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VULNERABILITY AND ENVIRONMENTAL RISK IN THE SIERRA OTOMÍ TEPEHUA (HIDALGO, MÉXICO): IMPLICATIONS IN THE RURAL-INDIGENOUS SCOPE

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ABSTRACT. Extreme geomorphological and hydrometeorological events cause landslides (gravitational processes) in vulnerable and marginalized communities, where the risk and effects of a natural disaster reduce responsiveness to environmental adversities. In the state of Hidalgo (Mexico) exists dangers as slope instability and processes of massive removal of soil, but in some municipalities of the Sierra Otomí-Tepehua (SOT) does not exist a municipal instrument that provides information on high-risk localities. This study evaluated landslide risk in 220 localities located in three municipalities of the Sierra Otomí-Tepehua region (SOT) using information from the 2020 national census. A geospatial analysis was built in localities with landslide risk, further social vulnerability was evaluated in 33 localities located on hillsides, and the Social Vulnerability Index of Housing (IVSV) was determined. 109 localities with a high and very high level of social vulnerability were identified due to the physical condition of the dwellings located in areas with landslide risk. Finally, risk map of landslides was developed through multi-criteria analysis to focus on mitigate and prevent disasters in the most vulnerable localities of the SOT.

Vulnerabilidad y riesgo medioambiental en la Sierra de Otomí Tepehua (Hidalgo, México): implicaciones en ámbito indígena-rural

RESUMEN. Los eventos geomorfológicos e hidrometeorológicos extremos provocan deslizamientos en comunidades vulnerables y marginadas, donde el riesgo y los efectos de un desastre natural reducen la capacidad de respuesta ante las adversidades ambientales. En el estado de Hidalgo (México) existen peligros como inestabilidad de laderas y procesos de erosión masiva de suelo, pero en algunos municipios de la Sierra Otomí-Tepehua (SOT) no existe un instrumento municipal que brinde información sobre puntos de alto riesgo. Este estudio evaluó el riesgo de deslizamientos en 220 localidades ubicadas en tres municipios de la Sierra Otomí-Tepehua (SOT) utilizando información del censo nacional 2020. Se construyó un análisis geoespacial en localidades con riesgo de deslizamientos, se evaluó adicionalmente la vulnerabilidad social en 33 localidades ubicadas en laderas y se determinó el Índice de Vulnerabilidad Social de la Vivienda (IVSV). Se identificaron 109 localidades con alto y muy alto nivel de vulnerabilidad social por la condición física de las viviendas ubicadas en zonas con riesgo de deslizamientos. Finalmente, se elaboró un mapa de riesgo de deslizamientos a través de un análisis multicriterio para mitigar y prevenir desastres en las localidades más vulnerables del SOT.

Key words: social vulnerability, risk, slope movements, landslide susceptibility, spatial analysis.

Palabras clave: vulnerabilidad social, riesgo, movimientos de ladera; susceptibilidad de deslizamientos, análisis espacial.

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1. Introduction

Extreme events disrupt the occurrence of natural phenomena; whether geological, atmospheric or a combination of both. The people who live on hillslopes that are susceptible to landslides would be affected since they do not have adequate housing safety (Cunha *et al.,* 2006) and are unaware of the potential danger they are in. Extreme events, in cases of mass removal processes, can increase vulnerability, especially in the poorest communities. Therefore, technology implementation is required as well as a new approach in line with the Sustainable Development Goals (SDG), for a country undergoing transformation seeking equitable and sustainable development, economic and social losses caused by natural phenomena are an unacceptable condition.

Information is an essential tool for decision-making and to develop public to benefit all social groups. Consequently, it is imperative to generate information considering social phenomena related to landslide risks and to identify priority issues that must be tackled to combat lags and reduce inequalities (Rodríguez, 2001). Measuring risk resulting from natural disasters is valid in developing countries; for example, in Mexico, aspects that go beyond the environment are revealed and involve factors such as resource management and their application in these categories (Merlinski, 2006).

The concept of vulnerability focuses mainly on the effects that a disaster can have on specific human groups (Cunha *et al.,* 2006) due to the inability to anticipate, survive or recover from environmental impacts (Kaztman, 2000). Vulnerability considers disasters as socio-natural phenomena related to environmental risks (Aledo and Sulaiman, 2015), where the pressures and the risk of being exposed to natural disasters can reduce the capacity to respond to environmental adversities (Gómez, 2001; Rodríguez, 2000); therefore, the risk includes the vulnerability of the population and the territory (Aledo and Sulaiman, 2015).

Current research work is based on the concept of vulnerability, which focuses mainly on the effects a disaster can have on specific human groups (Cunha *et al.,* 2006); the pressures said groups are subjects to the risk of being exposed to these effects and the factors that may reduce their responsiveness to environmental adversities (Gómez, 2001; Rodríguez, 2000). Vulnerability considers disasters as socio-natural phenomena in relation to environmental risks, in which historical factors come into play and that their effects, given their differences, are unevenly distributed among the population (Aledo and Sulaiman, 2015). Vulnerability is defined as a person's or a group of people's inability to anticipate, survive or recover from environmental impacts (Kaztman, 2000). Therefore, the risk includes the populations and the territory vulnerability (Aledo and Sulaiman, 2015).

According to Kaztman (2000), vulnerability focuses on the disparity in accessing the opportunities offered by the market, the State, society and household assets to capitalize on such opportunities to the maximum. As a consequence, the idea that families will have little or no access to better conditions has been associated (Pizarro, 2001), due to the inability of the weakest groups to face the adverse impacts, although this impotence is not necessarily associated with the poverty but to the little or null availability of assets (Kaztman *et al.,* 1999). For this reason, Cunha *et al.* (2006) relates vulnerability to the idea of risks or dangers that affect populations in conditions of impoverishment, with gender inequality, changes in family structures, family arrangements or in environmental aspects; although certain behaviors or environmental characteristics can also generate risks and infer vulnerability (Rodríguez, 2001).

The risk arises when human beings recognize their susceptibility to environmental changes, which give rise to new inequalities, causing systemic and often irreversible damage. (Beck, 1998). Inequalities in social wealth are subject to distribution and the impoverished sectors tend to lack access to consumer goods, income, educational opportunities, land ownership, among others. According to Kron (2013) and Marandola and Hogan (2006), the risk is the product of the danger due to the occurrence of a harmful event and the subjects are exposed due to the unequal distribution of resources linked to political decisions (Foshiatti, 2009).

For Hogan and Marandola (2005), a hazard is an event that can cause harm, while the risk is the probability of exposure to this hazard. In this way, a disaster is the occurrence of a hazard that exceeds the response capacity of the community and vulnerability represents the response capacity of an individual or a social group to respond to a threat, in addition to the social, economic and geographical that it has. To analyze these factors, new interactions have been incorporated that were not included in poverty measurement studies, but which are added to the core of the social problem, which allows a better understanding of social phenomena (Rodríguez, 2000).

There is a social component in all vulnerability processes. The study of social inequalities is based on the fact that social segments have different life opportunities, marginality, dependency, exclusion and segregation (Hogan and Marandola, 2005) that explain how to resist poverty (Moser, 1998) based on the tangible or intangible resources that are available (Kaztman *et al.,* 1999).

Environmental risks increase the social vulnerability of a person, natural hazards such as landslides, storms or floods increase the risks associated with degradation, pollution and health risks. Emphasis is usually placed on the causes of these risks; however, if the impacts on the population are highlighted, then community vulnerability will become the main determinant of these damages (Foschiatti, 2009). Therefore, it is necessary to create Geographic Information Systems (GIS) to contrast sociodemographic and environmental variables in vulnerable localities.

The Sierra Otomí-Tepehua (SOT) is located in the Sierra Madre Oriental, adjacent to the Sierra Norte de Puebla and the mountainsides of the Huastecas and Veracruz (Fig. 1 and 3) and comprises three municipalities: Tenango de Doria, San Bartolo and Huehuetla. The vegetation is abundant; however, the excessive illegal logging has caused a significant loss of forest cover and increased erosion, due to changes in land use for agricultural purposes (INEGI, 2020a).

