A Feasible Methodology
for Landslide Susceptibility Assessment
in Developing Countries:
A case-study of NW Nicaragua after Hurricane Mitch.

Marta Guinau, Raimon Pallàs and Joan Manuel Vilaplana

RISKNAT Research Group, Dpt. Geodinàmica i Geofísica. Facultat de Geologia,
Universitat de Barcelona, 08028, Barcelona (Spain)

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Corresponding author
Marta Guinau
Departament de Geodinàmica i Geofísica
Facultat de Geologia
Universitat de Barcelona
Zona Universitària de Pedralbes

e-mail: mguinau@ub.edu
08028 Barcelona
VOX: 93 402 13 78
FAX: 93 402 13 40

ABSTRACT

In October 1998, Hurricane Mitch triggered a large number of landslides (mainly debris flows) in Honduras and Nicaragua, resulting in a high death toll and in considerable damage to property. In recent years, a number of risk assessment methodologies have been devised to mitigate natural disasters. However, due to scarcity of funds and lack of specialised personnel few of these methodologies are accessible to developing countries. To explore the potential application of relatively simple and affordable landslide susceptibility methodologies in such countries, we focused on a region in NW Nicaragua which was among the most severely hit during the Mitch event. Our study included (1) detailed field work to produce a high-resolution inventory landslide map at 1:10.000 scale, and (2) a selection of the relevant instability factors from a Terrain Units Map which had previously been generated in a project for rural development. Based on the combination of these two datasets and using GIS tools we developed a comparative analysis of failure-zones and terrain factors in an attempt to classify the land into zones according to the propensity to landslides triggered by heavy rainfalls. The resulting susceptibility map was validated by using a training and a test zone, providing results comparable to those reached in studies based in more sophisticated methodologies. Thus, we provide an example of a methodology which is simple enough to be fully comprehended by non-specialised technicians and which could be of help in landslide risk mitigation through implementation of non structural measures, such as land planning or emergency measures.

Keywords: landslide susceptibility, debris flows, Geographic Information System, developing countries, Nicaragua, Hurricane Mitch

1. Introduction

Although natural hazards may occur in many parts of the world, their consequences depend on the relationship between the magnitude of natural phenomena and the vulnerability of human settlements to such an event (Alcántara-Ayala, 2002). Consequently, natural phenomena are more destructive in developing countries because of economic, political, social and cultural factors, which increase the vulnerability of these countries to natural hazards.

In recent years, a number of methodologies concerning natural hazard assessment and mapping have been devised in an attempt to determine suitable strategies to prevent and mitigate natural disasters (Brabb, 1984; Carrara et al., 1995; Soeters and van Westen, 1996). However, in developing countries insufficient funds, the absence of laws and the shortage of trained experts increase the difficulty in coping with natural disasters, which represents a considerable drawback to the socio-economic development. Moreover, many studies on the mitigation of natural hazards entail complex statistical techniques that provide results, which are often difficult to comprehend and, hence, implement by non-specialists in statistics such as planners or policy makers (Clerici, et al. 2002). There is a pressing need to test simple and low cost methodologies, which can be adapted to and used by national organisations with a low level of specialisation.

In 1998 more than 9000 people lost their lives and about 11% (3.2 million people) of the total population in Central America was affected by Hurricane Mitch. Most damage due to this event in NW Nicaragua was caused by landslides, mainly fast-moving debris flows (Pallàs, et al., 2004). These debris flows constituted the most destructive process, resulting in considerable human loss and damage to property in terms of both direct and indirect costs.

Following Hurricane Mitch, several national and international organisations carried out development projects in NW Nicaragua, the area most badly affected in this country (Solidaridad Internacional, 2001; Vilaplana et al., 2002; Pallàs et al., 2004; Guinau, et al., in press). These projects involved the systematic collection of data considered to have some bearing on rural development and potential land use. Although these datasets were not directly developed for landslide hazard assessment we were interested in testing if they could be used to implement a methodology to assess and map landslide susceptibility.

The aims of the present study are (1) to explore the potential of combining new field data with a pre-existing non-specific dataset to develop a methodology for landslide susceptibility zoning, and (2) to show an example of a simple and low cost methodology adapted to the limitations found in most developing countries, which could be used to implement non-structural strategies to mitigate landslide risk.

1.1. Study Area

Nicaragua, which occupies an area of 118.358 km^2, is located at the Isthmus of Central America, between 10º45' and 15º05' of north latitude and 83º15' and 87º40' of west longitude (Fig. 1). This location exposes Nicaragua to tropical rainfalls and cyclones that originate between the Caribbean Sea and the African Coast (INETER, 1998).

The study area (Fig. 1) extends over 473 km^2 and includes the municipalities of San Pedro del Norte, San Francisco del Norte, San Juan de Cinco Pinos, Santo Tomás del Norte and part of Somotillo, all of them in the Departamento de Chinandega, in NW Nicaragua. Located in the Interior Highland of Nicaragua, this area has a hilly landscape and an altitude between 300 and 1200 m. The area is largely constituted by Tertiary volcanic rocks of the Coyol and Matagalpa groups and Tertiary plutonic intrusions (Weyl, 1980; Fenzl, 1988). The Oligocenic Matagalpa Group is composed of rhyolitic to dacitic pyroclastic rocks, whereas the Coyol Group emplaced during Miocene-Pliocene period is made up of basaltic rocks, rhyolitic lavas, breccias, lahars and pyroclastic flows (Darce, et al., 1989; Ehrenborg, 1996). Most of these rocks are covered by an uneven layer of soil, which is composed of regolith and bedrock residual blocks.

