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# SUSCEPTIBILITY ANALYSIS OF LANDSLIDES IN RIVER BASINS: JAMAPA Y LA ANTIGUA

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**Abstract:** As part of the project: " Geological and hydrometeorological Microzonation hazards for the conurbations of Orizaba, Veracruz, and the main towns located in the lower sub-basins: Antigua and Jamapa", sponsored by the Joint Funds CONACyT-Government of the State of Veracruz, where it is studied comprehensively the natural phenomena hazards in the sub-basins and its main urban areas: Jamapa and Antigua, preliminary results of the evaluation of susceptibility to landslides and the basins are presented. In the assessment, the Mora-Vahrson method was used (Mora *et. al.*, 1992) to establish, approximately, the sectors with potential to present landslides by the combination of shooting factors: rain and earthquake. To accomplish this, diverse cartographic information published by INEGI was used: geology, lithology, humidity and rain, scale 1: 250,000. The slope maps were obtained from digital terrain elevation models available in the CEM3.0 tool (INEGI, 2016), with a pixel resolution of 15 x 15 meters. The results are presented through maps showing areas with different degrees of susceptibility to slip, where the overall objective of the study is to establish public policy for risk mitigation, properly regulating land and natural resources use in conurbated areas that are affected by this type of geological phenomena within the study area, setting a scenario showing the sliding threat for prevention purposes.
**Keywords:** Microzonation, Hazard, Vulnerability, Risk.

## INTRODUCTION

Veracruz state is characterized by a humid temperate climate with an annual rainfall of 1,500 millimeters. Throughout the state, landscape isdominated by plains, hills and valleys. The central region has a rugged topography formed by abundant hills that are part of Neovolcanic Axis of Mexico. Its geographical boundaries cover much of the Gulf Coast of Mexico, coastal boundary where occur many hurricanes and tropical cyclones generated in the Gulf of Mexico and Caribbean Sea, which generate numerous landslides in the state.

Because of this, it aroused the need to analyze the geological and hydrological variables that contribute to the generation of landslides, giving categories to their potential through observation and measurement of indicators and morpho-dynamic spatio-temporal distribution in the Jamapa and La Antigua river basins. This paper presents the results obtained in evaluating the regional landslide susceptibility in those two basins. In the assessment, the Mora-Vahrson (Mora et al., 1992) method was used to establish, approximately, the sectors with the potential to present slides by the combination of shooting factors: rain and earthquake.

## DESCRIPTION OF THE STUDY AREA

### LOCATION

The study area is located within the geographical limits: 97.40º W- 95.80º W longitude and 18.60º N -19.60 N latitude. The region is dominated by hills and valleys. It presents a rugged topography consists of hills that are part of Neovolcanic mountain range of Mexico. The highest elevation in the area is represented by the Citlaltépetl Volcano, with 5610 meters and the lowest altitude is in the Sierra La Garganta 860 meters.

### CLIMATE

The area is characterized by a humid temperate climate with an annual rainfall of 1,500 millimeters. The climates that predominate are: warm humid and humid temperate; however, a small percentage of this region is in the high parts of mountains (around the Citlaltépetl Volcano and Cofre de Perote) where the weather is cold, reaching snow in winter season.

The average annual temperature is 23 °C, the average maximum temperature is around 32 °C in the months of April and May; the average minimum temperature is 13 °C and it occurs in January. The predominant rainfall occurs during much of the summer, between June and October, however there are places where rainfall occurs all year. The average monthly evapo-transpiration is 100 mm.

## GEOLOGY

The region is located in an area of confluence between two geologic provinces, Sierra Madre Oriental (SMO) and the Trans-Mexican Volcanic Belt (TMVB). The rocks belonging to the SMO are limestones and shales stratified Middle and Upper Cretaceous, which are major topographic barriers with maximum heights ranging between 3,000 and 1,500 meters. Stratigraphically, these rocks form the pre-volcanic basement of the area, are intensely folded and faulted, forming a complex pattern of anticlines, synclines, normal and reverse faults, whose axes and planes are oriented NW-SE direction.

Rocks and volcanic materials are pyroclastic deposits and lava emitted by volcanoes Pico de Orizaba and Sierra Negra, as well as some cinder cones. In middle and high areas there is a predominance of pyroclastic flow deposits and fall, which are associated with explosive eruptions occurred in the past in both volcanoes.

