Graziella Devoli · Wilfried Strauch · Guillermo Chávez · Kaare Høeg

A landslide database for Nicaragua: a tool for landslide-hazard management

Abstract A digital landslide database has been created for Nicaragua to provide the scientific community and national authorities with a tool for landslide-hazard assessment, emergency management, land-use planning, development of early warning systems, and the implementation of public and private policies. The Instituto Nicaragüense de Estudios Territoriales (Nicaraguan Geosciences Institute, INETER) began to compile the database in a digital format in 2003 as part of a comprehensive geographical information system for all types of geohazards. Landslide data have been obtained from a variety of sources including newspapers, technical reports, and landslide inventory maps. Inventory maps are largely based on fieldwork and aerial-photo analyses conducted by foreign development agencies in collaboration with INETER and other Nicaraguan institutions. This paper presents the sources of landslide information, introduces the database, and presents the first analyses of the data at national and regional scales. The database currently contains spatial information for about 17,000 landslides that occurred in mountainous and volcanic terrains. Information is mainly recorded for the period 1826–2003, with a large number of events that occurred during the disastrous Hurricane Mitch in October 1998. The oldest historical event is dated at 1570, some events are recorded as prehistorical, and other events have unknown dates of occurrence. Debris flows have been the most common types of landslides, both in volcanic and nonvolcanic areas, but other types, including rockfalls and slides, have also been identified. Intense and prolonged rainfall, often associated with tropical cyclones, and seismic and volcanic activity represent the most important landslide triggers. At a regional scale, the influence of topographic (elevation, slope angle, slope aspect) and lithologic parameters on the occurrence of landslides was analyzed. The development of the database allowed us to define the state of knowledge on landslide processes in the Nicaragua and to provide a preliminary identification of areas affected by landslides.

Introduction

In the Central American countries, landslides pose a significant threat. As developing countries often have economic, political, social, and cultural factors that increase the vulnerability to natural hazards, they pay a high price in terms of human life, loss of fertile soils and pasture land, as well as destruction of property and infrastructure every time a landslide or a triggering event resulting in landslides occurs. In Central America, major landslides take place almost every year, primarily during the wet season, which lasts from May to October. However, they also occur during the dry season when triggered by earthquakes and during volcanic eruptions.

Before October 1998, the risk posed by landslides in Nicaragua was generally underestimated both in scientific circles and in the general population. The situation changed when catastrophic landslides resulted from Hurricane Mitch. They caused severe damages to cultivated and pasture lands, which support the principal socioeconomic activities of the country. Communication lines were also seriously affected by the destruction of bridges and the blockage of national highways and rural roads, leaving many important towns and villages isolated. The destruction of numerous dwellings and the large number of victims (Table 1) resulted in the relocation and reconstruction of entire villages. In particular, debris flows constituted the most destructive landslide process (Guinau et al. 2005). The single debris flow at the Casita Volcano (Sheridan et al. 1999; Scott et al. 2005) took about 2,500 lives and caused a tremendous impact nationwide and unprecedented interest by the scientific community, government, international donors, and the mass media. The hurricane provided devastating evidence of human vulnerability to landslides and revealed the lack of information and studies on landslide-prone areas, the underestimation of the potential hazards, the scarcity of trained experts and technical facilities, and the absence of laws and policies for disaster prevention and mitigation. After the hurricane, the country was in need of considerable humanitarian relief and aid for reconstruction, and it received financial and technical support from national and international organizations in the form of development projects. Considerable efforts were also made to identify national disaster management strategies that later prompted a new law on natural hazard risk prevention and mitigation (Law 337 2000). This law puts more emphasis on predisaster action than on postdisaster reaction. International organizations, in cooperation with personnel of the newly created Landslide Unit at Instituto Nicaragüense de Estudios Territoriales (INETER), and other national institutions led numerous landslide investigations in areas most heavily impacted by the hurricane. For the first time, these studies included the systematic collection of landslide data (e.g., Cannon et al. 2002; Menendez-Duarte et al. 2003). As these data were scattered and heterogeneous, a more comprehensive collection and storage at national scale was needed in a format that was easy to access, manage, update, share, and distribute, and which was capable of responding to the requests of different users (national government, municipalities, Civil Defense, universities, private sector, and international donors).

The compilation of a landslide inventory that records, for a given area, the location and, where known, the date of occurrence, and the types of landslides, is the simplest initial approach to any study of landslide hazard (Carrara et al. 1995; Soeters and van Westen 1996; Dai et al. 2002; Guzzetti et al. 2003). In the last two decades, several efforts have been made by local, regional, national, and international organizations to design, implement, and

Table 1 Number of victims, affected peoples, and economical losses related to the Hurricane Mitch in Nicaragua compared with those related to the most damaging landslide triggered by the same hurricane

	Number of victims	Number of people affected	Economical loss
Hurricane Mitch	3,045*	867,752*	988,000 US$***
Casita volcano debris flow	2,513**	16,575**	Not recorded

It is important to note that the official loss data related to the hurricane take into account the total number of victims without differentiating between the number of victims due to floods and landslides. Source of information: *CEPAL, 1999, **Base de Datos Históricos sobre Desastres en Nicaragua (2005), ***Inventario de Desastres en Centro América 1960–1999 (2005)

maintain digital landslide inventories and thematic databases at the national scale in different countries (e.g., Guzzetti et al. 1994; Dikau et al. 1996; Guzzetti and Tonelli 2004; Gaspar et al. 2004; Fajfar et al. 2005; Colombo et al. 2005; GSI 2005; Glade and Crozier 1996; Dellow et al. 2003; Grignon et al. 2004).

This paper presents the first version of an integrated national landslide database established by collecting data from multiple sources and describes the utilization of the postdisaster aid offered by the international donors to build and support local capabilities in Nicaragua. The purposes of the paper are: (1) to describe the sources of landslide information available in the country; (2) to show the present state of landslide mapping in Nicaragua; (3) to perform some analysis of the spatial and temporal distribution of landslides, the types of slope movements, and the factors that affect the slope stability; and (4) to discuss results with respect to problems with the type of sources used, data type and generation, and lack of data. It is not the aim of this paper to discuss database design and structure in details.

This work is part of a more extensive research in which the applicability of the database is also tested through the analysis of historical landslides recorded before 1990, presented in Devoli et al. (2006), and through the statistical analysis used to understand the landslide dynamics and run-out distances for debris flows and lahars (Devoli et al., submitted for publication).

This version of the database includes all landslide data available up to 2005 and which temporally occurred until 2003. The database is not completed yet, and it is under development and updating at INETER, which is the national government institution responsible for the investigation, mapping, assessment, and monitoring of landslides in Nicaragua and also in charge of the dissemination of landslide information, public awareness, and emergency response. The Landslide Unit of the Department of Geophysics of INETER is now in charge of periodic maintenance and updating of the database. A second updating of the database is in progress with the aim of integrating the landslides that occurred after 2003, updating the existing information, and correcting the errors found in the database structure and design. At INETER, other applications of the information stored in the database are also under development. Landslide spatial information presented in this paper has been used to prepare a susceptibility map for all of Nicaragua (http://www.ineter.gob.ni/geofisica/desliza/com/20050519-Adrian/mora-NO.jpg) and to prepare maps showing the location of the recorded landslides in each municipality (http://www.ineter.gob.ni/geofisica/desliza/municipios/index.html). A map server is also under construction (http://mapserver.ineter.gob.ni/website/Mapas/desli/viewer.htm) to present and disseminate the available landslide information, and it will be similar to Web-based systems developed in Canada (Grignon and Bobrowsky 2005), Australia (GA 2004), Japan (LSJ 2004), Norway (NGU 2005), and Italy (CNR-IRPI 2004).

At the present time, the map server contains the version of the database presented in this paper.

No similar efforts seem to have been reported for other developing countries in Central America, and it is hoped that the present study is useful for countries who wish to establish a similar database.

Study area

Located in the central part of the isthmus of Central America (Fig. 1), Nicaragua covers an area of 130,370 km², 63% of which is predominantly flat with extensive coastal plains and small and isolated hills. Thirty-seven percent of the total land area is occupied by mountainous and hilly terrain and a line of active volcanoes, with elevations ranging from 200 to 2,107 m a.s.l. Nicaragua has a population of about 5.4 million and is administratively divided into two autonomous regions and 15 departments.

The surficial geology consists mainly of Tertiary volcanic rocks in the central part of the country superimposed in the northern part on bedrock comprised of low-grade metasedimentary Paleozoic rocks and continental and marine Mesozoic sedimentary rocks, intruded by granitoid rocks of Cretacic and Tertiary age. In the western part of the country, Mesozoic and Tertiary sedimentary rocks and Quaternary volcanic rocks prevail. Recent sediments are represented mainly by alluvial, fluvial, and colluvial deposits covering the coastal plains and depressions in the eastern and western part of the country (Weyl 1980).

Nicaragua's climate is tropical with an average yearly temperature of about 25°C, although local temperatures are strongly dependent on the altitude, especially above 800 m a.s.l. The total annual rainfall varies greatly, ranging from 800 mm in a narrow sector, oriented NW–SE between Totogalpa and Sebaco, to 5,000 mm in the area of San Juan del Norte, located in the southeastern sector close to the border with Costa Rica. Both Atlantic and Pacific tropical cyclones, which include hurricanes, tropical storms, and tropical depressions, may affect the country from May to October.