The study area has a tropical climate with a marked dry season from November to April, during which only 10% of the annual rainfall is recorded, and a wet season from May to October with an average rainfall of 1200 mm (accounting for 90% of the annual rainfall). However, there is a marked decrease in rainfall from mid July to mid August. The temperature in the study area can fluctuate between 15 and 25ºC (INETER, 1998).

The Hurricane Mitch rainfalls affected Nicaragua from 21 to 31 October 1998. The total rainfall recorded in this period in Chinandega, about 100 km from the study area (Fig. 1), was 1597mm, more than the mean annual-rainfall, which in this region is 1420mm. Only on one day - 30 October - 485 mm were recorded in this zone (INETER, 1998). The effects of these torrential rains in the study area, i.e. mainly debris flows, affected 32% of the population, resulting in considerable damage to property and human life (Solidaridad Internacional, 2001).

2. Data available

Two types of information enabled us to develop and validate a methodology to produce a *landslide susceptibility map* in the study area: (1) a *landslide inventory* and map prepared by a member of RISKNAT and (2) a *terrain units map* obtained in the frame of a Solidaridad Internacional (Spanish non governmental organisation) and UPOLI (Polytechnic University of Nicaragua) project (Solidaridad Internacional, 2001).

2.1. Landslide Map

Landslide inventory and mapping is aimed at determining the processes concerning landslide development in the study area and the terrain instability factors involved.

To obtain the landslide inventory and map the procedure was as follow; (a) *Aerial photographs interpretation*: the aerial photographs taken in 2000 at 1:40.000 scale, were enlarged at 1:20.000 scale yielding an acceptable resolution and allowing a more detailed interpretation. The landslides caused by Hurricane Mitch were mapped; (b) *Compilation over orthophotos*: the compilation of these affected areas over orthophotos at 1:10.000 scale allowed us to obtain a preliminary *landslide map*; (c) *Field work*: the landslide map was checked and corrected to obtain the definitive *landslide map* at 1:10.000 scale, and field observations were made in areas with the highest density of landslides to obtain information on the mechanisms and the instability factors involved in terrain failures; (d) *Digitising of the landslide map*: the resulting digital landslide map included the areas affected by landslides (Fig. 2A), making the distinction between the areas affected by terrain-failure, where landslides start, and the areas affected by the path and the accumulation of the mobilised material (Fig. 2B).

2.2. Terrain units map

With the aid of aerial photointerpretation and field observations, it is possible to obtain significant information on terrain characteristics such as lithology, slope, soil characteristics, land use, which is used to classify the terrain into Terrain Units (Fig. 3A) (Hansen, et al. 1995; Guzzetti, et al. 1999). This term refers to a portion of land surface, which contains uniform ground conditions that differ from the adjacent units across definable boundaries (Hansen, 1984; Guzzetti, et al. 1999). Ground conditions are defined by a given combination of classes of each terrain factor (Fig. 3B).

The *terrain units map* used in the present study was developed in a GIS environment at 1:10.000 scale. Terrain Units were defined from fourteen different terrain factors. From this *terrain units map* it was possible to obtain *thematic maps*. Each map represents a terrain factor and the different classes that characterise it (Fig. 3A-B).

3. Methodology

According to the analysis of terrain conditions in areas affected by landslides in the past or present it is possible to determine zones with similar characteristics such as areas prone to landsliding, termed Landslide Susceptible Areas.

Although terrain instability is governed by a large number of geological and environmental factors, it is necessary to differentiate instability factors, which condition terrain-failure, from other factors, which influence the area affected by the reach of the mobilised material. In the present study only the areas affected by terrain-failures, i.e. the areas where landslides start, are taken into account when determining areas prone to failure (Irigaray, et al., 1999; Baeza and Corominas, 2001; Dai, et al., 2002; Chung and Fabbri, 2003). Thus, the susceptibility map resulting from this methodology represents the susceptibility to terrain-failure.

A given area is declared to be susceptible to terrain-failures when the terrain conditions at a given site are comparable to those in an area where the terrain-failure has occurred. Hence, a comparative analysis between terrain-failure zones affected by Hurricane Mitch and different instability factors allowed us to zone the study area according to its susceptibility to landslides.

Generally, a minimum of two rainfall events producing landslides are needed to validate a susceptibility map. In our study, lack of historical data or a rainfall event after Hurricane Mitch rules out the possibility of a validation of this kind. However, following the same approach as Baeza and Corominas, (2001), Chung and Fabbri (2003) and Remondo et al., (2003), the division of the study area into two zones (see Fig. 4) allowed us to develop the methodology in a Training Zone, and to validate it in a Test Zone. The main criteria for dividing the study area were the homogeneity of extension and terrain characteristics.

3.1. Selection of instability factors

Slope instability is governed by a complex set of interrelated terrain parameters but a simplified approach requires a selection of a limited number of key instability factors. The factors are selected in accordance with subjective expert opinion and depend on a prior knowledge of the external processes in the study area.

