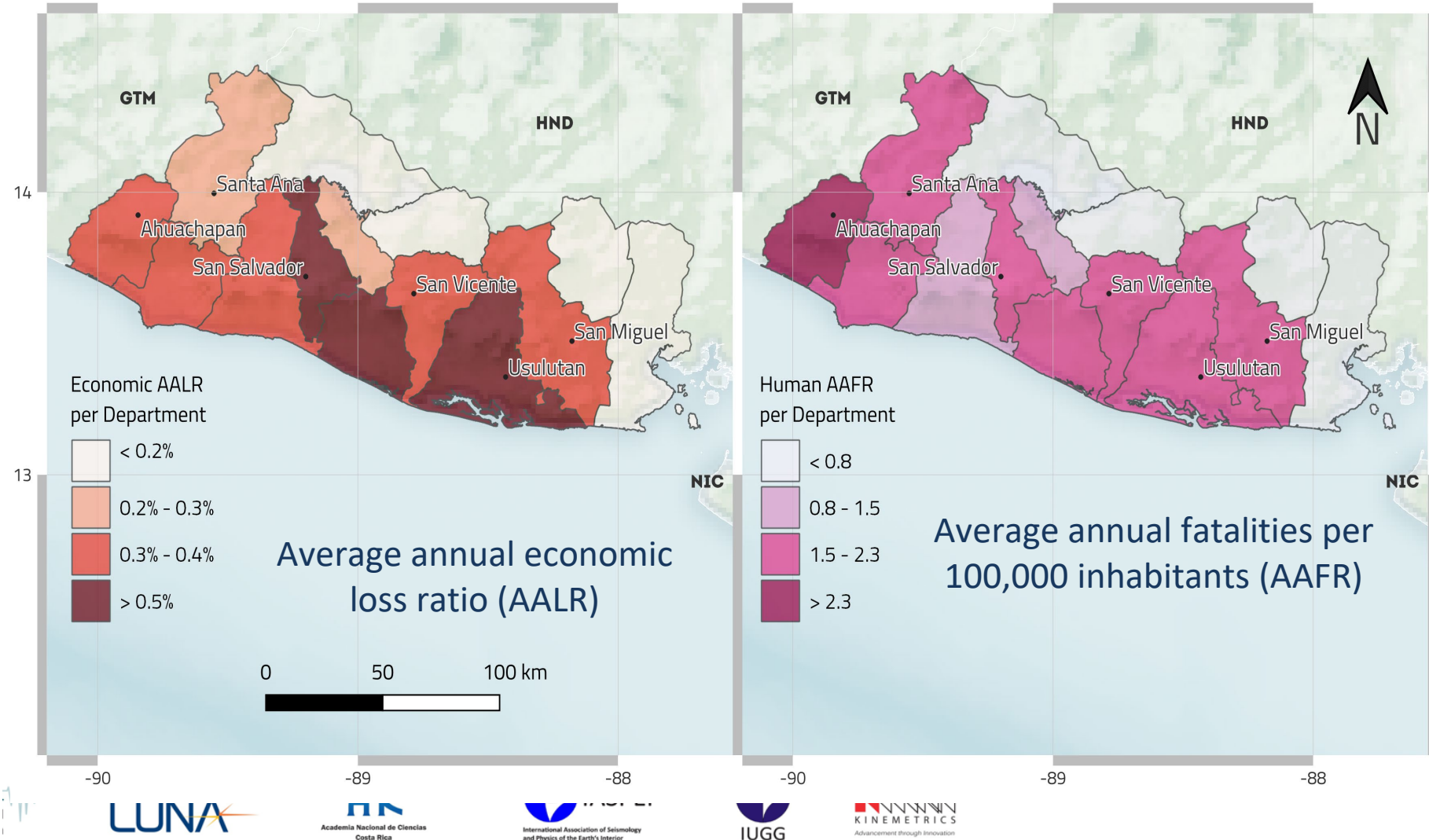
- Each one of the building classes identified in the National Exposure Model of El Salvador was mapped to one or more vulnerability curves, thus allowing the estimation of economic and human losses caused by damage in the structural components of the assets.





# PROBABILISTIC SEISMIC RISK ASSESSMENT: Average annual economic loss and fatalities ratios

- 100,000 Stochastic Events Sets with 1 year duration by each logic tree branch were conducted, resulting in hundreds of thousands of seismic events
- The national estimated economic AALR is **0.35%**. Some departments, such as Usulután, La Paz and San Salvador have an AALR above 0.40%.
- The national estimated human loss (AAFR) is **1.8**. An exception of note is the Ahuachapán department, where the AAFR exceeds 2.3

