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A pragmatic approach to debris flow hazard mapping in areas affected by Hurricane Mitch: example from NW Nicaragua

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Abstract

Although developing countries are vulnerable to landslide hazard, they generally lack policies for hazard assessment and mitigation. This may be attributed to the scarcity of good quality data on which to base any sound hazard assessment in addition to insufficient funds and lack of political will. Thus, there is an urgent need for developing feasible methodologies of landslide hazard assessment and mitigation, which can be readily tested and implemented under the conditions found in these countries. To this end, we selected an area of about 20 km^2 badly affected by Hurricane Mitch in October 1998, in the Departamento de Chinandega (NW Nicaragua). Mass movements (mainly debris flows) produced during the Hurricane Mitch rainfall event were investigated using two sets of aerial photographs at 1:60,000 and 1:40,000 scales. Data concerning regolith composition and thickness, landslide dimensions, failure slope angle and land use were obtained for 150 mass movements, and over 450 landslides were mapped at 1:10,000 scale in the field. A pragmatic approach was used to produce a qualitative hazard (sensu lato) assessment, based on the concepts of *number of events recorded*, *predictability* and *susceptibility*. This case study shows that a hazard assessment that is useful for management may be possible even where data are limited. Despite its inherent limitations, similar pragmatic approaches could help the sustainable development of other rural and sparsely populated areas of Central America.

Keywords: Landslide mapping; Landslide hazard mapping; Debris flows; Developing countries; Nicaragua

1. Introduction

Developing countries are prone to natural disasters. Not only are these countries situated in areas exposed to geological and climatic hazards, but they are also, and most importantly, vulnerable to socio-economic factors (Alcántara-Ayala, 2002, in press). These countries pay a high price in human life, loss of fertile soils and pasture land as well as destruction of property and infrastructure. Given that the infrastructure is generally basic and relatively inexpensive, economic loss due to natural hazards in developing countries is smaller than in industrialised ones (Alexander, 1995; McGuire et al., 2002). Nevertheless,

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these comparatively small losses still correspond to a large proportion of their GDP (Alexander, 1995; Alcántara-Ayala, 2002), resulting in long periods of recovery, which severely slow down or prevent growth in the long term. Although natural disasters are clearly a limiting factor for societal and economic growth, developing countries often lack policies for disaster prevention and mitigation.

Landslides cause loss of life and much devastation. They are widespread in areas prone to extreme rainfall and/or areas susceptible to seismic shaking, commonplace conditions in many developing countries. Loss of life attributed to earthquakes is, in many cases, caused by the devastating effect of seismically triggered landslides (Carrara et al. 1999; Guzzetti, 2000; Bommer and Rodríguez, 2002). This implies that mass movements are probably responsible for many more casualties than is generally recognised.

Developing countries are in urgent need of feasible methodologies of landslide hazard assessment and mitigation. *Feasibility* means that the methodologies should be simple and inexpensive, so that they can be learned and readily applied to large territories by governmental or nongovernmental agencies. The aim of the present paper is to provide a feasible approach to hazard mapping centred in a test area in the Departamento de Chinandega, NW Nicaragua.

1.1. Study area

The study area is located in the Interior Highlands of Nicaragua (Fig. 1), an extensive and heavily dissected volcanic plateau (Mc Birney and Williams, 1965; Fenzl, 1988). This region is mainly formed of Tertiary volcanic rocks of the Matagalpa and Coyol groups (Weyl, 1980), and sparse Tertiary plutonic intrusions (unpublished maps). The Oligocene Matagalpa Group is mainly characterised by rhyolitic to dacitic pyroclastic flows and falls, and rare epiclastic deposits, whereas the Miocene–Pliocene Coyol Group is dominated by basaltic to rhyolitic lavas, breccias, lahars and pyroclastic flows (Ehrenborg, 1996). The volcanic succession is cut by extensional faults and basaltic to rhyolitic dikes, and is affected by low-grade burial metamorphism and, locally, by strong hydrothermal alteration (Darce et al., 1989; Ehrenborg 1996). Due to the relatively complex geology, and the fact that bedrock exposures are scarce due to thick regolith and vegetation cover, geological mapping is poor in most areas, including the one under study.

Fig. 1. Location of the study area and localities referred to in the text. The path of Hurricane Mitch is shown in dark grey, based on USGS (1999) data.

Our pilot study is focused on the Cinco Pinos and San Francisco del Norte municipalities (Departamento de Chinandega). The area displays a hilly landscape and is 300 to 700 m in altitude (Fig. 2). It began to be settled approximately one century ago, and since then most of what used to be thickly forested land has been converted into bush land (about 50% of the area), degraded pastures (about 30%), agricultural fields (15%) and open forest (3%) (Consorcio-BIT, 1999b). The economy, which is among the poorest in the country, is based on subsistence corn, bean and cereal agriculture, and, to a lesser extent, on cattle (Consorcio-BIT, 1999b). The two municipalities number over 14,800 inhabitants (Consorcio-BIT, 1999a,b). The environment is being subjected to increasing pressure given the considerable demographic growth of the last decades. Traditionally, settlements were sparse, and construction materials consisted of locally available adobe and wood. Present demographic pressure is

Fig. 2. General aspect of the study area. View looking west from Cerro Chávez (Fig. 4C). Cerro Morroñoso is on the left, and Cerro Nancital on the background. White patches correspond to large debris flows and areas affected by rockfalls, which were triggered by Hurricane Mitch.

producing a rapid shift towards small and denser concentrations of housing promoted by international nongovernmental organisations.

