A study of the distribution, characteristics, behaviour and triggering mechanisms of Nicaraguan landslides

By

Graziella Devoli

THESIS

Presented for the degree of

Philosophiae Doctor

Department of Geosciences

Faculty of Mathematics and Natural Sciences

University of Oslo, Norway

January, 2008

Series of dissertations submitted to the
Faculty of Mathematics and Natural Sciences, University of Oslo
No. 717

ISSN 1501-7710

Cover: Inger Sandved Anfinsen.
Printed in Norway: AiT e-dit AS, Oslo, 2008.

Produced in co-operation with Unipub AS.
The thesis is produced by Unipub AS merely in connection with the
thesis defence. Kindly direct all inquiries regarding the thesis to the copyright
holder or the unit which grants the doctorate.

Unipub AS is owned by
The University Foundation for Student Life (SiO)

Abstract

The thesis investigates and proposes a suitable form of collecting, organizing and analysing landslide data in order to improve the knowledge of landslide processes in Central America. The study recommends the organization of existing and new data in a national landslide database for Nicaragua in a digital format. The database is intended to support the scientific community and local and national authorities in landslide hazard assessment, emergency management, land-use planning and the development of early warning systems. Valuable information on landslide events has been obtained from a great variety of sources, such as landslide inventory maps, technical reports, natural hazard catalogues, newspapers, historical monographs and scientific papers. Through analyses of landslide data stored in the database, the thesis presents the status of landslide knowledge in Nicaragua both at national and local scales and characterizes landslides in terms of spatial and temporal distribution, types of slope movements, triggering mechanisms, number of casualties and damage to infrastructure.

The research collected spatial and temporal information for about 17000 landslides that occurred in mountainous and volcanic terrains, between 1570 and 2003. Information is mainly recorded for the period 1826 to 2003, with a large number of events (62% of the total number) during the disastrous Hurricane Mitch in October 1998. Data on human losses and damages in historical documents were used to show consequences of landslides. The consequences in Nicaragua have up until now been greatly underestimated.

Debris flows have been the most common types of recorded events, both in volcanic and non-volcanic 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. The influence of topographic (elevation, slope angle, slope aspect) and lithologic parameters was analyzed for the northern part of Nicaragua.

Data, mainly from 348 fairly well documented events in Nicaragua and 19 from other Central American countries, have been treated statistically to search for possible correlations and empirical relationships to predict run-out distances for different types of landslides, knowing the height of fall or the volume. The mobility of a landslide, expressed as the ratio between height of fall (H) and run-out distance (L) as a function of the volume and height of fall; and the relationship between the height of fall and run-out distance were

studied for rock falls, slides, debris flows and debris avalanches. The results showed that debris flows and debris avalanches at volcanoes have the highest mobility and reach longer distances compared to other types of landslides in the region. Among them, the longest (~25 km) and the most catastrophic in Nicaragua occurred at the Casita volcano on October 1998 triggered by the rainfall associated with Hurricane Mitch.

The Casita event started as a flank collapse which rapidly evolved into a debris avalanche and transformed into a lahar while moving downstream. In this thesis field data were combined with mechanical models, to provide a better understanding of the initial flank collapse. New insight into the geology, tectonics, pre- and post-failure geometry, and stratigraphy of the scarp area were provided and the failure sequence and pre- and post failure slope stability were modelled combining data from previous published and unpublished works and observations. The flank collapse was constrained by confirming that it included three failure stages that occurred continuously during an interval of seconds to a few minutes, involving both the northern and southern area of the scarp as previously proposed by Vallance et al. (2004). The study established the most likely failure mechanism of the first stage and identified the most likely mechanism of failure of the second stage. Analyses indicate that sliding in the volcanic breccia overlying a unit of clay-rich pyroclastic deposits with low shear strength controlled the failure mechanism and the stability in the southern area of the scarp. The failure then propagated into the overlying loose materials. Slope stability analyses for undrained conditions indicate that the remaining southern slope becomes unstable if it gets saturated during intense and/or prolonged rainfall, i.e. same conditions as those produced during Hurricane Mitch. In dry conditions the slope is stable as long as the berm of colluvium at the toe is not removed.

Preface

This thesis is submitted for the Philosophiae Doctor degree in Environmental Geology and Geohazards at the University of Oslo, Department of Geosciences. The study has been financially supported by the Norwegian Centre of Excellence, International Centre for Geohazards (ICG) and performed in collaboration with the Department of Geophysics of the Instituto Nicaragüense de Estudios Territoriales (INETER) in Managua, Nicaragua.

The investigation utilised data collected by:

- The author during the present study and field works from 1999 to 2003;
- Foreign researchers as part of M.Sc. and Ph.D. studies (especially relating to the Casita lahar);
- Nicaraguan and foreign researchers who worked in international cooperation projects with INETER or other Nicaraguan institutions during the assistance to Nicaragua after the Hurricane Mitch (October 1998);

Oslo, January 2008

Graziella Devoli

Acknowledgments

The Research Council of Norway through the Centre of Excellence "International Centre for Geohazards" (ICG) and the Norwegian Geotechnical Institute (NGI) are gratefully acknowledged to support the research.

I am especially indebted to Oddvar Kjekstad, Deputy Managing Director of NGI, to Dr. Farrokh Nadim, Director of ICG, and Prof. Kaare Høeg who gave me the possibility to start my Ph.D. study in Norway. My supervisors Prof. Kaare Høeg and Dr. Farrokh Nadim are deeply acknowledged for encouraging me with their guidance, support and constructive criticism when needed. Prof. Anders Elverhøi and Prof. Bernd Etzelmüller contributed with much appreciated advices.

Many thanks also to my co-authors, Fabio Vittorio De Blasio, José Cepeda, Norman Kerle, and my colleague Bård Romstad, for invest much of their time and energy in an interesting collaboration. I also wish to thank my Nicaraguan co-authors: Prof. Alejandro Morales helped me with the tedious process of collecting historical documents from public libraries and Guillermo Chavez who guided me in the creation and development of the database. Thanks also to Maia Ibsen, Jeffrey A. Coe, Cees van Westen and anonymous reviewers for their criticisms and suggestions provided for the first three papers.

I am very grateful to the Instituto Nicaragüense de Estudios Territoriales (INETER) where I worked between 1999 and 2003. I owe thanks to Ing. Claudio Gutiérrez, former director of INETER, who regrettably passed away in August 2007. He promoted landslide investigation in Nicaragua and always supported my work. Dr. Wilfried Strauch, Director of the Department of Geophysics of INETER and also co-author of the second paper, put me in charge of landslide research in the country. Working side by side with him and his staff during those years has been very satisfactory and instructive for me in improving my knowledge about landslide processes. His energy and dedication to his work strongly influenced my decision to start my Ph.D. research. I would like to thank my Nicaraguan "landslide colleagues" for the time spent together, dealing with all kind of landslides and geological problems. Thanks to all seismologists and vulcanologists of the Department of Geophysics for teaching me about seismic and volcanic activity in Nicaragua, and to the meteorologists Marcio Baca and Mariano Gutiérrez of the Department of Meteorology from whom I learned a lot about meteorological conditions. A big thank to all the "Marthas" and all colleagues of INETER for the nice time spent together.

I would like to thank all those involved in international projects who mapped landslides triggered by Hurricane Mitch and contributed to improve landslide knowledge in the country: Eugene Schweig, Susan Cannon, Kathleen Haller, Ingrid Ekstrom, Kevin Scott, Jim Vallance, Mark Reid, Cynthia Gardner and Willie Scott (U.S. Geological Survey, USA); Rosana Menendez and Jorge Marquinez (INDUROT-University of Oviedo, Spain); Klaus Köhnlein (Lahmeyer International, Germany); Petr Hradecky and Jiri Sebesta (Geological Survey of the Czech Republic); Ali Neumann, Miriam Down and the other Nicaraguan geologists who took part in the ALARN project (Swiss Agency for Development and Cooperation); Frode Sandersen, Håkon Heyerdahl, Einstein Grimstad, Annette Wold Hagen (Norwegian Geotechnical Institute, Norway); Manuel Villaplana and Marta Guinau (Universitat i Barcelona, Spain); Dirk Kuhn, Lothar Winkelmann, Teckla Abel (Federal Institute for Geosciences and Natural Resources, Germany); Cristina Muñoz (AECI), and Raul Carreño. I had the pleasure to work with them during field surveys where I enjoyed exchanging experiences, expanding my geological knowledge or simply having fun. Thanks to Sophie Opfergelt from the Catholic University of Louvain (UCL) who provided me with rock samples from the Casita landslide and to Jürgen Schmitz from Agro Acción Alemana who provided landslide data from the municipality of San Juan de Limay.

I would like to thank the NGI staff (and in particular the Division of Natural Hazards) ICG post-docs, students and friends I met during these years in Oslo for creating a nice and pleasant work environment.

Special thanks to my parents and to my Italian and Nicaraguan families that once again had to accept another departure from them. My husband Martin and my children Rebecca and Desi followed me in this chapter of my life and they fast adapted to our host country Norway. Thanks for their support, encouragement and understanding.

List of papers

Paper 1

Devoli G., Morales A., Høeg K. (2007). Historical landslides in Nicaragua - Collection and analysis of data. Landslides: 4 (1), 5-18

Paper 2

Devoli G., Strauch W., Chávez G., Høeg K. (2007a). A landslide database for Nicaragua: A tool for landslide hazard management. Landslides: 4 (2), 163-176

Paper 3

Devoli G., De Blasio F., Elverhøi A., Høeg K., (accepted, 8th of March 2008). Statistical analysis of landslide events in Central America and their run-out distance. Geotechnical and Geological Engineering Journal

Paper 4

Devoli G., Cepeda J., Kerle N., (submitted). The 1998 Casita volcano flank failure revisited – new insights into geological setting and failure mechanisms. Submitted to the Engineering Geology Journal (27th of November 2007)

Other published contributions by G. Devoli on landslides and debris flows

- Devoli G. (2005). Collection of data on historical landslides in Nicaragua. In "Landslides, risk Analysis and Sustainable Disaster Management" Sassa K., Fukuoka H., Wang F., Wang G., (eds) proceedings of the First General Assembly of the International Consortium on Landslides (Washington, USA, 12-14 October 2005).
- Devoli G., Chavez G., Blanco R. (2005). Landslide database for Nicaragua and its use. Geophysical Research Abstracts Vol. 7, 04157. European Geosciences Union 2005 (Poster)
- Scott K.M., Vallance J.W., Kerle N., Macías J.L., Strauch W., Devoli, G. (2005). Catastrophic precipitation-triggered lahar at Casita volcano, Nicaragua: occurrence, bulking and transformation. Earth Surface Processes and Landforms: 30 (1), 59-79
- Vallance J.W., Schilling S.P., Devoli G., Reid M.E., Howell M.M., Brien D.L. (2004). Lahar Hazards at Casita and San Cristobal volcanoes, Nicaragua. U.S. Geological Survey. Open-File Report 01-468

- Menendez-Duarte R., Marquínez J., Devoli G. (2003). Slope Instability in Nicaragua triggered by Hurricane Mitch: distribution of shallow mass movements. Environmental Geology: 44, 290-300
- Heyerdahl H., Harbitz C.B., Domaas U., Sandersen F., Tronstad K., Nowacki F., Engen A., Kjekstad O., Devoli G., Buezo S., Diaz M., Hernandez W., (2003). Rainfall Induced Lahars in Volcanic Debris in Nicaragua and El Salvador. Practical Mitigation. Paper presented at the International Conference on Fast Slope Movement - Prediction and Prevention for Risk Mitigation, 11-13 May 2003, Sorrento, Italy
- Cannon S.H., Haller K.M., Ekstrom I., Schweig III E.S., Devoli G., Moore D.W., Rafferty S.A., Tarr A.C. (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

Table of Contents

1.Introduction

A successful landslide hazard and risk assessment requires awareness and good understanding of the potential landslide problems within the geographic area involved (Schuster and Kockelman, 1996). However, this requirement is not always met in developing countries where the population, the scientific community, and the government may not be aware of the landslide threat. The landslide hazard assessment is often neglected or is based on sparse and not well documented technical information.