The paper also uses the Department of Nueva Segovia as a study area for a specific analysis at a regional scale. The department is located in the northern part of the country, close to the border with Honduras (Fig. 1). The elevation of the area varies between 300 and 2,107 m a.s.l. The topography is characterized by heterogeneous and irregular mountainous terrain, consisting of very steep and rugged uplands with very narrow and deep valleys. The highest mountains in Nicaragua are located here. The highest peak, Cerro Mogotón, has an elevation of 2,107 m a.s.l. and is located in the Cordillera of Dipilto-Jalapa. The tropical climate in the Department of Nueva Segovia can be divided into two main categories: a hot and sub-humid climate with rainfall during the summer (May–October) varying between 600 and 2,000 mm, and a temperate and rainy climate in the highest mountains along in the Cordillera of

Fig. 1 Map of Nicaragua showing the administrative departments, cities, and main roads. Department of Nueva Segovia is *shaded dark gray*. The *inset* map shows the position of Nicaragua within the Central American isthmus
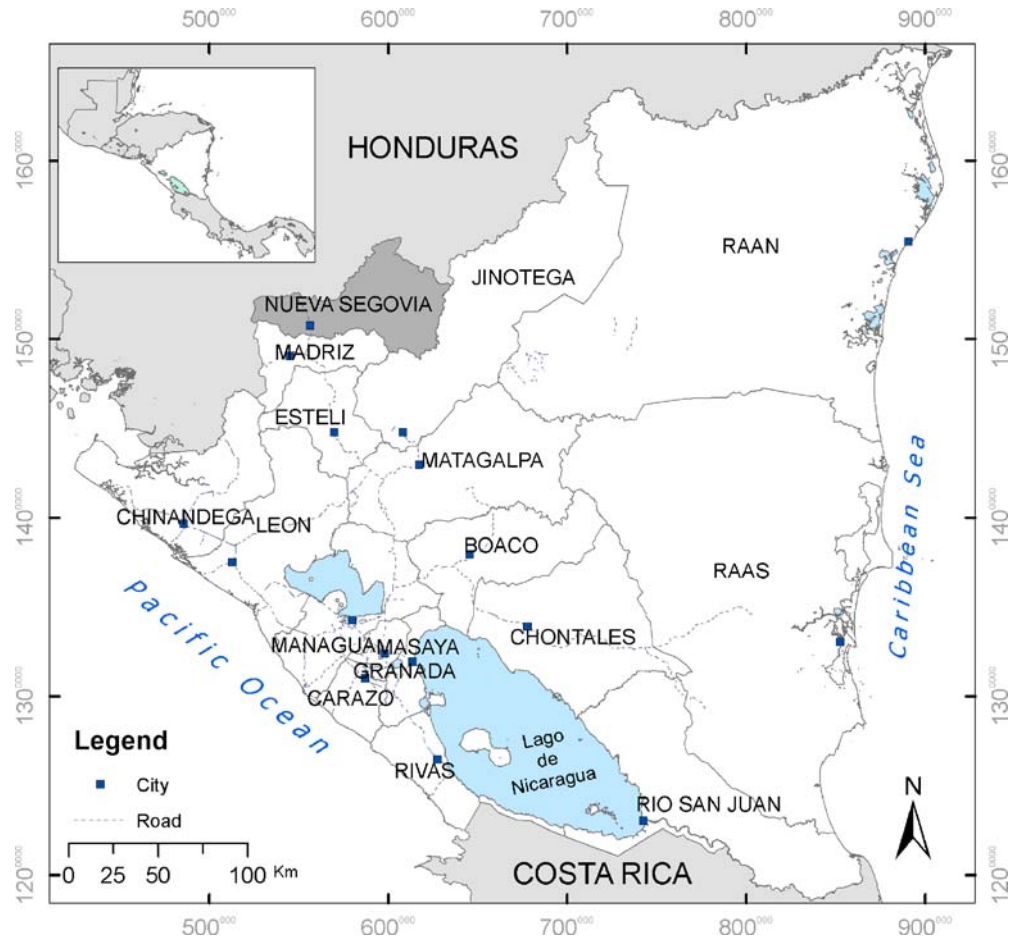
Dipilto-Jalapa, with an average annual precipitation between 1,000 and 1,800 mm. The geology in the department consists mainly of low-grade metasedimentary Paleozoic rocks comprised of phyllites and micaceous schists, interbedded with quarzites, marbles, slates and other metasedimentary rocks, and metavolcanic rocks. The metamorphic bedrock is intruded by granites, granodiorites, and tonalities. In the southern part of the area, Tertiary volcanic rocks (i.e., ignimbrites) are superimposed on the bedrock (Weyl 1980).

Methodology

The methodology adopted for the development of the database consisted of three main components: (1) data collection, (2) database design and generation, and (3) data analysis. The methodology is described and synthesized in the graphic presented in Fig. 2.

Data collection

Sources of landslide data
The database has been populated with data sets obtained from multiple sources that can be grouped into three main categories based on the type and format of landslide information provided:

– *Historical documents* such as newspapers, national catalogues, monographs, scientific papers, theses, bulletins, and old chronicles provided information on events that occurred before 1990 (Devoli et al. 2006). Old historical chronicles, monographs,

and theses have also provided information on prehistorical landslide events (before 1500). Landslide information was sporadic and not systematically recorded in these sources and is only available in analogue (paper) format.
– *Technical reports* and scientific documents produced by the national scientific community or foreign scientists describe landslides that occurred after 1990. No technical reports dated before 1970 were found, and landslide information in those found between 1970 and 1990 is sporadic. More systematic observations and studies have been made after 1999. Landslide data are available mainly in analogue format, except for those recorded in technical reports prepared after 1999.
– *Landslide inventory maps* have been made as part of the development projects completed in Nicaragua during the post-Mitch emergency (1999–2003) at large and medium scales. They represent the main sources of landslide data in the database, and the spatial and temporal data obtained from them are available in digital format. Figure 3 shows the study areas of the digital inventories that have been integrated in the database as of December 2005. In addition to the bibliographical references for the projects, hereafter, we also use Spanish acronyms and abbreviations to refer to them. Two main types of landslide inventory maps have been prepared: *geomorphological landslide inventory maps* and *Mitch-inventory maps*. Geomorphological landslide inventory maps have been prepared in three ways: (a) combining landslides with unknown date of occurrence mapped from the analysis of 1:40,000 and 1:30,000 scale aerial photo-

Fig. 2 Flow chart illustrating the process used to create the landslide database
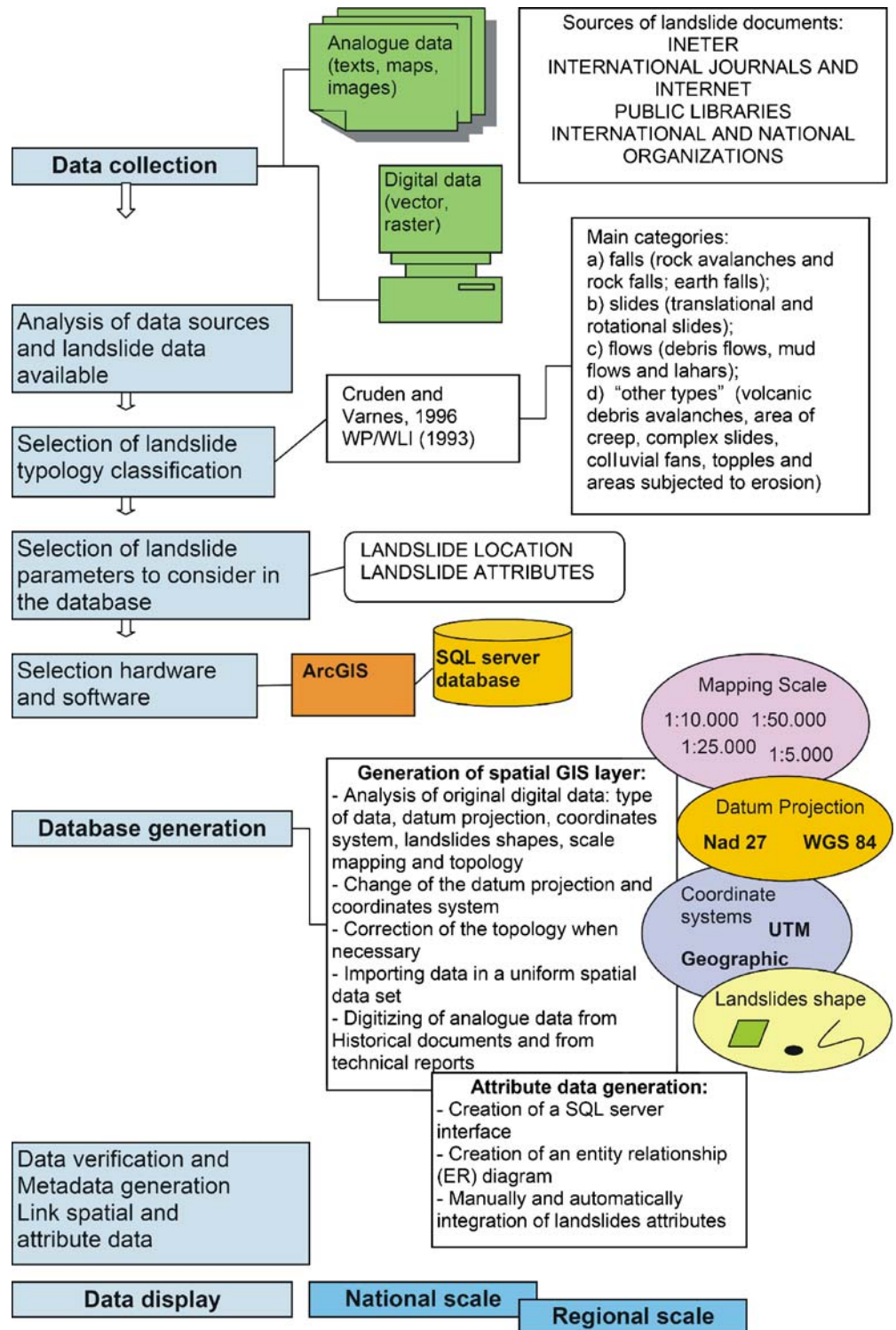
graphs taken in 1996 and before, and landslides triggered by Hurricane Mitch mapped from the analysis of 1:60,000 scale aerial photographs taken in December 1998 and from field surveys (e.g., Menendez-Duarte et al. 2003; Guinau et al. 2005); (b) combining landslides with unknown date of occurrence mapped from the analysis of 1:40,000 and 1:30,000 scale aerial photographs taken in 1996 and before and landslides triggered by Hurricane Mitch mapped based on field surveys and interviews with local people (ALARN 2002; Hradecký et al. 2002; Schmitz et al. 2003; INETER-AECI 2004; Devoli and Alvarez, 2004, unpublished report); and (c) showing landslides with unknown date of occurrence and landslides triggered by Hurricane Mitch mapped from the analysis of 1:5,000 scale aerial photographs taken in 2002, field surveys, and interviews with local people (Álvarez et al. 2003). Mitch-events inventory maps have been obtained by interpreting 1:60,000 scale aerial photographs taken after the hurricane in December 1998

