Slope instability in Nicaragua triggered by Hurricane Mitch: distribution of shallow mass movements

Rosana Menéndez-Duarte · Jorge Marquínez · Graziella Devoli

Abstract The heavy rains associated with Hurricane Mitch triggered off a number of slope instability processes in several Central American countries. Different instability processes have been acknowledged for the various mountainous regions of Nicaragua. An enormous movement of the Casita Volcano slopes resulted in numerous deaths and some deep movements have been reactivated. On the other hand, numerous shallow mass movements and debris flows have given rise to great material loss throughout a large part of Nicaraguan mountains. Mapping the shallow mass movements in an area of Central Nicaragua clearly reveals the close ties between their distribution and some geomorphological factors. A susceptibility model has been constructed for shallow mass movements based on field mapping of the shallow mass movement distribution, the geomorphological map as well as the digital slope and accumulated flow models. A logistical regression analysis was applied. The study area has been categorized into three classes of relative landslide susceptibility. Given that phenomena of this nature occur much more frequently in the high susceptibility class, 94% of the shallow mass movements that have been used to test the model are in the high and medium susceptibility classes . The geological and geomorphological conditions of the study area are representative of a large sector of the central Nicaraguan region. Consequently, the methodology followed in this paper is deemed to constitute a useful tool, both regarding the design of new infrastructures, and as a guide to the urban development of the area.

Keywords Hurricane Mitch · Slope instability · Shallow mass movements · Susceptibility model · Logistic regression

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Introduction

In some cases, as is the case with regard to the exceptionally high rainfall that is associated with Hurricane Mitch, the factor that triggered off the development of slope instabilities is very clear. This rainfall laid low the whole of Central America between the 28th and 31st of October 1998. The increase in mass movements linked to heavy rainfall has been sufficiently well-documented around the world (Pasuto and Silvano 1998; Ayalew 1999; Corominas and Moya 1999; Crozier 1999; Zêzere and others 1999), and is especially frequent in tropical areas (Larsen and Torres-Sánchez 1992; 1998; Ngecu and Mathu 1999; Dai and others 2001). Unfortunately, however, in Central America and other regions of similar climatic conditions, one can only expect that a situation similar to that experienced in October 1998 will repeat itself.

The greatest prevention possible for a particular area is to identify the conditioning factors that have given rise to the instabilities, and on the basis of the regional knowledge of these factors and the pinpointing of the instabilities in question, to establish a zoning of the areas of the territory in accordance with the documentation of said instabilities (Soeters and van Westen 1996). A susceptibility model, in which the areas most affected by mass movements are identified, is an essential document for guiding urban planning in these regions. Furthermore, such a document is also essential to the optimization of any effort invested in providing for possible corrective measures.

Even though it is not possible to come to a detailed understanding of all of the factors determining the development of instabilities in a particular region, prior

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knowledge of the processes to be tackled, as well as on-the-ground observations, enable us to postulate a series of factors that would be considered to be the most important. Generally, the geological, geomorphological and relief factors are deemed to be the most relevant determinants in the development of slope instability (Varnes 1984; Pachauri and others 1998). By using this data we can construct models or zones that are susceptible to slope instabilities. Currently, this method is always reliant on the use of a geographical information system (GIS) of various thematic layers and digital terrain models (DTM) (Guzzetti 1993; Carrara and others 1995; Chung and others 1995; van Westen and others 1997; Rowbotham and Dudycha 1998).

In this paper, a brief synthesis of the slope instability processes that are acknowledged to be the most important in each one of the Nicaraguan regions will be presented. From the point of view of the associated risk, or from the perspective of the possible preventive measures, the types of instabilities that are acknowledged are quite varied, and have very different meanings.

With respect to shallow landslides, which were the most frequent during the passage of Hurricane Mitch, a susceptibility model was constructed for a pilot area of the central mountainous region of Nicaragua. The geomorphological factors revealed in this model to be the largest determining factors in the distribution of instabilities, were mainly the presence and the type of surficial formation as well as the presence of some geomorphological elements such as mass movement scarps. Other factors that have been taken into account come from the digital elevation model (DEM) and together complete the information based on the geomorphological data.

Hurricane Mitch in Central America

The passage of Hurricane Mitch and the rainfall associated with it have given rise to important alterations in the physical and human geography of Central America. From the socio-economic standpoint, it is estimated that there will be a 30- to 50-year setback in the developmental forecast for some countries. The number of deaths caused by the hurricane have turned it into the second most deadly of its kind in history. As far as changes to the physical environment are concerned, these have been quite significant in some areas and permanent in others. The biggest changes that have come about affect the normal courses of the rivers and the development of numerous mass movements, of various types and dimensions, as well as the reactivation of pre-existent sliding masses.

Guatemala, El Salvador, Honduras, Nicaragua and Costa Rica are the countries that have been most directly affected by Hurricane Mitch. Given the path of the hurricane, Honduras, followed by Nicaragua, has been the most affected country. Overall, in all five countries, the estimated number of people affected—dead, missing, injured or displaced—is 10.9%. However, for the two latter countries, namely Honduras and Nicaragua, the amount of people affected rises to 24.2 and 19.5% respectively (according to UNICEF estimates). There were over 2,500 deaths in Nicaragua (according to WHO figures). Serious damage to infrastructures has also been registered in both of these countries. Road damage and blockage was mainly caused primarily by the destruction of bridges, and secondarily by slope instability processes.

The most affected regions of Nicaragua have been the western districts of Estelí, León, Matagalpa, Jinotega and Chinandega, along with some other areas close to Costa Rica. In Table 1, the daily rainfall values for seven stations situated in the west of the country are presented. These stations are identified in the map shown in Fig. 1a. The records for the last 10 days in October show extremely high values from the 28th to the 31st. In many cases, according to the reference values given in Table 2, the total daily rainfall exceeds the total average monthly rainfall for October. On the 30th, at the Chinandega station, the daily rainfall reached nearly 500 l/m^2.

