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MEASURING SOCIAL VULNERABILITIES TO EARTHQUKES IN THE ANDEAN REGION

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Abstract

Earthquake risk in South America is the result of a complex seismic zone, coupled with a high exposure of economic and infrastructural assets and low levels of resilience within human settlements. Together, these characteristics interact not only to create a high potential for loss, but also to differentially affect the ability of populations to prepare for, respond to, and recover from damaging earthquake events. In this context, the Global Earthquake Model (GEM) through the South America Risk Assessment (SARA) project considered loss and damage as part of a dynamic system in which interactions between natural systems, the engineered environment, and societal factors are integrated accounting for the major factors that redistribute loss and recovery potential following a damaging event. Part of the work entailed the development of a set of composite indicators of social vulnerability (characteristics within social systems that create the potential for harm or loss) at sub-national levels to measure the implication of societal factors in earthquake risk in the South American Andean Countries (Argentina, Bolivia, Colombia, Ecuador, Peru, Venezuela). This paper reports upon the methods, metrics, and social vulnerabilities observed within each country as they pertain to earthquake risk (human and/or economic losses). Results show the distribution of social vulnerability across parishes in the South American countries and the driving forces acting upon populations to shape their social vulnerability.

Keywords: social vulnerability, resilience

1 Introduction

The South American continent contains one of the world's most seismically active zones that is situated along the Andes mountain range. The region has experienced several earthquakes that have turned into national tragedies. The most recent of which, the April 16, 2016 Ecuador Earthquake, provides a poignant example of the devastating effects an earthquake can have within the region. This magnitude 7.8 (Mw) earthquake caused heavy damages throughout the country, resulted in approximately 650 casualties, and displaced over 30,000 people. Other notable South American earthquakes are outlined in Table 1. From a scientific and risk communication perspective, estimated losses of lives and infrastructure have been utilized as key metrics to demonstrate the potential magnitude of earthquake events that could occur in a given area. Few studies, however, have been conducted to assess the social and economic conditions of populations that may be affected by an earthquake event. The latter includes the poorest sectors of society, which exemplifies the notion that high vulnerability to hazards may not be solely dependent upon proximity to the source of a hazard or threat. While economic losses might be widespread in areas of highest potential for loss, the resident populations in those areas may have better financial resources to absorb and recover from damages quickly. Conversely, it could take only a moderate earthquake event to disrupt the well-being of a country's most vulnerable residents. The concept of social vulnerability, i.e. characteristics or qualities within social systems that create the potential for loss, was developed to describe such phenomenon.

Table 1. List of severe earthquakes that affected South American countries.

Country/Event	Magnitude	Fatalities	Building damaged	People displaced*	People affected*
Ecuador 2016	7.8	~650	-	30,223	720,000
Chile 2010	8.8	521	370,000	-	2,000,000
Peru 2007	7.9	595	58,500	60,000	-
Colombia 1999	6.1	1185	35,000	-	425,000

Global Earthquake Model (GEM), Openquake platform, earthquake consequences database [2].
*USAID/OFDA bulletins for earthquakes events – earthquake's fact sheet

The social vulnerability of South America's populations to earthquakes has increasingly become an area of interest for earthquake risk practitioners, researchers, and stakeholders. Researchers representing the network for Social Studies in Disaster Prevention in Latin America (La RED) have discussed the social vulnerability concept, identified its dimensions [3] and argued that social vulnerabilities within the region are the result of economic, social and political processes [4,5,6,7]. It is within this context that conceptual frameworks and metrics have been developed to describe the continent's social vulnerability from a regional perspective. This includes work supported by the Interamerican Development Bank and the World Bank that incorporates indicators of disaster risk and risk management and the Prevalent Vulnerability Index (PVI) that was developed to evaluate exposure and susceptibility, socio-economic fragility and the lack of resilience within communities by considering a fixed set of variables (often referred to as indicators) [8]. These metrics were designed and applied at the national level to compare and benchmark countries. However, metrics at a higher resolution such as at the community level are needed to meaningfully understand, identify, and compare the drivers of the social vulnerability of populations within countries in order to develop equitable public policies and plans to reduce earthquake risk.

