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Original Research Article

GIS and geomorphological mapping applied to landslide inventory and susceptibility mapping in the El Estado River basin, Pico de Orizaba, Mexico

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ABSTRACT

With the purpose of strengthening the knowledge and prevention of landslide disasters, this work develops a methodology that integrates geomorphological mapping with the elaboration of landslide susceptibility maps using geographic information systems (GIS) and the multiple logistic regression method (MLR). In Mexico, some isolated works have been carried out with GIS to evaluate slope stability. However, to date, no practical and standardized method has been developed to integrate geomorphological maps with landslide inventories using GIS. This paper shows the analysis carried out to develop a multitemporal landslide inventory together with the morphometric analysis and mapping technique for the El Estado River basin where, selected as the study area, is located on the southwestern slope of the Citlaltepetl or Pico de Orizaba volcano. The geological and geomorphological factors in combination with the high seasonal precipitation, the high degree of weathering and the steep slopes predispose its surfaces to landslides. To assess landslide susceptibility, a landslide inventory map was prepared using aerial photographs, followed by geomorphometric mapping (altimetry, slopes and geomorphology) and field work. With this information, landslide susceptibility was modeled using multiple logistic regression (MLR) within a GIS platform and the landslide susceptibility map was obtained.

Keywords: GIS; Geomorphological Mapping; Landslide Inventory Map; Landslide Susceptibility Map; Multiple Logistic Regression; Pico de Orizaba Volcano

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1. Introduction

The main objective of this work is to evaluate landslides and to provide standardized methods to develop landslide inventories and landslide susceptibility maps to support governmental authorities for risk mitigation and land-use planning in Mexico.

The El Estado River basin, which flows on the southwestern flank of the Pico de Orizaba volcano and which in turn forms part of the Chiquito river basin, was selected as the study area. In the volcanic regions of central Mexico, stratovolcanoes, due to their geomorphic characteristics, have a great potential to generate landslides and debris flows on their slopes due to their high topography, accumulation of voluminous pyroclastic flow deposits, steep slopes, progressive weakening of the volcanic edifice by hydrothermal alteration and other geographic characteristics[1]. Volcanic activity frequently generates voluminous landslides along drainage systems associated with the collapse of a sector of the volcano flank[2-4]. This type of landslide produces volumes greater than one hundred thousand cubic meters[4,5]. However, these catastrophic volcanic events are infrequent, generally separated by very long periods of time, from several hundred years to a few millennia[4]. It should be noted that, during quiescent periods, small landslides and debris flows occur continuously along river drainage systems in large stratovolcanoes. This type of landslides can generate volumes between one hundred and one thousand cubic meters[6] which create a potentially risky situation for the inhabitants of the surrounding localities and their property. Therefore, their cartographic representation and study are important for the evaluation of potential damage in human settlements, industrial areas, agricultural and livestock zones, and forestry.

In Mexico, volcanic regions with stratovolcanoes and monogenetic fields are very common; due to their characteristics they can cause landslides and debris flows, triggered by the collapse of slopes, earthquakes and intense precipitation. Such is the case of the Citlaltépetl or Pico de Orizaba volcano, the highest mountain in Mexico (5,675 masl), which has a great potential to generate landslides and debris flows due to steep slopes, torrential rains, poorly consolidated and fragmented material on its slopes, as well as human activity, mainly deforestation and agriculture. This creates a dangerous situation for more than 500,000 people living within a 27 km radius around the volcano. One such event, which occurred on June 6, 2003 on the Chiquitolo River, caused loss of life and severe damage to property and infrastructure due to the confluence of landslides upstream that fed a large debris flow that affected the town of Balastrera. This debris flow not only caused flooding but also ruptured and exploded pipelines belonging to Petróleos Mexicanos (PEMEX), which were located approximately 300 m from the town. Despite the importance of such processes, there are few maps of landslide and rockfall inventories. To date, there is no practical, standardized method for mapping and integrating the information into a GIS. Few studies have been done to model and locate the spatial distribution of landslides using landslide susceptibility models[1].