In the Central American countries the basic conditions for landslide hazard mapping and risk mitigation were first created after the catastrophic landslides triggered by Hurricane Mitch in October 1998, the earthquake in El Salvador in January 2001, and Hurricane Stan in October 2005. Single landslides took the life of thousands of people in Nicaragua (Casita lahar), El Salvador (Las Colinas landslide) and Guatemala (Santiago de Atitlán landslide) (Scott et al., 2005; Crosta et al., 2005; Connor et al., 2006), and they forced entire communities to be evacuated or relocated. Furthermore, thousands of smaller landslides caused loss of fertile soils and pasture lands, and made serious damages to the infrastructure.

Since those events occurred, the public awareness has increased and the region relies now on new local and national governmental laws and policies, on a number of landslide investigations, and on educational and training programs. Governmental scientific institutions (i.e. INETER, 2007; SNET, 2007; INSIVUMEH, 2007) have the responsibility to help land-use planners and public officials to reduce geological hazard losses. They are committed to work cooperatively with national, international, and local agencies, universities and the private sector to provide scientific information and improve public safety through forecasting and warnings. However, in order to provide successful long-term landslide hazard assessment, the scientific institutions must face challenges related to the scarcity and varied quality of available landslide information; collection and access to dispersed data and documents; organization of landslide information in a form that can be easy to access, manage, update and distribute in a short time to all sectors and users; and finally, the need of a comprehensive understanding of landslide processes.

1.1. Background

Landslides are complex processes characterized by a discontinuous nature in space and time. They can occur in different geological, geomorphological, hydrogeological and climatic conditions and can be triggered by different types of factors including intense and prolonged rainfall, earthquake, volcanic activity, and rapid snow melting. Landslides can involve flowing, sliding, toppling or falling movements and many of them exhibit a combination of different mechanisms of failure. The simultaneity and superposition of different types of failure is common and make it difficult to identify and analyze them, or even to estimate properly their extent and significance. They may occur as single events, small and frequently isolated and in rural areas, or in groups of several thousands affecting large areas. Both large and small landslides are capable of causing significant damage and loss of life. Sometimes the damage from many small ones may equal or exceed the impact of a single major failure.

In order to predict and mitigate the adverse occurrences of landslides, it is important to assess their character, causes and significance. Considerable knowledge and experience is required to predict the occurrence of different types of landslides and the basic failure mechanisms associated with each of them. The combination of different methods and disciplines such as engineering geology, geomorphology, mathematical modelling and management of geographic information, field mapping, interpretation of aerial photographs and GIS technology must be employed to make and present reliable predictions.

The essential first step in developing a programme of landslide hazard assessment is to establish the distribution, scale and severity of past landslide events. Collection and analysis of existing data are the first step in the evaluation of landslide hazard. Great care, however, must be taken when using these data because of limitations related to the source type, quality of information, and type of recording. Historical landslides improve the basis for hazard assessment by enlarging the chronological window of the past events, and are important in understanding the processes, historical frequency and magnitude (Guzzetti et al., 1994; Ibsen and Brunsden, 1996; Calcaterra and Parise, 2001). The collection of locally-focused, medium or large scale landslide inventory maps based on direct mapping allow to identify, delimit and analyze existing landslides and display their distribution. A digital landslide database that represents the available information in a systematic and standardised form would allow easy access and management of large amounts of multi-scale data collected from multi-temporal studies (e.g. Guzzetti and Tonelli, 1994; Colombo et al., 2005; Grignon et al., 2004). The database should be structured such that the data contained could be easily updated, shared, and distributed to the different users (national government, municipalities, Civil Defence, universities, private sector and international donors).

Debris flows are probably the most difficult type of landslide to predict and they can lead to substantial loss of life and revenue in the depositional zones, especially when they occur in volcanically active areas. Learning more about their behaviour will provide significant advantages to affected communities, and spare many lives. The information extracted from existing databases and derived from field surveys may be used to quantify a set of relevant parameters that describe the characteristics and behaviour of debris flows, such as run-out distance, inundated area, run-out angle, velocity, flow depth and maximum deposit thickness and volume (Jakob 2005; Corominas 1996). Empirical-statistical methods and mathematical models help to understand run-out behaviour and mechanics of mass movement, and, combined with fieldwork, provide the practitioner with useful tools to assess the debris flow hazard (Rickenmann, 2005). Empirical correlations can be used for predicting the run-out and extent of landslides and for calibrating the input parameters in the mathematical models that describe the physical behaviour of the mass movements.

Debris flows on volcano slopes, also called "lahars", can differ from non-volcanic debris flows in origin, size and downstream evolutions (Vallance, 2005). They could initiate as water floods and transform into debris flows by incorporating sediment through erosion, or they could begin as slope failures caused by an earthquake, simple gravitational collapse, hydro-volcanic activity, or intense precipitation. Complex and catastrophic slope failures in the upper part of the volcano (sector and flank collapses) often evolve rapidly into a mobile debris avalanche and may transform into a lahar that can devastate populations downstream of the volcano. In the final parts lahars can frequently evolve from a high-sediment-fraction volcanic debris flow (debris flow phase), to a low-sediment-fraction hyperconcentrated flow (hyperconcentrated flow phase), and or to a muddy streamflow phase. Besides research directed at understanding debris flow mechanics and predicting their run-out distance and inundation limits, it is important to perform studies on the initial landslide processes by examining the source characteristics. The combination of topographic, geological, geomorphological, and geotechnical data can be used in the assessment of the stability of a volcanic edifice or flank, to understand the controlling factors and triggering causes that may influence the instability, and for the correct choice, calibration and validation of the adopted modelling approach.

1.2. Aim of the study

The work behind this thesis was principally motivated during the period from 1999 – 2003 when the author was employed at INETER in Nicaragua, in the newly created Landslide Unit. The unit was established by the government of Nicaragua within the Department of Geophysics of INETER after the devastating landslides triggered by Hurricane Mitch in 1998. The unit has the mission to investigate, map, assess and monitor the landslides in the country, and be in charge of the emergency response, as well as dissemination of landslide information to increase public awareness. From the beginning the unit had to face the challenges related to the lack of available landslide data, and at the same time the large production of landslide inventory maps as results of development projects carried out by national and international organizations as part of the humanitarian relief and aid after Hurricane Mitch. Landslide inventory maps were prepared using different techniques and methodologies since there was not a national standard for mapping, recording, storing or accessing landslide data in Nicaragua. The maps contain varying degrees of information and have different work-scales, coordinate systems and data projection. Furthermore, different softwares were used to digitize landslide locations. Besides the challenges related with the types of maps and formats, the unit had to face the difficulty to coordinate these projects and guide the researches. Although most of the projects were conducted in active collaboration with INETER, others were conducted in isolation and the final products were difficult to obtain. In addition to this the unit had to face the challenge related to the lack of national and local understanding of landslide processes, especially debris flows.

The general purpose of the thesis research is to gain a more comprehensive and predictive understanding of landslide processes in Nicaragua and Central America organizing, in the form of a national database, information obtained from landslide inventory maps produced after Hurricane Mitch as well as from other sources. The study combines different methodologies and approaches of investigation for different work scales, from national to a local scale. It aims to provide the national scientific community with basic technical information, methodologies and tools for long-term landslide hazard assessment. The study also aims to develop a methodology that can be followed by other developing countries in the collection and organization of similar data which are needed to produce landslide hazard maps and zoning maps.

Because the database is still incomplete, both in what it concerns the spatial and temporal distribution and the availability of technical parameters for each landslide recorded, not all data are useful for predictive purposes and future hazard assessments, and consequently the results herein presented are mainly descriptive rather then predictive. The study cannot reach completely the aim to increase the predictive understanding of landslides, but it contributes to make landslide research and predictive analyses more feasible in future researches.

The first part of the thesis (Paper 1 and Paper 2) aims to improve the knowledge about landslides through the collection and analysis of existing and new information about past and recent landslides. More specifically, the research aims to: a) identify and describe existing documents which provide information about landslides in Nicaragua; b) consult other documents, also non-scientific ones, to find more information on the occurrence of landslides in the past; c) use GIS tools to collect and organize all available analogue and digital data such that they are easily accessed, managed, updated, shared and distributed; d) develop the first version of a national digital landslide database; e) analyze the landslides contained in the database to establish their spatial and temporal distribution, triggering mechanisms, main typologies, economical and social consequences; f) validate the applicability of the database and define limitations related to its content, design and structure through the performance of simple descriptive analyses; g) identify the most catastrophic types of landslides and evaluate their impacts and characteristics; h) analyze the influence of topographic parameters and lithology on the occurrence of landslides in a specific area, where data are available; and i) present the status of landslide knowledge and investigations in Nicaragua and provide context as a guide for future research.

The second part (Paper 3) aims to define landslide characteristics and parameters that permit a statistical investigation of the landslide run-out distance and mobility based on a combination of field data and empirical analyses. This part of the research has focused on the following specific objectives: a) define landslide characteristics and parameters to better understand the landslide dynamics and run-out distances in both volcanic and non-volcanic areas, and identify the differences between landslides in the two environments; b) compare Nicaraguan landslide events with other similar events in Central America and elsewhere; and c) provide empirical relationships that help in the prediction of the run-out distances.

The third part of the thesis (Paper 4) attempts to improve our understanding of the initial stages of the flank collapse of the catastrophic 1998 Casita lahar by defining initial critical conditions, failure initiation and propagation and geological factors that influenced the collapse and the sequence of failures and types of failure mechanisms. The study is based on previous knowledge about the event, unpublished data and new observations. The research aims to: a) improve our understanding of the geometry and geology of the scarp area; the results are presented through a geological map, stratigraphic columns and geological profiles across the scarp; b) identify lithologies and geotechnical characteristics that governed the failure mechanism; c) improve the previous description of the number and sequence of failures and failure mechanisms that compose the initial flank collapse; and d) perform slope stability analyses by applying limit-equilibrium methods, and through back-analyses of the initial failure, assess the stability of the remaining slope.

1.3. Thesis structure

The thesis is structured as a set of self-contained journal articles, each addressing a separate aspect. As such each article contains its own review of the relevant literature as well as a description of the methods used. Because all articles deal with landslides in Nicaragua there is a certain amount of overlap in the sections introducing the study area. The following chapter outlines the geographical and geological setting of Nicaragua within the Central American region and provides a brief history of landslide investigations in the region. The main results of the study are synthesized in the following chapters. Finally, conclusions and limitations are described and suggestions for further work are proposed.