This paper addresses the spatial distribution of social vulnerability in the Andean Region of South America. Under the auspices of the South American Risk Assessment project (SARA), funded by the Swiss Re Foundation, this research sought to develop a set of uniform social vulnerability indicators at the subnational level of geography. This research focuses on sub-national level comparisons within countries to better understand the drivers of social vulnerability in Andean region as a whole. The methods presented here will help emergency managers and other stakeholders to identify subgroups that are more susceptible to loss and to tailor public policy to reduce such loss.

2 Data Selection

One method to assess social vulnerability is through the use of composite indicators. An indicator is a measure derived from observed facts, and a composite indicator is the mathematical combination (i.e. aggregation) of a set of individual indicators. Data collection is the primary step in composite indicator development. The starting point for measuring social vulnerability in this project was comprised of a data selection process that allowed us to capture pre-existing social conditions related to the overall capacity of populations to prepare for, respond to, and recover from damaging events. There is a rich tradition of research focused on those factors that increase or decrease the social vulnerability of a given population, and the variables adopted for the measurement of social vulnerability for our analysis were discussed in seminal research papers [9,10]. It is within this context that a total of 430 indicators at the sub-national level (P3) for Argentina, Bolivia, Chile, Colombia, Ecuador, Perú, and Venezuela were collected, pre-processed, and categorized. The data was obtained from the most recent national censuses on population in each country [11,12,13,14,15,16]. Each country's database contains approximately 50-70 indicators. Variations in the number of indicators and the enumeration units represented for each country are outlined in Table 2 below.

Table 2. South American countries P3 subnational organization

Country	**Sub-national division**	**Subdivision count**	**Number of indicators collected**
Argentina	Departamento, Partido, Comuna	527	57
Bolivia	Municipio	341	68
Chile	Comuna	342	68
Colombia	Municipio	1114	60
Ecuador	Parroquia	1024	56
Peru	Distritos	1833	65
Venezuela	Parroquia	1130	47

Since it is difficult to measure the social vulnerability of populations in relative terms, variables were collected as proxy measures to represent the concept. We collected variables within broad categories for which drivers of social vulnerability are known to exist. This includes population, economy, infrastructure, health, and education dimensions by adhering to the taxonomic classification developed by Khazai [17] for the selection of socio-economic indicators typically used in social vulnerability assessments. A hierarchical approach was utilized in which variables were separated into sub-components (e.g. population, economy, infrastructure, etc.). These individual variables within sub-components are aggregated into sub-indicators, and the aggregated sub-indicators are combined to construct the final Social Vulnerability index. This approach was employed so that each subcomponent of social vulnerability could be mapped and analyzed in isolation. Table 3 presents a description of subcomponents and variables included for the analysis of social vulnerability.

Table 3 Description of subcomponents and variables included for the analysis of social vulnerability

	sub-component	**Variables included**	**Description**
social	Population	Age dependent, the homeless, the disabled, native indigenous population, female population among others	Describes population that are at risk in order to capture differential capacities of populations to reduce earthquake risk and to recover from damaging earthquakes when they occur

	Economy	Employment status, unemployed populations, population with unsatisfied basic needs, monthly income	Describes labor demographics, the distribution of wealth, and the incidence of poverty in a country
	Infrastructure	Access to potable water, electricity, transport and communication (internet and telephone usage)	Describes the characteristics related to access to energy and water resources, sanitation services, and the telecommunication and transportation capacities
	Education	population with no formal education, population that does not read and write, educational level completed, etc.	Describes the accessibility of a country's population to education in relation to recovery potential.
	Health	Population with no healthcare, access to private/public healthcare, distance to nearest medical center, etc.	Categorizes the health condition of a country's population, accessibility to health resources, and the ability of health systems to respond and provide healthcare to those affected during an earthquake

3 Social Vulnerability Assessment Methodology

The construction of sub-indicators of social vulnerability required the conversion of raw data into variables using percentages, per capita, and density functions. The data was then standardized using a Min-Max rescaling scheme to create indicators on a commensurate measurement scale. The Min-Max rescaling method transforms all values to a scale between 0 and 1. In our case, 0 represents the best rank for a specific indicator and a score of 1 is associated with the worst rank. These variables were then analyzed for significantly high correlations between individual variables in order to construct indicators that are parsimonious. When high correlations (i.e. Spearman's R >0.700) were found, variables were eliminated from further consideration.

