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Susceptibility to shallow landslides of soil in the municipality of Temoaya, Mexico: multicriteria analysis[1]

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Abstract. Owing to the mountainous character of the Mexican terrain, as well as the ecological effects of changes in land use, particularly in recent decades, and the occurrence of severe and frequent hydro-meteorological phenomena, the instability of slopes dislodged by precipitation constitutes a major hazard in various regions of the country, among them the municipality of Temoaya in the State of Mexico.

In this municipality, where the mountainous relief formed by poorly consolidated and faulting volcaniclastic deposits favours instability, there are 33 active processes of mass movement, of which thirty –the most important– are shallow soil translational landslides (SSTL), one is a debris slide and two are rock falls. The occurrence of SSTLs is controlled by the character of the volcaniclastic deposits, specifically pyroclastic flows of blocks, ash and pumice; because these are permeable materials they favour infiltration; if the subjacent material is impermeable or of low permeability, water accumulates on the sub-horizontal lithological contact and transforms into a flow that leads to the instability of the overlying material.

A map of susceptibility to SSTLs was generated by means of a multicriteria analysis. According to the map produced, 15% of the municipality is very highly susceptible to landslides, 35% is highly susceptible, 30% shows medium susceptibility, and the remaining 20% has low or very low susceptibility.

Key words: Shallow soil translational landslides, multicriteria analysis, susceptibility, Temoaya.

Susceptibilidad a deslizamientos superficiales de suelo en el Municipio de Temoaya, México: aplicación del análisis multicriterio

Resumen. Debido al carácter montañoso del espacio geográfico mexicano, así como del impacto ecológico generado por los cambios de uso de suelo, efectuados particularmente en las últimas décadas, y de la ocurrencia de fenómenos hidrometeorológicos de gran intensidad o frecuencia, la inestabilidad de laderas desencadenada por precipitación constituye uno de los peligros de mayor impacto en diversas regiones del país, entre ellas el municipio de Temoaya, Estado de México.

En este municipio, donde el relieve montañoso formado por depósitos vulcanoclásticos poco consolidados y afallados favorece la inestabilidad, existen 33 procesos de remoción en masa activos, de los cuales treinta –los más importantes–, son deslizamientos de suelo superficiales de tipo traslacional (DSST), un deslizamiento de derrubios y dos caídas de rocas. La ocurrencia de los DSST está controlada por el carácter de los depósitos vulcanoclásticos, específicamente flujos piroclásticos de bloques, cenizas y pómez, los cuales al ser materiales permeables favorecen la infiltración, por lo que si el material subyacente es impermeable o de menor permeabilidad, se presenta una acumulación de agua sobre el contacto

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litológico subhorizontal que se transforma en un flujo que conduce a la inestabilidad del material sobreyacente.

En este trabajo se presenta la aplicación del Método de Análisis Multicriterio para la generación de un mapa de susceptibilidad a deslizamientos de suelo superficiales de tipo traslacional para dicha zona. De acuerdo con el mapa elaborado, el 15% del territorio municipal presenta muy alta susceptibilidad a deslizamientos, mientras que la zona de alta susceptibilidad ocupa el 35% del área en cuestión. El nivel de susceptibilidad medio se concentra en el 30% del territorio, y en el restante 20% de la zona de interés, la susceptibilidad a deslizamientos es baja y muy baja.

Palabras clave: Deslizamientos de suelo superficiales de tipo traslacional, análisis multicriterio, susceptibilidad, Temoaya.

INTRODUCTION

Slope instability

Hillslopes can be subject to an instability known as mass movement processes or gravitational processes (Alcántara, 2000a). According to the EPOCH (1993) classification, these include falls, topples, slides, lateral expansions, flows and complex movements. Mass movement processes can be natural or anthropogenic. The natural events are highly important in the continuous sculpting of the mountainous relief, since they form part of the natural cycle of evolution of the relief of the land mass (Lugo *et al.*, 2001); they result from the direct influence of gravity in combination with internal or external factors, and of triggering mechanisms such as tremors, precipitation, volcanic activity and explosions (Crozier, 1986). Mass movement processes can also be the result of anthropogenic activities that generate a disequilibrium in the hillslopes through terracing, deforestation, agriculture (Alcántara, 2002:47), or there may even be an interaction of natural and anthropogenic factors.

According to Alcántara (2010), during the period 1900-2000 in Mexico and in Central America, disasters caused by mass movement processes affected 10 million people and 53,771 died. In Mexico, rains caused by tropical depression No.11 in 1999 caused gravitational processes in the Sierra Norte de Puebla that killed 250 people; this was considered to be the worst disaster of the 1990s in Mexico (Bitrán, 2000, Lugo *et al*, 2005:22).

In the State of México in 1912 a quake of 6.9 on the Richter scale caused a rockfall in the Acambay municipality, and several dwellings were affected and there were some 700 deaths (Gobierno del Estado de México, 1998). In February 2010, intense rains caused mass movement processes in a section of the Toluca-Temascaltepec highway in the Mesón Viejo community, damaging 20 cars and killing 10 people (*La Jornada*, 6 February 2010).

Temoaya municipality in the State of México, in the foothills of the Sierra de Las Cruces (Figure 1), is under considerable anthropogenic pressure owing to deforestation, mining, crop and livestock production, logging on the slopes to build houses, and roads. This has led to landslides and the potential for damage to dwellings, roads and agricultural lands. The present study assesses the threat of soil slides in this municipality with the aim of producing information that may contribute to the appropriate management of the region and to decision making in relation to disaster prevention.

Specifically, the present article aims to analyse the zones susceptible to shallow soil translational landslides (SSTLs) in Temoaya municipality, the State of México, by multicriteria analysis of interrelationships between variables such as gradient, geology, geomorphological units, land use, roads and morphometry.

Assessment of mass movement processes

Where many factors are important in the occurrence of a hazard, analysis involves complex investigations (Van Westen, 1994), and can be expressed through cartography, i.e. production of maps of various kinds of zoning, such as those of susceptible areas, which can serve as a basis for mitigation, planning and decision making.

The methods proposed for assessing mass movement processes form two main groups: qualitative (direct) and quantitative (indirect), (Soeters and Van Westen, 1996). The qualitative methods involve direct assessment of the mass movements, on the basis of specialist knowledge; they include *inventory of slope processes* and *heuristic analysis* (*geomorphological analysis and qualitative combination of maps*). The quantitative methods consist of mapping a large number of parameters that are subsequently analysed statistically, for example by *bivariate* and *multivariate statistical analysis*, which are based on the relationship of natural determinant factors to the distribution of existing landslides (Clerici, 2002:48), and also their relationship to the density of landslides, through the superposition of layers. The *deterministic methods* combine the parameters of the maps with calculations of slope stability (geotechnical data); the *probabilistic method* determines the probability or recurrence of a movement in a given period of time; finally, *evaluation of slope instability* calculates geomechanical and stability parameters (Aleotti and Chowdhury, 1999) in order to deduce the security factor. Most of the studies on mass movement processes (mainly landslides) have used quantitative methods, or have adapted quantitative methods by incorporating qualitative elements with the aim of comparing results and giving an objective approximation of the susceptibility to these phenomena.