Lahar deposits are abundant and are associated with volcanic eruptions and torrential rains. In some places unconformably cover the Cretaceous rocks and are found mostly along the cliffs. Structural differences, textural and resistance between the limestone, pyroclastic deposits and lavas, are decisive factors that determine the course of watercourses, as well as the quantity and characteristics of the material is transported to the lower areas. Approximately between heights of 4,500 and 2,500 m there is an abundance of volcanic material on the cliffs. They are unconsolidated pyroclastic deposits and epiclastic, with a grain size ranging between blocks of several meters in diameter (moved by rolling) to gravels, sands, silts and clays that are transported by entrainment, suspension and dissolution. In this area are located the main sources of supply of material carried by water currents. The main urban settlements are in the floodplain. In this unit are grouped the alluvial deposits and deposits left by hyper-concentrated flows whose particle size fraction is concentrated in the sands, silts and clays. This is material from pyroclastic deposits.

## METHODOLOGY

To carry out the assessment, diverse cartographic information published by INEGI was used: geology, lithology, humidity and rain, scale 1: 250,000. The slope maps were obtained from digital terrain elevation models available in the CEM3.0 tool (INEGI, 2016), with a pixel resolution of 15 x 15 meters. Due to the small increases in precipitation rates in the study area it was not possible to independently evaluate and detail the influence of heavy rains and trigger parameter, therefore, the influence of the two parameters, rain and earthquakehad to be evaluated in a single analysis. The results are presented through maps showing areas with different degrees of susceptibility to slip, with the overall objective of establishing public policies risk mitigation, regulating properly land use and natural resources in conurbations that are affected by this type of geological phenomena within the study area.

## METHOD MORA-VAHRSON

The Mora-Vahrson method (hereinafter MVM), heuristic type, consists of the evaluation and combination of the various factors and parameters involved in the process of sliding of a slope, which can be classified into two groups: Passive(conditioning ) and Dynamic (triggers) (Mora et al., 1992). The first group is composed of lithology, moisture and topography of the site under study. Dynamic factors are natural and anthropogenic phenomena that can disrupt balance and trigger a hillside sliding; however, it considers only MVM earthquakes and heavy rains as trigger parameters.

It is so that the degree of susceptibility slip is expressed as the product of the passive and dynamic factors (Mora et al., 1992), as expressed in the formula:

$$H = F_P * F_D \quad (1)$$

$$F_P = S_L * S_H * S_R \quad (2)$$

$$F_D = D_{LL} + D_S \quad (3)$$

$$H = (S_L * S_H * S_R) * (D_{LL} + D_S) \quad (4)$$

Where: $F_P$ passive factors, $F_D$ dynamic factors, $S_L$ lithologic susceptibility parameter, parameter $S_H$ soil moisture, $S_R$ parameter of the slope, $D_S$ trigger parameter quake and $D_{LL}$ trigger parameter rain. These parameters are obtained regularly, observation and measurement of indicators and morpho-dynamic spatiotemporal distribution.

## EVALUATION OF SUSCEPTIBILITY PARAMETERS

The evaluation of the factors was performed by assigning relative weights, according to their degree of influence on susceptibility to sliding. To do this, it was necessary to create a layer in raster format for each of the parameters involved in the analysis: Lithology ($S_L$), soil moisture ($S_H$), Slope ($S_R$), Earthquake ($D_S$) and Rain ($D_{LL}$). The procedure for evaluating each of the factors involved in the analysis and assigned according to the relative ranking of susceptibility of each factor, established in Mora et al.(1992) and (2002) is described next.

### Evaluation parameter the slope (Sp)

The assessment of this parameter is based on the classification of slopes proposed by Van Zuidam (1986) Table 1, which associates different slope categories to different characteristics and processes of denudation of the land. This is based on the fact that, in general, high slope values (> 50 ° -60 °) are associated to areas with removal processes such as turning and rock fall (Suarez, 1998; Gonzalez et al., 2002); average slopes (20-50°) are associated with falls by rolling, sliding, reptation and minor slopes (<20 °) to solifluction, creep and flows.