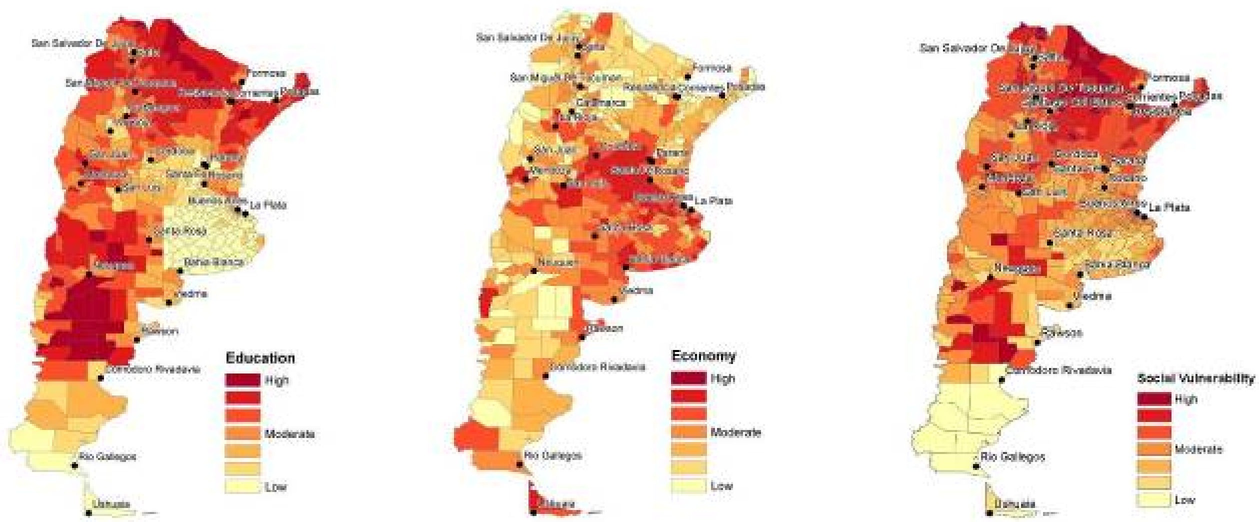
Once correlated variables were removed, the hierarchical method of aggregation that we briefly touched upon in the section above was employed to achieve final composite social vulnerability scores for each country. These scores were derived through the summation of sub-indicator scores composed of equally weighted variables within each of our respective subcategories of data (population, economy, infrastructure, education, health). In other words, sub-indicators were generated for each sub-component (i.e. Education) by averaging the respective variables, and these sub-indicators were summed to produce a final index of social vulnerability. This approach using averages was selected in order to reduce the influence of the different number of variables in each sub-indicator. Since five sub-components were considered in our analysis (Table 3), the summed score of the composite indicators for each P3 enumeration unit fall within a range from 0 to 5 (0 being the least socially vulnerable and 5 being the most). The aggregation method chosen for this paper uses equal weighting and an additive method since it is straightforward. The importance and relevance of the indicators were evaluated via consultation with stakeholders and earthquake risk experts within each country. These results will be reported on in subsequent publications.