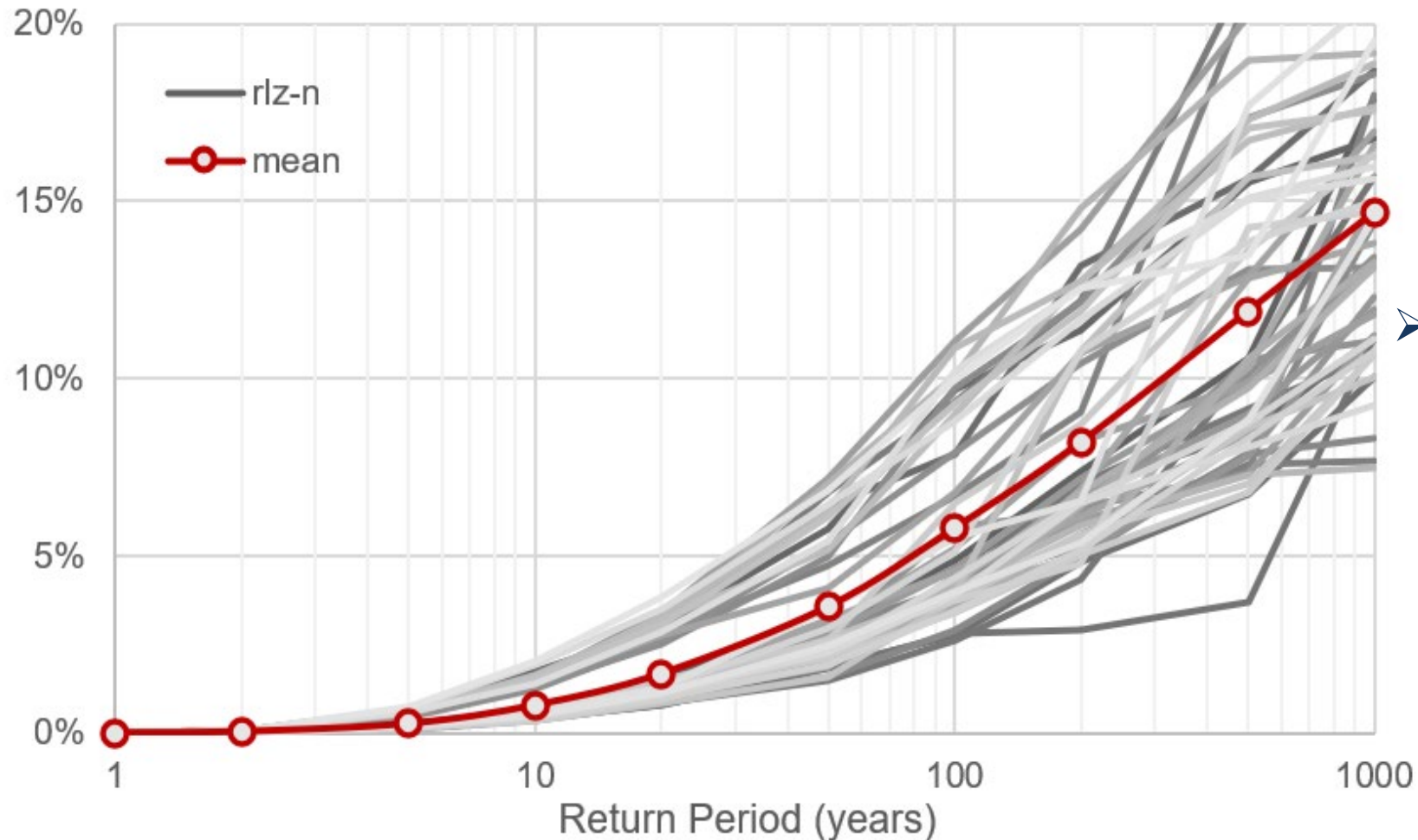






# PROBABILISTIC SEISMIC RISK ASSESSMENT: Loss exceedance curves for the National Building Portfolio

- Loss level as a percentage of total exposed economic value for a range of return periods



- Seismic events associated with 200 and 500 years of RP might cause a 7% and 12% loss of the national building portfolio economic value, respectively
- This level of loss is one of the highest in Central America and globally. This is primarily due to the significant seismic hazard across the nation, compounded by the physical vulnerability of its buildings.



# PROBABILISTIC SEISMIC RISK ASSESSMENT: Future Risk Mitigation and Management Profile

## Map of Average Annual Collapses

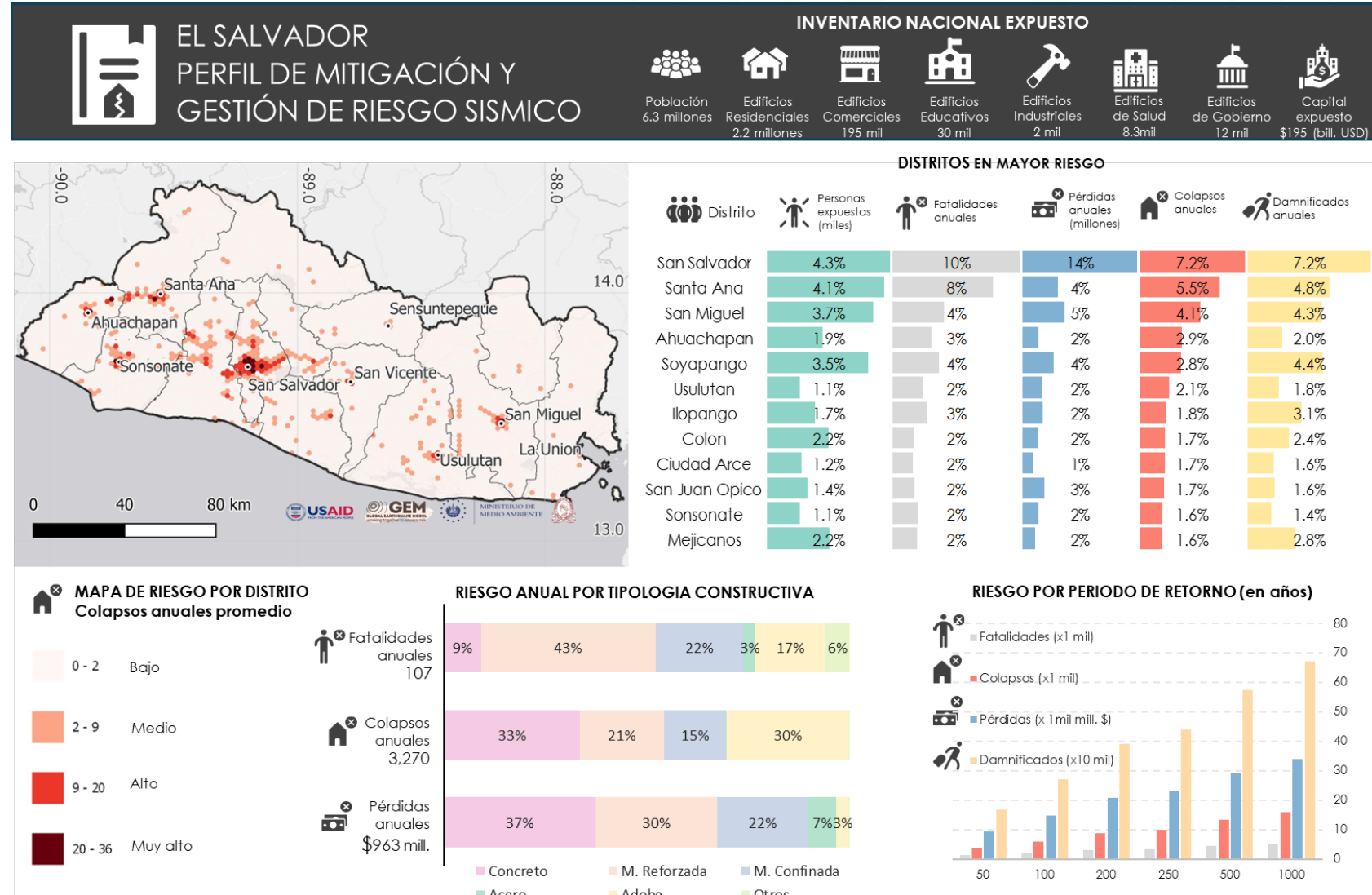
The most red-colored hexagons on the map would benefit most from improved construction oversight, seismic risk awareness campaigns, and long-term mitigation strategies.