The multicriteria method

Multicriteria assessment is a semi-quantitative method that combines techniques oriented towards assisting in decision making; it consists of data management and processing, and ranges from simple superposition of thematic maps for the identification of areas with specific conditions to the use of mathematical operators and integrated numerical models for prediction of the dynamics of natural phenomena (López, 2005).

In the geographical context it has been applied in the assessment of changes in land use and soil cover, conservation of natural resources, evaluation of natural hazards, and disaster prevention (Chen *et al.*, 2001; Aceves *et al.*, 2006, Komac 2006; Castellanos *et al.*, 2008; Muñíz, 2009). In the case of slope instability, multicriteria analysis quantifies the judgments and opinions of the specialists involved regarding the relative importance of each of the criteria that they use for identifying zones of susceptibility to landslides.

The multicriteria method consists in organizing the representation of the relationship of the criteria and the alternatives in a matrix, where the former occupy the principal column and the latter occupy the principal row (Voogd, 1983, in Barredo 1996). This matrix can have names such as decision matrix, effectivity matrix, project-effect matrix or evaluation matrix. Subsequently, values designated criteria scores are assigned within the matrix. They represent the value or level of desirability that each alternative has obtained in each criterion. This phase is important because the values assigned to the alternatives, frequently in Geographic Information Systems (GISs), are determined by a nominal scale; so the responsibility of quantitative values rests in the planning team, in each of the categories of each criterion.

The relative value of each criterion must be considered according to the type of assessment to be made; if there is a distinct hierarchy, a specific value must be assigned according to its relevance, i.e. a weight. This is through sounding the opinion of experts in the field, through consulting the literature and mainly with reference to the characteristics of the study area itself. The so-called pairwise comparison matrix (Saaty, 1997 in Aceves *et al.*, 2006:23) establishes a scoring of categories (a,b,c,d...) of the variable with the help of the scale of measurement established by allocating value judgments; it is of continuous type (ratios or proportion), (Saaty 1977, 1980; Table 1).

Calculation of the *eigenvector* is important because it serves to derive the weight that is to be assigned to each value; it represents the order of priority of the factors (rows). The maximum *eigenvector* is a measure of the consistency of the judgments; it is acquired from the quotient between each value and the value of the sum of each column; then the normalized values are summed by rows, so that it is obtained. It is normalized with the division of each of the values of this vector into the number of factors, and in this way the principal normalized *eigenvector* represents the weight of each factor.

STUDY AREA

The municipality of Temoaya lies in the eastern section of the State of México, 20 km from the city of Toluca at 19º 28' 50" N, 99º 36' 12" W (Figure 1),

Table 1. Scale for assessing the relative importance of the criteria used

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	¼	1/3	1/2	1	2	3	4	5	6	7	8	9
Extremely		Strongly		Moderately		Slightly		Equal	Slightly		Moderately		Strongly		Extremely	
LESS IMPORTANT										MORE IMPORTANT						

where
1/9 = extremely less important
1 = equally important
9 = extremely more important

at 2 680 m above sea level. It borders on the following municipalities: Jiquipilco and Nicolás Romero to the north; Toluca and Otzolotepec to the south; Isidro Fabela, Jilotzingo and Otzolotepec to the east; and Ixtlahuaca and Almoloya de Juárez to the west. Its area, 199.63 km^2, represents 0.88% of the area of the State of México, with an altitude that ranges from 2 600 to 3 300 m asl (Gobierno del Estado de México, 2003). There are 67 towns and a population of 90 010 (INEGI, 2010).

Owing to the altitudinal range (2600-3300 m asl), the climate varies (Figure 2). Three types predominate. In the highest parts, the climate is Cw(w2)(w)b´(i´)g´, temperate sub-humid with summer rains, a P/T quotient >55.3 and a winter precipitation that is <5% of the annual total. The media temperature mean of the coldest month oscillates between -3° and 18° C, the temperature of four months or more higher than 10° C. The summer (semi-cold) is long and with a thermal oscillation of 5- 7° C. The month with the highest mean temperature is after the summer solstice. The second climate type covers most of the municipality and is Cw(w2)(w)b(i´)g, which is temperate, sub-humid, with summer rains, a P/T quotient >55.3, and a winter precipitation that is <5% of the annual total. The mean annual temperature varies between 12° and 18° C, temperatures of the coldest month are between -3° and 18° C, and the mean temperature of the hottest month is <22°. The summer is long with a thermal oscillation of 5-7° C. The month with the highest mean tem-

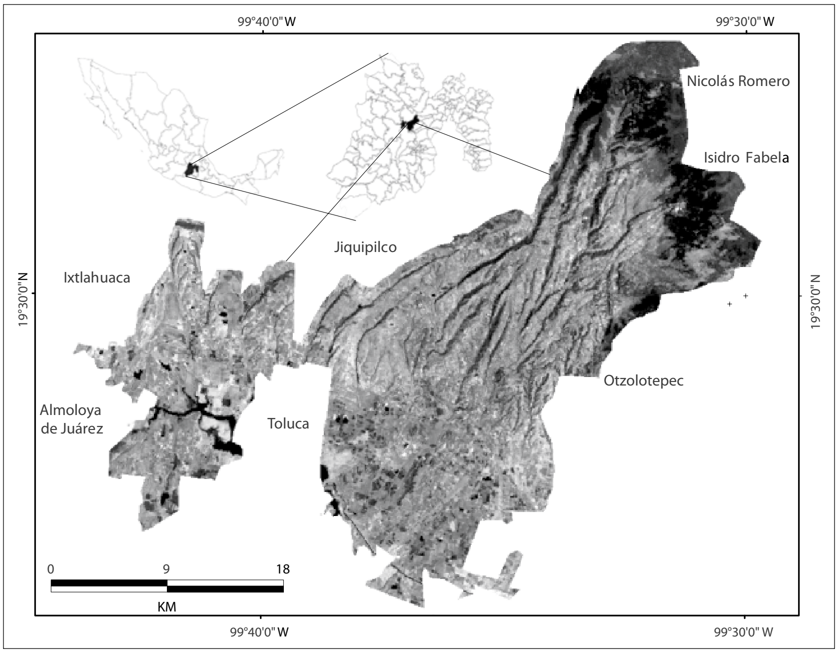

Figure 1. Location of the study area, the municipality of Temoaya, State of Mexico.

