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Susceptibility to mass movement processes in the municipality of Tlatlauquitepec, Sierra Norte de Puebla

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Abstract. Since historical times, mass movement processes have taken place in the Mexican territory as a result of its topography, heterogeneous lithology, intense rainfall and the impact of anthropic activity, particularly in mountainous areas such as the Sierra Norte de Puebla. In this region, as a result of extremely high rainfall, a large number of landslides occurred in October 1999. These were mainly slides and flows; they affected economic, structural and environmental aspects and caused the loss of dozens of human lives.

Among the various approaches to analysis of this type of hazard, cartography is of considerable importance since it allows the understanding and assessment of spatial distribution, as well as of the interactions of elements of the terrain that determine slope instability. Hence, some studies of landslide hazard cartography have been carried out in Mexico; these have mainly been based on the overlaying, against a background of geographic information systems, of layers of information concerning the parameters that are involved in slope instability. However, there is a tendency for this approach to establish similar degrees of influence for all factors, regardless of specific local conditions.

The present aim was to consider the influence of the five most important parameters controlling regional slope instability in the Sierra Norte de Puebla (slope, morphogenesis, relief dissection, deforestation and roads), and to validate the results by means of a recurrence index. Multicriteria analysis has allowed a map of susceptibility to mass movement processes to be produced for the municipality of Tlatlauquitepec.

Key words: Landslide susceptibility, multicriteria analysis, recurrence index.

Susceptibilidad a procesos de remoción en masa en el municipio de Tlatlauquitepec, Sierra Norte de Puebla

Resumen. Desde tiempos históricos, los procesos de remoción en masa (PRM) han ocurrido en gran parte del territorio mexicano. Lo anterior debido a la naturaleza de su relieve y litología heterogéneos, intensas lluvias y el impacto de la actividad antrópica, particularmente en las zonas montañosas, como la Sierra Norte de Puebla (SNP). En esta región, y como resultado de precipitaciones extraordinarias, en octubre de 1999 ocurrieron numerosos movimientos gravitacionales, principalmente deslizamientos y flujos que afectaron aspectos económicos, estructurales, ambientales y ocasionaron decenas de pérdidas humanas.

Entre los distintos enfoques empleados para analizar este tipo de peligros, la cartografía es de gran relevancia ya que permite entender y evaluar su distribución espacial, así como la interacción de elementos del terreno que condicionan la inestabilidad de laderas. En este sentido, en México se han realizado algunos trabajos de cartografía de susceptibilidad y peligro por deslizamientos, en los cuales predomina la

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sobreposición, en un ambiente de sistema de información geográfica, de capas de información de los parámetros que intervienen en la inestabilidad de laderas. Sin embargo, la tendencia de este enfoque implica establecer grados de influencia similares para todos los factores, sin considerar las particularidades del escenario en el que se realiza la investigación.

Con la idea de tomar en cuenta de manera específica la influencia de los cinco principales parámetros que inciden en la estabilidad regional (pendiente, morfogénesis, disección, deforestación y vías de comunicación –caminos–), así como la validación de los resultados por medio de índice de recurrencia, en este trabajo se generó un mapa de susceptibilidad a PRM del municipio de Tlatlauquitepec, ubicado en la SNP, a partir de la aplicación de un análisis multicriterio.

Palabras clave: Susceptibilidad a procesos de remoción en masa, análisis multicriterio, índice de recurrencia.

INTRODUCTION

In Mexico, as in other countries, the occurrence of disasters, whether caused by natural events or by human activity, substantially affects integral growth from both the social and the economic perspective. For this reason, an understanding of the dynamics, genesis and spatial impact of potentially dangerous natural phenomena assumes great importance for disaster prevention.

For several decades the Sierra Norte de Puebla (SNP) has experienced mass movement processes (MMP) owing to its lithology, hydrology and morphology. This situation has increased in importance in recent years because of population growth in the region. The effects of Tropical Depression 11 in 1999, and later the impact of Hurricane Stan in 2005, demonstrated the physical susceptibility of the zone to the occurrence of processes involving gravitation and flooding. Particularly in the municipality of Tlatlauquitepec – one of the 87 most affected in 1999 – dozens of slope processes have occurred (principally landslides and flows) caused by heavy rainfall, including events of more than 200 mm per day (Mendoza *et al.*, 2000, Alcántara-Ayala, 2004).

As a starting point for identifying zones of slope instability that can affect communities, numerous methods have been developed from the perspective of various disciplines (Guzzetti *et al.*, 1999; Clerici, 2000; Clerici *et al.*, 2002). From the point of view of geography, risk mapping has been regarded as a valuable tool (Panizza *et al.*, 1996; Hernández-Madrigal, 2005; Lin *et al.*, 2006). Hence, the objective of the present work is to propose a method of mapping susceptibility to mass movement processes on a municipality scale, applied in this case to Tlatlauquitepec; this is based on multicriteria analysis, and has the aim of applying the information in developing measures for disaster prevention.

THE MUNICIPALITY OF TLATLAUQUITEPEC

The SNP is a transition zone between a section of the Sierra Madre Oriental and the TransMexican Volcanic Belt (TMVB); it extends from the municipality of Huauchinango to Teziutlán, at the edge of the coastal plain of the Gulf of Mexico. This mountainous system comprises mainly folded Mesozoic sedimentary rock, partially covered by Pliocene and Quarternary volcanic rock, with rare outcrops of metamorphic rock (Fuentes, 1972).