## Annualized risk

Depending on the target metric for long-term mitigation, it can be seen which building typologies would benefit most from effective efforts.

## Risk by return period

Inform policies for preparedness, management, and risk transfer for seismic events, based on their frequency and impact.

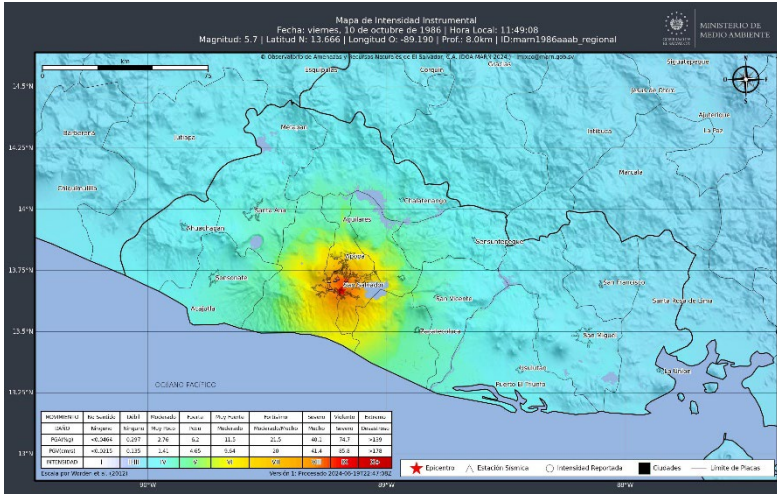


Este perfil evalúa el impacto sísmico del país con un enfoque probabilístico para guiar políticas de preparación y mitigación del riesgo de desastres. No es una normativa para construcción, planificación urbana o uso del suelo, ni reemplaza la zonificación sísmica, regulaciones de construcción o el plan de ordenamiento territorial vigente del país.

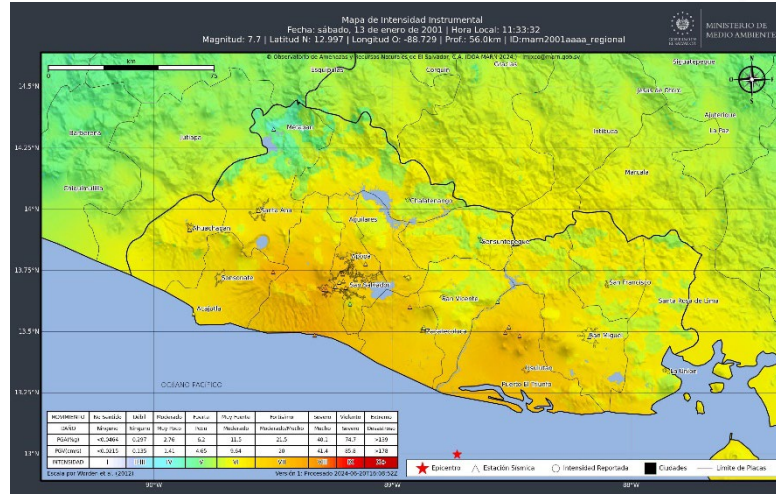


# DETERMINISTIC SEISMIC RISK ASSESSMENT: Preparation of Historical Seismic Scenarios occurred in El Salvador

10/10/1986 – Mw 5.7 – Depth: 8.0 km



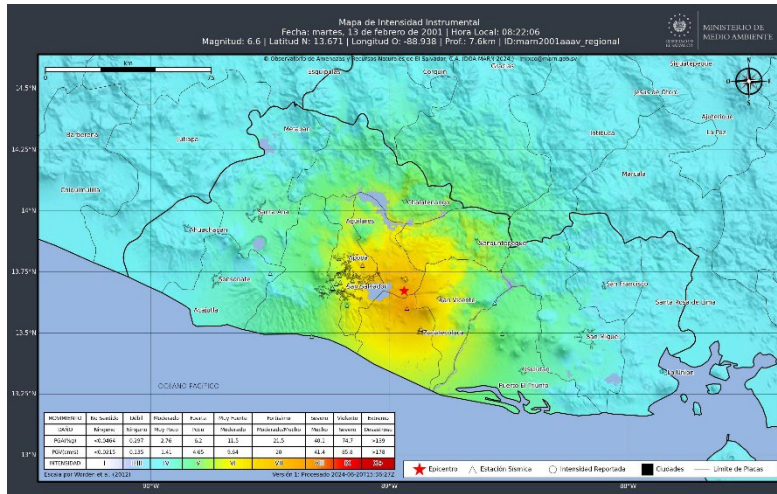
13/01/2001 – Mw 7.7 – Depth: 56 km



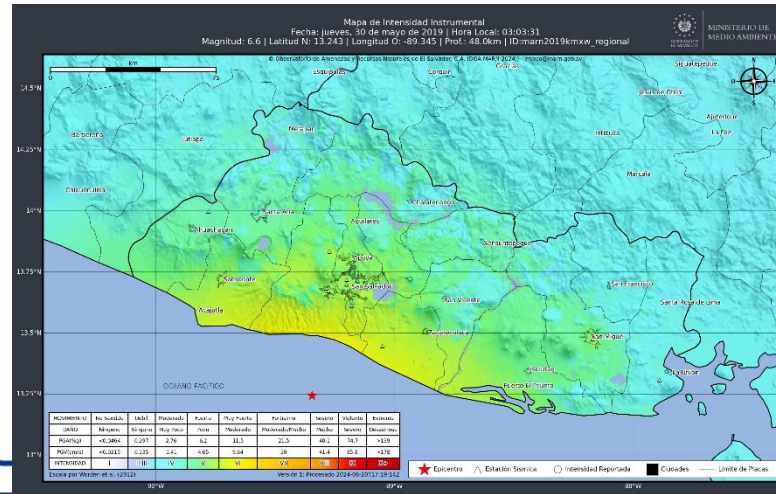
➤ Information related to the seismic rupture, the site model, the exposure model, and the fragility and consequence models are compiled.