Even though Hurricane Mitch has without doubt been the most serious natural catastrophe suffered by Central America in recent decades, the region has also recently suffered two bouts of El Niño from 1994 to 1995 and afterwards from 1997 to 1998, not to mention numerous other hurricanes and floods. In fact, in 1998, Mitch was the tenth hurricane to affect the Caribbean region; the first one of that particular year took place from the 24th of August to the 3rd of September. None of these events were as devastating as Mitch, but their frequency clearly reveals the vulnerability of the region to emergency situations caused by natural phenomena; so much so that the situation generated by the passage of the hurricane could hardly be considered a fortuitous event.

Table 1
Rainfall data for six weather stations located in the west of Nicaragua. The data was recorded on a daily basis and shows the values recordped over the last 12 days of October 1998

Station	October 1998 (daily data – l/m^2)												Total
	20	21	22	23	24	25	26	27	28	29	30	31	
Somotillo	0.0	12.3	0.0	0.0	0.0	21.0	60.8	74.2	268.0	250.0	163.7	90.0	940.0
Chinandega	0.3	14.5	38.5	3.5	17.6	0.0	43.5	74.3	309.6	422.4	484.8	202.9	1611.9
Corinto	0.0	0.0	7.4	2.4	25.5	6.5	27.2	46.7	61.1	222.7	258.4	182.0	839.9
León (Airpot)	0.0	2.0	15.8	15.7	20.6	22.9	87.0	71.1	164.7	269.8	289.6	144.2	1103.4
León	20.8	8.7	30.7	60.5	9.8	20.2	70.5	60.5	130.4	130.3	140.6	90.5	773.5
La Paz Centro	0.0	0.0	0.0	0.0	0.0	0.0	0.0	20.6	60.0	100.6	280.6	212.0	673.8

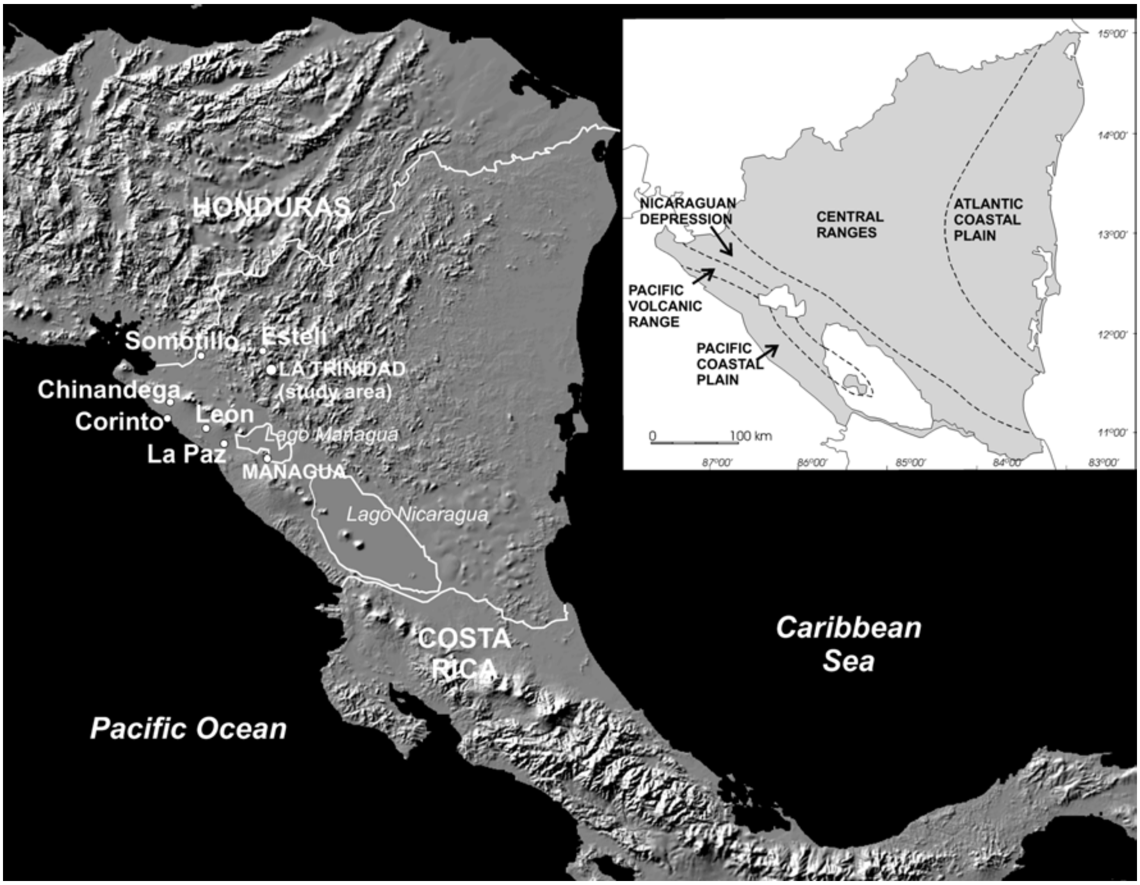

Fig. 1
Location of the area under study in the Central Range, District of Estelí and the weather stations (rainfall data in Tables 1 and 2) *Inset* Nicaraguan geomorphological units (Fenzl 1989)

The instability of Nicaraguan slopes

In Nicaragua it is possible to distinguish between several geomorphological units that display specific characteristics, as far as their relief and geology is concerned, and therefore exhibit different susceptibility in the face of various slope instability processes. Below, is a brief synthesis of the processes that have been observed to be the most frequent in each area. This synthesis was drawn up from nearly two months of fieldwork carried out from October to December of 1999 within the framework of a program run by the IGME (The Spanish Institute of Geology and Mining) and INDUROT (The Institute of Natural Resources and Territorial Planning of the University of Oviedo, Spain) in collaboration with INETER (The Nicaraguan Institute of Territorial Studies).