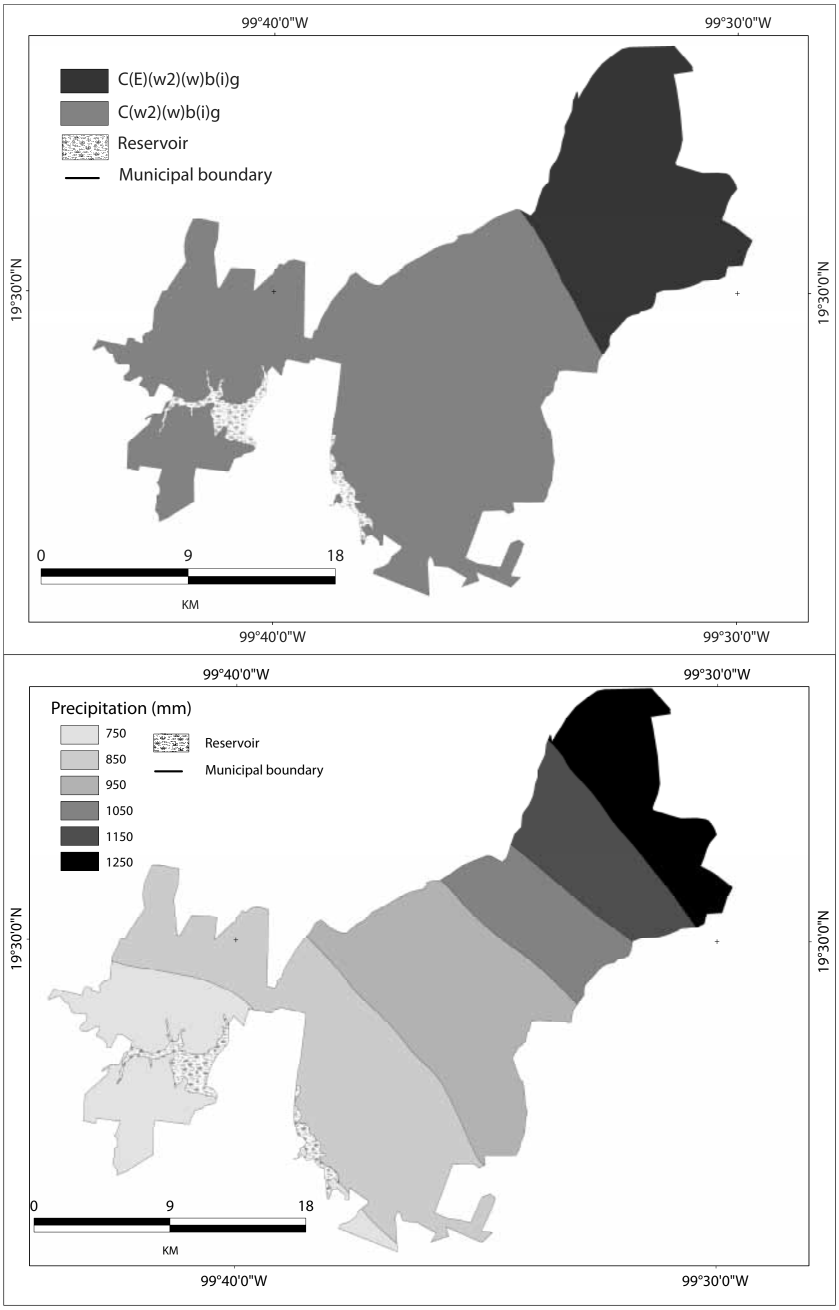

Figure 2. A. Climate distribution map. B. Map showing isohyets

perature occurs before the summer solstice. The third climate type, Cw(w2)(w)big, is temperate, sub-humid with summer rains, a P/T quotient >55.3, and a winter precipitation that is <5% of the annual total. The media mean temperature of the coldest month varies between -3° and 18° C, the temperature of the hottest month <22° C. The summer is long (semi-cold), with a 5° thermal oscillation. The month with the highest mean temperature occurs before the summer solstice, and occurs near the municipal capital. The distribution of the mean annual temperatures oscillates between 4° and 10.3° C in zones with an altitude greater than 3 000 m asl; for altitudes of 2 600-

3 000 m asl it is between 12.4° and 13.4° C, and on the plain between 13.5 and 14.8° C. During winter the mean monthly temperatures oscillate between 2.4° and 12.1° C; the lowest occur in the high part of the Sierra de Las Cruces. In the summer months the mean monthly temperatures are in the range 4.5- 16.6° C (Alvarado, 2008). The most abundant rains fall in summer and autumn. In summer, the mean precipitation values vary between 246 and 126 mm/month; the highest occur in the zones at highest altitude. The winter rains are low as a result of the cold fronts, and range from 6 to 22 mm/month. According to Alvarado (2008), the maximum rainfall per 24 h occurs during the months of July to December, while in summer the precipitation values are 21.5 mm to 40.4 mm/month and, unlike winter, the values oscillate by between 3.8 and 10.5 mm.

The municipality of Temoaya has nine soil types (Figure 3). The vertisols are dark and fine, with 30% or more clay, which is a product of accumulation; these are highly productive soils (Sotelo *et al.*, 2008:26). The luvisols are reddish varying to pale and with a high clay content. Both these soils are distributed in the southern part of the municipality. The phaeozems are dark with a high organic matter content, and they occur in the south-west, mainly in ravines and mountain ranges. The planosols are formed by alluvial deposits, on flat terrain or on gentle slopes. The andosols are of volcanic origin, dark and of medium texture, susceptible to erosion, and are found in the east. The cambisols form a dark superficial layer of 25 cm thickness, with a high organic matter content, but poor in bases or nutrients (Ca, Mg, K, Na) and are very susceptible to erosion even in the presence of vegetation (FAO, 2006); in the study area there are two types of cambisol in particular, the eutric and the chromic, occurring on the sides of some ravines. The fluvisols are young soils that develop in alluvial deposits and to a lesser extent in lacustrine deposits; in this municipality they occupy only a small area in the extreme north-west, near the reservoir. The lithosols occur on all types of rock and in all climates; they are shallow, of no more than 10 cm, are easily eroded and generally sandy, although they can have a clayey texture; they are restricted to south of the municipal capital.

