Multi-scale landslide risk assessment in Cuba

Enrique Armando Castellanos Abella

International Institute for Geo-information Science and Earth Observation, Enschede, The Netherlands

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ITC, P.O. Box 6, 7500 AA Enschede, The Netherlands

University of Utrecht

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Multi-scale landslide risk assessment in Cuba

Analyse van aardverschuivingrisico op meerdere schaalniveaus in Cuba

(met een samenvatting in het Nederlands)

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Enrique Armando Castellanos Abella

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Promotor:
Professor Dr. S.M. de Jong

Co-promotoren:
Dr. C.J. van Westen
Dr. Th. W.J. van Asch

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"Like stones rolling down hills, fair ideas reach their objectives despite all obstacles and barriers. It may be possible to speed or hinder them, but impossible to stop them",

José Marti, National Hero of Cuba

to my family

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E.A. Castellanos Abella
September/2008

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Acronyms list

Note:
The following list contains acronyms in English or in Spanish used in this book. When they are in Spanish a translation into English between brackets is follow. This translation was made by the author and do not imply the official name of the organization in English.

AMA	Agencia de Medio Ambiente (Environmental Agency)
ANN	Artificial Neural Network
CENAIS	Centro Nacional de Investigaciones Sismológicas (National Center for Seismological Research)
CIDERC	Comisión Nacional de Infraestructura de Datos Espaciales de la República de Cuba (National Commission of Spatial Data Infrastructure of the Republic of Cuba)
CIGET	Centro de Información y Gestión Tecnológica, Cuba (Center for Information and Technology Management)
CITMA	Ministerio de Ciencia Tecnología y Medio Ambiente, Cuba (Ministry of Science, Technology and Environment)
CNAP	Centro Nacional de Áreas Protegidas (National Center of Protected Areas)
CNV	Centro Nacional de Vialidad (National Center of Roads)
DEM	Digital Elevation Model
EMPIFAR	Empresa de Proyectos e Investigaciones de las FAR (Enterprise of Projects and Research of the Army)
ENIA	Empresa Nacional de Investigaciones Aplicadas (National Enterprise of Applied Research)
EO	Earth Observation
FAR	Fuerzas Armadas Revolucionarias (Revolutionary Armed Forces)
GIS	Geographic Information System
IGP	Instituto de Geología y Paleontología (Institute of Geology and Paleontology)
IGT	Instituto de Geografía Tropical (Institute of Tropical Geography)
INRH	Instituto Nacional de Recursos Hidráulicos (National Institute of Water Resources)
INV	Instituto Nacional de la Vivienda, Cuba (National Institute of Housing)
IPF	Instituto de Planificación Física (Institute of Physical Planning)
INSMET	Instituto de Meteorología (Institute of Meteorology)
MINSAP	Ministerio de Salud Pública (Ministry of Public Health)
MINAGRI	Ministerio de la Agricultura (Ministry of Agriculture)
MLP	Multi-layer perceptron used in ANN
NLRA	National Landslide Risk Assessment

NSDI	National Spatial Data Infrastructure
OACE	Organismos de la Administración Central del Estado (Organizations of Management the Central State)
EO	Earth Observation
ONE	Oficina Nacional de Estadísticas (National Statistics Office)
OTE	Oficina Territorial de Estadísticas (Territorial Statistics Office)
PGA	Ground Peak Acceleration
SDI	Spatial Data Infrastructure
SIGEOL	Sistema de Información Geológica de Cuba (Geological Information System of Cuba)
SMCE	Spatial multi-criteria evaluation
SRTM	Shuttle Radar Topographic Mission
UICN	Unión Internacional de Conservación de la Naturaleza (World Conservation Union)
UMIV	Unidad municipal inversionista de la vivienda (Municipal housing investment unit)
UPIV	Unidad provincial inversionista de la vivienda (Provincial housing investment unit)

CHAPTER 1

Introduction

Based on:
Castellanos Abella, E.A. and Van Westen, C.J. 2005. Development of a system for landslide risk assessment for Cuba. In: E. Eberhardt, O. Hungr, R. Fell and R. Couture (Ed), Proceedings, International Conference on Landslide Risk Management, May 31-Jun 3, 2005, Vancouver, Canada

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1. Introduction

1.1. Landslide problems in the World and in Cuba

Landslides are recognized as the third type of natural disaster in terms of worldwide importance (Zillman, 1999). Due to natural conditions or man-made actions, landslides have produced multiple human and economic losses (Schuster and Fleming, 1986; Guzzetti, 2000). Individual slope failures are generally not so spectacular or so costly as earthquakes, major floods, hurricanes or some other natural catastrophes. Slope failures are more widespread, and over the years they may cause more damage to properties than any other geological hazards (Varnes and IAEG, 1984). Most of the damage and a considerable proportion of the human losses associated with earthquakes and meteorological events are caused by landslides, although these damages are attributed to the main event (see Figure 1.1), which leads to a substantial underestimation in the available statistical data on landslide impact.

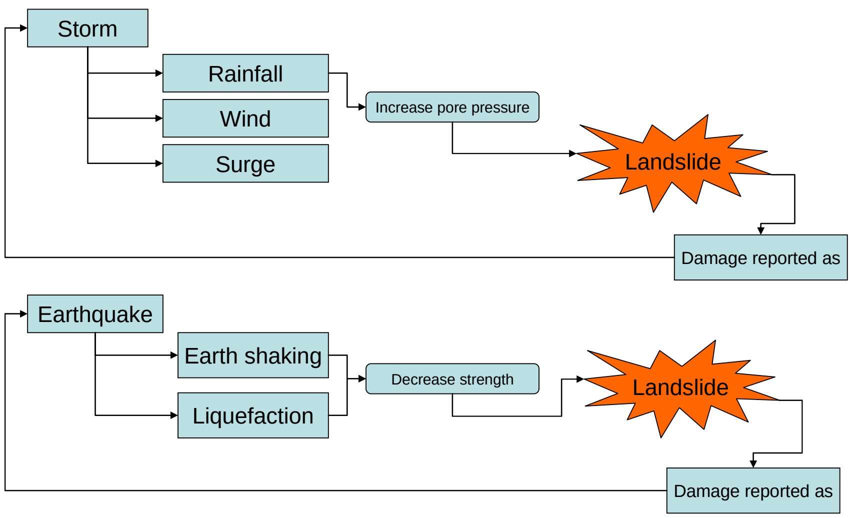

Figure 1.1. Chain of natural events causing landslides and their reporting.

This is illustrated in Table 1.1, which shows the statistics of landslides disasters per continent from April 1903 till January 2007 from the Emergency Disaster Database, EM-DAT, (OFDA/CRED, 2007). In this period landslides have caused 57,028 deaths and affected more than 10 million people around the world. The quantification of damage is more than US$5 billion. These losses have driven the politicians and the scientific community to produce disaster risk reduction plans for landslides, which imply first of all landslide risk assessment.

Table 1.1 World statistics for landslides. Source: EM-DAT database for the period 1903-2007 (OFDA/CRED, 2007).

Continents	Events	Killed	Injured	Homeless	Affected	Total Affected	Damage US (000's)
Africa	23	745	56	7,936	13,748	21,740	No data
Average per event		32	2	345	598	945	No data
Americas	145	20,684	4,809	186,752	4,485,037	4,676,598	1,226,927
Average per event		143	33	1,288	30,931	32,252	8,462
Asia	255	18,299	3,776	3,825,311	1,647,683	5,476,770	1,534,893
Average per event		72	15	15,001	6,462	21,478	6,019
Europe	72	16,758	523	8,625	39,376	48,524	2,487,389
Average per event		233	7	120	547	674	34,547
Oceania	16	542	52	18,000	2,963	21,015	2,466
Average per event		34	3	1,125	185	1,313	154
Total	511	57,028	9,216	4,046,624	6,188,807	10,244,647	5,251,675

Many examples can illustrate the catastrophic nature of landslides in the world (Brabb and Harrod, 1989; Brabb, 1991). Schuster and Fleming (1986) estimated annual losses in United States, Japan, India and Italy at one billion or more each. Subsequently, Schuster and Highland (2001) analyzed the socioeconomic impact of landslides in Western Hemisphere highlighting extreme events such as a debris avalanche in 1970 in Huascaran, Peru with a death toll of 20,000 people, a debris flow in 1985 in Nevado del Ruiz, Colombia killing 25,000 people and the 30,000 that were killed or are missing as result of the 1999 landslides and floods in northern Venezuela. The mismatch between these data and the ones from Table 1.1 is due to the manner in which events were recorded, and the minimum threshold for deaths and economic impact, which is used to include an event in the official EM-DAT database. Statistical data about landslide impacts varies considerably when comparing the reports of different organizations. This reflects that the comparisons are imprecise and that there is reason to assume higher losses (both economic and human) by landslides than reported, due to the following causes:

- Most landslides are secondary phenomena (Figure 1.1). Therefore, their statistics appear under the principal disaster such as earthquakes and hurricanes.
- Landslides occur frequently, and per event they do not cause such levels of damage as other types of events. Since many of the disaster databases apply a minimum threshold of victims or economic losses for disaster impact, most landslide disasters are not recorded.
- Landslide impacts in the past (historic events) are frequently not recorded.

- The records of countries under similar natural conditions show large variations.
- The registration of landslides in mountainous areas with low risk but high hazard is cumbersome as not many people are affected.

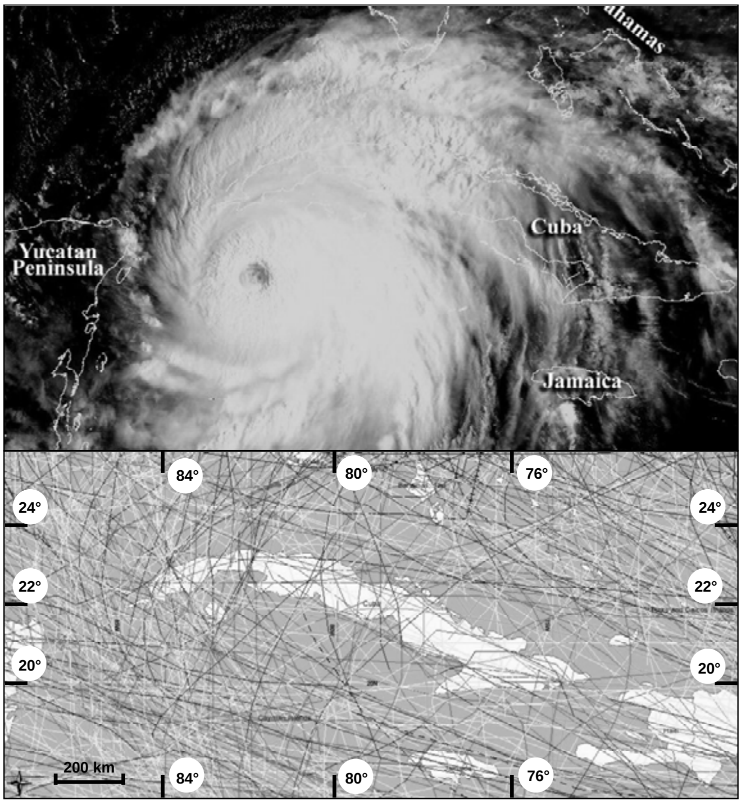

Figure 1.2. Above: GOES-12 image taken during the passage of hurricane Ivan on 13/09/2004, 13:15 UTC; Below: hurricane and tropical storm tracks during the period 1851-2003 (NOAA, 2006).

In Cuba, most of the studied landslides are associated with hurricanes, tropical storms or prolonged periods of rainfall (Viña et al., 1977; Formell and Albear, 1979; Díaz et al., 1983; Pérez, 1983; Iturralde-Vinent, 1991; Magaz et al., 1991; Castellanos Abella et al., 1998; Pacheco and Concepción, 1998; Castellanos Abella, 2000). Hurricanes can cause rainfall events going up to hundreds of millimetres within 24 hours, thus triggering landslides. As the landslide damage is normally recorded as associated to the main disaster there is no information on how many landslides have happened and where they are exactly located. From 1785 to 1984 a total of 108 hurricanes passed over Cuba, of which 23 were of high intensity (>200 km/h), 38 of moderate intensity (151-200 km/h) and 47 of low intensity (118-150 km/h) (Rodríguez, 1989). Figure 1.2 shows the tracks of hurricanes and major storms in Cuba for the period 1851-2003 (NOAA, 2006). Even though the pattern is very dense, it is possible to recognize some parts of the country that are more frequently affected. So far there are no official records for landslides related to these events. All disaster damage was included in the hurricane data and no specification was made for secondary disasters like landslides or flooding. Even though, in a report presented by the National Civil Defence Headquarters it was recognized that 45,000 inhabitants live in areas prone to landslides (EMNDC, 2002).

An analysis of the EM-DAT database (EMNDC, 2002; OFDA/CRED, 2007), revealed that during the 20th Century fifty six important disasters have been registered in Cuba, out of which twenty six were hurricanes and tropical storms. The other thirty disasters were comprised of eighteen flood events, six droughts, two earthquakes, two forest fires and two epidemics. During this period 5,127 people are reported to have died and a total loss of US$5,306,307,000 dollars has been registered. In all cases the highest losses belong to hydro-meteorological events, without subdividing the data according to possible secondary disasters as landslides. However, this database could be considered incomplete as many known events in Cuba are not registered, such as tropical cyclones and forest fires.

Due to the lack of a landslide inventory, the knowledge about geological, geomorphological, tectonic and hydrological conditions under which these events happen is limited or even unknown in Cuba. The interpretative criteria to identify and recognize these phenomena in aerial photos or satellite images for the case of Cuba have not been studied. Likewise, limited work has been done so far where landslides correlate with environmental variables like soils, slope, etc. to produce susceptibility and hazard maps. Even fewer studies have been carried out in areas where the landslide hazards are correlated to elements at risk to generate risk maps.

This study aim at improve our knowledge about the frequency, magnitude and types of landslides in Cuba and the possibilities of producing landslide risk assessment at different levels. The research is intended to contribute in reducing the lack of knowledge about landslide problems mentioned herein, as well as in applying innovative spatial analysis for landslide risk assessment at different scales, taking into account the specific situation with respect to data availability. Before the objectives of this study are defined, an overview of the most important research problems related to landslide risk assessment is presented below.

1.2. Landslide research problem

After analyzing the landslide research carried out in Cuba the main problems were found:

- Landslides are an important problem in mountainous regions in Cuba mainly due to tropical storm events Landslide disasters with human and economic losses are known.

- A historic record of landslides is incomplete and to date there is no landslide inventory system. As a consequence, landslide disasters are usually underestimated.
- Landslide vulnerability, hazard and risk maps are not available for Cuba. However, when available, the method that is applied is dubious.
- Every disaster management level requires a specific landslide risk map that must match their objectives, since larger scales require quantitative maps, whereas with smaller scales qualitative maps are more suitable.
- Due to scarce data availability, a combination of spatial analysis techniques, heuristic approach and modelling is required for landslide risk assessment in Cuba.

As landslides appear to produce an increasing number of disasters worldwide, due to climate change and increasing density population in mountainous areas, the research efforts related to risk reduction are increasing. This is especially relevant in developing countries like Cuba, where the disaster recovery phase is much more difficult due to the economical situation. Others worldwide landslide research problems can be found in the literature (Einstein, 1988; Fell, 1994; Dai et al., 2002; Glade et al., 2005).

1.3. Research objectives and scope

The main objective of this research is to design a framework for spatial landslide risk assessment in Cuba, using a multi-level approach at national, provincial, municipal and local level. The specific natural conditions of Cuba related to landslide types and distribution, data availability and organizational setting are taken into account. A methodology for landslide risk assessment is presented for four administrative levels by using four case study areas at different spatial scales, objectives, datasets available and analysis techniques.

The specific objectives are:

1. To design and implement landslide inventory at different scales using the existing Earth observation data in Cuba, and to propose a system for information collection about future events.
2. To design and apply appropriate indicators for landslide hazard and vulnerability at different scales in Cuba.
3. To propose, describe and implement spatial analysis models for landslide hazard, vulnerability and risk assessment.
4. To determine landslide hazard, vulnerability and risk assessment in four levels of scale in Cuba with specific objectives and expected outputs.

1.4. Landslide research questions

The main research question of this investigation is: How to design and implement a methodology for spatial landslide risk assessment considering the available data and the multi-level administrative set-up for disaster management in Cuba?

Research questions by subject

Below, questions that have been properly addressed during this research are posed.

Landslide inventory

- What Earth observation data is suitable for landslide inventory in Cuba?
- How can a national landslide inventory be implemented, given the administrative set-up? What pieces of information should be collected by whom at different levels in the Cuban context?
- What are the lithological, hydrological, morphological and tectonic conditions in which landslides are more likely to happen in the case study areas?

Hazard and vulnerability indicators

- Which type of spatial and non spatial data are required and available for doing landslide hazard, vulnerability and risk assessment at different scales in Cuba?
- What is the national context for geospatial data related to data availability, format, dissemination and legal framework?
- Which spatial analysis tools and methods could be applied to process existing data and produce hazard and vulnerability indicators?

Landslide hazard, vulnerability and risk assessment

- What are the most appropriate methods of spatial analysis for landslide hazard, vulnerability and risk assessment in Cuba considering the scale (level) and the data availability?
- Which approach for risk assessment (qualitative, semi-quantitative and quantitative) is more appropriated in the conditions of Cuba?
- What is the distribution of landslide hazard, vulnerability and risk in the study areas?

Landslide risk management

- How can landslide risk information be incorporated in disaster reduction plans and the early warning system in Cuba?
- What is the most appropriate design for landslide hazard, vulnerability and risk maps in various levels in terms of its content, cartographic visualisation and legend bearing in mind the scale of the map and the user requirements?

1.5. Research structure and book outline

This research is dealing with *multi-scale landslide risk assessment in Cuba*. *Multi-scale* means the analysis was carried out at different scales using a hierarchical approach. The study focuses on *landslides*, and some aspects of flooding and earthquakes are considered if they have a relation with landslide occurrences. The main target is *risk*, but hazards and vulnerability issues are also widely analyzed. From the risk management framework point of view the investigation is centred on the *assessment* part, nevertheless others issues such as risk monitoring or risk evaluation are also briefly discussed. All study areas are in *Cuba*, even though many of the aspects analyzed herein are also relevant for other countries too.

The book is organized into two parts (see Figure 1.3). The first part of this thesis contains an introduction and overview of general methodological and contextual issues. Chapter 2 includes theoretical overview of landslides inventory, hazard, vulnerability and risk assessment while chapter 3 provides the contextual elements for the research related to disaster management and geospatial data collection in the Cuban framework (Figure 1.3). This part is mostly the review and the foundation of the case study chapters in order to avoid repetition.

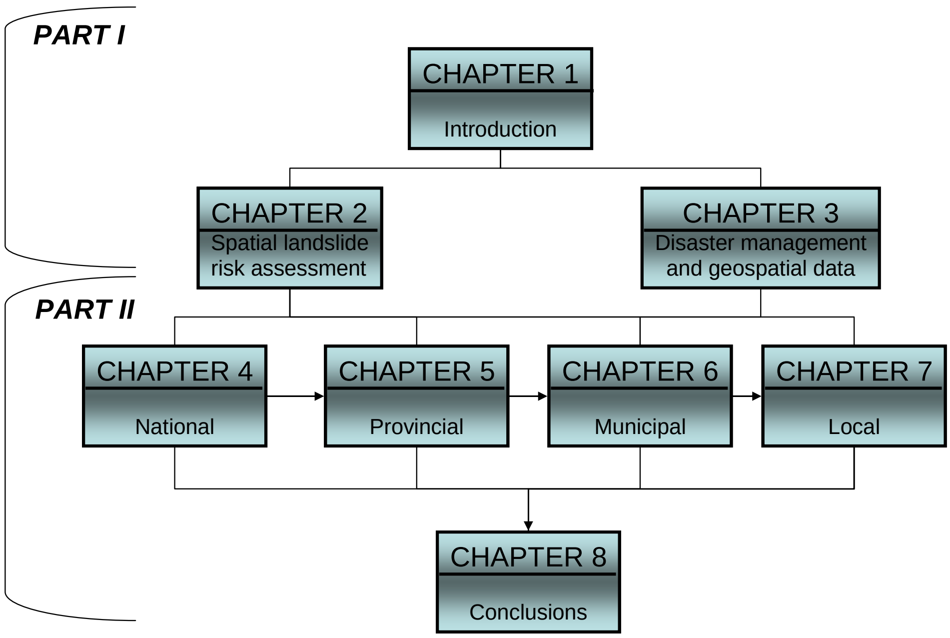

Figure 1.3. Outline of the book.

The second part consists of four case studies at different scales, followed by the conclusions. Some methods and data collection techniques are explained in this part since they are more closely related to one or two case studies. If a method is applicable to more than one level then it will be explained only in the upper level. Also, because the study areas of the lower level are always contained in the one of the higher level, when necessary the reader may be asked to search for specific information in previous (lower scale) chapters.

1.6. Overview of case study areas

The research has different levels of analysis, with different objectives, and availability of data. The reasoning behind this multi-level approach is explained in chapter 2, and an overview of the cases studies areas is given below. Detailed information about each study area is presented in their corresponding chapters. The analysis was carried out in four areas - one inside the other at different scales as explained in Figure 1.4. In every level a comprehensive landslide risk assessment considering all data collection, hazard, vulnerability and risk assessment was conducted.