➤ Multiple simulations of the ground motion field (GMF) are generated, taking into account the variability in the GMPEs

13/02/2001 – Mw 6.6 – Depth: 7.6 km



30/05/2019 – Mw 6.6 – Depth: 48 km



➤ The GMFs are conditioned with real observations from stations in order to reduce intra-event variability.

➤ The GMPEs that best fit the real observations are selected and logical trees are formed.





# DETERMINISTIC SEISMIC RISK ASSESSMENT: Risk profiles for emergency preparedness and response

## ➤ General data

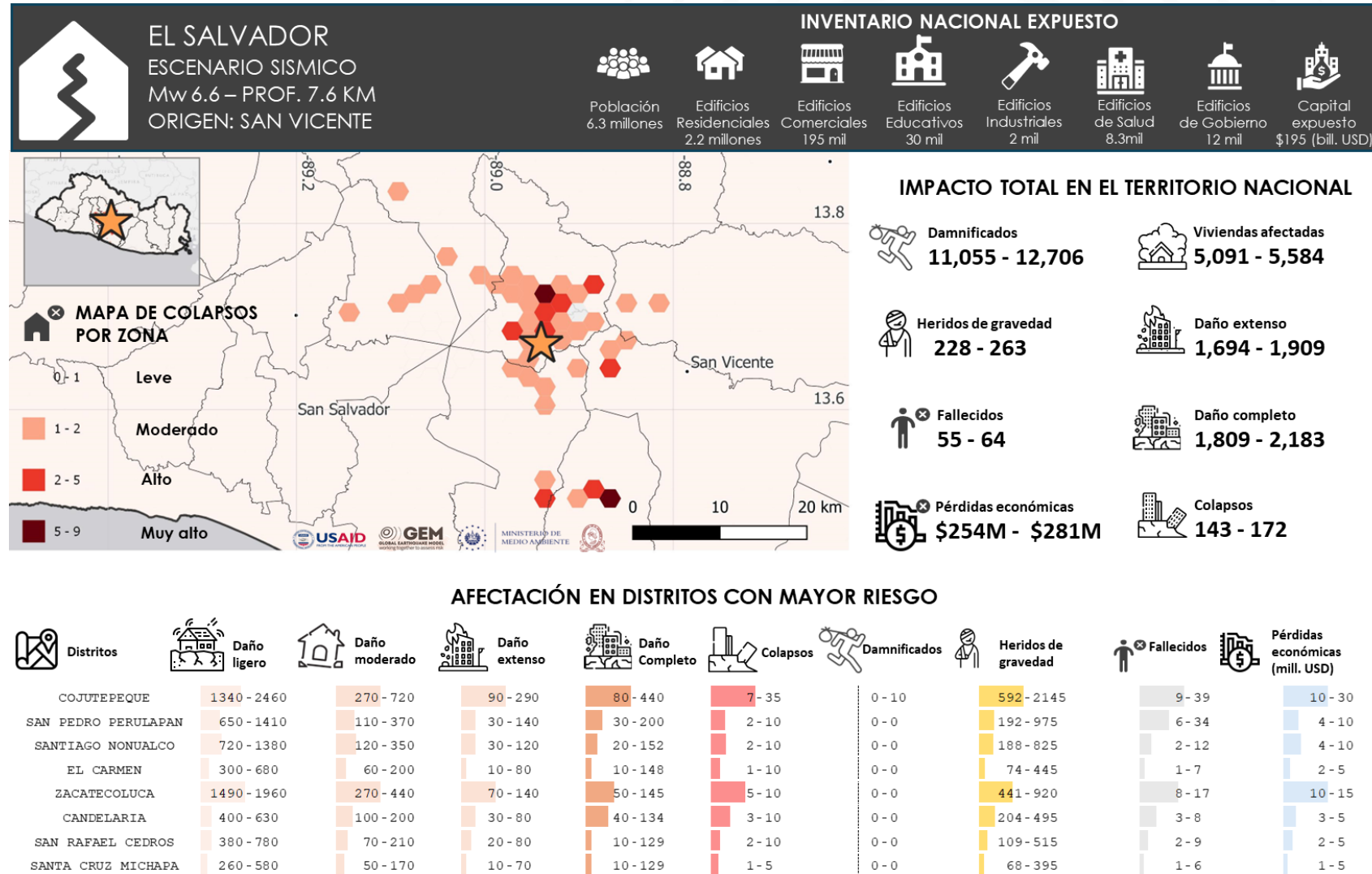
Includes general information about the seismic event (name, location, and magnitude) and summarizes the exposure model.

## ➤ Map of Collapses

The most red-colored hexagons on the map would help emergency response entities focus their rescue and debris removal efforts.