The geomorhpological units that have been distinguished are, broadly speaking, those established by Fenzl (1989; Fig. 1b). As far as slope instability is concerned, the units at most risk are the Pacific Volcanic Range and the Central Ranges. The classification and terminology used to describe the instability processes is based on Varnes (1978).

The Pacific Volcanic Range is one of the most outstanding features of Nicaraguan relief; moreover, it stretches beyond Nicaragua to other Central American countries. It is a volcanic range in which active volcanoes alternate with historically active and dormant ones. The prevailing lithology is lavas—andesites and basalts—and pyroclastic rocks (Fig. 2).

In the very slightly degraded stratacones, typical of active volcanoes, the instability processes that are recognized are (1) gullies and debris flows developing over the pyroclastic material and ashes, (2) rock avalanches linked to resistant rock levels in the upper part of the cone, (3) great complex

Table 2
Average monthly and yearly rainfall data for three of the six stations referred to in Table 1. These reference data allow the evaluation of the magnitude of the rainfall associated with Hurricane Mitch

Station	Year	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Total
Corinto	71–95	1.3	3.3	2.1	19.6	309.1	166.7	166.2	272.2	416.6	307.4	68.8	8.7	1,842.0
Chinandega	66–95	1.2	1.2	5.8	27.0	283.8	331.4	178.8	261.8	394.4	328.4	60.0	10.0	1,883.8
León	75–95	2.2	0.5	3.3	10.2	238.5	214.9	103.9	187.2	377.7	264.4	78.5	5.9	1,487.2

movements, slides, debris flows, earth flows, and (4) lahars, described by Pierson (1985) as volcanic debris or mud flows made up of a dense and viscous suspension of badly classified gravel, sand and mud.

In partially degraded volcanoes, or volcanoes with historical activity, the main processes that have been recognized are (1) great rock avalanches with a volume of 1 km^3 and block displacement of more than 10 km (Marquínez and others 2000a) (2) complex rock avalanche movements that have become debris flow as well as hyper-concentrated flows (3) the same type of lahars as those described in the slightly degraded stratacones and (4) small landslides and surface flows similar to those recognized on the rest of the country's slopes.

The Central Ranges cover over one third of Nicaragua and include the most important reliefs to be found in the country. The geological substratum of the unit is, for the most part, made up of volcanic rock of the Tertiary Age (Coyol and Mataglapa Groups), which frequently reveals a mature bed weathering. It is only to the north where we find some sedimentary and granitoid rocks, as well as metamorphic rock from the Paleozoic Age (Fig. 2). Extremely varied instability processes have been recognized in this unit such as (1) debris flows and earth flows in gullies, (2) rock falls and rock avalanches, (3) shallow flows and slides, (4) slides and complex landslides of an intermediate depth of less than 20 m, and (5) mixed and deep slides and complex movements, generally inactive at present.

The Pacific Coastal Plain is a strip of land that is generally less than 30 km wide. It has a hilly relief of between 200 and 500 m in height and, for the most part, exhibits short slopes. Mesozoic and Tertiary sediments as well as sedimentary rocks—detritic and volcanoclastic—prevail in the substratum (Fig. 2). The relatively low relief intensity means that the slope instability processes are not very active. Some debris flows and small gullies have been recognized, as well as some shallow mass movements.

Finally, the Nicaraguan Depression and the Atlantic Coastal Plain are practically flat areas full of recent sediment in which the incidence of slope instabilities and the associated risk is very low. Nevertheless, a small amount of instability, such as debris flows on isolated low ridges, has occurred in this area. For each area, the rainfall associated with the passage of Hurricane Mitch has given rise to numerous instability processes of the type described above (Scott 1999; Marquínez and others 2000a). Without a doubt, the most catastrophic that took place was the complex rock avalanche movement at the Casitas Volcano in the Pacific Volcanic Range, which turned into debris flow as well as hyper-concentrated flows. This process carried off two villages and was responsible for the death of over 2,500 people (Marquínez and others 2000b). Notwithstanding, a large number of minor instabilities were