Fig. 3 Map showing landslide inventories included in the database. Note that *INETER-preMitch* includes all reports from between 1990 and 1997 and *INETER-postMitch* includes all reports from between 1999 and 2003 written by INETER personnel
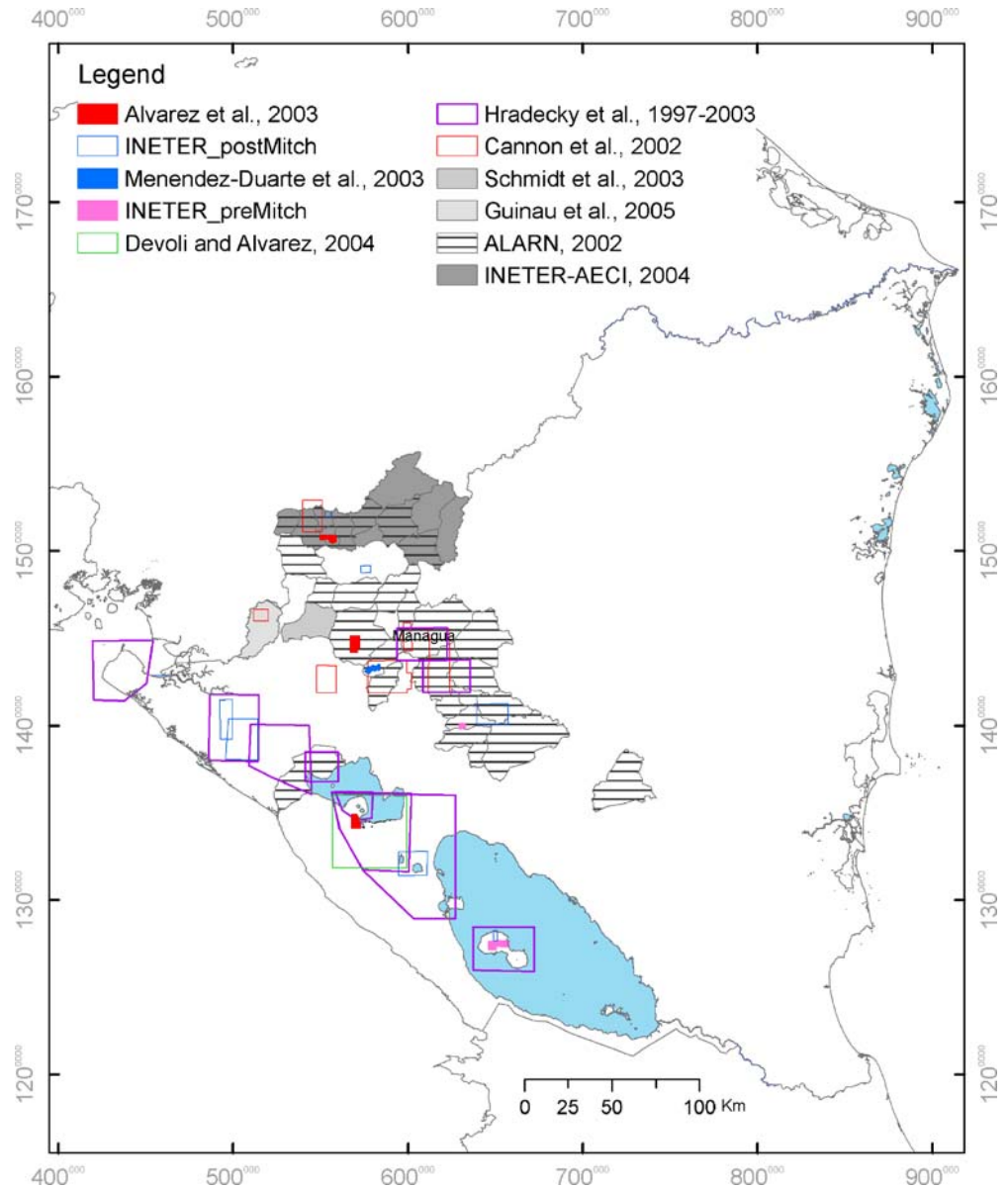
(Cannon et al. 2002), supplemented by field surveys. Some of these projects also resulted in hazard-zonation maps.

Type of landslide information

The database contains spatial data and thematic landslide information. Spatial information consists of geographical data to locate the landslide. Points (*x, y* coordinates) were used to represent: (1) landslides obtained from historical documents for which an approximate location close to the potential scarp area or close to the affected area is indicated, (2) the potential initiation location of the event (middle point of the scar) as indicated in Cannon et al. (2002), and (3) landslides difficult to map at the scale of the original work (it can be any point within the potential deposit or the scarp; ALARN 2002). Polygons represent the sliding area (both scarp area and deposit), or the deposit area or only the scarp area (Álvarez et al. 2003).

The landslide attributes (or thematic information) are represented by administrative and geographical details, slope geometry, date of occurrence, geological information, hydrogeological information, landslide type and characteristics (i.e., size, velocity, run-out distance, volume), number of casualties and infrastructure damaged, triggering mechanisms, meteorological conditions, and landslide control measures.

Database design and generation

The landslide database, known with the abbreviation "Iladeras" (a Spanish acronym for "Inventario nacional de inestabilidad de laderas," National inventory of slope instabilities), was designed by personnel of INETER between 2003 and 2004 (Mora and Blanco, 2004, unpublished report; Zambrana, 2004, unpublished report) as one of the thematic data sets within the national information system for geological hazards in Nicaragua. Modifications of the original design and improvements are still in progress. The first updating of the database, herein presented, was mainly generated between 2003 and 2005.

Database generation

In historical documents and technical reports, the locations of landslides were available in analogue format usually according to the name of the nearest locality. The location was transferred to the topographic maps at 1:50,000 scale based on the description given in the original text and on geomorphologic and topographic features (i.e., the presence of old scar and colluvial deposits). After transferring the location in a topographic map, a location point was digitized on a computer screen using topographic maps and/or orthophotographs. When the location was poorly described, the point had to be mapped close to the name of the locality or in the closest village or town. In a few data sources, the polygon of the affected area was already available in digital format. In other cases, orthophotographs at 1:10,000 scale were used to draw a polygon based on geomorphological features and information available in the original source.

In the landslide inventory maps, the location is represented in digital format by a georeferenced point or a polygon. In a few cases, the name of the locality is also indicated in the attribute table. Landslide inventory maps were reviewed with respect to the techniques and methodologies used, available GIS layers, datum projection, coordinate systems, landslide-shapes files, scale of mapping, and technical reports. Besides being stored in the database, original landslide inventory maps are kept in a common server that can be used separately for specific analysis. Before being stored in the database, the landslide-shape files of points and polygons were checked in their datum projection, coordinate system, and topology, reprojected, and imported into a common layer. Changes were made only in the datum projection and coordinate system, and then the digital data were stored in ArcGIS 8.3, together with the newly digitized data from historical and technical documents. Point and polygon layers were created. WGS 84 was chosen as the projection datum and Universal Transverse Mercator as the coordinate system. Line features, used in the original landslide inventory maps to describe the paths of debris flows or the sense of movement of a landslide, have not been integrated yet into the database, but their integration is planned in the next future, as especially debris flow paths are critical for hazards assessment.