## ➤ Impact Tables

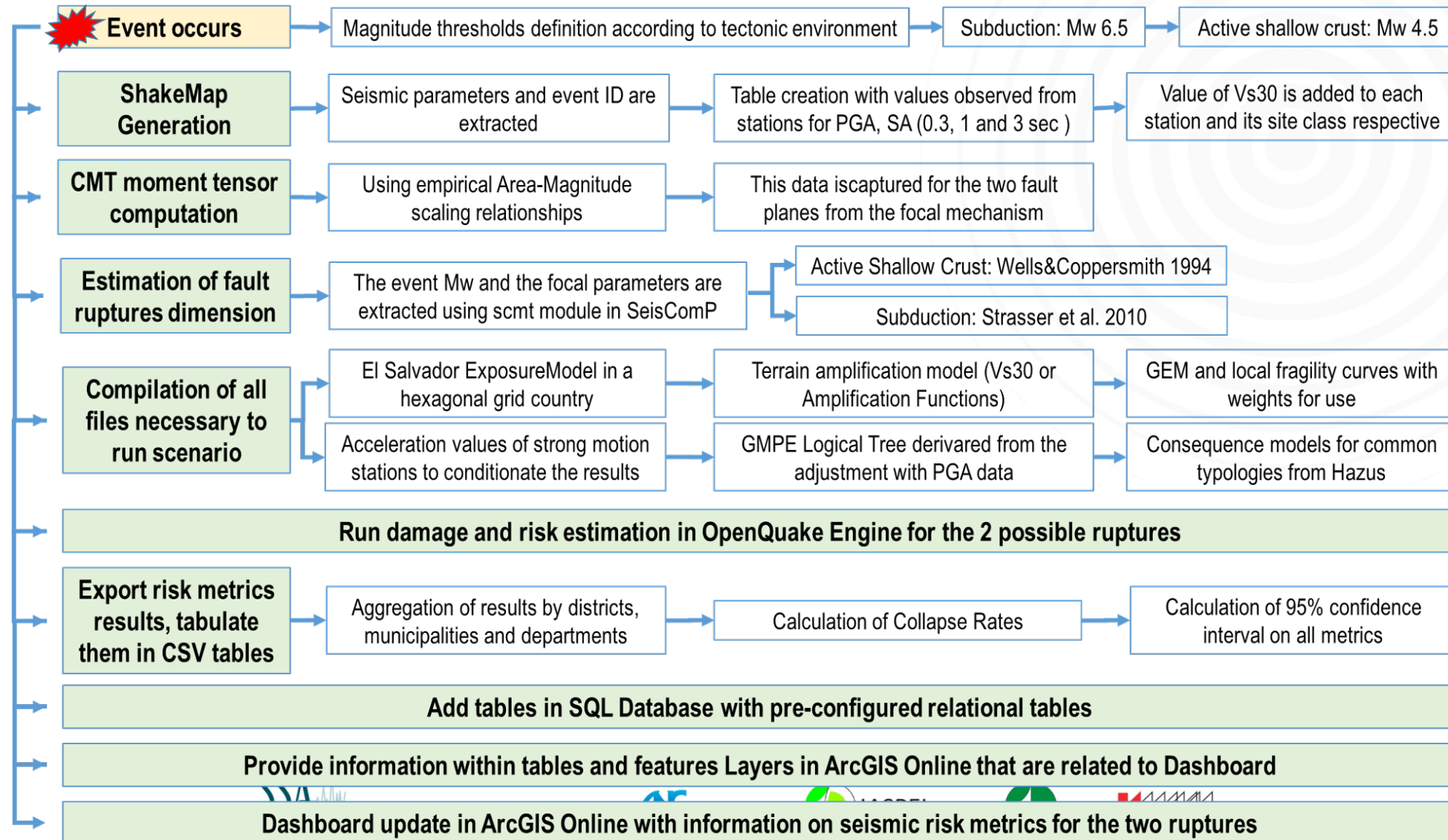
Aggregated ranges within localities of the total impact are provided, covering different states of structural damage and other risk metrics.



Este perfil evalúa el impacto sísmico del país con un enfoque determinístico para guiar políticas de preparación y respuesta ante emergencias derivadas de un escenario sísmico. No es una normativa para construcción, planificación urbana o uso del suelo, ni reemplaza la zonificación sísmica, regulaciones de construcción o el plan de ordenamiento territorial vigente del país.



# RAPID LOSS ESTIMATION AND COLLAPSES: Construction of an Automated Dashboard. Processing method





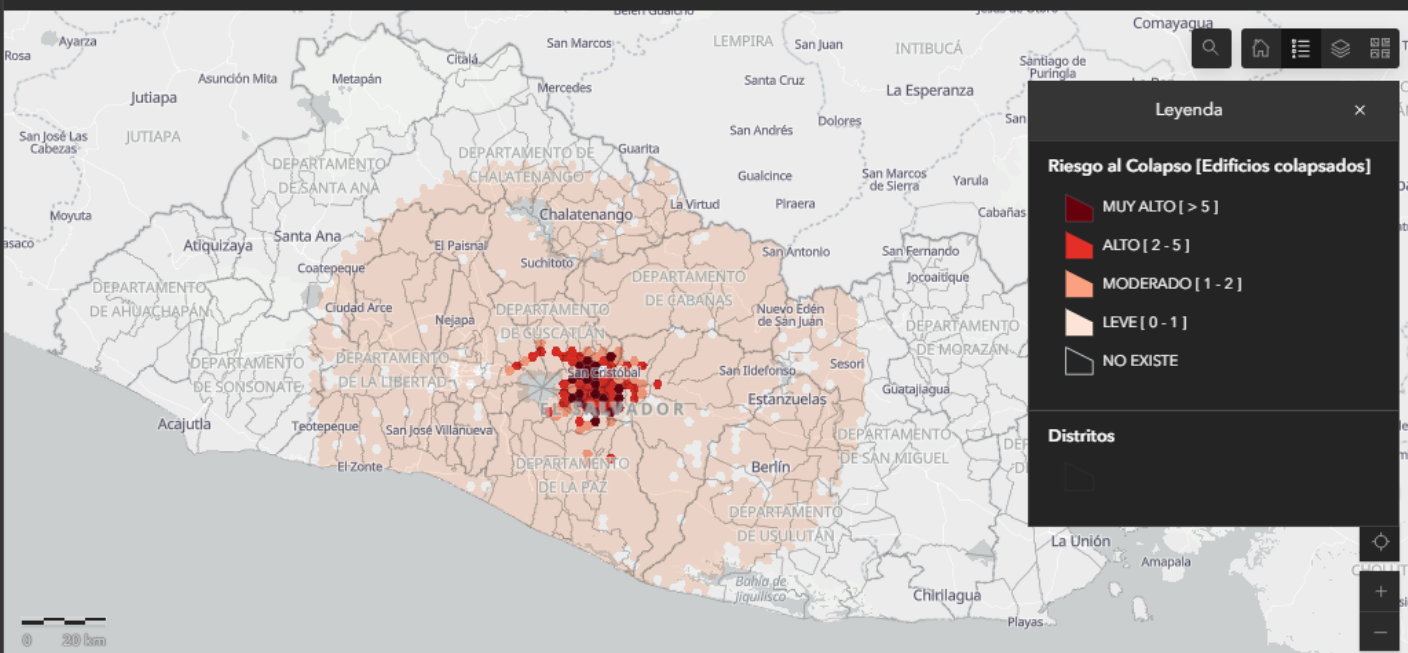
# RAPID LOSS ESTIMATION AND COLLAPSES: Construction of an Automated Dashboard (1)

