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Estimating exposure around San Miguel Volcano, El Salvador.

Diana Jiménez^{1,2}, Laura Becerril^{3,4}, Arline Carballo¹, Sara Baires¹, Joan Martí³.

¹ Gerardo Barrios University, Calle Las Flores y Avenida Las Magnolias, Colonia Escolán, San Miguel, El Salvador.

² Universitat de Barcelona, Facultat de Geologia, Dep. Geodinàmica i Geofísica, Martí i Franquès s/n 08028 Barcelona, Spain.

³ Institute of Earth Sciences Jaume Almera, ICTJA, CSIC, Group of Volcanology, SIMGEO UB-CSIC, Lluís Solé i Sabarís s/n, 08028 Barcelona, Spain.

⁴ Servicio Nacional de Geología y Minería (SERNAGEOMIN), Avda. Santa María 0104, Santiago, Chile.

Abstract

San Miguel, one of the most active volcanoes in El Salvador, is surrounded by several villages and cantons, which could be seriously affected in case of a new eruption. This study presents an exposure analysis of the San Miguel volcano area by considering population distribution, land use, private houses, official buildings (hospitals, schools, etc.), and communication infrastructure. We use spatial analysis Geographic Information System tools to estimate exposure for different volcanic hazards (air fallout, lava flows, pyroclastic density currents, lahars). Moreover, in the particular case of private houses and official buildings, we estimate a Vulnerability Index for the hazardous areas, applying the Physical Vulnerability Methodology based on the characterization of the type of construction materials of walls and roofs. We construct different exposure maps for: 1) population, 2) land use, 3) road networks, 4) schools, and 5) health centers. This approach identifies the elements at risk according to each potential hazard, thus providing the authorities with a comprehensive tool to better understand the problem and to define emergency plans to minimize risk.

Keywords: Exposure analysis, Vulnerability, Hazard assessment, San Miguel volcano.

1. Introduction

Assessment and management of volcanic risk are important scientific, economic, and political issues especially where volcanoes threaten densely populated areas. Appropriate responses to these concerns require accurate assessment and mitigation programs (Martí, 2017). Risk assessment is based on hazard, exposure, and vulnerability characterization (De la Cruz-Reyna and Tilling, 2008). A multidisciplinary approach is required to combine these aspects into comprehensive risk management plans (Martí et al., 2008). Assessing volcanic hazards consists in the identification of how a volcanic system (i.e., an active volcano or volcanic area) has behaved in the past and applying this knowledge to infer how it may behave in the future, thus determining the extent of potential hazards and the areas that they could impact. Exposure quantifies the social, economic, environmental, cultural, and strategic value in areas that could potentially be impacted by a given hazard (Birkmann, 2013; Scaini et al., 2014). Vulnerability analysis should define inventories of elements (people, properties, infrastructures, etc.) at risk from volcanic eruptions, determine the appropriate response (resistance) to the impact of volcanic hazards, and carry out impact assessments based on given eruption scenarios (e.g., Gehl et al., 2013).

In El Salvador, 88.7% of the territory is considered a risk area and 95.4% of the population is located on that surface (MARN, 2017), cataloging it as one of the most vulnerable countries in the world (CEPAL 2011 World Risk Report, 2017; MARN, 2017). Volcanic activity represents one of the highest risks for the country, since it has 23 volcanoes from which at least five are currently active (Agostini et al., 2006, DGOAM-MARN). Considering this, there is a strong need for exposure and vulnerability analyses based on volcanic hazards in El Salvador, in order to have a better view of the possible impacts that may be caused by future eruptions. However, very few efforts have been carried out until now (MARN, 2017), hence it is urgent to strengthen that line of research.

San Miguel volcano is one of the most active volcanoes in the country with at least 28 eruptions in the historical period (since AD 1586, arrival of the Spaniards). Due to the fertile nature of the soils and the cooler and more humid local microclimate, this volcano hosts on its flanks several villages and cantons, as well as a large number of plantations, mostly coffee. Its last important eruption occurred in 2013 and generated a 9-km-high eruption column that caused the deposition of a thick ash fallout layer on the surrounding areas, and a short pyroclastic density current that travelled around 500 m down the flanks of the volcano and buried several coffee plantations (Scarlato et al., 2016). A long-term volcanic hazard assessment for San Miguel volcano was conducted by Jiménez et al. (2018, 2019), providing the spatio-temporal occurrence probabilities for the different volcanic hazards, in addition to a hazard map. This information is now used to estimate the potential impact of such eruption scenarios on population, infrastructure, and land-use, and thereby to evaluate the potential exposure and vulnerability associated with such impacts.