There are dangers due slope instability and mass removal of soil processes; however, there is no municipal instrument that provides information on the high-risk towns. The social characteristics of its population highlight the risk and vulnerability conditions (Gómez, 2001). 82% of its population is categorized as high and very high marginalization levels (Rodríguez, 2000), with a significant percentage of the population speaking an indigenous language (Feres and Mancero, 2001). There are social deprivations and unmet basic needs (Aledo and Sulaiman, 2015) too, such as access to services such as drainage, electricity and tap water (Feres and Mancero, 2001).

This work aims to determine social vulnerability by measuring factors such as exposure to environmental risk and aspects of social vulnerability (physical characteristics of housing and access to services) to face geomorphological phenomena. The three municipalities that make up the Sierra Otomí-Tepehua are analyzed: Tenango, San Bartolo and Huehuetla. Given its location and geographical conditions, the risk of landslides due to slope instability, mass removal and housing vulnerability are emphasized, considering the social and physical characteristics of the houses that are at environmental risk.

2. Materials and Methods

2.1 Study Area

The state of Hidalgo is located in central Mexico (19°35´52´´and 21°25´00´´N and 97°57´27´´ and 99° 35´ 52´´W) (Fig. 1). It has a land area of 20,821.4 km^2 divided into 84 municipalities (INEGI, 2020a).

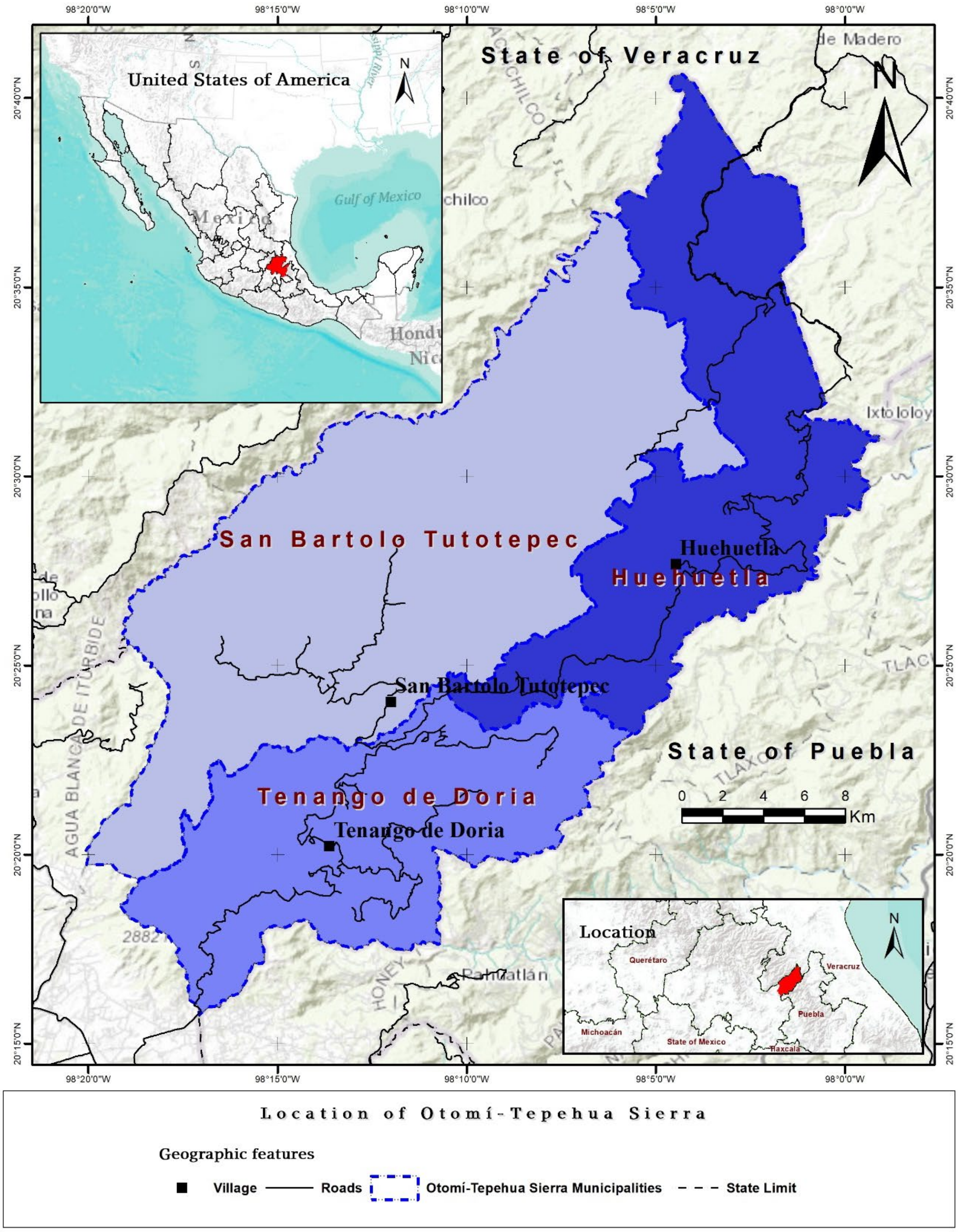

Figure 1. Location of Otomi Tepehua Sierra. Belongs to the Sierra Madre physiographic province Oriental, is characterized by being a region of steep mountains and valleys between mount us.

It borders San Luis Potosí to the north, Veracruz to the east and northeast, to the east, Puebla to the southeast; Tlaxcala to the south and Querétaro to the west (INEGI, 1992). There are three geological districts made up of the Sierra Madre Oriental, the Trans-Mexican Volcanic Belt and the Coastal Plain of the Gulf of Mexico (Fig. 2). The Sierra Madre Oriental extends parallel to the coast of the Gulf of Mexico, starting from the northeast of the state of Hidalgo to the municipalities of Huehuetla and Tenango de Doria, where it borders the state of Puebla (Cervantes-Zamora et al., 1990). The terrain is characterized by rugged landscapes where mountain ranges with highlands, rolling hills, plateaus, canyons, plains and intermontane valleys, and soil composed of sedimentary rocks (INEGI, 1992).