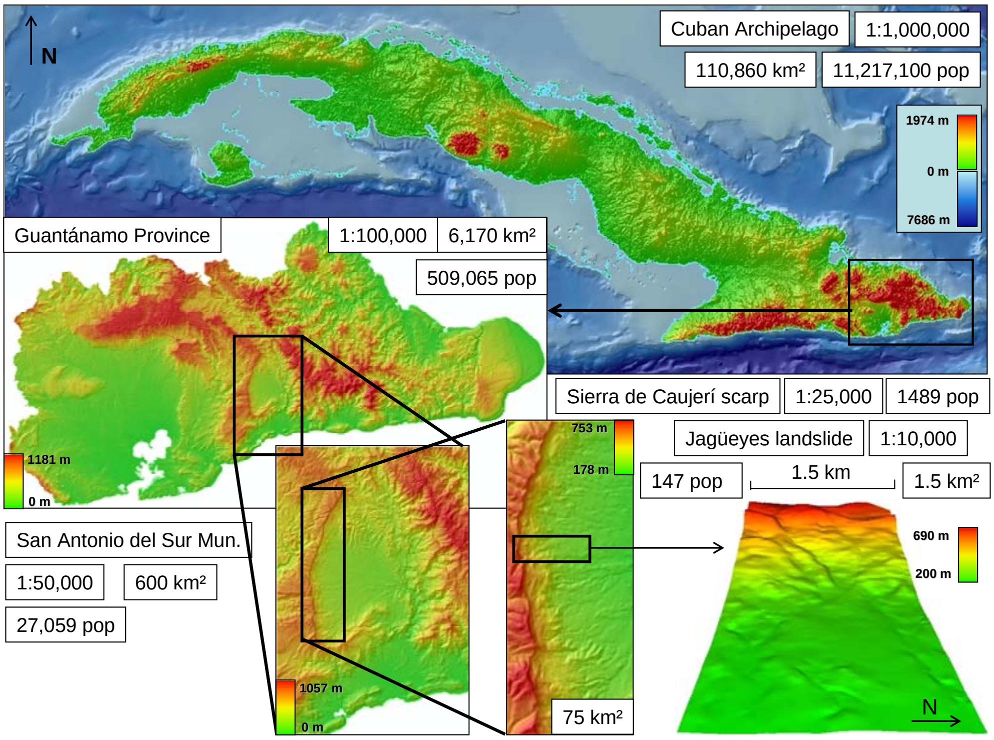

Figure 1.4. Case study areas for landslide risk assessment

For the multi-scale landslide risk assessment in Cuba different methods were applied at national, provincial, municipal and local levels. At the national level a landslide risk index was generated, using a semi-quantitative model with ten indicator maps using spatial multi-criteria evaluation techniques in a GIS system. Each indicator was standardized according to its contribution to hazard and vulnerability. The indicators were weighted using direct, pairwise comparison and rank ordering weighting methods, where the weights were combined in order to obtain the final landslide risk index map at a scale of 1:1,000,000. The results were analysed per physiographic region and administrative units at provincial and municipal levels.

The hazard assessment at the provincial scale (Figure 1.4) was carried out by combining heuristic and statistical landslide susceptibility assessment, its conversion into hazard, and the combination with elements at risk data for vulnerability and risk assessment. The method was tested in the Guantánamo province at a scale of 1:100,000. For the susceptibility analysis twelve factors maps were considered: geomorphology, geology, soil, landuse, slope, aspect, internal relief, drainage density, road distance, fault distance, maximum daily rainfall and peak ground acceleration. Five different landslide types were analyzed separately (small slides, debrisflows, rockfalls, large rockslides and topples). The susceptibility maps were converted into hazard maps, using the event probability, spatial probability and temporal probability. A semi-quantitative risk assessment was made by applying the risk equation in which the hazard probability was multiplied with the number of exposed elements at risk and their vulnerabilities.

At the municipal scale, a detailed geomorphological map formed the basis of the landslide susceptibility assessment. A heuristic model was then applied to a municipality of San Antonio del Sur in Eastern Cuba (Figure 1.4). The study is based on a terrain mapping units (TMU) map, generated at a scale of 1:50,000 by interpretation of aerial photos and satellite images and field data. Information describing 603 terrain units was collected in a database. Landslide areas were mapped in greater detail in order to classify the different failure types and parts. The different landforms and the causative factors for landslides were analyzed and used to develop the heuristic model. The model is based on weights assigned by expert judgment and organized in a number of components such as slope angle, internal relief, slope shape, geological formation, active faults, distance to drainage, distance to springs, geomorphological subunits and existing landslide zones.

At local level, digital photogrammetry and geophysical surveys were used to characterize the volume and failure mechanism of the Jagüeyes landslide (Figure 1.4) at a scale of 1:10,000. A runout model was calibrated based on the runout depth in order to obtain the original parameters of this landslide. With these results three scenarios (each with a different initial volume) were simulated in Caujerí scarp (Figure 1.4) at a scale of 1:25,000 and the landslide risk for ninety houses was estimated considering their typology and condition. The methodology developed in this study can be applied in Cuba and integrated into the national multi-hazard risk assessment strategy. It can also be applied, with certain modifications, in other countries.

CHAPTER 2

Basis of spatial landslide risk assessment

Cited as:
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2. Basis of spatial landslide risk assessment

2.1. Introduction

The ultimate goal of landslide hazard and risk studies is to protect the population, the economy and the environment against potential damage caused by landslides. This requires an accurate assessment of the level of threat from a landslide: an objective reproducible, justifiable and meaningful measure of risk (Crozier and Glade, 2005). Risk, in this context, is seen as a disaster that could happen in the future. Considering this relationship, it is evident that an accurate assessment model is of the utmost importance as it may under- or over-estimate the occurrence of future events. However, there is not yet a common agreement on risk assessment at least for landslide disasters and still many issues on methods and data remain partially under research. It is also relevant the spatial dimension of risk which depend on locations and on scales in which the assessment is carried out. Taking into account the importance and characteristics for disaster reduction, the investigations on risk assessment has increased enormously in the last decade.

The international call for risk assessment became more evident after the World Conference on Disaster Reduction (United Nations, 2005b) in Kobe, where one of the gaps identified from the Yokohama Strategy was 'Risk identification, assessment, monitoring and early warning'. With the expected outcome of a 'substantial reduction of disaster losses' the Conference proposed the so called 'Hyogo Framework for Action 2005-2015' (United Nations, 2005a) which includes three strategy goals and five priorities as actions. The second priority for action was: 'Identify, assess and monitor disaster risks and enhance early warning' with the following key activities:

a) Develop, update periodically and widely disseminate risk maps and information related to decision-makers, general public and communities at risk in an appropriate format.

b) Develop systems of indicators of disaster risk and vulnerability at national and sub-national scales that will enable decision-makers to assess the impact of disasters on social, economic and environmental conditions and disseminate the results to decision makers, the public and populations at risk.

c) Record, analyze, summarize and disseminate statistical information on disaster occurrence, impacts and losses, on a regular basis through international, regional, national and local mechanisms.

The recognition of updating, dissemination and format for risk maps are important issues in this context. They highlight the need for working at different levels, to search for appropriate indicators and the relevance of disaster inventory. Although the needs were clear the methods for implementation were not, forcing the scientific community to find methods for risk assessment per type of hazard - such as landslides contributing to a multi-hazard approach. As a consequence, the scientific community of disaster type started to develop their own framework and generally discussing assessment methods, monitoring, early warning and management. Landslide researchers also contribute to this priority and the latest outcomes are presented herein, along with the author's inputs. The objective of this chapter is to present a theoretical framework for spatial landslide risk and the latest developments on the approaches to assess landslide risk.

2.2. Landslide risk management framework

The term **landslide** was defined by Varnes and IAEG (1984) as 'almost all varieties of mass movements on slopes, including some, such as rock-falls, topples, and debris flows, that involve little or no true sliding'. Later, a similar and more accepted definition was established considering a landslide as 'the movement of a mass of rock, earth, or debris down a slope' (Cruden, 1991).

One of the motivations for generating standard concepts about landslide came up with the idea of producing a World Landslide Inventory (WLI). In order to support the implementation of the WLI, some publications were produced by the IAEG Commission on Landslides, the UNESCO working party on world landslide inventory and later by the IUGS Working Group on Landslides. These publications have led to support a certain level of standardization in fields related to landslides, including: nomenclature for landslides (IAEG-Commission on Landslides, 1990; UNESCO-WP/WLI, 1993a), activity of landslides (UNESCO-WP/WLI, 1993b), causes of landslides (UNESCO-WP/WLI, 1994), rate of movement of a landslide (IUGS-Working group on landslide, 1995) and remedial measures for landslides (IUGS-Working group on landslide, 2001; Popescu, 2002).

Recently, the three geotechnical societies ISSMGE, ISRM and IAEG have created the a so called Joint Technical Committee on Landslides and Engineered Slopes (JTC-1), which continues to work in the standardization and promotion of research on landslides among the different disciplines. If there is certain agreement about landslide nomenclature, activity, causes, movement and remedial measures; it is also true that many uncertainties still remain concerning methodologies for mapping and modelling landslides hazard, vulnerability and risk. The first set of definitions regarding hazard and risk, widely accepted was also proposed by Varnes and IAEG (1984). They are shown in Table 2.1.

Table 2.1 Definitions for landslide hazard and risk assessment (Varnes and IAEG, 1984).

Term	Definition
Natural hazard (H)	Probability of occurrence within a specified period of time and within a given area of a potentially damaging phenomenon.
Vulnerability (V)	Degree of loss to a given element at risk (see below) resulting from the occurrence of a natural phenomenon of a given magnitude. It is expressed on a scale from 0 (no damage) to 1 (total loss).
Specific risk (R_s)	Expected degree of loss due to a particular natural phenomenon. It may be expressed by the product of H times V.
Elements at risk (E)	Population, properties, economic activities, including public services, etc. at risk in a given area.
Total risk (R_t)	Expected number of lives lost, persons injured, damage to property, or disruption of economic activity due to a particular natural phenomenon, and is therefore the product of specific risk (R_s) and elements at risk (E). Thus: $R_t = (E)\ (R_s) = (E)\ (H \times V)$

A graphical representation of landslide risk is shown in Figure 2.1. From this perspective, risk is the zone where both vulnerability and hazard meet. The level of risk thus results from the intersection of hazard with the value of the elements at risk by the way of their vulnerability (Crozier and Glade, 2005). This intersection zone tends to grow due to climate change (for the hazard part) and due to further development and population growth (for the vulnerability part). During the fieldwork campaigns of this investigation it was observed that even at local level, decision makers and civil defence authorities reason in this way. They located risk areas in topographic maps where there was spatial matching between previously known events (hazard) and exposed elements at risk (vulnerability). They rank high risk areas by the magnitude and frequency of the events and the abundance of population or infrastructure. The same reasoning was implemented during this research, particularly for qualitative landslide risk models. A larger set of definitions was later presented by ISSMGE TC32 – Technical Committer on Risk Assessment and Management (2004) which also matched with the international terms recognized for hazard, vulnerability, risk and disasters, and was subsequently published by the United Nations (ISDR, 2004). Since these definitions were published, many approaches have been implemented (Einstein, 1988; Fell, 1994; Soeters and van Westen, 1996; Wu et al., 1996; Cruden and Fell, 1997; van Westen et al., 2003; Lee and Jones, 2004; Glade et al., 2005) allowing one to conclude that nowadays definitions regarding landslides risk assessment are generally accepted.

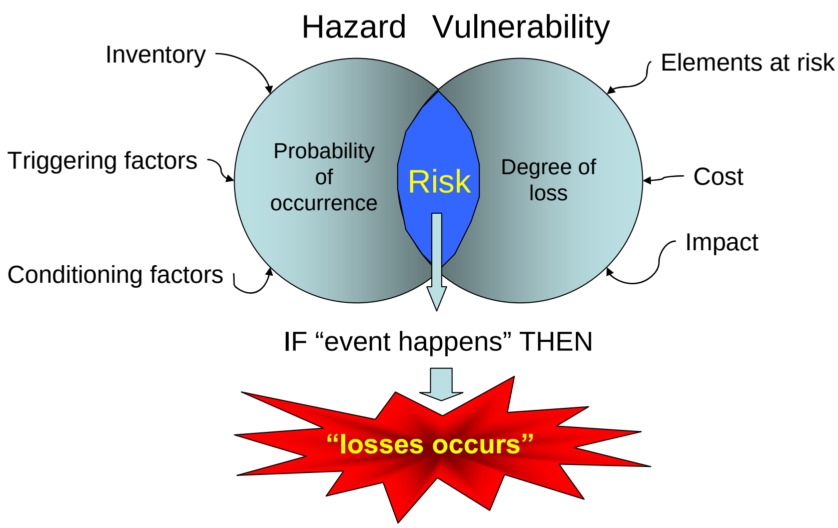

Figure 2.1 Graphical representation of landslide risk and its consequences (after Alexander, 2002).

However, as landslide risk assessment is part of a process rather than a single activity, it fits into a framework of landslide risk management which is also included into the overall landslide disaster risk reduction. The definitions of the different parts for the framework are shown in Table 2.2. Figure 2.2 shows the interrelationship among these concepts. This terminology was also accepted by other authors and organizations (Cruden and Fell, 1997; AGS, 2000; ICG, 2003). There are other concepts or terms like consequence, frequency, etc. that have been recommended, but they will be explained in subsequent sections of this chapter. Although this terminology used for landslide often does not match the terminology used in other types of disasters, it seems to have been generally accepted by the landslide scientific community.

Table 2.2 Definitions for landslide risk management (IUGS, 1997).

Term	Definition
Risk estimation	the process used to produce a measure of the level of health, property, or environmental risks being analysed. Risk estimation contains the followings steps: frequency analysis, consequence analysis and their integration.
Risk analysis	the use of available information to estimate the risk to individuals or populations, property, or the environment, from hazards. Risk analysis generally contains the following steps: scope definition, hazard identification, and risk estimation.
Risk evaluation	the stage at which values and judgements enter the decision process, explicitly or implicitly, by including consideration of the importance of the estimated risks and the associated social, environmental, and economic consequences, in order to identify a range of alternatives for managing the risks.
Risk assessment	the process of risk analysis and risks evaluation
Risk control or risk treatment	the process of decision making for managing risks, and the implementation, or enforcement of risk mitigation measures and the re-evaluation of its effectiveness from time to time, using the results of risk assessment as one input.
Risk management	the complete process of risk assessment and risk control (or risk treatment).
Individual risk	the risk of fatality or injury to any identifiable (named) individual who live in the zone impacted by the landslide; or follows a particular pattern of life that might subject him or her to the consequences of the landslide.
Societal risk	the risk of multiple fatalities or injuries in society as a whole: one where society would have to carry the burden of a landslide causing a number of deaths, injury, financial, environmental, and other losses.
Acceptable risk	a risk for which, for the purpose of life or work, we are prepared to accept as it is with no regard to its management. Society does not generally consider expenditure in further reducing such risks justifiable.
Tolerable risk	a risk that society is willing to live with so as to secure certain net benefits in the confidence that it is being properly controlled, kept under review and further reduced as and when possible.

As Figure 2.2 shows risk assessment have two major steps: risk analysis and risk evaluation. The first one is where the risk values are obtained based on certain hazard and vulnerability values. Such risk values are then evaluated according to the user criteria and decisions are made based on this assessment like developing a landslide risk reduction plan. Rather than risk evaluation, this study will focus mainly on the risk analysis. For risk evaluation, more input from social sciences is needed in order to better understand the human perception and behaviour of risk and disasters.

For the risk assessment approaches two clearly divided types of analysis were classified: qualitative and quantitative (IUGS, 1997). More recently, the risk assessment approaches have been divided in qualitative, semi-quantitative and quantitative (AGS, 2000; Chowdhury and Flentje, 2003). In the semi-quantitative approach, hazards and risk classes are sorted by a ranking system and weighted by a given criteria. Conducting landslide risk assessment spatially implies many steps seldom accomplished in published analysis (see the subsection on risk assessment for references).

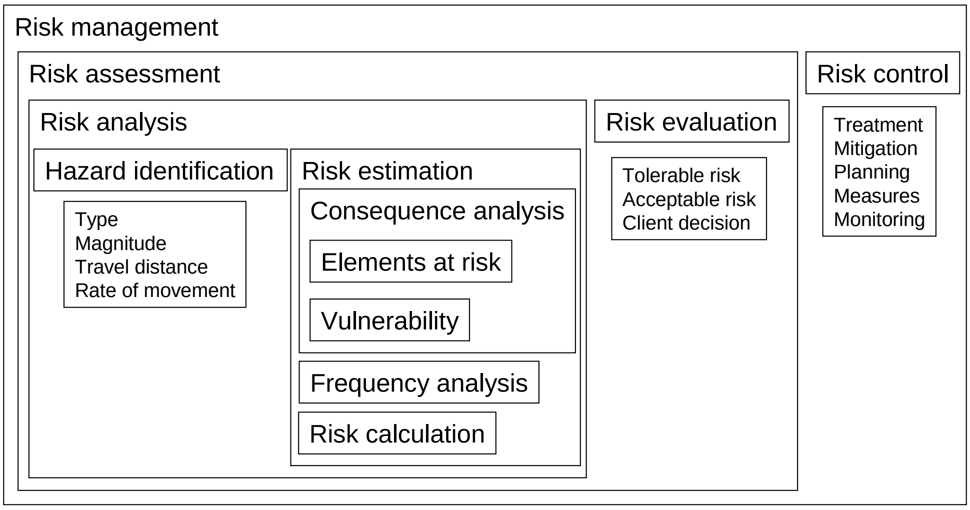

Figure 2.2 Conceptual framework for landslide risk management (concepts from IUGS, 1997).

Figure 2.3 present the proposed methodological framework for spatial landslide risk assessment which is further explained in the subsequent sections of this chapter. It has been made by a comprehensive study of the available literature regarding landslide inventory, susceptibility, run-out, hazard, vulnerability and risk assessment. This methodological flowchart was implicitly employed in every case study of this research, where specific adaptations according to the scale, objectives and data available were applied. Besides, every implementation uses different spatial tools and sometimes, the same tool could be applied in different ways according to the case study. Another representation of the GIS environment for landslide risk assessment can be found in Dai et al. (2002). Thus, four major steps have been identified:

A) Data collection for landslide risk assessment (Figure 2.3A) is the starting point where frequency analysis could be carried out on the landslide inventory, rainfall or earthquake databases, as explained in Section 2.3. This part usually consumes most of the time in every landslide risk assessment project.

B) The landslide hazard assessment (Figure 2.3B) is, maybe, the best known part for landslide studies since much research has been undertaken on this for the last twenty years. It is briefly explained in Section 2.4.

C) The landslide vulnerability assessment (Figure 2.3C) is probably the weakest part in the whole process since relatively little work has been made on the quantification of physical vulnerability due to landslides (van Westen et al., 2005). The latest advances on this topic are explained in Section 2.5.
D) Landslide risk assessment methods (Figure 2.3D) are broadly explained in Section 2.6 considering the latest examples published.

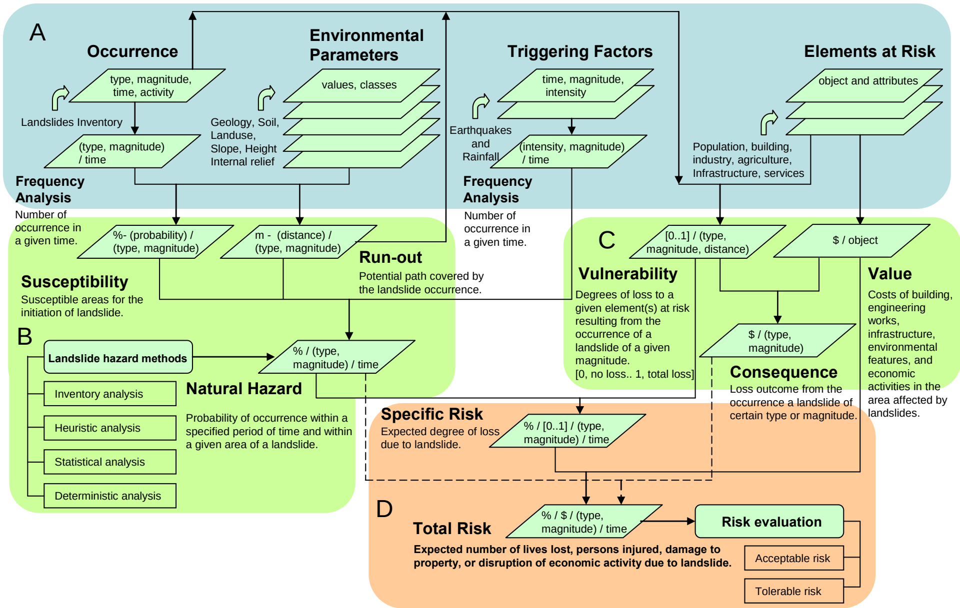

Figure 2.3 Methodological framework for spatial landslide risk assessment.

2.3. Data collection for landslide risk assessment

Research in landslide risk involves many different types of data as the problem becomes more complex when natural and social components are included. Many factors need to be considered for landslide risk assessment in an inter-disciplinary context. Landslide related data could be grouped into four sets: landslide occurrence, environmental parameters, triggering factors and elements at risk (Figure 2.3A). The landslide occurrence data is sometimes called landslide danger data (Einstein, 1988; Einstein, 1997). Indeed, it is a landslide inventory database that can be compiled for a certain area, a whole nation or even, the whole world (see Cruden and Lugt, 1989).

Nationally, many countries have developed their own national landslide inventory database. Large databases and their implementation in web mapping applications have been done by countries like Italy (Collotta et al., 1988; Guzzetti, 2000; Guzzetti and Tonelli, 2004), Switzerland, France (Faure et al., 1988; Faure, 2004; Faure and Pairault, 2004; Faure et al., 2004), Canada and Colombia (Gonzalez, 1989). Other countries have also developed a national landslide inventory database which helps the authorities to make decisions about landslides as disasters (Pasek, 1975; Koirala and Watkins, 1988; Chau et al., 2004; Graziella et al., 2007). Besides, regional landslide inventory databases have been compiled in order to evaluate the landslide hazard and risk (Carrara and Merenda, 1976; Wieczorek, 1984; Dikau et al., 1996; Castellanos Abella et al., 1998; Carrara et al., 2003). In Chapter 4, the landslide inventory designed to be implemented in Cuba is described in detail.

A landslide inventory is considered as 'indispensable' when attempting to produce any kind of probabilistic forecasting. Without a landslide inventory database it is not possible to predict the future behaviour of these events. With the analysis of a simple landslide inventory it is possible to obtain several results of great importance.