To that end, the present work provides exposure analysis that consists of five elements: 1) population distribution, 2) land use, 3) road networks, 4) schools, and 5) health centers. We construct different exposure maps according to the type of element studied. For private houses, schools, and health centers we estimated the Vulnerability Index in a village where lahars are frequent, considering the type of materials used to construct the walls and roofs of the different buildings. This study will help to improve the emergency plans, territorial planning, and risk management around San Miguel volcano and together with the previous studies will establish the necessary technical guide to assess the risk of the other active volcanoes in El Salvador.

2. Background

Volcanos in Central America are genetically related to the triple convergence between the North American, Caribbean, and Cocos plates (Bosse et al., 1976, Carr and

Stoiber, 1977; Carr et al., 2004; Rogers et al., 2002). El Salvador borders the Middle America Trench (Fig. 1), which is the active subduction boundary and seismic zone between the Cocos and Caribbean plates (Dewey et al., 2004). As a consequence of plate subduction, El Salvador is intersected by the Central America Volcanic Arc (CAVA) (Fig. 1), which is formed by 75 volcanoes that have basaltic to andesitic compositions, 31 of which were active in historical times (Simkin et al., 2000; Carr et al., 1984, 2004; Ferrés, 2014). CAVA is divided into eight tectonically controlled structural segments, with different geological and geophysical characteristics (Stoiber & Carr, 1973; Carr & Stoiber, 1977; Carr, 1984). The segment comprising El Salvador has an approximate length of 240 km and has shown intense seismic and volcanic activity since the Early Miocene (Carr, 1984; Martínez et al., 2004; Corti et al., 2005; Agostini et al., 2006).

San Miguel volcano is located in the eastern region of El Salvador (Fig. 1), and is considered one of the most active volcanoes in the country, with 28 documented eruptions over the past 500 years (Escobar, 2003; Chesner et al., 2004; Scarlato et al., 2016). Locally known as Chaparrastique volcano, this structure is a composite basaltic-andesite volcano, 2,130 m high, with a conical shape that has steep slopes of up to 40 degrees in its upper parts (Escobar, 2003; Ferrés, 2002, 2014; Jiménez et al., 2018). The volcano has a base of 9 km in diameter, a principal crater of about 0.9 km across, and a relict crater produced by the collapse of an ancestral cone (Escobar, 2003). San Miguel exhibits evidence of effusive and explosive activity during the Holocene (Escobar, 2003; Chesner et al., 2004; Jiménez et al., 2018), with a majority of Strombolian eruptions that have generated spatter, ashfall, and pyroclastic density current (PDC) deposits from the summit crater and basaltic and basaltic andesite lava flows from its flanks and its summit crater (Chesner et al., 2004).

Historically, San Miguel has erupted with a VEI of 1–2 (<http://www.marn.gob.sv>), producing eight lava flows with a total volume of 0.53 km³ DRE (dense rock equivalent) and numerous more modest explosive eruptions (Escobar, 2003; Scarlato et al., 2016). The largest lava flow emplaced during the historical period occurred in 1699, traveling 8 km downslope the volcano's southeastern flank until reaching 480 m a.s.l. Other important

effusive activity took place in 1762 and 1787, when lava flows reached San Miguel City (the fourth largest city in the country) and the area of today's Panamerican and Litoral highways (presently the most important roads in El Salvador), respectively. Other lava flows are present around the volcano but their ages are not well constrained, as they occurred in pre-historical times (before AD 1586).

From 1844 to present, at least 20 minor ash falls (volumes $< 10,000 \text{ m}^3$) have been reported that were generated from the summit crater. The two most significant episodes of explosive activity occurred between March and April of 1970 (volume = $7.5 \times 10^{-5} \text{ km}^3$) and on December 2013, (VEI-2, volume = 0.0085 km^3). This last eruption was characterized by the rise of a 9-km-high ash column, causing the expulsion of ballistics, pyroclastic surges, and debris flows (Martinez-Hackert et al., 2015), and prompted the evacuation of over 5,000 people living within a 3-km radius around the volcano (Martinez-Hackert et al., 2015; Scarlato et al., 2016), also halting air traffic at the international airport for a few hours.

Several villages and cities, including San Jorge, San Rafael Oriente, Chinameca, El Tránsito, San Miguel, Quelepa, and Moncagua, sit on San Miguel volcano (Fig. 2). The estimated population in the surrounding area is over 330,000 people, 60% of whom reside within the volcano's zone of influence (Ferrés, 2002, 2014; Jiménez et al., 2018) due to the fertile nature of the volcanic soils and the cooler and more humid local microclimate at higher altitudes, which allow many agricultural activities such as coffee plantations and vegetables.