A valuable tool that is complemented by the use of Geographic Information Systems (GIS) is the geomorphological survey, which provides precise and concrete information on geomorphological processes, the resulting forms and associated natural phenomena, such as landslides. Based on the analysis of topographic and geological cartography, photographs of areas and digital elevation models of the terrain, the areas susceptible to hazards due to gravitational processes are determined. Geomorphological mapping shows the relief forms by combining structural factors, lithology, tectonics and rock weathering to explain how the relief forms originated and their chronological sequence. Three morphometric maps showing the physical characteristics of the relief and its geomorphometry were prepared for this study. The altimetric map shows the different altitudinal levels of the basin. A slope map shows the gradient of the slopes of the basin and a geomorphometric map shows the types of landforms that exist in the relief obtained from the slope of the terrain.

2. Background

Globally, landslide susceptibility and risk zoning projects are considered to have been addressed through the compilation of landslide inventories and their modeling using GIS[7-9].

In Mexico, numerous GIS-based applications have been used to study and evaluate slope stability[10-12]. The studies include basic concepts and explanations of landslide classification, mechanisms that trigger landslides, criteria, considerations and analyses for risk recognition.

Regarding geomorphological cartography in Mexico, several works have already been carried out following the recommendations proposed by the Technical and Scientific Institute of the Netherlands[13], based on the analytical geomorphological survey to cartographically delimit the relief units of different types, oriented towards obtaining basic and monothematic geomorphological maps. Among the main ones are the geomorphometric, slope, hypsometric, morphogenetic and morphodynamic maps, such as those carried out in the Mexico Basin[14], in the Jocotitlán Volcano[15] and in the Nevado de Toluca Volcano[16,17].

Regarding hazard and risk maps, the Civil Protection Secretariat of the state of Veracruz prepared the Atlas of geological and hydrometeorological risks in the state of Veracruz in 2010, with the collaboration of other federal and state government agencies. Most of the research inherent to the Pico de Orizaba volcano has focused on the volcanic history to try to establish the present morphology of the landscape and the potential risk from volcanic events as well as the collapse of its flanks[2,18-21]. Lahar flow hazard maps have also been developed along the fluvial drainage systems of the volcano based on previous geological studies and computer simulations with GIS and remote sensing[22,23]. Although these types of investigations have already been carried out, there is still no practical, standardized, GIS-based landslide-specific mapping that identifies and describes small landslides in volcanic zones such as those that occur continuously along the river basins located on the slopes of Pico de Orizaba. Based on the experience of previous projects in other regions where landslide susceptibility and risk zonation has been assessed[7-9,24-26]. In this study, geomorphological mapping was integrated with landslide susceptibility mapping using the multiple logistic regression method (MLR). MLR was selected because its evaluation under natural conditions has been shown to be very accurate for the identification of slopes where landslides have been observed, proving to be adequate if sampled strategically and with an appropriate sample size and if the selected variables are strongly related to landslides[27,28].

2.1. Study area

The El Estado river basin was selected as the site to develop an inventory and landslide susceptibility. The watershed is located on the southwestern flank of the Pico de Orizaba volcano (Citlatepetl) and presents continuous landslides and debris flows. The study area covers an area of 5.2 km^2 and includes small portions of the states of Puebla and Veracruz. It is characterized by mountainous and steep terrain with elevations ranging from 4,248 to 2,677 masl and slopes of 56° in the mountainous