A landslide inventory can be developed by means of three main methods:

a) Field reports. For this method a standardized and continuous survey system is required in order to collect the landslide information. The reports are pre-defined forms, and the design of the report depends very much on the personnel that will fill it out. The personal reporting should, in any case, be trained accordingly. Verification of landslide reports will be undertaken in order to control their quality or to complete the more technical parts. One excellent example of this method including bibliographic revision is the AVI project described by Guzzetti et al. (1994).

b) Image-interpretation: the most inexpensive way to cover large areas in less time and it has been demonstrated to be an effective method (Kalaugher and Grainger, 1990; Brardinoni et al., 2003; Casson et al., 2003; van Westen and Lulie Getahun, 2003). It allows for the discovery of old landslides or those that are in inaccessible areas, and requires trained personnel with certain experience. The landslide features and their characteristics can be identified and delimitated. Finally, multi-temporal and multi-scale analysis will also be undertaken.

c) Multi-temporal classification of images and the digital elevation model: Multi-temporal images can be used to check land use changes that may reflect the landslide by the removal of surface material. The multi-temporal classification requires certain knowledge about existing land use classes and their spectral signature. The comparison of the digital elevation model allows researchers to locate mass movements by height difference analysis. Using recent Earth Observation data like LIDAR or INSAR, it is possible to apply this particular technique, although the implementation is still in the research stage. Examples of remote sensing applied to landslides inventory can be found in the literature (see van Westen, 2004; Metternicht et al., 2005; Rott and Nagler, 2006; Schulz, 2007).

Landslide survey methods could be complementary, as the local landslides reports can be studied by aerial photos and the aerial photo-interpretation survey can be cross checked during the fieldwork for more detailed information. In order to include the temporal probability analysis, detailed information should be collected on the occurrence dates of landslides. This could be done through both multi-temporal Earth Observation image classification (including interpretation) and through fieldwork form questionnaires. Where, the main focus should be on type, date and volume of landslides.

For the analysis of the landslide causal factors it is required to study different environmental parameters which could be affecting the areas with landslide problems. Depending on the level of detail and the conditions of the area, a number of parameters are essential to the study. The most frequently used parameters that should be surveyed and studied are listed in Table 2.3. Triggering factors are also included such as earthquakes and rainfalls. In the table it is shown how to acquire these data in Cuba for three levels of assessment. In provincial level some data could not be used because they are too general, while at local level some data will not be available in Cuba with enough spatial variability in order to have sufficient spatial difference, such that a comparison between areas of interest can be made.

Table 2.3 Summary of data needed for landslide hazard and risk assessment for the conditions of Cuba. Adapted from Soeters and van Westen (1996)

Data layer and types	Accompanying data in tables	Used methods for data collecting	Levels of analysis Nac. 1:1M	Prov. 1:100K	Mun. 1:50K	Local 1:25K
Landslide occurrence						
1. Landslides	Type, activity, depth, dimensions, etc.	API, fieldwork, national inventory	2	2	3	3
Environmental parameters						
2.Terrain mapping units	Units description	SII, walk-over survey	1	3	3	3
3.Geomorphological (sub)units	Geomorphological description	AP, fieldwork	2	2	3	3
4.Digital Elevation Model (DEM)	Altitude classes	SRTM DEM data, topographic map	3	3	3	3
5.Slope map	Slope angle classes	With GIS from DEM	2	2	3	3
6.Aspect map	Slope direction classes	With GIS from DEM	2	2	3	3
7.Slope length	Slope length classes	With GIS from DEM	2	2	3	3
8.Slope shape	Concavity/ convexity	With GIS from DEM	1	1	2	3
9.Internal relief	Altitude/area classes	With GIS from DEM	3	3	3	3
10.Drainage density	Longitude/area classes	With GIS from DEM	3	3	3	3
12.Lithologies	Lithology, rock strength, weathering processes	Existing, API, fieldwork and laboratory testing	1	2	3	3
13.Soils and material sequences	Soils types, materials, depth, grain size distribution, bulk density, *c* y φ	Modelling from lithological map, geomorphological map and slope map, fieldwork and lab. analysis	2	1	2	3
14.Structural geological map	Fault type, length, dip, dip direction, fold axis, etc.	SII, API, fieldwork	2	3	3	3
15.Vertical movements	Vertical movements velocities	Geodetic data	3	3	2	2
16.Landuse map	Land use types, tree density, root depth	SII, API, fieldwork	2	2	3	3
17.Drainage	Type, order and length	API, topographic map	2	3	3	3
18.Catchment areas	Order, size	API, topographic map	3	3	3	3
19.Water table	Depth of water table in time	Hydraulic stations	1	3	3	2

Table 2.3 Continuation

Triggering factors						
20.Rainfall and maximum probabilities	Precipitation in time	Meteorological stations and modelling	3	3	3	2
21.Earthquakes and seismic acceleration	Earthquake database and maximum seismic acceleration	Seismic data, engineering geological data and modelling	3	3	3	3
Elements at risk						
22.Population	Number, sex, age, etc.	Census and statistics information	3	3	3	3
23.Transportation systems and facilities	Roads and railroads types, facilities types	Atlas, topographic map, local information	3	3	3	3
24.Lifeline utility systems	Types of lifeline network and capacity of facilities	Atlas, topographic map, local information	2	3	3	3
25.Building	Type of structure and occupation	Topographic map, Housing information	1	2	3	3
26.Industry	Industry production and type	Atlas, topographic map, local information	2	3	3	3
27.Services facilities	Number and types of health, educational, cultural and sport facilities	Atlas, topographic map, local information	3	3	3	3
28.Tourism facilities	Type of touristy facilities	Atlas, topographic map, local information	3	3	3	3
29.Natural resources	Areas with natural resources combined	Atlas, topographic map, local information	3	3	3	2

Note: the last columns indicate the possibility of collecting data for levels of analysis: 3 = good, 2 = moderate and 1 = poor. Abbreviations used: SII satellite image interpretation, API = aerial photo-interpretation, DEM = digital elevation model, SIG = geographic information system.

The landslide causal factors could be divided into 'preparatory' and 'triggering'. A particular causal factor may perform either or both functions, depending on its degree of activity and the margin of stability (Popescu, 2002). However, there are generally two main causes that have been recognized: rainfalls and earthquakes. In Cuba almost all reported landslides are associated to intense or prolonged rainfall, in many occasions related to hurricanes, tropical cyclones or others low-magnitude meteorological events.

Related with earthquakes and rainfall, Table 2.3 shows a brief list of information that is needed for landslide hazard and risk assessment. For both types of phenomena there are specific maps to be collected. The rainfall analysis requires the records of the meteorological stations and the calculation of the occurrence probability for a certain period of time - which is carried out for each station. Later, these probability values are interpolated in order to obtain isolines maps with the spatial distribution of the probabilities. There are several papers already published about the relationship between rainfall and landslides (Crozier, 1999; Lida, 1999; Polemio and Sdao, 1999; Dai and Lee, 2001; Chleborad, 2003; Crosta, 2003; Alcántara-Ayala, 2004; Coe et al., 2004; Zezere et al., 2005; Chleborad et al., 2006; Giannecchini, 2006; Jakob et al., 2006). While some of them deal with specific cases, others are more concerned with the statistical relationship for creating correlation models and even produce forecasting models based on rainfall threshold values.

In case of seismicity, there are two different approaches. The first one is based on the use of dynamic parameters such as acceleration (maximum, peak or effective), velocity or displacement. A probabilistic method is used to determinate the probability for a certain return period. However, it has as a drawback, since rock and soil type information are required to determine the dynamic parameters, which are not always available. The second approach is based on the historical earthquake intensity isolines considered as 'characteristic earthquakes'. It is supposed that they can be used as a 'proof' of what is going to happen in the future if the same scope of earthquake occurs. The main disadvantage of this approach is the supposition that the new earthquakes will occur in the same location and with the similar characteristics than the previous one. There is also a proportional amount of publications about earthquakes and landslides investigations (Alkema et al., 1995; Keefer, 2000; Khazai and Sitar, 2004; Lin and Tung, 2004; Luo et al., 2004; Onder Cetin et al., 2004; Chen et al., 2005; Jibson et al., 2006; Hack et al., 2007). Some famous earthquakes that produce landslides have been studied in detail such as the Chi-Chi earthquake in Taiwan, 1999 (Khazai and Sitar, 2004). As Figure 2.3 shows, that with the landslide inventory data or with rainfall and earthquake triggering factors data, a frequency analysis can be carried out. If there is data available and the relationship is statistically proved, the frequency analysis may be used to produce a landslide hazard map with a probabilistic approach. Such a map shows the probability of landslide occurrence per type in a certain location, with a certain magnitude and for a certain return period.

To evaluate the landslide risks it is necessary to survey and analyze the elements at risk that could be potentially affected by the occurrence or these phenomena. Listing all elements at risk may be impossible since it depends very much on the case study area. Still there is no worldwide understanding on how to classify the elements at risk, but one general proposal is subdivided them into (UNDRO, 1991) infrastructure (roads, electricity, telecommunications, other networks, etc.), housing (modern/traditional building, etc.), economic activities (industrial or commercial) and community services (health, administration, education, etc.). However other publications classify the elements at risk differently such as physical, economical, societal and environmental, with a more detailed sublevel classification (UNPD, 2004; IADB, 2005). The elements at risk should be classified by their typologies such as types of housing, roads, bridges, etc., since each type of element requires a structural or engineering characterization, as well as monetary valuation. Thus, the structural assessment is used to determine the vulnerability to landslide occurrence, whereas monetary valuation is used for the loss estimation needed in the risk assessment. When monetary valuation is not possible, the quantity of elements at risk, complete or partially lost could be used. The study of 'the population at risk' requires a particular type of analysis, since its risk is expressed in human loss or people injured. The elements at risk are part of the vulnerability analysis that is described below. There are many elements at risk that are not used very often in the risk studies since its estimation is very subjective or qualitative – such members include: psychological and emotional damages, the interruption of social activities, as well as many other types of 'human' damage. This type of elements at risk should be taken into account although it is not quantified and mapped, as in certain areas it could have particularities that may imply serious consequences.

2.4. Landslide hazard assessment

The most precise way to assess the landslide hazard is by deterministic methods based on the modelling of safety factors from the physical/mechanical material properties, slope information and information on triggering factors. Techniques used in such studies are only feasible on a large scale and do not allow for the zonation of extensive areas (Soeters and van Westen, 1996). Besides, applying these methods over extensive regions is not suitable due to the large spatial variability of the input parameters and the high costs for laboratory analyses that are required. To compensate for this problem, regional assessment methods have been designed. The landslide hazard assessment methods have been divided into four groups of analysis (Table 2.4). The selection of one method over another depends on several factors such as: the data costs and availability, the scale, the output requirements, the geological and geomorphological conditions and the tectonogenetic and morphogenetic behaviour of the landslides. It is obvious that the assessment of 'hazard' is a very important part of landslide risk assessment (Chowdhury and Flentje, 2003).

Table 2.4 Landslide hazard assessment methods (van Westen, 1993).

Term	Definition
Inventory analysis	Analysis the spatial and temporal distribution of landslide attributes.
Heuristic analysis	Based on expert criteria with different assessment methods.
Statistical analysis	Several parameter maps are surveyed to apply bivariate and multivariate analysis
Deterministic analysis	Apply hydrological and slope instability models to evaluate the safety factor

By analyzing data from landslide inventory certain conclusions could be reached about landslide hazard. Three types of analysis have been recognized as the most useful (van Westen, 1993): i)distribution analysis: the objective is to know the spatial distribution of the landslides classified by types, subtypes, activity, style and distribution of activity, among other properties that may be surveyed; ii) activity analysis: also known as temporal analysis, as it allows for the recognition of temporal changes in the landslide activities and to correlate these changes with other like land use changes; iii) density analysis: visualize the landslide abundance per area or terrain units or classes of other type of maps like geological or geomorphological maps.

The landslide hazard assessment may be preceded by two different analyses that depend on the data availability and on the case study area: the susceptibility and the run-out or travel distance analysis. Although they may not be completely necessary, they may assist considerably in the understanding of landslide causes and affected areas. The landslide susceptibility assessment is a particular step in the landslide hazard assessment and it is usually based on the comparison of the previously surveyed landslides and the conditional or preparatory causal factors called here as environmental parameter (Figure 2.3). For instance, the lithological classes are spatially compared with landslides to determinate in which types of rocks the landslide occur more frequently and, therefore, are more susceptible for its occurrence. Likewise other causal factors are compared with the landslide. Finally, the susceptibilities of the causal factors are combined using a Geographical Information System (GIS) to obtain a landslide susceptibility map. Depending on scale of study and the data availability a specific method may be selected for producing the landslide susceptibility map. In susceptibility analyses triggering causal factors are often not considered. Some research has been done specifically related to the landslide susceptibility assessment (Lee et al., 2003; Sirangelo and Braca, 2004). Some papers refer the susceptibility analysis as part of the hazard analysis. More recently artificial neural network techniques have also been applied to susceptibility studies (Lee et al., 2004; Ermini et al., 2005; Lee et al., 2006; Melchiorre et al., 2007). A detailed explanation on landslide and neural network is presented in Chapter 5.

Generally, landslides not only imply the movement down slope but also the moving of the material slipped or fell slope onward. This implies that the elements at risk which are hundreds of metres or even kilometres from the slope may be seriously damaged. This 'runout' or travel distance has to be considered in the landslide hazard and risk analysis. Falls, topples and spreads have generally less displacements, from centimetres to metres while slides and flows may have movements from tens of metres up to kilometres. In the analysis different scenarios should be accounted for considering the water content and type of material which could be displaced. During intense or prolonged rainfalls the water content in soft material may cause liquid flow and travel long distances. In other scenarios, the slope material may fall into a dam or into a river resulting in overflow of the dam or breaking of the dike, producing a flash flood as a chain reaction. In the second case, the slipping or falling material can produce natural embanking on the river bed. Later on, after certain water level accumulation, the water and material can travel faster downwards producing serious disasters. Considering these scenarios a map of landslide travel distance or runout should be made exposing the areas which elements at risk may be affected. The research on landslide runout or travel distance is only starting (e.g. Hungr, 1995; Finlay et al., 1999; Chen and Lee, 2000; Okura et al., 2000; Fannin and Wise, 2001; Legros, 2002; Wang et al., 2002; Crosta et al., 2003; Hunter and Fell, 2003; Kilburn and Pasuto, 2003; Okura et al., 2003; Bertolo and Wieczorek, 2005; Hungr et al., 2005; Malet et al., 2005; e.g. Crosta et al., 2006; van Asch et al., 2006; Pirulli et al., 2007; van Asch et al., 2007a; van Asch et al., 2007b). Most of the publications use three types of approaches for runout analysis: the empirical approach from previous landslides and geomorphological analysis, the deterministic approach from the geotechnical parameters and the dynamic approach from numerical modelling of runout. In Chapter 7 detailed explanation about landslide runout is given along with the simulation of a single landslide.

The landslide hazard assessment itself has been widely covered in literature (e.g. Grainger and Kalaugher, 1988; Hartlen and Viberg, 1988; van Westen, 1992; van Westen, 1993; Terlien et al., 1995; Soeters and van Westen, 1996; van Westen et al., 1997; Aleotti and Chowdhury, 1999; Guzzetti et al., 1999; Alcántara-Ayala, 2004). The ideal landslide hazard map shows areas where certain landslide magnitudes or types may occur within a certain period of a certain probability. But in many cases this type of map cannot be produced since there is not landslide inventory over time and magnitude data available to determine spatial and temporal probabilities.

The landslide hazard map could be constructed by combining the susceptibility map and triggering factors in the study area. When landslide hazard map can not be made probabilistically the classes of the legend should have considerations about the actual meaning of each class, planning recommendations or mitigation measures, important for the planners, disaster manager or decision makers (Castellanos Abella and Van Westen, 2008). A parameter to assess the quality of the landslide hazard map could be the evaluation of how many previously surveyed landslides are in each hazard class. The most effective models are those where more landslides happen in the highest hazard classes (Guzzetti et al., 2002; Malamud et al., 2004). Very few landslide hazard maps show information on expected volumes or even on temporal probabilities. As Figure 2.3 shows, four types of landslide hazard methods will be considered in this research: inventory, heuristic, statistic and deterministic. In the case study chapters (4-7), different methods are applied considering the conditions of Cuba regarding to the level of analysis, data availability and landslide occurrence.

2.5. Landslide vulnerability assessment

Landslide vulnerability assessment is still considered a difficult process since it depends on several factors like landslide type and the way its impact may generate different degrees of damage. Although this research considers the aforementioned definition for vulnerability, in practice vulnerability could be interpreted from many other points of view. Discussions on this topic could be found in Morrow (1999), in Manyena (2006), Berkes (2007) and Haque and Etkin (2007). This problem implies practical implementation during the assessment of vulnerability. Even, Douglas (2007) explains why vulnerability should not be modelled, while van Westen et al. (2005) explain why this is still so difficult. Indeed, that is why a few publications may be found about the specific topic of landslide vulnerability such as Leone et al. (1996). In his publication, a detailed analysis shows a general framework considering the vulnerability components (Figure 2.4). In this figure, the overall vulnerability depends on damage functions or vulnerability functions where the characteristics of the landslide and their impact on the elements exposed are modelled. This could be carried out by i) historical data or ii) theoretical information. Usually it is a function of the distance between the starting point of the house and the element exposed (used for rockfalls) or exceeding distance from the element exposed downwards slope (used for debrisflows). In practice this is seldom accomplished and most vulnerability assessments use damage functions from other regions or from other type of hazards like earthquakes. Most publications that discuss about landslide vulnerability are included with hazard and risk assessment (see Mejia-Navarro et al., 1994; Ragozin and Tikhvinsky, 2000; van Westen, 2002; Hollenstein, 2005). Other publications analyze vulnerability with other types of disaster such as earthquakes (Panizza, 1991; Luzi et al., 2000; Manoni et al., 2002). Later, Glade (2003) discuss vulnerability issues concluding that estimation is heavily dependent on availability of historical data and recognizing that even with known limitations, numerous advantages result from detailed landslide risk analysis. In his publication, he also proposes a modified table (originally from Leone et al., 1996) with vulnerability values for different elements at risk.

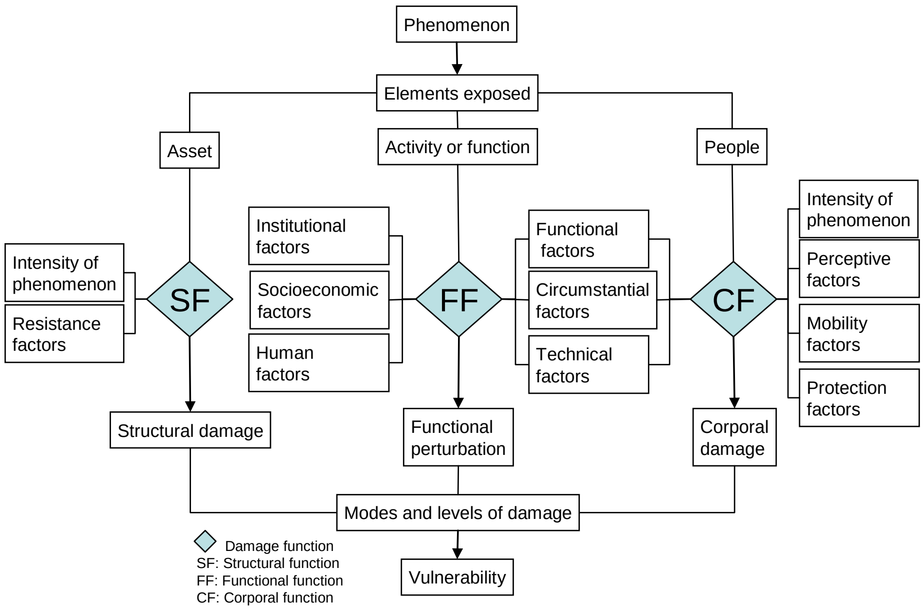

Figure 2.4. Flow diagram illustrating vulnerability components (Leone et al., 1996).

The vulnerability maps are expressed with values between 0 and 1, where 0 means no damage and 1 means total loss. A total failure of the slope almost completely destroys the structures on its surface. The elements at risk in a relatively flat runout area are more vulnerable as they are closer to the toe of the landslide. Therefore, the runout or travel distance area from the landslide initiation point till the element at risk should be known for the effective assessment of the vulnerability. For example, the same house may be differently affected by the same type and magnitude landslide just because its distance to landslide initiation point may be different. This assumes that the actual landslide vulnerability assessment needs to be known beforehand (i.e. the runout or travel distance). Landslide vulnerability maps could be made considering different elements at risk surveyed, which could be grouped by their structural types. Evaluation of vulnerability implies an analysis of the structural consequences for each element at risk. This allows recognizing the weakness of the structures for landslides disasters. Thus, it is possible to create the vulnerability functions in order to identify the boundary between the intensity of the phenomenon which impacts and the resistance or stability of structure. This is one of the more important starting points for reducing the risk by diminishing the structural vulnerability using effective mitigation plans. By collecting and processing historical damage, landslide vulnerability assessment could more precise when similar condition occurs. Fuchs et al. (2007) developed an empirical vulnerability function for debris flow affecting buildings located on the Austrian Alps.

Among the attributes of elements at risk surveyed are the costs related to each element in case of a disaster such as total value, recovering costs and service interruption costs. The disaster costs are classified as direct or indirect depending on their relation to the disaster (Barbat, 2003). Besides, the costs are classified as tangible or intangible depending on their possibility to be quantified (Coburn et al., 1994b). The assessment of the indirect and intangible costs in case of landslides is very difficult and still remains an important research topic. Due to the very detailed economic information needed for vulnerability assessment, there are several 'subjective' ways to assess vulnerability. For example, Finlay in 1996 cited by Dai et al. (2002) proposed vulnerability ranges and recommended values for death from landslide debris. In this study different spatial variants for vulnerability assessment are explored, starting from the principle that at regional scales where spatial information is aggregated areas with more elements at risk of the same type could be more vulnerable. Besides, when no monetary value is available it is still possible to rank the infrastructural objects or land-use types, which makes the assessment more qualitative but still prioritizing spatial objects with high value.

Once vulnerability assessment is made and disaster-related costs are estimated, the consequence analysis can be carried out. The consequence has been defined as the outcomes or potential outcomes arising from the occurrence of a landslide expressed qualitatively, in terms of damage, injury, loss of life or any other loss (ICG, 2003). With the consequence analysis it is possible to describe how much value may be lost in each location according to its vulnerability.