With an area of 593 km^2 and a population of 218,410 (DIGESTYC, 2016), San Miguel has a population density of 368 people per km^2 . It is the largest municipality near the volcano and within its urban area are many institutions and infrastructures (i.e., hospitals, power stations, water services, transport, and administrative offices) that serve neighboring municipalities in the region.

San Jorge municipality, which is located on the volcano's slopes and rich in wood for construction and cabinetmaking, has an area of 37 km^2 and 9,115 inhabitants

(DIGESTYC, 2016), with a population density of 242 people/km². In the case of Chinameca the area on the volcano corresponds to the Conacastal canton, which is recognized for its coffee plantations and local touristic areas: Las Placitas and La Arenera. San Rafael Oriente and El Tránsito have population densities of 295 people/km² and 246 people/km², respectively.

3. Volcanic hazards

Volcanic hazards associated to San Miguel volcano were identified and described by Jiménez et al. (2018, 2019), who conducted a long-term hazard analysis and characterization of the most probable eruption scenarios that may occur on this volcano in the near future. The main hazards include: Lava flows, fallout, lahars, and pyroclastic flows.

Each of these hazards may affect to different degrees people and their properties (houses, cars, growing fields, farms, animals, etc.), as well as important infrastructures (water conduits, energy supplies, roads, etc.) necessary for the development of the municipalities and their human settlements around the volcano.

The most likely scenarios described by Jiménez et al. (2018) involve ash fallout and secondary lahars. These most likely scenarios are applicable to a forecasting time window of two years, considering the last 430 years of activity. Simulations of these scenarios were performed by Jiménez et al. (2019) with the aid of the VOLCANBOX platform (Martí et al., 2016), and by this procedure the different partial and total hazard maps were obtained. Figure 3 shows the San Miguel Hazard Map, with three levels of hazard classified according to the number of hazards that may impact the same point, not by the relative potential damage that each hazard may imply: Green zone: one-hazard impact, yellow zone: two-hazard impact, red zone: three or more hazard impact. Detailed information on the estimation of the probability of occurrence for the main volcanic hazards at San Miguel volcano can be found in Jiménez et al. (2018), and for scenario simulations in Jiménez et al. (2019).

4. Methodology

The previous information on hazard assessment and eruptive scenarios (Jiménez et al., 2018; 2019) was used to determine the areas threatened by the San Miguel volcanic hazards. Using this information, we designed an exposure analysis method that considered a wide range of data, such as population distribution, social and economic conditions, productive activities and their role in the regional economy, as well as the distribution of the main infrastructure in the area. However, because of the limited availability of data and the difficulty of obtaining data in GIS format for many of these socio-economic indicators, our analysis was restricted to houses, infrastructures (i.e., health centers, schools), land use, and roads.

Combining the hazard map for San Miguel volcano (Fig. 3) with each set of elements collected, we made different exposure maps in order to estimate the possible impacts and to identify which elements can be affected. We used the information from the Dirección General de Estadísticas y Censos (DIGESTYC), Ministerio de Agricultura y Ganadería (MAG), Ministerio de Educación, Ciencia y Tecnología (MINEDUCYT), Ministerio de Salud (MINSAL), and Civil Protection. Moreover, students and academics from Gerardo Barrios University collected information from interviews and verified houses with people of Conacastal and La Morita.

The material assets considered in this study include: 1) land use, 2) road network, 3) schools, 4) health centers, and 5) private houses. For the first four we construct different exposure maps showing the subcategories of those sets. In the case of houses, we made an estimation of the Vulnerability Index in Conacastal canton for lahars, considering the construction materials used for walls and roofs of dwellings.

For land use we estimated a percentage of agricultural areas that would potentially be affected by hazards (Fig. 3), overlying for this purpose the map of land use on the hazard map. The intersected area between the two layers is the affected area, which we divided by the total area studied. In the case of road networks, schools, and health centers we used a similar procedure, but instead of estimating the percentage, we counted elements inside the hazard area. Road networks were divided into five categories depending on the legal classification from Ley de Carreteras y Caminos Vecinales de El Salvador, performing the analysis for each one separately. We used the QGIS 2.18.27 calculator for vectors and rasters for the different analyses.