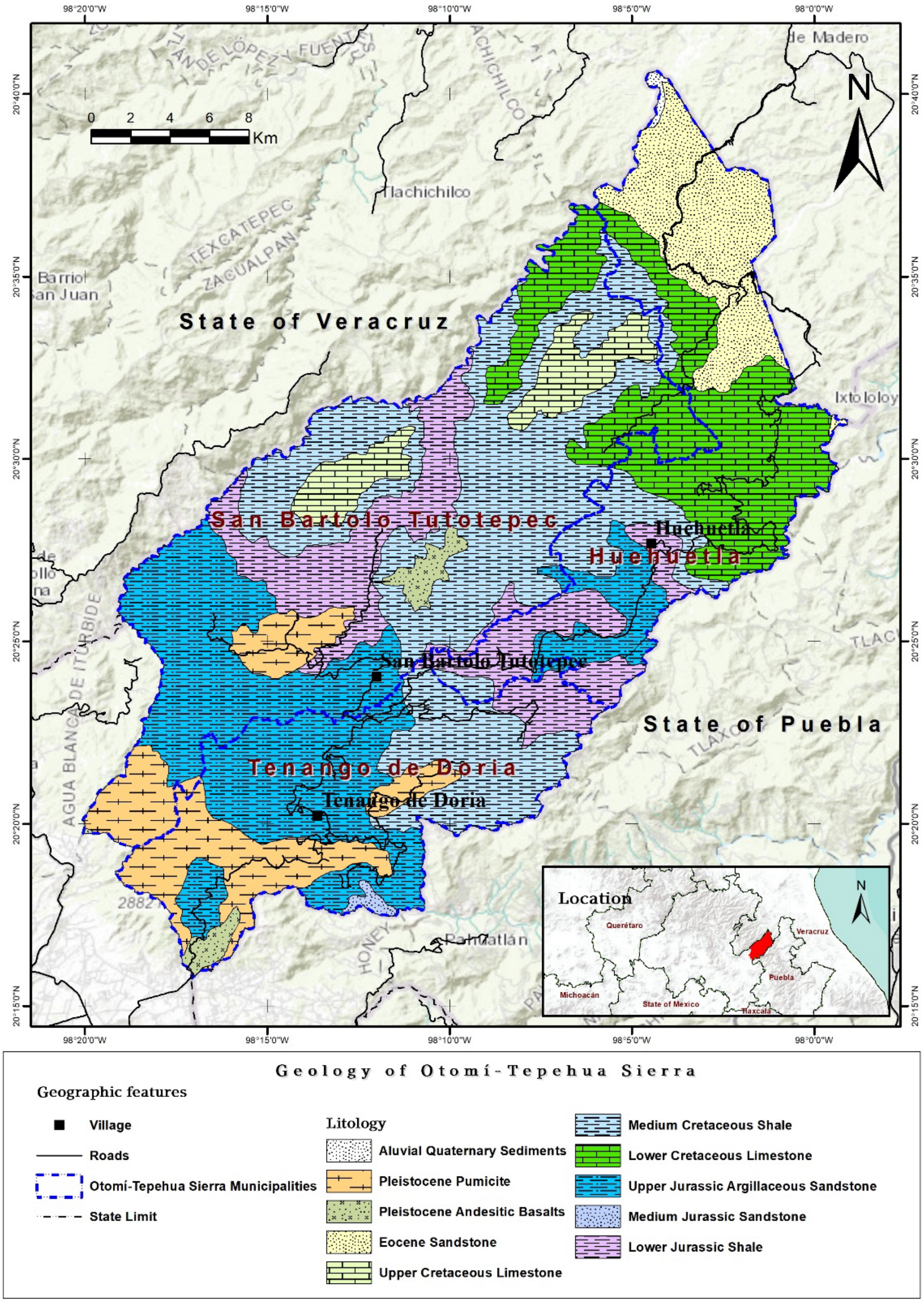

Figure 2. Geology in Otomi Tepehua Sierra. Map in which it is observed through the digital elevation model, the areas susceptible to danger due to gravitational processes.

In the Sierra Madre Oriental, there are mainly mountain ranges of volcanic origin with acid soils, coniferous forests, oak and mixed vegetation are located to the northwest of the state of Hidalgo, to the north and northeast is the ecoregion of rolling hills with evergreen forest (INEGI, 2000). This work is limited to analyzing the three municipalities comprising the SOT: Tenango, San Bartolo and Huehuetla; given their location and geographical conditions (Fig. 2).

2.2. Geographical Data

The orography is linked to the volcanic processes and the climatic changes, which led to the diversification of the genera *Pinus* and *Quercus* (Challenger and Soberón, 2008). In the Sierra Otomí-Tepehua (SOT), the ecoregions of the Veracruz Rainforest (Huehuetla and San Bartolo Tutotepec) and the Veracruz Montane Forest (Tenango de Doria and San Bartolo) prevail, where coniferous and oak forests, rolling hills covered in rainforest, rolling hills and mountains covered in pine, oak and mixed forest abound (INEGI, 2000; Challenger and Soberón, 2008). The types of soil in the region are umbrisol (56.95%), luvisol (36.2%), leptosol (4.32%) and phaeozem (2.33%) (INEGI, 2009).

The Sierra Madre Oriental also has sub-regions with less steep mountains and with fewer peaks, with slightly eroded soil. There are hills, intramountain plains and some deep ravines (Figs 3 y 4). The orographic conditions influence the distribution of rainfall and temperature, which has formed three climatic zones: the warm zone located in the Huasteca or Carso Huasteco region, the temperate zone in the mountainous region and the cold zone in the valley. The warm and temperate zones are rainy and cold zone is dry (García, 1987). The dry and semi-dry (39%), subhumid temperate (33%) and warm humid (16%) microclimates have been characterized; the annual average state temperature is 16 ° C, the minimum temperature is around 4 ° C (January) and the average maximum is 27 ° C (April-May). The rainy season is in summer from June to September, with an average annual rainfall of 800 mm (INEGI, 2020a). Warm and semi-warm climates, due to proximity to the coast, are characterized by abundant rainfall, humid winds and tropical cyclones, high temperatures and frequent rainfall, as a result of the orographic effect developed on the eastern slopes of the highlands; meanwhile, temperate climates have variable rainfall and temperature caused by the alternation of altitude between the plains, valleys and mountain slopes comprising the Sierra Madre Oriental and the Neovolcanic axis (INEGI, 1992).

There are three bioclimatic regions in the SOT. The semi-cold region is located in the upper part of the highland, comprising coniferous forests, with an annual average temperature of 15.9 ° C and an annual rainfall of 1,812.9 mm. The temperate region with cloud forest reaches an annual average temperature of 18.8 ° C and an annual rainfall of 3,129.5 mm. The temperate forest region has an annual mean temperature of 20.7 ° C with 1,891.1 mm of rain. In the hot-humid region, the primary vegetation is made up of forest, with average annual temperature is 24 ° C and rainfall of 1,478 mm annually (García and González, 2014).

Climate change projections for the state of Hidalgo showed moderate changes in rainfall for the SOT. By the year 2050 a temperature increases greater than 2 °C was predicted with more extreme rainfall events in the region (Otazo-Sánchez *et al.,* 2013). Droughts, overflows (flooding) and landslides or change the seasonal rain events have been observed in the last 5 consecutive years.

The RH-27/Tuxpan-Nautla hydrological region covers 5.05% of the state of Hidalgo and encompasses part of the SOT. The basins of this hydrological region are the Tecolutla (0.4%), Cazones (1.05%) and Tuxpan (3.6%) rivers. The latter flows into the Huehuetla or Pantepec river (INEGI, 2016). Due to its topographic characteristics, there are no water storage works (Otazo-Sánchez *et al.,* 2013).

Figure 3. Otomi-Tepehua context. Chevron type folds near San Bartolo Tutotepec. It is appreciated that the slopes are abrupt, which represents a high risk of landslides and rock falls for the communities that they live along the banks of the Pantepec River.

Figure 4. Otomi-Tepehua context. View of the community of San Clemente, which is located at the bottom of the Pantepec River valley.

2.3 Socio-demographic data

There are 3,082,841 inhabitants in the state of Hidalgo; 58,048 of which live in the SOT, distributed among the municipalities of Huehuetla (22,846), San Bartolo Tutotepec (17,699) and Tenango de Doria (17,503). The ethno-cultural diversity is made up of 362,629 people over 3 years of age who speak the original Nahuatl language (234,450 people), Otomí (120,492), Tepehua (1,656) and 891 people who speak Totonaco (INEGI, 2020b). There are 4,514 rural and 176 urban towns. 57% of the population living in urban areas and 43% in rural towns. 41.8% of homes are built with partition walls, brick, block, stone, quarry and cement (95.7%); they have a solid floor (64.3%) and some have earthen floors. The roofs are made of concrete (84.3%), galvanized sheet or corrugated cardboard.

2.4 Poverty and environmental risk in the SOT

The geomorphological characteristics in the SOT make the region prone to landslides and debris flows on its hill slopes due to their sharp relief, steep slopes, among other geographical characteristics. These characteristics were determined by the climate, type of soil and vegetation. This statement explains the spatial delimitation of this work, the SOT, which is on the basis of the existence of human relationships in the territory defined by geographical and social similarities.

The SOT is part of the Sierra Madre Oriental. Its population, according to INEGI (2020b), is dispersed throughout 271 towns. Ninety percent of these towns are rural with less than 500 inhabitants, while 1% of have more than 2,500 inhabitants. The SOT is prone to landslides and rock flows due to slopes with sharp declines, the occurrence of heavy rains, hill slopes composed of rocks with little mechanical stability, as well as human activity, mainly deforestation and farming. Small landslides and debris flows occur continuously along the drainage systems (Pantepec River Basin). This type of landslide can generate between one hundred and one thousand cubic meters of debris, creating a potentially risky situation for the inhabitants of the towns and their assets (Fig. 5).

Figure 5. Poverty and environment risk. Precarious housing in the municipality of Huehuetla, Hidalgo, Mexico.