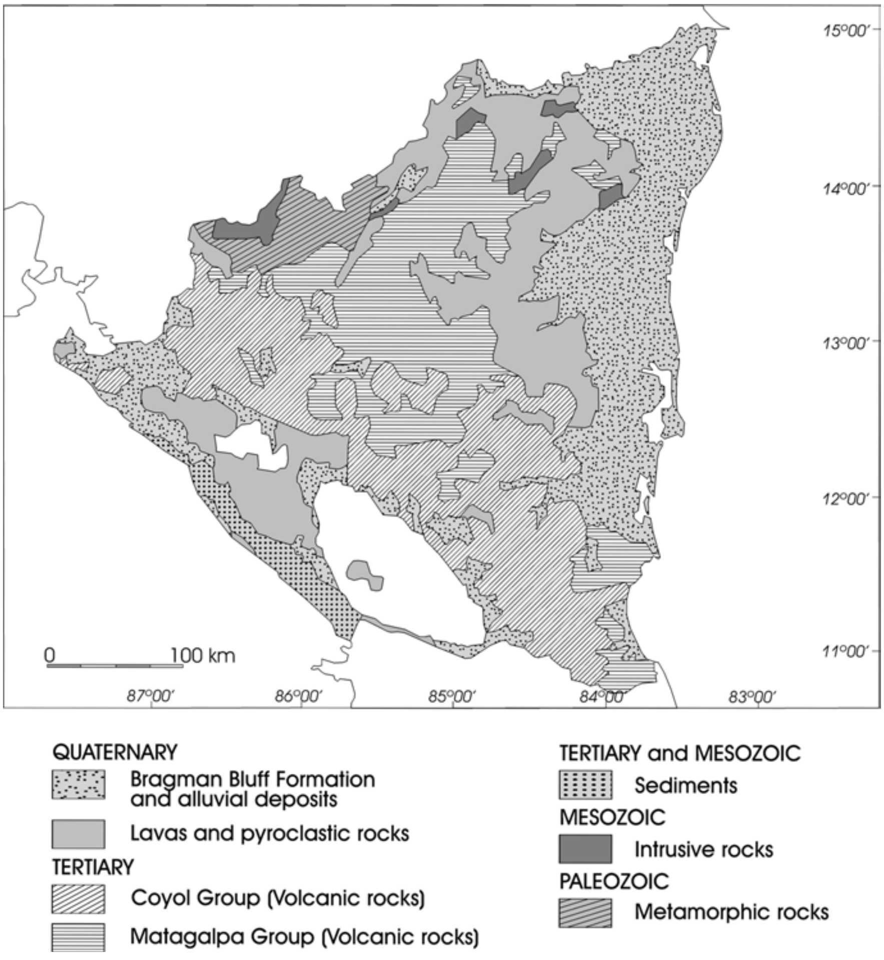

Fig. 2
Geological map of Nicaragua (INETER 1995)

also triggered off such as shallow mass movements and debris flows. Perhaps the most frequent was a shallow mass movement process, which included shallow landslides and soil slips of the type described in other Central American countries such as Puerto Rico (Larsen and Torres-Sánchez 1998).
A susceptibility model was constructed to quantify the high frequency of shallow mass movements in an area of the Central Ranges, making it possible to also qualitatively detect shallow mass movements around the entire mountainous territory of Nicaragua as well.

The susceptibility model of shallow mass movements

The study area

A susceptibility model has been constructed in the surrounding area of La Trinidad (Fig. 1a), a village situated in the district of Estelí, one of the areas most affected by Hurricane Mitch. The province of the Central Ranges is located within the borders of one of the greatest physiogeographical units that can be distinguished in Nicaragua (Fig. 1b). The predominant relief forms in the area of the Matagalpa and Estelí Mesas, are tablelands, "mesas", slopes and more or less irregular mountainous terrain (Parsons and others 1972). With a young fluvial system that fits in with the relief and a maximum height of up to 1,300 m in the mesa situated to the south, the relief characteristics of the La Trinidad area are similar to those mentioned in the area's general description. While the lower contour of the area under study is 600 m in the village of La Trinidad, it covers some 25.5 km^2 aerially. From a geological standpoint, the area is situated in the Tertiary Volcanic Province, which covers a large area of Nicaragua and basically includes two volcanic formations: the Matagalpa and Coyol Groups (Garayar1971; Fenzl1989). The bedrock of the study area is of the Upper Coyol Subgroup, belonging to the Coyol Group (Fig. 2).
Various units are to be distinguished within the Upper Coyol Subgroup (Parsons and others 1972). Nevertheless, basalt lava and agglomerate series are the most representative, with a gradual succession from flood tuff and basalt and agglomerate lavas in the lower series to increasingly more acidic ash at upper levels. Although there are various petrographic types in the study area, the substratum is basically homogenous; and, from the point of view of slope stability, every petrographic type can be considered similar.

Slope instability

Presently, inactive mass movements have been recognized in the area. These movements correspond to slides, flows and complex movements, and in some cases, possible rock falls and avalanches (Fig. 3). Although they are easily recognized in the landscape, the forms of deposit, as well as the scarps in these movements are covered with vegetation and do not reveal any evidence of recent activity. The planimetric surface areas of the mass movement deposits that have been mapped range from 13,000 to 500,000 m^2.
Only one complex landslide of greater dimensions has been mapped. This great landslide, with a surface area of

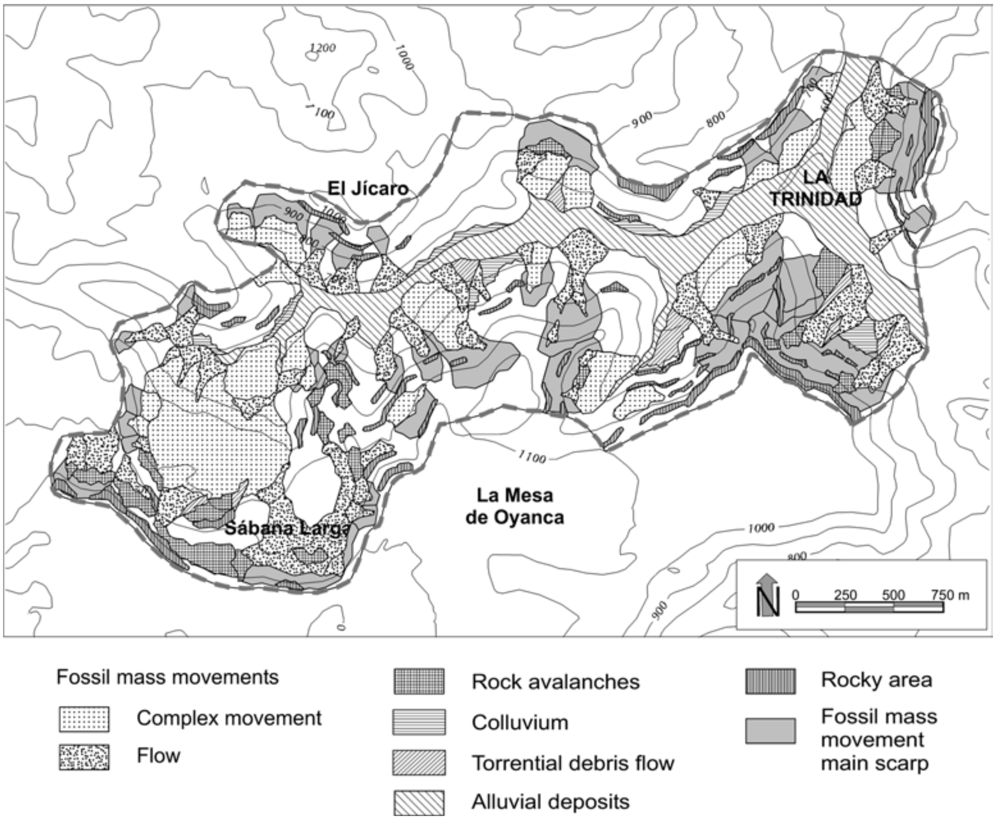

Fig. 3
A geomorphological map of the study area showing the surficial formations and some morphological elements. The original scale of this mapping is 1:25,000