With regard to private houses and other buildings we chose the Conacastal canton as the sample survey area in order to apply the Physical Vulnerability Methodology (GVF) proposed by Observatorio Ambiental from El Salvador (MARN, 2012). This methodology is based on the characterization of the construction materials of walls and roofs of stocks, since they constitute the most important structural component related to the resistance of the element (MARN, 2012). Considering the 2007 census and the additional fieldwork conducted during the present study, 14 types of housing were established with an associated value representing the fragility of each type (Table 1). These value assignments were made through iterations across statistical ranges by taking into account, under expert criteria, the possible construction materials and foundations (MARN, 2012). Even though this methodology is proposed for inundations and landslides, we use the “very high” coefficient of landslides (Table 1) in the case of secondary lahars because they could be considered landslides with a very a high water content (MARN, 2012).

To calculate GVF we used the equation

$$GVF = \frac{C_a * e_a * V_a + C_b * e_b * V_b + C_c * e_c * V_c + \dots + C_n * e_n * V_n}{C_a * C_b * C_c + \dots + C_n} \quad (1)$$

where:

GVF: physical vulnerability.

C_n: number of houses in typologies.

E_n : household exposure coefficient.

V_n : value assigned to the typology.

The GVF value is associated with the Vulnerability Index (Table 2) in order to obtain the classification.

The estimation of GVF was made considering a total of 300 Conacastal houses including the diversity of built morphology. We also used these criteria to calculate the GVF for schools and health care centers around the volcano.

5. Results

In order to have a more organized view of the different elements that can be affected by volcanic hazards around San Miguel volcano we constructed some maps showing the characteristics of the different vulnerable elements that we considered for this region.

We identify the number of cantons and related number of people exposed for each of the three hazard zones (Fig 4). Hazard zone 3, located in the Conacastal canton (blue square, Fig. 4) with a population of 3,045 inhabitants, corresponds to the towns of: La Cruz, Hercules, Joya Verde, Las Placitas, El Carmen, and El Progreso. Hazard zone 2 covers 20 cantons (red dots, Fig. 4), from Chinameca, San Jorge, San Rafael Oriente, San Miguel, and the El Transito municipalities, with a population of 17,696 individuals. Hazard zone 3 includes 29 cantons (orange diamonds, Fig. 4), with a population of 23,466 inhabitants. The population in this zone consists of urban and rural areas, unlike hazard zones 2 and 3 that basically contain rural populations. The three zones include an approximate total of 45,000 individuals.

Figure 5 shows the land use of the area, as well as the number of farms. It is clear that coffee plantations are the most significant agricultural activity on San Miguel Volcano, the farms being distributed mostly in the northeast and northwest flanks of the volcano. There are vegetables and sugar cane growing fields on the southeast and northeast flanks,

while on the southwest flank there are some forest areas. Figure 5 also shows a percentage of the potential affectation for each of these land uses; coffee plantation could be affected for over 8% of its production, meanwhile vegetables and forest areas could be affected by less than 1% (Fig. 5). The south flank has less agricultural activity, because of the occurrence of relatively recent effusive eruptions (1699, 1787, 1819 and 1855).

Considering the San Miguel hazard map (Fig. 3) the number of schools and health centers exposed in the hazard zones are seven and three, respectively (Fig. 6). In hazard zone 3 are two schools and one health center: Instituto Nacional García Prieto, Centro Escolar Sra. Rosa Hirlemann de García Prieto, and Unidad de Salud Conacastal (Fig. 6a) respectively. Hazard zone 2 includes two schools: Centro Escolar Calle Nueva and Centro Escolar Cantón El Brazo (Fig. 6b) with no health centers. Hazard zone 1 includes three schools: Centro Escolar Cantón el Papalón, Centro Escolar Caserío América, and Centro Escolar Cantón la Morita; and two health centers: Cantón El Niño and San Carlos, both from the San Miguel municipality. Figure 6 also shows the number of students in each hazard zone: Hazard zone 3 has 591 students, hazard zone 2 serves 137, and hazard zone 1 includes 580 students. A very important fact is that for hazard zone 3 there is a high school (Instituto Nacional García Prieto, Fig 6), which is attended by students from different cantons, therefore requiring regular travel along affected road networks.

Roads are very important elements for communication between villages and as potential evacuation routes in case of a volcanic crisis. We identified five types of roads (Table 3). Types one to three are made of blacktop or hydraulic concrete, while road types four and five are rural dirt roads. In hazard zone 1 we identify more than 300 roads: 19 of type 1, 35 of type 2, 118 of type 3, and 147 of type 4. Fig. 7 illustrates the number and type of roads in hazard zones 2 and 3; in hazard zone 2 are around 400 different roads, including the principal road on San Miguel volcano that communicates the municipalities of San Miguel, San Jorge, and San Rafael Oriente. In hazard zone 3 are 210 roads principally of type 4 (rural roads). Many roads pass through all the hazard zones, and in these cases they have been counted according to the longest stretch affected.