3.1 Social Vulnerability Index: some results

To illustrate the uneven spatial distribution of characteristics known to affect the social vulnerability of populations, we mapped sub-indicators of social vulnerability using our Economy and Education sub-indicators for Argentina (Figure 1). The spatial distribution of the education subcomponent (1a) shows potentially low levels of social vulnerability based on the education sub-component around the Buenos Aires province. Buenos Aires is an urban province that provides ample access to education compared to its rural counterparts. The economic sub-component (1b), on the other hand, shows factors potentially contributing to high levels of social vulnerability around Buenos Aires and Santa Fe provinces where Argentina's economic activity is concentrated. The latter is partially the result of a high concentration of employment within single sector economies, such as the commercial sector, that may be at high risk from damaging earthquakes. Figure 1c shows the composite social vulnerability scores considering all sub-indicators. The driving forces governing this spatial variability are explained thoroughly in section four.

4 Exploring the Drivers of Social Vulnerability in the Andean Region

The exploratory portion of this paper utilizes a Factor Analysis (FA) that adopts the rotation and factor interpretation methodology of the Social Vulnerability Index (SoVI) [18]. The SoVI method centers on the use of a Principal Component Analysis (PCA), specifically a Factor Analysis, to reduce a large number of variables into a smaller set of multivariate factors that are used to highlight potential drivers of social vulnerability within a given study area. We utilized a factor analytic approach for this research to describe the multivariate nature of the social factors affecting earthquake risk within the Andean Region, to uncover underlying dimensions of social vulnerability and to reveal how different variables change in relation to each other and how they are associated.



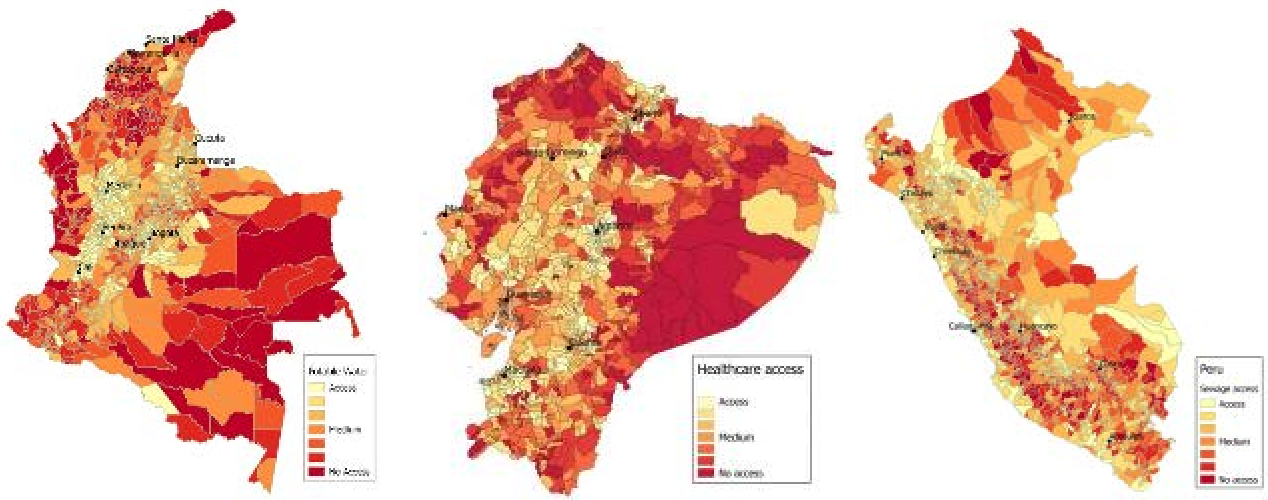
(a) (b) (c)

Figure 1. Argentina: (a) education and (b) economy subcomponents and (c) Social vulnerability Index

The FA we performed for each country produced a set of factors explaining the variance in the data for the variable selection. The factor loadings for each variable were analyzed, and each variable's viability as an explanatory driver of social vulnerability was subjectively considered based on the strength of each variable's factor loading. Factor loadings of 0.50 and higher and -0.50 and lower were considered important explanatory drivers of social vulnerability within the region. The results are consistent across countries with five broad factors per country explaining a considerable percentage of the variance in the data. These five factors represent five overarching demographic themes:1) access to basic needs, 2) dependent population, 3) employment and housing, 4) gender and ethnicity, and 5) Inequality and poverty. These are discussed in greater detail below.