Field observations contribute to the understanding of terrain-failure mechanisms and their conditioning factors. In our study case, most terrain-failures involved the total thickness or a portion of soil formation mobilised over the bedrock (Vilaplana et al., 2002; Pallàs et al., 2004). Based on the field observations, the instability factors from the *terrain units map* that were selected in this study are: slope, lithology, soil thickness, soil texture and land use.

3.2. Weighting instability factors in the Training Zone

As pointed out by van Westen, et al. (1997) and Carrara, et al. (1999), the heuristic method used to choose the relevant instability factors involves a relatively high degree of subjectivity. To determine more objectively the weight of each class for the different instability factors influencing terrain-failure we made a comparative analysis between the terrain characteristics and the distribution of failure-zones by using a Geographic Information System (GIS).

The comparative analysis consisted in superimposing the *failure-zones map* on each *thematic map*. Given that each instability factor is divided into a number of classes, it is possible to calculate the percentage of the area covered by failures in each class (W_i):

$$W_i = [A_{fi} / A_i] \times 100$$

where A_{fi} is the area covered by failures in a given class and A_i is the area of this class. This percentage W_i represents the weight or degree of influence of each class in terrain-failures (Campbell, 1973; Wright and Nilsen, 1974; Wright, et al., 1974; DeGraff, 1985; Guzzetti, et al., 1994; Clerici, et al. 2002; Dai, et al. 2002).

3.3. Landslide susceptibility calculation in the Training Zone

Given that each Terrain Unit is characterised by a combination of classes, each class corresponding to a terrain factor, it is possible to calculate a cumulative value, adding up the weights obtained previously (Table 1). This cumulative value represents the relative propensity of the terrain to failure in each Terrain Unit.

3.4. Landslide susceptibility classes and mapping in the Training Zone

Cumulative values obtained for each Terrain Unit can be classified into several intervals to define different susceptibility classes. These can be used to classify the land surface into different susceptibility degree domains. We divide the *maximum cumulative* *susceptibility value* (Cv_{max}) by the number of intervals (N), which we want to represent in the landslide susceptibility map, obtaining an interval size (X).

$$X = Cv_{max} / N$$

Once an interval size (X) has been chosen, GIS utilities allow the classification of the study area into N susceptibility classes. Figure 5 shows an example of subdivision into four susceptibility classes.

3.5. Validation of the susceptibility map in the Test Zone

Given that the terrain characteristics in the Test Zone resemble those of the Training Zone, a *landslide susceptibility map* could be obtained by integrating the weights previously determined for each class. Using GIS tools, cumulative values of the weights previously attributed to each class in the Training Zone were calculated for each Terrain Unit in the Test Zone. These cumulative values were distributed in a number of intervals or susceptibility classes (N) in the Test Zone (Fig. 6), coinciding with the number chosen for the Training Zone.

The *susceptibility map* was then compared with the failure-zones for validation. GIS tools allowed us to obtain the percentage of the area of failure in each susceptibility class ($\%A_{fi}$) with respect to the total area of failure when considering the whole test zone. $\%A_{fi}$ was obtained using the following expression:

$$\%A_{fi} = 100(A_{fi}/A_{sci}) / \Sigma (A_{fi}/A_{sci})$$

were A_{fi} is the area affected by failures in a given susceptibility class, A_{sci} is the class area. $\%A_{fi}$ allows us evaluate whether failure-zones coincide with the areas regarded as being highly susceptible to failure.

Figure 7 shows a gradual decrease in the percentage of failures between the areas of high susceptibility and the areas of low susceptibility. Equivalent distributions were found when applying this kind of validation to *susceptibility maps* corresponding to different number of susceptibility classes (N varying between 3 and 6). Such robust outputs suggest that our methodology is adequate to obtain *landslide susceptibility maps* in the study area.

4. Discussion

Hurricane Mitch constitutes the reference event in our study to develop a methodology to obtain landslide susceptibility maps. The dominant typology of landslides triggered by this event in the study area is debris flows. Therefore, the resulting *landslide susceptibility map* shows the propensity to debris flows resulting from heavy rainfalls.

The methodology developed in the present paper is based on a comparative analysis between the distribution of the observed failure-zones and the instability factors. Consequently, the *landslide susceptibility map* obtained shows the propensity of the terrain to failure but not the propensity to be affected by the path or the deposition area of the mobilised material. This is an important limitation of *susceptibility maps*, which could be improved by considering the fact that debris flows tend to merge with the drainage network. Thus, the methodology shown in the present paper could be complemented with the simplified method suggested by Pallàs et al., (2004) which, based on a Digital Terrain Model, permits the calculation of flow lines from potential source areas. The application of such a methodology is out of the scope of the present paper and is not shown here.

A limitation of the approach to susceptibility analysis presented here is that it implicitly considers that instability factors are mutually independent. Such an assumption may not be realistic and could produce a larger overestimation in the susceptibility values in high susceptibility classes. Thus, the susceptibility values assigned to each susceptibility class must be seen as relative, and need to be used as qualitative indexes. The resulting map is helpful in separating areas of increasing degrees of susceptibility, which is a reasonable first approach to hazard assessment considering the limited resources found in most developing countries.

The methodology suggested in the present paper enables to obtain landslide susceptibility maps with a variable number of susceptibility classes. It has to be pointed out that this number will depend on the requirements and possibilities of the study area. Thus, the technician in charge will need to base his choice on site specific criteria related to socio-economic factors and on the end use of the resulting *susceptibility map*. As an example, the best choice in the number of classes may vary if the map is to be used for management of emergencies or for land-use planning. Note that the *landslide susceptibility map* should only be used to establish non-structural strategies to mitigate landslide effects. To implement structural measures it would be necessary to estimate the magnitude of the landslides that can affect the area, which is beyond the scope of our general approach.