Conacastal canton is located in hazard zone 3, meaning that all possible future eruptive scenarios could affect it. Moreover, considering the recurrent secondary lahars that affected the area, we estimated the Vulnerability Index (GVF) following the methodology proposed by MARN (2012) based on the characterization of the construction materials used for walls and roofs of private houses. The sample used was from 300 houses made of different materials (see Table 4). Most of the houses are made of sheet metal or a combination of concrete and sheet metal. With this classification and the values of Table 1 we applied Equation (1), obtaining a GVF of 1. This number reflects the highest vulnerability ahead of secondary lahars according the range shown in Table 2. In the case of schools and health centers GVF is 0.02, meaning a low vulnerability to secondary lahars.

6. Discussion and conclusions

San Miguel volcano presents effusive and explosive activity, and also other associated hazards such as lahars. Considering the specific hazards and probable scenarios identified by Jiménez et al. (2018, 2019) it is also essential to know the potential impacts of those hazards on the individual elements (persons, road, private houses, agricultural terrains, public buildings, etc.) that are exposed. This provides a first approach to identify the elements at risk and helps authorities to realize the problem in a more comprehensive way and to define precise land use planning and emergency plans to minimize risk. We are aware of the restrictions of these types of studies as they depend on the availability and quality of data. However, the study presented here should be regarded as a first attempt to define a systematic methodology to be applied to the other volcanoes of El Salvador in order to provide the first quantitative evaluation of the risk they represent. Despite we focus our study on the proximal areas around the volcano and on the direct hazard impacts they might receive in case of a new eruption, it is worth mentioning that eruptions at San Miguel volcano may also impact more distal areas, as the international airport of San Salvador, as it occurred in 2013 due to the widespread distribution of airfall tephra.

A complete exposure analysis requires a wide range of data that in this case was limited by the availability of these data in GIS format for many of the socio-economic indicators we wanted to use. However, even so they were sufficient to present a good view of the potential affectation of San Miguel volcano on population distribution, infrastructures, and productive activities. For instance, we identified that the Cantón Conacastal is located in a zone that can be affected by any volcanic hazard, so it is necessary to pay attention to this region in order to be able to make actionable decisions such as to define the list of priorities of intervention, the responsibilities for each emergency operation, and the resources needed for this area with more than 3,000 people (Fig. 4). The methodology used here, employing existing GIS analysis tools, allowed us to identify the potential impact on the different elements considered and to construct useful exposure maps that can be easily understood. This enabled us to produce a preliminary impact assessment for the area. Furthermore, these results improve the overall discourse by providing guidelines for future optimization of local data management, thereby enhancing emergency planning.

In the particular case of private and public constructions, approximately 98% of them (houses, schools, and health centers) fit in the classification proposed by MARN to calculate the Vulnerability Index (Table 1), which means that the exposure values associated to them provide a realistic estimate (Table 4).

The exposure of agricultural terrains indicates that coffee plantations will be more affected (Fig. 5), thus suggesting a significant impact on the local socio-economic system, as these farms are an important source of local employment. It is also important to disseminate this information among the coffee organizations and government for the purpose of generating a discussion around the development of strategies to soften the economic losses in these cases, since most of the coffee in the country is produced in volcanic areas.

The road network analysis illustrates that many roads will be impacted by volcanic hazards. For instance, around 40 roads between types 1 and 2 (see Table 3) will be

affected by any given hazard (Fig. 7), including sectors of the most important connecting roads in the area, which are also considered to be potential evacuation routes. This shows the need to design a plan to define and construct alternative communication routes if some of the previous sectors are blocked. The Conacastal canton, besides being in a region in which at least four hazards can impact (Fig. 4), also has a high vulnerability index because almost 50% of the houses are made of sheet metal, a very vulnerable material (Table 4). This represents a high-risk area that requires a special plan. Schools and health centers have a low vulnerability index for lahar, considering that they are made of concrete or mixed walls and fibro-cement roofs (Table 4). Nevertheless, if we note that two of the schools, such as Instituto Nacional García Prieto and Centro Escolar Cantón La Morita (Fig. 6), are in areas exposed to different hazards, this implies firstly that they should not be considered as shelters, and secondly, to consider the possibility of relocating the García Prieto high school to a less hazardous location, which would decrease the number of people exposed.