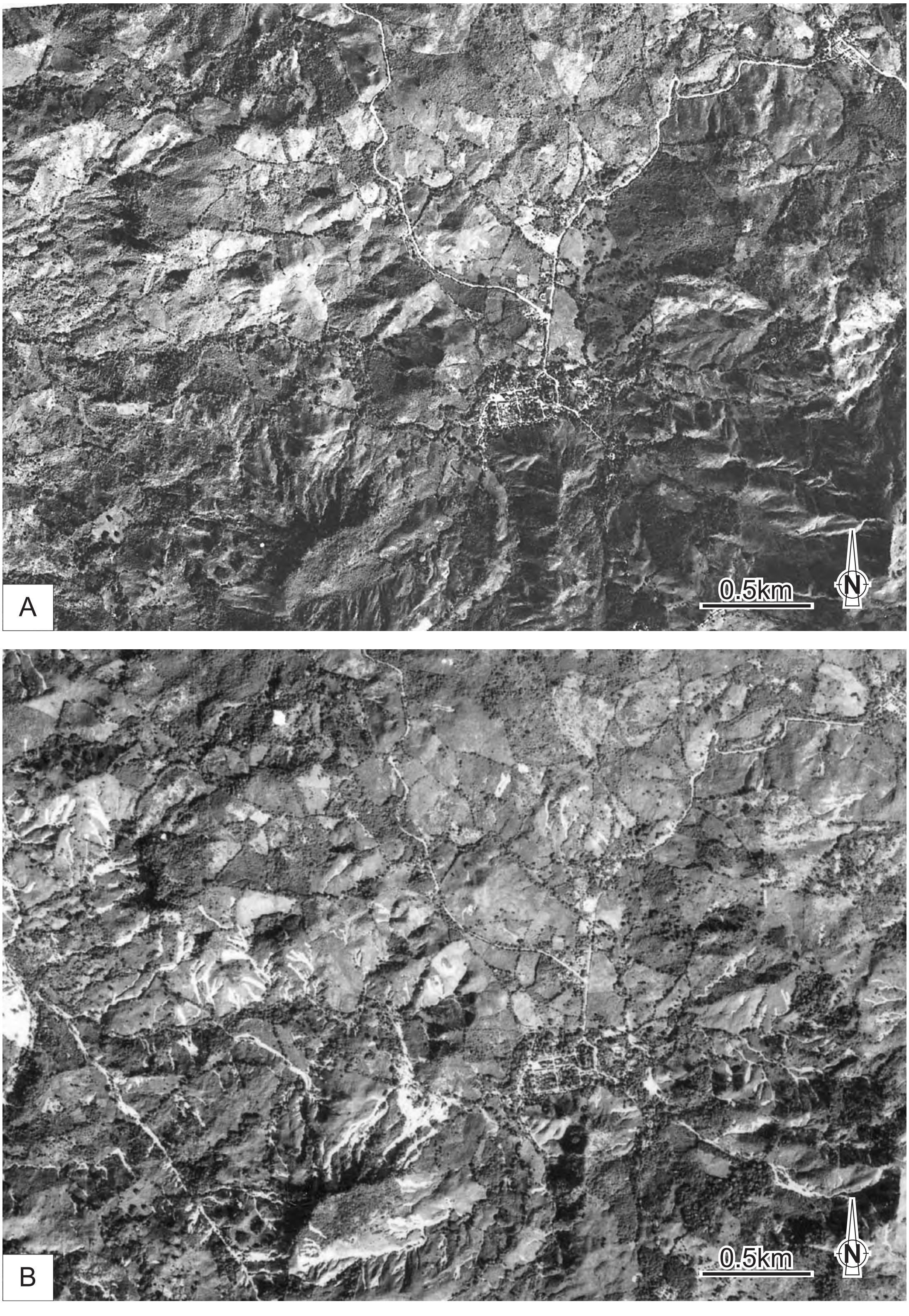
At about 13°N latitude, the region is affected by a savannah climate, with a marked dry season (November to April), which accounts for only about 10% of the annual rainfall (Fenzl, 1988). Like many regions in Nicaragua, Honduras and in El Salvador, the area under study was severely affected by Hurricane Mitch between 28 and 31 October 1998 (USGS, 1999, Fig. 1). In 10 days, 1597 mm were registered in Chinandega, corresponding to 86% of the local mean annual rainfall (INETER, 1998). Based on rainfall data from 1966 to 1998, the return period of the Hurricane Mitch rainfall event was calculated as greater than 100 years for Chinandega (INETER, 1998). The exceptional rainfall event associated with Hurricane Mitch caused extensive damage in the Departamento de Chinandega because of flooding and landsliding. In the Cinco Pinos and San Francisco area, landsliding was the main destructive process experienced, with an estimated 32% of the total population affected by property loss or damage (Solidaridad Internacional, unpublished data).

2. Data and methods

The 1:50,000 topographic base (INETER, 1990) was enlarged by a conventional large-format copier to 1:20,000 scale and was digitised. Printouts of the resulting digital base were plotted at 1:10,000 scale to facilitate mapping tasks in the field. Two black and white aerial photographs sets were available: (1) a 1:40,000 flight from 11 January 1996 (prior to Hurricane Mitch, hereafter referred to as *pre-Mitch*) and (2) a 1:60,000 flight from 4 December 1998 (1 month after Hurricane Mitch, hereafter referred to as *post-Mitch*) (Fig. 3). A detailed study of these two sets of photographs allowed a pre-selection of interesting localities.

Landslide mapping was restricted to three areas (Fig. 4A–C), covering a total area of 19.9 km^2. These target localities were selected on the basis of (1) high landslide density, (2) varied bedrock, (3) presence of vulnerable elements such as settlements and roads, (4) wide range in landslide typology and size, and (5) relatively good accessibility.

Bedrock is generally covered by in situ regolith and/or colluvial soil. Regolith in plutonic areas was sandy, highly porous, commonly including granite corestones, and had a yellowish colour. This was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clearly distinguishable from regolith in volcanic areas, which had a finer texture and was dark brown to reddish in colour. Volcanic regolith displayed homogeneous features regardless of specific lithologies. Superimposed on the regolith, most outcrops showed a widespread pervasive colluvium, consisting of massive diamicton, which included angular to subangular rock fragments of local lithologies, ranging up to block size, in a sandy to lutitic matrix.