Socio-demographic conditions also contribute to increasing vulnerability in these geographic conditions. According to CONEVAL (2020) and CONAPO (2020), poverty is prevalent in SOT: 83% of the inhabitants of Huehuetla, 73% of the inhabitants of San Bartolo and 70.4% of the inhabitants of Tenango de Doria. Access to urban facilities is limited: 91% of the population in the municipality of San Bartolo Tutotepec lack of health care access; 41% lack proper and spacious homes and 72% of the population have limited access to basic services, these data are shown in Table 1.

Table 1. Sociodemographic conditions for towns in the municipalities of the SOT by homes and towns (n=220).

Municipality	Homes	Homes no electricity	Homes with no tap water	Homes with dirty floor	Homes with no sewer service	VPH no basic services	Towns with very high degree of marginalization
Huehuetla %	6209 39.55	190 36.33	1408 69.88	594 34.10	908 43.80	1899 55.58	39 32.77
San Bartolo %	4920 31.34	253 48.37	510 25.31	899 51.61	827 39.89	1156 33.83	77 64.71
Tenango %	4571 29.11	80 15.30	97 4.81	249 14.29	338 16.30	362 10.59	3 2.52
SOT	15700	523	2015	1742	2073	3417	119

Source: Prepared with data from INEGI (2020c) and CONEVAL (2020)

Another important factor is the concentration of the indigenous language-speaking population (39%) in the study area and more than 14 % at the state level. The three municipalities studied have a significant indigenous language-speaking population at the municipal level: Huehuetla, 47 %; San Bartolo, 28 % and Tenango de Doria, 25 %.

2.5 Risk evaluation and analysis methodology

Landslide risk assessments are complex tasks which involve geographic data of large areas of surface such as: land use, road network, human settlements, topography, temporal data, wind speed and patterns and variation in population density. Such data can come from diverse sources (El Morjani *et al.,* 2007; Biass *et al.,* 2013). The main limitations of the application of geo-informatics are: (1) the high demand and cost of data, (2) the need for multivariate / multi-format analysis, (3) the need for frequent updates of said data, and (4) databases and parameters relevant to the assessment of social vulnerability are difficult to map (Ebert *et al.,* 2009). For these reasons, this study GIS analysis combines a free, easily accessible and open data set that can be combined with more detailed and accurate data, if it is available. Hazard assessments were achieved by applying GIS tools given their ability to enter, manage, manipulate, analyze and process georeferenced data (Aronoff, 1989).

Therefore, the first step was the creation of a GIS database in order to collect relevant thematic data. It was directly related to the problem of the study area and the budget restrictions. The open data sets used in this study are described below; the main source of socio-economic data is the 2020 Population and Housing Census (INEGI, 2020c). The roads data have been obtained from the OneStreetMap database (OpenStreetMap Contributors, 2015). The localities are georeferenced data come from the 2020 Population and Housing Census (INEGI, 2020c). One of the attributes of the shapefile is the total population by locality. In addition, this information was complemented with vector data from the vector data set on land use and flora from Instituto Nacional de Estadística y Geografía (INEGI). INEGI´s data provided the location, distribution and extension of different plant communities and agricultural uses with their respective variants in flora, agricultural uses, and relevant ecological information. Additionally, the vector data of agricultural areas came from the National Agrarian Registry (RAN).

2.6 Social Vulnerability Index

Measure vulnerability is essential for reducing disaster risk and requires an ability to identify the complexity of this concept to reduce the potentially gatherable data to a set of important indicators that facilitate the estimation of vulnerability (Birkman, 2006). Some approaches for measuring social vulnerability, define indicators by the spatial level, function, data basis, level of aggregation. Cutter *et al.,* (2003) use the hazards-of-place: those characteristics of communities and the built environment, such as the level of urbanization, growth rates, and economic vitality that contribute to the social vulnerability of places. Model of vulnerability examines the components of social vulnerability; include the individual characteristics of people like age, race, health, income, type of dwelling unit and employment.

Dwyer *et al.* (2004) is focusing on investigating aspects of social vulnerability and not hazard. Two indicators relating to hazard have been included in order to provide a context for investigating vulnerability. The indicator includes variables following a socio-economic criterion to establish the vulnerability of a person within a household to natural hazard impacts: age, income, residence type, tenure, employment, household type, disability, house insurance, health insurance debt and savings, car, gender, injuries and residence damage. In addition, Aroca-Jiménez et al. (2017) raises the need to build a comprehensive indicator which requires an understanding of a social component of risk. This approach has been based on calculating composite indices from sociodemographic and economic characteristics, which considers exposure, sensitivity and resilience. After a minacious selection process, the variables were classified in eight thematic information blocks: population, dependency, education, employment situation, healthcare services, development and infrastructures, buildings y collective vulnerability.

In Hernández and Ruiz (2016), population and housing data variables were used, such as the population under 14 years of age and without education, the population with incomes of less than one minimum wage, housing without basic services, and the population with disabilities or without free medical care.

In addition, Rodríguez (2000), include three dimensions to measure the social vulnerability: 1) Habitat, which is related to the physical state of the house, such as floor materials, number of rooms and services such as electricity, sewer system, water and access to goods and technologies; 2) Human capital, considering individuals over the age 15 with no schooling; 3) In the economic scope (dimension), the occupation status is considered and in the social protection scope (dimension), the population that has no health care access is included. With information from the 2020 Population and Housing Census (INEGI, 2020c), the principal component analysis technique is used to create the social vulnerability index (SVI) separated by town and how it affects the territory with Geographic Information Systems.

Based on existing literature, the variables considered for constructing the SVI are shown below for town in the municipalities of the SOT (Table 2).

The Principal Component Analysis (PCA) measures the proximity between observations and grouping them into clusters according to their characteristics (Alaminos *et al.,* 2015). The objective of the PCA is to reduce the variables in a synthetic indicator that reveals the social vulnerability conditions based on the variables included in the index and the dimensions considered; for SOT locations.

With information from the 2020 Census, a social vulnerability indicator was constructed, which is classified into 5 vulnerability levels using the *natural breaks method*. The classifications were: very high, high, moderate, low and very low. Geographic Information Systems were used to show the SVI values and their behavior in the territory. Once the existing social vulnerability levels have been identified, an analysis of susceptibility to slope movements is performed to identify the towns that were most exposed to disaster risk.

Table 2. Variables used for social vulnerability models for towns in the municipalities of the SOT (n=220).

Variable	**Indicator**
p_unemp	Unemployed population
p_nohealt	Population with no health care access [1]
p15nosch	Population aged 15 years and over with no school
phdf	Private homes with dirt floors
phob	One-bedroom private homes
phnoel	Private homes with no electricity
phnowin	Private homes with no water indoors
phnosew	Private homes with no sewer system
phnoinctec	Private homes without information and communication technologies
phnoas	Private homes with no assets
aver-liv	Average number of people living in the home
depdem	Population aged 0-14 and more than 60 years old
p_female	Female population
density	Percentage of population

[1] Source: Prepared with data from INEGI (2020c)

2.7 Analysis of the factors influencing the susceptibility to slope movements.

The research process was carried out at three main levels of analysis to evaluate the susceptibility to landslides. In the first instance, a literature review was carried out and the relief mapping was made by processing the digital map with contour lines every 20 meters, with field work. A digital terrain elevation model was developed, obtained by using the Digital Topographic Map from the National Institute of Statistics, Geography and Informatics (INEGI).

The Digital Elevation Models (DEM) are a representation of the surface that is a raster object which combines geospatial information with elevation values. The DEMs were created with the Delaunay triangulation method (Legrá-Lobaina et al., 2014) using TIN (Triangle Irregular Network) by triangulating a set of vertices (points) related to contour lines. Subsequently, a slope raster was created, heuristically reclassifying it to obtain the degrees of inclination of the terrain at different points in the SOT.

The objective of risk assessment and risk mapping is to represent variations in the spatial intensity of both hazard and vulnerability. Thematic risk maps are necessary tools in order to develop more adequate public policies for land use planning. In addition to taking appropriate measures in the event of an emergency (Lirer and Vitelli, 1998). According to the United Nations Office for Disaster Risk Reduction (UNDRO), risk can be defined as the expected number of lives lost, people injured, property damaged and economic activity interrupted due to a particular natural phenomenon (Torrieri, 2002).