One identification number for a single landslide (ID) has used to record landslide location (point or polygon) and permit a link with its associated attributes in the database. For some landslides, both polygons and points are available, and they received the same identification number.
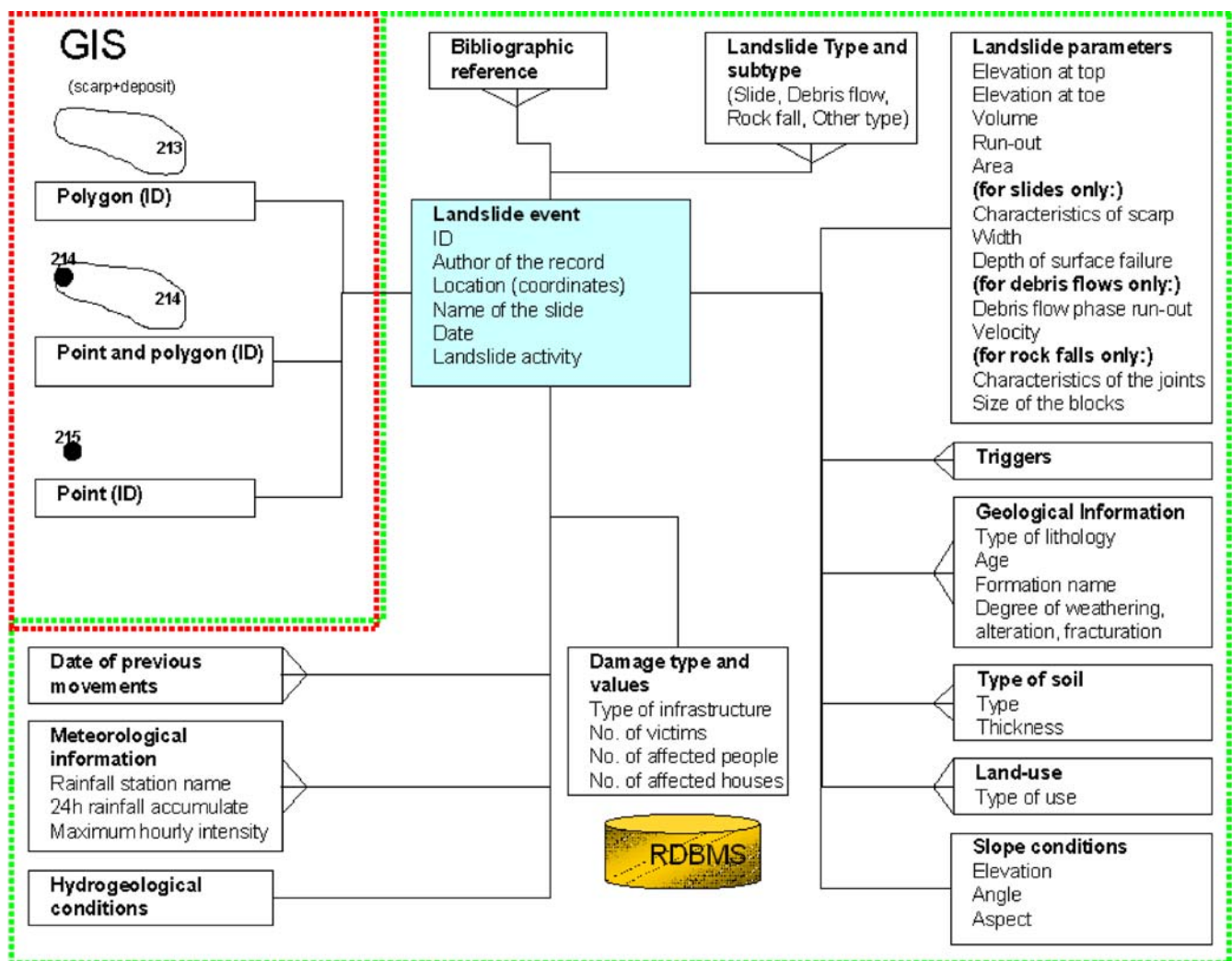

Fig. 4 Simplified database structure

A relational database management system was chosen to store landslide attributes through a graphical interface (Zambrana 2004, unpublished report). An entity relationship diagram was also designed to capture, visualize, query, and manipulate landslide attributes (Mora and Blanco 2004, unpublished report). The storage of thematic data was usually done manually but was sometimes done automatically when a large number of events were available having the same attribute. The input of the attribute data consisted of a record with an identification number equal to the ID of the polygon or point corresponding to the attributes. To keep track of the source layer, the bibliographic references were given as attributes. Each record contains the original landslide-mapping methodology used, the original scale and spatial accuracy, and the modifications (i.e., changes in the coordinates system, topology, etc.) made to store the spatial information in the database. This allows for complete information recovery regarding different source-mapping methodology, scales, and precision.

The database interface was created from a landslide data sheet form prepared to collect data during field surveys that was based on existing landslide forms available at the international level (e.g., Cruden 1991; Glade and Crozier 1996; Amanti et al. 1996). The form lists a variety of information and is quite complex. Such a complex form has disadvantages because in the field, it is difficult to compile all suggested parameters because of the environmental conditions (e.g., extreme heat and humidity, inaccessible and mountainous areas) that prevent the collection of structural, lithological, and geomorphological data. However, this form was preferred to a simple one with a limited number of possible entries because it accounts for all the possible types of data that could be collected. Modifications of the original landslide form were made during the preparation of the interface, and improvements are still in progress to better adapt to the national conditions and to be consistent with the international and national professional landslide community. The relational database structure is constituted by a series of tables (Fig. 4) connected by primary keys in which data are inserted and organized according to the selected spatial data. Landslide attributes are included in three main modules (record, basic, and technical data) divided into 15 sections (Mora and Blanco, 2004, unpublished report).

Data analysis

Simple interactive queries have been used for the analysis and display of the data at the national and regional scales. For the analysis performed at national scale, we used all the data stored in the database, whereas at regional scale, we used only data provided by the Agencia Española de Cooperación Internacional (AECI; INETER-AECI 2004) and the Programa Regional de Reconstrucción de America Central (PRRAC; Álvarez et al. 2003) projects. Because the database is still under development and some of the thematic data have not yet been updated, we conducted the analysis at regional scale using data already stored in the database (PRRAC project) and data from the original sources (AECI

Fig. 5 Spatial distribution of the landslides within the different geomorphological units and administrative departments
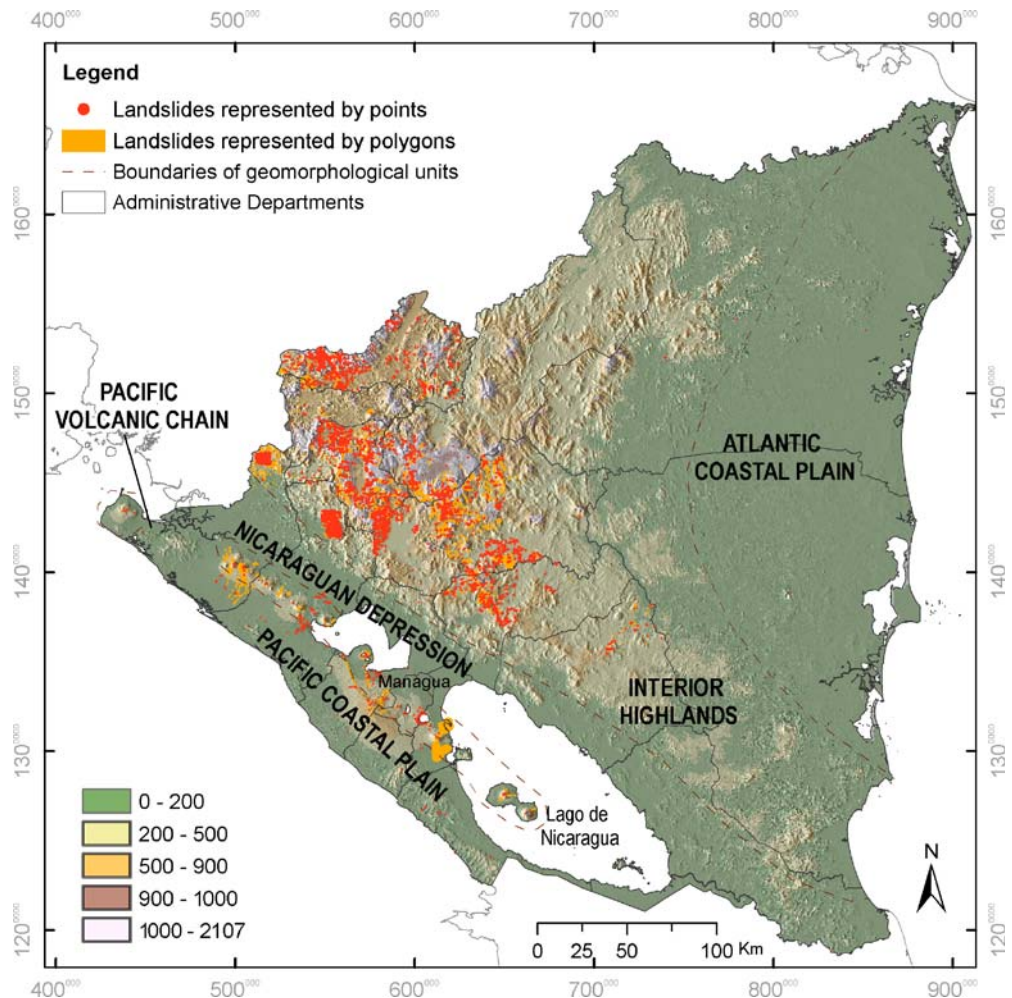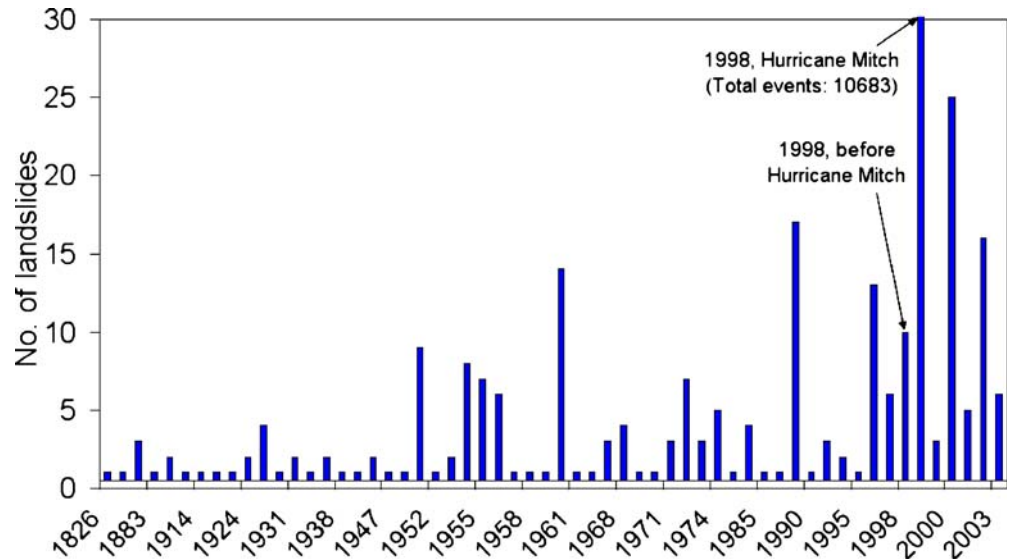
Fig. 6 Temporal distribution of recorded landslides in the period 1826–2003. A total number of 10,907 landslides (almost 64% of the total number of landslide recorded) are shown in this figure. The event dated 1570; those with the date of occurrence unknown and those that must be updated have been excluded from the graphic