Two years after Hurricane Mitch, most large to medium mass movement scars were still clearly visible on the landscape and were easily mapped in the field. In contrast, most accumulation areas and small landslides were already overgrown with vegetation, and could only be detected as highly reflective areas in the post-Mitch aerial photographs (Fig. 3B). Moreover, the pre-Mitch aerial photographs, despite the vegetation cover, showed scars, gullies and irregular lobated slopes, revealing extensive slope instability older than 1998. Systematic enquiries to locals about pre-Mitch instability events yielded little information, probably because of the relatively recent settlement in most areas, and because of the overwhelming memory of the Hurricane Mitch event. Qualitative temporal information on landslide activity was reflected in the landslide inventory map (Fig. 4A–C) to show which mass movements corresponded to instability prior to Hurricane Mitch, which ones were associated with Hurricane Mitch, and which were active in both periods (i.e. reactivated).

A range of landslide typologies was observed, including debris flows, earth flows, and rockfalls (classification based on Varnes, 1978). Debris flows were characterised by curved crown scarps (sometimes showing some translational slide blocks at the crown), a large length-to-width ratio, and a lack of clear morphology in the accumulation areas. Earth flows were large mass movements ($>60 \times 10^3$ m^2) with small length-to-width ratios characterised by lobated accumulation areas, and showing, in some cases, a rotational slide component at the head. Areas affected by rockfall were restricted to steep sloping bedrock outcrops, locally involving accumulation of large volumes of fresh angular bedrock fragments. Debris flows were the most abundant type of mass movement, accounting for 98% of the 458 landslides mapped and affecting 1.54×10^6 m^2. Earth flows and areas affected by rockfalls shared the remaining 2% of the total landslides mapped, affecting 0.65×10^6 and 0.73×10^6 m^2, respectively.

Apart from mapping the type, extent and timing of landslides, field work was aimed at obtaining a large number of in situ observations and measurements in the source area. Slope angles at debris flow scars were measured with the aim of establishing the original topographic gradient where failures occurred. Measurements were taken visually by a clinometer along the escarpment flank, as observed from the opposite flank, with an accuracy of $\pm 2°$. Slope angles at 130 debris flow scars were measured, 97 corresponding to areas with volcanic bedrock and 33 corresponding to areas with plutonic bedrock. Debris flow volumes were deduced by estimating scar length, width and depth, and ranged from several tens of cubic metres to 10^5 m^3.

3. Data analysis and interpretation

3.1. Materials affected by instability

The homogeneity of regolith in volcanic areas suggests that the weathering patterns of the volcanic rock types found in this area may yield relatively homogeneous results, probably resulting in similar behaviour with regard to slope instability. This justifies a distinction of bedrock lithologies limited to two generic types: volcanic and plutonic.

The regolith has a maximum measured thickness of 2.5 m, and is commonly covered by a widespread sheet of colluvium, with a measured thickness ranging between 0.1 and 2.5 m. The fact that it supports a well developed organic soil and is often present under thickly forested areas is indicative of former long-term (Pleistocene? or Holocene?) slope activity.

Fig. 3. Cropped and enlarged aerial photographs corresponding to the San Francisco del Norte area (Fig. 4C). Compare photograph (A), taken prior to Hurricane Mitch, from (B) taken after Hurricane Mitch. White patches on (b) correspond to large debris flows and areas affected by rockfalls triggered by Hurricane Mitch. Graphic scale is approximate. The area is illuminated from the south; rotate 180° for easier relief appreciation.