The main difficulty when trying to produce sound hazard assessments is the lack of reliable field and historical data. This is especially true in developing countries where data are scarce and where specific studies are rarely made. Our study relies on the combination of two main datasets: On the one hand we made a new collection of high resolution quality data in the field that enabled us (1) to construct a reliable *landslide map* at 1:10.000 scale and (2) to gain sufficient knowledge about the key factors involved in debris flow failure in the area. This was a key part of the study, and required the participation of personnel specialised in landslides and time-consuming work in the field. On the other hand we also used a pre-existing non-specific dataset from which the factors relevant to instability were chosen. Although the *thematic maps* and classes included in these datasets were far from ideal, we have shown that, complemented with good-quality high-resolution field data covering a large portion of the study area, they could be used as the basis for a consistent susceptibility analysis.

In recent years a number of methodologies to produce landslide susceptibility maps have been developed in an attempt to mitigate natural disasters. However, the complexity of these methodologies and the socio-economic situation of developing countries highlight the need for simple and low cost methodologies to obtain necessary information to mitigate natural risks. As recognised by Carrara, et al. (1999) and Clerici, et al. (2002), sophisticated statistic methods may provide relatively accurate results but may be too difficult to comprehend by non-specialists in statistics to be applied with success. A more simple methodology like the one presented in this paper may have the drawback of being less accurate but has the advantages of (1) being feasible when data is limited and (2) being easily learned, fully comprehended and handled by technicians trained in landslide assessment without a high level of specialisation in statistics.

The validation of our susceptibility assessment (Fig. 7) suggests that the application of relatively simple methodologies, even when using non-ideal datasets, can give results which are comparable with those based on sophisticated statistical methods and exhaustive, expensive selection of specific data (e.g. Neuland, 1976; Duque et al., 1990; Irigaray et al., 1999; Baeza and Corominas, 2001; Chung and Fabbri, 2003; Remondo et al., 2003). Obviously different areas and datasets may behave differently, and some kind of validation will always be required. Providing that division into two homogeneous areas is possible, the validation through a training and a test zone appears to be a good approach for those areas where only one reference event is available.

5. Conclusion

The methodology suggested in the present paper allows the detection of potential debris flows source areas under heavy rainfall conditions. This methodology, complemented with simple methods aimed at establishing preferential debris flows paths, could provide a useful document to help in the mitigation of debris flow risk through the implementation of non-structural measures.

Even in developing countries there are regions where datasets collected for purposes other than risk mitigation are available. When combined with good-quality high-resolution specific data and GIS technologies, the use of such datasets can help in reducing the costs of susceptibility analyses, making them available to areas where they could otherwise not be afforded.

Any susceptibility study using non-specific datasets needs to develop some kind of validation process. The division of the study area into training and test zones is a promising approach for validation in areas where, as in most developing countries, little historical information is available.

Simple methodologies for susceptibility assessment are more easily comprehended and handled than sophisticated ones. They may provide a good cost-effective compromise, making them accessible to developing countries where specialised personnel and funds are scarce.

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FIGURE CAPTIONS

Fig. 1: Study area location (in black), and place names referred to in the text. The dark grey band shows Hurricane Mitch path, based on USGS (1999) data.

Fig. 2: (A) *Landslide map.* (B) Enlarged portion of the *landslide map* showing failure-zones (in dark grey) and the areas affected by the path or the deposition of mobilized material (in light grey). Coordinates are Universal Transverse Mercator.

Fig. 3: (A) Terrain units map (grey levels corresponding to terrain units 1 to 491) and a portion of the associated data table showing the first twenty Terrain Units and six terrain factors. The values in the second column in the table correspond to terrain unit codes. Columns three to eight show an example of the classes of each terrain factor which characterize Terrain Units. (B) Example of *thematic maps* obtained from the *terrain units map.* Each one shows a terrain factor defined by a given number of classes.

Fig. 4: Division of the study area into Training Zone (in dark grey) and Test Zone (in light grey).

Fig. 5: *Landslide susceptibility map* obtained in Training Zone.

Fig. 6: *Landslide susceptibility map* obtained in Test Zone.

Fig. 7: Graph showing the percentage of area affected by failures on each Susceptibility Class.

FIGURES AND TABLES

Fig. 1_Guinau et al.

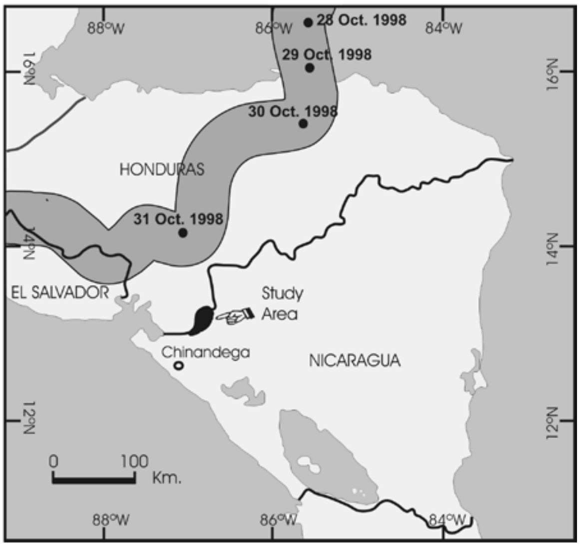


Fig. 2_ Guinau et al.