project). We used these two sets (instead of data contained in Cannon et al. 2002 and ALARN 2002) because they provide a more complete and homogeneous collection of specific parameters based on field observations. The PRRAC project mapped the landslides close to the urban and suburbs of the city of Ocotal at 1:5,000 scale, whereas the AECI project mapped the landslides in all municipalities of the Department of Nueva Segovia at 1:50,000 scale. In both data sets, there are landslides triggered by Hurricane Mitch, landslides of unknown date of occurrence, and a few landslides that occurred in 2003.

Results of data collection and analysis

The database currently contains about 17,000 landslides. In this paper, we present four basic analyses of the information stored in the database for the country as a whole (Figs. 5, 6, 7, and 8) and a specific analysis at a regional scale for the Department of Nueva Segovia (Figs. 9, 10, and 11).

National scale analysis

The analysis of the spatial distribution of landslides at the national scale naturally shows a strong relation between landslide occurrence and the hilly and mountainous areas of the country (Fig. 5). Almost all recorded events occurred in the northern and central regions of the country (Interior Highlands) or along the volcanic slopes of the Pacific volcanic chain at elevations higher than 500 m. Only a few landslides have been recorded in the hilly areas within the Pacific and Atlantic coastal plains at elevations between 200 and 500 m. The largest numbers of landslides were mapped in the departments of León (3,865), Chinandega (3,306), Estelí (2,361), Matagalpa (2,355), and Nueva Segovia (1,949), and the municipality of El Sauce in the department of León, which had the highest number of recorded landslides (3,510) of any of the departments. The spatial distribution (Fig. 5) depends strongly on the locations where landslide mapping was performed, especially after Hurricane Mitch. There are about 30 municipalities having hilly and mountainous relief potentially prone to landsliding that were not affected during Mitch and where landslide mapping has not yet been performed. There are very few municipalities that are

not landslide prone; most of these are located in flat terrain on the Atlantic and Pacific coastal plains.

Landslides recorded in the database are temporally distributed between 1570 and 2003. One recorded landslide occurred in 1570, and the rest of the landslides were documented as occurring between 1826 and 2003 (Fig. 6). As expected, a large number of records are dated October 1998 and are recorded as triggered by Hurricane Mitch. These represent 62.4% of the total amount of the data stored. Only 1.0% of the recorded events occurred before 1998 and 0.3% between 1999 and 2003. The rest (36.3%) includes landslides with unknown dates of occurrence from historical (1,135) and prehistorical times (2) and those for which the date of occurrence must be updated (5,082). Figure 6 displays the annual number of recorded landslides in the period from 1826 to 2003. Even when excluding data triggered by Hurricane Mitch (the outlier point in Fig. 6), we observed an increase in the number of landslides recorded during the period of record. This is due to the more efficient collection of recent data and not because of a higher frequency of recent landslides. Furthermore, we expect an increase in frequency of recorded slides because, in recent years, more people in Nicaragua are being exposed to landslides because of increased population, the expansion of the agricultural frontiers,
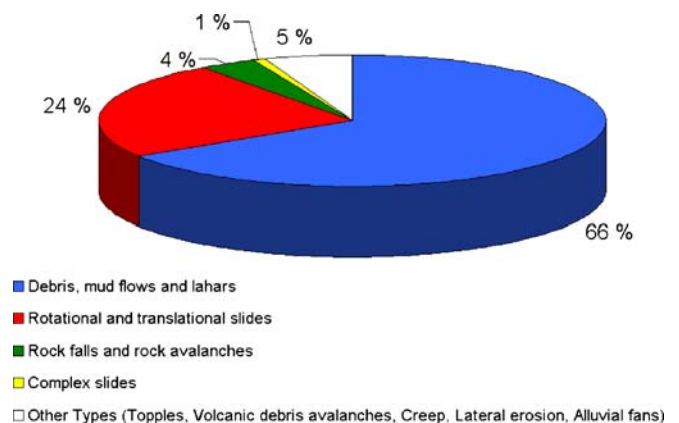

Fig. 7 Types of slope movements in the database

Fig. 8 Graphic showing the main triggering mechanisms distinguished by landslide type. Rainfall trigger landslides are divided into those triggered by intense and prolonged rainfall associated with tropical cyclones (fifth and sixth column) and those triggered by intense or prolonged rainfalls related to other synoptic systems (third and fourth column)
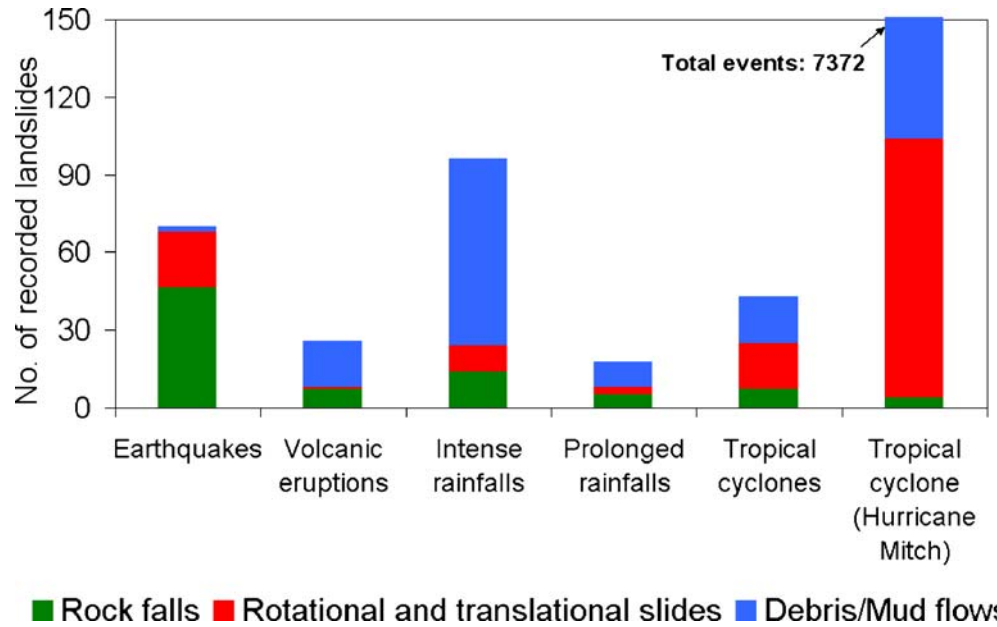
the high rate of poverty that forces a large population to migrate toward susceptible lands without proper planning, and accelerating deforestation from new and expanding settlements.

The monthly distribution of landslides shows that the majority of the recorded landslides have occurred during October, followed by May and September, which is in accord with the period of the rainy season in the Pacific and Northern and Central regions. In addition, May and October are the months during which the country has the highest probability of being impacted by hurricanes. A similar trend was observed with data recorded before 1990 (Devoli et al. 2006).

Landslides are classified by type for about 16,298 landslides in the database. Debris flows, mud flows, and lahars are the most common types of landslides, representing 66%. These are followed by rotational and translational slides, which comprise 24%, and rockfalls, which represent only 4% (Fig. 7). Other types such as topples, volcanic debris avalanches, areas of creep, alluvial fans, and areas of lateral erosion represent 5% of landslides in the database, and complex movements represent 1%. Most of the landslides triggered by Hurricane Mitch have been classified as debris flows. However, many of them probably initiated as rotational and translational slides.