The predominant vegetation is temperate forest. From 3 000 m asl it is a pine-sacred fir forest, mainly of *Pinus hartwegii, Abies religiosa/Pinus hartwegii, Abies religiosa, Abies religiosa/Garrya lau-*

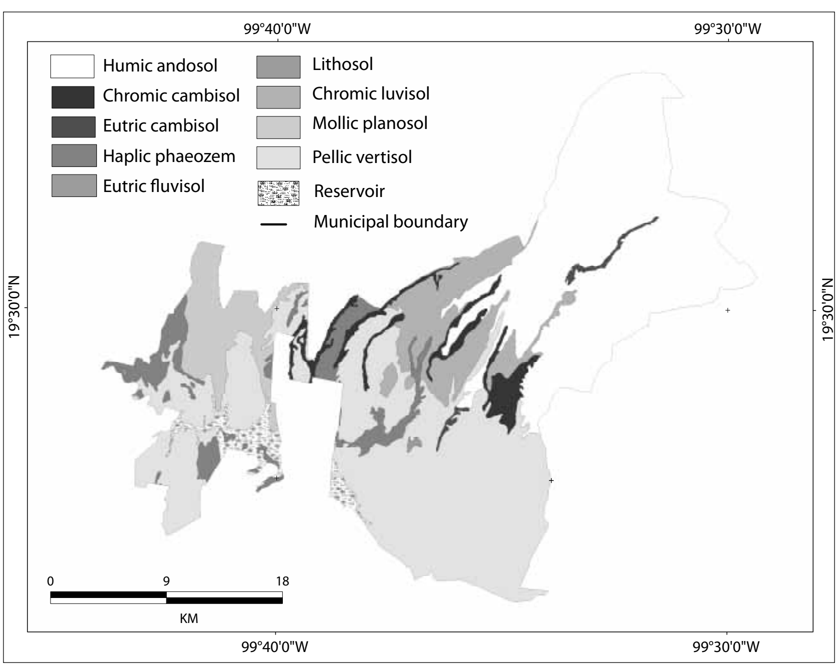

Figure 3. Distribution of soils in the municipality of Temoaya, State of Mexico.

rifolia, Garrya laurifolia. There are some deforested areas now occupied by induced pasture. Between 2 700 and 2 900 m asl there is oak forest, particularly *Quercus crassipes, Quercus texcocana* and *Quercus microphylla*; however, this is mixed with agricultural land and settlements (García Romero, 2002:22).

The municipality lies on the western slopes of the Sierra de Las Cruces and on part of the plain. The Sierra de Las Cruces is elongated towards the NNW with a maximum altitude of 3800 m asl, and rises 1 500 m high from the base to the summit; it forms part of the Trans-Mexican Volcanic Belt. The sierra is the product of tectonics and the N-S, E-W alignment of volcanoes as well as of exogenous processes, mainly fluvial, which have modified its morphology. The municipality includes a series of volcanoes, domes, craters and associated lava flows of andesitic and dacitic composition (Schlaepfer, 1968); the foothills are formed from volcaniclastic deposits (Mooser *et al.*, 1996, where they are termed the Tarango formation) characterized by flows of ash, pyroclastic flows of blocks and ash, and flows of pumice. The alluvial plain, formed from Quaternary alluvial and lacustrine deposits, lies mainly in the south-west of the region (Figure 4).

SLOPE INSTABILITY IN HE MUNICIPALITY OF TEMOAYA, STATE OF MEXICO

Mass movement processes have been classified according to diverse criteria. One of the classifications most widely accepted internationally is that developed by the European Programme on Climatology and Natural Hazards (EPOCH), which is based on the mechanism of movement: falls, topples, slides, lateral expansions, flows and complex movements (Alcántara, 2000b). For the study area, there is neither historical nor cartographic information regarding mass movement processes, so 33 sites with this type of process were recorded in the field with the aid of a global positioning system (GPS), (Figure 5). Of these, thirty are shallow soil translational landslides (SSTLs), two are rock falls and one is a complex movement resulting from a combination of falls and a flow of debris. Given that the SSTLs are the most frequent and that their effects on communication routes, dwellings and arable land are of such importance, the present study, using multicriteria analysis, focussed on them.

SSTLs occur in three types of deposits: volcanic ashes and pyroclastic flows, alluvial material and conglomerates. However, field observations showed that most are volcanic ashes and pyroclastic flows.

In the towns of Temoaya and Pothé, there are morphological features of two SSTLs on a straight

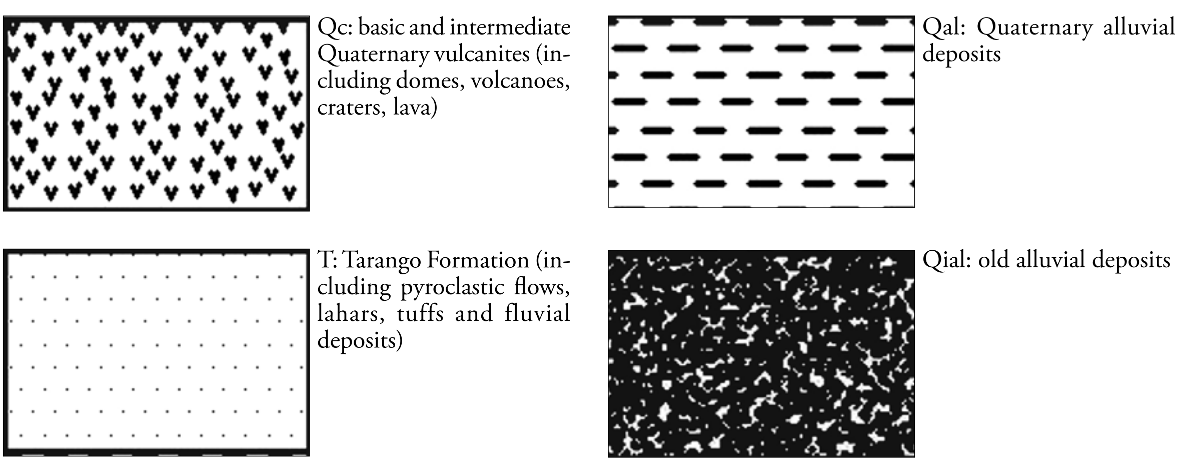

Figure 4. Principal geological units in the municipality of Temoaya, State of Mexico.