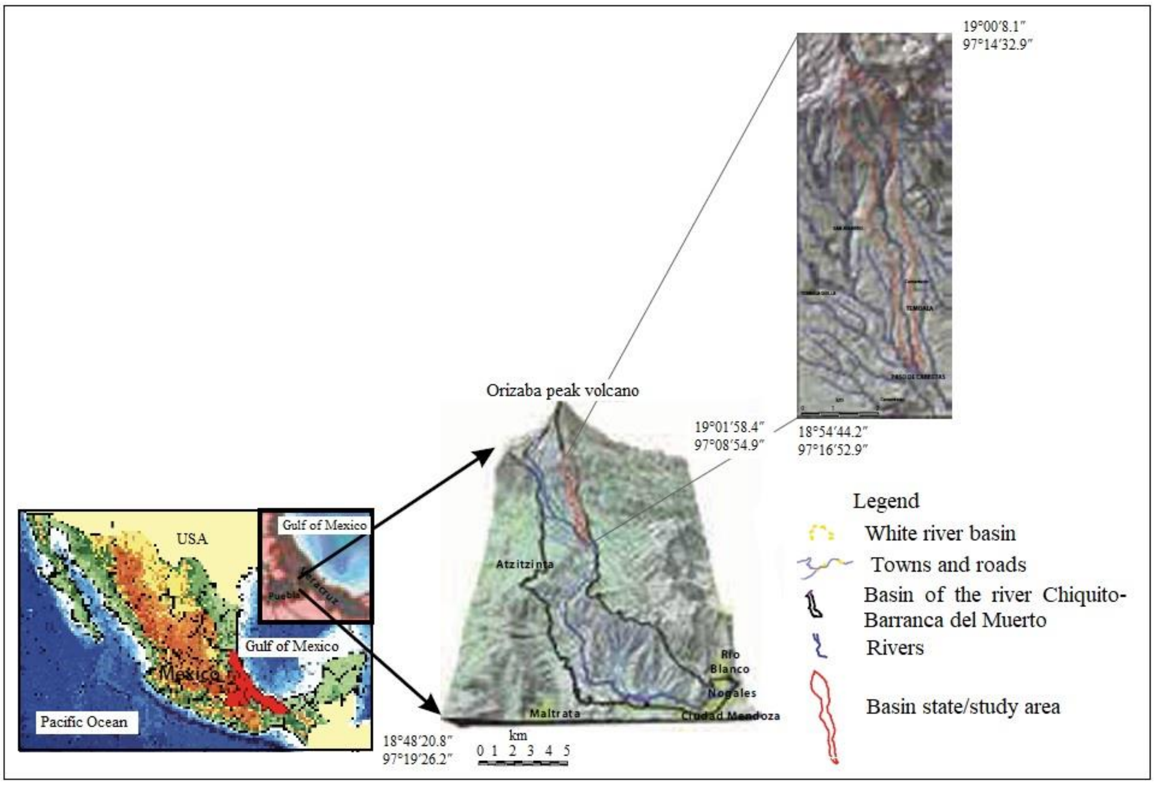

Figure 1. Location map of the study area.

part and 6° in land valleys with relatively flat plains. The El Estado River is a tributary of the Chiquito-Barranca del Muerto River, which discharges into the Blanco River, which flows into the Gulf of Mexico (**Figure 1**).

The geomorphological processes observed in the El Estado basin are conditioned by the different types of lithological outcrops, especially the lavas and pyroclastic flows eroded by the fluvial current.

In the main channel, active and inactive deep-seated landslides are observed, developed in ash deposits and pyroclastic flows, as well as debris slides, debris flows and landslides, while rockfalls occur on slopes formed by lava flows and lahar deposits.