Fig. 9 Geographical distribution of recorded landslides in the Department of Nueva Segovia. The elevation range values are the same as those shown in Fig. 5. Landslides represented as points and polygons have been mapped by Cannon et al. (2002), ALARN (2002), Álvarez et al. (2003), and INETER-AECI (2004)
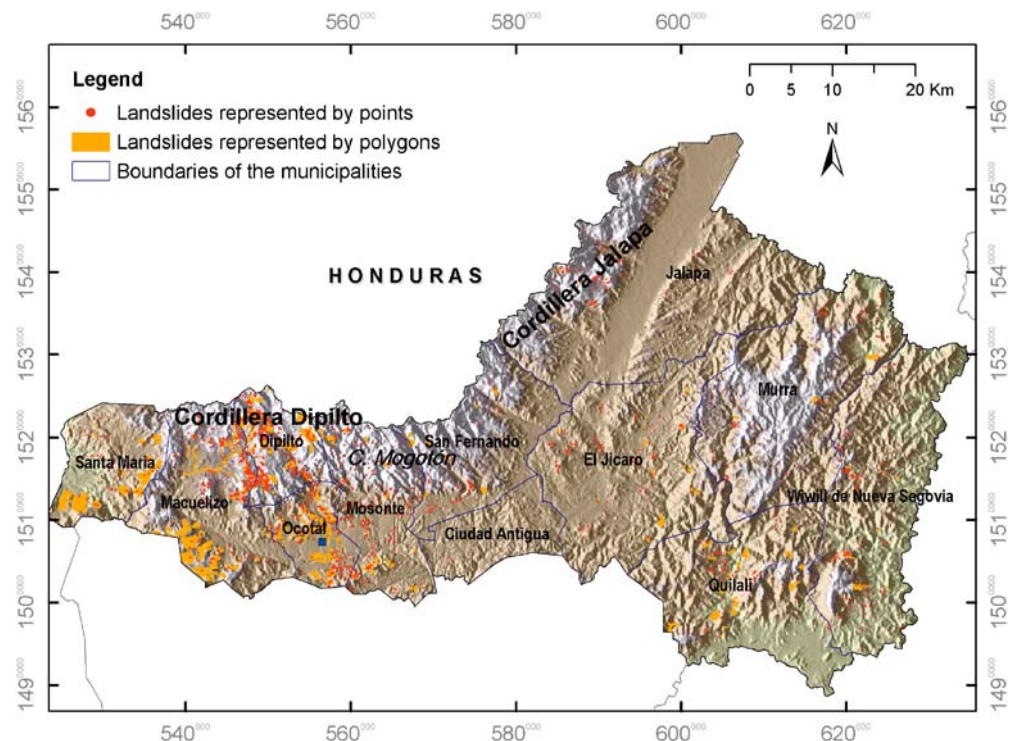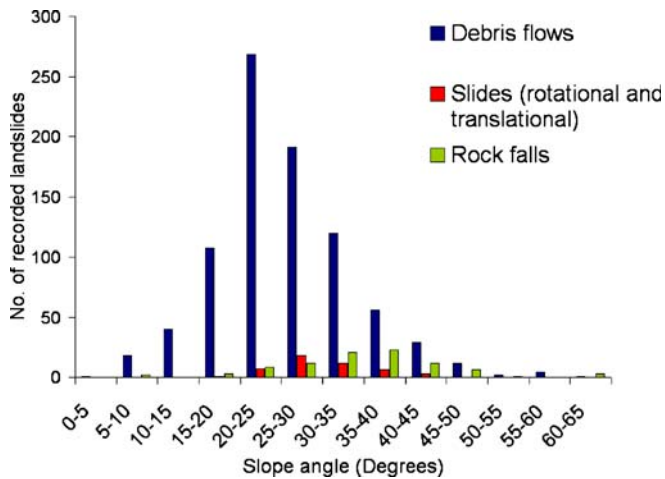
Fig. 10 Histogram of slope angles for flows, slides, and rockfalls. The graphic shows data from 986 records

Continuous monitoring analysis of landslides from 1999 to 2003 and the analysis of those occurred before 1990 (Devoli et al. 2006) shows that landslides are associated with natural processes (i.e., rainfall, earthquakes, tropical cyclones, volcanic eruptions). Figure 8 shows which main triggering mechanisms have been recorded for the different types of landslides in the database. Based on the information available, an effort was also made to distinguish those landslides triggered by intense and prolonged rainfalls during tropical cyclones from other synoptic systems (i.e., Intertropical Convergence Zone and El Niño Southern Oscillation). If we exclude the large number of events triggered by Hurricane Mitch (7,372, in the last column), the figure shows that rainfall and earthquakes represent the main triggering mechanisms. Both Atlantic and Pacific tropical cyclones have triggered landslides: Isabelle (October 1964), Irene (September 1971), Fifi (September 1974), Alleta (May, 1982), Gilbert (September 1988), Joan (October, 1988), Cesar (July, 1996), Lili (October, 1996), Mitch (October 1998), Keith (September 2000), Alma (May, 2002), and Isidore (September, 2002). Landslides triggered by rainfall are limited in time to the wet season that
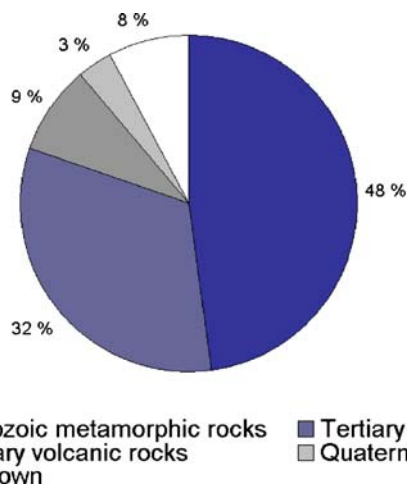

Fig. 11 Lithologies underlying areas affected by landslides. The analysis was done using 1,118 landslides

lasts from May to October. Landslides from earthquakes and volcanic eruptions are largely independent from the season and the meteorological or climatic conditions. Rainfall has caused all types of failures, whereas earthquakes most frequently trigger rockfalls and slides, and volcanic eruptions most frequently trigger rockfalls and debris flows (or lahars). Rockfalls have usually occurred in the upper part of volcanoes, very close to the crater, and are usually triggered by earthquakes during volcanic eruptions. Lahars are common during or after a volcanic eruption.

Regional scale analysis

At regional scale, landslides have been analyzed in the Department of Nueva Segovia to better define topographic factors that affect slope instability, such as slope elevation, slope angle, and slope aspect, or the relationship between type of lithology and the number of landslides. The spatial distribution of all landslides mapped and recorded in the area (Cannon et al. 2002; ALARN 2002; Álvarez et al. 2003; INETER-AECI 2004) is shown in Fig. 9. A high concentration is observed in the municipalities of Macuelizo, Dipilto, Ocotal and Mozonte, and Santa Maria.

A total of 1,118 landslides have been analyzed, 983 of them recorded by INETER-AECI (2004) and 135 by Álvarez et al. (2003). The recorded landslides include rockfalls, rotational and translational slides, and debris flows. The latter typology seems to be the most common. In this area, about 50% of the landslides analyzed occurred before Hurricane Mitch. Most of these landslides were identified through the analysis of aerial photographs and are not dated. Most of the rest of the records represent landslides triggered by Hurricane Mitch.

Information on the elevation of the starting point was available only for 189 landslides. Eighty-two percent of these started at elevations between 500 and 1,000 m a.s.l., and 18% started at elevation higher than 1,000 m a.s.l (up to 1,800 m a.s.l.). Debris flows were initiated at all elevations between 500 and 1,800 m, showing a wider elevation range than the other types of landslides. Looking closely at the slope conditions, and based on the data available in the database, one observes that the majority of recorded landslides have started in the middle parts of mountain slopes.

The analysis of the slope angle showed that about 91% of landslides initiated on slopes ranging 15–45°. Rockfalls occur on steeper slopes than debris flows and slides, with most of the data falling between 35 and 40° (Fig. 10). Debris flows triggered by Hurricane Mitch present a trend similar to that of older debris flows; the hurricane-induced failures occurred mainly on slopes ranging from 15 to 35°. Slides have occurred most frequently in slopes with angles between 25 and 30°.

Information on the slope aspect was available only for 356 landslides. The analysis of the slope aspect shows that rockfalls occurred along slopes facing in all different directions, whereas recorded debris flows mainly occurred on SE-facing slopes and slides on S-facing slopes.

The relationship between rock type and landslide occurrence was also analyzed (Fig. 11). Based on this analysis, 48% of the analyzed landslides occurred in Paleozoic metamorphic rocks represented by phyllites and schists. As many as 32% of the recorded landslides occurred in deeply altered and weathered Tertiary intrusive rocks such as granites and granodiorites.

Although landslides were concentrated on certain gradients, aspects, and geologic units, the concentrations could be attributed either to susceptibility or to an abundance of those gradients aspects and geologic units in the study area. More detailed investigations need to be performed in the future to better understand the controls of landslide occurrence.

Discussion and conclusions

The descriptive analysis presented in this paper shows for the first time the available information in Nicaragua and allows us to characterize the landslide occurrence in terms of spatial and temporal distribution, types of slope movements, triggering mechanisms, and other factors that influence stability. The analysis also allows for detailed investigation of the database content, design, and structure and helps us to identify those limitations that might compromise the results and the performance of future susceptibility and hazard analyses. Limitations related to the type and quality of information stored, and to the design and structure of the database, are described below.

At the present time, the database contains a large number of landslides triggered by Hurricane Mitch in 1998, which distorts the real spatial and temporal distribution of landslides in Nicaragua. In the northern and central areas of the country, the major part of landslides occurred during Hurricane Mitch, and the rest have unknown dates of occurrence. Only a few of them (less than 20) have occurred in well-known periods. The spatial distribution in this sector shows large areas without landslides and other areas with a high concentration of landslides. The lack of records is related to the lack of landslide mapping and not to the absence of landslides. The spatial distribution of landslides shows only those areas where landslide inventory maps were performed or where landslide records were found through newspapers, technical reports, and other documents. Many of the landslides in the database were mapped in areas severely hit by Hurricane Mitch, where aerial photos and topographic maps were available, or where the financing organizations had social, economical, or political interests, such as the development of infrastructure or new settlements. The choice of the area was also strongly influenced by the purpose and time of the projects. Consequently, even the landslides triggered by Hurricane Mitch are not spatially well represented. For example, the municipality of El Sauce accounts for the highest number of landslides triggered by Hurricane Mitch. However, those landslides are not spatially distributed over the entire municipality but only in a small area where aerial photos after the hurricane were available (Cannon et al. 2002). Along the volcanic chain, landslides are spatially and temporally better distributed because they have occurred more frequently, affecting big cities and infrastructure located nearby, and have been recorded in newspapers or technical reports.