4.1 Access to basic needs (education, health, lifelines)

Access to basic needs captures between 30 and 40 percent of the variance explained for each country. This category is comprised of: households with no access to an improved water source, population with no formal education, population with no healthcare, and population with no access to a sewage system. Figure 2 shows the spatial distribution for (a) access to potable water in Colombia, (b) population with no healthcare in Ecuador, and (c) access to sewage service in Peru. The spatial distribution of these variables show the parishes colored in red experiencing limited access to basic services, mostly located in rural areas. Conversely, major cities e.g. Bogota, Medellin, Quito Guayaquil, Santo Domingo, Lima, Callao, and surrounding parishes receive better access to basic services. Population in parishes having better access to basic services are more likely to have emergency plans in place, proper response units, and the capacity to recover and adapt to the effects of an earthquake. In the same factor, we found variables such as population living in renting units, population employed in the commercial industry, and population employed in the hotel and restaurant sector.

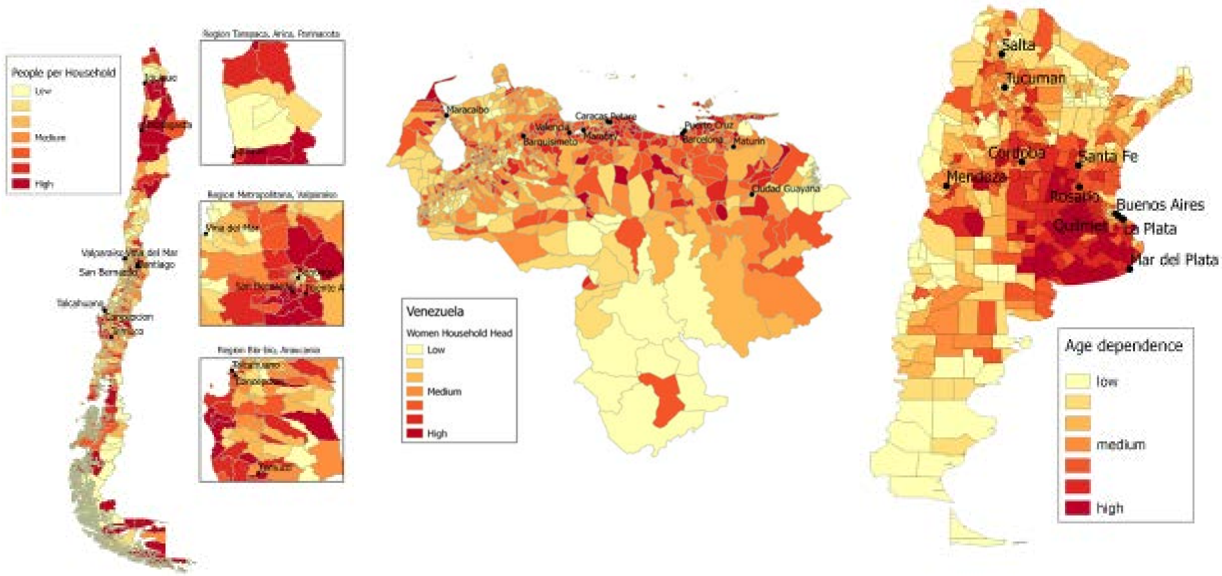


(a) (b) (c)

Figure 2. Spatial distribution for the variables (a) Colombia access to potable water, (b) Ecuador access to healthcare, (c) Peru access to sewage service

4.2 Dependent populations

The second component represents between 10 and 20 percent of the variability within the data for all South American countries. It captures the following variables across the countries: total females, age dependence, total population with a disability, and number of people per household. These results correspond to the social vulnerability indices developed for each country in which the population sub-indicators were designed to reflect different capacities of populations to reduce earthquake risk and to recover from damaging earthquakes when they occur. The latter is exemplified by Figure 3 which illustrates basic characteristics of social vulnerability in the population, the spatial distribution of people per household in Chile (3a), and female heads of household with no husband present in Venezuela (3b). Similarly, people with social disadvantages contribute to vulnerability under this component, meaning that sub-national divisions with children and elderly (figure 3c) might be more vulnerable during an earthquake. As stated by J. Wood in community variations in social vulnerability “the number of people per household suggests that families with many dependents encounter greater obstacles when responding to an emergency and may have less financial means to recover. Research and experience also suggests that children, the elderly, and women may require extra assistance in the event of an earthquake initially for evacuation and after for access to recovery resources” [19].