The region has two major climatic zones: a humid zone that occupies the slope towards the Gulf of Mexico, and a semi-dry region on the inner slope; and there is a fringe area of transition between the two zones (Galván *et al.*, 1999). Its rainfall index is one of the highest in Mexico, exceeding 2500 mm per year (García, 1998), and it is periodically affected by one-off events such as hurricanes Beulah (1967), Fifi (1974), Diana (1990), Gert (1993) and, most recently, hurricane Stan in 2005 (Alcántara-Ayala, 2004).

The municipality of Tlatlauquitepec lies 110 km north-east of the city of Puebla, in the southern part of the SNP (Figure 1). The whole is under the influence of the prevailing north-easterly to south-easterly trade winds, which carry humidity from the Gulf of Mexico up the mountainsides, where adiabatic processes cause it to be precipitated as rain.

The area has a mountainous relief with steep slopes, ravines and deep valleys with intense fluvial erosion; the lithology is complex with numerous

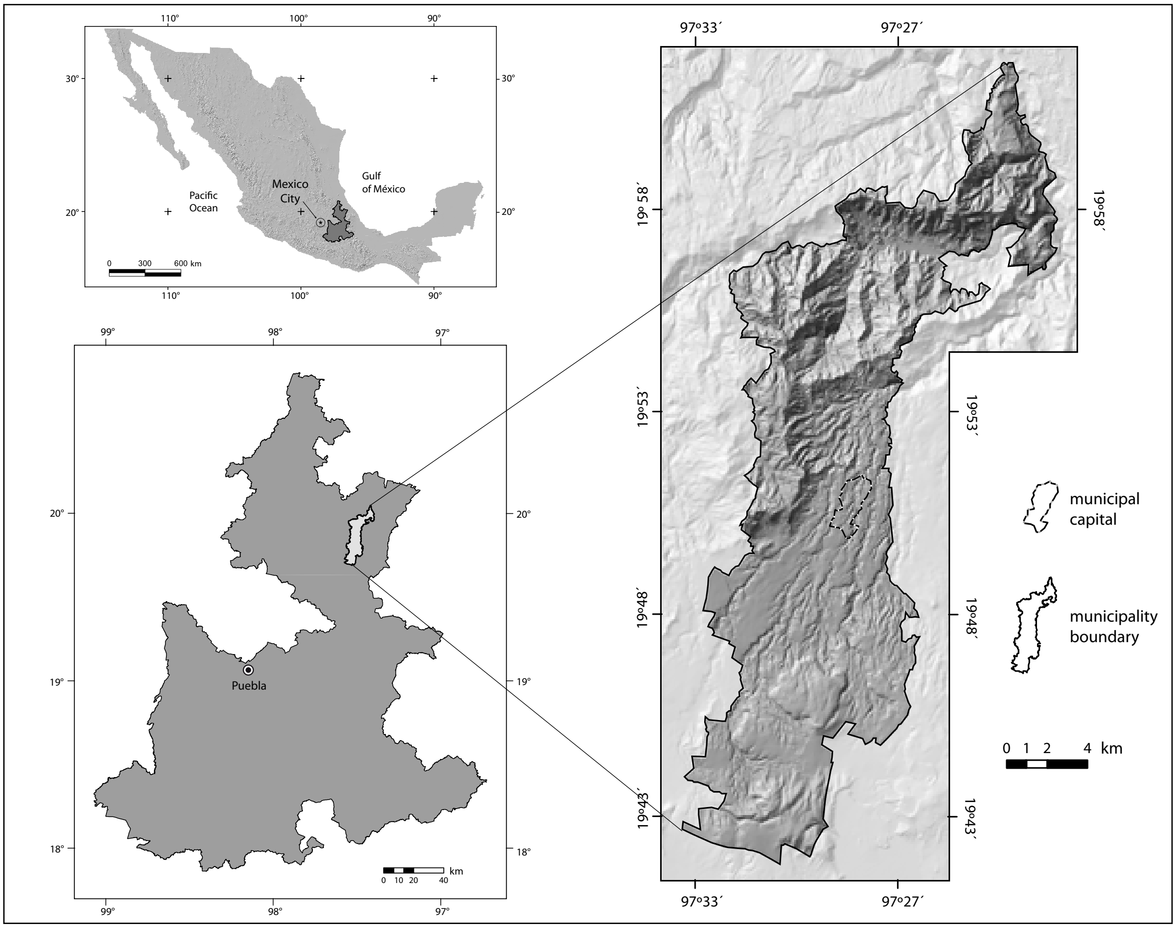

Figure 1. Location of the municipality of Tlatlauquitepec.

areas of contact between materials with different properties; precipitation is high, and this, together with an accelerated process of deforestation, directly influences flooding and saturation of the soil; all these in conjunction lead to instability.

FACTORS OF INSTABILITY AND SUSCEPTIBILITY TO MASS MOVEMENT PROCESSES

Factors in instability

Instability of the terrain is the result of interaction of diverse and complex factors. Some factors determine the stability of a slope in such a way that they can influence the size, speed and depth of a landslide; other factors are considered to be catalysts, whose presence or occurrence initiates a movement (Alcántara-Ayala, 2000).