Sismo Mw 6.6 - 13/02/2001-08:22:06 - Distrito San Ramón, San Vicente Sur - Ruptura 1 =  $\phi$ : 94 -  $\delta$ : 70 -  $\lambda$ : 179

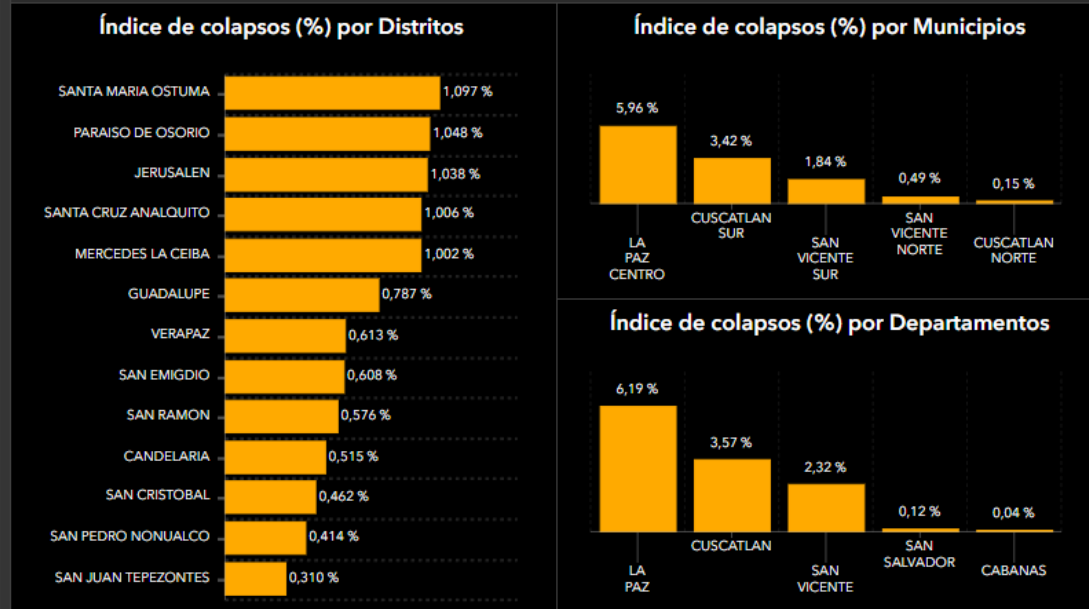
## RESUMEN DE IMPACTO TOTAL ESTIMADO EN EL TERRITORIO NACIONAL

<b>Bandera Verde</b> <b>46,3k - 48,6k</b> Edificaciones	<b>Bandera Amarilla</b> <b>25,6k - 27,2k</b> Edificaciones	<b>Bandera Naranja</b> <b>4,7k - 5,2k</b> Edificaciones	<b>Bandera Roja</b> <b>5,9k - 6,8k</b> Edificaciones	<b>Damnificados</b> <b>28k - 31,1k</b> Personas	<b>Heridos</b> <b>506 - 571</b> Personas	<b>Fallecidos</b> <b>129 - 147</b> Personas	<b>Pérdidas Económicas</b> <b>\$543,0 - \$590,0</b> Millones
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## DISTRIBUCIÓN DE EDIFICACIONES COLAPSADAS



## DISTRIBUCIÓN MEDIA ESTIMADA DE ÍNDICE DE COLAPSOS (%)



El Índice de Colapsos es una métrica que se utiliza para evaluar la proporción de edificios que han colapsado en una localidad en relación con el número total de edificios contabilizados dentro de la misma. Esta métrica permite identificar las áreas con mayor impacto en términos de colapsos estructurales.



# RAPID LOSS ESTIMATION AND COLLAPSES: Construction of an Automated Dashboard (2)

**Mapa de Riesgo al Colapso**  
 Área de Sismología - Observatorio de Amenazas y Recursos Naturales

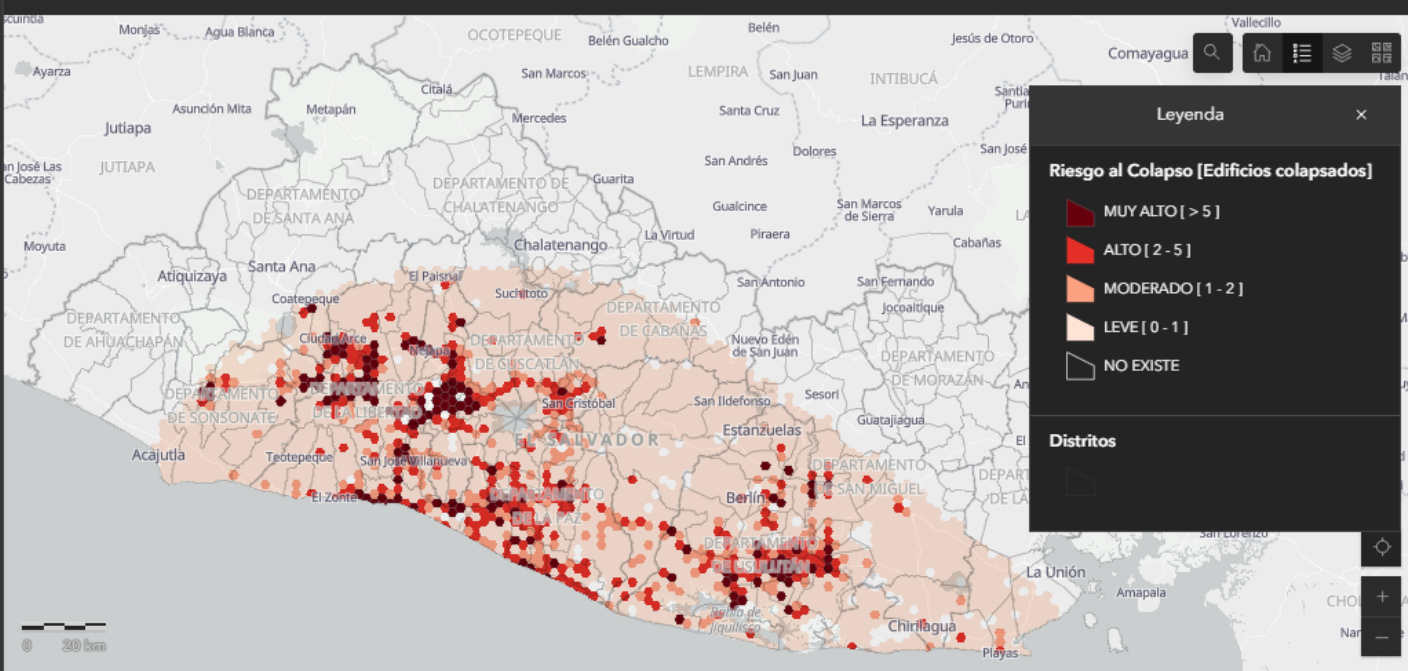
**INVENTARIO NACIONAL EXPUESTO**  
 Población: 6.2 millones  
 Edificios Residenciales: 2.2 millones  
 Edificios Comerciales: 195 mil  
 Edificios Educativos: 31 mil  
 Edificios Industriales: 2 mil  
 Edificios de Salud: 8 mil  
 Edificios de Gobierno: 12 mil  
 Capital Expuesto: \$195 (Bil. USD)