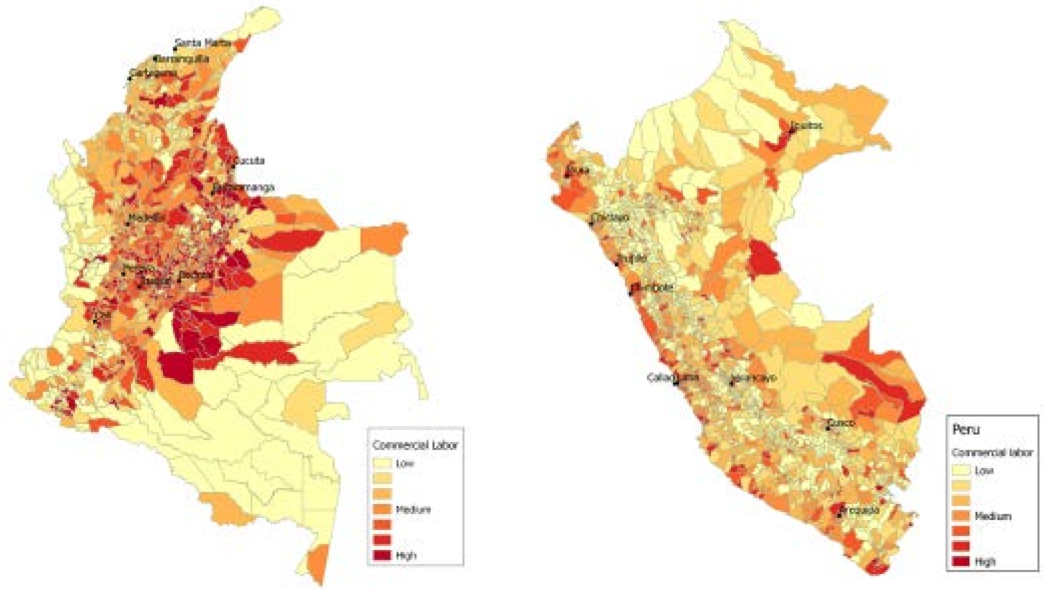


(a) (b) (c)

Figure 3. Spatial distribution for variables (a) Chile people per household, (b) Venezuela women head of household, and (c) Argentina age dependence population

4.3 Employment and Housing

This factor represents between 7 and 10 percent of the data's variance and is composed of the following indicators that load above or below the threshold adopted: population working in the manufacturing industry, population working in the commercial industry, and population living in dwellings with inadequate physical characteristics. These variables refer to employment and housing across the Andean countries suggesting that drivers of social vulnerability may include urban sub-national areas that are associated with individuals working in service industries and commercial activities. This suggests that the economic sector plays an important role on people's livelihoods which can either increase or reduce their social vulnerability to earthquakes. Figure 4 is a map of the people employed in the commercial sector variable for Colombia and Peru. The geospatial distribution of this variable shows a high number of people employed in an economic sector highly vulnerable to losses in jobs following an earthquake. In addition to employment is single sector economies, rapid migration into cities drives the social vulnerability of populations. In the case of Peru, a rural-urban migration beginning in 1940 caused a rapid urbanization and extensive informal settlements [20]. In 2007, the estimated housing deficit in the country was around 1.8 million dwellings with nearly 80% of this reflecting deficiencies in the quality of dwellings in terms of material used for walls and floors, overcrowding, and access to public services [21]. This deficit reflects a considerable number of households living in inadequate and non-engineered dwellings that could be adversely affected during earthquake events. Regarding the economic conditions of the households considered in housing deficit, near to 0.48 million of heads of households (around 26% of the total deficit) do not earn any income. This population is either unemployed or part of the non-economically active population [INEI 2009].[PH1] As a result, different factors (such as migration, unemployment) influenced the construction of vulnerable urban environments characterized by low-income communities, with limited capacity to mitigate risk and to recover from earthquake events.