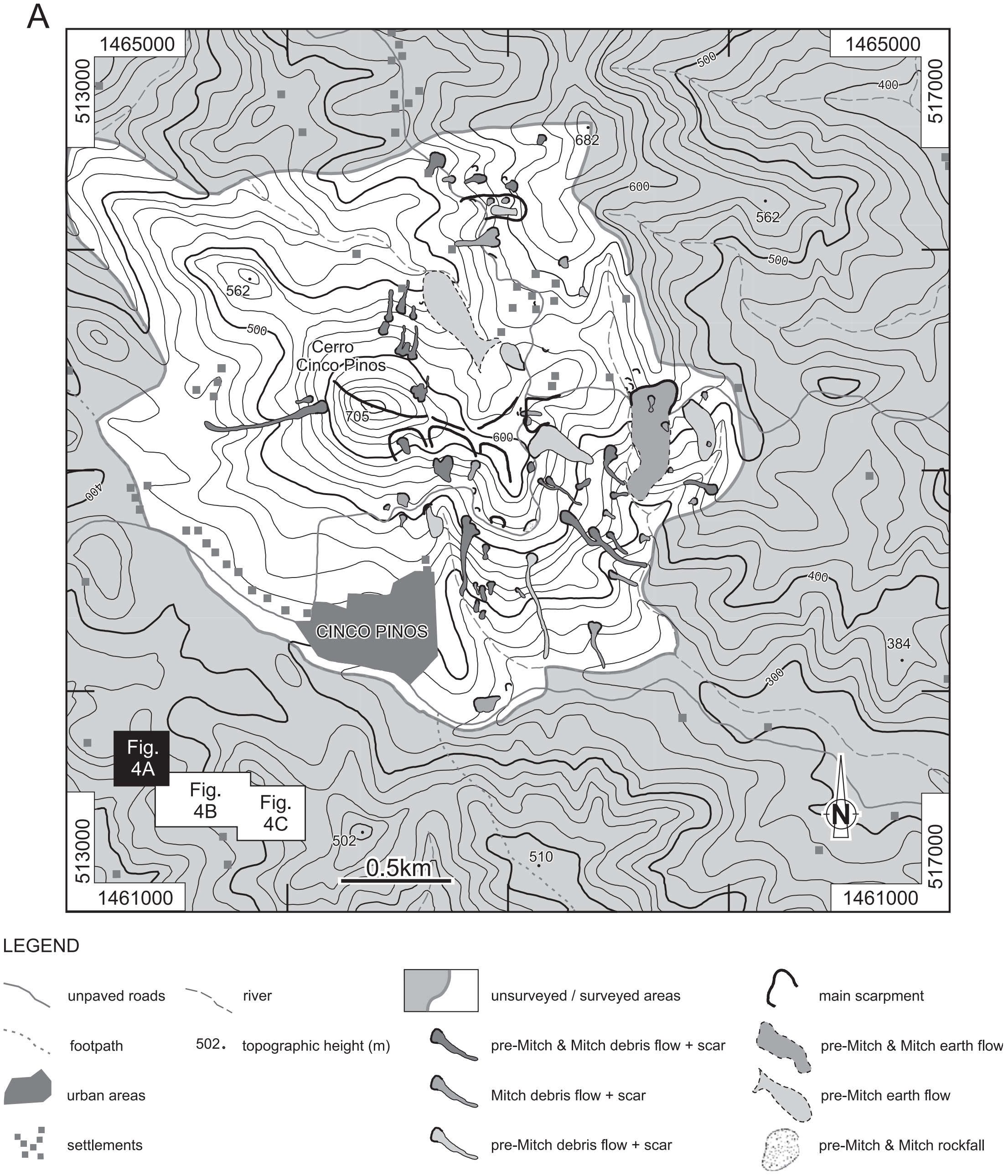

Fig. 4. (A) Landslide inventory map of the Cinco Pinos area. Elevations are in m, and coordinates are Transverse Mercator. (B) Landslide inventory map of the Cerro San Diego and El Nancital areas. Elevations are in m, and coordinates are Transverse Mercator. (C) Landslide inventory map of the San Francisco del Norte area. Elevations are in m, and coordinates are Transverse Mercator.

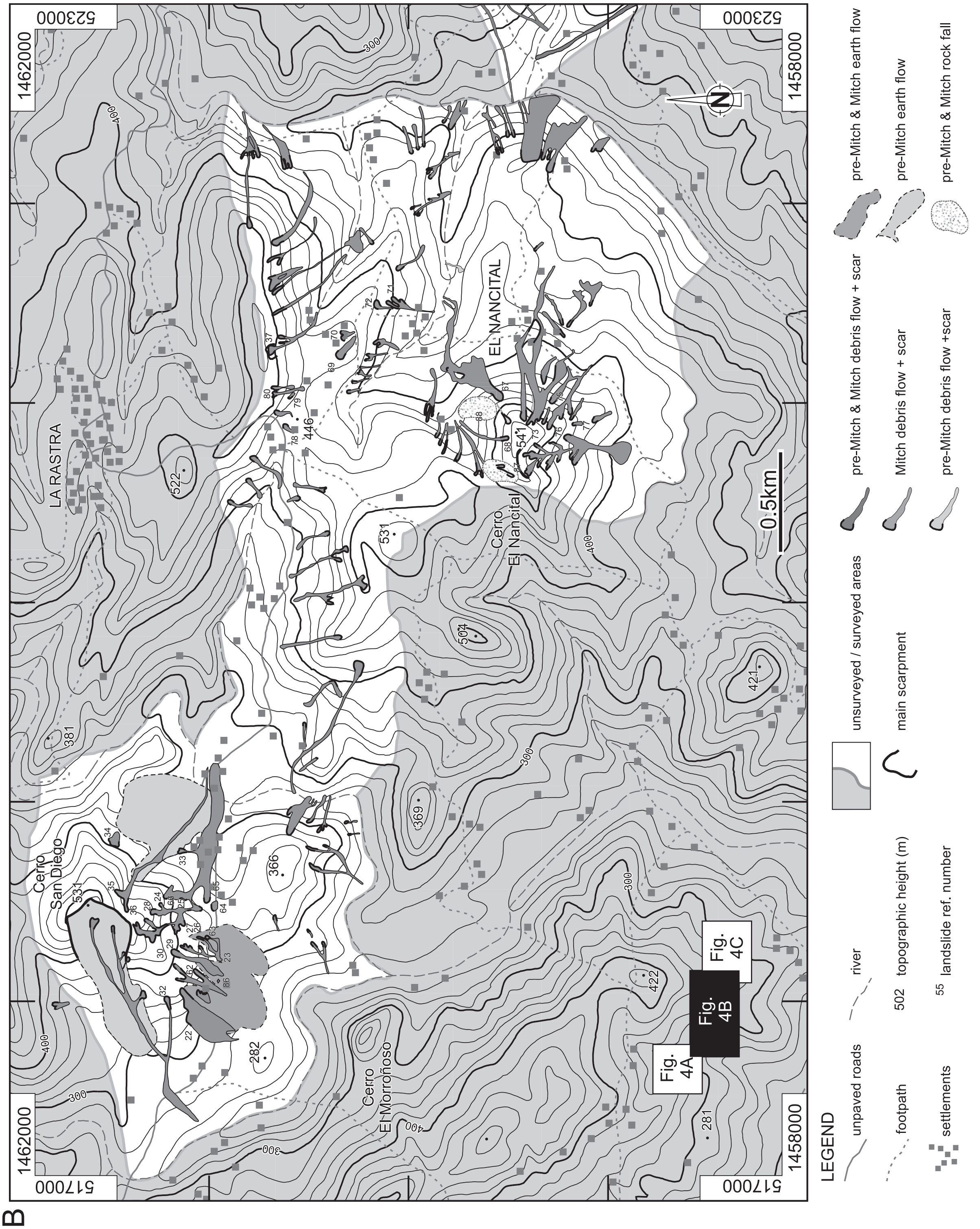

Fig. 4 (*continued*).

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Landslides in the area generally affect colluvium (where present), and part or all of the regolith. The accumulation areas of large debris flows often show large blocks (up to several metres in diameter) derived from corestones included in the original regolith. Bedrock is rarely entrained, and only in the areas affected by rockfalls.