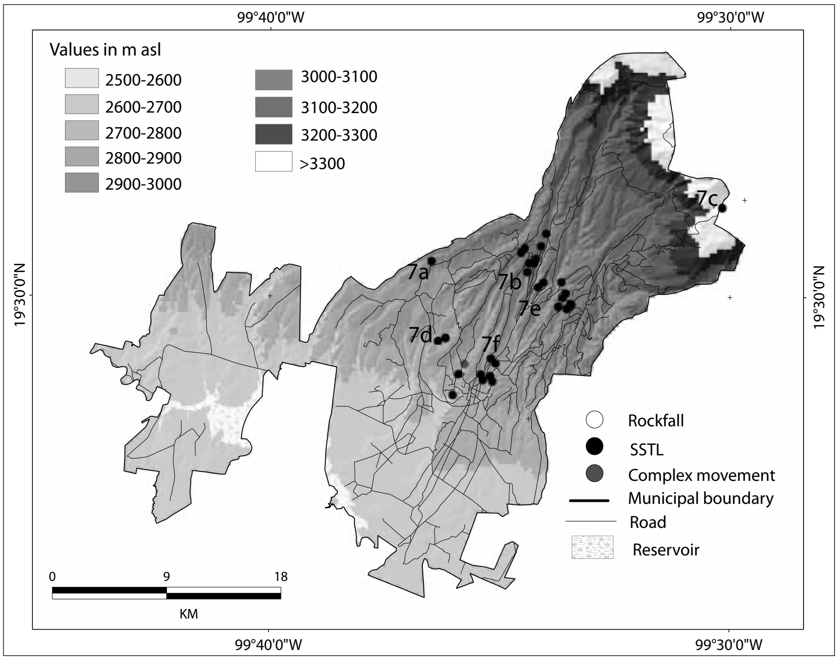

Figure 5. Distribution of landslides in the municipality of Temoaya, State of Mexico. Numbers with letters indicate mines and roads with characteristics of landslides.

west-facing slope with a 45° gradient, associated with a normal SW-NE fault (Mooser *et al*., 1996), oak-pine vegetation and a pellic vertisol, medium-texture eutric cambisol and medium-texture humic andosol (Figure 6a), in volcaniclastic materials, mainly ashes and pyroclastic flows, there are natural terraces and leaning trees.

In Cerrito del Panal, near the boundary with the municipality of Jijipilco, there is a SSTL on the slope of a ravine with a gradient of approximately 45° and gully development; this is on a fine-textured chromic luvisol (Figure 6b) and deposits formed by grey pyroclastic flows of ash (Figure 7a). In Jijipilco El Viejo, six SSTLs were recorded on slopes of river valleys occupied by agriculture, housing and schools (Figure 6c), on a medium-texture eutric cambisol – ochric andosol soil), the types of deposits on which these movements arise are mainly ashes and pyroclastic flows (Figure 7b).

On the state highway near the Otomí Ceremonial Centre, there is a translational landslide of debris on a slope of the Jilotzingo crater on grey pyroclastic deposits (Figure 7c). Near the town of San Pedro Arriba, there are five SSTLs on ash, whose source has not been identified nor reported in the literature.

On the alluvial and conglomerate material there are 15 SSTLs. Two are on alluvial material (sands) in Loma Alta (Figure 7d), and one on the side of a ravine with a 45° gradient that affects cambisol soils with medium-texture ochric andosol and fine chromic luvisol. Another occurs on a concave slope with a 45° gradient and a medium-texture ochric andosol – eutric cambisol soil, with an oak forest (Figure 6d), while on fluvial materials there are 13 SSTLs; in the town of Enthavi, 2nd Section, there are 6. Of these, two are of special interest as follows. One is on agricultural land with dwellings, on a concave, south-facing slope with a mean gradient of 30°; evidence of movement lies in slightly leaning trees, with an undulating surface at the upper edge, and fractures or ruptures in the asphalt of the road (Figures 6e, 7e). The other is on a steep, south-facing slope with a gradient of more than 45°, associated with a normal east-west fault; it is an elongate, deforested area with a very few oak trees and some shrubs; because of this landslide, the local inhabitants have had to protect against damage by amassing sandbags along the edge of the road, although these are constantly collapsing.

Lastly, in El Laurel and Tlaltenango (Figure 7f) there are seven processes with characteristics

Figure 6. Topographic evidence of landslides: a) Temoaya; b) boundary with the municipality of Jijipilco; c) Jijipilco 2nd Section (cutting in the slope for construction of a school; upper part, an escarpment of not more than 1 m height); d) south-east of Enthavi 2nd Section, escarpments showing movement; e) Enthavi 2nd Section.

similar to the zone at Enthavi, which affect mainly agriculture and human settlements, three of them being in Tlaltenango on the 45° side of a ravine.

TOOLS AND METHODS

Materials and tools

Cartography was based on the topographical and geological maps E14A38, A14A27 and E14A28, scale 1:50 000 (INEGI 1996, 1998 and 1999), as well as a multispectral (6 bands) Landsat ETM satellite image from the year 2000, path 26, row 047, resolution 30 m, projection UTM, datum WGS 84, zone 14 north. A zone of 1151 columns and 953 lines was selected. The image was processed with the IDRISI ANDES program, which served to generate the map of land use. Generation of vectorial information (geomorphological units, faults, land use and roads) and data rastering used the ArcMap 9.3 program.

Methods

Production of the base maps

Map of land use

Since land use is held to be a fundamental element in analysing danger from landslides, a land use map was produced. This was developed from a Landsat ETM 2000 satellite image, on the IDRIS ANDES platform. On the basis of the composition