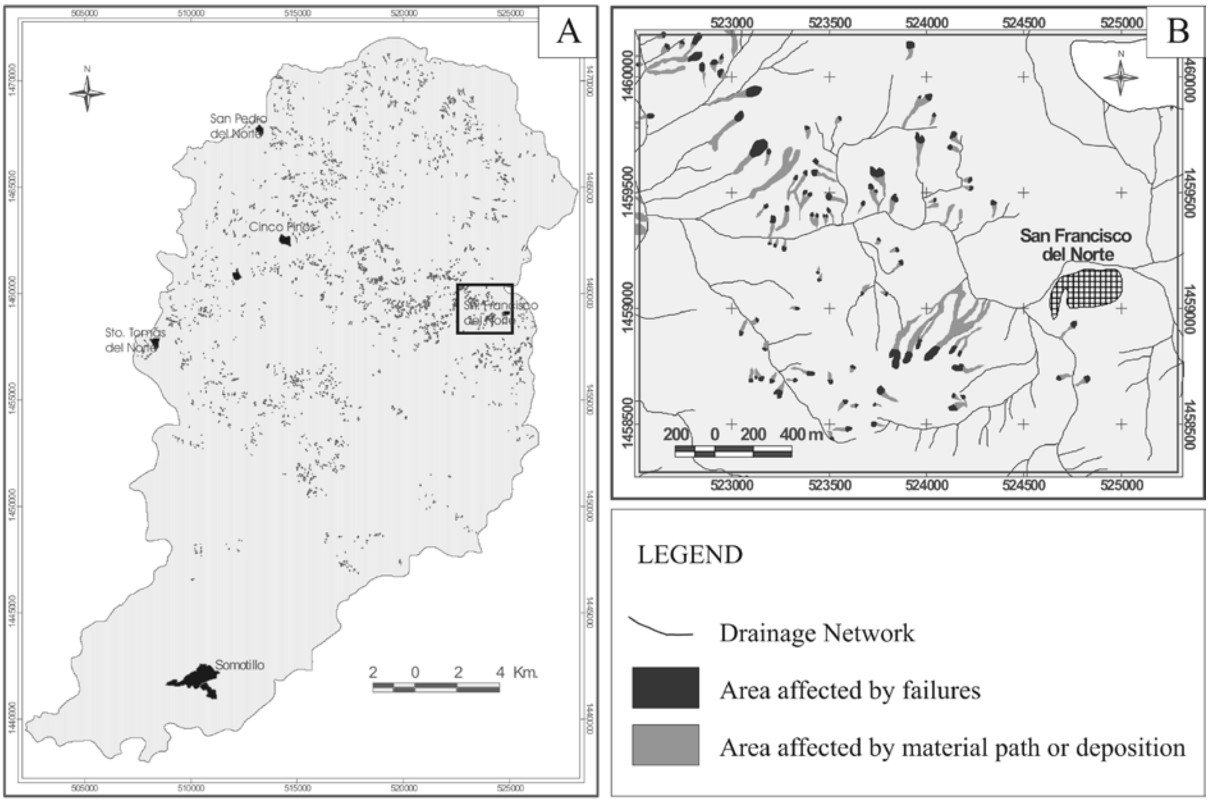
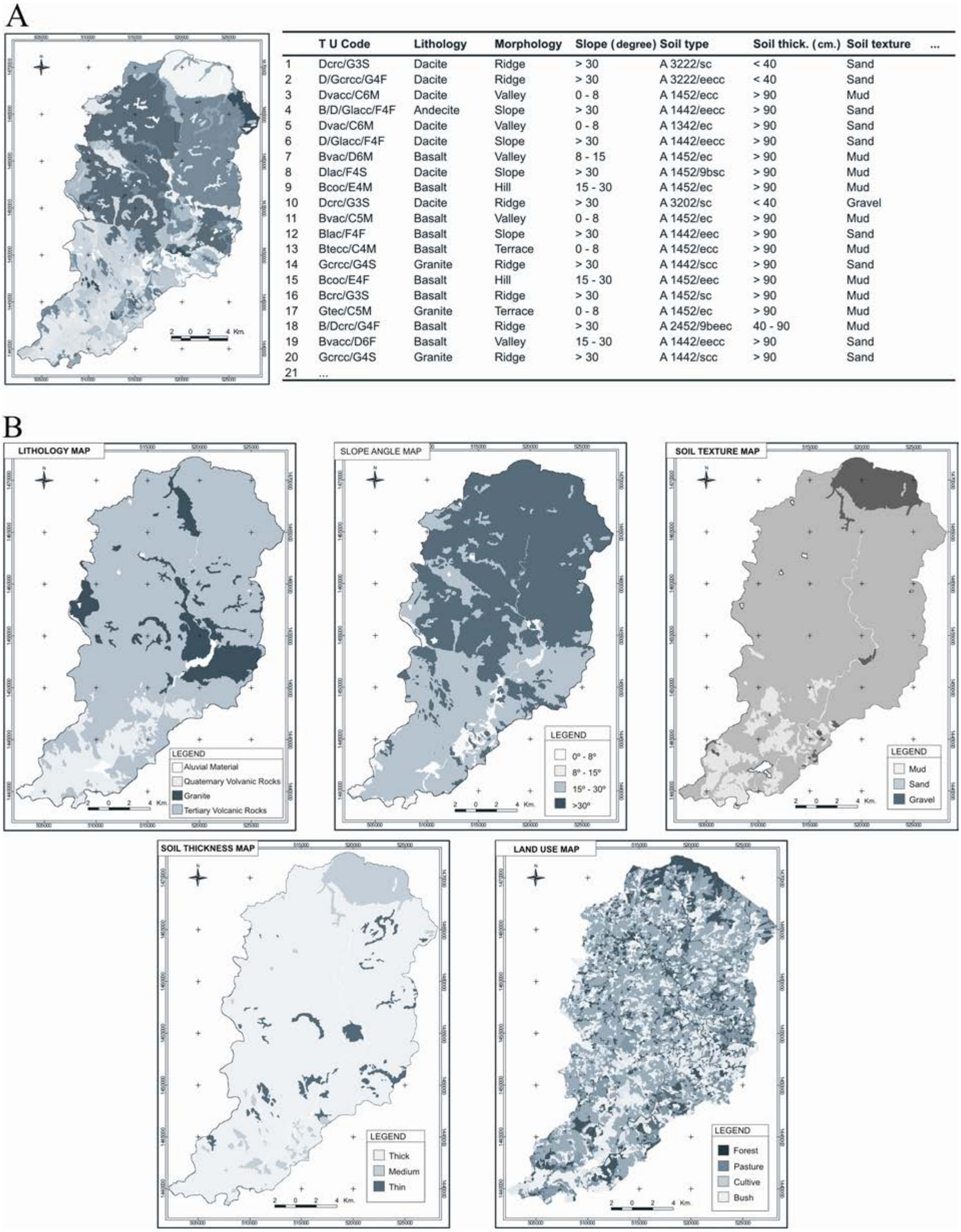