2.6. Landslide risk assessment, an overview

As explained before, the total risk map could be obtained by combining hazard and vulnerability. This can be achieved in three different ways (Figure 2.3):

Total risk = Specific risk x Value
Total risk = Natural Hazard x Vulnerability x Value
Total risk = Natural Hazard x Consequence

From the above formulas it is possible to derive that:

Specific risk = Natural Hazard x Vulnerability
Consequence = Vulnerability x Value

Total risk assessment could be made directly or specific risk or consequence maps can be created and analyzed in order to achieve some preliminary conclusions. However, for landslide risk assessment many considerations need to be taken into account. Figure 2.5 shows some of the elements conditioning the landslide risk equation. In real case studies some of these elements are assumed or simply not considered. This is due to the difficulties in getting appropriate information which makes landslide studies much more difficult, as compared to other types of disasters.

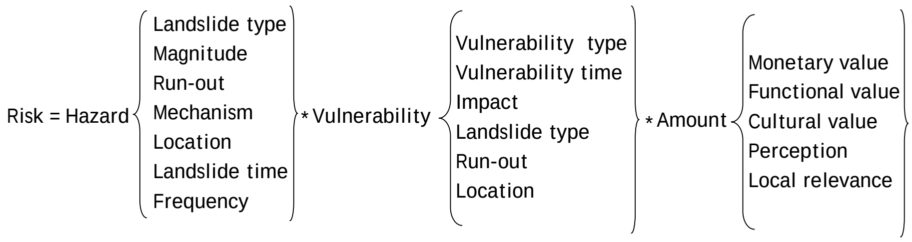

Figure 2.5. Elements to be considered for landslide risk assessment.

To illustrate difficulties in landslide risk assessment, different typical circumstances in which landslide risk is calculated could be explained. Similar houses could have different vulnerabilities because they are geographically located in diverse positions compared to a landslide predicted surface or they have different structure or different replacement cost. Consequently, risk calculation for each house will get a different value for the same hazard (e.g. ten year return period of a rotational rock slide). Another example is if three potential sliding surfaces may impact a single house (element at risk) with an estimated cost. Each predicted movement has its probability to happen (hazard) and due to its volumes, the vulnerability of the house may be different for each one. Here, a single element at risk may have different risk value for each hazard scenario. These two examples show partially the complexity in assessing landslide risk. A number of existing approaches are described in the sub-sections.

The classification of the landslide risk assessment methods could be considered still on 'developing stage' as only few methodologies have been implemented. At the moment of this research the classification proposed by the Sub-committee on Landslide Risk Management of the Australian Geomechanics Society was adopted but its typologies could be improved with more meaningful categories. The classification is based on the level of quantification dividing the landslide risk assessment methods in qualitative, semi quantitative and quantitative (AGS, 2000; Powell, 2000; Walker, 2000). The same classification approach was later published by Chowdhury and Flentje (2003). Table 2.5 summarizes landslide risk assessment methods found in literature. As shown, it was found in the literature that there are more quantitative approaches. However, most of them are based on a large amount of assumptions and simplifications mostly due to scarcely available data.

Table 2.5 Landslide risk assessment methods with some references

Method	Principle	References
Qualitative	Based on risk classes categorized by expert judgment. Risk classes: High, Moderate and Low	(Lateltin, 1997; AGS, 2000; Budetta, 2004; Cascini, 2004; Ko Ko et al., 2004; Mossa, 2004; IADB, 2005; Nadim et al., 2006)
Semi-quantitative	Based on ranking and weights assignments by a given criteria. Risk index: ranked values (0-1, 0-10 or 0-100). (dimensionless)	(Brand, 1988; Koirala and Watkins, 1988; Chowdhury and Flentje, 2003; Blochl and Braun, 2005; Castellanos Abella and Van Westen, 2005; Saldivar-Sali and Einstein, 2007)
Quantitative	Based on probabilities or percentage of losses expected. Risk value: probabilistic values (0-1) over certain amount of monetary or human loss.	(Einstein, 1988; Morgan et al., 1992; Fell, 1994; Leroi, 1996; Ragozin, 1996; Cruden and Fell, 1997; Einstein, 1997; Fell and Hartford, 1997; Leroi, 1997; Ragozin and Tikhvinsky, 2000; Kong, 2002; Bell and Glade, 2004; Decaulne, 2005; Fell et al., 2005; Karimi and Hullermeier, 2007; Roberts, 2007)

Although risk assessment was defined as the process of risk analysis and risk evaluation, it is intended here to focus primarily on risk estimation methods as the process to produce a measurable level of risk. The main landslide risk assessment methodologies found during literature review will be presented in the next three subsections according to the different groups of methods.

2.6.1. Qualitative landslide risk assessment

The qualitative approach is based on the experience of the experts and the risk areas are categorized with terms as 'very high', 'high', 'moderate', 'low' and 'very low' risk. The number of qualitative classes varies but generally three or five classes are accepted which should have a direct line with practical indications (e.g. in very high risk areas: 'immediate physical and no-physical remedial measures are required and no more infrastructure development must be allowed in this area'). Fell (1994) proposed terminology definitions for qualitative risk assessment considering classes for magnitude, probability, hazard, vulnerability and specific risk. A terminology proposal guideline for assessing risk to property was developed by the Australian Geomechanics Society and the Sub-committee on Landslide Risk Management (AGS, 2000) considering a combination of landslide likelihood and the possible consequences as shown in Table 2.6. The methodology proposed was later discussed (Powell, 2000; Walker, 2000) with some remarks regarding i) the possibility of having two levels of risk in the same cell e.g. M(medium)-H(high) (Table 2.6), ii) the compatibility of risk levels with the Australian Standard and iii) an alternative table for the definition of vulnerability and consequences. This method is applicable for spatial analysis using GIS. These approaches are usually applied at national or regional levels as in these scales the quantitative variables are not available or they need to be generalized.

Hong Kong has perhaps the only working system for qualitative assessment of slopes. Wong (2005) discusses the 'qualitative slope rating systems' and present a table for comparison within fifteen approaches. Some of them are applicable for all facilities and some for roads and railways systems. Among the approaches the most common primary applications are for risk ranking and prioritization for action.

Table 2.6 Qualitative risk analysis matrix – level of risk to property (AGS, 2000). VH: Very High, H: High, M: Moderate, L: Low and VL: Very Low risk.

Likelihood	Consequences				
	Catastrophic	Major	Medium	Minor	Insignificant
Almost certain	VH	VH	H	H	M
Likely	VH	H	H	M	L-M
Possible	H	H	M	L-M	VL-L
Unlikely	M-H	M	L-M	VL-L	VL
Rare	M-L	L-M	VL-L	VL	VL
Not credible	VL	VL	VL	VL	VL

A similar approach was proposed by Ko Ko et al. (2004), based on a number of forms and planned for situations where an inexpensive and fast method is required for landslide hazard and risk assessment. The method uses a scoring and weighting approach emphasising on i) formalization of field data collection in the form of data sheets for different types of slopes; ii) quantifying the subjective components involved in the hazard and risk assessment procedure as much as possible; iii) defining terms as precisely and clearly possible and iv) development of categories of hazard, consequence and risk that may be presented in a quantitative format. After collecting basic data, such as rock and soil material, geological structure, morphology, etc. the hazard assessment is made by the rating options given in Table 2.7. Once the landslide hazard has been qualitatively estimated, the consequence is assessed for different services like railway lines, roads, etc. For each type of service and possible human casualty the consequences are rated into the five levels: VH, H, M, L, VL and a risk rating is assigned. Then, a risk assessment table is used to identify the cell were the risk rating for both human casualties (columns) and service and property (rows) are crossed. In upper left cell the risk rating is 1.1 while in the lower right cell the risk is 5.5. The first risk rate number is due to the human casualty and the second one to the service or property.

Other proposed approaches were found in the literature, like to the produced by FOWG in Switzerland (Lateltin, 1997), that do not seem to be very different from the ones explained above. Some of them are also based on qualitative classes but they are defined in technical documents established by law (Mossa, 2004). In terms of accuracy, the Ko Ko et al. (2004) approach showed high consistency rates, probably due to the use of the questionnaire with predefined answers for the different level of hazard, consequence and risk. In this way, qualitative risk assessment can provide reliable results achieving the objectives proposed.

Table 2.7 Qualitative landslide hazard assessment (Ko Ko et al., 2004).

Score	Description	Annual probability	Hazard level
>100	The event is expected and may be triggered by conditions expected over a 5 year period	> 0.2 (within 5 years)	Very High (VH)
80 - <100	The event may be triggered by conditions expected over a 5-50 year period	0.2 – 0.02 (within 5 to 50 years)	High (H)
60 - <80	The event may be triggered by conditions expected over a 50-500 year period	0.02 - 0.002	Medium (M)
40 - <60	The event may be triggered by conditions expected over a 500-5000 year period	0.002 – 0.0002 (within 500 to 5000 years)	Low (L)
<40	The event is possible and may be triggered by exceptional circumstances over a period exceeding 5000 year	> 0.0002 (> 5000 years)	Very Low (VL)

2.6.2. Semi quantitative landslide risk assessment

The main difference between qualitative and semi-quantitative approaches is the assignment of weights under certain criteria which provide numbers as outcome instead of qualitative classes. The semi quantitative estimation for landslide risk assessment is found useful in the following situations (AGS, 2000): i) as an initial screening process to identify hazards and risks; ii) when the level of risk (pre-assumed) does not justify the time and effort and iii) where the possibility of obtaining numerical data is limited. Semi-quantitative approaches consider explicitly a number of factors influencing on stability (Chowdhury and Flentje, 2003). A range of scores and settings for each factor may be used to assess the extent to which that factor is favourable or unfavourable to the occurrence of instability (hazard) and the occurrence of loss or damage (consequence). The matrix of hazards and consequence is used to obtain a risk value ranked. This is made by combining a set of hazard categories with a set of consequence categories. The final risk values can also be categorised and ranked with qualitative implications. The risk estimation can be done separately for loss of life and economic loss.

A semi-quantitative approach (by ranking) was used in Hong Kong as a risk classification system for cut and fill slopes as well as for natural slopes on which future development will take place (Koirala and Watkins, 1988). The evaluation uses nineteen parameters related to slope, geology, hydrology, stabilization measures and distance to elements at risk. For each component a score is given. The score range is variable for each component. Some of them range from 0 to 20, but for others the maximum value is unlimited and the actual value in metres is taken. Using these components empirical formulas are used for estimate instability and landslide consequence. The risk is then calculated as the sum of instability and the consequence scores. The formula was applied to 8,500 slopes in Hong Kong and the slopes scored were organized in a ranking list. The development of the formula involved considerable discussion and substantial trial and review till the various scoring and multiplying factors adequately reflected the importance of the components. The authors stated that was necessary to 'calibrate' personnel involved in the ranking exercise because many of the ranking criteria are quite subjective.

The ranking system was found useful for recognising most risky slopes where more detailed investigation is needed and for taking remedial actions in descending ranking scores. However, there were also a number of limitations found (Koirala and Watkins, 1988): i) for the higher ranked slopes, the total score is dominated by the consequence score component, ii) the data used for calculating scores were extracted from field data sheets where other subjective assessment had been made and iii) system considered the proximity of a building to a slope and the use of that building, but not the construction form or structure of the building. More details about the weighting and scoring system used in Hong Kong were later published by Wong (2005). A broader explanation of the different hazard and risk assessment methods applied in Hong Kong by the Geotechnical Control Office can be found in Brand (1988). This office developed the Geotechnical Area Studies Programme (GASP), under which a terrain evaluation approach has been used for a geotechnical assessment of the whole territory in order to provide a series of user-oriented maps at regional (1:20,000) and district (1:2,500) scales. The land was classified into four classes of geotechnical difficulty and a 'reasonably well' correlation with the standard stability analysis was found. The ranking system, based on an empirical risk assessment index, was then used in order to establish the order of priority for investigations of about 8500 existing slopes and retaining walls.

Besides the limitations found, this semi-quantitative approach could be adapted from the slope based to cover larger areas (spatial or GIS-based). In any case, there will always be the dilemma of adapting the scoring system to each particular region where the analysis will be made, since landslide instability and consequences estimations depend very much on the particular conditions of the study area. This approach may be applicable at any scale or level of analysis, but more reasonably used in medium scales. Nowadays, such a semi-quantitative approach can efficiently use spatial multi-criteria techniques implemented in GIS that facilitate standardization, weighting and data integration in a single set of tools.

2.6.3. Quantitative landslide risk assessment

Quantitative landslide risk assessment (QRA) has been used for specific slopes or very small areas using probabilistic methods (see Whitman, 1984; Chowdhury, 1988). Among the quantitative approaches found in literature there are a few examples (Bell and Glade, 2004) as case study areas that cover a larger extension. The total risk equation in most quantitative approaches uses the same combination of hazard and consequences, but differs in practice on many details. Table 2.8 shows some methods for calculating landslide total risk.

Table 2.8. Quantitative landslide risk assessment methods.

Reference	Equation, Risk =
• (Morgan, 1992)	**P(H) x P(S|H) x V(P|S) x E** - P(H): annual probability of landslide event - P(S|H): probability of spatial impact given the event - V(P|S): vulnerability of the property (proportion of property value lost) - E: element at risk (the value of the property)
• (Einstein, 1988; 1997)	**P[Danger] x u(x)** - P[Danger]: danger probability - u(x): vector of attributes, which are consequences
• (Fell, 1994; Fell et al., 2005)	**∑ (E x P x V)** - E: element at risk (value) - P: probability of hazard - V: vulnerability
• (Anderson et al., 1996)	**$P(P_i)$ x P(L|O) x P(C|L) x L_e** - $P(P_i)$: probability of ith pathway - P(L|O): conditional probability of the exposure of property to the outcome - P(C|L): conditional probability of property damage given this exposure - L_E: resulting economic consequences
• (Ragozin, 1996; Ragozin and Tikhvinsky, 2000)	**$P^*(L)$ x $V_m(L)$ x $V_e(L)$ x D_e** - $P^*(L)$: landslide probability occurrence - $V_m(L)$: landslide vulnerability degree - $V_e(L)$: vulnerability degree of object under the event (L) - D_e: full cost of objects with definite damage degree
• (Leroi, 1996; Leroi, 1997)	**$\sum A_i \times (\sum V_{ji} \times C_j)$** - A_i: hazard i - V_{ji}: vulnerability of object j exposed to hazard i - C_j: "cost" or value of the object j
• (Bell and Glade, 2004)	**H x C x E** - H: Hazard - C: Consequence - E: Element at risk
• (Lee and Jones, 2004)	**$P(H_i) \times \sum(E \times V \times E_x)$** - $P(H_i)$: probability of particular magnitude of landslide - E: value of element at risk - V: vulnerability of proportion of E - E_x: exposure of element at risk
• (AGS, 2000)	**$P_{(H)} \times P_{(S:H)} \times V_{(prop:S)} \times E$ or $P_{(H)} \times P_{(S:H)} \times P_{(T:S)} \times V$** - $P_{(H)}$: annual probability of landslide - $P_{(S:H)}$: probability of spatial impact according to the travel distance - $V_{(prop:S)}$: vulnerability of the property - E: element at risk - $P_{(T:S)}$: temporal probability of the building of being occupied - V: vulnerability of the individual

Although there are certain similarities, some differences appear between the approaches. They include either the way to calculate the hazard or to calculate vulnerability and consequence. Commonly agreement was found among the methods in combining hazard as probability of sliding and vulnerability as consequences. There are other specific methods for risk assessment such as for rockfall in road or railway systems (see Budetta, 2004; Jarman, 2006), but essentially all are based on combining a probabilistic interpretation of hazard and the value of the element at risk and vulnerability. Expert system techniques have been applied to either landslide hazard and risk assessment (Faure et al., 1988; Wislocki and Bentley, 1991; Al-Homoud and Tahtamoni, 2000; Pistocchi et al., 2002). After knowing landslide hazard and risk, the expert systems have also been used for recommending remediation options (Grivas and Reagan, 1988; Lawrence et al., 1992). The expert systems are often very site-specific and only deal with one or two landslide types. Since, knowledge about landslide mechanisms is still limited, the suitability of expert systems is reduced.

2.7. Landslide risk evaluation and control

Once the risk analysis is made the risk assessment processes must be concluded with a landslide risk evaluation. It implies a decision making process for the user (local authorities, disaster manager, physical planner, etc.) about the evaluation of the level of risk for being considered 'acceptable', and the level of risk for being considered 'tolerable'. For certain reasons, many people use to live and even 'enjoy' their leisure time close to (or in) highly hazardous areas. Therefore assessing landslide hazard and risk does not imply directly taking management actions in the high risk areas. According to Fell (1994), there are three main ways to evaluate the risk: i) risk comparison, involving comparison of the calculated risk with socially 'acceptable risk', either for landsliding or other activities (usually this is in terms of the assumed probability of loss of life), ii) cost effectiveness of risk reduction (this is commonly in terms of the cost of saving lives) and iii) cost-benefit analysis e.g. comparing the annual cost of risk reduction measures with the annual reduction in risk.

The risk acceptance level is actually the risk value up to which the user is prepared to accept disregarding for its management (ICG, 2003). Theoretically, the areas below this level of risk do not need landslide risk control measures like mitigation, monitoring, physical or non physical remediation measures (Figure 2.6). In practice, low risk but high hazard areas may be carefully looked after for some remedial measures in order to reduce its hazards. The same consideration could also have been taken for low risk, but only in areas of high vulnerability (or consequences). Bell et al. (2004; 2005) discuss deeply the problems in defining acceptable level of risk with examples from Iceland, Hong Kong and Switzerland.

Risk tolerance considers the possibility to live under a certain value of risk as long as some measures are taken to control and reduce the current risk value whenever possible. There are situations where individuals are forced to live under a risk value that they actually would not like to live, but they still tolerate these values. Consider the representation in Figure 2.7, in order to understand these concepts it is possible to suppose that risk is a value increasing from 0 up to 100. Everyone might accept up to a certain value of risk such as 25, as this is regarded as an acceptable risk value. Above 25 it is not possible to accept any more risk unless some actions are taken to control it. From 25 and up to say, 50 the risk is 'tolerable' always considering that mitigation measures are taken. From certain value of risk and higher (in this case 50) the risk could not be tolerable even with control actions. This risk segment, from 50 up to 100, could be called intolerable and immediate measures need to be considered in order to reduce the amount of risk.

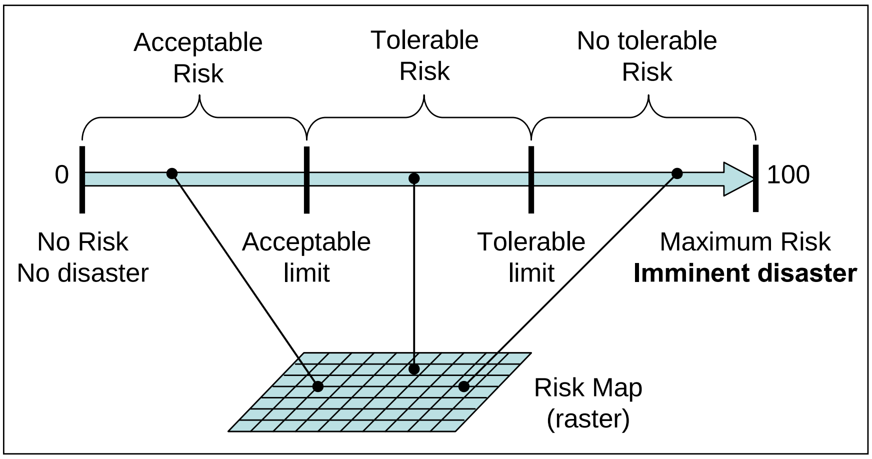

Figure 2.6. Landslide risk acceptance and tolerance.

In some places acceptance and tolerance limits are officially established. Figure 2.7 shows the society risk criteria (no mandatory) for Hong Kong (GEO, 1999). The logarithmic graph presents four regions with different criteria for risk. There is a discussion whether or not an 'acceptable' region should be defined. Instead, the term 'broadly acceptable' was proposed. The principle of ALARP (As Low As Reasonably Practicable) means a zone where risk reduction measures need to be taken, normally identified by a cost-benefit analysis. They also established a vertical line between 1000 and 5000 fatalities in order to define a zone where certain types of developments could be implemented considering local social needs. Similar landslide risk criteria could be defined in other countries because it is very useful for planning disaster risk reduction. These criteria need to be agreed with all stakeholders and periodically updated.

It is evident that all these risk threshold values depend on risk perception that may be different from one user to another and may also change in time. Likewise, the landslide risk evaluation can be shown in a map in which the risk values are classified with the threshold criteria for risk acceptance and tolerance. Few studies have been undertaken on this topic for landslides. For reference about this subject the following papers can be read: Alexander (1993), Fell (1994), Finlay and Fell (1997), Leone et al. (1996). These publications recognize that landslide risk rank very low as compared to other type of risks which are faced every day such as being injured in a car accident. Coburn et al. (1994a) show a graph about the perception of risk of an study carried out in Oregon where the boundaries over and under estimation are considered. Besides, Sjoberg (1999) highlight the dilemma about the disagreement on risk perception comparing the public and the experts point of view. Some results obtained from these studies allow us to conclude that 1) there is much evidence to indicate that the population accepts higher levels of voluntary risk (e.g. driving a motor vehicle) than involuntary imposed risk; 2) there is some evidence that population is less willing to accept multiple-death events than a number of events with fewer deaths, i.e. the scale of risk has an influence on its acceptability; and 3) there is a distinction between acceptable risk to an individual, e.g. the risks to a person living on a landslide, and the risk to the population as a whole (this is linked to voluntary and involuntary risks). Research on risk perception still needs stronger linking between social sciences and natural sciences for a better understanding as to how to deal with existing risk assessment.