Sismo Mw 7.7 - 13/01/2001-11:33:32 - Frente a costa de Usulután - Ruptura 2 =  $\phi$ : 307 -  $\delta$ : 55 -  $\lambda$ : -87

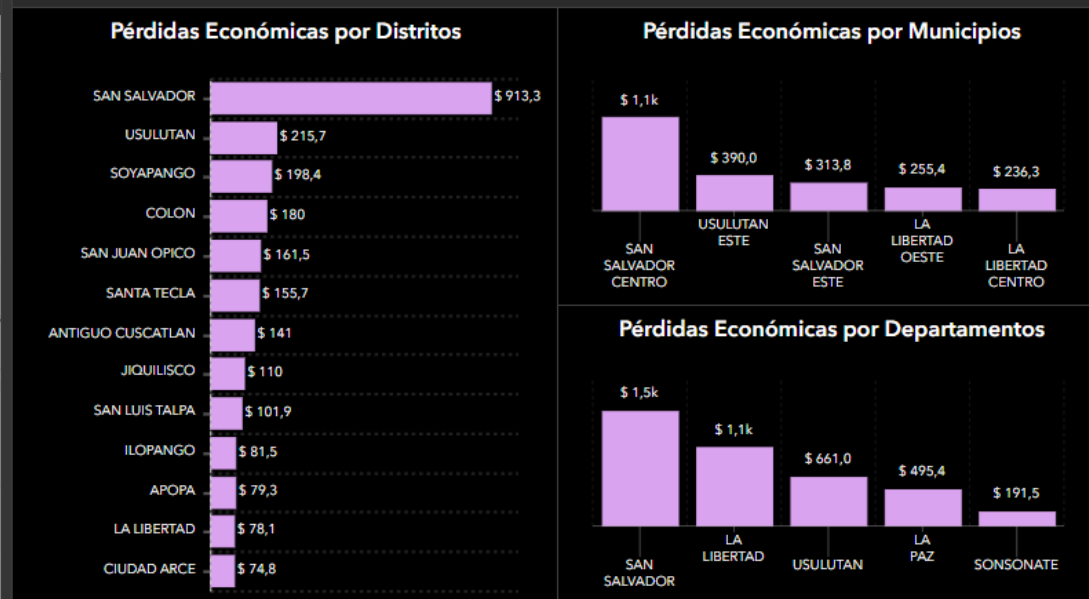
## RESUMEN DE IMPACTO TOTAL ESTIMADO EN EL TERRITORIO NACIONAL

<b>Bandera Verde</b> 188,9k - 192,9k Edificaciones	<b>Bandera Amarilla</b> 111,7k - 114,4k Edificaciones	<b>Bandera Naranja</b> 27k - 28,2k Edificaciones	<b>Bandera Roja</b> 40,7k - 43,8k Edificaciones	Damnificados 221,2k - 237,2k Personas	Heridos 5,4k - 5,9k Personas	Fallecidos 1,5k - 1,6k Personas	Pérdidas Económicas \$4,7k - \$5,0k Millones
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## DISTRIBUCIÓN DE EDIFICACIONES COLAPSADAS



## DISTRIBUCIÓN MEDIA ESTIMADA DE PÉRDIDAS ECONÓMICAS (en millones de \$)



La métrica de **Pérdidas Económicas** estima el costo total esperado de daños materiales y la interrupción de actividades comerciales debido a un terremoto. Este análisis combina la exposición económica (valor de los activos expuestos), la vulnerabilidad de los activos frente al movimiento del terreno y las consecuencias económicas esperadas de los diferentes niveles de daño estructural.