Fig. 3_ Guinau et al.



	T U Code	Lithology	Morphology	Slope (degree)	Soil type	Soil thick. (cm.)	Soil texture	...
1	Dcrc/G3S	Dacite	Ridge	> 30	A 3222/sc	< 40	Sand	
2	D/Gcrcc/G4F	Dacite	Ridge	> 30	A 3222/eecc	< 40	Sand	
3	Dvacc/C6M	Dacite	Valley	0 - 8	A 1452/ecc	> 90	Mud	
4	B/D/Glacc/F4F	Andecite	Slope	> 30	A 1442/eecc	> 90	Sand	
5	Dvac/C6M	Dacite	Valley	0 - 8	A 1342/ec	> 90	Sand	
6	D/Glacc/F4F	Dacite	Slope	> 30	A 1442/eecc	> 90	Sand	
7	Bvac/D6M	Basalt	Valley	8 - 15	A 1452/ec	> 90	Mud	
8	Dlac/F4S	Dacite	Slope	> 30	A 1452/9bsc	> 90	Mud	
9	Bcoc/E4M	Basalt	Hill	15 - 30	A 1452/ec	> 90	Mud	
10	Dcrc/G3S	Dacite	Ridge	> 30	A 3202/sc	< 40	Gravel	
11	Bvac/C5M	Basalt	Valley	0 - 8	A 1452/ec	> 90	Mud	
12	Blac/F4F	Basalt	Slope	> 30	A 1442/eec	> 90	Sand	
13	Btecc/C4M	Basalt	Terrace	0 - 8	A 1452/ecc	> 90	Mud	
14	Gcrcc/G4S	Granite	Ridge	> 30	A 1442/scc	> 90	Sand	
15	Bcoc/E4F	Basalt	Hill	15 - 30	A 1452/eec	> 90	Mud	
16	Bcrc/G3S	Basalt	Ridge	> 30	A 1452/sc	> 90	Mud	
17	Gtec/C5M	Granite	Terrace	0 - 8	A 1452/ec	> 90	Mud	
18	B/Dcrc/G4F	Basalt	Ridge	> 30	A 2452/9beec	40 - 90	Mud	
19	Bvacc/D6F	Basalt	Valley	15 - 30	A 1442/eecc	> 90	Sand	
20	Gcrcc/G4S	Granite	Ridge	> 30	A 1442/scc	> 90	Sand	
21	...							

Fig. 4_ Guinau et al.

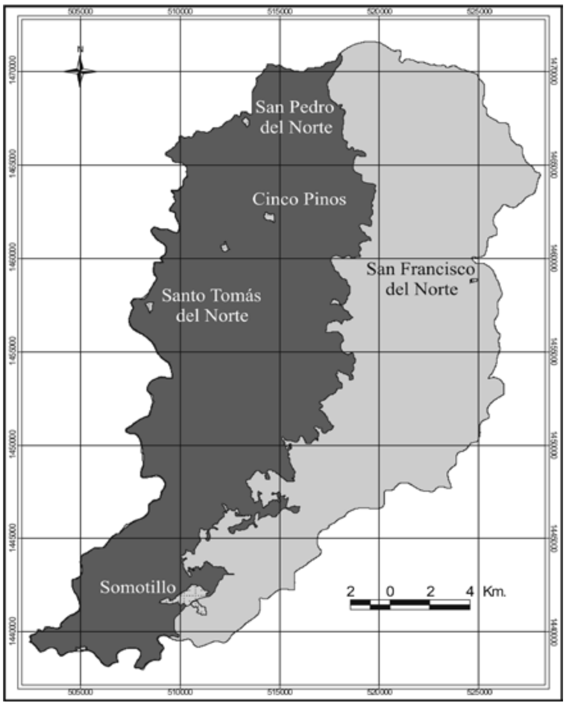


Fig. 5_ Guinau et al.