over 1.5 km^2, is situated in the Sabana Larga area and has a circular scarp shape with a heavily sloped escarpment and a very small vertical shift, with respect to the volume of mass that has apparently moved. This amphitheatrical morphology, clearly different from the rest of the complex movements in the area, has given rise to its being interpreted as a collapse related to that of an ancient volcanic structure. Comparable morphologies have been described in other areas (Kara and others 1999). This slope movement represents a different process in relation to the rest of the instabilities recognized in the area's sloping ground. Apart from these inactive movements mapped in Fig. 3 in November through December of 1999 when the fieldwork was being carried out, practically all of the slopes in the area showed evidence of recent instabilities. These recent instabilities are shallow mass movements, affecting both weathered material and bedrock, as well as debris flow reactivated in torrential systems. There still remains a scarred area without vegetation in both, at times exhibiting erosion channels and deposit areas. The majority of these instabilities, according to accounts from local witnesses, arose during the rains associated with Hurricane Mitch (Fig. 4). Shallow mass movements, such as slides—debris slides and earth slumps—and flows—mud flows and earth flows—as well as complex movements, are the most frequent types of instabilities (Fig. 5). Altogether, 150 shallow mass movements have been mapped (Fig. 6). The movements in question exhibit a circular concave surface break, generally quite shallow, as well as a sliding mass of a slightly undulated morphology. They have a minimum length of 20 to 30 m, a minimum width of 15 to 20 m and usually a depth of less than 5 m. These mass movements affect slope deposits, old mass movement accumulations, colluviums, and in some cases, the substratum represented by weathered tuff.

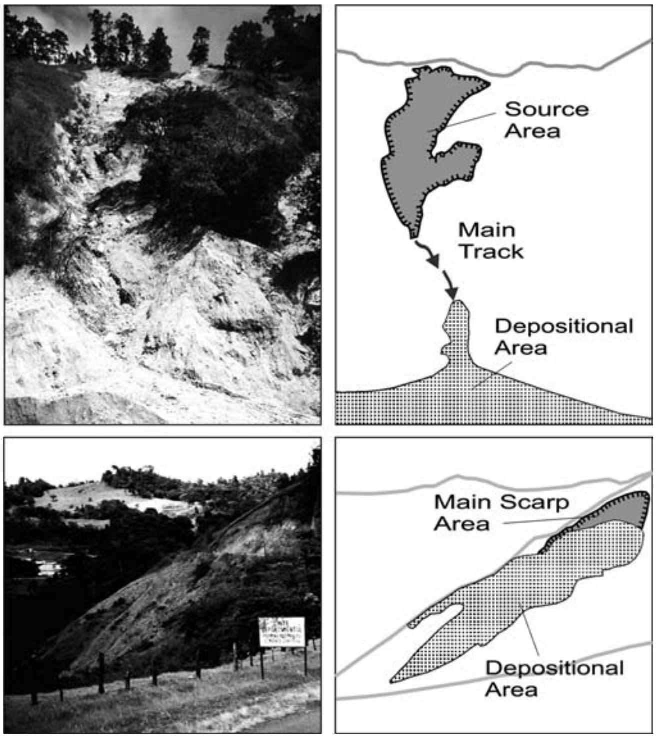

Fig. 5
Shallow mass movements in the region of the Central Range

Methodology

The inventory of shallow mass movements reveals that these instabilities are present in practically all of the slopes in the area under study (Fig. 6). The data that have been collected show that there is a correlation between the distribution of landslides and some geomorphological and topographical factors. Concerning the latter, the methodology that was followed consisted of combining the inventory of shallow mass movements with a detailed geomorphological mapping and models derived from the digital elevation model (DEM).

All of the analyses were based on the GIS. All the thematic maps that were drawn up, as well as the DEM and derived models, were executed by the GIS. In order to carry out the

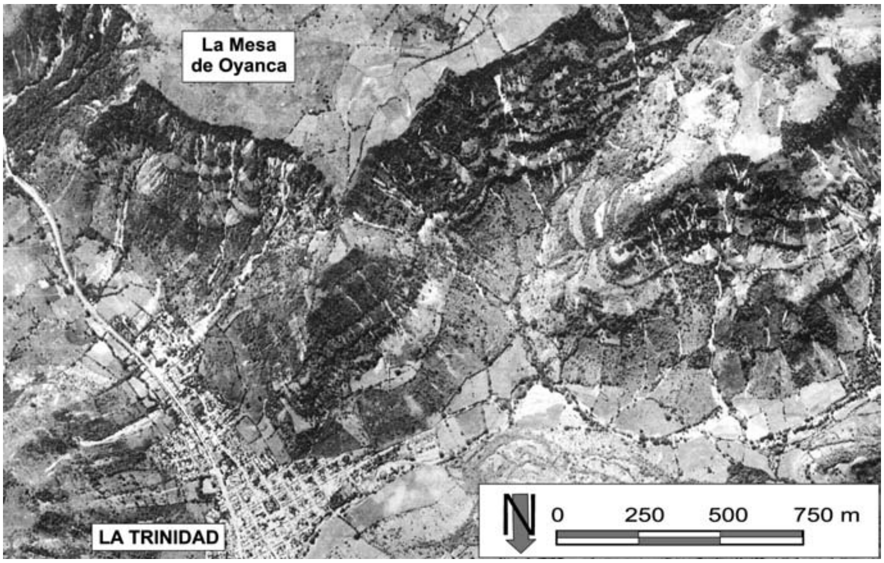

Fig. 4
Aerial photography of a sector of the area under study taken a few days after the passage of Hurricane Mitch. Numerous evidence of erosion can be seen—lines and fractures in white in the image—which correspond to torrential systems and shallow mass movements triggered off by the rains linked to the hurricane