The specific weighting of each of the factors that influence the instability of the terrain depends on the conditions in which these processes arise, and hence it is necessary to determine their relative importance. Often, susceptibility is mapped by means of the superimposition of layers of information about the parameters that are considered to influence stability (Baeza and Corominas, 2001; Komac, 2006). The results of this type of procedure allow general conclusions to be drawn and large-scale zones of instability to be identified, although in reality it is assumed that all the factors have equal influence, which is by no means always the case (Carrara, 1983; Clerici and Dall'Olio, 1995; Lan *et al.*, 2004).

The parameters that were considered in mapping susceptibility are as follows: slope, morphogenetic regions, vegetation cover, density of dissection of the terrain and distance from roads. These have been considered as fundamental elements of instability in diverse investigations, as in the following examples: when gravity is taken into account, the slope is included in practically all studies of instability worldwide; morphogenesis (Komac, 2006; Castellanos-Abella and Van Westen, 2008); density of dissection (Foumelis *et al.*, 2004; Castellanos-Abella and Van Westen, 2008); vegetation cover (Glade, 2003; Budetta and Vivenzio, 2008); and distance from roads (Ayalew and Yamagishi, 2005; Yalcin, 2008).

Slope

A factor that is, by definition, of great influence in instability is the slope of the terrain, because of its inherent relationship with the force of gravity, and also for its particular characteristics, such as its surface area, orientation, amplitude and, in particular, gradient. The character of the slopes results from the tectonic origin of the mountains of the north and the volcanic relief of the central and south of the area, modified by intense fluvial erosion and a change in altitude of more than 2400 m over a distance of little more than 40 km.

Morphogenetic regions

The morphogenetic regions express the origin of the forms of relief based on their development over time (Lugo, 1989). In the municipality there are three principal types of relief: endogenous relief, structural-denudative relief and exogenous erosive relief. Endogenous relief is represented by the crater of Los Humeros, in which pyroclastic ramps and pyroclastic fluvial deposits are particularly striking among other morphogenetic units; in all, these reliefs cover about 75% of the surface of the municipality. The structural-denudative relief comprises mountainous complexes of limestone, Jurassic and Cretaceous material, with marked folds aligned from the south-east to the north-west and variable dissection. Finally, the exogenous erosive relief, basically represented by valleys defined by fluvial currents, is found in the centre and south of the municipality, while in the north the valleys become narrower and their length decreases within the mountainous complexes.

Density of dissection

The density of dissection represents in part the intensity of erosive action of fluvial currents on the relief of a specific area (Lugo, 1986). The density of dissection in this municipality ranges from 3 to 7 km/km^2, with values being lowest in the south and increasing steadily in a northerly direction as far as the periphery of the La Soledad dam, a strip beyond which the density of dissection gradually decreases.

Vegetation cover

Vegetation cover has acquired greater significance in studies of instability in recent years, from the perspective of the change in land use through deforestation, both in terms of its negative influence on the stability of the terrain, and in proposals for the rehabilitation of the forest cover in order to lower the incidence of mass movement processes. Various studies have focused on analysis of the root systems (Waldron, 1981; O´Loughlin and Ziemer, 1982; Megahan, 1983) and their relationship with the cohesion of materials, increase in erosion and processes of sedimentation, among other processes. Certain investigations focussing on the SNP analyse the importance of deforestation in slope instability (Alcántara-Ayala *et al.*, 2006; Borja-Baeza *et al.*, 2006).

The vegetation cover in the Tlatlauquitepec municipality is heterogeneous; in the north there are large areas of arboreal vegetation, whereas deforested areas predominate in the south. These are interspersed with areas of transition or of partial deforestation, with a tendency to change this condition. In quantitative terms, and in agreement with interpretation of aerial photographs and satellite images, 50% of the municipality supports conditions of arboreal vegetation, while 32% is deforested and the remaining 18% is in a process of transition.

Distance from roads

Human activities have a marked influence on slope instability. They are an important causal factor, owing to the modifications in the natural geometry of the slopes that can be caused by the construction and/or establishment of human settlements on them. Also, the degree of influence occurs during a relatively short space of time in contrast to the evolution of the relief, to natural changes and, of course, to geological time.

In the sphere of human activities, the infrastructure of roads is considered to be a key element in the changes of land use that can cause serious instability in the terrain. For the SNP, this is accentuated by the mountainous relief of the region. This is not the only anthropic factor, but it is the one with the greatest impact in the region.

Susceptibility to mass movement processes

The maps of susceptibility to mass movement processes establish regions with the same degree of stability of the terrain on the basis of various parameters, defined as determinants of instability and of one or more triggers. Among the most important parameters to be considered, the following are of particular interest: lithological properties (Gritzner *et al.*, 2001; Chigira, 2002), seismic activity (Wasowski and Del Gaudio 2002; Keefer, *et al.*, 2006), volcanic activity (Gamberi and Marani, 2007), exceptional precipitation (Dai and Lee, 2001; Alcántara-Ayala, 2004) and human activity (Lugo *et al.*, 2001; Remondo *et al.*, 2005).

In general, mapping susceptibility through slope processes (Zaragoza, 2006) involves, in addition to overlaying layers of information, the analysis of various different elements: for example the density, area, distribution and frequency of mass movement processes and their relation with some aspects of the physical and even social environment, such as population density and growth (Duman *et al.*, 2005). Techniques of mapping susceptibility include the following: development of inventories of MMP, and the use of remote sensing and satellite images (Lee and Lee, 2006; Nichol *et al.*, 2006); photogrammetry – probably the most used and widespread of the techniques (Weirich and Blesius, 2007); monitoring of one or more processes considered to be active (Pasuto and Soldati, 1999); and evaluating the behaviour and mechanisms of slope processes in the field (Guzzetti *et al.*, 2006).