The results presented, albeit preliminary and incomplete due to the limitations explained above, permit to identify exposed areas and to infer possible impacts on society. Furthermore, they should contribute to recognizing priorities and to better identifying the potential problems that may surface if a new eruption of San Miguel volcano occurs. This is crucial to precisely define 1) emergency plans, and 2) modify land use as the two necessary actions to be undertaken to minimize volcanic risk.

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References

- Agostini, S., Corti, G., Doglioni, C., Carminati, E., Innocenti, F., Tonarini, S., Manetti, P., Di Vincenzo, G., Montanari, D., 2006. Tectonic and magmatic evolution of the active volcanic front in El Salvador: insight into the Berlín and Ahuachapán geothermal areas. *Geothermics* 35:368–408. <https://doi.org/10.1016/j.geothermics.2006.05.003>
- Birkmann, J., 2013. Exposure to natural hazards. In: Bobrowsky, P.T. (Ed.), *Encyclopedia of Natural Hazards*, Encyclopedia of Earth Sciences Series. Springer-Verlag, Berlin Heidelberg.
- Bosse, H.R., et al., 1976. Geologische karte der Republick El Salvador/Mitte-lamerica.
- Carr, M.J., 1984. Symmetrical and segmented variation of physical and geochemical characteristics of the central american volcanic front. *J. Volcanol. Geotherm. Res.* 20: 231–252. [https://doi.org/10.1016/0377-0273\(84\)90041-6](https://doi.org/10.1016/0377-0273(84)90041-6).
- Carr, M.J., Feigenson, M.D., Patino, L.C., Walker, J.A., 2004. Volcanism and Geochemistry in Central America: Progress and Problems. In: Eirler, J.M., (Ed.) *Inside the Subduction Factory*. Geophysics monography Series, 138. AGU, Washington DC, 153-174.
- Carr, M.J., Stoiber, R.E., 1977. Geologic Setting of some destructive earthquakes in Central America. *Geological Society of America Bulletin*, 88, 151-156.
- Chesner, C.A., Pullinger, C.R., Escobar, C.D., 2004. Physical and chemical evolution of San Miguel volcano. El Salvador. *Geol. Soc. Am. Spec. Pap.* <https://doi.org/10.1130/0-8137-2375-2.213>.
- Corti, G., Carminati, E., Mazzarini, F., Garcia, M.O., 2005. Active strike-slip faulting in El Salvador, Central America. *Geology*, 33 (12), 989-992.
- De la Cruz-Reyna, S., Tilling, R., 2008. Scientific and public responses to the ongoing volcanic crisis at Popocatepetl Volcano, Mexico: importance of an effective hazards warning system. *J. Volcanol. Geotherm. Res.* 170, 121–134. <http://dx.doi.org/10.1016/j.jvolgeores.2007.09.002>.
- Dewey, J.W., White, R.A., Hernández, D.A., 2004. Seismicity and Tectonics of El Salvador. En: Rose, W.I., Bommer, J.J., López, D.L., Carr, M.J., Major, J.J., (ed) *Natural Hazards in El Salvador*. Geological Society of America. Special paper 375, 363-378.
- Dirección General de Estadísticas y Censos de El Salvador DYGESTIC. 2016. Informes de Estadísticos.

Dirección General del Observatorio Ambiental de El Salvador DGOA, 2015. Informe Interno.

Dirección General del Observatorio Ambiental de El Salvador DGOA, 2016. Informe Interno.

Escobar, C.D., 2003. San Miguel Volcano and its Volcanic Hazards (Unpublished Thesis), El Salvador. Michigan Technological University, USA.

Ferrés, D., 2002. Gestión integral de amenazas y vulnerabilidades en el municipio de San Miguel, Departamento de San Miguel, El Salvador. Desastres de origen natural y cooperación al desarrollo. *Geólogos del Mundo*, pp. 64–69.

Ferrés, D., 2014. Estratigrafía, geología y evaluación de peligros volcánicos del complejo volcánico de San Salvador (El Salvador) (Phd Thesis). Universidad Nacional Autónoma de México.

Gehl, P., Quinet, C., Le Cozannet, G., Kouokam, E., and Thierry, P. (2013). “Potential and Limitations of Risk Scenario Tools in Volcanic Areas through an Example at Mount Cameroon.” *Nat Hazards Earth Syst Sci* 13: 2409–2424. doi: 10.5194/nhess-13-2409-2013.