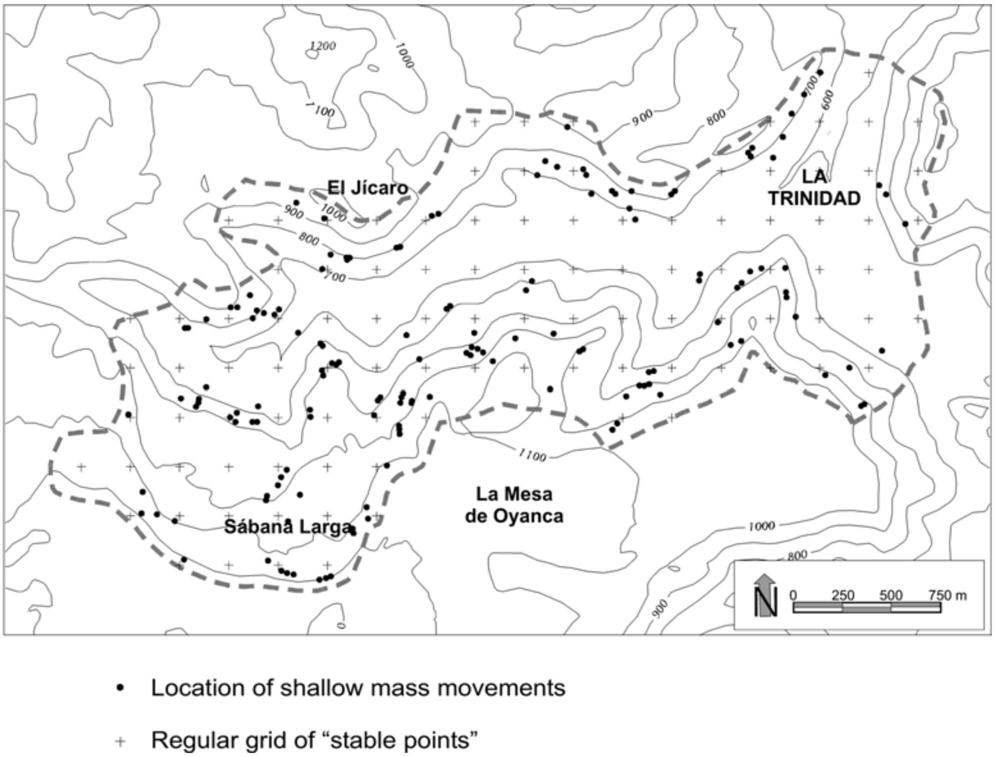

Fig. 6
Topographical map of the area under study and the shallow movements that have been mapped. There were a total of 150 occurrences of this type of observed instability during the field work in November 1999. Of these observations 100 were used to construct the susceptibility model, while the remaining 50 were employed to test it. The original mapping scale is 1:25,000

statistical analysis, the data was transferred and analyzed by means of a statistical package.

Geomorphological factors: surficial formations and morphological units

The geomorphological map (Fig. 3) was drawn up on a scale of 1:10,000 based on fieldwork and aerial photographic support. The original scale of the mapping was 1:25,000. The surficial formations were mapped according to a genetic criterion so that deposits could be distinguished from complex movements, flows, torrential debris flows, etc. This map shows the cartography of mass movements and other surficial formations which were mapped at a scale of 1:25,000. Recent shallow mass movements were represented on the map as a point (Fig. 6).

In addition to the surficial formations, the rocky areas have also been mapped. These have a reduced extension and always follow a linear track that is in accordance with the horizontal layout of the volcanic series in the area. Finally, the erosion surface has also been plotted on the geomorphological map corresponding to old mass movement main scarps. These surfaces display a recognizable morphology both in the field and in aerial photography; also, the field observations derived from them indicate a greater concentration of instability evidence.

Topographical factors: slope and accumulated flow

The conditioning factors that have been taken into account arising from the topography are the slope and the accumulated flow, both calculated by use of the DEM, which is a 25-m regular cell matrix model. This model was specifically constructed for this work in the INETER Department of Mapping by means of photogrammetric plotting based on aerial photographs taken in 1997.

The slope is one of the first factors to be taken into account in any stability analysis, and any qualitative evaluation clearly reveals the relationship that exists between this parameter and the stability of the materials forming the slopes. This relationship is especially strong with respect to slightly cohesive materials such as soils, weathered rocky substrata or transported material. The slope model of the area was obtained by using the DEM to identify the maximum rate of change in value from each cell to its neighbor's.

The accumulated flow model (AFM) represents the amount of rain that would normally flow through each cell, assuming that all rain became runoff and there was no interception, evapotranspiration or loss to groundwater. Therefore, this model indicates those areas prone to shallow landsliding due to topographical surface effects on hydrologic response. The AFM was constructed on the basis of the DEM and calculates the number of cells flowing into each cell (Jenson and Domingue 1988). Using the elevation matrix, the computer constructs the direction flow model, a matrix showing the direction of outflow for each cell. This direction of flow is determined by finding the direction of the steepest descent. The AFM is calculated by accumulating the weight for all cells that flow into each downslope cell.

Multivariate analysis: logistic regression

The multivariate analysis technique of logistic regression was used in order to construct the susceptibility model. Multivariate regression analysis has already been used as a statistical technique to construct slope instability–suscep-

Table 3
Shallow movement frequency in each type of surficial formation and morphological unit. In each case, the frequency corresponds to the ratio *number of instabilities/total surface area* of the unit under consideration

Surficial formations	Area (km^2)	Number of instabilities	Frequency
Fossil complex movements	391	32	8.2
Fossil flows	348	15	4.3
Rock avalanches	103	3	2.9
Colluvium	43	0	0
Torrential debris flow	32	0	0
Alluvial deposits	278	0	0
Geomorphological units			
Fossil mass movement scarp area	364	57	15.6
Rocky area	131	0	0
Rest of territory	855	42	4.9

tibility models (Carrara 1983; Chung and others 1995; Rowbotham and Dudycha 1998; Dai and others2001; Lee and Min 2001). This type of analysis has the advantage, as compared to other techniques such as discriminating analysis (Carrara and others 1991; Baeza and Corominas 1997, 2001), of being less demanding in regards to the way the variables are entered for analysis. While its main disadvantage is the fact that probability function coefficient values only indicate the incidence of each variable in the classification, it cannot, however, be directly or quantitatively interpreted.