The calculation of the angle of the slope was carried out using a digital terrain elevation model with a resolution of 15 m per pixel: north, south, east and west: For each raster point (base point), the slope in four directions was calculated. The angle of the slope employed corresponds to the maximum value of the four directions analyzed. The unit in which the value of the slope is expressed is a percentage, which represents the ratio of the difference of elevation and horizontal distance between the base point and the point in the direction analyzed (see Figure 1).

| Classification pending | | Pending qualifier | Value SP |
|---|---|---|---|
| Degrees (°) | Percentage (%) | | |
| 0 – 4 | 0 – 7 | Plain | 1 |
| 4 – 8 | 7 – 15 | Short | 2 |
| 8 – 16 | 15 – 30 | moderate | 3 |
| 16 – 35 | 30 – 70 | Strong | 4 |
| 35 – 55 | 70 – 140 | Very strong | 5 |

Table 1. Rating slope parameter (SP).

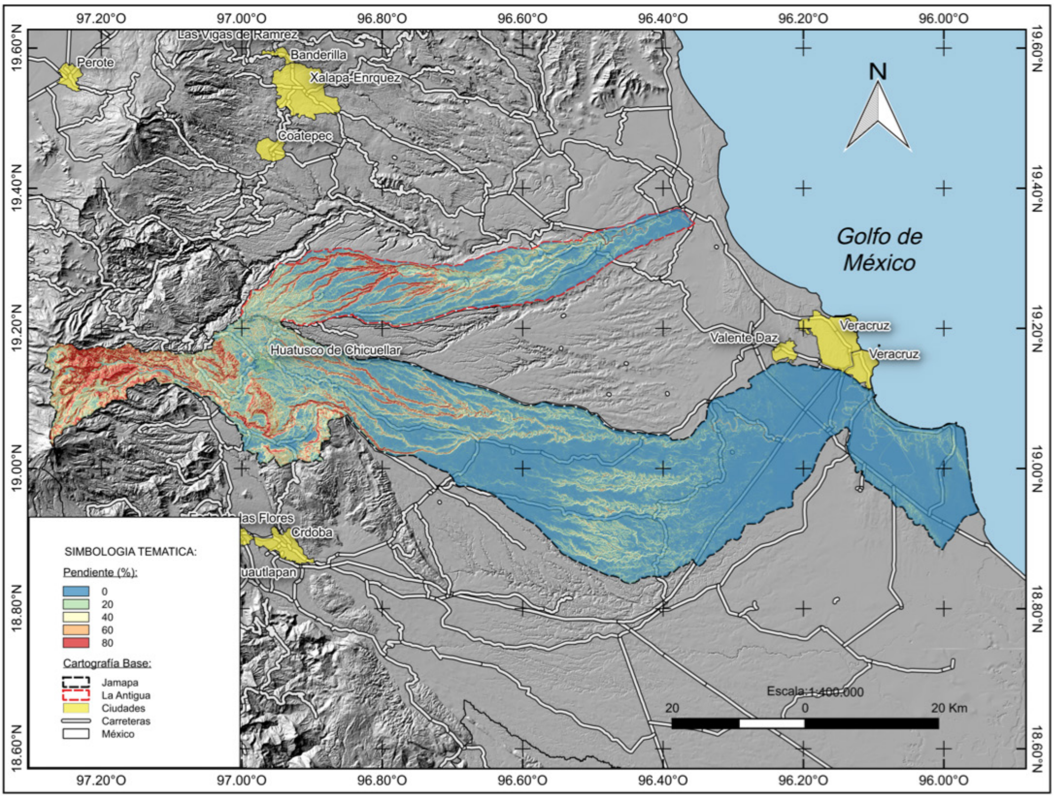


Figure 1. Map of slopes in the basins: Jamapa and La Antigua.