Jiménez, D., Becerril, L., Bartolini, S., Escobar, D., Martí, J., Building a qualitative volcanic hazard map by combining simulated scenarios: An example for San Miguel Volcano (El Salvador). Sent may 2019 to *Bulleting of Volcanology*.

Jiménez, D., Becerril, L., Bartolini, S., Martí, J. ., Spatio-temporal hazard estimation in San Miguel volcano, El Salvador, *J. Volcanol. Geotherm. Res.* (2018), <https://doi.org/10.1016/j.jvolgeores.2018.04.003>.

Ley de Carreteras y Caminos Vecinales de El Salvador, 1992. https://www.asamblea.gob.sv/sites/default/files/documents/decretos/171117_07292572_5_archivo_documento_legislativo.pdf

Martí, J. (2017, September 06). Assessing Volcanic Hazard: A Review. *Oxford Handbooks Online*. <https://www.oxfordhandbooks.com/view/10.1093/oxfordhb/9780190699420.001.0001/oxfordhb-9780190699420-e-32?print=pdf>

Martí, J., S. Bartolini, and L. Becerril (2016), Enhancing safety in a volcano’s shadow, *Eos*, 97, <https://doi.org/10.1029/2016EO054161>

Martí, J., Spence, R., Calogero, E., Ordoñez, A., Felpeto, A., & Baxter, P. (2008). “Estimating Building Exposure and Impact to Volcanic Hazards in Icod de los Vinos, Tenerife (Canary Islands).” *J Volcanol Geotherm Res* 178: 553–561.

Martínez Díaz, J.J., Álvarez-Gómez, J.A., Benito, B., Hernández, D., 2004. Triggering of destructive earthquakes in El Salvador. *Geology*, 32 (1), 65-68.

Martinez-Hackert, B., Bajo, J., Escobar, D., Gutiérrez, E., Mixco, L., Hernández, W., 2015. Chaparrastique (San Miguel) Volcano Eruptions Since Dec. 29th, 2013, El Salvador, Abstract V23A-3087. Presented at 2015 Fall Meeting, AGU, San Francisco, Calif., 14–18 Dec.

Ministerio de Medio Ambiente y Recursos Naturales - Dirección General del Observatorio Ambiental de El Salvador, 2012. Metodología para el análisis de la vulnerabilidad.

Ministerio de Medio Ambiente y Recursos Naturales MARN, 2017. Informe Nacional del Estado de los Riesgos y Vulnerabilidades de El Salvador.

Programa Social para América Latina CEPAL, 2011. Informe de Evaluación sobre los Eventos Extremos Ocurredos en El Salvador.

Rogers, R.D., Kárasón, H., Van der Hilst, R.D., 2002. Epeirogenic uplift above a detached slab in northern Central America. *Geology*, 20 (11), 1031-1034.

Scaini, C., Felpeto, A., Martí, J., and Carniel, R. (2014). "A GIS-Based Methodology for the Estimation of Potential Volcanic Damage and Its Application to Tenerife Island, Spain." *J Volcanol Geotherm Res* 278–279: 40–58.

Scarlato, P., Mollo, S., Del Bello, E., Von Quadt, A., Brown, R.J., Gutierrez, E., Martinez-Hackert, B., Papale, P., 2016. The 2013 eruption of Chaparrastique volcano (El Salvador): effects of magma storage, mixing, and decompression. *Chem. Geol.* 448: 110–122. <https://doi.org/10.1016/j.chemgeo.2016.11.015>.

Simkin, T., Siebert, L., 2000. Catalog of Historically Active Volcanoes on Earth. En: Sigurdsson, H.. et al. (ed): *Encyclopedia of Volcanoes*, Appendix 2. Academic Press.

Stoiber, R.E., Carr, M.J., 1973. Quaternary Volcanic and Tectonic Segmentation of Central America. *Bulletin of Volcanology*, 37 (3), 304-325.

World Risk Report, 2017; Bündnis Entwicklung Hilft. www.WorldRiskReport.org. Bündnis Entwicklung Hilft.

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List of Figures

Figure 1: (a) General map of the Central American Volcanic Arc (CAVA), formed by the subduction of the Cocos Plate beneath the Caribbean Plate. (b) El Salvador Volcanic Cordillera with the volcano of San Miguel marked in the red circle.

Figure 2: Shaded relief map of the San Miguel volcano area showing the municipality divisions, main nearby cities and villages, and the number of inhabitants for each municipality. Photo from Ciudad Pacifica toward San Miguel volcano (<https://www.facebook.com/carnavaldesanmiguel>)

Figure 3: (a) San Miguel Hazard Map showing three hazard zones: Green represents a one hazard, yellow a two hazard, and red a three or more hazard impact area, respectively. (b) Ash fall simulation, the most probable and frequent eruptive scenario. (c) Lahar simulation map, one of the most likely eruptive scenarios. In both cases simulations are for a two-year time window (2018 – 2019); more details in Jiménez et al., 2019.