3.2. Typologies of mass movements: occurrence

Single debris flows were smaller than single earth flows and than the areas affected by rockfalls, but debris flows were the most widespread and most common landslide typology (98% of mapped landslides). The abundance of debris flows observed during Hurricane Mitch is evidence that this must be the favoured rainfall-induced landslide type in this region. According to the post-Mitch aerial photographs and to information obtained through enquiries with locals, most debris flows active during Hurricane Mitch travelled long distances, merging into the drainage network. Thus, there must have been a gradual transition between debris flows, hyperconcentrated flow, and fluvial bedload. Although landslide types other than debris flows are extensive, they are of local occurrence.

3.3. Failure angle of debris flows

When considering both volcanic and plutonic bedrock areas, the sample of 130 measured debris flow failure angles ranged from 20° to 49°. To detect any difference in behaviour between volcanic and plutonic bedrock areas, both subsamples were plotted separately (Fig. 5). To determine the areas with slope angles susceptible to failure, we must focus on the lowest angles of the total range rather than on the central values of the population. The plutonic subsample is close to a normal distribution, with the exception of a sharp drop in frequency at angles lower than 25°, with no angles measured in the 20–24° range. This may be due to undersampling, or to the fact that slopes below 25° may be underrepresented in plutonic areas. This suggests that the lower values of the population may be around 20° not only for volcanic bedrock but also for plutonic bedrock areas. Thus, 20° may be taken as the threshold stability angle of debris flows triggered by the rainfall conditions experienced during the Hurricane Mitch event.

4. Approach to hazard (sensu lato) analysis

The concept of natural hazard, as defined by Varnes (1984), refers to the probability of occurrence of a potentially damaging phenomenon within a given area and within a given period of time. It is generally acknowledged that this definition involves the concepts of *geographical location*, *magnitude* and *frequency* of events (e.g. Guzzetti et al., 1999). In the study area, quantitative information is not available to establish the magnitude or frequency of landslides and, hence,

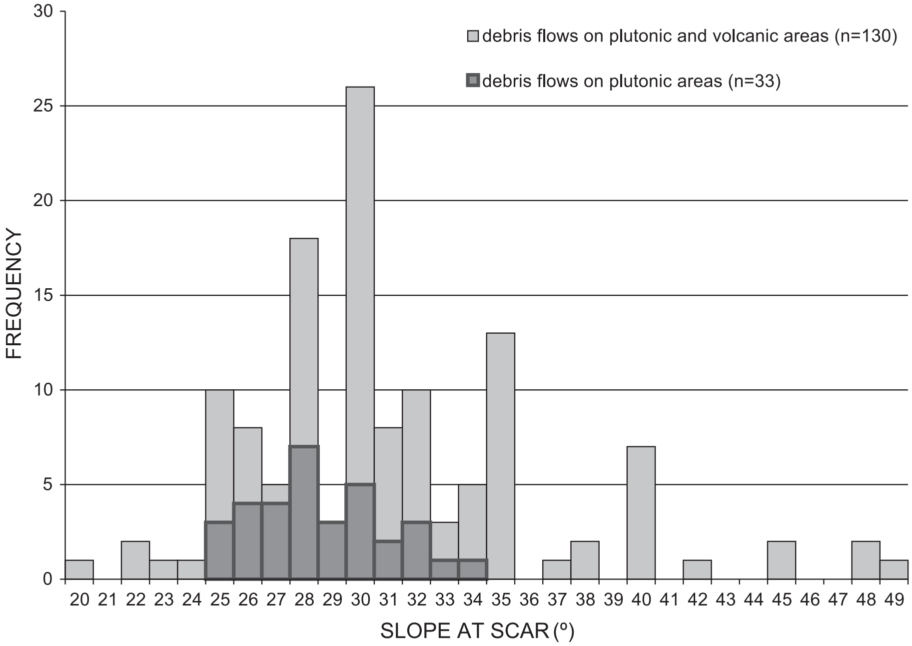

Fig. 5. Frequency distribution of debris flow failure angles measured in the field. The histogram in dark-grey corresponds to angles measured both in volcanic and plutonic areas. The superimposed histogram in white corresponds to angles measured in plutonic bedrock areas.

hazard cannot be quantified. To map areas with different degrees of exposure to potentially hazardous phenomena, we adopt a pragmatic approach based on a combination of concepts which are related to hazard and to some extent to vulnerability. While acknowledging that the concepts included in our analysis do not conform with the strict definition of *hazard*, we use, in the present paper, the term *hazard* (sensu lato) to refer to exposure to potentially damaging mass movements once preventive action (such as regular inspection of unstable areas and implementation of a warning system) has been taken. The term *risk* is not used in the absence of a comprehensive vulnerability assessment. In this section, the main ideas and limitations underlying our hazard (sensu lato) analysis are discussed, including the concepts of magnitude, frequency, number of events recorded, predictability and susceptibility.

4.1. Ruling out the application of magnitude

In principle, large magnitude landslides will be more hazardous than smaller ones. Nevertheless, the extreme fragility of all man-made structures found in the area implies that total destruction can occur whatever the magnitude of a destructive phenomenon; even the smallest magnitude phenomenon observed has the potential for causing extensive damage and loss of life. This means that in this specific case the concept of magnitude is not of practical use for differentiating between degrees of hazard.

4.2. Number of events recorded as an approach to frequency

Quantification of landslide hazard implies determining the *frequency* of instability phenomena. If several sets of aerial photographs are used, the frequency of slope failures can be determined (e.g. Guzzetti et al., 1994; Ibsen and Brunsden, 1996). Given the fact that only two sets of photographs are available in the study area, only a qualitative and imprecise approach to the temporal behaviour of mass movements can be attempted. The concept closest to frequency that can be estimated in this case is the *number of events recorded*; slopes which failed several times in the past may be considered more hazardous than slopes which failed only once. Thus, in descending order of a hazard scale, slopes can be classified as (1) *two events recorded* (i.e. pre-Mitch + Mitch), (2) *one event recorded* (i.e. pre-Mitch or Mitch) and (3) *no event recorded*.