Based on the selection of the determining factors that cause gravitational movement, weights or weightings are assigned based on their relative influence on instability. Subsequently, the relative weight of each factor with respect to the others was determined, using the multi-criteria analytic hierarchy process method by Saaty (1980). With this method, a square matrix is first created, in which the number of rows and columns is defined, in this case by the number of instability factors. Each element of the matrix is assigned a weight, which is a value that represents the relative importance of the factor in its row with respect to factor in its column in terms of possible instability. The factors and / or variables that were considered to determine the susceptibility to mass movements were land use and vegetation, type of slope, geology (type of rock) and edaphology. An important aspect of the method used is the generation of condensed and systematic information on landforms and associated environmental phenomena, all reinforced and verified by field work. The data generated integrated with GIS was useful for the preparation of the hazard map with great precision.

Matrix was built with the variables slope, geology, geomorphology and land uses and vegetation that were compared and weighed. Subsequently, the multi-criteria evaluation was continued, which is applied if the criteria have different relevance to the proposed evaluation, and is based on the analysis, discussion and hierarchy of alternatives in order to generate solutions to territorial problems, dangerousness and vulnerability. To evaluate the processes of landslide risk, a decision rule was chosen and structured to integrate the criteria which was established from this objective (in this case four), and the selection alternatives that were represented by the spatial objects (pixels) contained in the thematic layers (digital maps). Each of the criteria constitutes a thematic map of the GIS database, so at this stage it is understood that for the entire evaluation it is crucial to define and make the selection of criteria in an appropriate way.

The multicriteria analysis based its operation on integrating all the variables in a matrix, called decision or evaluation, where the main column contains the criteria, the main row, the alternatives, and inside the matrix are the scores obtained from the criteria. These scores represented the value, level of preference, degree of attraction or significance that each alternative has obtained for each criterion. Thus, in the matrix, quantitative values were assigned to the corresponding categories or classifications of the criteria, since generally in the printed maps or in the consulted bibliographic sources they were dimensioned in nominal or qualitative scale, so they were converted to a common range or quotient scale (Table 3).

Table 3. Factor comparison matrix to determine landslide susceptibility.

	Geology	Slope	Land Use and Vegetation	Geomorphology
Geology	1	-	-	-
Slope	7	1	-	-
Land Use and Vegetation	5	2	1	-
Geomorphology	9	3	1/4	1

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Extremly		Strongly		Moderately		Slighty		Equal	Slighty		Moderately		Strongly		Extremly	

This assessment or interpretation allowed, using the GIS, that the cartographic and thematic information of the criteria for each of the alternatives (pixels), was subjected to a series of operations of classification, overlapping, interpolation, calculation of distance or proximity in order to represent the different classes or values of hazards. The alternatives were reclassified into values from lower to higher according to the managed score scale (1=lowest risk, 5=highest risk). Once the evaluation matrix and the thematic maps were established, the relative importance of the criteria was established, because not all of them have the same influence or preference intensity as the type of evaluation projected, and assigned a specific weight or weighting.

This assignment was based on the previous references, views and experience of the specialists (researchers and decision makers), the consultation and opinion poll with experts on the subject, in the literature consulted, for all of which the characteristics of the study area were taken into account. There are different approaches to establish the weights of the criteria, among which one of the most widespread in studies of the territory and in the GIS environment is the one known as "analytical process through hierarchies" which was developed by Saaty (1980).

The scale of measurement established for the allocation of weights is a numerical scale of 17 values or hierarchies, ranging from a minimum value of 1/9 (the least important) to 9 (the most important); in the diagonal of the matrix only values of 1 were assigned, which denotes equality with itself in the comparison of each criterion. Similarly, if two factors had the same importance, they gave a value of 1. GIS has a module that allows to perform the automated matrix summation procedure (and consequently maps), by superimposing and multiplying each map by a constant (weight of criteria), producing a new map, in this case the landslide risk map.

3. Results

There are social vulnerability and poverty conditions in the towns of the municipalities comprising the SOT. There is a significant lag in the supply of basic services that can be explained by the geographical conditions, which physically and socially isolates the SOT and highlights inequalities in relation to other regions of Hidalgo.

3.1. Social vulnerability index

3.1.1. SVI construction

To construct the SVI, the dimensions were considered on the basis of assets: physical, social and human. According to the analysis carried out, the variables associated with physical and infrastructure conditions play a significant role in explaining social vulnerability in SOT towns. Such characteristics are grouped in the first component, with a data variability greater than 60%. The physical characteristics of homes, such as infrastructure conditions, dirt floors, access to electricity, overcrowding and access to technology and goods, make up the first component, called the Social Vulnerability Index for Housing Infrastructure (SIVH), which corresponds to the physical capital dimension mentioned above.

3.1.2. SVIH

The towns with high rates of social vulnerability are mainly located to the south of the municipality of San Bartolo, to the north of municipalities of Tenango de Doria and Huehuetla (Fig. 6). The towns identified with high levels of social vulnerability are mainly located in the municipality of San Bartolo, which is classified as having a high degree of marginalization and is characterized like the other municipalities of the SOT for having lag in the coverage of basic services.

More than 50% of the towns comprising the municipalities of the SOT are grouped in very high and high social vulnerability. Of the towns that are in very high and high vulnerability, 76 and 50% are in the municipality of San Bartolo, respectively. While 25 and 20% of the very high and high vulnerability towns are in the municipality of Huehuetla. Table 4, seen below, shows the towns with landslide susceptibility and some degree of vulnerability, by municipality. When comparing social vulnerability index data with landslide risk in the SOT, it can be observed that the towns with higher levels of social vulnerability are also at greater risk of disaster due to landslides. Such is the case for El Popotillo, Rincón del Cerro Macho, El Candeje, El Piñal, Cerro de Buena Vista, Xuchitlán, Juntas del Río, El Rincón and La Flor de Santiago (Fig. 6).

In the case of towns with a high degree of vulnerability, the following are noteworthy: Río Chiquito, La Segunda Ranchería, La Cruz, El Zenthe, Pie del Cerro, Cerro Verde and Vista Hermosa.