In the logistic regression analysis carried out, the dependent variable was the presence–absence of shallow landslides, and the independent variables were the surficial formations and morphological units, as well as the slope and the accumulated flow. The presence of shallow landslides are represented by the 150 mapped field locations (Fig. 6). Of the 150, 100 have been taken at random as examples of unstable locations. The remaining 50 locations have been used as testing points in order to verify the resulting model.

In order to obtain a sample of locations lacking instability, a regular grid with 500-m sides was constructed. The nodes of the grid were used as sample points. The number of grid nodes included in the area under study came to 104. For each of these 104 points, as with the 100 points of instability, surficial formation and morphological unit, as well as slope and accumulated flow values were obtained. The sample needed to carry out the regression analysis was constructed with these values.

Two of the dependent variables, slope and accumulated flow, are continuous distribution numerical variables. In the case of surficial formations and morphological units, a factor was calculated in accordance with the number of instabilities mapped per area unit for each type of surficial formation and morphological unit (Table 3). The value of this factor was then used in the regression analysis.

Of the possible analysis techniques that were available in the statistical package used, the Wald regression method was employed. In this method, the first regression function is calculated with all the independent variables. Those that contribute less information to the classification are then eliminated. The contrast for the elimination is brought about by means of Wald's statistic.

Table 4
Coefficients and significance of the variables and independent terms used in the construction of the regression function. The values in the columns represent: the variable, coefficients and independent terminology including typical error estimate, Wald statistic and the p contrast value of said statistic

Variable	Coefficients	Error	Wald	Significance
Geomorphology	0.1328	0.0365	13.2754	0.0003
Slope	0.0970	0.0225	18.6183	0.0000
Accumulated flow	−0.0025	0.0063	0.1636	0.6859
Constant	−3.2081	0.5963	28.9466	0.0000

Results

Susceptibility model

The regression function obtained consists of three measured independent variables: geomorphological factors—surficial formations and morphological units—slopes and accumulated flow. The values of the coefficients and their level of significance are presented in Table 4.

Two of the independent variables that were used to construct the regression function, namely geomorphology and slope, display high values in Wald's statistic. This indicates that they are highly significant in the construction of the function. On the contrary, however, the variable accumulated flow displays an extremely low value in this statistic and appears to be a variable that contributes very little to the construction of the function. According to the method followed, in order to carry out the regression analysis, the accumulated flow would be the first variable to be eliminated from the function. Nevertheless, the elimination of this variable slightly reduces accuracy, so consequently all of the variables have been kept in the function.

The function obtained with the coefficients presented in Table 4 is: $p=1/1+e^{(-3.2081+0.1328\times\ \mathrm{geomorphology}\ +\ 0.0970\times\ \mathrm{slope}-0.0025\times\ \mathrm{flow})}$. This function was programmed into the GIS, resulting in a probability value for each cell of the area under study. These continuous probability values were grouped into three intervals with p values between 0 and 0.3, >0.3 and 0.5 and >0.5 and 1, distinguishing low, medium and high susceptibility areas, respectively (Fig. 7). Of the total 25.5 km^2 area under study, 6 km^2 belongs to the high susceptibility class, 7 km^2 to the medium susceptibility class and 12.5 km^2 to the low susceptibility class.

Model validation

The 50 mapped instability points that had not been used to construct the statistical function were superimposed on the susceptibility model (Fig. 7), resulting in an extremely high degree of accuracy. Of these 50 points, 36 (72%) are located in the high susceptibility area and 11 (22%) in the medium susceptibility area. Only 3 of the 50 instability points, as well as those cells in the slope model with a value