2.2 Method

The research process was carried out at three main levels of analysis to evaluate landslide susceptibility. At level I, a bibliographic review was carried out and geomorphological cartography was prepared by processing the digital map with contour lines every 10 m, as well as with the interpretation of photos of areas at scale of 1:10,000 and 1:20,000, complemented with field work. A digital elevation model of the terrain obtained from the digital topographic map of the National Institute of Statistics and Informatics (INEGI) with a pixel resolution of 10 m was elaborated. Three maps were prepared with this cartographic base. The hypsometric map (**Figure 2**) was heuristically classified to highlight the differences in altitude shown in the basin and to identify the main relief features. The slope map (**Figure 3**) was obtained by means of algebraic and trigonometric operations related to contour lines. The map was heuristically reclassified to obtain the degrees of slope that the terrain presents in various parts of the basin. The morphographic map (**Figure 4**) was elaborated by reclassifying the slope map; in it the relief forms can be identified based on the slopes of the landforms[29,30]. An important aspect of this first level of the method used is the generation of condensed and systematic information on landforms, geomorphological processes and associated environmental phenomena, all of which is reinforced and verified by field work. The above allows the generation of information that, integrated with GIS, is useful for the elaboration of the hazard map with a high degree of precision.

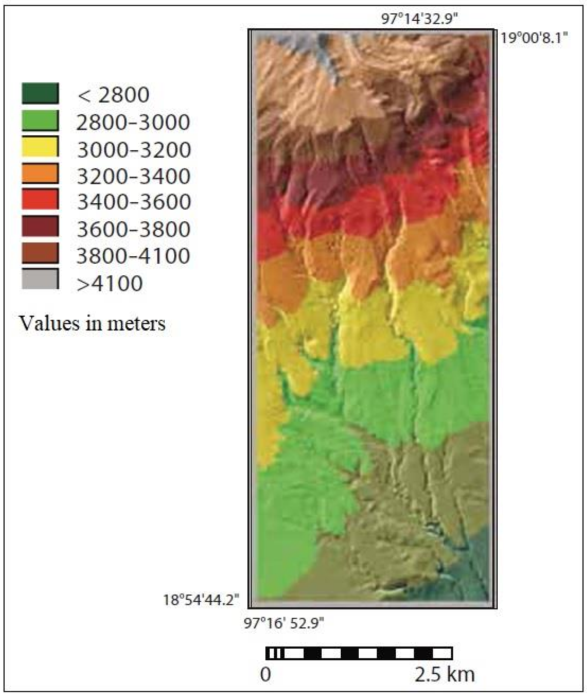

Figure 2. Altimetric map.

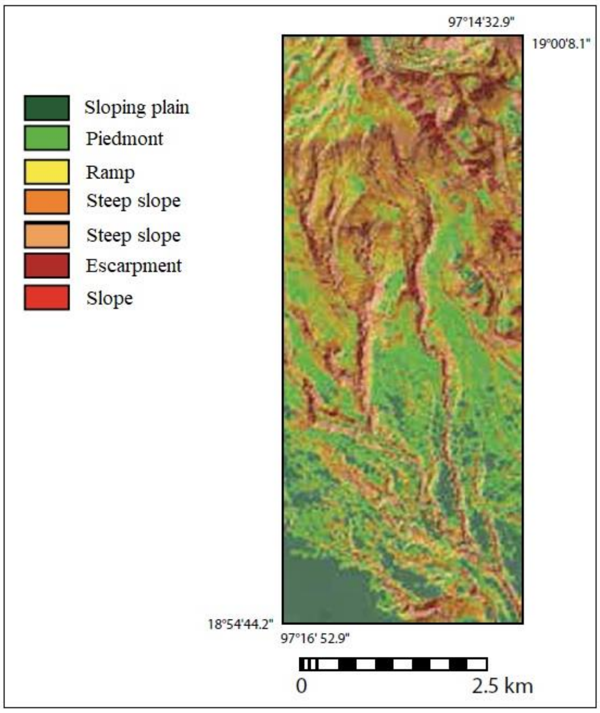

Figure 3. Slope map.