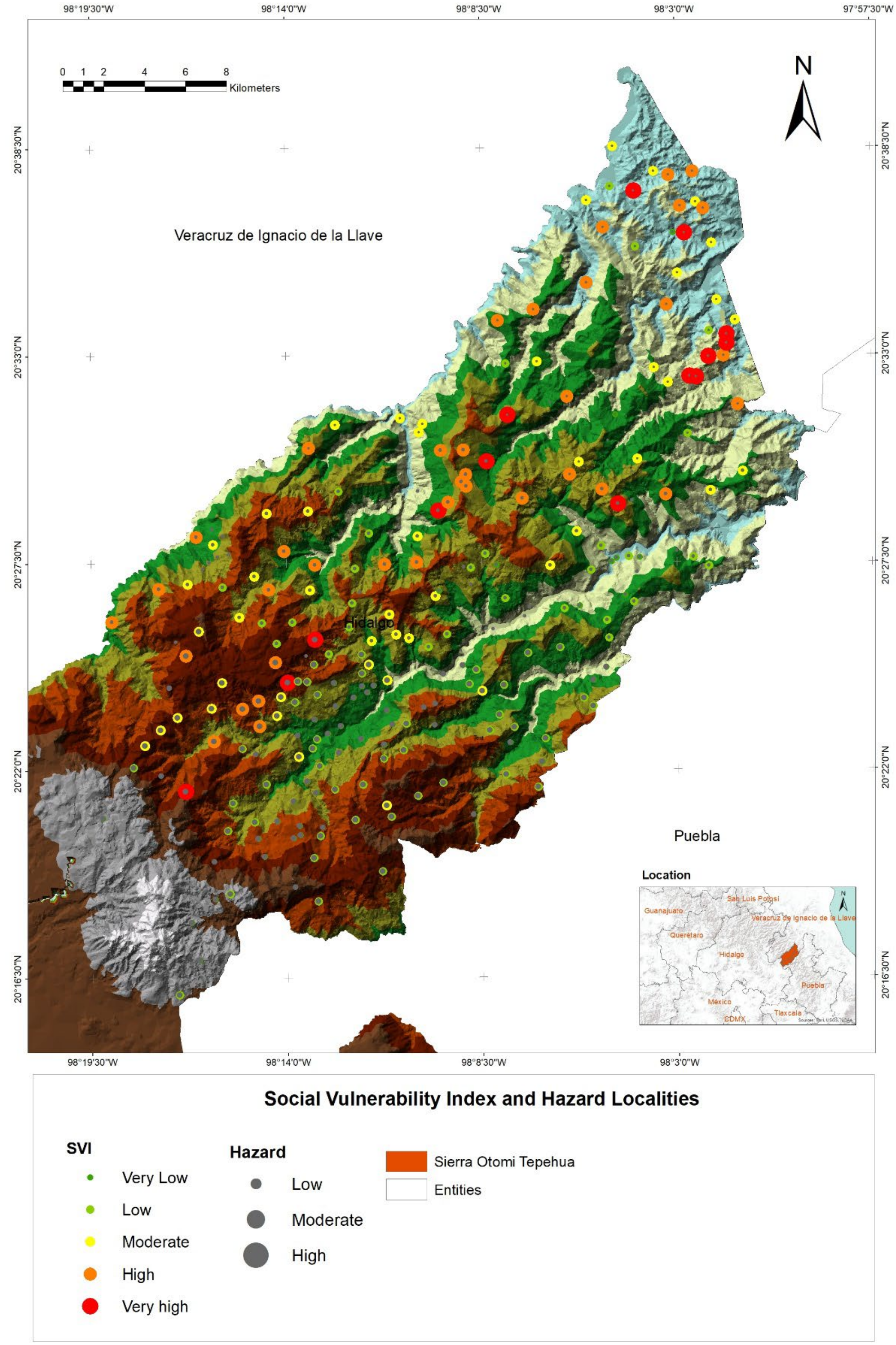

Figure 6. Spatial distribution of the social vulnerability index for housing in the SOT towns (2020).

Table 4. Factor comparison matrix to determine landslide susceptibility.

Municipality	Town name	INEGI Code	Population	SVIH	Risk
Huehuetla	La Cruz	130270077	210	High	Medium
Huehuetla	El plan del Recreo	130270030	156	Moderate	Medium
Huehuetla	La Cañada	130270120	23	Moderate	Medium
Huehuetla	El Palote	130270110	6	-	Medium
Huehuetla	Cerro del Caballo	130270092	12	-	Medium
Huehuetla	Milpa Redonda	130270084	31	Moderate	Medium
Huehuetla	Vista Hermosa	130270046	6	High	Medium
San Bartolo	Rincón del Cerro Macho	130530083	31	Moderate	High
San Bartolo	Cueva Ahumada	130530020	27	Very high	Medium
San Bartolo	La Flor de Santiago	130530099	48	Very high	Medium
San Bartolo	El Rincón	130530106	18	Very high	Medium
San Bartolo	El Candeje	130530011	88	High	Medium
San Bartolo	Río Chiquito	130530065	152	High	Medium
San Bartolo	La Segunda Ranchería	130530109	91	Very high	Medium
San Bartolo	Juntas del Río	130530066	71	Very high	Medium
San Bartolo	Xuchitlán	130530091	439		Medium
San Bartolo	Monte Grande	130530041	36	Very high	Medium
San Bartolo	El Popotillo Grande	130530061	83	High	Medium
San Bartolo	Pie del Cerro	130530057	31	High	Medium
San Bartolo	Cerro Verde	130530017	200	High	High
San Bartolo	Arroyo Seco	130530094	5	Very high	High
San Bartolo	Cerro Buena Vista	130530014	82	High	Medium
San Bartolo	El Zenthe	130530092	140	Very high	Very high
San Bartolo	El Piñal	130530147	89	Moderate	Medium
San Bartolo	La Soledad	130530076	1	Very high	Medium
Tenango de Doria	El Madhó	130600050	57	Moderate	Medium
Tenango de Doria	El Desdaví	130600011	181	Low	Medium
Tenango de Doria	La Concepción	130600008	13	-	Medium
Tenango de Doria	Piedras Negras	130600066	38	Moderate	High
Tenango de Doria	La Palizada	130600058	162	Moderate	Medium
Tenango de Doria	El Xindhó	130600054	127	Moderate	Medium
Tenango de Doria	El Juanthé	130600059	17	-	Medium
Tenango de Doria	Cerro Grande	130600045	17	Moderate	Medium[1]

[1] Source: Prepared by authors with information from INEGI (2020c). The aforementioned towns are highlighted.

3.2. Cartography

In order to apply the method, the factors that can contribute to hillside landslides were defined. For the analysis of variables, a weight was assigned based on the literature, the experience of the researchers and the field work. In the preparation of the risk map, it was decided to use intervals of 1 to

5, assigning the value of 1 to the lowest risk and 5 to the highest risk (Table 5). We compared the five variables related to the help of a scale or continuous appreciation table (Table 3), which indicates the relative importance of the first variable with respect to the second, this with the third and so on, and allows to form a simultaneous comparison matrix by pairs. The scale varies from 1/9 indicating an extremely low importance of the first variable with respect to the second, to 9 in case the first variable is extremely more important than the other variable. The sliding risk matrix was developed considering 4 variables (geology, slope, land use and vegetation and geomorphology). It was established that geology was 9 times more important than geomorphology, 7 times more than slope, 5 times more than land use; the slope is twice as important than land use and 3 times more important than geomorphology, and finally, land use is 1/4 less important than geomorphology.

Table 5. Values used to reclassify map contents, which were later used to build the final map through multivariate analysis.

GridCode (pixel) for design risk level	Geology	Slope	Land Use and Vegetation	Geomorphology
1 (Very low)	Basalts	<1°	Seasonal agricultura, evergreen forest, meshophyll forest	Alluvial plain
2 (low)	Limestone	1 – 5°	Cultivated grassland, pine forest	Plateau
3 (medium)	Ash deposits	15-25°	Secondary vegetation	-
4 (high)	Sandstone	25-45°	-	Hills
5 (very high)	Colluvual deposits, shale	>45°	-	Steep mountain

The slope is a very important factor in the evaluation for the susceptibility analysis of gravitational movements. To carry out the susceptibility analysis, five slope ranges or degrees were considered: very slow slope (<1°), slow slopes (1 to 5°), moderate slopes (5 to 15°), steep slopes (15 to 25°), and the latter corresponds to very steep slopes (25 to 45°) and extremely steep slopes (>45°). Additionally, in terms of susceptibility, mass removal processes, landslides, rockfall, and water and wind erosion mostly occur on very steep and steep slopes.

The geological map (Fig. 7) was prepared with the lithological database from the GeoInfomex system of the Mexican Geological Service (SGM). The determination of lithology susceptibility is extremely complex and is defined based on the grouping of different types of rocks in geological formations, which influence their geo-mechanical properties (discontinuities) and resistance (weathering). The type of material, dominant material, structures or discontinuities in the municipal territory were reclassified (the description of the rock massifs was also considered). The geomorphology map was reclassified using the geomorphological units reported by INEGI, the mountain ranges had the highest susceptibility to gravitational processes.

The specialized mapping made will be used to show the risk due to slope instability and mass removal, linked to social vulnerability due to poor housing conditions of the population in the SOT towns. As a result of the analysis and the field work carried out, maps were made that made it possible to form the Factor Comparison Matrix to determine the susceptibility to landslides. The variables that determined the susceptibility to massive movements of slopes such as land use and vegetation, type of slope and geology, are shown in the generated cartography.

Regarding land use and vegetation, based on the soil cover, it was determined that deforested areas, areas with no visible vegetation, pastures (grasslands) and rainfed agriculture are the most susceptible to gravitational processes, while oak forests and pine and coniferous forests are the least susceptible.

Condensed information was obtained on geographical features and environmental phenomena that allowed the elaboration of maps showing the risk of slope instability and mass removal. The above constitutes an additional contribution of the present work since it does not exist for the SOT. A very useful supplementary tool for this research was the Geographic Information Systems, which, facilitated geomorphological analysis and provided precise and concrete data on geomorphological processes and the phenomena associated with them, as is the case with landslides (Fig. 7).