2. Nicaragua and the Central American region

2.1. Geographical and geological setting

Central America is a narrow isthmus (~538,000 km^2) connecting North and South America and bordered by the Caribbean Sea to the east and the Pacific Ocean to the west. It includes seven small countries: Guatemala, Belize, Honduras, El Salvador, Nicaragua, Costa Rica and Panama. With an area of 130,370 km^2, Nicaragua is the largest country of the isthmus, having a landscape predominantly flat, with extensive coastal plains and small and isolated hills, and with 37% of the total land area composed of mountainous and hilly terrain and a line of active volcanoes, with maximum elevation of 2107 m a.s.l. (Paper 1, Fig. 1).

Although differences exist among Central American countries, common features can be observed with respect to geology, climate and seismic and volcanic hazard.

Geologically, the Central American region can be divided in two blocks: the Chortis block containing Guatemala, Honduras, El Salvador and northern Nicaragua; and the Chorotega block extending from southern Nicaragua to Panama. Nicaragua is composed of meta-sedimentary Paleozoic rocks intruded by granitoid rocks and overlain by continental and marine Mesozoic sedimentary rocks in the northern part. Extensive plateaus of Tertiary volcanic rocks are superimposed on it covering most of the Interior Highlands. Mesozoic and Tertiary sedimentary and volcanic rocks, and Oligocene volcanic rocks are exposed in the Pacific Coastal Plain. Pleistocene terraces and Holocene alluvium cover the coastal plains and depressions (Atlantic Coastal Plain and the Nicaraguan Depression) of the eastern and western part of the country. Quaternary volcanic rocks composed of pyroclastic deposits, andesitic and basaltic lava flows, volcano-clastics sediments and colluvial deposits are exposed along the Pacific Volcanic Chain (Paper 1 and Paper 2).

The subduction of the Cocos plate beneath the Caribbean plate occurs along the Middle American Trench in the Pacific Ocean. It exposes the region to high rates of volcanism and seismicity. Product of this subduction is the Central American Volcanic Chain, a common feature to all Central American countries that runs parallel to the Pacific coast from the Guatemala-Mexico border to Panama, composed of active and dormant volcanoes of Quaternary age. The largest earthquakes are produced along this subduction zone, but the seismic activity is also influenced by the interaction of other major plates (North American, South American, and Nazca).

The region has a tropical climate and experiences a rainy season that begins in May and extends to October. Both Atlantic and Pacific tropical cyclones may affect the region during the rainy season. In Nicaragua the average temperature is around 25.4 °C, and the annual rainfall varies greatly between 800 and 5000 mm (Paper 2).

Because of its geographic position and geologic setting, the region is subject to a large variety of natural phenomena such as tropical cyclones, droughts, floods, landslides, earthquakes, volcanic eruptions, and tsunamis. Floods, droughts and landslides are regular consequences of the tropical climate, the constant movement of the line of the Intertropical Convergence Zone, the El Niño Southern Oscillation, and the yearly visits of tropical cyclones.

2.2. Past landslide investigations

In spite of the hazard, historically landslides have not been considered as serious threats in these countries. It is necessary to review the history of each Central American country and take into account the different and complex political, social and economical settings, in order to understand why there is a lack of awareness of the landslide hazard, and why the local scientific community did not develop a systematic knowledge of landslide processes during the past. Scientific institutions have disappeared or suffered internal turbulence, because of the frequent political changes and changes in political priorities. They have received limited financial support and were forced to delay many investigations, or in the worst of the cases to interrupt them. The few local scientists were forced to move from one institution to another and some of them had to migrate abroad, because of economical and political crises.

The knowledge of the geological, seismological and geotechnical sciences have not been advanced in the past, and most of the contributions helping to understand the geological processes of the region have been made by foreign scientists from government agencies, universities and international private enterprises, only a few of them in collaboration with local scientific institutions. Consequently, there has not been a systematic recording of landslide information, and documents were moved and dispersed among institutions, or lost.

No technical landslide reports have been found dated prior to 1970 in Nicaragua, and only a few investigations were made in Costa Rica to study the lahars that occurred at the Rio Reventado-Taras in 1963 (Mora, 1989), and at the Irazú volcano in 1967 (Waldron 1967).

The reports made in Nicaragua during the 1970's were focused on geological mapping or volcanic hazards identification (i.e. Ferrey and Williams, 1971; Hazlett, 1977; Darce and Rodríguez, 1979) seldom mentioning landslide problems or only discussing the occurrence of lahars at the San Cristóbal and the Concepción volcanoes.

In the 1980's, Ui (1983) and Hradecky (1988) briefly mentioned the debris avalanche that occurred at the Mombacho volcano (Nicaragua) and a few landslide analyses were published in Costa Rica as a consequence of extensive exposure of the population and infrastructure (Mora, 1989). In the other Central American countries very little is known about the extent and types of landslides. Harp et al. (1981) studied landslides triggered by the 1976 earthquake in Guatemala. A few unpublished reports are known in Honduras

(King, 1989), and in El Salvador only landslides triggered by earthquakes have been characterized during those years (Rymer and White, 1989). Little has been written about landslide problems in Panama, except those resulting from the construction of the Panama Canal (Stewart and Stewart, 1989).

It is during the 1990's that existing scientific institutions received more financial support, materials and technologies, and started to pay more attention to natural hazards, improving seismic and volcanic monitoring and performing landslide investigations. The new situation coincided with the combination of several conjunctures such as the end of armed conflicts, the consolidation of the democracies, the beginnings of the economical growth, and the major exposure to some of the most severe natural hazard events in the 20th century. Although it seems that the declaration of the International Decade for Natural Disaster Reduction by United Nation did not have a strong repercussion in Nicaragua, the workshops organized as part of it, at the beginning of the 1990's, helped local scientists to consider landslides as possible threats. During this decade landslide information was recorded in the form of unpublished reports. A small group of scientists in INETER (Nicaragua) issued the firsts preliminary reports describing landslides that attracted the attention of the scientific community, the population and the mass media (i.e. Taleno et al., 1993; Buitrago et al., 1997; Izaguirre y Taleno, 1997). Some of the reports (Izaguirre and Navarro, 1990) once more describe the occurrence of lahars at the Concepción volcano that on several occasions have threatened the life of inhabitants located on its slopes. The same information is briefly recorded in international bulletins like BGVN (1991, 1993 and 1996) or in newspapers. Rock falls occurred during 1996, 1997 and 1998 inside of craters were the consequence of the volcanic activity and they were mentioned in the bulletins published monthly at INETER. In Costa Rica landslide investigations were made in the form of theses or articles published in Costa Rican journals and bulletins (i.e. Mora et al., 1992). Historical landslides have been investigated by Peraldo and Molina (1993) and Peraldo and Rojas (1998). Vallance et al. (1995) described volcanic debris avalanches and other related hazards in Guatemala.

It is after October 1998 and from the beginning of 2000, that the major part of the investigations has been performed in the form of: a) landslide inventory maps (i.e. Crone et al., 2001; Baum et al., 2001; Bucknam et al., 2001; Harp et al. 2002; Cannon et al., 2002; Zaitchik et al., 2003; Coe et al., 2004; INETER-AECI, 2004; Jibson et al., 2004;) with a few of them attempting to estimate the landslide susceptibility or hazard (Vallance et al., 2001a; 2001b; 2004; ALARN, 2002; Menéndez-Duarte et al., 2003; Guinau et al., 2005);

b) geological and geomorphological maps (i.e. Hradecky et al., 2001 and 2002); c) landslide national inventories (Peraldo and Rojas, 2000; INSIVUMEH, 2007); and d) studies of specific landslides (Evans et al., 2004; Mora, 2001; Crosta et al., 2005; Siebert et al., 2006; Peraldo and Rojas, 2003; Bommer and Rodriguez, 2002; Alvarado et al. 2000; Alvarado et al., 2004; Hidalgo et al, 2004; Devoli et al., 2000; Devoli, 2001; Pérez and Devoli, 2000; Álvarez et al., 2003; Álvarez and Obando, 2005).

3. Collection of landslide information and database development

Most of the sources of landslide information presented in this thesis have been found at INETER consisting of technical reports; theses; bulletins; geological and geomorphological maps; landslide inventory maps and national catalogues describing the occurrence of catastrophic earthquakes, volcanic eruptions and hurricanes (Paper 1 and Paper 2). The inventory maps and reports not prepared in collaboration with INETER were found at the international development agencies and organizations that financed the projects. Public libraries in Managua and León provided national newspapers, monographs and old chronicles (Paper 1). Sporadic scientific papers and bulletins were found in international journals and through internet (Paper 1 and Paper 2).

All landslide data extracted from the previous sources have now been collected in a national landslide database. The development, design, structure and contents of this database are presented in Paper 2.

4. Landslide characterization

4.1. Terminology and classification

Inconsistencies in the use of landslide classifications, terminologies and definitions are well known in the literature (Hungr et al., 2001). The landslide investigations performed after Hurricane Mitch in Nicaragua (1998) have adopted international classifications like Varnes (1978, 1984), Carson and Kyrkby (1975), Selby (1993), and Cruden and Varnes

(1996). The English terms have been translated into the Spanish language. In some cases classifications were modified based on the Nicaraguan conditions. In other cases, classifications proposed in the Spanish language by Corominas (1989) and WP/WLI (1993) have been used. The use of one particular classification depended on the choice of the scientist that performed the work or who financed the project, because a specific classification had not been yet adopted in Nicaragua. Consequently, ambiguous terminology and definitions of landslide types were often observed, both within English and Spanish reports, or when terms were translated from one language to the other. In the Spanish language reports terminology discrepancies were found among those prepared by scientists from Spain and those prepared by scientists from Latin American countries. Often the term used in Spain to describe a specific type of slope movement is not necessarily used in Latin American countries to refer to the same type of landslide. Even among Latin American countries different terms are being used and, usually, local names and not always scientific ones are preferred. One attempt to classify and define slope movements in Nicaragua was made recently by INETER-COSUDE (2005), however contradictions are still observed between the definition used for a specific landslide and the English terminology. The description and terminology for landslides in volcanic areas is partly lacking.

In order to classify and define landslides in this study, the terminology and definitions proposed in the previous investigations were taken into account, but the general terminology and classification adopted is based on Cruden and Varnes (1996). In addition, to describe flows the classification proposed by Hungr et al. (2001) was used, combined with the terminology proposed by Vallance (2000) for debris flows in volcanic areas, and by Ui (2000) for debris avalanches in volcanic areas (Paper 3). In the following chapter, besides the English terminology, a Spanish terminology more commonly used in Nicaragua is given.