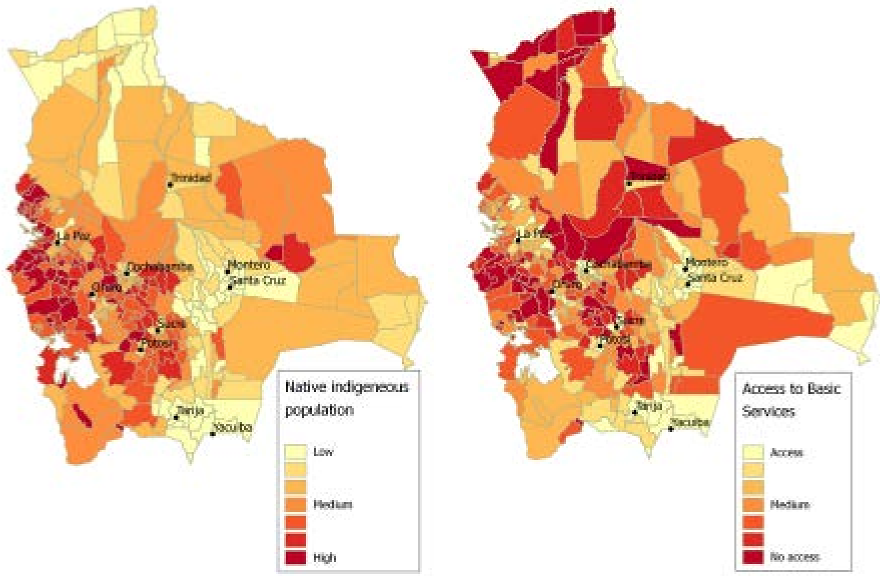


(a) (b)

Figure 4. Spatial distribution for the variables (a) Colombia - population employed in the commercial sector, and (b) Peru - population employed in the commercial sector

4.4 Gender, Ethnicity, and Poverty

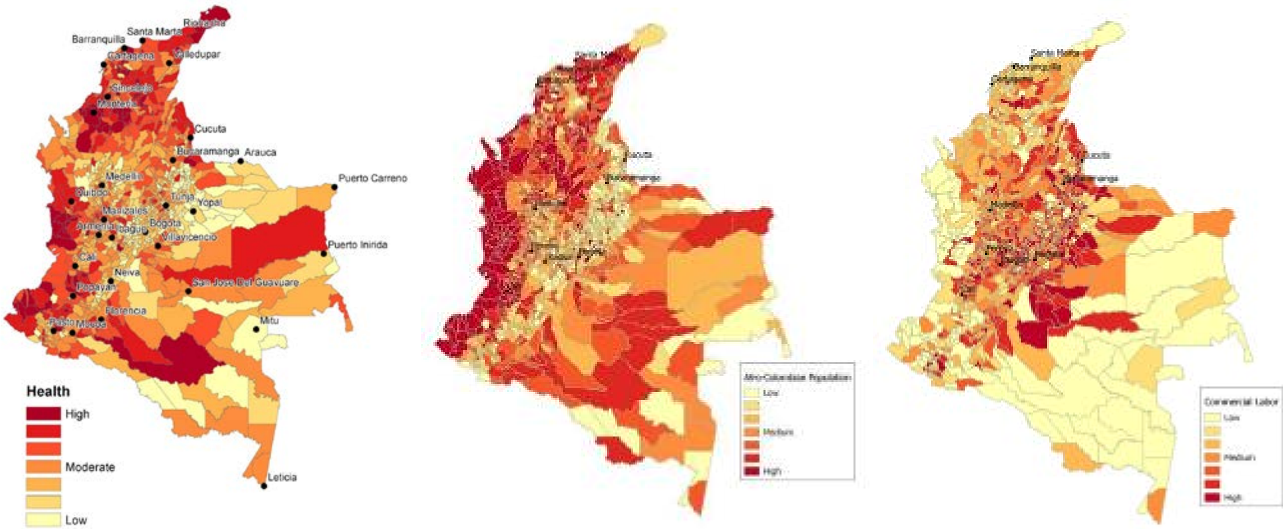
Gender, ethnicity, and poverty indicators are cross cutting proxies among all the components in our analysis. Indicators such as: female heads of household, female population, native indigenous populations, and race, and ethnicity influence individual sensitivity to natural hazards due to racial patterns and ethnic inequalities in South America. Bolivia, in particular, has a resident population in which nearly 42% of the people within the country belong to an indigenous group. These populations are mainly located at the western side of the country (La Paz) and in Sub-Andean valleys (Cochabamba) figure 5a where earthquake risk is significant. According to Gigbler [22], there is a high and persistent correlation between being poor and being indigenous; the poorest regions of the country are also the ones where most of the indigenous groups are located. Here, indigenous populations mainly work as domestic servants, in street markets, or in forms of cheap labor. Among the underlying factors that have limited the capacity of indigenous groups to overcome poverty are continuous lack of access to social services (education and health) and productive assets. In addition to access to financial resources, native indigenous groups are often isolated from urban areas and their livelihoods and receive inferior access to basic public services like potable water, electricity, and public infrastructure (Figure 5b). This isolation may compromise disaster preparedness and planning activities as well as response and recovery efforts in case of an earthquake.