The methods of mathematical analysis used (Allison *et al.*, 1993; Dai and Lee, 2001) can be classified basically as qualitative and quantitative. The former are based on the description of the conditions of instability. The latter, the quantitative methods, express in numerical terms the relationship between the occurrence of mass movement processes and their causal factors (Anderson and Richards, 1987; Brunsden, 1999; Yalcin, 2008). These causal factors are divided into deterministic and statistical. The deterministic factors are based on the calculation of the security factor and are applied generally in small areas, whereas the statistics employ mathematical processes in order to estimate the susceptibility values in relation to the interactivity of the parameters that favour the occurrence of MMP (Aleotti and Chowdhury 1999; Fall *et al.*, 2006).

A fundamental part of the analysis of stability of the terrain is an inventory of MMP. According to the objectives and resources, inventories are developed at various scales, from the local to the national, using a variety of techniques, for example photointerpretation, identification in the field and interpretation of historic records (Duman, *et al.*, 2005), although there is no sole criterion for this type of analysis (Galli *et al.*, 2008).

It is important to establish that the maps of susceptibility are a model of reality, and that the degree of certainty of the results is conditioned by diverse aspects, such as the knowledge that is available concerning the phenomenon under analysis, the number of parameters that interact in the occurrence of that phenomenon, and the selection of these. In addition to the above, the optimal management and processing of the information is extremely important, whether in the design, functionality or precision of the programs and models employed. A solid theoretical base is indispensable for the selection or design of the technique or method adequate for the type of study that is to be carried out, and thereby to be able to adapt, modify and apply the selected model in the correct form, with the objective of reducing to the minimum the factor of uncertainty or error.

Despite scientific advances in the study of slope instability, there are still difficulties in the construction of maps of susceptibility and of risk, owing to the complexity of the process *per se*, the interrelationships among the factors and the cartographic generalization of a process of relatively little surface area. Also, from a purely technical perspective, it is necessary to establish the confidence limits of the data that have been obtained and generated, and also to take into account the conflicts inherent in the binary processes in the geographic information systems, which are related to the digital information introduced in the computer programs (Ardizzone *et al.*, 2001).

METHODS

After defining the study area, evaluating the conditions of regional instability and selecting the procedure to apply in order to map the susceptibility to MMP, the next step is to generate the digital information for each of the parameters of high incidence in the occurrence of slope processes in the region (see next section), with the aid of cartographic bases, photo-interpretation and analysis of satellite images.

Multicriteria analysis is applied, either manually by using a conventional spreadsheet or with the aid of a geographic information system, GIS (IDRISI®). The latter allows comparison of procedures and verification of their efficacy. Subsequently, with a value assigned to each layer of digital information, the mathematical procedure is performed (superposition or 'sum' of the layers of digital information) in a GIS (Arcview®) in order to map the susceptibility. When this cartography has been completed, with the aid of the MMP inventory, a recurrence index is estimated in order to validate the results of the mapping of the regions of susceptibility (Figure 2).

Multicriteria analysis

Multicriteria analysis was developed in the 1960s and has been employed as an analytical tool for decision making; with it, it is possible to consider simultaneously and quantitatively the influence of divers parameters on the same phenomenon or process, and to ensure that the final results reflect equitably the opinion of the specialists involved (Díaz, 1998). Additionally, the analysis allows the procedure to be made transparent and the impor-

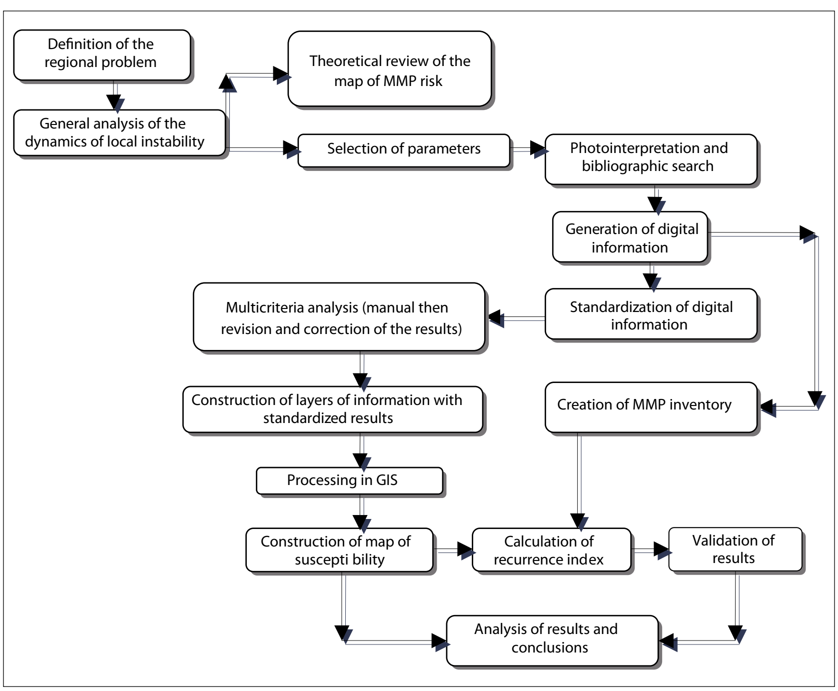

Figure 2. Methods.

tance of each of the parameters to be identified (Saaty, 1984).