4.2. Types of landslides

In Nicaragua, falls (*caídas*) represent 4% of the total landslides recorded in the database (Paper 2). They started as rapid detachment of a single mass (*caída de bloques*) or a group of rocks (*derrumbe*) on slopes with angles higher than 30º (Paper 2) and often in steep nearly vertical slopes, natural and artificial ones represented by: cuts prepared for roads, stream banks, mine or quarry areas, overhanging rocky cliffs and outcrops made of resistant material, inner walls of calderas and craters, or steep slopes which are the remains of collapsed old volcanic edifices. The inappropriate design of the slope and the lack of protective measures were observed as main conditioning factors and responsible for the repetition of falls in the same slope along roads, also after short periods of time (Paper 1). The recurrence of falls in the inner walls of craters and calderas is related with the constant micro-seismicity associated with the volcanic activity. Rock falls occurred in highly fractured resistant volcanic rocks (i.e. andesites, basalts, ignimbrites, dacites, riolites, conglomerates) metamorphic rocks (schists, marbles) and intrusive rocks (granites). Earth falls involved partly consolidated cohesive alluvial material or pyroclastic deposits. Undercutting *(erosión al pie)* typically were observed at the toe of a cliff undergoing sea wave attack (i.e north-western coastlines of the Cosigüina volcano, Hradecky et al., 2001) or in eroding riverbanks (i.e Ocotal area, Álvarez et al., 2003a). Large rock avalanches (*avalanchas rocosas*) have been identified in the north-central area of the country or inside of craters and calderas (Paper 3). The oldest ones are densely covered by vegetation, but with a deposition area still evident and composed of angular or sub-angular metric fragments of rocks (Menéndez et al., 2003). Roads, tourist infrastructures located in the proximity of calderas and craters, and the old railway line have been frequently affected by falls (Paper 1 and Paper 3). Because of this frequent impact on roads and the old railway, rock falls have been quite well described in Nicaraguan newspapers sometimes better than other types of landslides (Paper 1).

Topples (*volcamientos*) have not been systematically identified and recorded in the country probably because they are often confused with rock falls. Only a few events have been classified as topples in the central area of Nicaragua, close to the urban areas of Esquipulas (Izaguirre and Taleno 1997b) involving andesites of Tertiary age.

Slides (*deslizamientos*) represent 24% of the total landslides recorded in the database. They occurred mainly on slopes with angles ranging between 20° and 45° and those in the northern area of Nicaragua occurred on south-facing slopes (Paper 2). Slides occurred frequently along roads, in unpopulated areas, or in open slopes and have affected communication lines and agricultural areas used for crops (coffee plantations, beans, corn) and pasture fields, and in forests (pine trees). Rocks involved were metamorphic schists and phyllites, volcanic rocks (basalts, ignimbrites, andesites, dacites, conglomerates), granites, colluvial deposits and residual soils (Paper 3). Based on the depth of the sliding surface, slides have been described as deep-seated (> 10 m) or shallow (< 3 m) slides. Deep-seated rotational slides (*deslizamientos rotacionales profundos*) were more commonly observed than translational (or planar) ones (*deslizamientos traslacionales* or *planares*). They are quite old and inactive covered by vegetation, with a still visible semicircular and concave head scarp and a deposit having an irregular morphology. Others are characterized by a complex activity, with a slow evolution and periods of acceleration. Often they suffer a reactivation, like during Hurricane Mitch, in the form of a shallow debris slide or a small debris flow, or rock falls in the head scarp or at the toe. They occupy the entire slope having an area of several square kilometers and a depth of hundreds of meters and involving large portions of the bedrock and soil that covers it. Shallow translational and rotational debris slides (*deslizamientos superficiales* or *peliculares*) initiated on open slopes or close to an established channel and frequently on top of larger and older deep-seated slides. They involved soils and the upper altered and weathered portions of the bedrock, as well as colluvial and alluvial deposits. Because most of the observed shallow slides transformed into earth or debris flows, it was difficult to classify and describe them, so in the original sources they are described sometimes as shallow slides and sometimes as flows.

Five main types of flows *(coladas or flujos)* have been recognized in Nicaragua: earth flows, mud flows, debris flows, debris avalanches and soil creep. The difference among types of flows is based on the material involved (Cruden and Varnes, 1996; Hungr et al., 2001). They all involve soil that is further divided into *debris* and *earth*. The term *debris* refers to loose unsorted material of low plasticity containing more than 20% gravel and coarse sizes (<80% sand and finer particles) and a significant portion of organic material (including logs, tree stumps and organic mulch). The term *earth* refers to unsorted clayey (plastic) colluvium with less than 20% coarse sizes (>80% sand and finer) derived from clays or weathered clay-rich rocks, with a consistency closer to the plastic than the liquid limit. Geologically, the term *mud* refers to liquid or semi-liquid clayey material. Hungr et al. (2001) suggested to use this term for soft remoulded clayey soils whose matrix (sand and finer) is significantly plastic (Plasticity Index > 5) and whose Liquidity Index during motion is greater than 0.5. While the textural composition of the matrix material helps to distinguish debris flows from earth flows, the same criterion cannot be applied to distinguish earth flows from mud flows because they may involve material of similar texture. The grain-size distribution criterion cannot be solely applied, particularly when flows are described from aerial photographs or even during fieldworks, because the average grain size distribution cannot easily be estimated due to lateral and vertical heterogeneity of these deposits. Other concepts and parameters must be used simultaneously, such as genetic concepts or velocity of movement and the average water content (Hungr et al., 2001).

In Nicaragua, debris, earth and mud flows represent 66% of the total landslides recorded in the database (Paper 2). Earth flows and mud flows (*coladas de tierra* and *flujos de lodo*) have not been systematically identified and recorded in the country since they are often mistaken from one another, especially if not recently deposited or contain materials that are similar in texture. The term "earth flow" (*colada de tierra*) was used to describe inactive and old landslides composed of fine material containing angular blocks, observed in the northern part of the department of Chinandega (Pallàs et al., 2004) and in the municipality of La Trinidad (Menéndez et al., 2003). These landslides have characteristic "hourglass" shape features with an arcuate and depressed head scarp and an elongate and lobulo-shape area of accumulation. The term "mud flow" (*flujo de lodo*) has often been used inappropriately to refer to debris flows, earth flows and, shallow slides. In historical documents floods are frequently recorded and described as they contain a large amount of "mud". This may suggest that mud flows may have occurred instead or in combination with floods, but this is not always well defined (Paper 1).

To indicate a debris flow (*Flujo de detritos* or *de escombros*) that occurred in the mountain ranges of the interior, the term *non-volcanic* is used in this study, while the term *volcanic debris flows* is used to indicate those that occurred on slopes of quaternary volcanoes and other volcanic structures (Paper 3). Most of the debris flows recorded occurred during Hurricane Mitch often on top of old deep-seated slides starting with a translational or rotational slide mechanism (Paper 2). They appeared sometimes as shallow slides of a few square meters in area, a few meters in depth, and later evolved into debris flows traveling a few hundreds meters downslope, commonly stopping on the gently-sloping colluvial apron (Pallàs et al., 2004; Cannon et al., 2002). In the northern area of the country, non-volcanic debris flows initiated on SE-facing slopes with angles ranging between 15 and 35° (Paper 2). They involved soil, colluvium and weathered rocks (schists, phyllites, ignimbrites, conglomerates) of Paleozoic and Tertiary age (Paper 3). Volcanic debris flows (or lahars) occurred along the steep slopes and gullies of active and dormant volcanoes, along inner walls of calderas, and in small hills remaining after volcanic collapses (Paper 3). They involved loose pyroclastic materials and ashes, blocks of lavas, and pyroclastic deposits. Lahars that occurred in active volcanoes started as water floods and transformed into debris flows, eroding and incorporating loose pyroclastic material deposited on the slopes also after recent eruptions. The deposits consist of large blocks of

1-2 m diameter, cobbles, pebbles, and sand in a very mixed state. Clay and silt fractions are almost completely absent (Paper 3). Lahars on slopes of dormant and deeply eroded volcanoes began with small flank collapses and showed the tendency to change behaviour while moving downslope (Scott et al., 2005). They were highly mobile and eroded fine material even beyond the edifice, increasing in volume by sediment entrainment (bulking) to volumes several times the volume of the failed flank and moved over 20 km.

Scarce information exists about the debris avalanche (*avalanchas de detritos*) distribution in the country. Non-volcanic debris avalanches have not been recognized yet. Such types are often mistaken by debris slides since their characteristics are not fully understood. Evidences of volcanic debris avalanches have been found only at the Casita and Mombacho volcanoes (Paper 1 and Paper 3).

Large areas of soil creep (*reptación*) have been observed mainly in the northern and central part of Nicaragua, especially in deforested slopes often used as pasture land and on top of large deep-seated slides. They occurred on lateritic soils, colluvial deposits and in the upper altered and weathered portions of the bedrock (ALARN, 2002; Álvarez et al., 2003a; INETER-AECI, 2004; Hradecky et al., 2002).

Finally, channel bank failures have been identified along main rivers and streams in the northern and western part of the country. They are small shallow debris slides or small rotational slides and involve alluvial or colluvial material, poorly consolidated pyroclastic material, and weathered and altered rocks. These small failures have been responsible for much of the flooding problems caused during Hurricane Mitch, because they produced huge sediment influxes leaving a large amount of sand and gravel size sediment in the bed of the channels, reducing the stream capacity. Some of the houses located on the steep slopes above the rivers and streams were damaged because of these channel bank failures.

4.3. Temporal and spatial distribution

Landslides recorded in the Nicaraguan 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 (Paper 1 and Paper 2). A large number of records are dated October 1998, which represent 62 % of the total amount of the data stored (Paper 2). 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 and when the country has the highest probability of being impacted by hurricanes (Paper 1 and Paper 2). The annual number of landslides presented in Paper 2 for the period from 1826 to 2003 shows major landslide activity in 1960, 1988, 1996, 1998, 2000 and 2002 with more than 10 landslide events per year. It is observed that a high number of events per year is usually related to a strong triggering mechanism or to the combination of two or more triggers in the same year (Paper 1). Even when excluding data triggered by Hurricane Mitch, an increase in the number of landslides is observed in time (Paper 1 and Paper 2). This is mainly due to the increased awareness and more efficient collection of recent data, and probably not because of a higher frequency of recent landslides. However, an increase in frequency of recorded landslides is to be expected in the future because in recent years more people are being exposed to landslides due to increased population, the expansion of the agricultural frontiers, the high rate of poverty that forces a large population to migrate toward susceptible land areas without proper planning, and accelerating deforestation from new and expanding settlements. The spatial landslide distribution at the national scale shows a strong relation between landslide occurrence and the hilly and mountainous areas of the country. 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 and up to 1800 m (Paper 2). 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 number of landslides was mapped in the Departments of León, Chinandega, Estelí, Matagalpa, and Nueva Segovia. The municipality of El Sauce in the Department of León had the highest number of recorded landslides of any of the Departments (Paper 2). Historical data (Paper 1) showed that the same locality frequently was affected more than once by landslide processes.

4.4. Triggers

The landslides recorded have been triggered by rainfall, earthquakes, tropical cyclones, volcanic eruptions or by the combination of two or more of these phenomena. A few of them have been triggered by human activities (i.e. excavations, vibrations, explosions). Rainfall is the most frequent triggering mechanism, also associated with tropical cyclones (Paper 1 and Paper 2). All types of landslides can be triggered by rainfall, but debris flows and translational shallow slides are more frequent. Landslides triggered by rainfall are limited in time to the wet season that lasts from May to October and an increase in the number of events is observed during the months of September and October (Paper 1). Both Atlantic and Pacific tropical cyclones (i.e. Isabelle, Irene, Fifi, Alleta, Joan, Mitch, Keith, Alma and Isidore) have triggered landslides (Paper 2). Landslides from earthquakes and volcanic eruptions are largely independent of the season, but there are evidences that strong earthquake shaking have increased the susceptibility to rainfall-triggered landslides in certain areas due ground cracks generated by the preceding earthquake. Furthermore, loose deposits that result from earthquake-triggered slides may become unstable during a subsequent rainfall. Earthquakes triggered mainly rock falls and slides (translational or rotational) along roads. Seismic activity associated with volcanic eruptions can trigger rock falls in the upper part of the volcano. Landslides related to volcanic activity have been recorded at the Masaya, Cerro Negro, Concepción, and San Cristóbal volcanoes. High intensity rainfall of short duration, during or following an eruption, always seems to trigger lahars (Paper 2).