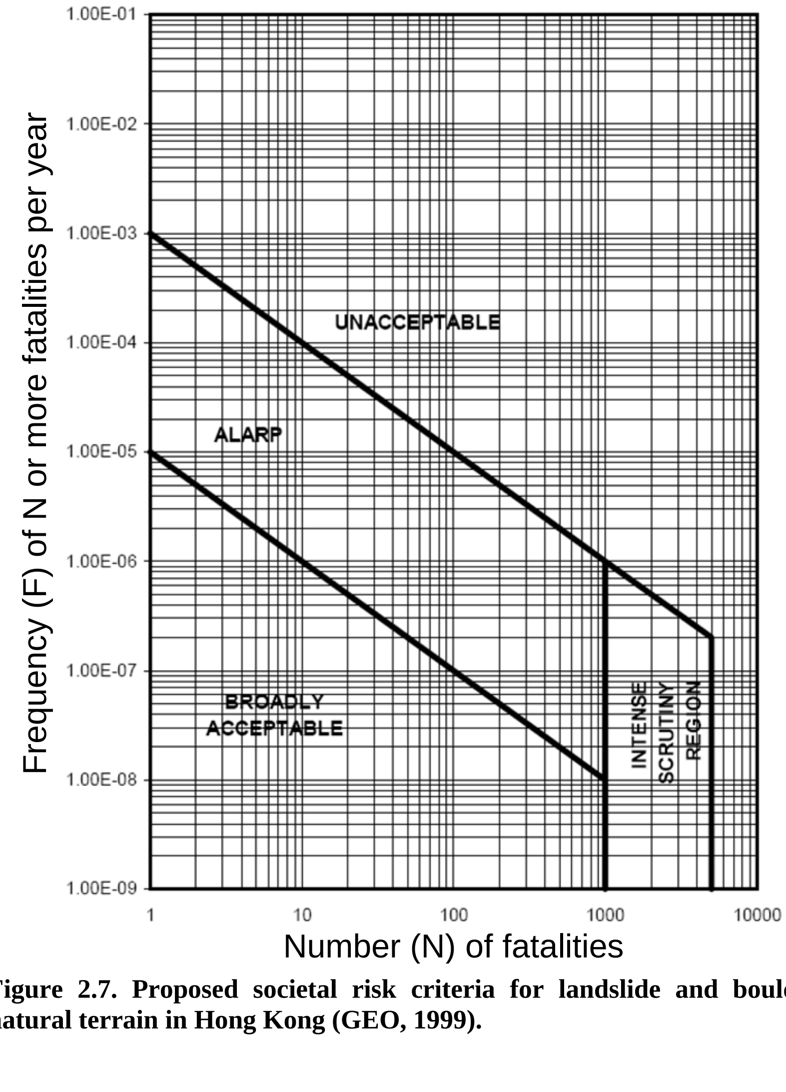

Figure 2.7. Proposed societal risk criteria for landslide and boulder falls for natural terrain in Hong Kong (GEO, 1999).

2.8. Multilevel approach

Previous landslide research carried out in Cuba and in the rest of the world has shown that the assessment and mapping of landslides have a hierarchical approach. This allows for the approximation of higher risk areas at different levels with particular objectives, scales, methods and results. Thus, the hierarchical approach implies that the assessment evolves from regional scales to detailed ones. The size of the study area decreases while more detailed and more precise methods are applied. In this approach, the cost per kilometre increases at every subsequent level but the uncertainty in the results is diminished. This strategy is not new, in fact, it has been used for many years in mineral exploration due to economic reasons (see Pan and Harris, 2000b).

For risk assessment analogue scheme of hierarchical or multilevel approach could be made. Every territorial management level for disaster or planning purposes requires a risk map at appropriate scale. There are two ways to tackle this issue, from top to bottom and from bottom to top. The first one seems to be more economic since only areas detected at certain levels are studied in detail at lower levels. Besides, countries with poor information about landslides and lack of human and economic resources can implement this top to bottom hierarchical approach. This approach requires the definition (at every level) of the method to assess the risk and the data to be collected. However, in other places information about landslides has been collected in every place at the lowest level (Guzzetti et al., 1994; Guzzetti and Tonelli, 2004). Also, other countries such as France, Switzerland and Germany are currently implementing multi-hazard risk assessment for every low-level territory and, therefore, assessing landslide risk wherever such events appear. Then, they face the task of aggregating the risk values to present the results at lower scale for the authorities at upper levels. In Cuba, as the knowledge of landslides is partially unknown and resources are limited, the top to bottom approach is implemented.

The selection of different levels of analysis at specific scales for landslide risk assessment depends on:

- The geographic extension and population distribution of the country.
- The management and political structure of the country and the extent of each management level (province, departments, county, etc.).
- The magnitude of the landslides that occur in correspondence with the relief of the country.
- The capacity of human and technological resources to carry out the assessment.

One misunderstanding in applying landslide risk assessment has come for having copied assessment frameworks from countries with different natural and political-management characteristics. Table 2.9 shows statistics and ratio for United States, The Netherlands and Cuba, three countries with different governments and administrative structures. The number of municipalities in The Netherlands (458) is much larger than in Cuba (169) for almost half of the area, although the population is slightly higher. As a consequence, the average of population per province is smaller in Cuba, but the country has higher average of population per municipality.

Table 2.9 Comparative statistics and indicators in three countries. Sources: CIA Fact Book, Wikipedia and VNG-NET.

	United States	The Netherlands	Cuba
Area (km^2)	9,826,630	41,526	110,860
Population	301,139,947	16,570,613	11,394,043
Administrative divisions	50 states 3077 counties	12 provinces 458 municipalities	14 provinces 169 municipalities
Area/division	196,533 km^2/state 3,193 km^2/county	3,460 km^2/prov. 91 km^2/mun.	7,919 km^2/prov. 656 km^2/mun.
Population/division	6,022,799 pop./state 97868 pop./county	1,380,884 pop./prov. 36,180 pop./mun.	813,860 pop./prov. 67,420 pop./mun.

In Cuba the management division is dense and homogenous allowing for the use of the same division for the landslide risk assessment levels. Every Organization of Management the Central State (OACE in Spanish) has provincial representation and many of them also have it at the municipal level. This allows for the identification of support and responsibilities in the management structures at each level and locating and managing financial and material resources at each level. According to the aforementioned considerations, the following levels for landslide risk assessment are proposed for Cuba:

- National level, 1:1,000,000 scale (one single map)
- Regional level, 1:250,000 scale (western, central and eastern)
- Provincial level, 1:100,000 scale (14 provinces)
- Municipal level, 1:50,000 scale (169 municipalities)
- Local level, 1:25,000 scale (selected areas with landslide problems)
- Site investigation Level, 1:10,000-1:1,000 scale (selected landslides events)

The objectives and results of every level are different in correspondence with objectives and functions of management at this level. As mentioned before, applying top-bottom approach implies defining an appropriate method for hazard, vulnerability and risk assessment which requires a specific data set. Figure 2.8 shows how at the detailed levels the methods tend to be more quantitative in increasing the accuracy and reducing the uncertainty. Examples of methods are shown in the second part of the book, where case studies for landslide risk assessment are implemented.

The scales coincide with the topographic maps in that they are produced and regularly updated. The national level is a single map that can be easily manipulated by the national authorities. The method of how to produce such a map is described in Chapter 4. The territory for regional level (at 1:250,000 scale) is different from the one defined by the army, which also carry out the disaster reduction management, and the one regularly known by the public. As at this level there is no actual political administration, as it is recommended to generalize the risk maps produced at province scales instead of creating a model and a data set for this level. Also, the magnitude of landslides that occurred in Cuba could not be represented at this scale - only as single points. Provinces and municipalities have clear boundaries and they are well structured and organized along the whole country. However, many natural regions of Cuba are not limited to the province and municipality boundaries (e.g. The Sierra Maestra mountainous area is located in the Santiago de Cuba and Granma provinces). It is feasible that the hazard and risk assessment at 1:100,000 and 1:50,000 scales could be carried out by subdividing the territory in natural units of the relief. Similarly, a local level of scale 1:25,000 could be study areas that may include the administrative boundary of two municipalities in the assessment. In each case it is important to integrate both governments and administrative organizations of the corresponding level before, during and after the 'making' of the assessment. Co-ordination among authorities for both administrative units is required for this. On the other hand, it is possible that after the assessment at province level (1:100,000 scale), troublesome areas could be recognised to have local assessment (1:25,000 scale) or even geotechnical project assessment (> 1:10,000 scale) without waiting for the inter-level assessments. The assessments should be interdisciplinary and all parts should participate from the beginning during the planning, support, performance, conclusions and recommendations, as each assessment could have a Mitigation Plan for Landslide Risk Reduction in the studied area. The content of each plan may vary according to the level of assessment.

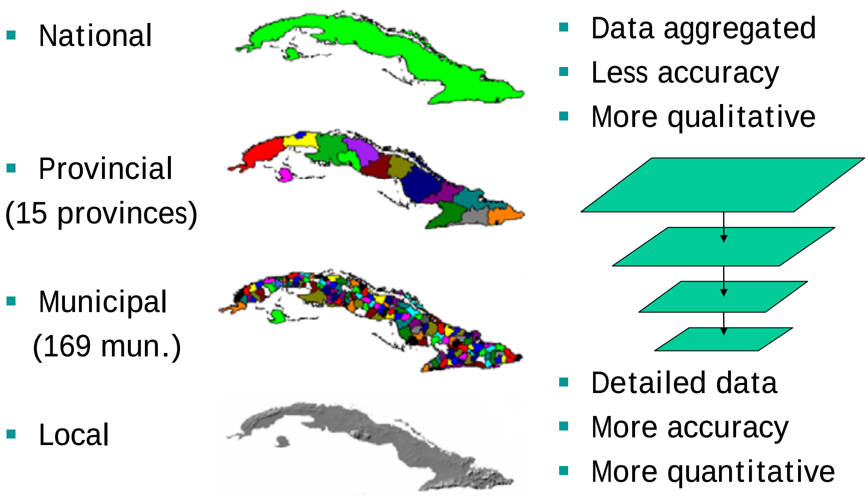

Figure 2.8. Representation of some levels for landslide risk assessment in Cuba.

2.9. Conclusions and recommendations

The tendency in using quantitative approach has strongly been influenced by the trend of probabilities. The use of probabilistic (stochastic) methods is now widely used in earth sciences even when it is unknown whether or not the process is governed by a stochastic law. The reason, as mentioned by Pan and Harris

(2000), is that "even if a phenomenon is considered to be deterministic in nature, a scientist may choose to estimate or model it with a stochastic model because of the lack of complete conditioning information, provided that the data -under one or more appropriate transformations- meet the conditions required for parameter estimation". In this case, the influence of the missing variables is represented by an error term, and the model is considered to be stochastic (Pan and Harris, 2000a). Besides, among the quantitative methods listed in Table 2.5 the following common problems were found:

- The concepts are not always understandable from the published papers.
- The measuring units in the equations do not always match.
- The calculation of equation components is often unclear.
- The equations can often not be executed in spatial analysis using GIS.

There are publications (Eusebio et al., 1996 for example) which show the general flowchart where landslide risk assessment is made, but no mathematical expressions for the risk estimation are given. Other authors (Bosscher et al., 1988; Rezig et al., 1996) refer to landslide risk assessment but in fact the methodology explained is about landslide hazard assessment. Although there are a number of landslide risk assessment methods proposed in the literature, only few applications are shown in publications and some of them are not spatially based.

Risk mapping is a complex multidisciplinary task which requires the participation of various disciplines (UNDRO, 1991). It is a compilation process that identifies the potential loss in recognized areas as being hazardous. The most effective spatial landslide risk assessment is the one which, for a certain area, expresses the probability of loss in monetary value if a landslide of certain magnitude or type would occur for a certain return period. When the assessment is not taken into account to actual cost it could be called a specific risk (see Figure 2.3). Since loss of life is treated differently from economic loss, occasionally, two risk maps are made: one for economic losses and one for the human casualties. These maps could be divided by types of landslides, or be joined with other types of hazards that are landslides triggering factors such as the earthquakes and intense or prolonged rainfall.

As previously mentioned, there are some approaches to produce risk maps which depend on the data availability and on the objectives that need to be reached for the level of analysis. The risk maps can become more quantitative at more detailed scales, where landslide hazard and vulnerability analysis can be also quantified properly. Besides the scale dependence of the quantification process, for risk maps of any scale, certain objectives can be achieved in correspondence with the detail of the surveyed data. A misunderstanding may occur when a non-detailed risk map is used for making decisions at local level without evaluating the risk at this level beforehand.

Due to the multi-organizational character in the landslide risk assessment it is necessary to identify and contact the appropriate organizations in the affected regions for potential disasters to discuss their respective contributions in the assessment and mapping process. Another very important point is the recognition of the fact that landslides need to be monitored and controlled in a continuous mode since a change in the components of the analysis, such as hazard or vulnerability, implies a change in the risk. Thus, the risk maps should be considered as dynamic maps that require being updated periodically. Selecting a qualitative, semi quantitative or quantitative method depends on a number of factors including:

- Objective of the study (including outcome requested, mapping scale and resources available).
- Data availability (including quality and accuracy).
- Nature of the problem (including triggering factors).

The risk should be considered in the physical planning. The planners introduce the risk considerations in tasks as (UNDRO, 1991): i) evaluate the specific risk (probable % of loss per time unit) for different types of existing structures in any location within the region of study, ii) compare the risk in locating a type of structure in one or another site with different level of hazard, iii) decide about appropriate planning measures in order to control or reduce risk.

Associated with the risk assessment there is always, and seldom considered, a level of uncertainty. Few publications can be found regarding this topic in landslide research. Some of then are only related to landslide susceptibility or hazard (Davis and Keller, 1997; Chowdhury and Flentje, 2002; Guzzetti et al., 2006). The result in estimating risk will be more and more imprecise as the level of uncertainty increase (Lee and Jones, 2004). Mistakenly, quantitative assessments are seen as less uncertain than qualitative ones, which is theoretically true. But real situations show an increasing number of assumptions applied for risk assessment in order to make them quantitative, without recognition of the uncertainties. This aspect becomes more relevant when the authorities should be given information about the risk. As well as with risk estimation, uncertainty on risk value comes also either from the probability of hazard or from the vulnerability. Lee and Jones (2004) discuss the uncertainty regarding landslide risk assessment and conclude a need to have a "clear balance between providing sufficient information about uncertainty and taking attention away from the reality of the situation by dwelling on the unknown".

Methods for validating landslide risk assessment are rarely mentioned in the literature. One question that usually arises when concluding the assessment is how to validate the results? For hazard and susceptibility there are some publications that refer the accuracy assessment by re-evaluating the existing landslides (Chung, 2003; Remondo, 2003; Dymond et al., 2006; Guzzetti et al., 2006; Irigaray et al., 2007). However, for risk assessment no published information was found. The main problem is the vulnerability part of the risk equation, which is 'socially' constructed. That means the element at risk to be considered, their standardization and weighting are decided by the social context where the risk assessment is carried out. As risk is the estimation of loss for the future, one method for validation is usually called 'wait and see', meaning wait for the next event to happen and compare the losses with the amount predicted. Even when viable to apply, it was not possible to find in literature such validation for landslides. Another possible method is to test in the same area or nearby, the risk assessment for an event that had happened, also comparing the estimation with the losses known. One obvious difficulty is that this method needs the exact conditions (both natural and social) in which the event had occurred. Usually, most risk assessment implementations are considered 'validated' when the scenarios projected match the expectations to the user requirements. Thus, validation for landslide risk assessment is a topic that need more research in the near future.

CHAPTER 3

Disaster management and geospatial data in Cuba

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3. Disaster management and geospatial data in Cuba

3.1. Introduction

After having analyzed state-of-the-art techniques in landslide risk assessment, this chapter gives the framework of disaster management in the Cuban context, considering two relevant elements: the role of Civil Defence in disaster reduction management and the availability of geospatial data for risk assessment in Cuba.

Cuba is considered a model in hurricane risk management by The United Nations (Sims and Vogelmann, 2002; ISDR, 2004b; ISDR, 2004c; ISDR, 2004a) as a result of the reduced number of casualties caused by hurricanes, as compared neighbouring countries with different economical, social and political context such as: Haiti, Jamaica or the United State of America. This statistics and more information can be found in Wisner et al. (2006). "The Cuban way could easily be applied to other countries with similar economic conditions and even in countries with greater resources that do not manage to protect their population as well as Cuba does", explained Salvano Briceno, director of the ISDR secretariat in Geneva (ISDR, 2004b). The reasons for this achievement stem from "an impressive multi-dimensional process" using as foundation "a socio-economic model that reduces vulnerability and invests in social capital through universal access to government services and promotion of social equity" (Thompson and Gaviria, 2004). The disaster reduction in Cuba is controlled by the Civil Defence, which is not a single organization but "a system of defensive measures" to be carried out during normal times and during exceptional situations "with the purpose of protecting the people and the national economy" against destruction means of enemy and natural disasters or other types of catastrophes (Ley No. 75, 1995 art. 111). A detailed explanation about evolution, current organization and success is given in the next section.

Besides having an appropriate framework for disaster reduction, the availability of appropriate information is also crucial. Some governments have pointed out the relevance to provide information necessary for disaster reduction and the level of standardization required for this information (GDIN, 1997; Board on Natural Disasters, 1999), whereas another report refers to the legal issues on access and disclosure of this information (Bledsoe et al., 1999). Recently with the development of spatial data infrastructure (SDI) other issues concerning their use for disaster reduction and management have been addressed (Rajabifard et al., 2004; Zhao et al., 2005; Köhler and Wächter, 2006; Mansourian et al., 2006; National Research Council, 2007). The use of geoinformation and the technology for natural disaster both in general and in particular for landslide studies have been generally addressed previously (Rengers et al., 1992; van Westen, 1993; Mantovani et al., 1994; Mortensen et al., 1995; Mantovani et al., 1996; van Westen and Hofstee, 2001; Giardino et al., 2004; van Westen, 2004). Cuba is working to bring together the appropriate information for disaster reduction and the latest developments of spatial data infrastructure. This includes information needed for multi-hazard risk assessment at local level which is co-ordinated nationally. Besides latest development, still problems were found during the landslide risk assessment in the case study areas of this research. The current setting and framework for obtaining geospatial data to support landslide risk assessment are discussed in Section 3.3.

3.2. Disaster risk reduction and management in Cuba

3.2.1. Civil Defence system in Cuba

The disaster reduction in Cuba is organized and controlled by the Civil Defence, an organization which has its roots in the 1959 revolution. Table 3.1 shows the main historical facts of the civil defence system in Cuba. A detail explanation can be found in Castellanos and Carretero (2008). Derived from the National Revolutionary Militia (MNR in Spanish) in 1961 the Military Organization of Industries (OMI in Spanish) was created. Its main duty was vigilance and protection of economic and political targets in the Country. However, in 1962, OMI was transformed into the Central Headquarters of Popular Defence, commonly known as Popular Defence, which was organized in all different levels (provinces, regions, municipalities, etc.) and later renamed 'Civil Defence'. The first main test with respect to natural disasters was in October 1963, when the country was severely affected by hurricane Flora, causing about 1200 casualties. This event changed the responsibilities of the Cuban Civil Defence and a natural disasters response was added. The tasks of the Civil Defence at that time included the organization of a warning system, emergency response planning and to plan how to continue production during military aggressions and natural disasters. After accomplishing many missions and developing structures and functions in July, 1966 Law no. 1194 (Ley No. 1194, 1966) officially declared the 'Civil Defence of Cuba'. Therefore, since 1986 a disaster response simulation exercise, called 'Meteoro' has been conducted on an annual basis. Initially the exercise was designed to be better prepared for the cyclone season (June-November), but gradually started to include all other disaster types in all disaster management levels with high involvement of the local population. Other legal documents (as shown in Table 3.1) denoted important hits in the developments of civil defence in Cuba.

In the past decades the Civil Defence had to deal with numerous natural, technological and sanitary disasters which lead to a substantial improvement of the organization. Since then, the territories and local authorities started to have a broader view of disasters considering all different scenarios including dam breaks, chemical contamination, epidemics, etc. Also authorities and Civil Defence started to pay more attention to prevention measures besides the original focus on response. In 1997 the structural organization of the Civil Defence was established as shown in Figure 3.1.

Table 3.1. Main facts of civil defence system in Cuba (Castellanos Abella and Carretero, 2008).

Year	Facts and references	Description
1961	Military Organization of Industries (OMI)	Organization of local workers to protect economic target from sabotage.
1962	Popular (Civil) Defence	July 31- Official creation of civil defence with representative in all levels.
1963	Flora Hurricane disaster	Major disaster with 1200 casualties, civil defence was used to cope natural disaster.
1966	Civil Defence Law 1194 About the organization of the Civil Defence (Ley No. 1194, 1966)	First civil defence law to protect population and economy from military aggressions and natural disasters.
1976	Civil Defence Law 1316 About improvement of the structure for the Civil Defence (Ley No. 1316, 1976)	Adaption to the new political and administrative structure of the country.
1986	Meteoro Exercises	National exercise every year to test civil defence organization against natural disasters.
1995	National Defence Law (Ley No. 75, 1995)	Re-affirm and establish civil defence definitions and principles fitting into defence system of the country.
1997	Decree-Law 170 'System of Measures of Civil Defence' (Decreto Ley No. 170, 1997)	Re-establish the role of organizations regarding civil defence measures and include disaster cost into planning.
1997	Decree 223 Military Reserve (Decreto No. 223, 1997)	Regulate the use of resources in case of disasters.
1999	Decree 262 Compatibility of socio-economic development with defence (Decreto Ley No. 262, 1999)	Regulate how new investment need to be compatible with civil defence.
2005	Directive 1/2005 – Vice-president of the Council of State (CDN, 2005)	Created for planning, organization and preparation of the country in case of disasters.

The role of the Civil Defence was re-established with several functions. The first one was to identify and evaluate, in co-ordination with the organizations, companies and social institutions, the hazard, vulnerability and risk factors as well as to provide the planning needed to cope with them. Many laws have articles related to natural disaster reduction (such as decree no. 262 (Decreto Ley No. 262, 1999)) in order to make it compatible with the economic and social development of the country for the interest of defence. In 2004, Cuba was hit by two major hurricanes in a relative short period: Ivan and Charley. After this it was decided that each territory should have a disaster reduction plan and disasters reduction measures will be included in the social-economic plan every year. The importance of the Civil Defence system in Cuba is illustrated in Table 3.2, which gives some statistics related to the major hurricanes that have affected Cuba. The large number of evacuations and low number of deaths is only possible due to the implementation of an effective early warning system as a component of the Cuban Civil Defence system.