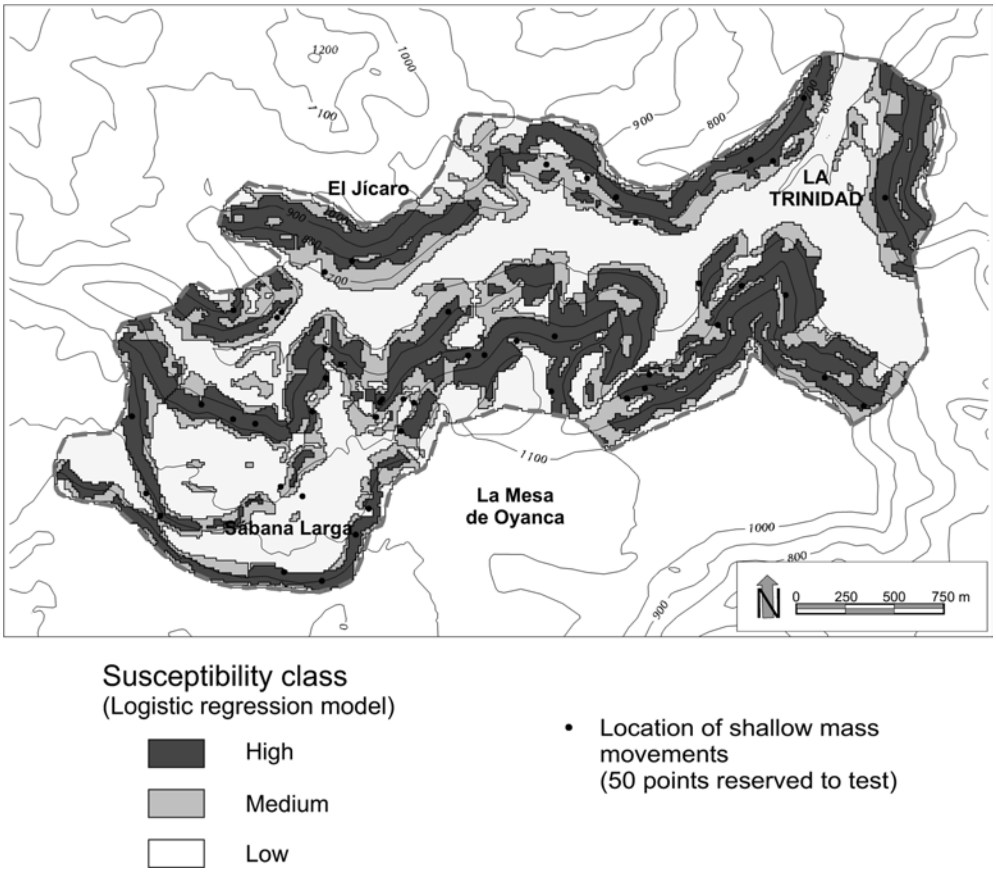

Fig. 7
Susceptibility model for shallow mass movements obtained by logistic regression. The probability values are grouped into three classes of relative susceptibility. The 50 instability points used to test the model are superimposed on the model

below 8°, can be found in the area classified as being of low susceptibility. On the geomorphological map, one of these is on a colluvium, another on a fossil flow and the third in an area without surficial formations.

To test the results, this validation method, which compares the distribution of instabilities that have not been used in the construction of the model, was employed in several projects where either a part of the sample was saved, or another area of instability was tested. This second area may correspond to instabilities triggered off by a later event of intensive rain, or be based on successive collections of aerial photographs (Irigaray Fernández and others 1999).

Discussion

A preliminary hazard assessment is the first step in drawing up a description of the nature of a hazard and the type of exposure in a particular region to that hazard (Slaymaker 1999). In Nicaragua, after the passage of Hurricane Mitch, this preliminary risk assessment clearly reveals that:

- Different slope instability processes still prevail in different regions of the country; this variability is governed by the country's geological and geomorphological history.
- The various processes of instability are different in magnitude, scope and frequency, thus the risk associated with each one of them, along with the possible preventive measures to be taken are quite divergent.
- Heavy rains, like those associated with hurricanes, are the main factors triggering many mass movements, especially shallow mass movements and the reactivation processes of some deep movements.

The shallow mass movements have been extremely frequent in the Central Range region. Given their reduced size, the shallow mass movements are not very destructive processes, and, considered separately, only in very concrete circumstances do they pose a real risk. Nevertheless, the high frequency of these shallow mass movements makes them dangerous, and above all, means that they represent high costs through loss of infrastructures, dwellings and farmed land (Larsen and Torres-Sánchez 1998; Marquínez and others 2000a).

The high frequency of shallow mass movements has enabled us to obtain a statistically representative sample from which it has been possible to construct a susceptibility model. The construction of this type of model is widely documented in the bibliography. In reference to the model constructed for the La Trinidad area, it is necessary to point out the low number of independent variables that were used. Moreover, the model shows the large extent of control that geomorphological factors have on the development of instabilities; its similarities to the mapping of surficial formations is documented on the final map, along with the presence of scarps that were produced by old mass movements.

As far as slope instability is concerned, the presence of surficial formations implies the existence of an important thickness of loose material with a different mechanical behavior to that displayed by the rest of the territory (Preston and Crozier 1999). Moreover, the presence of a surficial formation influences hydrological behavior, favoring infiltration and the presence of high phreatic levels. The relationship between soil permeability and thickness in regards to controlling shallow landsliding has been dealt with in numerous studies (Baeza and Corominas 1997, 2001; Costra 1998; Borga and others 1998; Crozier1999; Van Asch and others 1999) and seems to be especially important in landslides triggered by heavy rainfall (Bell and Maud 2000).

With regard to the rest of the variables that have been considered, and which are derived from the DEM, the slope is the most important in terms of instability distribution. The relationship between slope and instability is obvious to such an extent that this parameter is used in practically all the statistical analyses of landslide susceptibility. Frequently, stability analyses consider slope and ground properties—thickness, type etc.—combined with other geological factors including relief intensity, or other topographical descriptors, and DEM derivatives—curvature, orientation, drainage area, etc.—to be priority factors (Pachauri and others 1998; Burton 1998; Ngecu and Mathu1999).

The highly homogeneous geological features of the area under study have enabled us to obtain a valid model without the need for carrying out detailed geological mapping tasks. In reference to slope instability, this geological homogeneity is increased by intense weathering. The intense weathering, typical of regions that are subject to tropical climate, favor the presence of considerably thick mantle-rock with only a few other resistant levels such as rocky areas. Because of this, the collecting of data needed to obtain the susceptibility model is considerably reduced; thus, with only an extremely small number of variables, a model with a high degree of accuracy was obtained.

The region of the Central Ranges covers 33 % of the total surface area of Nicaragua (Fenzl 1988) and, in this great expanse, the geological history is homogenous to the extent that the lithology, the structure of the substratum as well as the relief evolution are presumably comparable throughout the entire unit. These circumstances allow us to assume that the results that have been obtained will be applicable to a large sector, and moreover, that they can be quantitatively representative of all the mountainous regions of Nicaragua.

It is worthwhile pointing out that the town of La Trinidad, the only one included in the area, possesses, in compliance with relevant decree, the “La Trinidad Physical Town Planning Scheme,” which contains data on population, economic analyses, town structure, transport, etc. In this report, alternatives are put forward and physical growth proposals are made in which the mountainous nature of the place and its surrounding areas are highlighted, as well as the problems involved in choosing sites to locate new settlements. Notwithstanding, and on a small scale, the development of this nucleus brings to light the problems raised by Gupta and Ahmad (1999) with respect to tropical regions. The validation accomplished in this work enables one to assume that the susceptibility map obtained is a tool which can be very useful in guiding this growth.

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