4.5. Human and economical losses

International, regional and national natural disaster databases (i.e. “EM-DAT: The OFDA/CRED International Disaster database”; “Inventario de Desastres en Centro América 1960-1999”; “Base de Datos de Desastres Naturales” and “DESINVENTAR”) were consulted to find how many disasters were the results of landslides, the number of victims and affected people, and the magnitude of economical losses related to them. Because landslides mainly occur in combination with or are consequences of other natural phenomena (like hurricanes, earthquakes or volcanic eruptions), their occurrence is not properly recorded and is subordinated to the primary event that triggers them. The databases consulted (CRED, 2005; CEPREDENAC, 2005; CEPAL, 2000; La RED, 2004) record the primary event, and catastrophic landslides triggered by it are not recorded separately. Therefore their impacts are not reflected separately in the databases. As an example, the 1998 Casita lahar (Paper 4) killed about 2500 people (La RED 2004). The victims are recorded under Hurricane Mitch, although the number of victims in the landslide comprised 83% of the total number of the victims due to the hurricane (3045 victims reported by CEPAL, 2000). The same was observed for the 2001 Las Colinas landslide that buried almost 500 people in El Salvador (Baum et al., 2001; United Nations, 2002). The victims related to this event are included in the total number of victims due to the 2001 El Salvador earthquake.

The analysis of these databases shows no records of human and economical losses due to landslides in the period considered in the present research. However, through the analysis of historical documents, the information of landslide damages and casualties was extracted (Paper 1) and helped to give an estimate of the number of victims related to landslides and the types of damages prior to 1990. The preliminary analysis of all data stored into the database shows that a total of 28 landslide events caused the death of a total 2982 people and seriously affected 17068 people. Because of no systematic collection of landslide consequences, probably these numbers are too small and do not represent the real situation in the country. However, the analysis allowed defining which types of landslides have been the most catastrophic ones and which types of damages are related to a specific type of landslide. It also helped to see the distribution of victims in relation to the number of landslides.

Debris flows and debris avalanches in volcanic areas have produced the highest number of victims in the country and are particularly dangerous to life and property. In most cases it was a single event that caused hundreds or even thousands of casualties. The 1998 Casita lahar is the event that caused the highest number of victims (2513) in the country (Paper 2 and Paper 4). The second most catastrophic landslide was the debris avalanche that occurred in 1570 on the southern flank of the Mombacho volcano. It killed 400 people according to the old Spanish chronicles (Paper 1). At least 3 debris flows and secondary floods on the southern slopes of the El Chonco and San Cristóbal volcanoes were triggered by a strong storm in 1960 and buried the village of San Benito killing about 43 people. In 1996 a debris flow on the northern slope of the Maderas volcano caused 6 victims.

Single landslide events in the interior mountain ranges have not caused as many fatalities as those in the volcanic chain. However, non-volcanic debris flows sometimes occur in a group of small events that may coalesce in a common drainage path and flow great distances to alluvial fans at the base of the mountain range, causing human casualties (Strauch, 2004) and large damage to the infrastructure and the economy of the area (Coe et al., 2004).

Estimates of economical losses related to landslides are not available for the country, but the present analyses allowed to identify types of infrastructure affected and types of damages associated with them. Landslides in Nicaragua have mainly affected roads, bridges, cultivable and pasture lands, touristic areas (such as national volcanic parks) (Paper 1). Landslides that occurred before 1990 frequently created damage to the old railway line that was connecting the main cities of Granada, Masaya, Managua, León, Chinandega and the harbour of Corinto. In terms of damages, debris flows both in volcanic and non volcanic environments have been the most catastrophic because of their long run-out distance.

4.6. Landslide characteristics

The physical characterization of landslides in Nicaragua could be made only for a small number of events (348) recorded in the database, because the rest of the 16785 events did not contain the parameters required (Paper 3). The characterization helped to quantify some important parameters (i.e. run-out distance, inundated area, run-out angle, and volume). The database was expanded by taking into account 19 events that occurred in other Central American countries.

Landslide volumes ranged from less than 100 m^3 (for small rock falls) up to 16 km^3 for large volcanic debris avalanches. The smallest slides had a surface area of about 500 m^2 and the larger ones up to 1 km^2. Volcanic debris avalanches showed the largest areas up to 540 km^2 (Paper 3). The run-out distances observed were extremely variable. In rock/earth falls the run-out distances varied from 12 to 870 m, while for slides run-out distances between 20 m and 2.5 km were observed (Paper 3). Non-volcanic debris flows reached distances up to 1.5 km, similar to debris flows in quaternary volcanic structures (i.e inner walls of calderas, craters). Debris flows that occurred on volcanoes usually reached a minimum distance of about 4 km up to maximum distances of about 25 km. In Nicaragua, volcanic debris avalanches showed similar run-out distances to volcanic debris flows up to 13 km, but longer distances (of about 50 km) were reached by volcanic debris avalanches in other Central American countries (Paper 3).

4.7. Debris flow run-out prediction

Debris flows represent the most common types of landslides in Nicaragua and together with debris avalanches in volcanic environments are the most catastrophic types of landslides, characterized by long run-out distances and large volumes. In order to provide useful tools for predicting their run-outs and extent, empirical-statistical analyses were applied, using the data stored in the Nicaraguan database and then compared with similar

Central American cases and with those presented in the literature from earlier studies (Paper 3). The data were analyzed and presented in the form of relationships among the run-out distance, height of fall, the travel angle, and landslide volume. Besides debris flows and debris avalanches in volcanic and non-volcanic environments, other landslide types were considered such as rock falls and rock avalanches, planar slides, earthflows and mudflows (Paper 3).

One of the relationships derived consider run-out distances and vertical heights of fall. The plots presented in Paper 3 show that volcanic debris flows that occur on volcanoes (conical shape) reach longer distances than those that occurred in the inner walls of calderas and craters. They also reach longer distances than debris flows in non-volcanic areas, and longer than for falls and slides. This is probably because of different slope geometry, slope inclination and topographic constraints. For rock falls and slides the relationship between run-out distance and height of fall is approximately linear. For volcanic debris flows the run-out distance increases proportionally to the height of fall up to a run-out distance of about four kilometres, but larger run-outs seem to be independent of the height of fall (Paper 3, Fig.4). On the basis of these plots empirical relationships were proposed that may help to predict run-out of distances (L) knowing the height of fall (H):

Debris flows $L = -3000 \ln\left(1 - \frac{H}{1600}\right)$

Rock falls $L = 3.22\,H^{0.865}$

Slides $L = 1.69\,H^{1.117}$

However, it is important to note that the height of fall alone is not sufficient for predicting the run-out distance, because as shown by the relationship between the height of fall and the ratio H/L, different values of H/L (i.e. mobility) can be found for the same height of fall (Paper 3, Fig. 6).

The values of the ratio H/L, which is often used as a measure of landslide mobility, showed that volcanic debris flows and volcanic debris avalanches exhibit greater mobility (H/L is not higher than 0.5) than non-volcanic debris flows, rock falls, rock avalanches and planar slides (H/L can be higher than 1.6) (Paper 3). The ratio H/L was also compared with the volume of the event and shows a clear tendency to decrease with increasing landslide volume consistent with the data available in the literature. For Central American data the empirical relationship that can be used to predict run-out distances knowing the volume can be expressed as $L = 1.06V^{0.105}H$.

4.8. The 1998 Casita lahar and its initial flank collapse

This lahar occurred at the southern slope of the Casita volcano on 30 October 1998 and was triggered by the rainfall associated with Hurricane Mitch. So far it is the most famous landslide in Nicaragua, not only because it was the largest event that occurred during Hurricane Mitch in Nicaragua, but also because it was the most catastrophic one that killed 2513 people, buried two entire villages, destroyed several small settlements in the municipality of Posoltega and disrupted the Pan American Highway at numerous bridges (Paper 4). Since its occurrence, several studies were undertaken, aimed at its assessment in different aspects. Field observations revealed evidences of previous repeated rock falls, debris avalanches and debris flows in the southern flank of the Casita volcano (Carreño, 1998; Hradecky et al., 1999; Scott, 2000; van Wyk de Vries et al., 2000; Kerle and van Wyk de Vries, 2001). Erosion produced during Hurricane Mitch in the gullies of the volcano flank, also revealed the presence of at least three large pre-historical lahars (8300 radiocarbon years) both along the drainage of the 1998 Casita lahar and in neighbouring ravines. They inundated almost the same area in the past, having similar clast size and texture and similar or greater thickness to the 1998 flow. The historical research carried out in Paper 1 found the occurrence of two main types of landslides before 1990. Rock falls, usually triggered by earthquakes, have been recorded only when they affected the rural road between Bella Vista, Argelia and Santa Narcisa (upper-middle part of the southern slope). Lahars triggered by rainfall, were recorded when they reached the lower southern part and cut bridges along the Panamerican Highway or along the old railway.

The Casita lahar is the longest debris flow that has occurred in Nicaragua (among those identified so far) having reached a maximum distance of about 25 km. In terms of volume (2.7 mill m^3 for the debris flow phase) it is the third largest landslide following the 1570 and pre-historical debris avalanches at the Mombacho volcano (1 km^3) (Paper 3). The Casita event started as a flank collapse rapidly evolved into a debris avalanche and transformed into a lahar while moving downstream characterized by the following phases: a transitional or hyperconcentrated-flow phase, debris flow phase, transitional or hyperconcentrated-flow phase and streamflow phase (Scott et al., 2005). Analyses carried out in Paper 3 (Fig. 7) show that this event has a higher mobility than the other volcanic debris flows in the Central American region. This is related to the fact that it changed behaviour, transformed and bulked its volume while moving downstream, while the other debris flows reported in Paper 3 did not transform. Separate values of mobility have been presented for its three main phases (debris avalanche, debris flow and hyper-concentrated flow) and increasing mobility is observed while it transformed downstream (Paper 3, Fig.7). The values of H/L found for the debris and the hyper-concentrated phases are comparable with large volcanic debris flows and debris avalanches in other countries that similarly transformed from a flank collapse or a sector collapse.

To asses the hazard posed by such large and complex events and to be able to predict their occurrence, the combination of different tools is required. Besides empirical-statistical methods that can be used to predict their run-out and extent, combined with fieldwork, also numerical models are required to reproduce the dynamic and run-out behaviour of the landslide and a mechanical model that can locate unstable areas in a volcanic edifice. Therefore, a good understanding of the geology (i.e. lithologies, stratigraphy, faults distribution), internal structures, distribution of material properties, and of the processes instigating instability is critical to improve empirical and numerical tools and validate the modelling results.