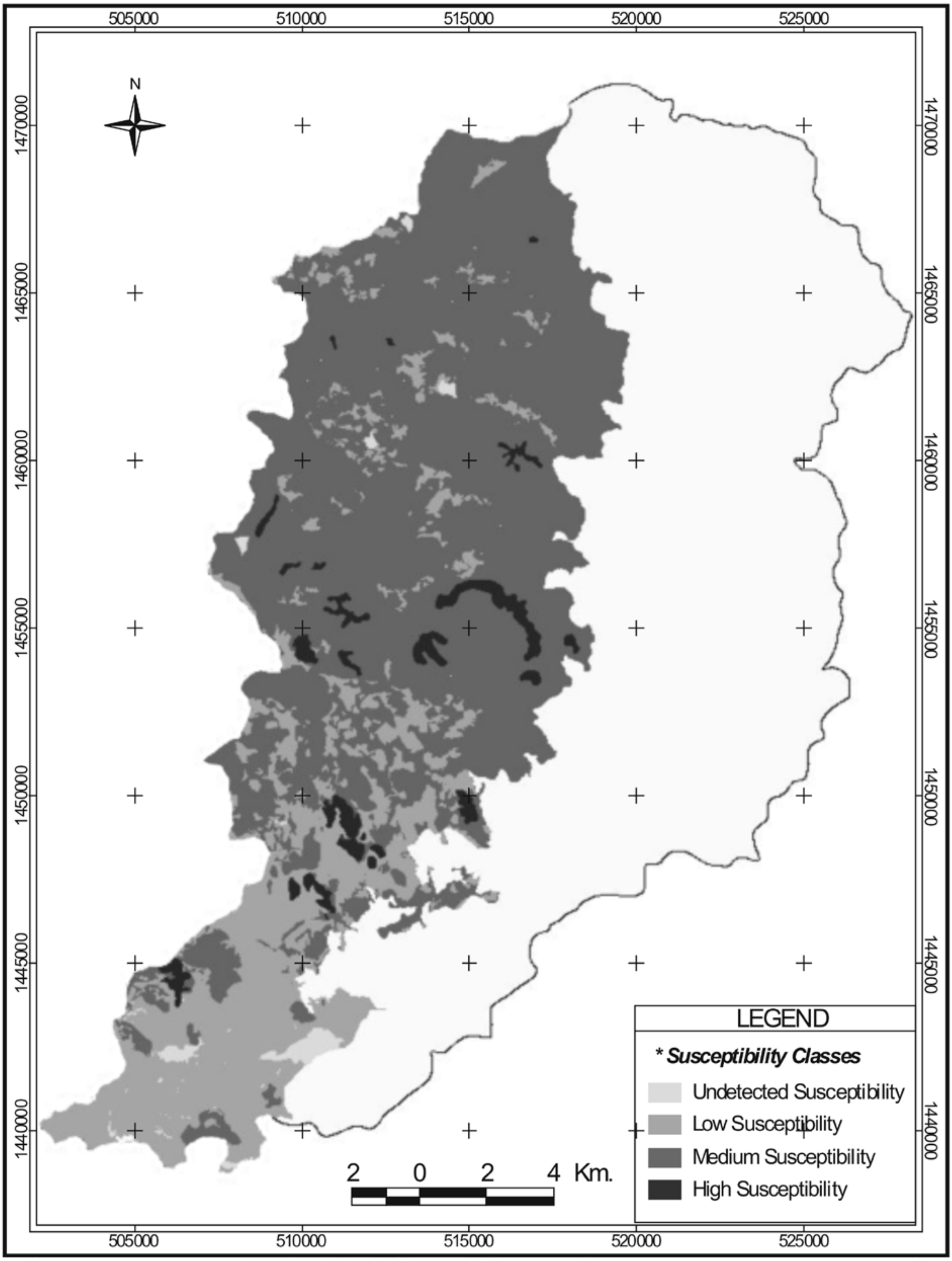


Fig. 6_ Guinau et al.