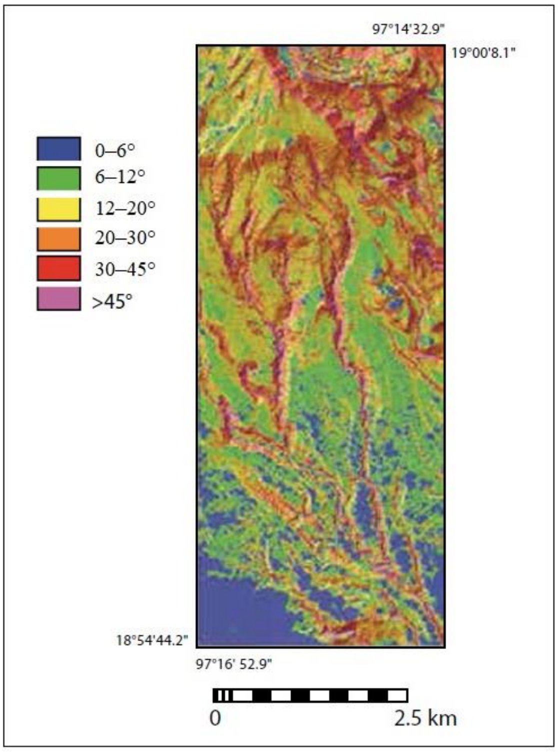

Figure 4. Geomorphographic map.

A historical landslide inventory was prepared at level II. More than 100 landslides were identified in the study area based on multi-temporal analysis, aerial orthophotos and field work to identify and describe the spatial distribution of landslides. The landslides were digitized in GIS and a digital database of landslides was developed.

For the historical landslide inventory, prior information was compiled to provide context and establish a generalized characterization of mass wasting processes within the watershed of the El Estado River basin. The information included geology, relief, land use, climate, and hydrology, as well as pre-existing landslide maps and field reports. The information was georeferenced and incorporated into ArcMap GIS.

At level III, the susceptibility for the basin was calculated to generate the knowledge to establish the areas where the necessary conditions for landslide processes to occur exist.

The eight independent variables used for the landslide susceptibility analysis were obtained from the information collected in the historical landslide inventory.

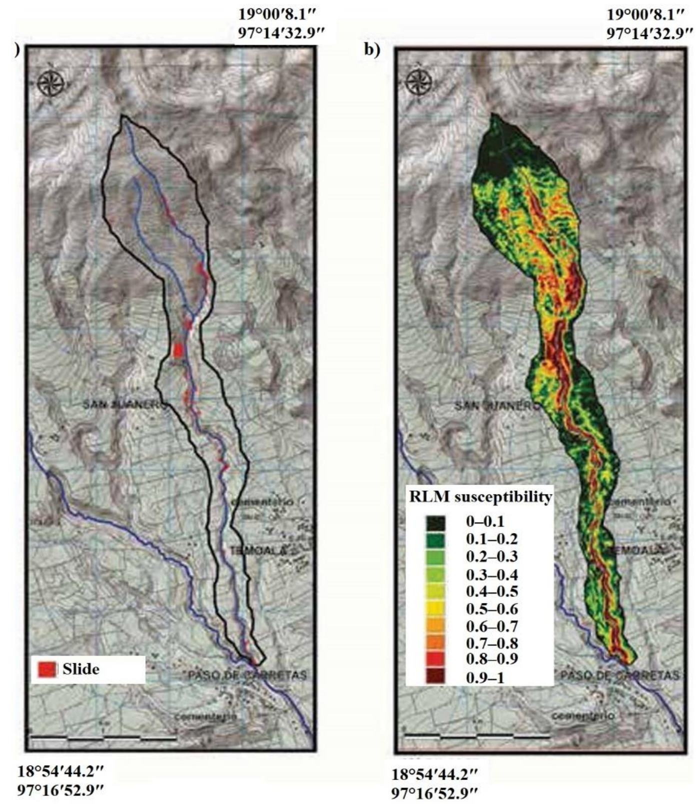

Figure 5. a) Landslide inventory map; b) MLR susceptibility model with ten classification schemes.