In recent years the application of multicriteria analysis has spread across GISs, and programming has even been proposed oriented to process this relationship, although its application in earth sciences has not yet been standardized, specifically in the evaluation of dangers of natural origin (Chen *et al.*, 2001); however, it has been applied in some studies for determining zones of susceptibility to mass movement processes (Komac, 2006; Castellanos-Abella and Van Westen, 2008; Yalcin, 2008).

Multicriteria analysis has as a starting point the standardization in a common scale of classification for all the parameters or factors included in this process (Figure 3); later, the relative importance of these parameters is compared in a pair matrix, whose analysis determines the specific weighting of each factor (Table 1). This procedure is effected for each of the opinions added to the analysis by the specialists; the mean results are obtained (Table 2) and, where necessary, statistical errors are corrected (Saaty, 1984).

As a consequence of the variety of alternative possibilities for the relative importance of the factors, it is necessary to determine a degree of consistency in obtaining the values of comparison; generally, a procedure proposed by Saaty (1984) is employed, in which a quotient or proportion of consistency is calculated. The proportion of consistency indicates the probability that the values in the matrix are randomly generated. In this case the

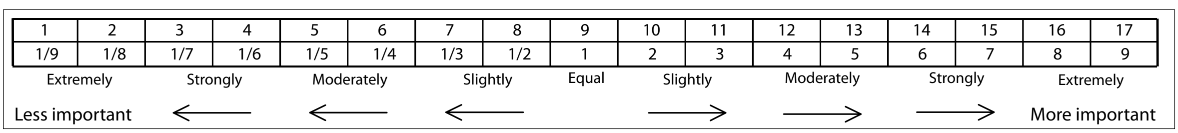

Figure 3. Base diagram for comparing the relative importance of parameters in multicriteria analysis.

Table 1. Comparison of the relative importance between pairs among the selected parameters (example of a table obtained from a consultation with a specialist)

	Gradient	Morphogenetic regions	Tree cover	Distance from roads	Density of dissection
Gradient	1	1/5	5	5	4
Morphogenetic regions	5	1	3	3	3
Tree cover	1/5	1/3	1	1	1/3
Distance from roads	1/5	1/3	1	1	1/3
Density of dissection	1/4	1/3	3	3	1

Table 2. Specific weight calculated for each parameter on the basis of a multicriteria analysis (average of various opinions consulted)

	Gradient	Morphogenetic regions	Tree cover	Distance from roads	Density of dissection	Specific weight (%)
Gradient	0.2889	0.2562	0.3636	0.3297	0.4468	33.7
Morphogenetic regions	0.506	0.3811	0.2871	0.245	0.3295	34.98
Tree cover	0.0652	0.1079	0.0782	0.1836	0.0454	9.61
Distance from roads	0.0477	0.0912	0.0365	0.0568	0.0421	5.49
Density of dissection	0.0921	0.1635	0.2346	0.1849	0.1361	16.22
Total	1	1	1	1	1	100

mean quotient obtained (in the IDRISI® program) was 0.06, which lies within the range of acceptable consistency.

Slope instability: specific parameters

According to the opinion of the specialists consulted, and on the basis of the multicriteria analysis, the slope and the morphogenetic regions are the parameters of highest incidence in the occurrence of MMP in the municipality of Tlatlauquitepec; the density of dissection has a moderate influence on the instability of the terrain and, finally, the influence of the road network and of the vegetation cover is less, although still important.

The parameters selected were grouped into five categories on the basis of their influence in the instability (with the exception of plant cover, which was divided into three categories in order to avoid errors in photo-interpretation). The values for gradient were classified according to the ranking usually considered for defining changes in the form of the relief (Lugo, 1986). The ranking of the tree cover, since it derived from photo-interpretation and was therefore qualitative, was classified into areas with closed tree cover (more than 80% of the canopy), open tree cover and absence of vegetation (Figure 4).

The ranks of the density of dissection were determined at constant intervals between the minimum and maximum values; the distance from roads was determined at equal intervals of 50 m, the interval most used in the specialized literature (Yalcin, 2008). Roads constructed on gradients of less than 6° were not considered, because in this case the disturbance of the terrain is very slight and, generally, the slope does not need to be cut into (Figure 5).

Finally, morphogenetic regions were ranked as a function of the number of MMPs registered in each of them (Figure 6). Table 3 shows the ranks used for each parameter.

RESULTS AND VALIDATION

On the basis of the multicriteria analysis, the map of susceptibility to mass movement processes in the municipality of Tlatlauquitepec was drawn up (Figure 7). Of the whole municipal territory, approximately one-half has conditions that favour the occurrence of MMP (22% very high susceptibility and 28.5% high), while only 15% presents a favourable setting for the stability of the terrain (4.5% very low susceptibility and 10% low), and 35% of the territory comprises regions of transition between the two scenarios. These results, in combination with the high regional vulnerability (Marcos-López, 2003; Castilla-Torres, 2007; Preciado-López, 2007), assume the existence of a high level of risk of MMP for the municipality.

With the aim of validating the results of the map of susceptibility, an index of MMP recurrence in the municipality was derived with the aid of an inventory of slope processes (modification of the procedure of Alcántara and Murillo, 2008) based on satellite images, photo-interpretation and field trips (Figure 8). The index was calculated by means of the following formula:

$$Ir = \frac{t}{\sum t}$$

where

I_r is the recurrence index.

$t = p_m/a$.

p_m represents the mass movement processes per zone of susceptibility.