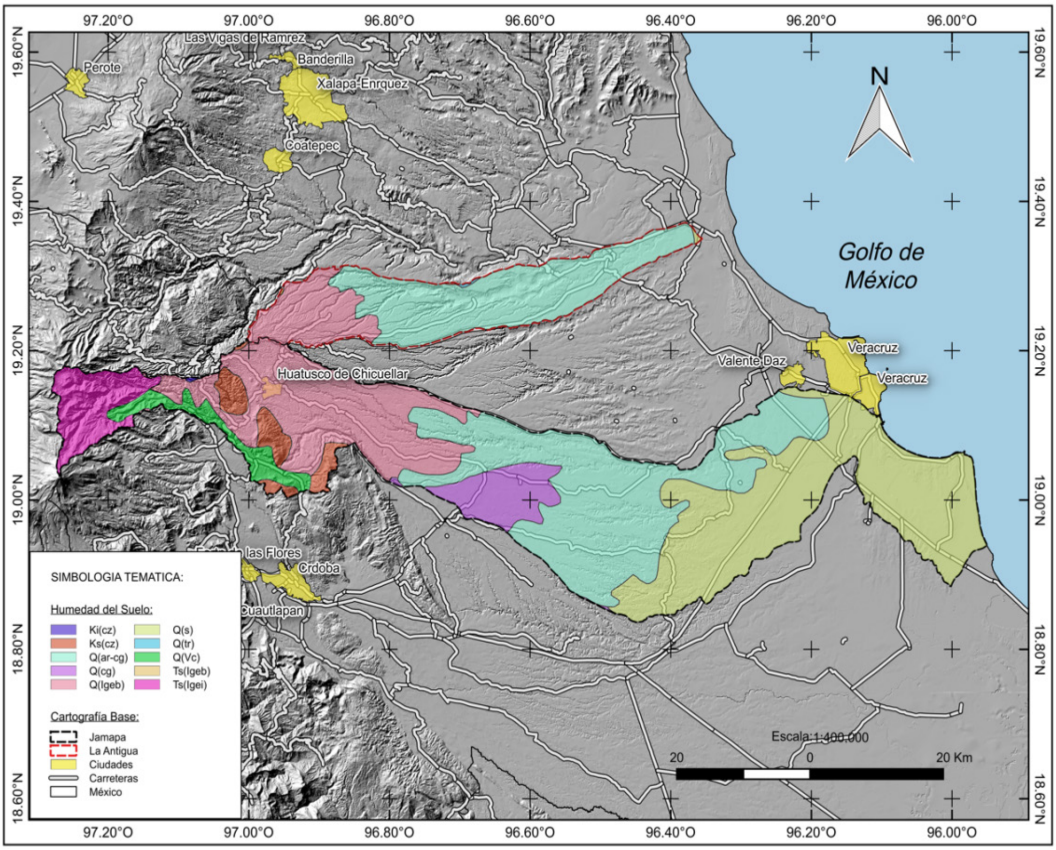


Figure 2. Lithologic map of basins: Jamapaand La Antigua.

### Evaluation parameter field lithology (SL)

The types of soils and rocks have an important role in the dynamic behavior of the slopes. Mineralogical composition, moisture holding capacity, thickness and degree of weathering, the state of fracturing, dip angle, position and variation of groundwater levels, etc., clearly influence the stability or instability of the slopes (Mora et al., 1992). Geological and lithological information from INEGI was used in the calculation of this factor, as well as tables of average values of mechanical properties of representative soil of each lithological group used for the purposes of this study (specific gravity', cohesion c', and angle of friction, φ'); the values have been compiled by various authors (Barton, 1974; Hoek and Bray, 1981; Suarez, 1998; Jibson et al., 2000; González et al., 2002). For the assessment of the lithological units that make up the study area (see Figure 2) the proposed values in Table 2 were used.

| Unidad Geológica | Litología | Valor SL |
|---|---|---|
| Q(legb) | Igneous extrusive | 2 |
| Q(ar-cg), Q(legb), Q(Tr), Q(cg) Ts(legi), Ts(legb) | Sandstone - Cluster | 3 |
| Ks(cz), Ki(cz), Q(Vc) | Limestone - Siltstone, Limestone-Shale, Gypsum Caliza | 4 |
| Q(s) | Alluvial Deposits | 5 |

Table 2. Classification and measurement of lithological units (SL).