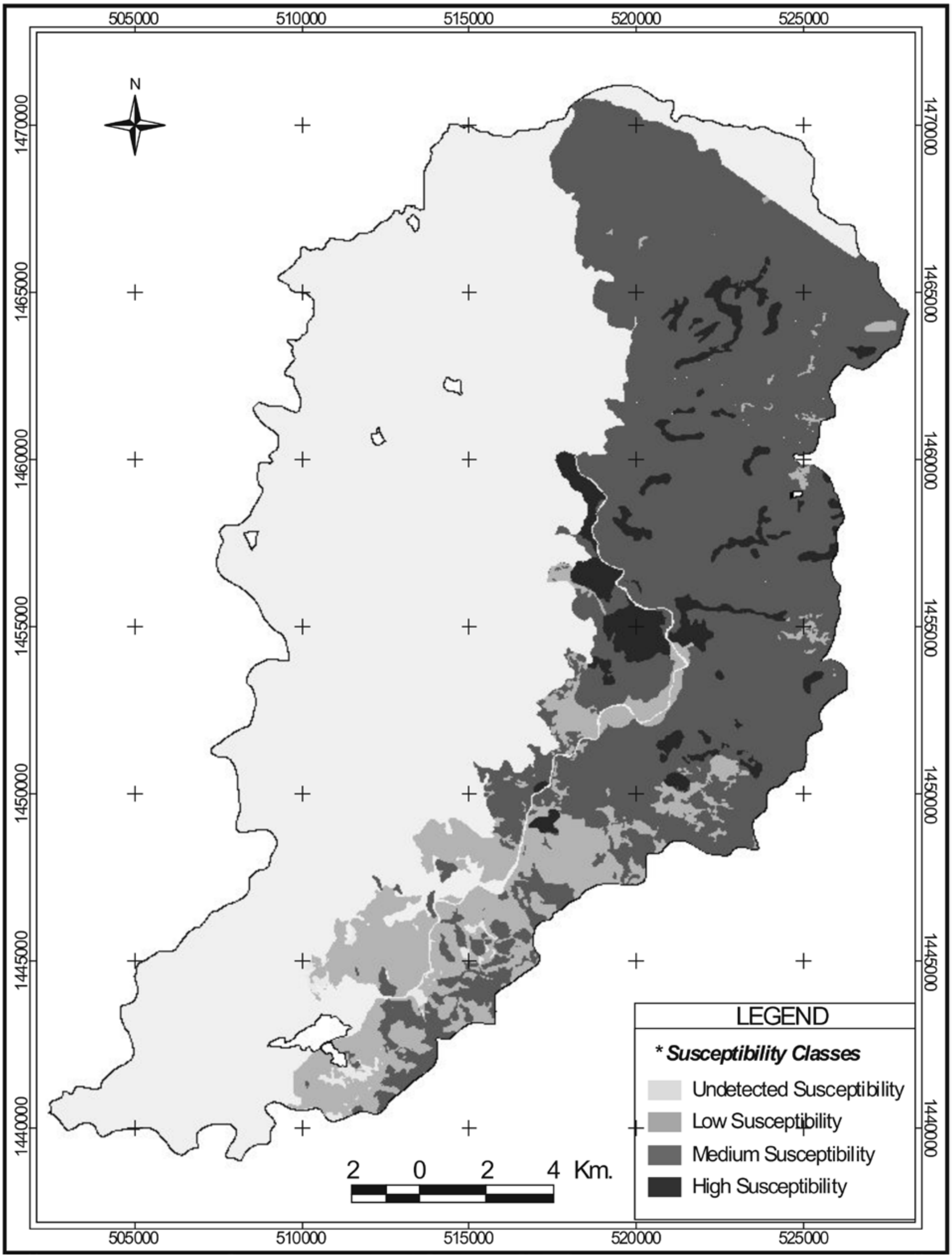


Fig. 7_ Guinau et al.

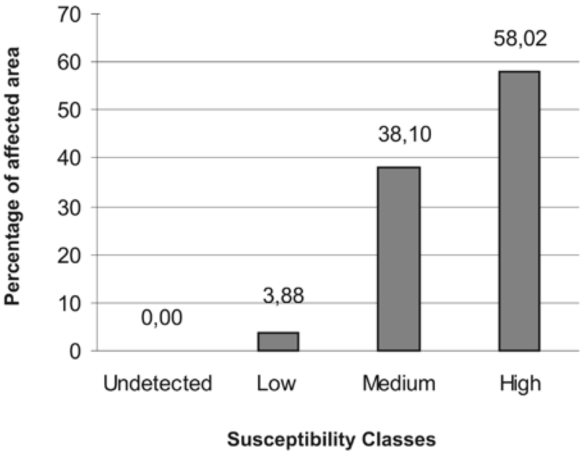


Table 1_ Guinau et al.

Table 1: Example of the Terrain Units and the weights associated to their classes. Cumulative values are shown on the right column.

Terrain Unit Code	Slope Class Weight	Lithology Class Weight	Soil Thick. Class Weight	Soil Texture Class Weight	Land Use Class Weight	Cum. Value
Gacc/G4F	<30º = 0,32	Granite = 0,45	Low = 0,00	Gravel = 0,31	Forest = 0,13	**ΣW = 1,21**
Dvac/B3S	8º - 15º = 0,00	Tertiary V = 0,20	High = 0,33	Mud = 0,03	Cultivate = 0,10	**ΣW = 0,66**
Iva/B6L	0º - 4º = 0,00	Quat V = 0,00	Medium = 0,18	Sand = 0,20	Pasture = 0,22	**ΣW = 0,60**
Ava/F4M	10º - 30º = 0,30	Alluvial = 0,00	Low = 0,00	Gravel = 0,31	Bush = 0,21	**ΣW = 0,82**
Dplcc/D5L	0º - 4º = 0,00	Tertiary V = 0,20	High = 0,33	Gravel = 0,31	Pasture = 0,22	**ΣW = 1,06**
Dvacc/C6M	4º - 8º = 0,00	Tertiary V = 0,20	Medium = 0,18	Mud = 0,03	Cultivate = 0,10	**ΣW = 0,51**

Tertiary V: Tertiary Volcanic Rocks (Andesite, Dasite and Basalt) and Quat V: Quaternary Volcanic Rocks (Ignimbrite and Pyroclast)