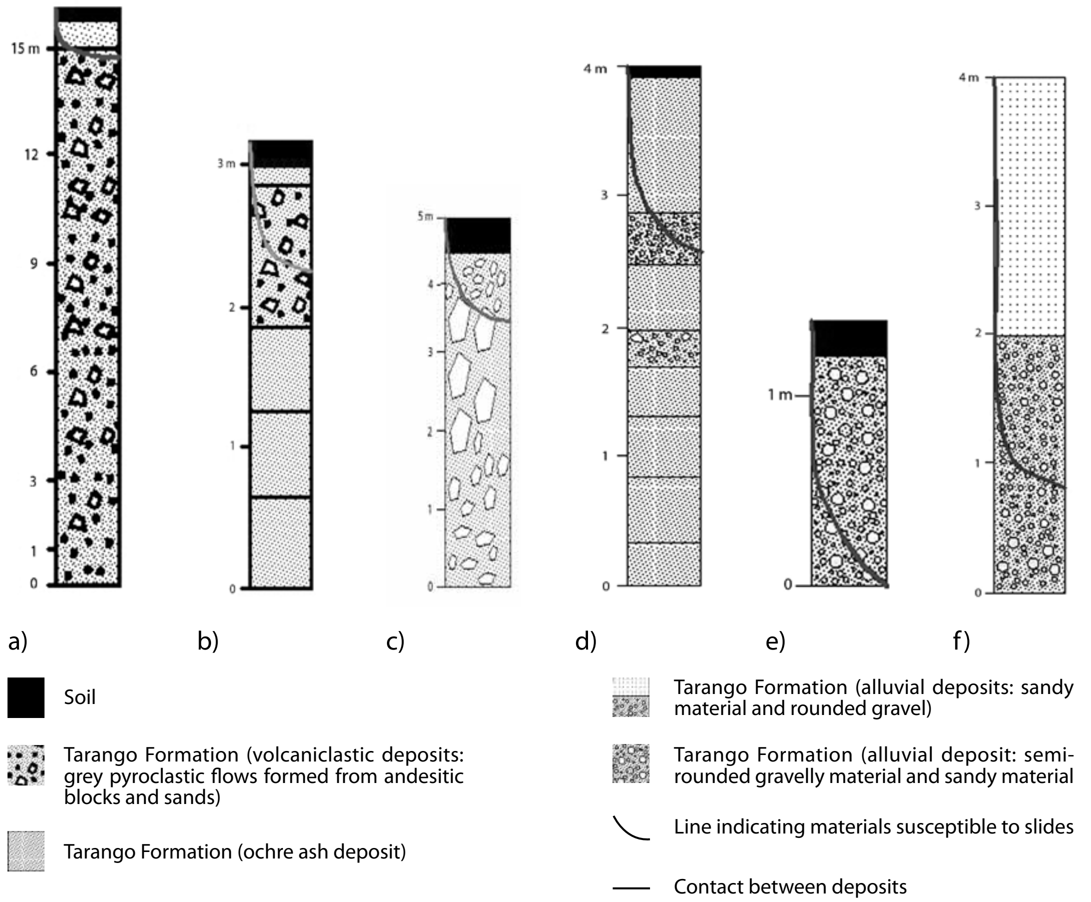

Figure 7. Profiles from mines and roads where there are characteristics of landslides: in volcaniclastic materials (ashes and pyroclastic flows) a) Cerrito del Panal, b) Jijipilco El Viejo, c) Otomí Ceremonial Centre; in alluvial materials, d) Loma Alta, e) Enthavi , f) Tlaltenango.

of bands 3, 4 and 5, the respective categories of land use were established (rain-fed agriculture, irrigated agriculture, dense forest, semi-open forest, pasture, settlements, water bodies and erosion). Preparatory sites were established, defined as areas of interest, with the aim of grouping similar features that identified each use in order to be able to generate the classification. Spectral signatures were also obtained; these indicate the reflectance that each surface has. Finally, the image was reclassified by the algorithm *maximum likelihood classification*; this process was repeated various times with the aim that the result would coincide with reality, and then this was exported to the ArcMap platform, version 9.3.

Geomorphological maps

- ***a) Geomorphological units.*** The topographical and geological maps were analysed in conjunction with the digital model of elevations. The main units of relief were determined with the help of field observations.
- ***b) Morphometry.*** Three maps were produced: density of dissection, energy of the relief, and depth of dissection. Cartography was based on the criteria of Lugo (1988) in conjunction with GISs, with the use of ArcMap 9.3.

Multicriteria evaluation

The core method of analysing susceptibility to landslides was that of multicriteria analysis; this allows the use of both quantitative and qualitative information, starting by assigning levels of importance or weight to certain criteria that can be placed in a hierarchy on the basis of various opinions, mainly those of experts on the topic and on the study area. Its advantage is that it does not necessarily require complex and specialized processes, since once the basic information has been obtained its development is rapid, inexpensive, flexible and practical with the use of GIS.

Variables

Gradient. The map of gradients was obtained by generation of the digital model of elevations with a 30 m resolution, based on the contour lines produced by INEGI, using ArcMap version 9.3. The lack of detailed topographical information in the study area precludes work at a higher resolution. Five classes were used, 0°- 5°, 5°- 15°, 15°- 25°, 25°- 35°, 35°- 60°, with the aim of homogenizing the categories employed in all the maps that were used as input for the multicriteria method.

Lithology. This used the geological map (scale 1:50 000) from Mooser *et al.* (1996) (Figure 8A).

Faults and discontinuities. An important control in slope movement is the presence of faults and areas of weakness, and of discontinuities. Given that there have been no specific studies of the role of faults or discontinuities in the occurrence of SSTLs in this area, only their presence or absence was registered.

Geomorphological unit. The map of geomorphological units shows regions homogeneous in relief form and type of rock. It was produced at a scale of 1:50 000 and six geomorphological units are defined: mountain, higher foothills, medium foothills, low foothills, upper plain and lower plain (Figure 8B).

Land use. The categories used in the map are rain-fed agriculture, eroded zones, semi-open forest, dense forest, pasture and irrigated agriculture (Figure 8C).

Communication routes. With the aim of analysing the potential influence of the roads in the study area a 20 m buffer was considered, since this is a distance greater than that occupied by the width of the road (4 m each lane) and of the hard shoulder (2 m), (Figure 8D).

Application of the method

The initial phase involved construction of a *pairwise comparison matrix*. First, the factors to be analysed were decided on the basis of criteria established by specialists on this topic. They were then ordered according to the importance that each represents in the generation of landslides in the municipality, following the scale of relative importance proposed by Saaty (1977). Comparison of the criteria or factors is shown in Table 2a. The weight of each criterion was obtained (Table 2b) by normalizing the values and obtaining the principal *eigenvector*.

Production of the map of susceptibility used ArcMap version 9.3, where the weight of each factor indicated its level of importance, for use in the algebraic procedure in the program. The parameters of each factor were classified into five categories on the basis of their influence on the instability: very high, high, medium, low and very low. Then these underwent the same procedure as did the factors, to obtain the weight of each parameter; these were added to the table of attributes of each of the vectorial layers. Then it was reclassified on the basis of the five above-mentioned categories, with the determination of the weights (Table 3). The vectorial information (maps) was transformed to raster format with the tool Raster Calculator in order to sum the layers of information, and thence to assign susceptibility values (very high, high, medium, low and very low).