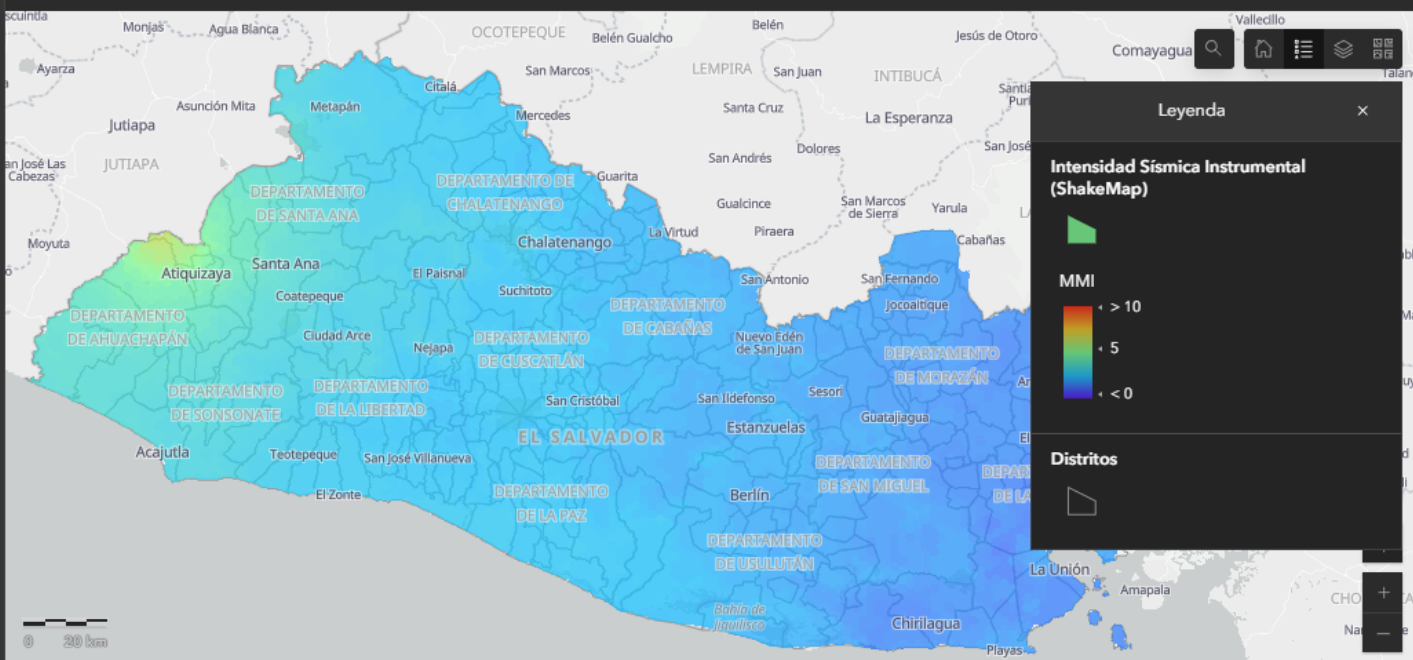
# RAPID LOSS ESTIMATION AND COLLAPSES: Construction of an Automated Dashboard (3)

Sismo Mw 5.1 - 15/01/2023-17:07:53 - Distrito San Lorenzo, Frontera Guatemala y El Salvador - Ruptura  $2 = \phi: 186 - \delta: 73 - \lambda: -47$

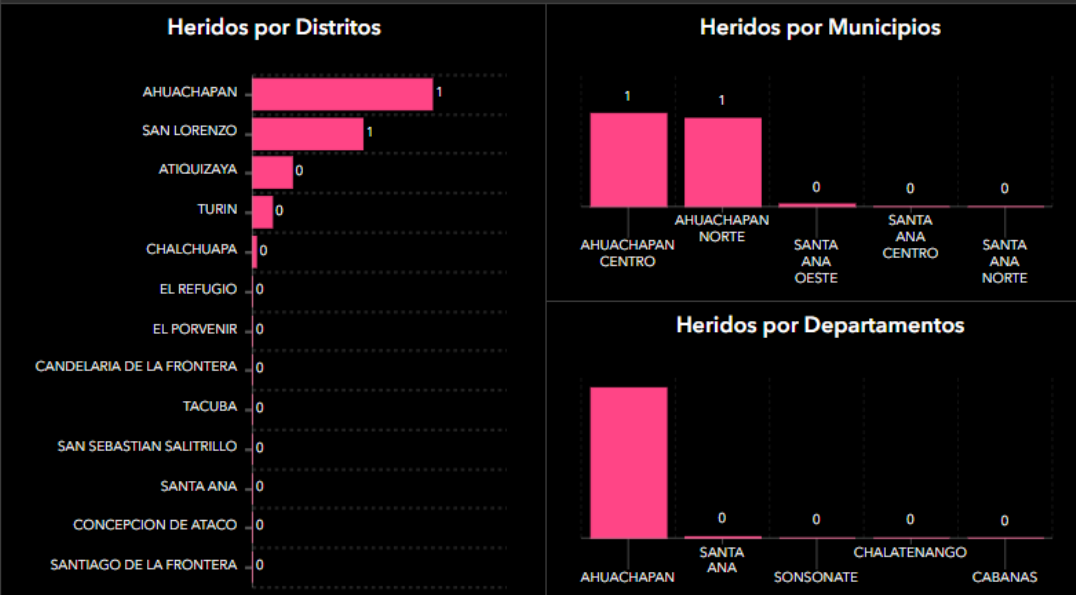
## RESUMEN DE IMPACTO TOTAL ESTIMADO EN EL TERRITORIO NACIONAL



### MAPA DE INTENSIDAD SÍSMICA INSTRUMENTAL (Mercalli Modificada)



### DISTRIBUCIÓN MEDIA ESTIMADA DE PERSONAS HERIDAS



La estimación media del número de Heridos considera solo el impacto del movimiento del terreno por el terremoto, combinando el modelo de exposición (cantidad y ocupación de edificios) con la probabilidad de daño estructural (vulnerabilidad) y tasas de heridos para cada nivel de daño (consecuencia), excluyendo otras causas como deslizamientos o tsunamis.







# CONCLUSIONS AND REMARKS

- At present, the PSHA model suggests that seismic hazard in El Salvador can be as high as a PGA with a 10% probability of exceedance in 50 years of 0.50 g in the heavily urbanized departments of the Metropolitan Area of San Salvador, and over 0.60 g close to active shallow faults.
- A total of 2 million structures have been identified and classified into 156 building classes, with a total economic value of around 200 billion USD and 6.2 million occupants.
- The national average annual economic loss ratio or AALR for El Salvador was estimated as 0.35%, and the average annual human loss ratio or AAFR is 1.8 fatalities per 100,000 inhabitants. This level of relative risk at a national level is higher than the one proposed in previous studies.
- The above outcome can be attributed to the inclusion of vulnerable building portfolios not considered in previous studies, like the educational facilities of El Salvador, which have been found to have significant physical vulnerability to ground shaking.
- Within the context of the FORCE project, MARN will continue working in collaboration with the University of El Salvador and the GEM Foundation to use the national seismic risk model to generate earthquake risk profiles that can support the ongoing risk management efforts in public institutions.



# THANKS FOR YOUR ATTENTION