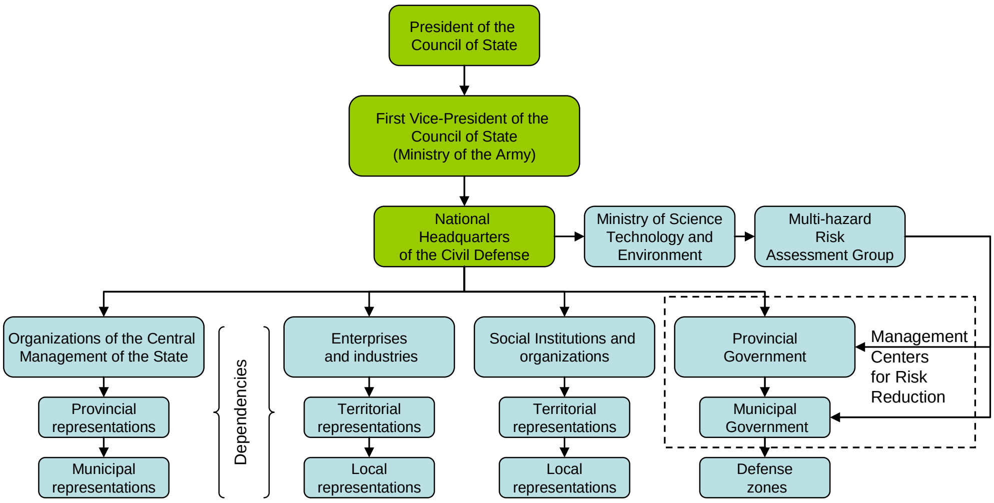

Figure 3.1 Structural organization of Civil Defence System in Cuba and risk assessment (After EMNDC, 2007a).

Table 3.2. Statistics of disaster management in Cuba for 11 selected storms. DT: Tropical depression. (Source: National Civil Defence).

Cyclone	Year	Evacuated	In shelter	Transport	Mobilized	Deaths
Flora	1963	175,000	-	-	-	1157
Kate	1985	473,400	143,200	14,600	41,800	2
Lili	1996	421,200	276,700	5,600	74,500	0
Georges	1998	818,800	215,200	10,300	118,100	6
Mitch	1998	50,600	1,900	1,800	22,400	0
Irene	1999	33,600	11,200	1,500	12,600	4
Michelle	2001	783,400	166,300	6,100	102,400	5
Isidore	2002	307,000	34,500	2,700	48,800	0
Lili	2002	385,300	56,300	5,000	81,700	1
DT no. 14	2002	70,000	3,300	1,500	20,900	0
Charley	2004	224,449	35,749	2,444	45,082	4
Iván	2004	2,226,066	416,123	13,016	215,122	0
Totals (exc. Flora)		5,793,815	1,360,472	64,560	783,404	22

The success of civil defence in Cuba has been internationally recognized (see ISDR, 2004b; ISDR, 2004c; ISDR, 2004a). However, there is discussion about how this success was possible. The main factors for the success can be summarized below (EMNDC, 2007a):

a) Management at the highest level. Due to the missions to be accomplished and the potential destruction of disasters, civil defence system can only be managed by the head of each organization or territory. They are responsible for measures of civil defence in their range of action.

b) Multipurpose (multifaceted) character of the protection. The civil defence system must provide protection to all of the population and economy against any type of military aggression and any type of natural, technological and sanitary disaster.

c) National and institutional scope. The civil defence system covers all territories in the country, all levels of management and all organizations and institutions. It is everywhere.
d) A differentiated way for planning and organizing of protection. Despite the full coverage, every territory and facility must be protected from particular hazards and reduce their own vulnerabilities and risk, taking into account their own characteristics and capacity to cope in every phase of disaster cycle.
e) Effective co-operation of Army and the Ministry of Interior. Active participation of both forces subordinated to local governments during disasters has been crucial for accomplishing regular missions when protecting the population and the economy.
f) Organization according to the socio-economic development of the Country. The civil defence organization is highly dynamic, adapting periodically to the changes produced in the society from any point of view, such that they do not become obsolete and remain focused on their task (e.g. for planning the measures, actual human, materials and financial resources are always updated).

Besides these principles other elements have been appreciated for success of civil defence in Cuba. Thompson and Gaviria (2004) prepare a report which analyses' the Cuban experience on disaster risk reduction. They argued long term strategy reasons such as: poverty reduction, literacy, investment in infrastructure (roads, electricity), the health system and so on. Besides they support Cuba's "impressive work" on five intangible assets that could be replicated by other countries i) local leadership, ii) community mobilization, iii) popular participation in planning, iv) community implementation of lifeline structure and v) creation and building of social capital.

One of the most important components of the Civil Defence system that needs some more detailed explanation is the establishment of effective Early Warning Systems (EWS). A short explanation about the Cuban EWS and the comparison with neighbouring countries can be found in Wisner et al. (2006). In Cuba, EWS are adapted to the socio-economic characteristics, institutional capacities, organization, level of education and preparation of the authorities and population (EMNDC, 2007b). The main elements of the EWS in Cuba are i) the (scientific) organizations capability to detect and to monitor certain threats, ii) decision making authorities at each level who receive the information of the potential threat, iii) the mass media and social organizations which disseminate the information about the threat and the decisions made and iv) the population who receive the information and respond accordingly.

The EWS in Cuba are part of the Civil Defence System and they are organized in two levels: centralized, for those hazards of national magnitude such as tropical cyclones; and decentralized for those hazards that can start at the base such as epidemic or those of local relevance such as local rainfall. With EWS civil defence can activate four response phases (Informative, Alert, Alarm, and Recovery) by producing an official notification. Figure 3.2 shows how the response phases for whole country changed during the passing of hurricane Iván in 2004, based on the forecasts of the Meteorological Institute. In this case, the response phases were activated by province, but in other cases it is also possible to activate them by municipalities or even at a more local level like specific disaster areas.

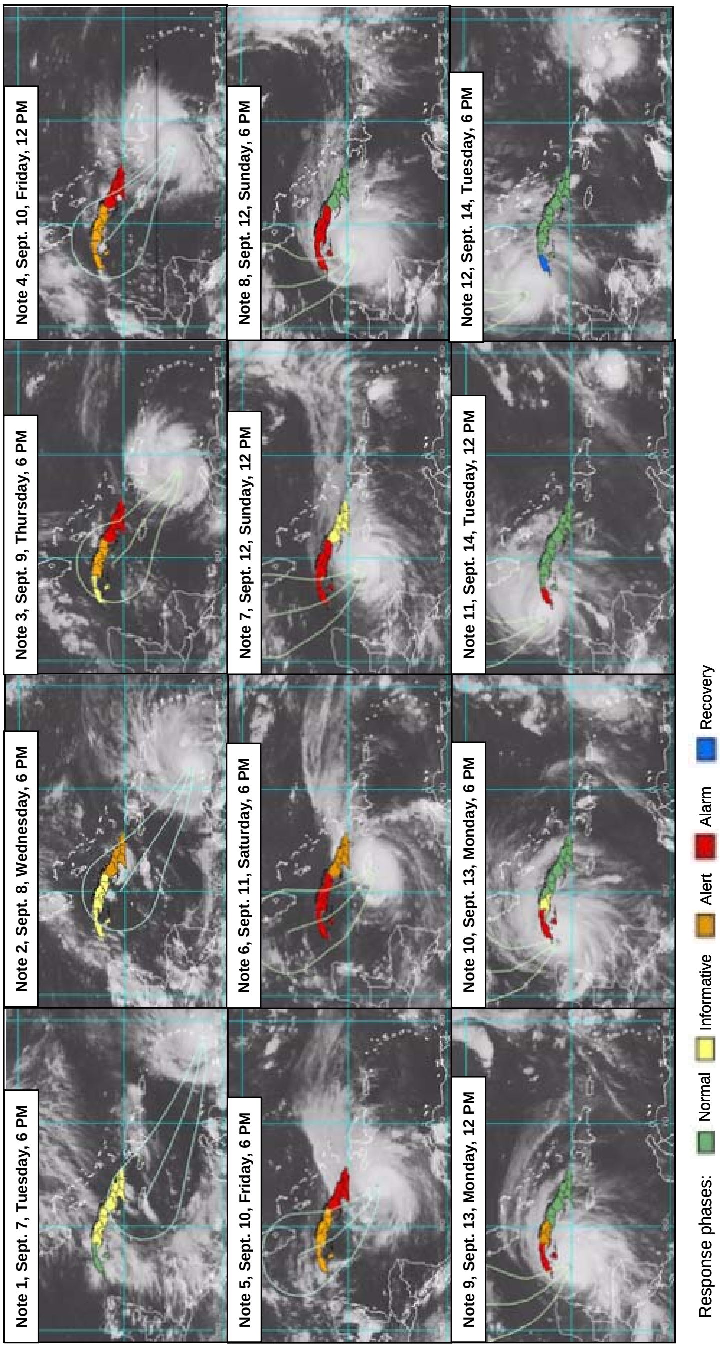

Figure 3.2. Response phases in Cuba during the Hurricane Iván (2004) declared by Civil Defence notes.

Every response phase has particular implications for measures to be taken by provincial and municipal authorities, described in disaster reduction plans for every territory in case of tropical cyclones. During hurricane Iván, the forecasting was changing as the actual path deviated from the predicted path and the hurricane passed along the south and only affected the western province. Consequently, 2,226,066 people were evacuated during these days but no casualties were recorded (EMNDC, 2004). This illustrates that in this case the four elements of the early warning system (mentioned above) worked properly. EWS are less difficult to implement during cyclones since they can be detected and monitored three to five days in advance. A long term aim for landslide research in Cuba is to include in the early warning system areas where landslides are to be expected - which are usually triggered by certain rainfall threshold when a tropical cyclone approaches the archipelago.

Although the Civil Defence System in Cuba has reduced the number of casualties considerably, the amount of physical damage by natural catastrophes is still very high. The national economy, already in crisis since the beginning of the nineties, is suffering the accumulative costs for facing one or two devastating hurricane every year. As explained earlier the system is dynamic and continues to improve. Although, nowadays it tends to focuses on: i) better implementation of the disaster reduction process considering improving risks reduction management and strengthening the management of response and recovering actions; ii) integration of disaster reduction cycle into the economic and social planning of the country and iii) to continue improving the actions and measures for different types of hazard and military aggression including the supplies.

3.2.2. Multi-hazard risk assessment

The official responsibility as main co-ordinator for conducting risk assessment in every municipality (169 in all) was assigned to the Ministry of Science, Technology and Environment (CITMA in Spanish) as shown in Figure 3.1. Many other organizations are involved depending on the type of hazard, therefore leading to a multidisciplinary team for risk assessment. The minimum spatial unit was set up at the Popular Council or Defence Zone, a spatial administrative unit lower than the municipality. The main idea was to establish a methodology where risk could be comparable spatially (among municipalities) and temporally (during years) in order to provide priorities and to monitor the progress in risk reduction. In this sense the vulnerabilities play a relevant role in the risk equation. The management of risk reduction is seen as an obligation of the State which includes all organizations involved. For its implementation every municipality and province will have, progressively by priorities, a Management Centre for Risk Reduction (Figure 3.1) with the financial support of the UNDP. These centres have direct subordination from the President of the Government at this level. They receive the output of the first multi-hazard risk assessment and control the progress of disaster reduction. Their main functions are i) periodic assessment, evaluation and monitoring the risk in the territory; ii) support with equipment and information the

Council of Defence (municipal and provincial) during the respond and recovery phase; iii) record actions taken in disaster reduction and iv) contribute in training local people as well as dissemination of measures for disaster reduction (EMNDC, 2006). These centres should also have historic data about previous disasters besides receiving periodic information from the different early warning systems.

As ordered in 2005 by the vice-president of the National Council of Defence, the Ministry of Science, Technology and Environment (CITMA) is responsible for conducting risk assessment studies in the country, and the Agency of Environment (AMA) was also enrolled in this task creating a multi-disciplinary group for risk assessment. This group, which does not yet have a permanent legal status, started to develop risk assessments for flooding, strong wind and sea surges in the municipalities of Havana City, which would be replicated in the rest of the country (AMA, 2007). When introducing the methodologies into the countryside several modifications were required. Also, it is not yet defined how other hazard types will be introduced into this local multi-hazard risk assessment. CITMA specialists train other local researchers in the provinces and municipalities, who are responsible for conducting the risk assessments in their own areas. Data forms have been created in order to standardize the data collection process. The general procedure has four stages (AMA, 2007) as indicated in Figure 3.3.

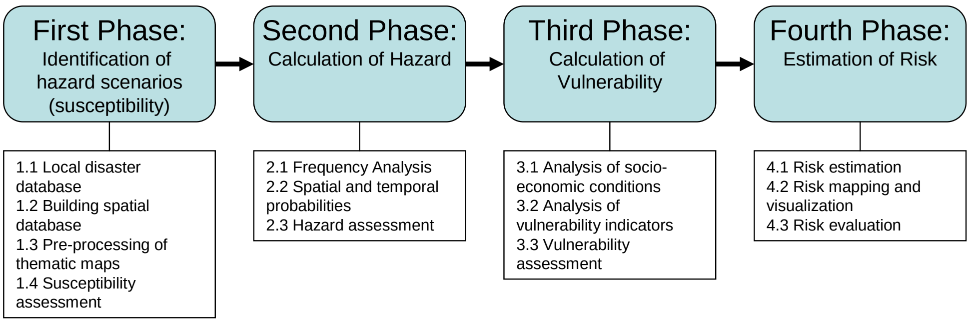

Figure 3.3. Stages for multi-hazard risk assessment in Cuba (after AMA, 2007) and main tasks for landslide risk assessment. Terminology used as in the reference.

The main tasks involved in multi-hazard risk assessment are shown in Figure 3.3, and a manual describing the landslide risk assessment methodology is currently being preparation. The multi-hazard risk assessment will be carried out in every province by a team of experts, which are trained by the national group and which have their own resources. Depending on the type and extend of the hazards within a province, the provincial group chooses to make the analysis for the entire province at once or separately by municipalities. The implementation of a uniform methodology for multi-hazard risk assessment for all municipalities of the country requires a high level of standardization. However, on the other hand the method should also be flexible enough to be adapted to the local conditions. Therefore, seven principles were proposed to accomplish the methodology of each type of disaster:

1. **Objective**: the method has to respond to the needs of disaster reduction in the country according to the current possibilities using the appropriate technology, not always the most advanced one.
2. **Applicable**: the requirements should have the possibility to be accomplished by all territories and based essentially on existing information.
3. **Reproducible**: the method should be clear and precise, and should be reproducible by independent experts.
4. **Flexible**: it should have the possibility to adapt itself to the local needs and local conditions.
5. **Spatially comparable**: although flexible, it should be possible to be compared amongst each other for different municipalities and provinces.
6. **Temporally comparable**: the results should also be possible to compare through the time in order to monitor the effect of disasters risk reduction measures.
7. **Updateable**: the methodology should include procedures for updating the different datasets, and the results.

The results of the current research on landslide risk at different levels in Cuba are an important input to set up the methodology for landslide risk assessment in the country. In 2004 the National Civil Defence authorities agreed to set up a research project for landslide risk assessment at different levels whose main results are exposed in the case study chapters of this book (4-7). The research is co-ordinated with the National Science-Technological Innovation Program for Civil Defence (PNCIT) in Cuba and with the National Headquarters of the Civil Defence (EMNDC) in Cuba. The Institute of Geology and Palaeontology (IGP) has been carrying out this research project since January 2004 for the four case study areas in co-ordination with the SLARIM research project: Strengthening Local Authorities in Risk Management of ITC (www.itc.nl). The multi-hazard risk assessment group of CITMA is now providing training on this methodology in different provinces and is establishing groups of local experts. It is expected that the first round of risk assessment for the whole country will be completed in the next few years.

3.2.3. Disaster database in Guantánamo

Knowledge of previous disasters is a prerequisite for any risk assessment, and the methodology for multi-hazard risk assessment developed by the Cuban Civil Defence system, therefore initiates with an inventory of disaster information from historical archives, such as newspapers or scientific reports. The case study areas at provincial, municipal and local levels of this research are located in the Guantánamo province. Therefore, a historical disaster database was developed by the Centre for Information and Technology Management (CIGET) in Guantánamo, which belongs to the Ministry of Science, Technology and Environment (CITMA). This required analysis and compilation of information on disaster occurrences from different sources, their registration and the creation of a database. The method followed for data collection was similar to the one applied in Italy at national level (Guzzetti et al., 1994), expecting to analyze landslide disasters similar to the one published by Guzzetti (2000).

For searching disaster information territorial organizations were included such as provincial library, territorial statistics office, seismology institute, historical provincial archives, meteorological institute and other provincial offices. The information was recorded first in simple form by information source and event (i.e. a news paper column about a flood) and later summarized by event considering all information available (i.e. a flood disaster event). Then a database in Microsoft Access was created allowing researchers/users to query by type of disaster (five types), source of information (fourteen sources) and year (since 1900). This database was carried out as a pilot study in order to later replicate the experience in other provinces co-ordinated by the national civil defence.

The database reported fifty-eight intensive rainfalls, two earthquakes, three landslide, nineteen sea surges, and seventy-eight tropical storms or hurricanes. As in other disaster databases, landslide events are under represented due to the fact that they usually occur as a secondary event during floods or earthquakes. Figure 3.4 shows some examples of newspaper photographs for some of the disaster events.

Figure 3.4. Disasters photographed by mass media in Guantánamo province. 1-2: Tropical storm Ernesto (1/9/2006), 3-11: Intensive rainfall (different times), 12: Landslide in Yateras (28/05/1994), 13-16: Flora Hurricane (4-8/10/1963). Photos published in 'Venceremos' and 'Revolución' news papers.

The Guantánamo Valley, where the capital of the province is located, had a higher record of flooding disasters. In other municipalities the relief is mountainous and the floods are more localized in specific zones close the mouth of the river. As Figure 3.4 shows, the bridges, railways and houses are the elements at risk which are more affected.

Considering that most disaster recorded are due to rainfall events it is possible to believe that many more landslides had happened related to these events. It was noticed, from a disaster management point of view, that much of the news focused on the recovery measures rather than on describing the disasters, and that the damage reported were always declared by an official source.

3.3. Geospatial data as a support for risk assessment in Cuba

Landslide risk assessment is strongly dependent on available information. Its multi-disciplinary character only makes assessment possible if many different types of information sources are involved. The more data sources involved the more complicate the study is, as every organization has its own rules on data production. This is particularly relevant in developing countries where most information is still in analogue format or where the digital information is produced without consistent and interoperable standards.

In Cuba the situation with spatial information for risk assessment is improving progressively. This is due to the increasing use of computers and professional GIS for producing maps, the data digitalization process, the improvement in data transfer through the communication systems and the recently created national spatial data infrastructure platform. However, there are still problems affecting the use geoinformation for risk assessment. Some of these problems are explained in the following sub-sections and some examples are detailed in the case study chapters (4-7). Organizations involved in risk assessment are acknowledging the current situation and are aiming to improve the efficiency of the process.

3.3.1. Earth observation data for landslide studies in Cuba

Earth observation data have been extensively applied to landslide studies worldwide (Rengers et al., 1992; Mantovani et al., 1994; Wasowski and Singhroy, 2003; Chadwick et al., 2005; Metternicht et al., 2005; Barlow et al., 2006; Hong et al., 2007; Weirich and Blesius, 2007). The applications range from landslide recognition to landslide monitoring in specific areas. In Cuba some investigations (1991; Magaz et al., 1991; Castellanos Abella et al., 1998a; Castellanos Abella et al., 1998b; Castellanos Abella and van Westen, 2001) have also utilized earth observation data (mostly aerial photographs) for landslide studies. The photos have been used mainly in landslide recognition and inventory making it possible to carry out hazard assessment.

The application of earth observation data for natural sciences in Cuba goes back to the first half of the twentieth century, when mainly foreign geologists carried out different geological surveys using aerial photos (Pérez Pérez, 1997). There are three main nationwide aerial photo surveys in Cuba:

1. In 1956-1957 (called ASC) by Aero-Service Corporation at 1:62,000 scale,
2. In 1970-1971 (called K-10) by the Cuban Institute of Geodesy and Cartography at 1:36,000 scale and,
3. In 2000-2001 (called VG-vuelo general) by Geocuba (Cuban mapping agency) at 1:25,000 scale (Figure 3.5 A, F and G).

The first two surveys produced several photo products such as photomaps at a scale of 1:100,000 and 1:50,000 respectively. These products were extensively applied by earth scientists in Cuba for several types of studies regarding natural sciences. Locally, at more detail scales there are multiple aerial surveys commonly used for other applications such as cadastral. The aerial photos and the derivative products from these surveys are available without restriction nowadays at Geocuba, the Cuban mapping agency. In fact, other organizations such as the Institute of Geology and Palaeontology (IGP) or the Institute of Tropical Geography (IGT) also have copies of these photos. Unfortunately, the additional information such as flight camera information is missing in particular cases which make it difficult to carry out any ortho-photogrammetric analysis.

Satellite imaging also was employed in Cuba for geological and geomorphological studies since the 70s. From the middle of the 70s photo-geological outline maps were created from different parts of the country which were upgraded with satellite images. In 1975, Cuba started to work in a joint research programme with ex-socialist countries using remote sensing data for earth science. Three main experiments were conducted with remote sensing data for natural sciences from 1977-1980 called 'tropic I', 'tropic II' and 'tropic III' (Pérez Pérez, 1997). The main objectives of the experiments were to characterize the spectral signatures and geological and geomorphological features of Cuban territory. In last one (tropic III), simultaneous spectral measurements were taken at the ground, aerial and space level using the first space flight for a Cuban astronaut between 18 and 26 September 1980. At the end of the 80s commercial earth observation data (mostly Landsat MSS and Landsat TM images) were used as in many parts of the world for earth sciences. Several hundred researches have been trained abroad in the use of earth observation data and processing, for example, around 160 followed post-graduate courses at the ITC. All these aerial and satellite data from different sources support interpretation of relief and landforms to produce basic information for landslide studies. Furthermore, some landslides were identified and mapped which are included in the national landslide database created during this research.