### Evaluation of soil moisture parameter (SH)

To evaluate the parameter soil moisture, it was used information from the monthly averages of precipitation is published by the CLICOM and the chart of Soil Moisture and Evapotranspiration of Mexico (scale 1: 1,000,000) published by INEGI. From the information gathered and according to what was proposed by Mora et al. (1992), a simplified hydric balance was used, in which a reference value as established in Table 3, is assigned to the average monthly precipitation making the sum of these values for the twelve months of the year, thus obtaining a value ranging between 0 and 24 units and is classified according to table 4.The result reflects aspects of saturation and temporal distribution of soil moisture (Mora et al., 1992). It should be noted that the monthly average evapotranspiration which turned out to be 100 mm / month was deducted from the average monthly precipitation of the study area.

| Average precipitation (mmmonth) | Assigned value |
|---|---|
| <125 | 0 |
| 125 – 250 | 1 |
| > 250 | 2 |

Table 3. Value assigned to the average monthly rainfall.

| Sum of values assigned to each month | Qualification | Value SH |
|---|---|---|
| 0 – 4 | Verylow | 1 |
| 5 – 9 | Low | 2 |
| 10 – 14 | Medium | 3 |
| 15 – 19 | High | 4 |
| 20 - 24 | Veryhigh | 5 |

Table 4. Parameter values soil moisture (SH)

Figure 3 shows the map of soil moisture obtained by analyzing the average monthly rainfall values and assigning them a reference value in Table 3. When making the sum of these values for the twelve months of the year, a map with values ranging from 12 to 24 units was obtained, which was classified according to Table 4 to apply the MVM.

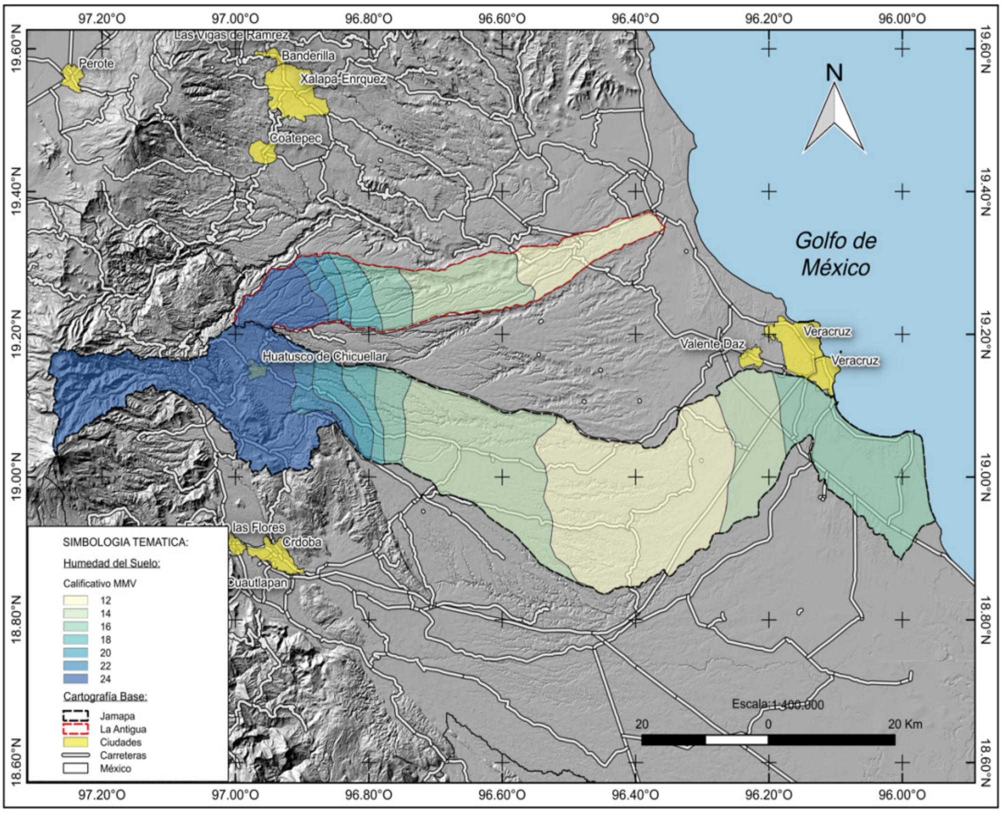


Figure 3. Map of moisture of basins: Jamapa and La Antigu.

**Evaluation parameter shot by Earthquake (DS)**

Because the uncertainties in predicting the occurrence of a seismic event are very high as are theseismic demands that induces the sliding of a slope, it became necessary to carry out a probabilistic seismic hazard analysis (hereafter PSHA) to account for these uncertainties through probabilistic models of seismic source and attenuation models that estimate the intensity an earthquake at a particular site, from its magnitude in the source that generated and the distance between the source and the site of interest.