For the 1998 Casita lahar event, some of the previous studies have thoroughly characterised the lahar phases and transformations (Scott et al., 2005) and investigated anticipated run-out distances and inundations limits (Vallance et al., 2004). However, the detailed initial failure processes and the factors governing them are still poorly understood and the information available is scattered among internal reports and publications. Previously the geology and tectonics of the scarp area have been only described at a small scale or partially described, and very limited data on mechanical properties have been available. Differing opinions have been presented about the number of stages that composed the initial failure, types of failure mechanisms involved (Sheridan, et al., 1999; Carreño, 1998, Vallance et al., 2004) and the sliding surface(s) along which the failure occurred (Grimstad and Wold Hagen, 2003; Opfergelt et al., 2006).

The investigations carried out in Paper 4 provided new insight into the initial landslide process and the mechanical properties on the basis of previous knowledge, additional unpublished field data and new observations. The integrated analyses strongly confirmed that the initial flank collapse included three failure stages that occurred continuously during an interval of seconds to a few minutes and involved both the northern and southern area of the scarp, as proposed by Vallance et al. (2004). The analyses also allowed to define that all stages of failure have occurred along an almost planar sliding surface at the interface between the volcanic breccia (units IV and IVa) and the lower impermeable units of clay-rich pyroclastic deposits (unit VI) and altered lavas (unit VII) (Paper 4). Each stage started with a failure involving the volcanic breccia (units IV and IVa). The different characteristics of the breccia (degree of alteration and fracturing) between the northern and southern areas governed the type of failure mechanism in each stage. The analyses allowed to confirm the type of mechanism of the first stage of failure and to identify the most likely failure mechanism of the second stage. Slope stability back-analyses of the second stage of failure were done, and the stability of the remaining slope was assessed using limit-equilibrium methods.

The first stage of slope failure started in the northern area of the scarp as a detachment of blocks and fragments of the intensively altered volcanic breccia. Blocks started to disaggregate and move downslope in form of a debris flow as proposed by Vallance et al. (2004).

The second stage of failure occurred in the southern area of the scarp involving the stronger and impermeable volcanic breccia and the overlying loose volcanic material. The back-analyses performed indicated that sliding in the volcanic breccia overlying the unit of clay(smectite)-rich pyroclastic deposits with low shear strength, was the main controlling feature of the failure mechanism. The likely triggering factors of the sliding within the breccia were the removal by erosion of a unit of stabilizing colluvium at the toe of the slope by the flow from the initial upstream failure in the northern area in combination with the build-up of a hydrostatic pressure within the sub-vertical (75°) open cracks in the breccia. The colluvium at the toe of the slope had previously acted as a stabilizing berm. A retrogressive failure may have occurred involving the overlying loose volcanic material. The heavy rainfalls associated to Hurricane Mitch played a key role, saturating the loose material (unit III) on top of the breccia and building up of water pressures along the interface between the breccia and unit III, along the subvertical slope-parallel open fractures within the breccia, and along the interface between the breccia and the underlying clay-rich altered pyroclastic deposits.

The third stage of failure was caused by the occurrence of the first and second failures and involved the fractured lavas. Its mechanism of failure is still unclear.

The slope stability back-analyses allowed to obtain a range of undrained shear strengths at the base of the breccia (470 to 640 kPa) and to investigate the sensitivity of the factor of safety to hydrostatic pressures and the thickness of the breccia and the colluvium. For the remaining southern slope, the results of the analyses (Paper 4, Table 3) for undrained conditions, which are considered the most likely to occur in these settings, indicated that it can become unstable when the slope is fully saturated, i.e. same conditions as those produced during Hurricane Mitch. For the perched water table scenarios a factor of safety lower than 1 is obtained if the colluvium berm is removed from the toe, but in "dry" conditions the slope is stable as long as the colluvium at the toe is not removed.

5.Conclusions and recommendations

The development of a national digital database has reached the goal of collecting and organizing the available landslide data in Nicaragua within a centralized government institution (INETER). A total of about 17000 events temporally distributed between 1570 and 2003 have been collected in the database. Valuable information on landslide events has been obtained from a great variety of sources, such as natural hazard catalogues, technical reports, newspapers, landslide inventory maps, historical monographs, scientific papers and internet. The database is intended to support local and national authorities, the scientific community and international donors, and it allows an easier access and management of large amounts of multi-scale data collected from multi-temporal studies. The analyses carried out during the present research, show for the first time the available landslide information in Nicaragua, and allow characterizing landslides in terms of spatial and temporal distribution, types of slope movements, triggering mechanisms, number of casualties and damage to infrastructure. Economical and human consequences of landslides in Nicaragua have up until now been grossly underestimated. Data on human losses and damages were found in historical documents and may be used to make preliminary estimates of consequences of landslides. Historical research not only helped to prove the occurrence of landslides in the past, but helped as well to understand in which context landslides occurred and the relation with their triggering mechanisms. A more comprehensive understanding of their triggers will help in the prediction of future landslide events. Physical characterization of landslides was done on the basis of the data stored in the database. Relationships among the important parameters, such as run-out distance, landslide volume, height of fall and run-out ratio, were studied and emerged as useful tools for landslide run-out distance predictions. They provided a better understanding of the physical characteristics and behaviour of landslides in Nicaragua and in its neighbouring countries of El Salvador, Costa Rica and Guatemala. The analyses showed that volcanic debris flows and debris avalanches (started as volcanic flank or sector collapse and later transformed into a lahar) show the highest mobilities reaching longer distances compared to other types of landslides in the region.

Besides empirical-statistical methods, that can be used to predict their run-out distances, the use of mechanical models combined with field data (i.e. geological, tectonic, stratigraphic and geotechnical data), were also investigated to asses the hazard posed by such large and complex events and to provide a better understanding of the initial failure processes and the factors instigating the instability.

The initial flank collapse of the 1998 lahar that occurred at the Casita volcano was investigated. New insight into the geology, tectonics, pre- and post-failure geometry, and stratigraphy of the scarp area were provided, and the failure sequence and pre- and post failure slope stability were modelled combining data from previous published and unpublished works and field observations. The flank collapse was constrained by confirming that it included three stages of failure that occurred continuously during an interval of seconds to a few minutes, involving both the northern and southern area of the scarp as previously proposed by Vallance et al. (2004). The study confirmed the most likely failure mechanism of the first stage and identified the most likely failure mechanism of the second stage. It defined that all failures seem to have occurred along an almost planar sliding surface at the interface between the volcanic breccia and the lower impermeable units of clay-rich pyroclastic deposits and altered lavas. Back-analyses of the second stage of the failure were done, and the stability of the remaining slope was assessed. The results of the analyses performed for undrained conditions indicated that the remaining southern slope is unstable if it becomes saturated during intense and/or prolonged rainfall, i.e. the same conditions as those produced during Hurricane Mitch. The research showed the importance of having a fairly detailed geologic description and at least some geotechnical data in the assessment of the stability situation.

Finally this study has attempted to develop a methodology that can be followed by other countries in the Central American region, collecting available landslide data required to produce landslide hazard and zoning maps.

Although the study has achieved a much improved characterization of landslide processes respect to the past, it also demonstrates that the database is still incomplete both in what it concerns the spatial and temporal distribution and the availability of technical parameters for each landslide recorded. As consequence of that the analyses presented are only descriptive and the results obtained are influenced by the lack of data. Statistical analyses and slope stability analyses can be performed (as it was attempted in Paper 3 and Paper 4) only at medium or local scale when data are consistent and complete. The thesis also highlights the limitations of the database and demonstrates that a collection of more data is needed to increase a predictive understanding of landslides.

5.1. Limitations of the database

The limitations, typical of any historical research, are described in Paper 1, while those related with the database development are described in Paper 2. Besides the limitations related to the types of sources used, and the availability of data, others were related to the original descriptions of the landslide events, classification and terminology adopted. The reliability and usefulness of the data depend on the mapping methods used, the surveyor's and collector's experience, available documentation, coordinate systems and data projection, available software, and type of thematic data collected. The results presented herein depended also on the type of collection, analysis and interpretations of the data. The collection of the data in a digital format was limited by the structure and design of the original database which was the starting point for the development described herein (i.e. lack of fields and sections to enter specific technical parameters, accuracy values, and other uncertainties concerning the data). Consequently, the spatial distribution of landslides shows only those areas where landslide inventory maps were made or where landslide records were found through newspapers, technical reports and other documents. Large areas still lack landslide information because of the absence of landslide mapping and not necessarily because of the absence of landslides. Most of the landslides that occurred before 1990 have been recorded in the Pacific region probably because this was the most populated area and because the newspapers that were consulted had their offices in the cities of this region. Because landslides occur in combination with other natural phenomena, landslides are not properly recorded in historical sources, but are rather subordinated to the primary events that triggered them. Also in terms of temporal distribution the database is influenced by a large number of landslides (62% of all events recorded in the database) triggered by Hurricane Mitch in 1998, which give an erroneous impression of the real distribution of landslides in Nicaragua.

The lack of thematic data limited the performance of more complex analyses (Paper 3). Reliable physical landslide parameters are scarce. Volume values were seldom available, while run-out distances and areas were better recorded. In general, it is observed that landslides that occurred in the Pacific region and especially along the volcanic chain, are better described and recorded in newspapers or technical reports, because they have occurred here more frequently, affecting big cities and infrastructure located nearby. In the rest of the country, landslides have been recorded mainly when they have affected roads or when they have caused victims, but these landslide reports often lack information about technical parameters. For instance, the analyses presented in Paper 4 are strongly limited by the lack of information about geotechnical parameters.

5.2. Future work to improve landslide hazard mapping and risk mitigation

This study has provided basic landslide information and tools that are now already in use at INETER in Nicaragua. Future work is needed to improve long-term landslide hazard assessment and zoning in Nicaragua and in Central America in general.

5.2.1. Collection and organization of data

- The scientific community (both national and international organizations working in Central America) should provide a comprehensive and systematic collection of landslide data when new events occur. In addition to the mapping of the landslide scarp, path and deposition areas, physical landslide parameters, characteristics of the triggering mechanisms (i.e. daily amount and duration of rainfall, location, magnitude and fault mechanism of earthquakes) as well as economic and human losses must be collected based on the form used for the database presented in Paper 2. Landslide data contained in internal reports that are published must be improved in their quality.
- The present version of the Nicaraguan database requires some changes in its design and structure in order to incorporate values of specific technical parameters, uncertainties or other data typical for historical events. Limitations must be considered and resolved before using the database for further analyses. The analysis of discrepancies among the landslide inventory maps in the current database must be performed and the existing duplicates of landslide polygons should be removed.

The information contained must be improved through updating of the thematic data and other parameters available in the written reports.

- INETER must provide better coordination among landslide investigations by different international organizations to avoid duplication of efforts when the projects overlap in the same area or have similar purposes.
- Landslides need to be mapped through field surveys and analyses of aerial photographs in those areas where no landslide mapping has been performed (Central and north-eastern areas of Nicaragua).
- The historical research can be continued by investigating those years not included in the present research and by looking for other possible sources available in other institutions, ministries, universities, civil defence, and private companies.
- A more rigorous large scale geological, structural and geotechnical mapping of the areas surrounding a landslide is strongly recommended. The distribution of faults, fumaroles, hydro-thermally altered rocks, fractured and weathered areas is needed to improve tools and methods used in landslide hazard assessment.
- The government scientific institutions must organize landslide studies in archives and in a database to avoid dispersion of reports and data and provide easy access to the users. The database must be periodically updated and maintained. Digital landslide data from future projects must be incorporated.