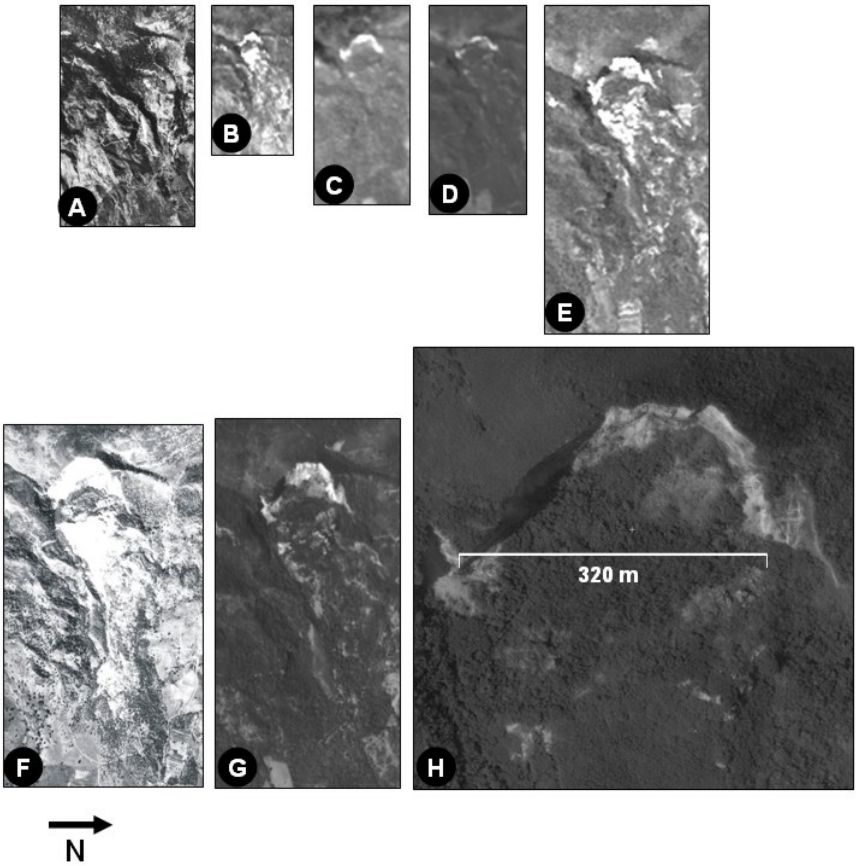

Figure 3.5. Examples of different types of optical remote sensing images for recognizing the development of a large landslide in the Caujerí scarp, San Antonio del Sur, Guantánamo province, Cuba. A: section of an Aerial-photo, scale 1:62,000 from 13-Jan-1956,scanned at 300 dpi (displayed at 25% of its size), taken before the occurrence of the landslide in 1963; B: section of a LANDSAT TM image with spatial resolution of 30 m. from 15-Jan-1985; C: section of a LANDSAT ETM image with spatial resolution of 15 m. from 08-Mar-2001; D: section of an ASTER VNIR image with spatial resolution of 15 m. from 14-Feb-2002; E: section of a Spot PAN with spatial resolution of 10 m. from 28-Dec-1994; F: section of an Aerial-photo with scale of 1:37,000 taken on 16-Feb-1972, and scanned at 300 dpi (displayed at 25% of its size); G: section of an Aerial-photo with scale of 1:25,000 taken on 02-Feb-2000 and scanned at 300 dpi (displayed at 25% of its size); H: section of a QuickBird image with spatial resolution of 70 cm. from 16-Nov-2005 (displayed at 25% of its size).

The relief of Cuba is not as high and dissected as in other parts of the world. The highest point is 1974 m and highest vertical dissection (internal relief) is 471 metres per square kilometre (Reyes, 2004). This geomorphic characteristic and the geological setting produce relatively small landslides compared to other countries. In consequence, the resolution of earth observation data for landslide studies in Cuba need to be as high as possible in order to recognize landslide features from the data. Figure 3.5 shows the largest historical landslide in Cuba, the Jagüeyes landslide located in the San Antonio del Sur Municipality, which is also a study area for this research. The figure shows several earth observation products including aerial photography and satellite images for this landslide. The aerial photos are represented at 25 % of their original size, and are more suitable for landslides interpretation in Cuba. With regard to satellite images, landslide features are not well represented with the exception of high resolution images like Quickbird (Figure 3.5 H). Both, aerial photos and satellite images have advantages and disadvantages for their use in landslide studies in Cuba. The aerial photos are cheap and available from historical archives, but are both costly and difficult to arrange (new flights) after major landslide events. High resolution satellite images are taken more often but they represent cloud problems and their prices are still too high for a country such as Cuba.

3.3.2. Main data producers, providers and users

Although Cuba is a developing country, the context regarding information for landslide risk assessment could be different than in other countries. In Cuba the situation is less problematic concerning the existence of the data but more difficulties are present in accessing and standardizing the data format. During this research many dataset were collected from diverse organizations. There were large differences in their data distribution policies. Some didn't even have a policy. It is important to highlight that the situation is gradually improving by the instauration of national commission of spatial data infrastructure for the republic of Cuba (IDERC).

This section provides an overview of the sources of data for environmental factors, triggering factors and elements at risk, at the different scales of analysis, explained in chapter 1 and 2. Table 3.3 shows the main data sets for landslide risk assessment and the providers for this data in Cuba at different levels during this research. At the national level most spatial information was collected from the national atlas at the same scale of the study. Other thematic information was obtained from national organizations such as the Institute of Meteorology and the National Statistics Office (ONE). At the national level two data sets were acquired from foreign providers: natural protected areas and the digital elevations model, was obtained from SRTM (see Chapter 4). Unfortunately there was no DEM available at national scale for the whole country from the national mapping agency called Geocuba.

Data collection for the provincial assessment was one of the most extensive parts. Here, as in other more detailed areas, the landslide inventory was obtained by photointerpretation and fieldwork campaigns. Elevation data from digitized contour lines of good resolution were processed to obtain geomorphometric maps. In this case study digital maps were processed such as geological and topographic maps at 1:100,000 scale. For both, exhaustive processing and editing was required. The geological map in CARIS GIS format from IGP was delivered per topographic sheets with several errors which required editing and building the topology again. Data contained in digital topographic maps of Geocuba at a scale of 1:100,000 were processed for many variables of landslide risk assessment. Although, much processing was needed, elements at risk could be obtained such as houses, roads and facilities. It is important to highlight that among all organizations supplying data, IGP and Geocuba were the only ones with certain standardization in digital data production. Other thematic data obtained for provincial landslide risk assessment was acquired either from national organizations such as the soil institute, and from provincial organizations such as the territorial statistics office.

Table 3.3. Data providers or source for landslide risk assessment in Cuba.

Data layer and types	Levels of analysis			
	National 1:1,000,000	Provincial 1:100,000	Municipal 1:50,000	Local 1:25,000
Landslides inventory	-	Photointerpretation	Photointerpretation	Photointerpretation
Terrain mapping units	-	-	Photointerpretation	-
Geomorphology	Atlas	Atlas and re-interpretation	Processing	Photointerpretation
Digital Elevation Model (DEM)	SRTM	Group of mountain studies	Topomap	Digital photogrametry
Slope angle	From SRTM	From DEM	From Topomap	-
Slope orientation	-	From DEM	-	-
Slope shape	-	-	From Topomap	-
Internal relief	-	From DEM	From Topomap	-
Drainage (density)	-	EMPIFAR	From Topomap	Photointerpretation
Springs		-	From Topomap	From Topomap
Geology	Atlas	IGP	IGP	IGP
Soils	-	Soil Institute	-	-
Faults	Atlas	IGP	IGP	-
Landuse	Atlas	IPF	From EO	-
Water table	-	-	Topomap	Topomap
Rainfall and maximum probabilities	ISMET	ISMET, INRH	INRH	INRH
Earthquakes and seismic acceleration	CENAIS	CENAIS	-	-
Population	ONE	ONE/OTE/ Topomap		Surveyed
Roads	Atlas	Topomap	Topomap	Surveyed
Lifeline utility systems	-	-	Topomap	-
Housing	INV	Topomap	Topomap	Surveyed
Building	-	Topomap	Topomap	Surveyed
Production	ONE		-	-
Facilities	-	OTE/Topomap	Topomap	-
Protected areas	UICN	CNAP	-	-

Note: See acronyms list for the name of the organizations

For municipal landslide risk assessment at a scale of 1:50,000 most data was produced by digitizing topographic maps and interpreting aerial photos (Table 3.3). Even data about the elements at risk such as houses and roads were digitized and classified from the topomaps. That was because the digitalization process of topographic maps in Cuba was implemented at scales of 1:25,000 and 1:100,000, but not at a scale of 1:50,000. Some thematic maps such as terrain mapping units and geomorphology were made by photointerpretation and fieldwork. Similar procedures were used for local landslide risk assessment at a scale of 1:25,000. At this level aerial photos support the geomorphological interpretation of landslide bodies and the digital photogrammetry to create digital elevation models before and after landslide occurrence. Some geotechnical parameters of rocks and soils were obtained from the Water Resources Institute at provincial level. In summary, while at national and provincial levels it was possible to use both national and international data providers, at more detailed scales (such as municipal and local) most data was obtained from topomaps or aerial photo interpretation.

In Cuba most data is distributed by the producer itself. There are some exceptions, for example, geological data is either distributed by the producer itself or by the National Office of Mineral Resources (ONRM in Spanish). Table 3.4 shows a summary of main data providers for landslide risk assessment in Cuba. The table was made after compiling all data for the four cases studies in this research. The characteristics of data provision could gradually change when the service improves. All of the providers mentioned are national organizations, but some of them have representations at provincial and municipal levels such as the national statistic office (ONE).

Table 3.4. Main data providers for landslide risk assessment in Cuba

Data type	Provider	Characteristics
Landslide inventory		
	IGP/IGT/CENAIS/ENIA/CNV	Research reports, engineering works
	Newspapers/Historical archives/Church/Police	Historical event records
Hazard related data		
Geomorphometry	GeoCuba	Derived from topomaps (analogue or digital)
Environmental factors	IGP/IGT/Soil Institute/IPF/CNAP	Requires digitalization or editing
Triggering factors	CENAIS/INSMET/INRH	Requires digitalization or editing
Element at risk		
Statistic information	ONE/INV/MINSAP	Associated to administrative units
Spatial data	Geocuba/IPF/MINAGRI	Requires digitalization or editing

Note: See acronyms list for the name of the organizations

The final users of the information related to disaster risk are identified as the local authorities at different levels. They are responsible for managing the risk, and are supported by the civil defence specialists, locals organizations and the local population. However, there is a difference between the final user of the risk assessment and the user of the data for conducting risk assessment.

By the experience gained during data collection six levels of situation with data where found in this research including:

1. The required data was not available. Unfortunately, some data does not exist or it is not possible to recognize where to find it. This situation occurred with some economic data or some lifeline systems at national and provincial level.
2. The required data was available but not updated. Depending on the type of data and the level of update governed whether it could be used or not. For example, the landuse map was not updated at national scale, but at this level this data does not change very often in Cuba.
3. The required was not accessible. Due to data policy of the organization there was no access to the information. As an example, the National Institute of Water Resources (INRH in Spanish) of the Guantánamo province level, only provides summary statistics of rainfall data but not daily records.
4. The format of the required data was incorrect. This requires extra work in converting, editing or digitizing the data. This is the most common situation found with many examples like lithological data available in CARIS GIS format.
5. The spatial data was not properly linked to the attribute data. Some statistical information is not spatially linked by co-ordinates or a code which makes it virtually useless. This was relevant for census data that belongs to certain area but without location.
6. The data contained substantial errors. Data with content or co-ordinate errors makes extensive works on reviewing when possible. That occurred for settlement centroids with co-ordinate errors which locate the settlement at sea or with a code for geological units for units that do not exist in the study area
7. There were a few exceptional occasions when the data was available, accessible, up to date, error free, and the right format. For example data provided about housing and statistical data for municipalities was used directly.

3.3.3. Spatial data infrastructure

The introduction of a national spatial data infrastructure initiative started in 1999, when the Hydrographical and Geodetic Service in Cuba identified the need to develop NSDI in the Country. Comprehensive description of NSDI in Cuba can be found in Delgado Fernández (2005) and Elderink (2006). During 2001-2003, training to build capacity was conducted in different ways. Since 2004, the Geospatial portal was established and two agreement of the Council of Ministry were approved creating the national commission of SDI called CIDERC. Since then, it gradually began to organize different elements of data infrastructure like metadata, data policy, etc. Also, some applications have been implemented as examples of how to share spatial data among organizations that can improve the economy and society in general. The NSDI commission is also looking at other relevant applications in the country such as risk assessment and disaster management, but no implementation has been undertaken as of yet (e.g. initiatives to design SDI for risk management (Usländer, 2005) considering standards for ISO TC 211).

The use of information produced by any organization in Cuba should be regulated according the Law Decree 199 (Decreto Ley No. 199, 1999) "about the security and protection of official information". According to this regulation any 'official information' should be either 'classified', 'limited' or 'ordinary'. According to this, information considered ordinary does not produce damage or risk for the organization - even if the information is disseminated in an unauthorized way. When requesting data for landslide risk assessment in this research it was found that some organizations had an effective system for data and information delivery, for example national and territorial statistical offices. Upon an official data request a mechanism was initiated and the data was delivery shortly after that. However, other organizations did not allow access even when their information was 'ordinary' by arguing several reasons. Others, without an official data policy had mechanisms for obtaining the data that were very slow. The amount of information required for risk assessment is so large that countries without a consistent policy for data access find it a serious constraint for implementing a nationwide system for risk assessment of any hazard. Besides, if the assessment will only consider ordinary information, government authorities and civil defence should know the consequences as disaster does not classify objects to be damaged in such a way.

The developments in Information Technology (IT) in Cuba have been extremely limited by more than fifty years of a US Embargo. Either by the influential role of the US in the IT worldwide or by the short distance among the two countries, the ban imposed by US to get access to IT forced Cuba to find alternative solutions. According the Ministry of Informatics and Communications (MIC in Spanish) internet access is only authorized by the US Treasure Department via a satellite with only 65 Mbps for output and 124 Mbps for input (www.mic.gov.cu). Computer hardware is imported from other countries, and generally costs 30% more than other countries, which are either completely imported or assembled in the country. The number of computer has grown from 225,000 in 2001 up to 430,000 in 2006 (ONE, 2007). For the use of software, the situation is different and more difficult. Since US law prohibits Cubans to use any software with a US license, organizations in Cuba have been forced to use standard systems (Windows, Office, etc.) and professional software like GIS without any support, warranty and training. Therefore, the policy of the organizations for data digitalization and data transfer has been affected and as a consequence, situations as described in previous section are common place when requesting data. As GIS software usually needs a high level of customization there are many problems when projects like risk assessments are implemented by using data from several organizations. In this point, the spatial data infrastructure is playing a crucial role in recognizing main data producers and supporting interoperable data transfer.

The country has made huge investments in telecommunications. The number of telephone lines have grown from few thousand in 2001 up to over one million in 2006 (ONE, 2007) and the digitalization percentage of telephone stations has grown from 69 up to 92 in the same period. This process has been supported the recent installation of optical fibre along the whole country linking first the fourteen provincial capitals and now progressing in linking the municipal capitals. The use of this technology is progressively impacting the economy and society, and certainly is contributing to specific tasks requested by the government such as nationwide multi-hazard risk assessment.

3.3.4. An example of data producer: housing inventory system in Cuba

Among the data collected during this research was the housing data for the Guantánamo province which is very relevant for vulnerability and risk assessment. As an example of a national system of collecting data for a specific element at risk, this section explains the system for collecting housing data and shows some results in the Guantánamo province for the year 2004. Similar data will be processed in all case studies (Chapters 4-7). Housing is one of the main social problems in Cuba with high relevance in disaster vulnerability. For example, between November 2001 and September 2002, three hurricanes affected Cuba with a high impact on the economy and the population. During hurricane Michelle (4-5/11/2001) 166515 houses were reported damaged (OCHA, 2001) while hurricanes Isidore (19-20/09/2002) and Lili (28/09-01/10/2002) together damaged another 211322 houses (UN interagency mission, 2002). The amount of damage is extremely large and unfortunately occurs on a cycle that makes it very difficult to improve the current housing situation given the present economical condition. Considering this, the housing inventory and its condition according to the 2004 statistics in the Guantánamo province were analyzed.

The classification of the houses in Cuba is organized by the National Institute of Housing (INV). They establish the policy and set of plans for housing development in the country (MICONS, 2007) and they are represented hierarchically in the 14 provinces and 169 municipalities. Besides, they also have provincial and municipal investment units (UPIV and UMIV) which act as investor role for housing construction by the government and also control private constructions or repairing. This organization classifies the houses in six typologies and three states of condition. Annex 3.A shows the description of the each typology according to the walls, roofs and floors of the houses. A yearly report records the statistics of houses at three levels based on an updating system. Updating the housing statistics (categories and status) in a year is a combination of actual changes due to demolishing, repairing or building and the housing depreciation index applied to the inventory. Table 3.5 show how these statistics are calculated for the year 2004, published by Provincial Investment Unit (UPIV) of the National Institute of Housing (INV) in 2005. For every status and category the initial inventory is reduced by the number of houses that were demolished or repaired. Houses that have been demolished do not exist any longer in the inventory while houses that have been repaired are either moved to another category or are reclassified with another status. Every category has a depreciation index established by INV. This index 0.1666 (1/6 a semester) is multiplied by the current inventory and gives the number of houses moved to the next status. In 2004, there were 24,345 houses in good condition for the category I, from this amount 45 houses were depreciated and moved to regular conditions of the same category. This updating system is validated by direct inspection of the houses at local level and by controlling the licenses for new constructions or repairs carried out either by the government or privately.

Table 3.5. Updating housing inventory in Guantánamo province for the year 2004 (Housing Institute-Guantánamo, 2005).

Status	Type	Depreciation Index	Initial Inv. 2004	Removed	Repaired	Current Inv.	Depreciated negative	Inv. less depreciation	New building	Repaired	Depreciated positive	Other new	Total inv. 2004
Good	I	0.011	24345	0	0	24345	45	24300	107	40	0	3	24450
Good	II	0.014	1534	0	0	1534	4	1530	0	0	0	0	1530
Good	III	0.020	19432	0	0	19432	65	19367	42	29	0	6	19444
Good	IV	0.025	11727	0	0	11727	49	11678	88	7	0	0	11773
Good	V	0.033	5646	0	0	5646	31	5615	0	0	0	0	5615
Sub Total			**62684**	**0**	**0**	**62684**	**193**	**62491**	**237**	**76**	**0**	**9**	**62813**
Regular	I	0.011	15409	0	20	15389	28	15361	0	0	45	0	15405
Regular	II	0.014	648	0	0	648	2	646	0	0	4	0	650
Regular	III	0.020	11698	39	18	11641	39	11602	0	2	65	0	11669
Regular	IV	0.025	10032	0	16	10016	42	9974	0	0	49	0	10023
Regular	V	0.033	4458	0	4	4454	24	4429	0	0	31	0	4461
Sub Total			**42245**	**39**	**58**	**42148**	**135**	**42013**	**0**	**2**	**193**	**0**	**42208**
Bad	I		2987	3	4	2980		2980	0	0	28	0	3008
Bad	II		229	0	0	229		229	0	0	2	0	231
Bad	III		2015	3	4	2008		2008	0	0	39	0	2047
Bad	IV		2764	14	2	2748		2748	0	0	42	0	2790
Bad	V		1721	5	0	1716		1716	0	0	24	0	1740
Bad	VI		20904	9	5	20890		20890	0	0	0	0	20890
Bad	VII		554	4	5	545		545	0	0	0	0	545
Sub Total			**31174**	**38**	**20**	**31116**	**0.0**	**31116**	**0**	**0**	**135**	**0**	**31251**
TOTAL			**136103**	**77**	**78**	**135948**	**328**	**135620**	**237**	**78**	**328**	**9**	**136272**

Table 3.6. Summary of housing conditions in Guantánamo province for the year 2004 (Housing Institute-Guantánamo, 2005).

	Total	Good	Regular	Bad	R & B	% R & B
Initial inv.	136103	62684	42245	31174	73419	53.9
Final inv.	136272	62813	42208	31251	73459	53.9
Relation	169	129	-37	77	40	
Relation %	100.1	100.2	99.9	100.2	100.1	
Evolution %	0.1	0.2	-0.1	0.2	0.1	

As the Table 3.5 shows, in 2004 Guantánamo had 136272 houses of which only 78 were repaired and 237 were new in that year. In Table 3.6 the housing conditions are summarized showing that almost 54 percent of the houses are classified as being in 'regular' or 'bad' condition and that the evolution of construction in the province is only 0.1 %.

The provincial housing inventory is fed from the municipal housing inventories which follow the same procedure. In order to show the statistics of housing conditions and typologies for all municipalities Table 3.7 was made from the municipals inventories. Beside, the housing condition index used for national assessment of Good/(Regular + Bad) was calculated for each municipality. Numbers shows a large variation in the province ranging from 0.64 up to 2.07. But only two municipalities (Caimanera and Niceto Pérez) have 50% or more houses in good condition. Unfortunately, these two municipalities only have 5 % of the houses in the province. The worst situation is in El Salvador and in the San Antonio del Sur municipalities.

Table 3.7. Number of houses per status and typology in the 10 municipalities of Guantánamo province.

Status	Type	El Salvador	Guantánamo	Yateras	Baracoa	Maisí	Imías	San A. del Sur	M. Támes	Caimanera	Niceto Pérez
Good	I	638	17064	125	2955	319	303	419	287	1109	1231
Good	II	37	646	11	654	15	57	40	19	24	27
Good	III	1408	7839	925	2848	1471	1505	1267	878	461	842
Good	IV	2645	3082	571	2636	1058	503	527	233	139	379
Good	V	629	771	682	1621	881	445	327	60	40	160
Subtotal		**5357**	**29402**	**2314**	**10714**	**3744**	**2813**	**2580**	**1477**	**1774**	**2639**
Regular	I	450	13326	71	578	220	103	186	168	227	75
Regular	II	60	204	12	229	12	32	17	30	43	11
Regular	III	811	8061	258	617	380	298	313	558	96	276
Regular	IV	1733	4836	692	1287	354	70	308	303	235	206
Regular	V	803	875	715	877	647	177	186	24	88	68
Regular	VI	0	0	0	0	0	0	0	0	0	0
Subtotal		**3857**	**27302**	**1749**	**3589**	**1613**	**681**	**1010**	**1083**	**688**	**635**
Bad	I	116	2231	13	419	40	16	48	62	52	9
Bad	II	16	49	3	123	1	8	8	11	10	1
Bad	III	264	1374	39	45	39	60	87	90	27	22
Bad	IV	550	1339	137	384	21	27	155	140	30	5
Bad	V	528	467	40	313	205	30	10	89	50	8
Bad	VI	3038	1936	1294	6366	1983	1974	2436	976	0	887
Bad	VII	19	104	21	231	0	82	37	47	0	4
Subtotal		**4531**	**7501**	**1547**	**7881**	**2290**	**2197**	**2782**	**1416**	**170**	**936**
Total		**13745**	**64205**	**5609**	**22184**	**7647**	**5691**	**6372**	**3976**	**2632**	**4211**
Housing index		**0.64**	**0.84**	**0.70**	**0.93**	**0.96**	**0.98**	**0.68**	**0.59**	**2.07**	**1.68**

The three tables reflect the lack of investment either for new buildings or for repairing the existing ones. Fortunately, the situation is improving since from 2006 when the Government put in place a plan for constructing 100,000 new houses per year for the whole country, as countermeasure against the housing problem due to natural disasters and the economic crisis. It is also important to highlight, as mentioned in the national assessment (Chapter 4), that the Guantánamo province has the second lowest quality of housing in Cuba according to the 2004 record.