The topographic base was obtained from digital elevation data generated and provided by INEGI (10 m resolution) and obtained from topographic maps (E14B46, E14B55, E14B56) of the area at a scale of 1:50 000. Six data layers were obtained from this information: altitude, slope, slope curvature, contributing area, flow direction and saturation. In addition, two digital layers were obtained from INEGI's printed geology and land use maps at a scale of 1:250,000, captured in GIS and converted to a 10 m per pixel digital format. Landslide data were obtained from two sets of orthophotos, supplemented and verified with field work to produce a map of historical landslides. The total set of orthophotos covers a period of 14 years; the first group corresponds to 1994, at a scale of 1:20,000 and the second group corresponds to the year 2008, at a scale of 1:10,000. A total of 107 sites identified as landslides were marked on the map and with this information the spatial distribution of landslides was evaluated and described (**Figure 5a**).

By means of detailed observations and aerial photographs the landslides were classified according to the landslide zoning protocol of the Department of Natural Reserves, Washington State Forest Practices Division[7], supplemented with the criteria proposed by Cruden and Varnes[31] and Wieczorek[32]. The classification yielded the following types: shallow landslides, debris flows, debris slides, deep-seated landslides, and block falls. All landslides were digitized in GIS and a spatial database was created. To complement the desk work, field verification and reconnaissance was done to provide an accurate picture of the watershed, relief and landslide types. The field verification covered 37% of sites with landslides along the main channel, which allowed confirming the validity of the method for landslide assessment.

Table 1. Variables used for the map

Variable	Index	Reference
Altimetry	Not coded	Raw data
Slope angle	Not coded	Raw data
Curvature of the terrain (relief)	-1	Concave relief
	0	Flat relief
	1	Convex relief
Direction of flow	Not coded	Raw data
Saturation	Not coded	Raw data
Support area	Not coded	Raw data
Geology	1	Q massive dacitic lava flows
	2	Q andesitic lava flows in blocks
	3	Q basalt-andesites (brecciated and blocky lava flows)
	4	Q basalts, lahars and fall deposits
Land use	1	Rainfed agriculture
	2	Secondary pasture
	3	Oyamel forest (*Abies religiosa*)

For the calculation of susceptibility, a multicollinear analysis was performed with the eight independent variables (**Table 1**) using the variance inflation factor (VIF)[33].

Prior to the application of multiple logistic regression (MLR), landslide susceptibility was calculated and mapped using the LOGISNET program[34] and the SPSS statistical package. Three steps were followed to model the RLM in LOGISNET. In the first step, random samples of areas with landslides and areas without landslides were used to conduct the RLM analysis. Forty percent of the total area of all headwaters (0.0169 km^{2}) of landslides and the same number of random samples in non-landslide areas were used[35].

The second step consisted of exporting the information to the thematic maps of the 8 independent variables to LOGISNET, converting the digital image to an ASCII file to calculate the interceptor and coefficients, as well as to evaluate the RLM model with the logistic regression module of the SPSS Statistics program[1]. The elaboration of the suscep-

Table 2. Table of coefficients for obtaining the multiple logistic regression (Backward Method) for logit evaluation and statistical test

of RLM, VIF, variance inflation factor, WSig, degree of significance in the Wald test and Hosmer and Lemeshow test