Figure 4: Demographic-exposure map showing number of villages and cantons, and the population number in the different hazard zones.

Figure 5: Land use exposure map visualizing the agricultural activity and the main farms in the study area. Bars on the left represent the percentage of crops within the hazard zones.

Figure 6: Schools and health centers exposure map indicating the number of elements in each hazard zone. Bars to the right represent the number of students in each hazard zone.

Figure 7: Road network exposure map showing the roads intersecting different hazard zones. Bars on the right represent the number of roads according to the classification used in this study.

Table 1: Combination number of types of structures considering walls and roof materials and their respective fragility values. Moreover, considering secondary lahar as a landslide

with high water content, we present the exposure coefficient contemplating its type combination. Adopted from the methodology of MARN (2012) for estimating vulnerability.

Table 2: Range of values of the vulnerability index (From MARN, 2012).

Table 3: Road classification by Ley de Carreteras y Caminos Vecinales de El Salvador.

Table 4: Classification of infrastructures (houses, schools, and health centers) in Conacastal, according to walls and roof materials.

Table 1. Combinations.

Combination number	Fragility Value	Relation between materials of roof and walls.	Exposure coefficient
1	1	Housing with walls and roof made of waste, palm and/or other vegetable.	1
2	0.92	Housing of waste walls and metal sheet roof.	1.09
3	0.84	Housing with wooden walls and metal sheet roof.	1.19
4	0.76	Housing with metal sheet walls and metal sheet roof.	1.32
5	0.7	Housing with bahareque walls and tile roof.	1.43
6	0.66	Homes with bahareque walls and metal sheet roof.	1.52
7	0.61	Housing with adobe walls and tile roof.	1.64
8	0.57	Housing with adobe walls and metal sheet roof.	1.75
9	0.52	House with wooden walls and tile roof.	1.92
10	0.4	Housing of concrete or mixed walls and metal sheet roof.	2.5
11	0.28	Housing of concrete or mixed walls and tile roof.	3.57
12	0.2	Housing of concrete or mixed walls and asbestos roof.	5
13	0.1	Housing of concrete or mixed walls and fibrocemento roof.	10
14	0.01	Housing of concrete or mixed walls and concrete slab roof.	100

Table 2. Range of values of the vulnerability index.

Value	Vulnerability Index
0.76 – 1.00	Very High
0.51 – 0.75	High
0.26 – 0.50	Medium
0.00 – 0.25	Low

Table 3. Road classification

Road type	Classification
Type 1	Traffic intensities > 2,000 vehicles/day, with 12.00 meters of platform, 7.30 meters of road surface and a minimum of 7.90 meters of surface on bridges.
Type 2	Traffic intensities between 500 - 2,000 vehicles/day, with 9.50 meters of road surface, 6.50 meters of surface and a minimum of 7.40 meters of surface on bridges.
Type 3	Traffic intensities between 100 - 500 vehicles/day, with 6.00 meters of surface
Type 4	Traffic intensities = 100 vehicles/day, with 5.00 meters of surface and a minimum of 3.00 meters of surface on bridges.
Type 5	Ground surface trails

Table 4: Classification of infrastructures.

Combination number	Fragility Value	Number of Houses	Number Schools or Health centers
1	1	5	
2	0.92	2	
3	0.84	23	
4	0.76	146	
5	0.7	0	
6	0.66	0	
7	0.61	11	
8	0.57	18	
9	0.52	0	
10	0.4	69	5
11	0.28	37	
12	0.2	0	
13	0.1	11	2
14	0.01	0	

Highlights.

- Exposure estimation analysis around San Miguel volcano (El Salvador)
- Exposure maps: population distribution, land use, private houses, and official buildings.
- Physical Vulnerability Methodology based on the characterization of the type of construction materials of walls and roofs of stocks.
- Study results are crucial to define precise emergency plans to minimize risk.

Figure 1

Figure 2

(b) Ash fall

(c) Secondary Lahar Map

Figure 3

Figure 4

Figure 5

- ▲ SCHOOLS
- ◆ HEALTH CENTERS
- HAZARD ZONE 1
- HAZARD ZONE 2
- HAZARD ZONE 3

STUDENTS PER HAZARD ZONE

Figure 6

Figure 7