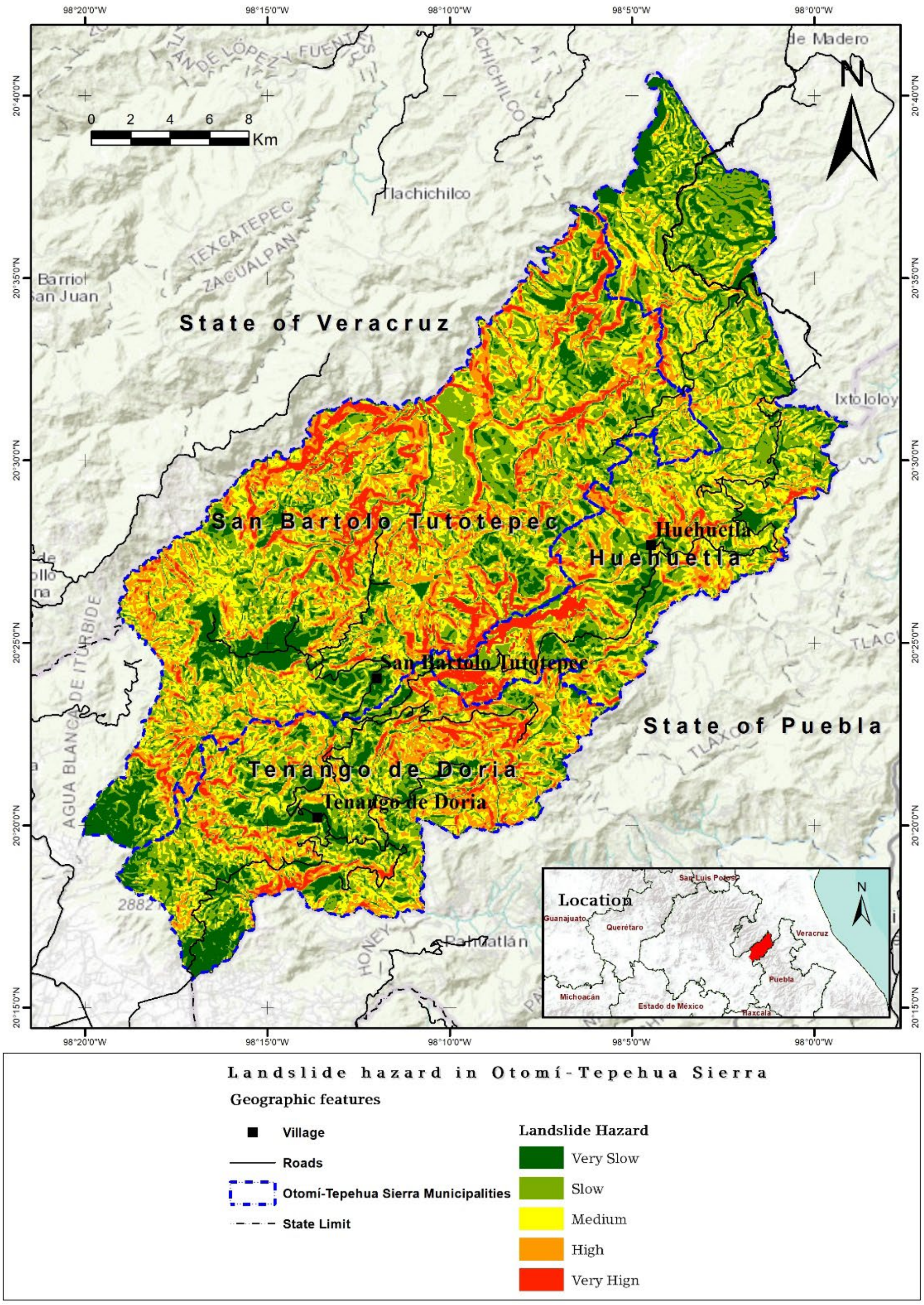

Figure 7. Landslide hazard in Otomi Tepehua Sierra. Map showing the most vulnerable areas to suffer a landslide impact in the municipalities of the study area.

Based on the analysis of the topographic and geological mapping, and the digital elevation models of the terrain, zones susceptible to danger due to gravitational processes were determined. Geomorphological mapping shows the landforms, combining structural factors, lithology, tectonics and weathering of the rocks to ex-plain how the landforms and their chronological sequence happened.

For this study, four morphometric maps were prepared, which show the physical characteristics of the relief and its geomorphometry. The slope map shows the different altitudinal declines of the basin. A topoform system map showing the types of shapes in the relief, which is a geological map that shows the lithological varieties of the region as well as one of land use and vegetation, where the regional soil usage is shown (Figs. 8 and 9, respectively).

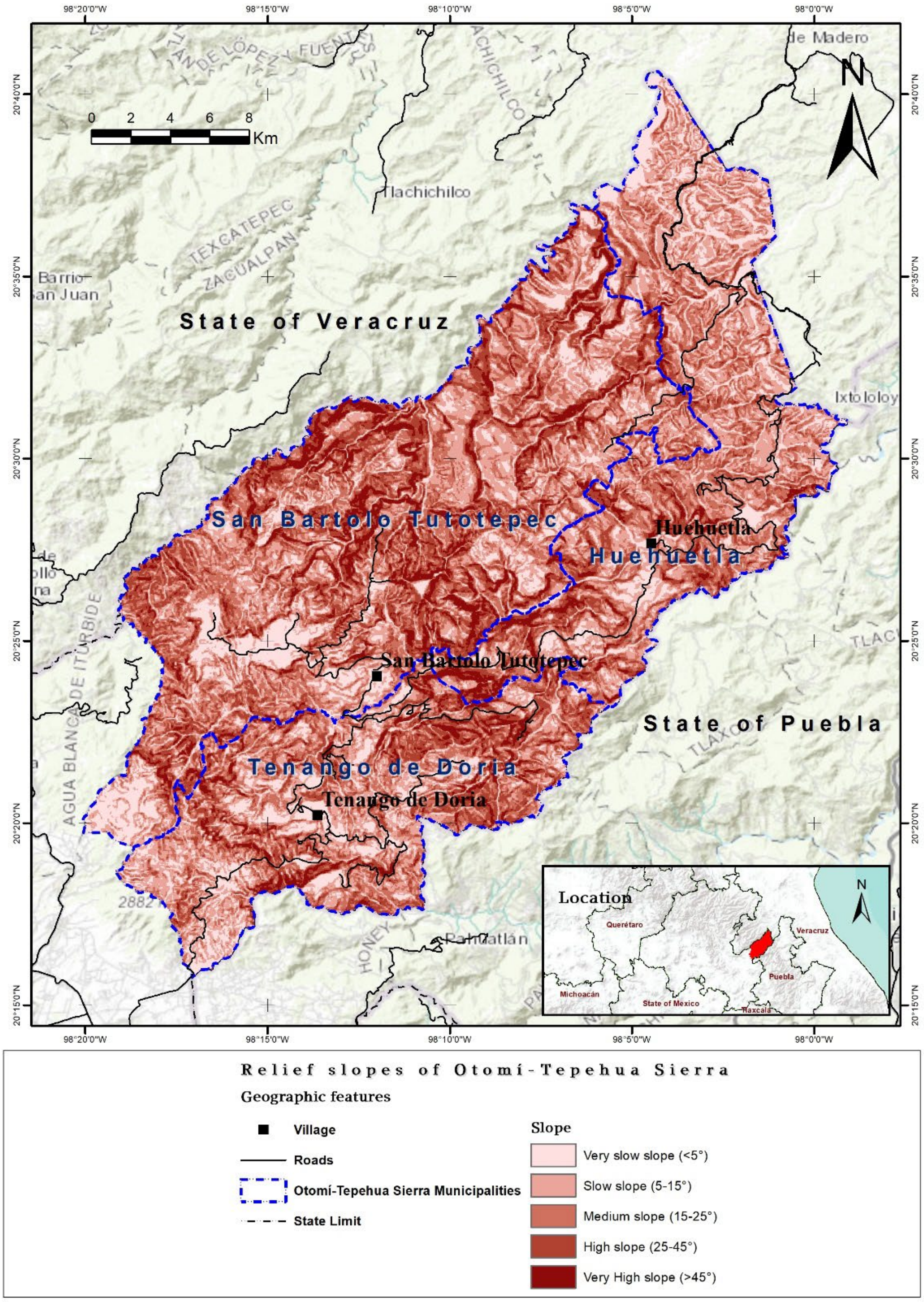

Figure 8. Slope risk in Otomi Tepehua Sierra. Map showing the altitudinal declines of the basin of the study area.