A is the area per degree of susceptibility (km^2).

Table 4 shows the results for the recurrence index, which are correlated with the zoning obtained by the multicriteria analysis and shown on the map of susceptibility.

In this context, 81% of the total of the MMP registered occurred in the zones of very high and high susceptibility, and only 17% in the strips of medium susceptibility, the majority of these due to diverse anthropogenic factors, e.g. felling for specific construction projects. Finally, three landslides are in the region of low susceptibility; these were favoured by felling in the construction of roads without recognition of any slope process; in the zone of very low susceptibility, extraordinary conditions would

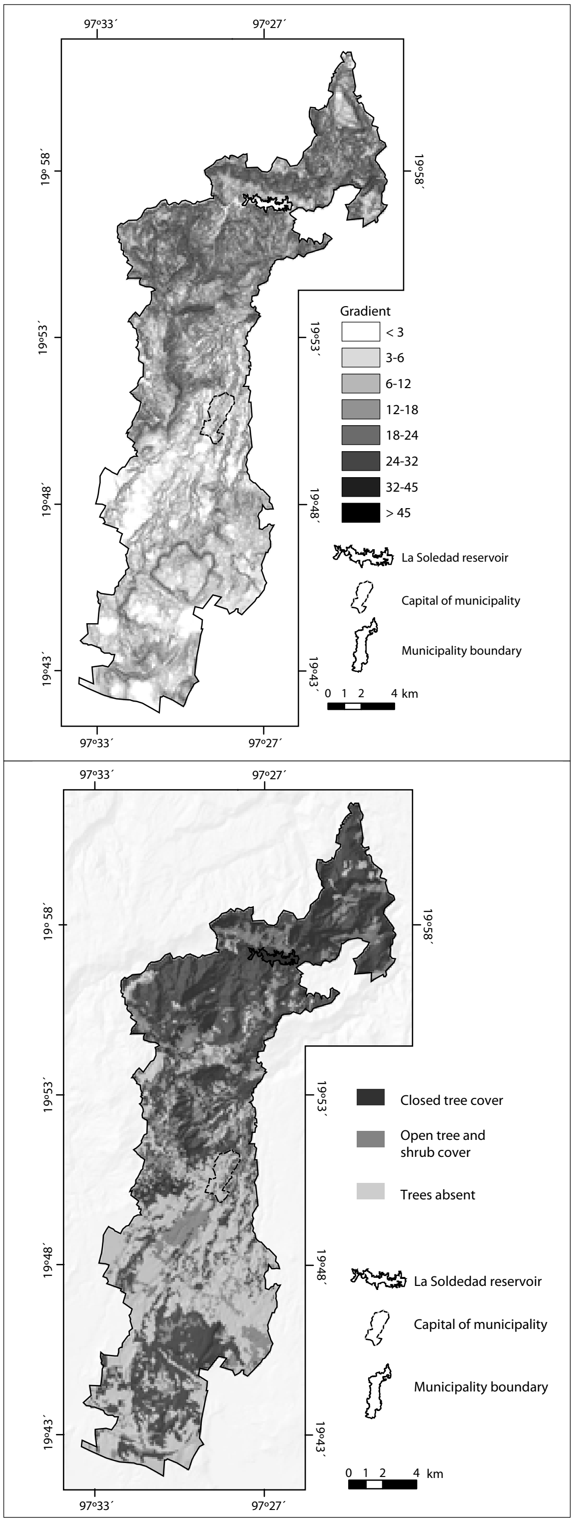

Figure 4. Slope and plant cover of the municipality of Tlatlauquitepec.