5.2.2. Landslide analyses

- To improve landslide predictions, analyses must be performed periodically and at different scales, combining field observations, empirical relationships, laboratory studies and numerical simulations. Because of the numerous landslide emergencies each year, Nicaraguan scientists do not have time (and sometimes experience) to analyse the landslide data, leaving this task to foreign scientists as part of cooperation projects. The performance of analyses will give the Nicaraguan scientists the possibility to have control of the amount and quality of landslide information in their country, to learn about landslide characteristics and conditions of occurrence, to calibrate the amount and quality of data collected, to identify and calibrate the most appropriate methods and numerical models for landslide prediction, and to identify the optimal monitoring and early-warning systems.
- Susceptibility and hazard analyses must take into account differences in relief, geology, geomorphology, meteorological factors and seismicity among areas in the

country. Landslides must be studied within the geographic and geologic context where they occur, so methods and models must be calibrated for these conditions.

- It is strongly recommended that landslide specialists acquire knowledge about other natural phenomena that can trigger landslides in Nicaragua, or that can be triggered by landslides. Knowledge of the characteristics and behaviour of volcanic rocks which are so commonly distributed in the country is required. Landslide specialists must have knowledge also about the seismic and volcanic activity and meteorological systems of the country and ultimately of the Central American region. A multidisciplinary effort involving geologists, engineers, meteorologists, volcanologists, seismologists and hydrologists is necessary to better predict landslide events.
- Prediction of landslides at active and dormant volcanoes requires good knowledge of the geology, tectonics, internal structures, historical landslide activity and eruptive behaviour of each one of them. Changes in seismic, volcanic and fumarolic activity must be considered and analysed together with possible triggering mechanisms.
- Efforts must be made to identify rainfall thresholds that can trigger landslides. Thresholds must be identified for the different geologic zones and the different meteorological systems that affect the country (e.g. large tropical or local convective systems).
- The combination of high seismicity and rainfall or volcanic activity is a likely triggering mechanism and needs to be investigated further for better landslide prevention.
- Historical landslides must be investigated together with other natural triggering mechanisms (earthquakes, volcanic eruptions, hurricanes). A combined investigation is useful not only for the assessment of the landslide hazard, but also to assess the hazard posed by other natural threats that frequently affect the country.
- Analyses of economic losses due to landslides in the country must be promoted together with civil defence and national road authorities to have estimates of their socio-economic significance.
- Landslide mitigation structures along main roads must be planned and constructed to avoid the occurrence of frequent landslides on uncovered and unprotected slopes.

5.2.3. Collaboration among institutions

- The future collection of landslide information must be done in a strong collaboration and interaction with civil defence authorities, national government institutions and universities in order to have a homogeneous landslide database avoiding the presence of several natural hazard databases (that at the present time underestimate the socio-economic significance of landslide processes). Collaboration must also be promoted among Central American scientists to allow exchanging experiences and identifying common patterns in the occurrence of landslides in the region.

6.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)

Alvarado, G.E., Sigarán, C., Pérez, W. 2000. Vulcanismo: sus productos y geoformas. In: Editorial Tecnológica de Costa Rica (ed), *Geología de Costa Rica*. Compiled by Percy Denyer and Siegfried Kussmaul, 133-154

Alvarado, G.E., Vega, E., Chaves, J., Vásquez, M. 2004. Los grandes deslizamientos (volcánicos y no volcánicos) de tipo debris avalanche en Costa Rica. *Revista Geológica de América Central 30, 83-99*

Álvarez, A., Devoli, G., Chávez, G., Talavera, E. 2003. Lahares La Chirca en Octubre de 2002, volcán Concepción, Isla de Ometepe.Rivas. Internal report Instituto Nicaragüense de Estudios Territoriales, Managua, Nicaragua

Álvarez, A., Devoli, G., Chávez, G., Mayorga, E. 2003a. Amenazas por Deslizamientos en Ciudad Sandino, Estelí y Ocotal. Chapter III In Amenazas geológicas en Ciudad Sandino, Estelí y Ocotal, 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. Dirección General de Geofísica, Instituto Nicaragüense d Estudios Territoriales, Managua, Nicaragua.

Álvarez, A., Obando, T. 2005. Deslaves en el volcán Casita. Reporte de evaluación, 11 y 12 de octubre. Internal report. Dirección de Geología Aplicada, Dirección General de Geofísica, Instituto Nicaragüense de Estudios Territoriales, Managua, Nicaragua

Baum, R.L., Crone, A.J., Escobar, D., Harp, E.L., Major, J.J., Martinez, M., Pullinger, C., Smith, M.E. 2001. Assessment of landslide hazards resulting from the February 13, 2001 El Salvador earthquake. U.S. Geological Survey Open File report 01-119

BGVN, 1991. Bulletin of the Global Volcanism Network, BGVN 02/91, Smithsonian Institution

BGVN, 1993. Bulletin of the Global Volcanism Network, BGVN 03/93, Smithsonian Institution

BGVN, 1996. Bulletin of the Global Volcanism Network, BGVN 9/1996, Smithsonian Institution

Bommer, J.J., Rodríguez, C.E. 2002. Earthquake-induced landslides in Central America. *Engineering Geology 63, 189-220*

Bucknam, R.C., Coe, J.A., Mota, M., Godt, J.W., Tarr, A.C., Bradley, L-A., Rafferty S., Hancock D., Dart R.L., Johnson M. L. (posted 9 April, 2002). Landslides Triggered by Hurricane Mitch in Guatemala - Inventory and Discussion. U.S. Geological Survey Open File report 01-0443

Buitrago, N., Bobadilla, O., Bodán, M., 1997. Deslizamiento en el Cerro San Pedro, Palo Alto, Comarca El Vergel en el municipio de Muy Muy, departamento de Matagalpa. Internal report Dirección General de Geofísica, Instituto Nicaragüense de Estudios Territoriales, Managua, Nicaragua

Calcaterra, D, Parise, M. 2001. The contribution of historical information in the assessment of the landslide hazards. In: Glade, T., Albini, P., Frances, F. (eds), *The use of historical data in natural hazards assessment.* Kluwer Academic Publishers, 201-217

Cannon, S.H., Haller, K.M., Ekstrom, I., Schweig, E.S., Devoli, G., Moore, D.W., Rafferty, S.A., Tarr, A.C. (posted 9 April, 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)

Carson, M.A., Kirkby, M.J. 1975. Hillslope form and process. Cambridge University Press, Oxford.

CEPREDENAC, 2005. Inventario de Desastres en Centro América 1960-1999. http://www.cepredenac.org/inventariodesastres2.htm. Centro de Coordinación para la Prevención de Desastres Naturales en América Central

CEPAL, 2000. Un tema del desarrollo: La reducción de la vulnerabilidad frente a los desastres. Comisión Económica para América Latina y el Caribe. Report prepared for the meeting “Enfrentando Desastres Naturales: una cuestión del desarrollo” New Orleáns, 25-26 March 2000

CRED, 2005 EM-DAT: The OFDA/CRED International Disaster Database http://www.em-dat.net . Center for Research on the Epidemiology of Disasters. Université Catholique de Louvain - Brussels - Belgium

Coe, J.A., Godt, J.W., Baum, R.L., Bucknam, R.C., Michael, J.A. 2004. Landslide susceptibility from topography in Guatemala. In: Lacerda, W.A., Ehrlich, M., Fontura, S.A.B., Sayao, A.S.F. (eds), *Landslides: Evaluation and stabilization*. Taylor & Francis group, Vol.1, 69-78

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

Connor, C., Connor, L., Sheridan, M. 2006. Assessment of October 2005 debris flows at Panabaj, Guatemala, and recommendations for Hazard Mitigation. Report prepared for OXFAM GB

Corominas, J. 1989. Estabilidad de taludes y laderas naturales Monografía n° 3, Sociedad Española de Geomorfología. Zaragoza, 249pp.

Corominas, J. 1996. The angle of reach as mobility index for small and large landslides. *Can. Geotech. J. 33, 260-271*

Crone, A.J., Baum, R.L., Lidke, D.J., Sather, D.N.D., Bradley, L-A., Tarr, A.C. (posted 9 April, 2002). Landslides Induced by Hurricane Mitch in El Salvador - An Inventory and Descriptions of Selected Features. U.S. Geological Survey Open File report 01-0444

Crosta, G.B., Imposinato, S., Roddeman, D., Chiesa, S., Moia, F. 2005. Small fast-moving flow-like landslides in volcanic deposits: The 2001 Las Colinas Landslide (El Salvador). *Engineering Geology 79, 185-214*

Cruden, D., Varnes, D. 1996. Landslide Types and Processes In: Turner, A., and Schuster, R. (Eds) *Landslides: Investigation and Mitigation.* Transportation Research Board, National Research Council, 247, 36-75

Darce, M., Rodríguez, N. 1979. Riesgos geológicos y volcánicos, Isla de Ometepe, Estudio Preliminar. Instituto de Investigaciones Sísmicas, Publicación No. 1-79. Managua, Nicaragua

Devoli, G. 2001. Amenaza por Movimientos de laderas. In INETER (Ed) *Amenazas Naturales de Nicaragua*. Instituto Nicaragüense de Estudios Territoriales, Managua, Nicaragua. 1st ed, 201-222

Devoli, G. Cruz, E., Rueda, E., Baca, M., Cruz, J., Martínez, F., Tenorio, V., Donado, J., Guerrero, F. 2000. Lahares ocurridos en el entorno del volcán San Cristóbal y relacionados a la actividad volcánica de 1999-2000. Volcán San Cristóbal, Departamento de Chinandega. Internal report Instituto Nicaragüense de Estudios Territoriales, Managua, Nicaragua

Evans, S.G., Ben,t A.L. 2004. The Las Colinas landslide, Santa Tecla: A highly destructive flowslide triggered by the January 13, 2001, El Salvador earthquake. In: Rose, W.I., Bommer, J.J., Lopez, D.L., Carr, M.J., Major, J.J. (eds), *Natural hazards in El*

Salvador. Geological Society of America, Special Paper 375, 25-37. Boulder Colorado

Ferrey, C.J., Williams, R.L., 1971. Geología de la Isla de Ometepe. Archivo Accesible Informe 7. Catastro e Inventario de Recursos Naturales, Managua, Nicaragua

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

Guinau, M., Pallas, R., Vilaplana, J.M. 2005. A feasible methodology for landslide susceptibility assessment in developing countries: A case-study of NW Nicaragua after Hurricane Mitch. *Engineering Geology 80, 316-327*

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

Guzzetti, F., Tonelli, G. 2004. Information system on hydrological and geomorphological catastrophes in Italy (SICI): a tool for managing landslide and flood hazards. *Natural Hazards and Earth System Sciences 4, 213-232.* European Geosciences Union, 2004

Harp, E.L., Hagaman, K.W., Held, M.D., McKenna, J.P. 2002. Digital inventory of landslides and related deposits in Honduras triggered by the hurricane Mitch. U.S. Geological Survey Open File report 02-61

Harp, E.L., Wilson, R.C., Wieczorek, G. 1981. Landslides from the February 4, 1976, Guatemala Earthquake. The Guatemala earthquake of February 4, 1976. U.S. Geological Survey Professional Paper 1204-A

Hazlet, R. 1977. Geology and hazards of the San Cristóbal volcanic complex, Nicaragua. M.S. Thesis, Dartmouth College, Hannover, NH, 212 pp., June 1977

Hidalgo, P.J., Alvarado, G., Linkimer, L. 2004. La lavina del Valle Central (Costa Rica): Lahar or Debris avalanche? *Rev. Geol. Amér. Central 30, 101-109*

Hradecky, P., 1988 Geología del volcán Mombacho y sus alrededores. Instituto Nicaragüense de Estudios Territoriales, Managua, Nicaragua

Hradecky, P., Havlicek, P., Opletal, M., Rapprich, V., Sebesta, J., Sevcik, J., Mayorga, E. 2001. Mapas Geológicos y Reconocimiento de las Amenazas Geológicas en el Volcán Cosigüina, Nicaragua. Geological Survey of the the Czech Republic (ČGS). Report prepared for the Instituto Nicaragüense de Estudios Territoriales. Managua, Nicaragua.