(a) (b)

Figure 5. Bolivia spatial distribution for (a) native indigenous population and (b) Access to basic services

Similarly, variables related to poverty and inequality are cross cutting proxies in our analysis. The South American region is characterized as having an immense gap between the poor and the rich. This gap is noteworthy when it comes to accessing vital public services. In terms of managing the risk to earthquakes, poverty levels play an important role in planning and mitigation mechanisms as well as in response and recovery capacity. Figure 6a shows the spatial distribution of the health subcomponent for Colombia. We chose to map the health component because it provides an example of unequal access to resources based on the gap between the rich and poor mentioned above. The distribution of the data suggests that the red colored parishes are highly vulnerable because of their limited access to health services. In the case of Colombia, the percentage of total population in poverty is around 20% [23]. Regarding the geographical distribution of poverty in the country, [24] argued that peripheral areas (the Atlantic and Pacific coasts, the plains and rainforest) are immersed in what the authors refer to as poverty traps: groups of municipalities with persistent conditions of poverty over time (figure 6b). Such areas concentrate near the 38% of the total population and comprise 60% of the population with unsatisfied basic needs. Such traps are associated with other factors known to affect social vulnerability such as less access to formal education and less employment opportunities (figure 6c) because of discrimination based on ethnicity.



(a) (b) (c)

Figure 6. Colombia spatial distribution for (a) health sub-component of social vulnerability, (b) Afro-Colombian population and c) population employed in the commercial sector

5 Conclusions and Recommendations

Across South America the socially vulnerable tend to be the poor populations given their limited access to resources and the lack of ability to cope with the impacts of an earthquake. Recent earthquakes in the region i.e Ecuador 2016, Chile 2010 reveal that human losses remain high when an earthquake strikes in South America, the effective response and recovery capacity of south American countries is also still a concern. Specific preparedness and planning policies are not represented across every parish, community, or region in South America. Precise risk information that includes a community's social vulnerability becomes essential for hazard preparation, response activities, planning, and it is vital for proper decision and policy making. The social vulnerability results demonstrated within the SARA project can be used to identify those sub-national divisions experiencing moderate to high social vulnerability. This information can be coupled with the GEM-SARA risk losses results to identify areas under high seismic risk. The work can be further investigated in rural and urban areas to provide guidelines for DRM practitioners to develop regional risk-reduction strategies tailored specific to local contexts and population needs in order to reduce social vulnerabilities and earthquake risk.

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