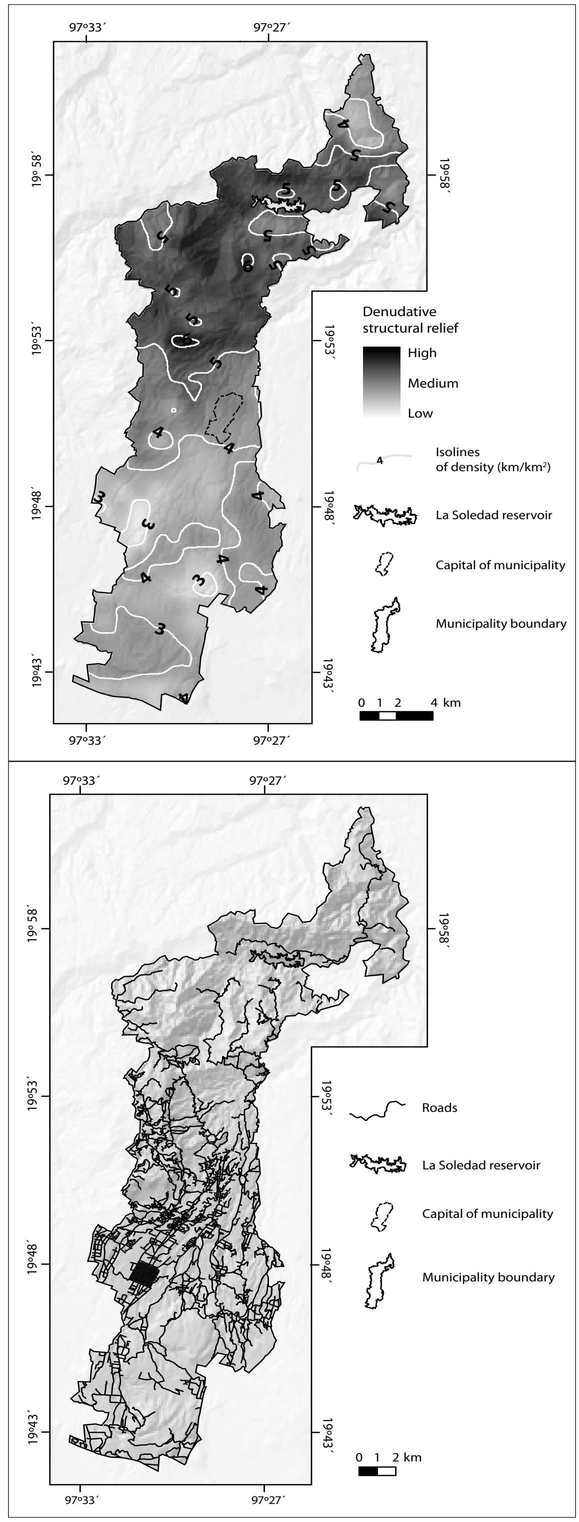

Figure 5. Density of dissection and communication routes in the municipality of Tlatlauquitepec.

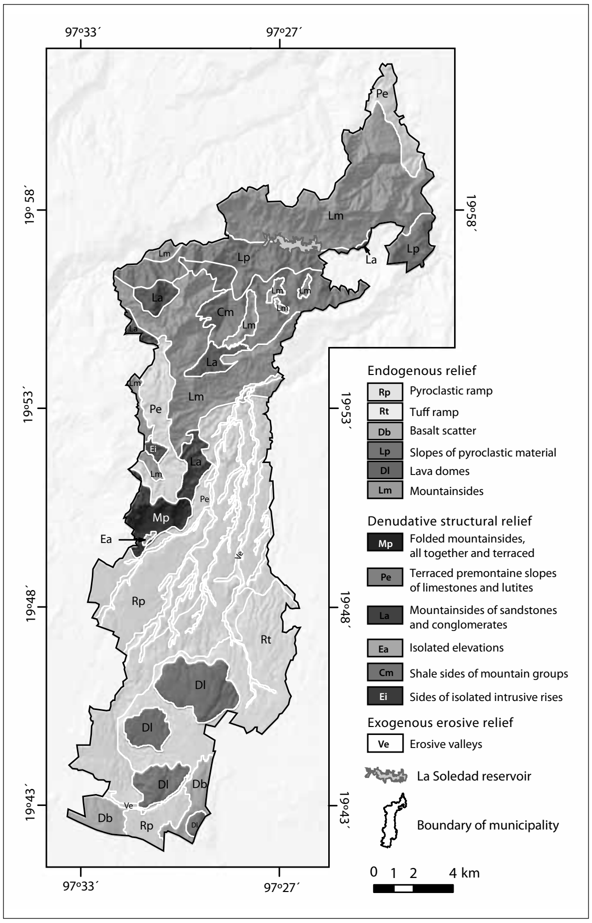

Figure 6. Morphogenesis in the municipality of Tlatlauquitepec.

Table 3. Ranks of the parameters used in the multicriteria analysis

	SUSCEPTIBILITY TO MMP				
Parameter	Very low	Low	Medium	High	Very high
Gradient	≤ 6°	6° - 12°	12° - 24°	24 ° 32°	≥ 32°
Morphogenetic regions*	Bs, Ld, Ie, Ii	Fm,	Ph, Ll,	Rt, Sc, Ev	Pr, Ms, Ss
Density of dissection (km/km^2)	≤ 3	3 - 4	4 - 5	5 - 6	≥ 6
Plant cover**	With natural vegetation	N.A.	Partially deforested	N.A.	Deforested
Distance from roads (m)	≥ 200	150 - 200	100 - 150	50 - 100	≤ 50
	← High Stability of the terrain Low →				

***Pr**, Pyroclastic ramp; **Rt**, Ramp of tuff; **Bs**, Basalt scatter; **Ph,** Hillsides of pyroclastic material; **Ld**, lava domes; **Ms**, Mountainsides; **Fm**, Folded mountainsides, all together and terraced; **Ll**, Terraced premontaine slopes of limestones and lutites; **Sc**, Mountainsides of sandstones and conglomerates; **Ie**, Isolated elevations; **Ss**, Shale sides of mountain groups; **Ii**, Sides of isolated intrusive rises; **Ev**, Erosive valleys