Another limitation is the uncertainty of the spatial location of the landslide, which depends on the mapping methodology, surveyor's experience, resources available (type, quality, and scale of available aerial photographs and base maps), coordinate systems and data projections used, and finally, available software (Carrara et al. 1992; Malamud et al. 2004; Ardizzone et al. 2002; Guzzetti et al. 1999). Only data provided by Cannon et al. (2002) was registered with the original spatial precision. For the remaining records, the spatial accuracy was assumed to be the same as that of the topographic maps used to map the landslides and was based on conversations with the original surveyors. At the moment, the accuracy is indicated for each record in the observations section of the database. In the future, a special section must be introduced to separate the records according to their degree of reliability in a more automatic way, when required.

The problem of reactivated landslides happening at the same location at multiple times is being dealt with by using multiple polygons, especially in the case of volcanic debris flows occurring in the same gully. Different polygons with different IDs and attributes are used. Only one polygon is used for the slow landslides with a movement of a few centimeters per year. As attributes, more than one date of the previous movements is added. However, in this case, the database does not allow the introduction of parameters related to different activities. The use of one polygon prevents showing the area affected by the later movements.

The risk of counting the same event twice appears when a landslide is represented by two polygons (one for the scarp and another for the deposit, e.g., Álvarez et al. 2003) and when a landslide was mapped twice in two different inventory maps. In the first case, two different IDs have been used to identify, respectively, the scarp polygon and the deposit polygon, whereas the same attributes are recorded for both polygons in the database. On one occasion, the data extracted from the database were filtered ahead to perform the regional scale analysis to avoid this problem. This solution is not practical if large amount of data need to be analyzed. As for the second case, a landslide has been sometimes mapped twice or more times in different landslide inventory maps (Fig. 12). As a result, there are many different polygons with different attributes and different IDs in the database representing the same event. This could happen because, although most international projects were conducted in active collaboration with INETER, some of them were conducted in isolation. Therefore, some areas were mapped as many as five times, whereas other landslide-prone areas have not been mapped at all. Because of the large number of records and because it was not the aim of this work, an analysis of discrepancies among the inventories has not been performed yet.

The lack of thematic data limited the performance of more complex analyses. Data for landslides triggered by Hurricane Mitch were scarce and sporadically recorded at critical sites, as a large number of events needed to be mapped. Thematic data are available in the original reports and not always recorded as attributes in a digital format. This complicates their integration and updating in the database because it will be necessary to store one record at a time. The typology for these events was always recorded, but other parameters were seldom available. Parameters such as volume and thickness of the deposit were mainly recorded in technical reports and mainly for events that occurred after Hurricane Mitch. For some areas, the information on geology, slope angle, slope aspect, and land cover was available. As a result, little information is available at national scale. At a regional scale, the analysis was performed to show that if data are collected systematically during field surveys, it is possible to identify better the parameters that influence slope stability.

Other limitations that have been found are related to the lack of fields and sections in the database for entering specific technical parameters, accuracy values, and other uncertainties concerning the data. The relation among the tables in the database sometimes prevents the formulation of simple queries.

Fig. 12 Examples of areas where landslides were mapped in more than one landslide inventory map. The *number* is the ID used to identify the record in the database
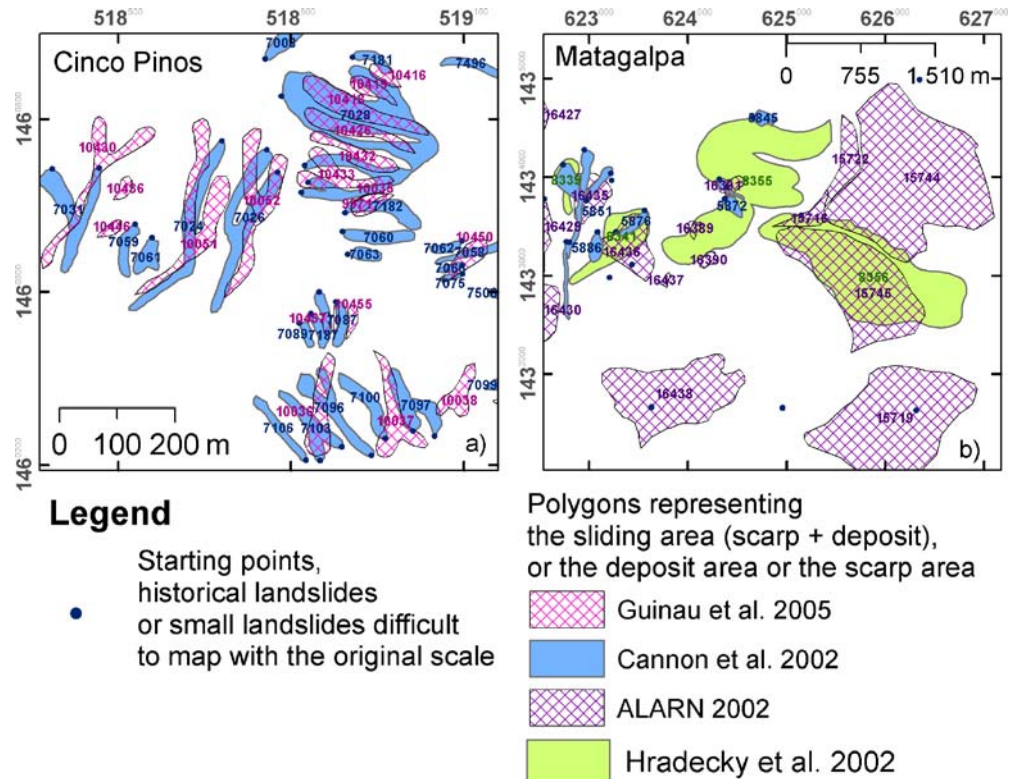
These limitations need to be considered and resolved before using the database in the future because they influence the accuracy and reliability of susceptibility, hazard, and risk analyses. The database must be seen as a long-term collaborative effort among government institutions and the scientific community that requires changes, updating, and improvements to optimize its functionality in the long-term hazard assessment. The information contained must be improved through updating the thematic data and other available parameters now contained in the written reports. It is necessary to continue the classical landslide research through field surveys and mapping in areas where hardly any landslide mapping has been performed. It is also necessary to continue the collection and organization of digital landslide data from upcoming projects and the historical research through newspapers and historical documents (Devoli et al. 2006).

In spite of the limitations mentioned above, the development of the national database has reached the goal of collecting and organizing the available landslide data in Nicaragua. All landslide information found is now collected and organized in a single database within a centralized government institution, which has the responsibility to investigate landslides in the country and spread its information through Internet services, publications, and maps. Part of its mandate is to have a capable staff with the responsibility of maintaining, updating, and analyzing the information. The digital database allows an easier management of large amount of multiscale data collected from multitemporal studies, and its development enables the scientific community to collect and verify landslide data using standardized methodologies that satisfy the national conditions and requirements of the Nicaraguan society. The landslide database was conceived to facilitate the introduction of new data and to guide its future collection in a more comprehensive and homogeneous way. The landslide information can be easily accessed by national authorities, international organizations, and users in general. It can be stored and used impartially and can support local and national authorities, the scientific community, and international donors working on prevention and mitigation of risks posed by landslides in Nicaragua. The implementation of the landslide database within a national information system for geological hazards would help to acquire a synoptic view of landslide processes in relation to multiple and diverse triggering mechanisms, rather than as isolated phenomena.

The work presented herein has also shown the challenges that the scientific community has to face to improve the landslide-hazard assessment in countries like Nicaragua, where political, social, and economical reasons have prevented a stable scientific and academic development throughout the history. As a result, landslide assessment has not always received the required attention, and the information available is extremely variable in type and quality. The experience, and the approach and methodology presented in the paper, may help other developing countries, particularly in Central America where they are facing similar challenges in landslide-hazard assessment.