The seismic hazard in the study area is governed by three types of seismogenic regions: subduction, midwater (inslab) and superficial. The interplate events correspond to subduction earthquakes generated by the friction between the North American plate and the oceanic Cocos and Rivera plates along their contact area. The inslab events correspond to normal faulting earthquakes of intermediate depth, located within the subducting oceanic plate under the continental plate. The shallow crust earthquakes correspond to shallow earthquakes occurring within the North American plate. Model attenuations used were as follows: Abrahamson and Silva (1997) for earthquakes of surface crust, Arroyo et al. (2010) for subduction earthquakes and Garcia et al. (2005) for earthquakes of normal fault of intermediate depth. The data processing was performed with the CRISIS 2015 program (Ordaz et al., 2012), which allows the inclusion of the site effects in the calculation of seismic hazard through amplification factors (ratios spectra response), which depend on the location of the site, the structural period and the level of soil movement.

To take into account the effects of site in the study area, the parameter of the shear wave velocity (Vs30) was used to calculate local amplification factors (Leonardo-Suarez, 2016). This comes from the hypothesis that it is possible to calculate the "average" Vs30 from the slope. To do this, the average values Vs30 recommended by the USGS (United States Geological Survey) for active tectonic regions with a sharp and stable continental regions where changes in topography are smoother (see Table 5), were used. These values were obtained by correlating geological information and measurements Vs30 with land slope in several countries including: US, Japan, Australia and Italy(Trevor et al, 2007).

| Soil Classification | Range Vs30 (m/s) | Slope range (m/m) | |
|---|---|---|---|
| | | Tectonically active | Continental Stable |
| E | < 180 | < 3.00E-4 | < 2.00E-5 |
| | 180 – 240 | 3.00E-4 – 3.50E-3 | 2.00E-5 – 2.00E-3 |
| D | 240 – 300 | 3.50E-3 – 1.00E-2 | 2.00E-3 – 4.00E-3 |
| | 300 – 360 | 1.00E-2 – 1.80E-2 | 4.00E-3 – 7.20E-3 |
| | 360 – 490 | 1.80E-2 – 5.00E-2 | 7.20E-3 – 1.30E-2 |
| C | 490 – 620 | 5.00E-2 – 1.00E-1 | 1.30E-2 – 1.80E-2 |
| | 620 – 760 | 1.00E-1 – 1.38E-1 | 1.80E-2 – 2.50E-2 |
| B | > 760 | > 1.38E-1 | > 2.5E-2 |

Table 5. Slope ranges for various categories of Vs30 according to NERHP.

The information for shear wave velocity was obtained from the "Global Vs30 Map Server" Web application developed by the USGS (http://earthquake.usgs.gov/hazards/apps/vs30/). This application allows the user to calculate Vs30 maps for a specific region of the world.

The intensity level of ground motion in the study area (Jamapa and La Antigua,) was measured in terms of ordered response spectrum (5% of critical damping) for seven structural periods (Te) from 0.01 to 3 seconds, associated with a return period (Tr) of 100 years. To assign values to the seismic parameter, the acceleration values associated to spectral ordinate (Te) equal to 0.15 seconds (see Figure 4) were used and classified according to those values proposed by Mora et al.(1992), shown in Table 6.

| Modified Mercalli Intensity | Acceleration (cm/s2) | Value DS |
|---|---|---|
| III | 0.3 – 2.2 | 1 |
| IV | 2.2 – 4.5 | 2 |
| V | 4.5 – 8.9 | 3 |
| VI | 8.9 – 17.7 | 4 |
| VII | 17.7 – 35.4 | 5 |
| VIII | 35.4 – 70.5 | 6 |
| IX | 70.5 – 140.8 | 7 |
| X | 140.8 – 280.8 | 8 |
| XI | 280.8 – 560.4 | 9 |
| XII | >560.4 | 10 |

Table 6. Earthquake triggered factor(DS).

**Evaluation parameter shot by Rain (DLL)**

The assessment of this parameter is performed according to what is stated in Mora et al., (1992). Intervals classification and respective weights are shown in Table 7. The series of annual daily maximum values recorded at weather stations distributed in the study area were used for evaluating this factor. The calculation of the maximum rainfall associated with a return period (Tr) 100 years, was obtained by applying the method of Gumbel.