Hradecky, P., Havlíček P., Kycl, P., Mlčoch, B., Mrázová, Š., Novák, Z., Opletal, M., Rapprich, V., Šebesta, J., Ševčík, 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). Report prepared for the Instituto Nicaragüense de Estudios Territoriales. Managua, Nicaragua.

Hungr, O., Evans, S.G., Bovis, M.J., Hutchinson, J.N. 2001. A review of the classification of landslides of the flow type. *Environmental & Engineering Geoscience Vol VII, 3, 221-238*

Ibsen. M-L., Brunsden, D. 1996. The nature, use and problems of historical archives for the temporal occurrence of landslides, with specific reference to the south coast of Britain, Ventnor, Isle of Wight. *Geomorphology 15, 241-258*

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 and Agencia Española de Cooperación Internacional, Managua, Nicaragua.

INETER-COSUDE, 2005. Recomendaciones técnicas para la elaboración de Mapas de amenaza por inestabilidad de laderas. Proyecto MET-ALARN, Instituto Nicaragüense de Estudios Territoriales and Agencia Suiza para el Desarrollo y la Cooperación, Managua, Nicaragua.

INETER, 2007. www.ineter.gob.ni

INSIVUMEH 2007. www.insivumeh.gob.gt

Izaguirre, A., Navarro, M. 1990. Riesgo por desastres naturales: Volcán Concepción, Nicaragua. Instituto Nicaragüense de Estudios Territoriales, Managua, Nicaragua. Conference for the VII Congreso Geológico de América Central, 19-23 de Noviembre de 1990, San José. Costa Rica

Izaguirre, A., Taleno, H. 1997. Informe, Movimientos de Tierra, Municipio de Esquipulas. Internal report Dirección General de Geofísica, Instituto Nicaragüense de Estudios Territoriales, Managua, Nicaragua

Jakob, M. 2005. Debris flow hazard analysis. In: Jakob M, Hungr O (eds), *Debris-flow hazards and related phenomena.* Praxis, Springer Berlin Heidelberg, 411-438

Jibson, R.W., Crone, A.J., Harp, E.L., Baum, R.L., Major, J.J., Pullinger, C., Escobar, D., Martinez, M., Smith, M.E. 2004. Landslide triggered by the 13 January and 13 February 2001 earthquakes in El Salvador. In: Rose, W.I., Bommer, J.J., Lopez, D.L., Carr, M.J., Major, J.J. (eds), *Natural hazards in El Salvador.* Geological Society of America, Special Paper 375, 69-88 25-37. Boulder Colorado

King, A.P. 1989. Landslides: Extent and economic significance in Honduras. In: Brabb & Harrods (eds) *Landslides: extent and economic significance.* Balkema Rotterdam, 81-91

La RED, 2004. Project: DESINVENTAR. http://www.desinventar.org/desinventar.html Red de estudios sociales en prevención de desastres naturales en America Latina

Menéndez-Duarte, R., Marquínez, J., Devoli, G. 2003. Slope Instability in Nicaragua triggered by Hurricane Mitch: distribution of shallow mass movements. *Environmental Geology 44, 290-300*

Molnia, B.F., Hallam, C.A. 1999. Open skies aerial photography of selected areas in Central America affected by Hurricane Mitch. U. S. Geological Survey Circular 1181.

Mora, R. 2001. El deslizamiento de Las Lagunas de Arancibia Costa Rica: un desastre dos veces anunciado. EIRD Informa No. 2.

Mora, S. 1989. Extent and social-economic significance of slope instability in Costa Rica. In: Brabb & Harrods (eds), *Landslides: extent and economic significance.* Balkema Rótterdam, 93-99

Mora, S., Alvarado, G., Morales, L., 1992. Mapa preliminar sintético de amenazas geológicas de Costa Rica. Su importancia en el desarrollo de la infraestructura civil. *Rev. Geol. Amér. Central 25-26, 355-371*

Pallas, R., Vilaplana, J.M., Guinau, M., Falgas, E., Alemany, X., Munoz, A., 2003. A pragmatic approach to debris flows hazard mapping in areas affected by Hurricane Mitch: example from NW Nicaragua. *Engineering Geology 72, 57-72*

Peraldo, G., Molina, F. 1993. Reconstrucción histórica del deslizamiento de Santiago de Puriscal. *Rev. Geol. Amér. Central 16, 85-94*

Peraldo, G., Rojas, E., 1998. La deslizable historia del ferrocarril al Caribe de Costa Rica. Anuario de Estudios Centroamericanos, Universidad de Costa Rica 24(1-2), 97-128

Peraldo, G., Rojas, E. 2000. Guía para investigadores. Catalogo de deslizamientos historicos para Costa Rica, periodo 1772-1960. Revista Informe Semestral, vol. 36

Peraldo, G., Rojas, E., 2003. Cuando Itzo ataca: análisis de la información sobre el Catalogo de Deslizamientos Históricos para Costa Rica (1772-1960). Rev. Geogr. Venez. 44(2), 177-188

Pérez, M., Devoli, G. 2000. Informe geológico de los sismos ocurridos en la laguna de Apoyo y Masaya. Fisuras y Derrumbes en la laguna de Apoyo. Fisuras en La Ceibita. Bulletin "Sismos y Volcanes de Nicaragua" July 2000. Dirección General de Geofísica, Instituto Nicaragüense de Estudios Territoriales, Managua, Nicaragua.

Rickenmann, D. 2005. Run-out prediction methods. In: Jakob M, Hungr O (eds), *Debris-flow hazards and related phenomena.* Praxis, Springer Berlin Heidelberg, 305-321

Rymer, M.J., White, R.A.1989. Hazards in El Salvador from earthquake-induced landslides. In: Brabb & Harrods (eds), *Landslides: extent and economic significance*. Balkema Rotterdam, 105-109

Schuster, R.L., Kockelman, W.J. 1996. Principles of landslide reduction In: Turner, A.K and Schuster, R. L. (eds), *Landslides: Investigation and Mitigation*. Transportation Research Board, National Research Council, Special Report 247, 91-103.

Scott, K.M., Vallance, J.W., Kerle, N., Macías, J.L., Strauch, W., Devóli, G., 2005. Catastrophic precipitation-triggered lahar at Casita volcano, Nicaragua: occurrence, bulking and transformation. *Earth Surface Processes and Landforms 30, (1), 59-79*

Selby, M.J. 1993. Hillslope materials and processes. Oxford University Press, Oxford.

Siebert, L., Alvarado, G.E., Vallance, J.W., van Wyk de Vries, B. 2006. Large-volume volcanic edifice failures in Central America and associated hazards. In: Rose, W.I., Bluth, G.J.S, Carr, M.J., Ewert, J.W., Patino, L.C., Vallance, J.W. (eds), *Volcanic hazards in Central America*. Geological Society of America Special paper 412, 1-26 doi: 10.1130/2006.2412(01)

SNET, 2007: www.snet.gob.sv

Stewart, R.H., Stewart J.L. 1989. Slides in Panama. In: Brabb & Harrods (eds) *Landslides: extent and economic significance*. Balkema Rotterdam, 101-104

Strauch, W. 2004. Deslizamientos, flujos de lodo e inundaciones en el Cerro Musún, junio 2004. In: INETER (ed) Bulletin *Sismos y Volcanes de Nicaragua*, June 2004. Dirección General de Geofísica, Instituto Nicaragüense de Estudios Territoriales, Managua, Nicaragua

Taleno, H., Izaguirre, A., Navarro, M., 1993. Estudio de la amenaza y vulnerabilidad generada por el deslizamiento San José del Sur, Isla de Ometepe. Nicaragua. Project ¨Monitoreo de laderas peligrosas mediante estudios específicos: Deslizamiento de tierra, ladera San José del Sur¨ CEPREDENAC - INETER.

Ui, T. 1983. Volcanic dry avalanche deposits -Identification and comparison with non volcanic debris stream deposits. *Journal of Volcanology and Geothermal Research 18 (1983) 135-150.*

Ui, T., Takarada, S., and Yoshimoto, M. 2000. Debris avalanches. In: Academic Press (ed) *Encyclopedia of Volcanes*. 617-626.

United Nations, 2002. Living with risk. A global review of disaster reduction initiatives. Preliminary version. United Nations, Geneva, Switzerland.

Vallance, J.W., Schilling, S.P., Devoli, G. 2001a. Lahar hazards at Mombacho volcano, Nicaragua. U.S. Geological Survey Open File report 01-455

Vallance, J.W., Schilling, S.P., Devoli, G., Howell, M.M. 2001b. Lahar hazards at Concepción volcano, Nicaragua. U.S. Geological Survey Open File report 01-457

Vallance, J.W., Schilling, S.P., Devoli, G., Reid, M.E., Howell, M.M., Brien, D.L. 2004. Lahar hazards at Casita and San Cristóbal volcanoes, Nicaragua. U.S. Geological Survey Open File report 01-468

Vallance, J.W. 2000. Lahars. In: Academic Press (ed) *Encyclopedia of Volcanes*. 601-616

Vallance, J.W. 2005: Volcanic debris flows. In Jakob, M., and Hungr, O. (eds) *Debris-flow hazards and related phenomena*. Praxis, Springer Berlin Heidelberg, 247-271.

Vallance, J.W., Siebert, L., Rose, W.I., Girón, J.R., Banks, N.G. 1995. Edifice collapse and related hazards in Guatemala. *Journal of Volcanology and Geothermal Research 66, 337-355*

Varnes, D.J. 1978. Slope movement types and processes. In: Schuster R.L., Krizek R.J. (eds) *Landslides: analysis and control*, National Academy of Sciences, Transportation Research Board, Washington DC, Special Report, 176 (2) 11-33

Varnes, D.J. 1984. Landslide hazard zonation: a review of principles and practice. Commission on landslides on the IAEG, UNESCO, Natural Hazards, no. 3

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

Waldron, H. 1967. Debris flows and erosion control problems caused by the ash eruption of Irazu volcano Costa Rica. *USGS Bulletin 1241, 1-37*

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

Zaitchik, B.F., van Es, H.M., Sullivan, P.J. 2003. Modeling slope stability in Honduras: Parameter Sensitivity and scale aggregation. *Soil Sci. Soc. Am. J. 67, 268-278*