4.3. Predictability

Providing that the areas prone to landsliding are monitored (e.g. inspection by trained locals) and that some kind of warning system is implemented, the most hazardous mass movements are the ones which activate rapidly, without giving any external warning signs. Mass movements which start slowly and provide some warning indicators (e.g. slow movement, tilting of trees or houses, opening of cracks) may be considered less hazardous since they allow sufficient time for evacuation. This concept will be referred to here as *predictability*. In descending order of a hazard scale, slopes can be classified in the study area as follows: (1) *non-warning*, including debris flows and rockfalls; and (2) *warning*, including earth flows.

4.4. Susceptibility

The concepts of *number of recorded events* and *predictability* introduced above may be useful for a qualitative hazard assessment of areas where past mass movements had been detected. Nevertheless, areas where no activity has been previously detected may also be prone to instability and should be considered in the hazard analysis. We include these areas in the analysis using the concept of *susceptibility*, defined as the probability of occurrence of a landslide event (Dai et al., 2002). The susceptibility of a slope to failure will be high if it has the same combination of instability factors as the areas that failed several times in the past. Rainfall-triggered debris flows may be affected by a complex combination of topographic, lithologic, and land use factors (Dai et al., 1999; Zhou et al., 2002; Lorente et al., 2002). Thus, the relationship between these factors would need to be addressed to establish the susceptibility of a slope to debris flows. Such a quantitative susceptibility analysis falls outside the scope of the present study given the lack of data. Nevertheless, a simplified qualitative approach to susceptibility is still possible. Based on the range of slope gradients measured in the field, we can assume that debris flows are more likely to occur on slopes above a certain gradient threshold. This is the case, at least, when an extremely intense trigger (such as Hurricane Mitch) is used as the reference event. Although this might also be true for other factors, such as distance to divide, or contributing area (Baeza and Corominas, 1996), we focused our attention on the topographic gradient because it is simple to measure and readily available in the field and from a DTM. According to the sample of debris flow failure angles, the threshold above which debris flows may occur during extreme rainfall events in the study area can be established at around 20°. Thus, as a first approach, slopes with gradients equal to or greater than 20° can be considered as susceptible to failure, and could act as source areas for debris flows. The areas susceptible to debris flows

Fig. 6. Example of the susceptibility map corresponding to the Cinco Pinos area (locality in Fig. 4A). Areas highlighted in grey correspond to the ones sloping equal to or higher than 20°, and are the ones considered susceptible to failure. Flow lines correspond to possible debris flow paths, taking the areas highlighted in grey and mapped scars as possible source areas. See text for detailed discussion.

include these source areas together with the runout zone. Accordingly, in descending order of the hazard scale, we are able to differentiate between the areas that are (1) *susceptible*, and those that are (2) *non-susceptible* to debris flows.

5. Approach to hazard mapping

5.1. Determining the areas potentially prone to debris flows

A Digital Terrain Model (DTM) was obtained from the digitised 1:50,000 topographic map (contour spacing of 20 m), and a Triangle Irregular Network (TIN) was generated. The TIN model included all the original data points digitised from contour lines, talveg break lines and single elevation points, with no filtering. Based on the TIN model, a slope map was constructed to highlight areas with topographic gradients equal to or higher than 20°. These are the areas considered to be susceptible to debris flow failure. The problem of estimating the runout distance of landslides can be simplified by considering the fact that, in these areas and under intense rainfall events, debris flows tend to travel long distances merging with the drainage network. Debris flows follow the maximum slope and often grade to hyperconcentrated flows and to fluvial bedload while maintaining or increasing most of their destructive power. Flow lines were generated automatically following the maximum slope of the TIN facets, starting from the areas highlighted in the slope map (those considered susceptible to failure, Fig. 6). The starting points were selected by hand to obtain the widest possible assemblage of flow lines for each slope. The resulting flow

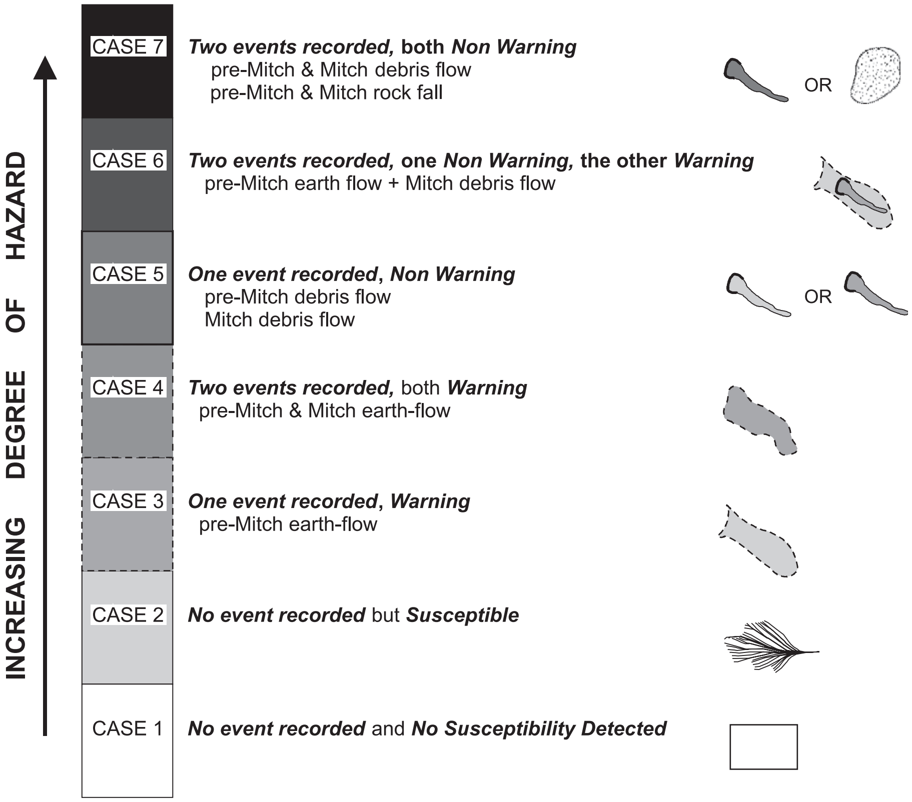

Fig. 7. Range of possible cases from higher to lower hazard. The symbols at the right-hand side are in correspondence with the legend in Fig. 4. Different cases, 1 to 7, correspond to the seven degrees of hazard distinguished in the hazard map (Fig. 8). See detailed discussion in text.