References

ALARN (2002) Mapas indicativos de peligros y propuesta de zonificación territorial. Project: Apoyo local para el análisis y manejo de los riesgos naturales (ALARN). Agencia Suiza para el desarrollo y la Cooperación COSUDE. Programa de Prevención de Desastres Naturales en América Central (PREVAC)

Álvarez A, Devoli G, Chávez G, Mayorga E (2003) Amenazas por Deslizamientos en Ciudad Sandino, Estelí y Ocotal. Chapter III in "Amenazas geológicas en Ciudad Sandino, Estelí y Ocotal, Nicaragua". Dirección General de Geofísica, Instituto Nicaragüense d Estudios Territoriales, Managua, Nicaragua. Report prepared for the Project: "Elaboración de mapas de riesgos naturales en tres zonas de intervención del PRRAC". Programa Regional de Reconstrucción de America Central (PRRAC), European Union

Amanti M, Casagli N, Catani F, D'orefice M e Motteran G (1996) Guida al censimento dei fenomeni franosi ed alla loro archiviazione. Miscell. Serv. Geol. d'It., VII, 109 pp, Roma

Ardizzone F, Cardinali M, Carrara A, Guzzetti F, Reichenbach P (2002) Impact of mapping errors on the reliability of landslide hazard maps. Nat Hazards Earth Syst Sci 2:3–14

Base de Datos Históricos sobre Desastres en Nicaragua. (2005) Sistema nacional para la prevención, mitigación y atención de desastre. http://www.sinapred.gob.ni/Territorio/Consultas.asp. Date of citation 4/04/2005

Cannon SH, Haller KM, Ekstrom I, Schweig ES, Devoli G, Moore DW, Rafferty SA, Tarr AC (2002) Landslide response to Hurricane Mitch rainfall in seven study areas in Nicaragua. U.S. Geological Survey Open-File Report 01-0412-A Version 1.0 (posted 9 April)

Carrara A, Cardinali M, Guzzetti F (1992) Uncertainty in assessing landslide hazard and risk. ITC J 1992-2, pp 172–183

Carrara A, Cardinali M, Guzzetti F, Reichenbach P (1995) GIS technology in mapping landslide hazard. In: Carrara A, Guzzetti F (eds) Geographical information systems in assessing natural hazards. Kluwer, Dordrecht, The Netherlands, pp 135–175

CEPAL (1999) Centroamérica: evaluación de los daños ocasionados por el Huracán Mitch, 1998. Sus implicaciones para el desarrollo económico y social y el medio ambiente Naciones Unidas. Comisión Económica para América Latina y el Caribe

Colombo A, Lanterni L, Ramasco M, Troisi C (2005) Systematic GIS-based landslide inventory as the first step for effective landslide hazard-management. Landslide 2:291–301

Cruden DM (1991) A suggested method for a landslide summary. Working Party on World Landslide inventory. Bull Int Assoc Eng Geol 43:101–110

Cruden DM, Varnes DJ (1996) Landslide types and processes. In: Turner AK, Schuster RL (eds) Landslides investigation and mitigation, special report 247. Transportation Research Board, National Research Council, Washington, pp 36–75

CNR-IRPI (2004) Internet map server. http://www.irpi.cnr.it/it/link_maps.htm and SICI http://sici.irpi.cnr.it/. Date of citation 19/03/2004

Dai FC, Lee CF, Ngai YY (2002) Landslide risk assessment and management: an overview. Eng Geol 64:65–87

Dellow GD, Glassey PJ, Lukovic B, Word PR, Morrison B (2003) Data sources of the New Zealand landslide database. Geophys Res Abstr 5, 13867 (European Geophysical Society, 2003)

Devoli G, Morales A, Høeg K (2006). Historical landslides in Nicaragua—collection and analysis of data. Devoli, G., Morales, A., and Høeg K. 2006. Historical landslides in Nicaragua—collection and analysis of data [online]. Landslides. DOI: http://dx.doi.org/10.1007/s10346-006-0048-x. Published online 28 July 2006

Dikau R, Cavallin A, Jäger S (1996) Databases and GIS for landslide research in Europe. Geomorphology 15:227–239

Fajfar D, Ravnik D, Ribičič, M, Komac M (2005) Slovenian national landslide database as a solid foundation for the landslide hazard analysis. Geophys Res Abstr Vol. 7, 02998 (European Geosciences Union, 2005)

GA (2004). Australian landslides DATABASE. Australian Government, Geoscience Australia. http://www.agso.gov.au/databases. Date of citation 31/03/2004

Gaspar JL, Coulart C, Queiroz G, Silveira D, Gomes A (2004) Dynamic Structure and data sets of a GIS database for geological risk analysis in the Azores volcanic islands. Nat Hazards Earth Syst Sci 4:233–242 (European Geoscience Uniton 2004)

Glade T, Crozier MJ (1996) Towards a national landslide information base for New Zealand. NZ Geogr 52(1):29–40

Grignon A, Bobrowsky P (2005) Empowering scientists, planners and the public to reduce landslide losses: a simplified web interface to access a national landslide database in Canada. Geophys Res Abstr Vol. 7, 05511, 2005 European Geosciences Union, 2005

Grignon A, Bobrowsky P, Coultish T (2004) Landslide database management philosophy in the Geological Survey of Canada. Geo-engineering for the society and its environment. 57th Canadian Geotechnical Conference and the 15th joint CGS-IAAH Conference, Québec, Canada, October 24–27, 2004

GSI (2005) Landslide working group Ireland. Geological survey of Ireland. http://www.gsi.ie/workgsi/geohazards/wgroup.htm. Date of citation 4/07/2005

Guinau M, Pallas R, Vilaplana JM (2005) A feasible methodology for landslide susceptibility assessment in developing countries: a case-study of NW Nicaragua alter Hurricane Mitch. Eng Geol 80:316–327

Guzzetti F, Tonelli G (2004) Information system on hydrological and geomorphological catastrophes in Italy (SICI): a tool for managing landslide and flood hazards. Nat Hazards Earth Syst Sci 4:213–232 (European Geosciences Union, 2004)

Guzzetti F, Cardinali M, Reichenbach P (1994) The AVI Project: a bibliographical and archive inventory of landslides and floods in Italy. Environ Manage 18 (4):623–633

Guzzetti F, Carrara A, Cardinali M, Reichenbach P (1999) Landslide hazard evaluation: a review of current techniques and their application in a multi-scale study, Central Italy. Geomorphology 31:181–216

Guzzetti F, Aleotti P, Malamud BD, Turcotte DL (2003) Comparison of three landslide event inventories in central and northern Italy. Proceedings of the 4th EGS Plinius Conference, Mallorca, Spain October 2002. Universitat de les Illes Balears (Spain)

Hradecký P, Havlíček P, Kycl P, Mlčoch B, Mrázová Š, Novák Z, Opletal M, Rapprich V, Šebesta J, Ševèìk J, Vorel T, Devoli G (2002) Estudio geologico de riesgos naturales. Área de Matagalpa (Hoja de mapa 1:50 000 3054/IV). Geological Survey of the Czech Republic (ČGS)

INETER-AECI (2004) Sistema de Información geográfica aplicado a la cartografía de multiamenazas en el Departamento de Nueva Segovia. Amenaza Naturales por sismo, sequia y huracanes. Internal report Instituto Nicaragüense de Estudios Territoriales y Agencia Española de Cooperación Internacional, Managua, Nicaragua

Inventario de Desastres en Centro América de 1960–1999 (2005) Centro de Coordinación para la Prevención de Desastres Naturales en América Central. http://www.cepredenac.org/inventariodesastres2.htm. Date of citation 8/03/2005

Law 337 (2000) Ley Creadora del Sistema Nacional para la Prevención, Mitigación Atención de Desastres, Decreto 53-2000, La Gaceta, No 70, 7 of April, 2000, Managua, Nicaragua

LSJ (2004) Landslides database. Research Committee for Landslide Information Network, The Landslide Society of Japan. http://gisws.media.osaka-cu.ac.jp. Date of citation 31/03/2004

Malamud BD, Turcotte DL, Guzzetti F, Reichenbach P (2004) Landslide inventories and their statistical properties. Earth Surf Processes Landf 29:687–711

Menendez-Duarte R, Marquinez J, G (2003) Slope instability in Nicaragua triggered by Hurricane Mitch: distribution of shallow mass movements. Environ Geol 44:290–300

NGU (2005) National landslide database. Norwegian Geological Survey, Trondheim Norway. http://www.ngu.no/kart/skrednett. Date of citation 4/07/2005

Schmitz J, Gonzalez E, Vicuna E, Lopez E, Cornavaca R, Castillo H, Rosales MG, Espinoza J, Betanco M, (2003). Informe final: prevención, preparación, mitigación. Project Nic. 1004 Prevención, Mitigación y Atención a desastres en el municipio de San Juan de Limay, Departamento Estelí, Nicaragua. Agro Acción Alemana/ECHO Comisión Europea, Oficina de Ayuda Humanitaria/Instituto de Promoción Humana INPRHM-Estelí, Nicaragua

Scott KM, Vallance JW, Kerle N, Macías JL, Strauch W, Devóli G (2005) Catastrophic precipitation-triggered lahar at Casita volcano, Nicaragua: occurrence, bulking and transformation. Earth Surf Processes Landf 30(1):59–79

Sheridan MF, Bonnard C, Carreno R, Siebe C, Strauch W, Navarro M, Calero JC, Trujillo NB (1999) 30 October 1998 rock fall/avalanche and breakout flow of Casita Volcano, Nicaragua, triggered by Hurricane Mitch. Int Newsl Landslide News 12:2–4

Soeters R, van Westen CJ (1996) Slope instability recognition, analysis, and zonation. In: Turner A, Schuster R. (eds) Landslides: investigation and mitigation, Chapter 8. Transportation Research Board, National Research Council. Special Report 247, pp 129–177

Weyl R (1980) Geology of Central America. Gebruder Borntraeger, Berlin, Stuttgart (Second, completely revised edition, 371 pp)

WP/WLI (1993) Multilingual landslide glossary. The Canadian Geotechnical Society, BiTech Richmond

G. Devoli (✉) · K. Høeg
International Centre for Geohazards, c/o Norwegian Geotechnical Institute,
P.O. Box 3930, Ullevaal Stadion,
0806 Oslo, Norway
e-mail: gde@geohazards.no

W. Strauch · G. Chávez
Instituto Nicaragüense de Estudios Territoriales, Dirección General de Geofísica,
Apartado Postal 2110, Managua, Nicaragua

G. Devoli · K. Høeg
Department of Geosciences, University of Oslo,
P.O. Box 1047, Blindern,
0316 Oslo, Norway