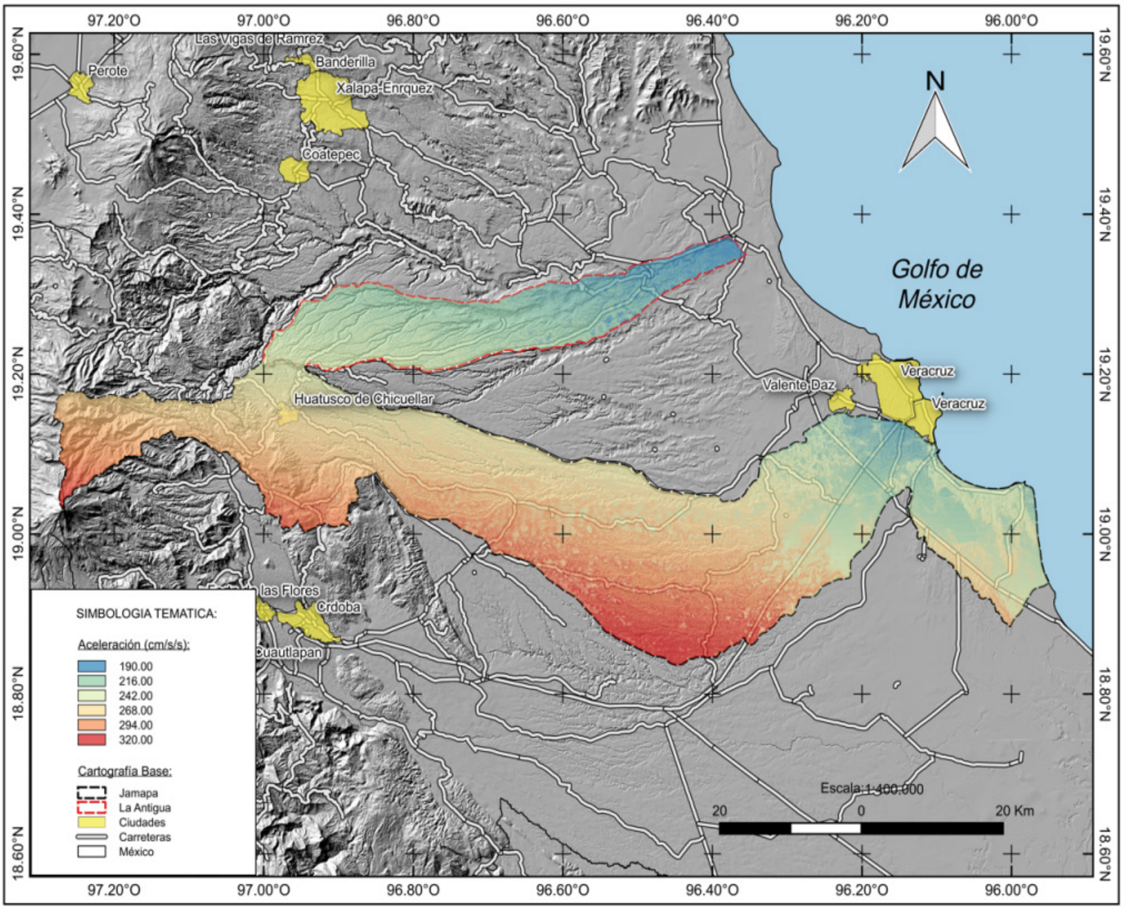


Figure 4. Map intensity of ground motion associated with the spectral ordinate (Te) equal to 0.15 seconds and a return period (Tr) of 100 years.

| Tr = maximum rainfall 100 years (mm) | Qualification | Value DLL |
|---|---|---|
| <100 | Very low | 1 |
| 100 – 200 | Low | 2 |
| 201 – 300 | Medium | 3 |
| 301 – 400 | High | 4 |
| >400 | Veryhigh | 5 |

Table 7. Rating factor triggering rainfall (DLL).

## RESULTS

As a result of the combination of the parameters, a zoning of the susceptibility to slip for the study area was obtained, as shown in Figure 5. This map shows that the sitemost likely to slip is near the Citlaltépetl Volcano (elevation 5747 m), consisting of materials of volcanic origin and interspersed with fluvial deposits with low cementation, and on the banks of the rivers that form the Jamapa basins and Antigua, which have a very steep topography with steep slopes and above 60° cuts. Some of the major municipalities that may be affected by landslides are: Alpatlahua, Calcahualco, Escola, Huatusco, Ixhuatlan del Cafe, Ocotitlan, Sochiapa and Vaquería.