** **N.A.**, Not applicable.

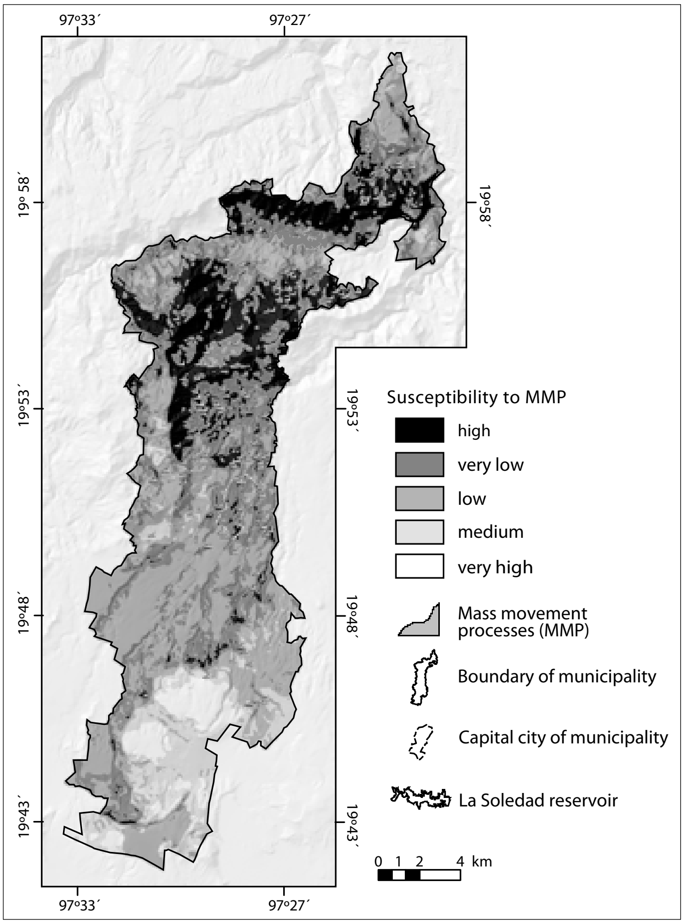

Figure 7. Map of susceptibility to mass movement processes.

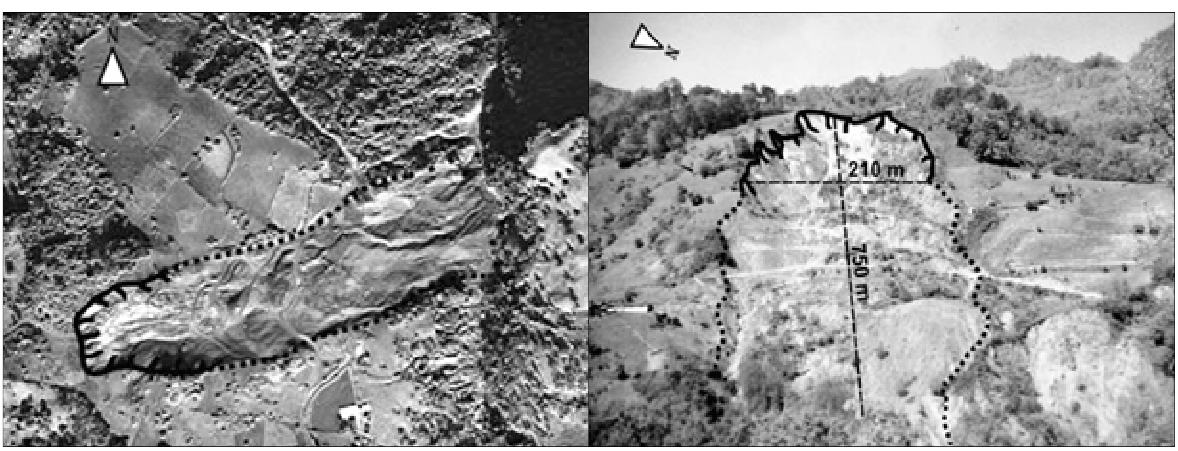

Figure 8. Satellite images and aerial photographs used in developing the inventory of mass movement processes.

Table 4. Recurrence index of mass movement processes

Susceptibility	Area in km^2 (%)	Mass movement processes (%)	Recurrence index
Very high	63.99 (22%)	80 (44.7 %)	0.504
High	80.39 (28.5%)	66 (36.9 %)	0.331
Medium	99.8 (35%)	30 (16.8 %)	0.121
Low	28.85 (10%)	3 (1.6 %)	0.042
Very low	13.1 (4.5%)	0	0.00
Total	286.15	179	1

have to occur for there to be a landslide, specifically through human activity.

CONCLUSIONS

The development of maps of susceptibility is a very important activity in studies of risk and as a contribution to its prevention. However, they cannot be considered as definitive elements for decision making, since analysis at a more detailed level is required.

It is indisputable that there are universal factors that affect regional instability (gradient, lithology), but also the influence of others can vary in different scenarios; for this reason it is necessary to identify these causal factors and to estimate the degree of influence of each one.

Multicriteria analysis is one option for calculating the specific weight of the instability factors, independently of the total number of parameters included.

The method for mapping susceptibility to MMP in the municipality of Tlatlauquitepec, according to the validation achieved, gives good results in the estimation of regions of instability. It also has the advantage of not requiring a great investment of scarce resources, since these are frequently affected by the occurrence of landslides, in particular in the Sierra Norte de Puebla. The method presented here can be applied in regions with an obvious problem of instability, if the necessary adjustments are made (for example, in the selection of parameters of instability and the specific weighting of these), but with a structure similar to the one presented here.

In order to analyse the sensitivity of the method used, a recurrence index was derived, on the basis of the most extreme values suggested by the panel of experts. This was generated on the basis of assigning distinct weights to those used in the multicriteria analysis described above, these weights being as follows: morphogenetic regions, 0.40; gradient, 0.29; plant cover, 0.74; distance from roads, 0.74; and density of dissection, 0.15. As a result of the use of these values, the estimation of the recurrence index was as follows: very low susceptibility, 0.03; low, 0.28; medium, 0.14; high, 0.40; and very high, 0.38. These results suggest an inconsistency in the index, since values proportional to the degree of susceptibility would be expected; in other words, the lower the susceptibility the lower the value of the index and vice versa. The above is interpreted as an indication that the criteria used in the above analysis were the correct ones and that the multicriteria technique was used in an appropriate manner for the identification of the zones of susceptibility to slope instability in the area under consideration.

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