RESULTS AND CONCLUSIONS

According to the observations and field records in the study area there are 33 mass movement processes, of which 30 are SSTLs, one a debris slide and two rockfalls. Of the landslides recorded, 26 (80%) are on the sides of ravines, with an average gradient of 35°, in volcaniclastic deposits (pyroclastic flows of blocks, ash and pumice), and shallow soils with

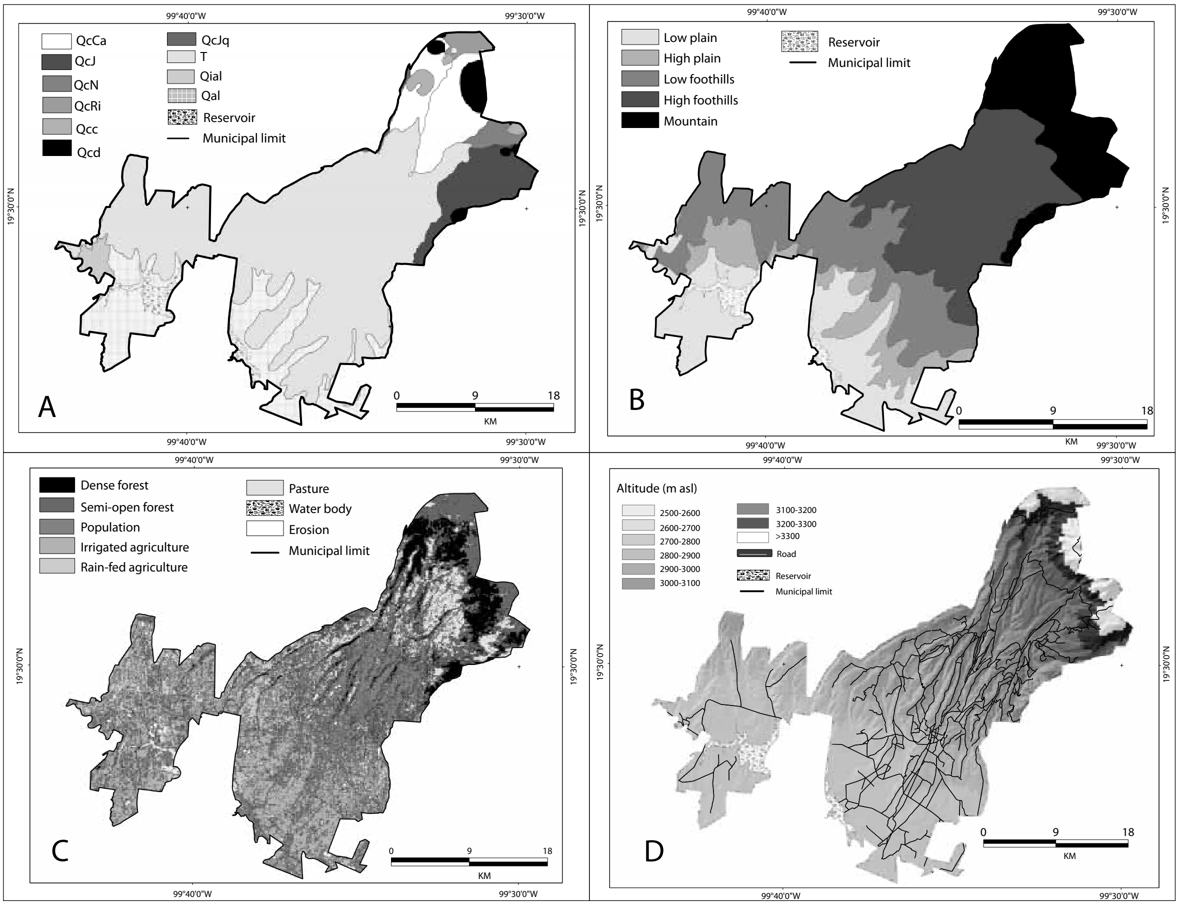

Figure 8. A. Geological map (QcCa: Sierra de Las Cruces, Catedral crater, QcJ: Sierra de Las Cruces, Jilotzingo crater, QcN: Sierra de Las Cruces, Navajas crater, QcRi: Sierra de Las Cruces, old windmill, Qcc: volcanic cone, Qcd: dome, T: Tarango Formation, Qial: old alluvial deposits, Qal: Quaternary alluvial deposits). B. Geomorphological units. C. Land use map of the municipality of Temoaya, State of México. D. Map of roads (20 m buffer).

sandy and limey texture, with the land being used for agriculture and dwellings.

Multicriteria analysis led to production of a map, scale 1:50 000, of susceptibility to landslides for the municipality of Temoaya, State of México (Figure 9). Susceptibility is very high in 15% of the municipality, with conditions favourable for the occurrence of landslides. These areas are in the high foothills, on the sides of ravines, with gradients greater than 30°, in materials mainly of pyroclastic flows, volcanic ash, and flows of pumice and conglomerates; with the additional presence of faults, human settlements and areas of cultivation, there are 19 SSTLs in this zone.

Susceptibility is high in 35 % of the area; this includes the high foothills in which the gradients range from 25° to 35°, and crops and pastures predominate. Here, 11 movements were recorded. Both in this zone of high and that of very high susceptibility, the morphometric values are similar: depth of dissection 200-270 m, density of dissection 2.5-4.5 km/km^2 and energy of the relief 100-400 m.

Susceptibility is medium in 30% of the area; most of this is in the mountainous zone, formed by slopes of domes that form the crater La Catedral in materials of andesitic lavas, pyroclastic flows and volcanic ashes, and with gradients greater than 35°. Dense coniferous forest predominates, and only one SSTL and two rockfalls are recorded, which indicates that the vegetation in this zone has been a factor inhibiting the generation of these processes.

Table 2. Pairwise comparison matrix: a. Comparison of relative importance between pairs among the parameters; b. Obtaining the principal eigenvector for determining the weight of each criterion

a.

Criterion (j)	Gradient	Materials	Faults	Geomorphological unit	Land use	Roads
Gradient	1	1/4	3	3	4	5
Materials	4	1	4	3	5	3
Faults	1/3	1/4	1	4	2	1/3
Geomorphological unit	1/3	1/3	1/4	1	1/2	1/2
Land use	1/4	1/5	1/2	2	1	1/2
Roads	1/5	1/3	3	2	2	1
Normalization of the values						
Criterion (j)	Gradient	Materials	Faults	Geomorphological unit	Land use	Roads
Gradient	1	0.2	3	3	4	5
Materials	4	1	4	3	5	3
Faults	0.3	0.2	1	4	2	0.33
Geomorphological unit	0.3	0.3	0.2	1	0.5	0.5
Land use	0.2	0.2	0.5	2	1	0.5
Roads	0.2	0.3	3	2	1	1
Total	6.1	2.3	11.7	15	13.5	10.3

b.

Criterion (j)	Gradient	Materials	Faults	Geomorphological unit	Land use	Roads	Principal eigenvector	Weight
Gradient	0.1	0.10	0.2	0.2	0.2	0.4	2.3	0.3
Materials	0.6	0.4	0.34	0.2	0.3	0.2	2.2	0.3
Faults	0.05	0.1	0.08	0.26	0.1	0.03	0.6	0.1
Geomorphological unit	0.05	0.1	0.02	0.06	0.03	0.04	0.3	0.05
Land use	0.04	0.08	0.04	0.1	0.07	0.04	0.4	0.06
Roads	0.03	0.1	0.02	0.1	0.07	0.09	0.4	0.07

Susceptibility is low in 15%, covering the low foothills and the zone of domes. It is very low in only 5%, on the low foothills and the plains where the gradients are less than 20°, in mainly alluvial and conglomerate material and in large part used for agriculture.