lines merged together along the drainage network and their downslope length was only limited by the extent of the DTM (Fig. 6). The areas potentially affected by debris flows correspond to the union of areas sloping ≥ 20° and the areas crossed by the flow lines.

In principle, an accurate DTM should produce a slope map in which the debris flow scars measured in the field should always coincide with the highlighted ≥ 20° range. Comparison of the mapped scars and the highlighted areas in the slope map (Fig. 6) reveals that 28% of the scars do not match the slope areas in the model. This indicates that the DTM does not describe all the relevant topographic variations in sufficient detail for an accurate slope map to be constructed. A second set of flow lines were generated using the mapped scars as possible source areas in order to

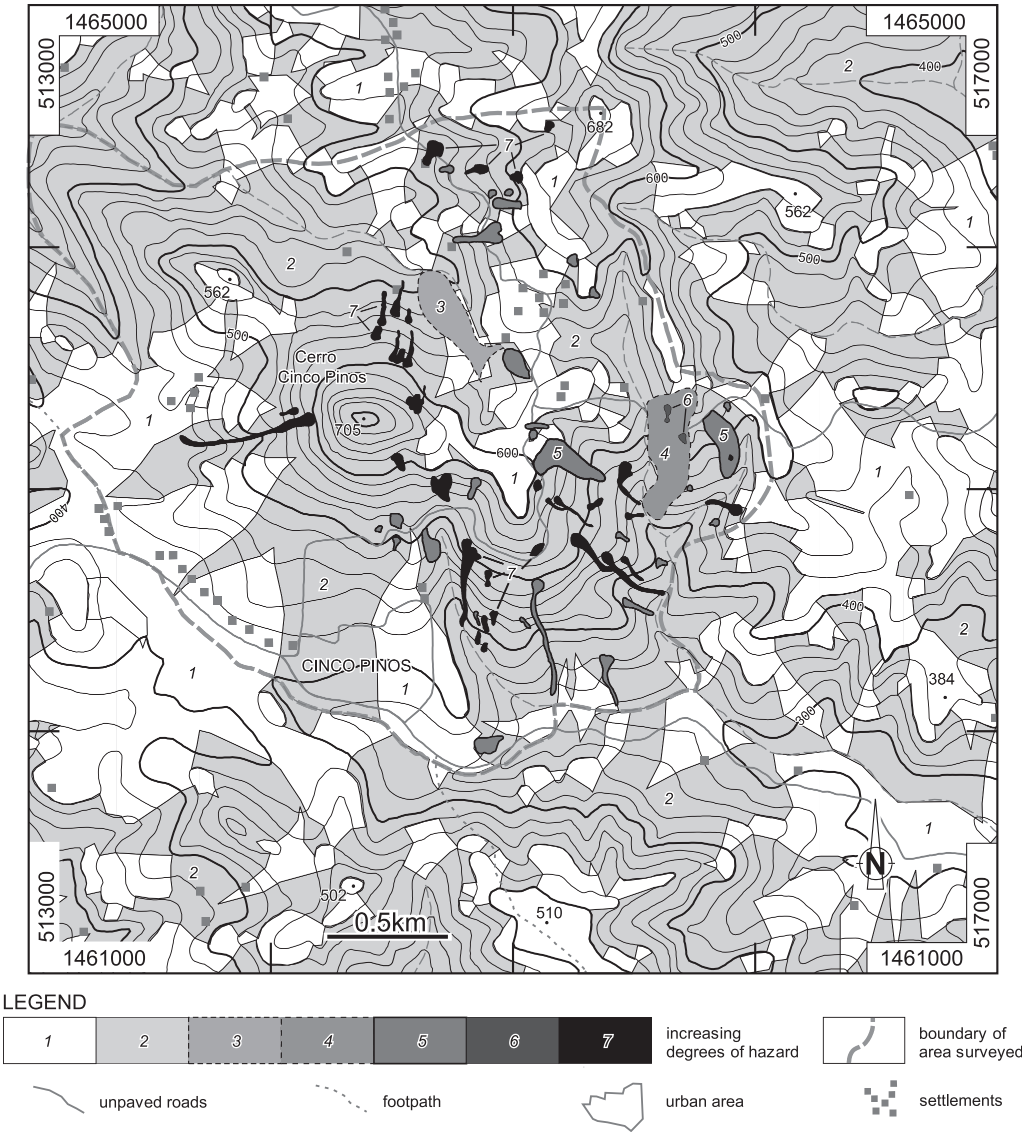

Fig. 8. Example of the landslide hazard map corresponding to the Cinco Pinos area (locality in Fig. 4A). See detailed discussion in text.

minimise the effect of the low resolution of the DTM (Fig. 6).

5.2. Constructing the landslide hazard map

In the study area, there are three concepts which can be used to qualitatively establish different degrees of hazard: *number of events recorded*, *predictability* and *susceptibility*. Each of these concepts allows us to differentiate between a number of situations, and their combination yields seven cases which can be ranked on a hazard scale (summarised in Fig. 7). Cases 1 and 2 correspond to areas with no recorded activity, whereas Cases 3 to 7 correspond to areas where past mass movements had been detected. Note that areas classed as *one event recorded* but showing some *non-warning* phenomena (Case 3) were considered more hazardous than areas classed as *two events recorded* but showing only *warning* landslides (Case 4). The order of the seven cases forms the basis for the construction of the hazard map (Fig. 8).