One of the logical application of these studies is to establish public policies for risk mitigation, properly regulating land use and natural resources in conurbations that are affected by this type of geological phenomena.

Some general recommendations for risk mitigation are: rehabilitation of vegetated slopes exposed to the weather, do not urbanizestrategic areas that may start mass movements and subsidence. In urbanized areas, stabilize the slopes and hillsides susceptible to slide through some type of civil work (retaining walls, anchors, coatings, terrain cuts, mass compensation, etc.) to control the movement of sediment or rocks, as well as secondary works necessary (storm drains, sinks, fittings, cultivation of plant species that help control runoff, etc.) to allow proper surface drainage and underground drainage to eliminate leaks whenmaking walls that support the unstable slopes.

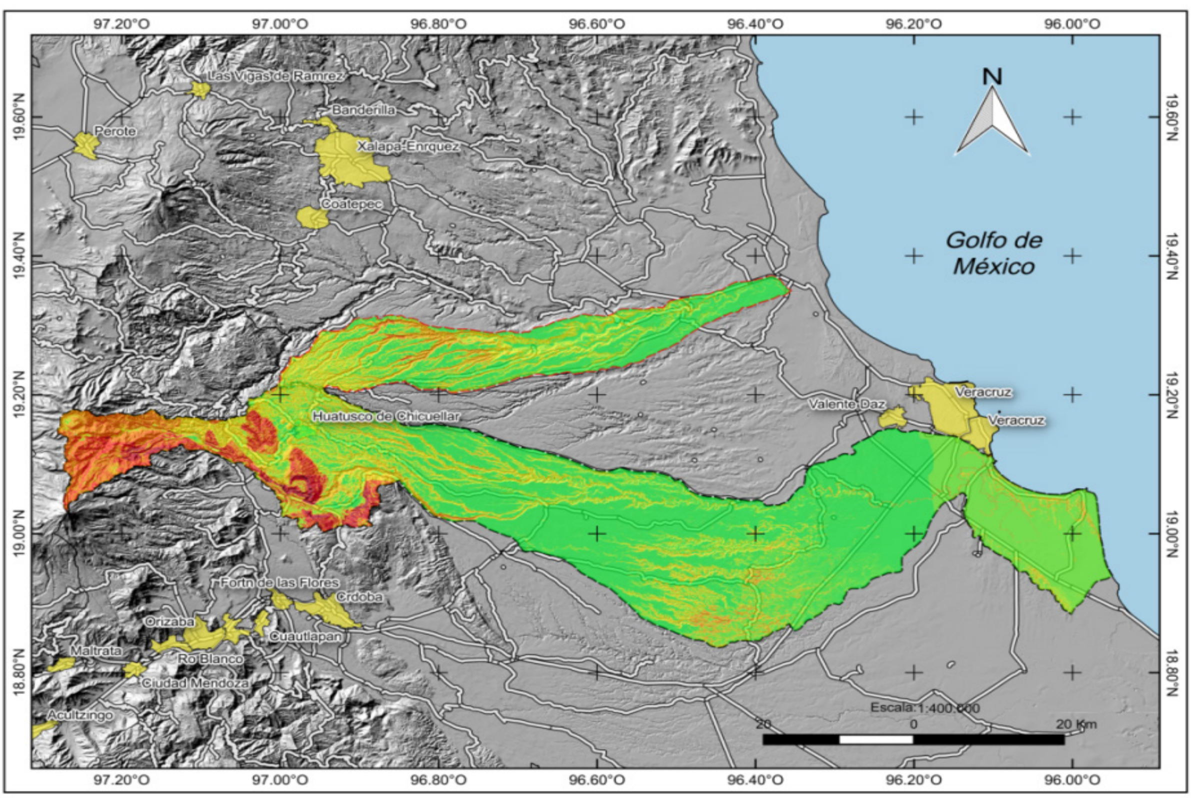


Figure 5. Mapof susceptibility to slip in slopes of the basins Jamapa and La Antigua.


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