RLM (Backward Method)									
Variable	**Coefficient**	**S.E.**	**Wald**	**df**	**WSig**	**Exp (β)**	**95% C.I. for EXP (β)**		**Statistical collinearity**
							Inferior	**Superior**	
Interceptor	18.470	3.035	37.029	1	2.4E-12	0.995			VIF
Altimetry	-5.5E-03	0.001	49.106	1	1.4E-41	1.154	0.993	0.996	7.223
Pending	0.143	0.011	182.505	1	3.0E-03	0.975	1.130	1.178	1.318
Direction of flow	-0.025	0.008	8.816	1	3.7E-11	0.523	0.959	0.991	1.048
Land use	-0.647	0.098	43.743	1	1.1E-05	0.640	0.432	0.634	2.874
Geology	-0.447	0.102	19.369	1	1.0E-04	1.386	0.524	0.780	4.535
Curvature	0.327	0.084	15.047	1	1.2E-09	1.1E+08	1.175	1.635	1.078
Logit Form	1/1 + exp - (18.469774 + elevation map (-0.005463) + slope map (0.143026) + flow direction map (-0.025160) + land use map (0.326680) + geologic map (0.326680) + curvature map (-0.647303))								
				Model			Hosmer and Lemeshow test		
% Ranking index	-2 log likelihood	Cox & Snell R Square	Nagelkerke R square	Chi-Square	df	Sig.	Chi-Square	df	HLSig.
82.185	714.493	0.416	0.555	452.767	6	0.000	18.608	8	0.017

tibility map (**Figure 2b**) was performed under LOGISNET using the logit function. The logit function estimates the probability that an event (such as a landslide) may or may not occur[36,37]. The RLM was calculated pixel by pixel mapped on the basis of the logit function: 1/1 (Exp (-18.469774)* altimetric map (-0.005463) slope map (0.143026)* flow direction map (-0.025160)* land use map (0.326680)* geology map (0.326680)* curvature map (-0.647303)) (see **Table 2**).

The last step consisted of comparing the RLM susceptibility map with the historical landslide inventory map and observing the spatial differences and overlaps. The percentage coverage between the two maps is the measure of how well the model is able to truthfully identify areas with landslides. To facilitate the comparison, a two-classification scheme (landslide and non-landslide) was used. This scheme was used for both the inventory map (**Figure 5a**) and the susceptibility map of the RLM model (**Figure 5b**). For the RLM, a two-classification scheme was used based on a probability of 0.5 as the rupture point[37]. Values greater than 0.5 are classified as landslide areas and values less than 0.5 as no landslide areas. The evaluation of the RLM model against the landslide inventory was performed in terms of: (1) total accuracy which is the total number of correctly classified landslide and no landslide pixels divided by the total number of pixels in the study area; (2) producer accuracy, which is the ratio of the number of correctly classified pixels in each category to the total number of true pixels for that category; (3) user accuracy determined by the proportion of the number of pixels correctly classified in each category divided by the total number of pixels that are classified by the model in that category, and (4) model efficiency, which is obtained as the proportion of correctly classified pixels minus the proportion of misclassified pixels divided by the total number of classified pixels from mapped true landslides[38].

3. Results

During the evaluation field work in the El Estado River basin, 107 landslides were inventoried and five types of landslides were identified. Debris slides and debris flows predominate (40.2% and 28%, respectively), followed by rock falls (13.1%), shallow landslides (10.3%), and deep-seated landslides (8.4%). The overlay of geology, geomorphography and landslide inventory shows that more than three-quarters of the landslides are in volcanic lahars and landslide deposits from steep slope and scarp areas (>18°) within valleys. These areas are affected by subsistence agriculture and deforestation. The remaining landslides are found in the foothills and ramps (6°–18°) composed of eroded andesitic and dacitic lavas, where there are deposits of flows, blocks and ash covered by fall ash deposits.

Geomorphometric analysis shows that the El Estado River basin is located between 2,700 and 4,000 meters, and that between 3,000 and 3,200 meters, deep ravines have developed, with slopes ranging from 20 to 45°, which has favored the development of both superficial and deep landslides, while the predominant slope in the basin is between 6 and 20°. These conditions of high slopes and large height differences, together with the poor consolidation of the volcaniclastic materials, have allowed the development and triggering of landslides (**Figures 2**, **3** and **4**).

The variance inflation factor VIF (**Table 2**) showed that altimetry, slope, terrain curvature, flow direction, saturation, contributing area, geology, and land use were the most important variables to use in the RLM analysis. These eight variables are closely related to the probability of the distribution of the dependent variable (landslide or no landslide), but not strongly related to each other.