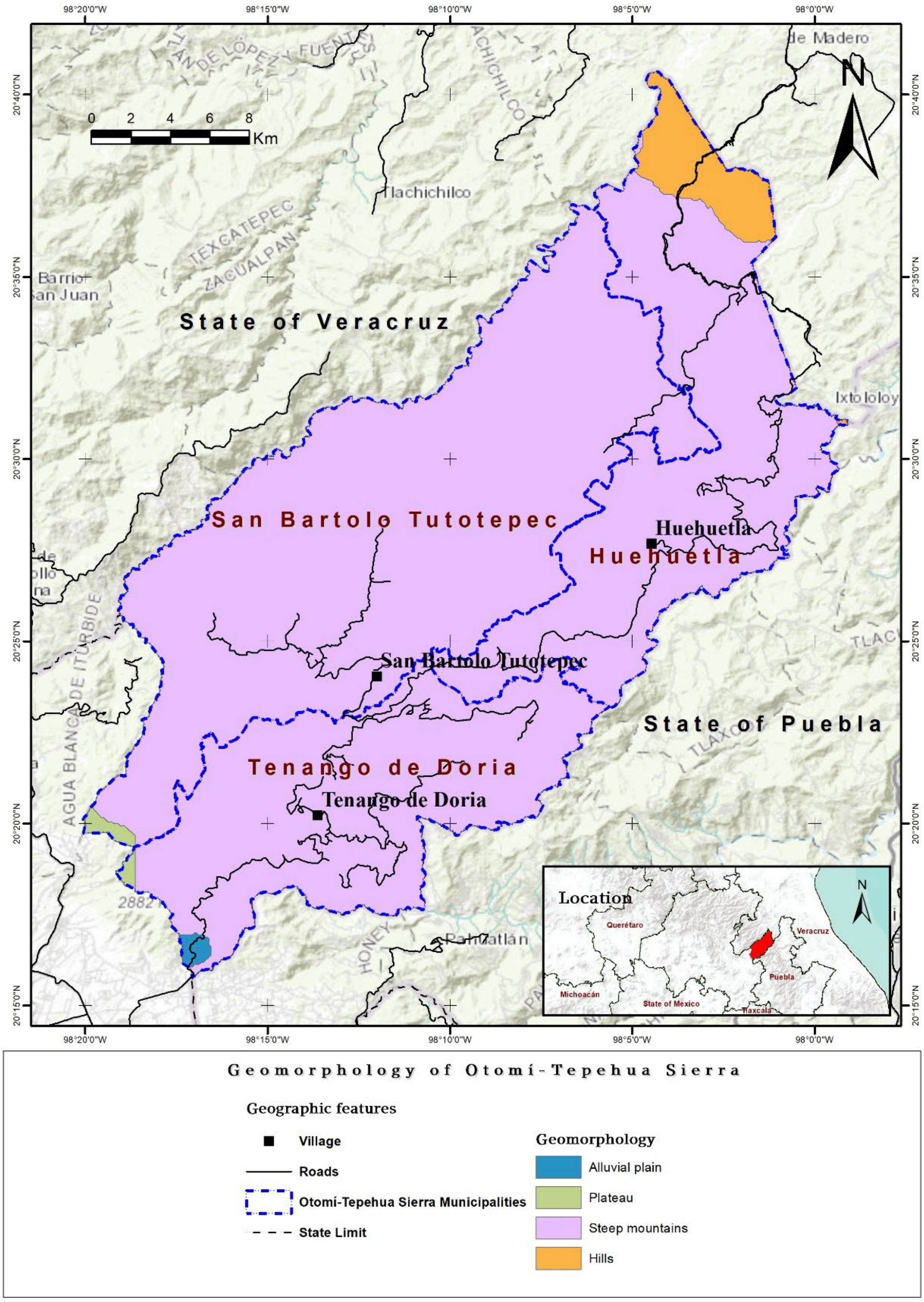

Figure 9. Geomorphology of Otomi Tepehua Sierra. Map showing the relieve varieties of the study area.

4. Discussion

In Mexico every year phenomena of geological origin take place, their effects are appreciated in the population, the infrastructure and in the territories where they occur (CENAPRED, 2019).

Conditions such as the climate, the type of soil and the local vegetation, increase landslide hazard for houses built on land comprising rocks with little mechanical stability. The land has also been deteriorated due to human activity like deforestation and change of land use to agriculture. The landslides that occur along Pantepec River basin drainage system can produce large volumes of debris, up to a thousand cubic meters, which can potentially pose a risk to the inhabitants of the SOT towns and their homes. Climate change projections for the state of Hidalgo show increased rainfall in recent years in the SOT, which could gradually cause droughts, overflows and landslides or change seasonal rain events.

Physical conditions, among other social variables, increase vulnerability under such geographic conditions. Variables associated with physical and infrastructure conditions played a significant role in explaining social vulnerability in SOT towns. Social vulnerability and risk from disasters such as landslides were relevant because they can be alternatives in the regulations for their management, with the intention of reducing inequalities and their negative effects on disadvantaged sectors. With the previous consideration, it would be achieved that the most vulnerable groups would stop suffering the consequences in the disaster processes.

In Hernández and Ruiz (2016), the conditions that reproduce social vulnerability to landslides in settlements in the state of Puebla, Mexico, are analyzed. As a result of the conjunction of a low-pressure system and a cold front, extraordinary rainfall occurred in eastern Mexico, in the entities of Hidalgo, Oaxaca and Puebla. The effects of this phenomenon were mass removal processes. The Sierra Norte de Puebla was the most affected region, due to the considerable economic damage and numerous human losses (Borja Baeza and Alcántara Ayala, 2004). The results of this analysis, which are very similar to those obtained in the SOT, were combined with a vulnerability index developed based on population and housing data, obtaining the risk map for mass removal processes for the municipality of Zacapoaxtla, Puebla, Mexico. This municipality, located in the Sierra de Puebla, like the SOT, is made up of folded sedimentary rocks covered by volcanic rocks, in which fractures and faults have been generated. Human settlements on unstable slopes, added to the socioeconomic characteristics of the population, generated risks due to slope processes.

To make a comparison, in the SOT, more than 50% of the towns comprising the municipalities of the SOT were classified as very high and high social vulnerability. Landslides caused by debris movements from the slope will mainly affect the most vulnerable population in the SOT towns where households have very limited or no access to basic services and houses are poorly constructed. It is estimated that, in the event of landslides, due to climatic issues and deforestation, the levels of social vulnerability and poverty will increase, and will impede the affected population’s ability to recover from poverty. In the risk map, very high-risk areas are characterized by having the most favorable topographic, lithological and relief conditions for the occurrence of mass removal processes, in addition to a high vulnerability of the population to face difficulties due to the action of natural phenomena. Both study areas share similar geographic, geological, and human characteristics. Its population shares social, economic and demographic characteristics that allow comparisons in the results.

5. Conclusions

Human settlements with fewer resources are the ones most exposed to the occurrence of sudden movements of soil and rock masses on hillsides. So, this analysis of social vulnerability and landslide risks allowed for the identification of towns with the population most likely to lose their assets to focused on public policies that should be established to reduce the adverse effects of the geomorphological onslaughts in the SOT. Comparing social vulnerability index data with landslide risk in the SOT made it evident that the towns with higher levels of social vulnerability are also at greater risk of disaster due to landslides.

The use of geographic information systems was useful in understanding the spatial dimension of the relationships between the distribution of conditions of social vulnerability due to poor access to basic services, housing infrastructure and access to goods, with their exposure to risks; to identify and understand their behavior and generate strategies to reduce inequalities and risk. The geomorphological mapping generated was an important contribution to the identification of physical characteristics such as relief, slopes, and land use and type of vegetation making it possible to also identify the regional soil usage. The above data does not exist for said municipalities despite the need for related studies in the SOT.

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