6. Discussion

Throughout the process of the hazard map generation, there were a number of key steps in which errors were inevitably introduced. Despite the care taken throughout the generation of the DTM, subsequent checking showed maximum horizontal discrepancies of about 15 m between the original and the digitised contours. These inaccuracies, introduced in the copying and digitising stages, may have produced errors as large as ± 5° for slopes around 20° in the angles calculated from the DTM. Although substantial, these errors occurred only locally. The mismatch between mapped scars and the slope map discussed in Section 5.1 is mainly due to a much more important limitation: the low resolution of the 1:50,000 topographic base. This is the source of the low resolution of the DTM and the source of the low resolution of the susceptibility map (Fig. 6). As a result, the boundaries between *susceptible* and *nonsusceptible* areas in the hazard map can only be seen as approximate.

The final hazard assessment is mainly based on the occurrence of and susceptibility to debris flows. This is in accordance with the (1) much larger proportion of debris flows (98%) triggered by rainfall events, (2) their large extent (affecting the 7.7% of the area surveyed) and (3) their low predictability. Of less relevance are rockfalls, which may be extensive and also difficult to predict, but which are restricted to the few areas where steep bedrock crops out. Earth flows also affect relatively large areas, but their contribution to hazard is relatively small because they occur only locally, and because their reactivation can be predicted if a simple warning system is implemented.

The present study implicitly uses the Hurricane Mitch rainfall event as a reference. Both the landslide map and the susceptibility map (Figs. 4 and 6) are based on data taken from landslides triggered during Hurricane Mitch. For example, all the measurements on slope angles have been taken from debris flows triggered by this extreme rainfall event. Slopes with gradients exceeding 20° could be more than sufficiently stable under most rainfall events and could be triggered only during extreme events such as Hurricane Mitch. Thus, the resulting hazard map (Fig. 8) should be seen as covering worst-scenario cases, involving rainfall intensities similar to the reference event. Obviously, if the recurrence interval of the reference event was very large, the resulting hazard map would be excessively pessimistic, would impose unnecessary constraints on management decisions, and would have the drawback of becoming costly. Nevertheless, the return period of around 100 years estimated for Hurricane Mitch rainfall at meteorological stations in the proximity can be considered suitable for the present assessment. In addition, the worst-scenario approach adopted has the advantage of providing a reassuring safety factor.

Despite the fact that Nicaragua is an area prone to seismicity, the mapping presented in this paper is only based on rainfall-triggered landslides. The possibility of earthquake-induced landsliding was not taken into account, which limits the validity of the resulting hazard assessment. In principle, there is a greater likelihood of seismic triggering of landslides during the wet season in the study area, when hydrologic conditions are more suitable. The preferred mass movement typologies triggered by earthquakes could differ considerably from those produced during rainfall events (Jibson, 1996). Some old (prior to Hurricane Mitch) and large landslides observed in the study area could have been triggered by seismic events rather than by rainfall. This could be the case of those mass movements not necessarily involving large amounts of water, such as earth flows and rockfalls. Nevertheless, according to Bommer and Rodríguez (2002), earthquakes in Nicaragua tend to trigger landslides over very small areas, suggesting that seismic triggering may be less relevant than in other areas of Central America.

It is commonly acknowledged that loss due to landslides can be considerably reduced by effective planning and management, which includes (1) restriction of development in susceptible areas, (2) development of warning systems, and (3) stabilisation of landslide areas by engineering works (Dai et al., 2002). The last line of action is not realistic in the study area given the large areas susceptible to landsliding, and the lack of funds. The approach and mapping presented in this paper could be implemented in management decisions and emergency planning in accordance with local needs. For example, new buildings and services could be restricted to areas where susceptibility has not been detected, while a local warning system and evacuation strategy could be developed for areas susceptible to landslides.

7. Conclusion

The most limiting aspect of the methodology suggested here is the low resolution of the DTM used to deduce the areas susceptible to debris flows. The same methodology could produce more reliable results if topographic maps at a resolution higher than 1:50,000 were available. A higher resolution DTM would permit further improvements by introducing into the analysis other morphological factors, such as the contributing areas to debris flow scars.

The most hazardous landslides in the study area are debris flows because they are the most widespread type of mass movement and because they are difficult to predict. The fact that landslide hazard is largely based on the occurrence of a single type of mass movement allows us to make a relatively simple approach to hazard assessment.

Landslide assessment is highly improved if an extreme event such as Hurricane Mitch can be used as a reference. Using extreme events has the advantage of providing a safety factor in hazard estimation. It is highly advisable to take full advantage of extreme events in order to produce consistent and complete landslide inventory maps. It is of paramount importance to undertake aerial photograph coverages immediately after any significant landslide-triggering event. If the effects of such extreme events are recorded and studied in detail immediately after their occurrence, a great deal of information and the opportunity of providing future hazard assessments with good quality data will not be lost.

The hazard map provided should reflect the hazard associated with landslides triggered only by rainfall. Although probably small, the seismic contribution to landslide hazard was not assessed.

On the basis of a pragmatic approach a qualitative hazard assessment is still possible in some cases even though the amount and type of data available is rather limited. Our approach has the advantage of being cost-effective and, although the resolution of the hazard map is low, the methodology is most helpful in highlighting the areas that are likely to be safe. This provides the local decision makers with guidelines on the areas to be settled, and on the most suitable land uses. Moreover, the information provided is useful for planning emergency strategies, and for raising the population's awareness of landslide hazard. We believe that a pragmatic and simplified approach similar to the one presented in this study could be helpful in reducing human and material loss in other rural areas of Nicaragua, Honduras and El Salvador.

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