After the multicollinearity assessment, the RLM was calculated. The analysis shows that from the original eight variables, only elevation, slope, flow direction, land use, geology and terrain curvature contribute important information to the model. Statistical tests show that an interceptor and β coefficients are sufficiently reliable for the RLM model (**Table 2**). The statistics show that RLM is reliable. The Hosmer and Lemeshow test shows non-significant results (0.017). Therefore, using all six variables the model does not differ significantly from the data and can predict the real world quite well. The reliability of the interceptor and β coefficients were evaluated with a Wald test and the WSig. The two R^2 values (0.416 and 0.555) suggest that only between 41.6% and 55.5% of the slips are explained by the six variables (Cox and Snell and Nagelkerke R^2 test) (**Table 2**).

With the estimation of the interceptor and the β coefficients for the six variables, the landslide probability was mapped pixel by pixel based on the logit function. Finally, the comparison between the susceptibility map and the inventory through overexposures in GIS allow us to evaluate the degree of certainty of the model (**Figures 5a** and **5b**).

4. Conclusions

This paper briefly shows the application of a method for landslide mapping and its respective susceptibility assessment in unstable volcanic terrains.

The study in the El Estado River is an attempt to adapt and produce the prototype of standardized methods for future landslide studies in the volcanic regions of central Mexico. The method proposes the standardization and integration of thematic layers and their correlated geodatabase with the support of digital analysis supported by GIS computer technology. Preparing the landslide inventory map is a major step in modeling landslide susceptibility in the El Estado River basin.

By superimposing layers in the GIS, it was possible to determine that the abundance and types of landslides are determined by geomorphological conditions and are also related to land use. In the upper part of the basin, andesitic and dacitic lava flows are not easily eroded and there is strong infiltration. Therefore, surface landslides are infrequent, but rock falls are abundant.

A multiple logistic regression analysis was used to define the spatial distribution of landslide susceptibility in the watershed at a scale of 1:50,000. The RLM method indicates that elevation, slope, flow direction, land use, geology, and terrain curvature are the most important factors for landslide generation in the study area. The amount of overlap between the landslide susceptibility map and the inventory map provides an assessment of model accuracy and efficiency. The overlap between the inventory and susceptibility models shows that the RLM is 79.81% successful in predicting landslide areas. The theoretical aspects of geomorphological mapping contribute to developing a conceptual support base for landslide mapping and the establishment of its analytical character represents an approach and a tentative effort to try to establish what are the minimum aspects of the relief that should be considered for the study and elaboration of landslide risk maps. The morphometric maps highlight the differences in altitude of the different types of relief and their changes in slope, as elements that favor landslides.

It should be noted that this article is part of the work and landslide inventory that has been carried out in this area, and of which a first stage of the work has already been published in Legorreta *et al.*[1]. Likewise, other landslide inventories are being carried out in the Nevado de Toluca and in the Sierra de Guadalupe to compare and make susceptibility maps with this proposed methodology.

The methodology applied here is an alternative procedure for the construction of prevention maps in areas with scarce geological and geographical information.

We emphasize that the study is subject to modifications and improvements based on better topographic and thematic mapping and additional validation in other volcanic areas. We recognize the technical limitation of the landslide inventory whose quality depends on the availability of information, the skills and experience of the investigators, ease of access and safety of the fieldwork sites, and the complexity of the study regions. Despite its limitations, the landslide inventory of the El Estado River basin has the potential to be the basis of an integrated methodology to manage and support slope instability forecasting studies.

Knowledge of these aspects will benefit the state and municipal authorities of Puebla and Veracruz so that the necessary planning and precautionary measures can be taken to mitigate the danger of landslides.

Future research will consist of modeling of individual landslide types, characterization of specific landforms and landslide types, volume calculation and modeling of their distribution in the lower parts of the basin.

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Conflict of interest

The authors declare that they have no conflict of interest.

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