That 50% of the area is highly or very highly susceptible indicates that conditions are favourable for the occurrence of SSTLs. This shows that slope instability in the municipality of Temoaya is controlled by the character of the volcaniclastic deposits, specifically pyroclastic flows of blocks, ash and pumice; these are permeable materials favouring infiltration, and if the subjacent material is impermeable or of lower permeability water accumulates on the subhorizontal lithological contact and transforms into a flow that leads to the instability of the overlying material.

Although the map represents the spatial distribution of zones susceptible to SSTLs, this is not

Table 3

FACTOR	SUSCEPTIBILITY TO SHALLOW SOIL TRANSLATIONAL LANDSLIDES (SSTLs)				
	Very low	Low	Medium	High	Very high
Gradient	0-5°	5° - 15°	15° - 25°	25 ° 35°	35°-45°
Lithology	Alluvial deposits	lavas	Monte Alto crater	La Catedral crater	Pyroclastic flows, flows of pumices, ash and conglomerates
Faults	None	N.A	N.A	N.A	Present
Geomorphological unit	Low plain	High plain	Low foothills	Mountain	High and medium foothills
Land use	Irrigated agriculture	Dense forest	Semi-open forest, pasture and erosion	Population	Rain-fed agriculture
Distance from roads (m) *N.A. Not applicable	20	N.A	N.A	N.A	50

intended to be a tool for identifying other types of mass movement processes such as rockfalls, since each type of process is the result of particular mechanisms closely related to the materials involved. For this reason, the map shows zones of steep gradient with rocky outcrops that are not identified as of high or very high susceptibility to SSTLs, but which evidently are areas very susceptible to the occurrence of falls or topples.

Most landslides that occur in the municipality of Temoaya, State of Mexico, have affected roads, both paved and unpaved, thereby impeding the free passage of vehicles and people. In addition, there have been effects in areas of cultivation, principally of maize, and in zones of coniferous forest (>3 000 m asl) and oak forest (2 700-3 000 m asl). With respect to the damage to dwellings, there is cracking in walls in buildings near the municipal capital, on the low foothills. One of the landslides in this area involves fluvial deposits on the sides of a ravine.

Multicriteria analysis proved very useful in zoning susceptibility to SSTLs, owing to its accessibility and ease of information management, since it does not require complex processes or high costs, and can be applied via the use of GIS. Specifically, when applied to slope instability it allows general analyses at a regional scale; this can lead to identification of critical zones that will require detailed attention. This can be of great importance to the civil protection authorities, since it can supply information to assist in mitigating and anticipating possible effects on the infrastructure, the centres of human habitation and economic activities. It is crucial to make known these results to the populations centred on the areas of high susceptibility so that they have the option of translocating or of formulating non-structural strategies; the knowledge of mass movement processes and of the underlying danger will stimulate organization of positive actions during events of intense or continuous precipitation, since these are the principal trigger of instability in the study area.

In various parts of the world innumerable human settlements are in zones at potential risk of landslides or have been affected by slope instability. Nevertheless, mitigation measures are frequently not undertaken because of the costs associated with the extent of the unstable area in terms of the area affected. For this reason, it is important to use tools that contribute to the diminution of the effects on the population, by the simple identification of potentially unstable sites that can be made known to the populations exposed to them; these sites can be

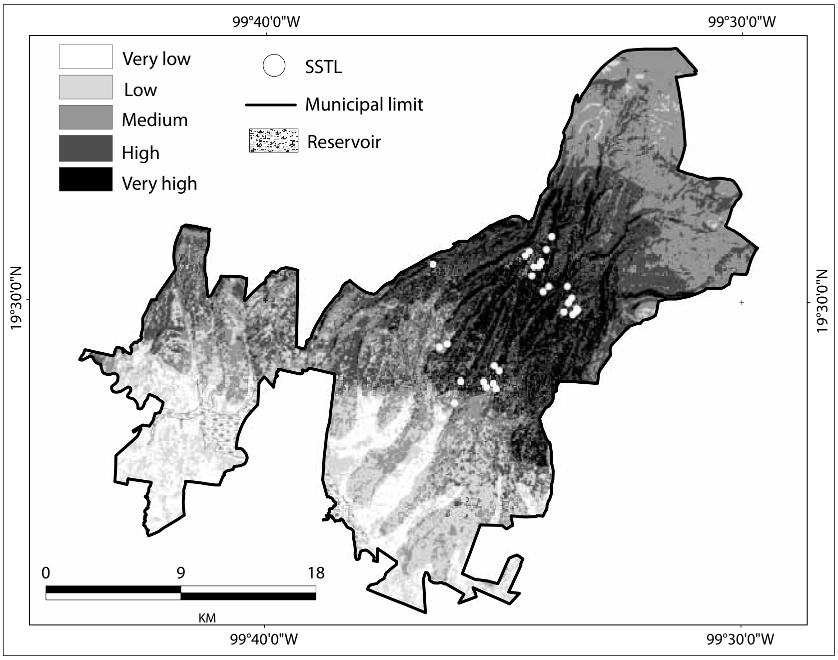

Figure 9. Map of susceptibility to landslides in the municipality of Temoaya, State of Mexico.

expressed in an appropriate manner in maps of zones susceptible to mass movement processes, or more specifically to particular processes such as SSTLs.

A fundamental aspect of disaster prevention must be emphasized. Exact knowledge of the hazards is very important for understanding the phenomenon *per se* and its potential impact; nevertheless, the degree of vulnerability of the population is what determines the magnitude of the disaster and the time required for recovery and mitigation. Additionally, disaster prevention is strongly related to the diminution of risk, and this in its turn with the reduction of vulnerability and an increase in the resilience of the communities (Alcántara, 2010).

The present results illustrate the usefulness of maps of susceptibility in formulating strategies for prevention of disasters associated with slope instability –or of other hazards– in areas where specific analyses are not feasible because of lack of time or human resources or materials. However, a second pass that is essential and of great importance in disaster prevention is the analysis of vulnerability of the communities exposed, because only from the understanding of the interactions between hazard and vulnerability is it possible to understand the risk; this last is a fundamental ingredient for the management and prevention of disasters.

RECOMMENDATIONS

Multicriteria analysis represents a valuable tool for identifying zones susceptible to slope instability. However, to perform this type of work it is particularly desirable to have detailed field observations, base cartography – in particular detailed topography – and inputs of high-resolution satellite images that allow high-precision identification and assessment of zones that are potentially unstable. It is also highly recommended that the properties of the materials involved be studied, as well as the mechanisms that trigger instability, with the aim of being able to assess specific critical sites.

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