3.4. Conclusions

This chapter aims to locate the research in the appropriate context of Cuba. Two main components where selected: the context of disaster risk reduction and management and the context of available geospatial data in Cuba. As demonstrated in the case study chapters, these are two determinant components for defining landslide risk assessment methods. As practical examples, the disaster database and housing inventory of the Guantánamo province were presented.

Despite the well recognized success of the Civil Defence system in Cuba, economic losses continue to affect the whole country. One of the latest developments of the Civil Defence is the implementation of multi-hazard risk assessment for all municipalities in order to improve disaster risk reduction plans. These assessments are carried out progressively by hazard and following specific principles. As explained key factors are involve in the success of civil defence in Cuba. Besides these factors it is demonstrated by its evolution that civil defence system in the country is a long term process continuously improved by adaptations and enhancements. In addition, the vulnerability side of the risk equation has been reduced many years ago by social and infrastructural investments.

The context of geospatial data is vital for risk assessment. As data creation is very expensive and sometimes unaffordable, most risk assessment models must be based on existing data – where any existing data providers are crucial. In Cuba, there already is data useful for spatial landslide risk assessment although major problems arise with accessibility, format and quality of the data. However, the situation is gradually improving by two main forces: the improvement of the data infrastructure and the organization from the national level of multi-hazard risk assessment.

CHAPTER 4

National landslide risk assessment

Based on:

Castellanos Abella, E.A. and van Westen, C.J. 2007 Generation of a landslide risk index map for Cuba using spatial multi-criteria evaluation. In: Landslides: journal of the International Consortium on Landslides, 4, pp. 311-325.

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4. National landslide risk assessment

4.1. Introduction

Landslides cause a considerable amount of damage in the mountainous regions of Cuba, which cover about 25% of the country. The national landslide inventory shows that a significant number of people are affected by landslide disaster events, and usually suffer economic loss (as recorded Castellanos and Van Westen, 2005). Although the Cuban system for natural disaster management is recognised by international organisations as a 'good example', worthy of being followed by neighbouring countries (ISDR, 2004), Cuba's economic losses due to continued natural disasters is still on the increase. Only for 2004, Charley and Ivan hurricanes caused a total damage worth 2,146 million USD and resulted in 5,360 houses completely destroyed and 100,266 partially damaged (Rodríguez, 2004). In order to reduce disaster losses, the Civil Defence authorities are putting emphasis both on improving existing disaster preparedness and response planning, as well as on risk reduction planning, which must be based on multi-hazard risk assessment at all management levels.

Until now, only a limited amount of research has been carried out in the field of landslide risk assessment in Cuba. Most landslide studies in Cuba have concentrated on landslide inventory mapping, landslide descriptions and qualitative hazard assessment and do not cover the country as a whole (Viña et al., 1977; Formell and Albear, 1979; Iturralde-Vinent, 1991; Magaz et al., 1991; Castellanos et al., 1998b; Guardado and Almaguer, 2001a). Most of these investigations were carried out in the south-eastern part of the country. Therefore, the National Civil Defence organisation of Cuba in collaboration with the Institute of Geology and Palaeontology, initiated a national landslide risk assessment project. The aim of the project was to include the landslide risk in the multi-hazard risk assessment for the national system of disaster management. As a component of this, a research project for the development and implementation of a suitable methodology for landslide risk assessment from a national to a local level started in 2004.

For large-scale landslide risk assessment, a range of methodologies have been published (see Bonnard et al., 2004; Lee and Jones, 2004; Eberhardt et al., 2005; Glade et al., 2005), but only a limited amount of research has been done on landslide risk assessment for large areas such as entire countries (Guzzetti, 2000; Yoshimatsu and Abe, 2006). At such small scales, the aim is generally to produce a landslide risk index, pinpointing the high-risk areas for more detailed studies. Risk indexes have been applied in small-scale studies either for specific countries (Davidson, 1997; Carreño et al., 2007) or at a global level (Evans and Roberts, 2006; Nadim et al., 2006a; Nadim et al., 2006b). The results are intended to support national decision makers in prioritizing funding for risk assessments at local, municipal and provincial levels. With the outcomes of the study in Cuba, the Civil Defence organisation will be able to alert local authorities about the risk levels and to link the information to the national hurricane early warning system, therefore allowing for early warning and evacuation of landslide-prone areas.

The main goal of this research is to design a methodology for the assessment of a nationwide landslide risk index for Cuba given the limitations in data availability. This risk index does not intend to quantify the risk according to the definition of (Varnes and IAEG-Commission on Landslides and Others Mass Movements on Slopes, 1984), as the data available for the entire country is not suitable for that. These data do not allow the application of deterministic landslide hazard assessment methods, which are required to derive quantitative landslide risk maps. Furthermore, the application of statistical or probabilistic methods is not possible because of the lack of a sufficiently complete national landslide inventory. Therefore, given the data available, it was decided to produce a qualitative landslide risk index using spatial multi-criteria evaluation (SMCE) methods in a Geographic Information System (Integrated Land and Water Information System [ILWIS]-GIS). The landslide risk index use indicator maps collected from a variety of national information sources. The methodology must enable annual updates of the landslide risk index map based on new landslide information collected during and after the hurricane season. Besides new landslide information, there are some datasets in the model such as population density or economic production that could be regularly updated.

The management level determines the objectives of the risk assessment (Figure 4.1). The National Civil Defence in Cuba as the main user of the expected results indicated that the landslide risk assessment at the national level should allow them to:

1. Locate, in the national territory, the areas with relatively higher risk and identify the main causes in terms of hazard and vulnerability indicators used in the assessment.
2. Alert provincial and municipal civil defence authorities about potential disasters in their respective areas, with the aim that they include landslide risk in their disaster reduction plans.
3. Agree with the governmental organisations, businesses and social institutions, on the required measures of prevention and preparation, in order to cope with the identified risk in their respective areas.
4. Approve and implement, in agreement with the Ministry of Science, Technology and Environment, a mitigation plan aiming to study in more detail the identified areas of higher risk, its causes and the implementation of measures in order to reduce the risk.

4.2. National landslide risk assessment model

4.2.1. Design issues and objectives

The landslide risk index method starts with the selection of indicator maps, the way the criteria are structured and the selection of standardisation and weighting methods. Figure 4.1 presents an overview of the various components of the landslide risk index method. The constitutive elements are limited by the boundary conditions, including not only data but also expert opinions. In this research, the experts were the civil defence authorities for vulnerability assessment and the author for hazard assessment. The rest of the model is included in the spatial multi-criteria evaluation where the criteria tree is divided into hazard indicators and vulnerability indicators. In the following sections the steps in Figure 4.1 will be explained.

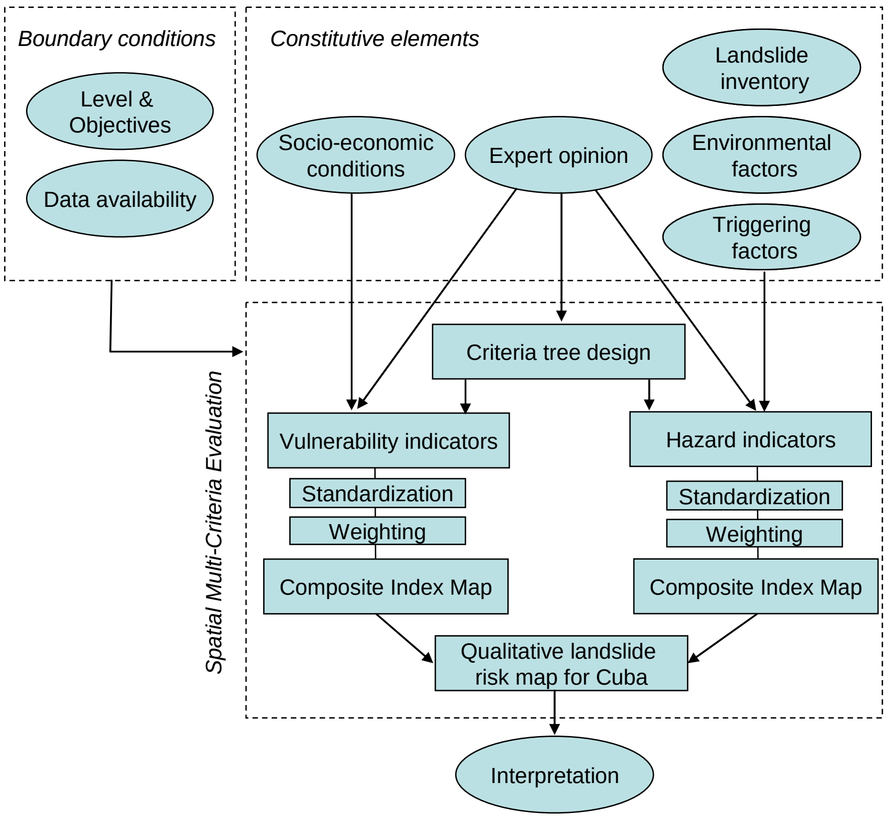

Figure 4.1. General framework for building the landslide risk assessment model.

An important source for the hazard indicators is the analysis of an existing landslide inventory (Figure 4.1). There are good examples of the use of landslide inventories for hazard assessment in the literature (see Guzzetti et al., 1994; Guzzetti, 2000; Chau et al., 2004; Guzzetti and Tonelli, 2004). However, the existing landslide databases often present several drawbacks (Ardizzone et al., 2002; Guzzetti and Tonelli, 2004) such as to the coverage in space and in time and the fact that in many cases they are only mentioned if they have affected infrastructures such as roads.

As mentioned above, the landslide inventory in Cuba is still under development and does not have complete national coverage. The current national landslide database has similar problems, such as countries in terms of coverage and event reporting. Furthermore, quantitative damage information is not available for most of the landslides in the database. It was for this reason, that the national landslide database was used with caution during the course of this study, as it did not give a complete overview for the country. However, if a complete landslide database was available, it could have served along with other sources as a useful input to the landslide risk index. The landslide density and landslide damage per municipality could have then been considered as hazard and vulnerability indicators respectively. As part of the national landslide risk assessment project for the National Civil Defence, a research project was also initiated in order to improve the national landslide inventory, using local Civil Defence personnel trained in reporting the occurrence of new landslides and multi-temporal landslide maps based on Remote Sensing (Castellanos and Van Westen, 2005).

Additional components for designing the landslide risk index are datasets related to environmental factors and triggering factors related to the occurrence of landslides. For both aspects, expert knowledge is essential in making the selection of relevant indicator maps for the index. In order to get a better idea of the importance of these factors, physical models for estimating slope instability (Terlien et al., 1995; van Westen and Terlien, 1996; Moon and Blackstock, 2004) can be used to derive trends. These deterministic models require a number of input maps, related to soil depth, soil strength, soil–water conditions and slope angles. Sensitivity analyses have shown the relative importance of the indicators (see van Asch et al., 1999; Zaitchik et al., 2003; Schmidt and Dikau, 2004; van Beek and van Asch, 2004).Therefore, combining inventory analysis (empirical modelling) and physical rules (established in the deterministic models) a better understanding for designing appropriated hazard indicators can be established.

When designing vulnerability indicators, it is necessary to take into account the socio-economic conditions, which may vary from country to country. In general, vulnerability can be divided in four different types, such as physical, social, economic and environmental (UNPD, 2004), which can be combined in order to derive a qualitative index. There are relatively few publications related to landslide vulnerability assessment (Leone et al., 1996; Ragozin and Tikhvinsky, 2000; Barbat, 2003), and most of them deal with large-scale studies or are on a site-investigation scale (Glade, 2003). On a very small scale, such as a national landslide risk assessment, it is not feasible to represent the degree of impact depending on the magnitude of the hazardous event and the characteristics of the elements at risk. The vulnerability indicators used in this study are more representations of the amount of elements at risk per administrative unit (e.g. population density per municipality) than actual measures of vulnerability. Therefore, they are not specific for landslide vulnerability, and could also be used to assess the vulnerability of other hazardous phenomena at a national scale.

Two interrelated boundary conditions have great influence in designing a model for the national landslide risk index assessment: the data availability and the level of analysis (Figure 4.1). Data availability is especially relevant in developing countries, where data is scarce, scattered or not available in the appropriate format. Furthermore, the level of analysis is relevant as it determines the quantity of data, in terms of areal coverage and detail. National level assessment involves small-scale input data, which are generalized and which determines the type of analysis method that can be used. It is this issue, along with funding, that can overrule all other aforementioned aspects when designing the model. In practice, there is always a certain amount of discrepancy between the desired and available information. However, even if the desired type of information is available, it may still be in the wrong format or be insufficient in its detail.

4.2.2. Multi-criteria analysis and analytic hierarchy process

When considering the aforementioned objectives for the assessment of a national landslide risk index map, in combination with a large study area and limitations in available data, a semi-quantitative approach was selected. The main difference between qualitative and semi-quantitative approaches is the assignment of weights given certain criteria. The semi-quantitative estimation for landslide risk assessment is considered useful in the following situations: as an initial screening process to identify hazards and risks, when the level of risk (pre-assumed) does not justify the time and effort or where the possibility of obtaining numerical data is limited (AGS, 2000).

Semi-quantitative approaches consider explicitly a number of factors influencing the stability (Chowdhury and Flentje, 2003). A range of scores and settings for each factor may be used to assess the extent to which that factor is favourable or unfavourable to the occurrence of instability (hazard) and the occurrence of loss or damage (consequence). A good example of such a semi-quantitative approach was the ranking method used in Hong Kong, since the approach adopted a risk classification system for cut and fill slopes, as well as for natural slopes on which future development will take place (Koirala and Watkins, 1988).

For implementing the semi-quantitative model, the SMCE module of ILWIS-GIS was used. The SMCE application assists and guides users when performing multi-criteria evaluation in a spatial manner (ITC, 2001). The input is a set of maps that are the spatial representation of the criteria, which are grouped, standardised and weighted in a 'criteria tree.' The output is one or more 'composite index map(s),' which indicates the realisation of the model implemented. The theoretical background for the multi-criteria evaluation is based on the Analytical Hierarchical Process (AHP) developed by Saaty (1980). The AHP has been extensively applied on decision-making problems (Saaty and Vargas, 2001), and only recently, some research has been carried out to apply AHP to landslide susceptibility assessment. Komac (2006) designed multivariate statistical processing techniques in order to obtain several landslide susceptibility models with data at 1:50,000 and 1:100,000 scales. Based on the statistical results, several landslide susceptibility models were developed using the AHP method. Yoshimatsu and Abe (2006) used AHP for evaluating landslide susceptibility assigning scores to each factor of micro-topography of landslide-prone areas in Japan.

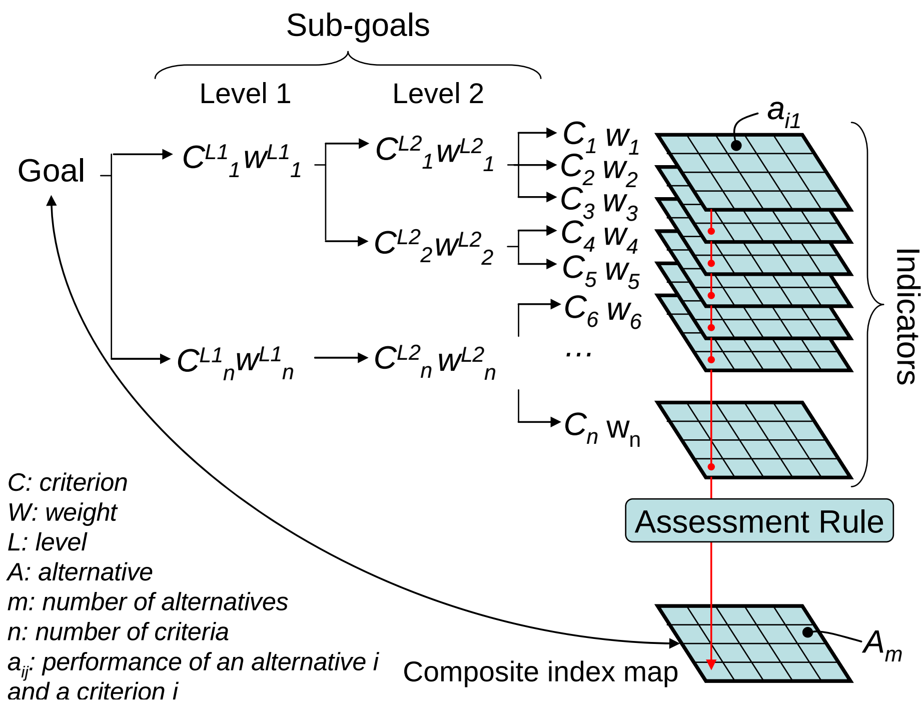

Figure 4.2. Schematic procedure for spatial multi-criteria evaluation based on the analytical hierarchical process

From a decision-making perspective, multi-criteria evaluation can be expressed in a matrix (Triantaphyllou, 2000) as shown in Table 4.1. The matrix A contains the criteria in one axis (C_1 to C_n), and a list of possible alternatives, from which a decision has to be taken on the other axis (A_1 to A_m). Each cell in the matrix (a_{ij}) indicates the performance of a particular alternative in terms of a particular criterion. The value of each cell in the matrix is composed of the multiplication of the standardised value (between 0 and 1) of the criterion for the particular alternative, multiplied by the weight (W_1 to W_n) related to the criterion. Once the matrix has been filled, the final value can be obtained by adding up all cell values of the different criteria for the particular alternative (e.g. a_{11} to a_{1n} for alternative A_1).

For implementing this matrix according to the AHP, three principles steps need to be considered: i) decomposition, ii) comparative judgement and iii) synthesis of priorities (Malczewski, 1996). The first one decomposes the problem (and the weights) into a hierarchical structure. The second one considers the weighting process, employing the pairwise comparisons of the criteria, and the synthesis is related to the multiplications among the hierarchical levels. Additionally, in the spatial implementation of this procedure, every criterion (C_j) becomes a raster layer, and every pixel (or set of pixels) of the final composite index map eventually becomes an alternative *Aj* (Malczewski, 1996). Note that the notion of 'alternative' is different in this context. The 'alternative' described herein is not a choice of action but a different spatial realisation of the final goal (e.g. landslide risk), as explained in Figure 4.2. The goal (landslide risk index) has been decomposed into criteria levels C_{L1} and C_{L2}. The intermediate levels are often indicated as sub-goals or objectives (e.g. in level 1, the sub-goals are a 'hazard index' and a 'vulnerability index'). Each criterion of each level will also have an assigned weight. Therefore, the values for the layers of the intermediate levels are obtained through the summation of the performance for the alternative at lower levels. As the criteria consist of raster maps, their spatial performance (a_{ij}) and the alternative (A_i) will be identified for particular raster cells.

	C_1 $(w_1$	C_2 w_2	C_3 w_3	… …	C_n $w_n)$
A_1	a_{11}	a_{12}	a_{13}	…	a_{1n}
A_2	a_{21}	a_{22}	a_{23}	…	a_{2n}
.	.	.	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.
A_m	a_{m1}	a_{m2}	a_{m3}	…	a_{mn}

Table 4.1. Multi-criteria decision matrix.

The composite index map (e.g. landslide risk) is obtained by an assessment rule (sometimes also called decision rule), which is calculated by adding up the performance of all cell values of the different criteria (a_{ij}) for the particular alternative. However, the performance of every element in the matrix (a_{ij}), is obtained in a different way:

$$a_{ij} = v_{ij}^{*} \prod_{L=0}^{h} w_j^L \qquad \text{[eq. 1]}$$

In this equation, v_{ij} refers to the standardised value of criterion (C_j) for alternative (A_i), and weight w^L_j refers to the weight of criterion (C_j) for level L (0–h levels). During the analysis, it could be desirable (and sometimes necessary for a better definition of the weights w^L_j) to produce the intermediate criteria maps. In this case, Eq. 1 should not be applied because weights need to be multiplied with the standardised values only up to the specific level of the intermediate maps. The intermediate maps might also be combined using different methods. In this particular situation, the landslide risk index is generated by multiplying the two composite index maps for hazard and vulnerability, to resemble their joint behaviour in resemblance of the landslide risk equation of Varnes (1984).

As mentioned earlier, the quantification of the expected losses for landslides is not possible, given the limitations in data availability and size of the study area. Therefore, the landslide risk is represented by a semi-quantitative risk index. The index will be high only if both the hazard and vulnerability index maps are high. In fact, the hazard component only represents landslide susceptibility, as it does not include the time factor required for estimating probability. The intermediate map of hazards is constructed again by multiplying two other intermediate maps of Conditions and Triggering Factors. Conditions are the intrinsic environmental parameters of the terrain that lead to particular susceptibility for landslide occurrence, and Triggering Factors are the most frequent triggering mechanisms that make landslide event occur. The intermediate map of Vulnerability is generated by combining the four aforementioned vulnerability types. A schematic representation of the landslide risk assessment model is given in Figure 4.3.

4.2.3. Standardisation, weighting and evaluation rules

In order to facilitate spatial multi-criteria analysis, the input layers need to be standardised from their original values to the value range of 0–1. It is important to notice that the indicators have different measurement scales (nominal, ordinal, interval and ratio) and that their cartographic representations are also different (natural and administrative polygons and pixel based raster maps). Taking these elements into account, different standardization methods provided in the SMCE module of ILWIS (ITC, 2001) were applied to the indicators (as will be explained).

Table 4.2. Overview of indicators (italic), intermediate maps or sub-goals (bold), with their corresponding weight values. The weighting and standardization method is indicated in the right columns.

National Landslide Risk Model				Weighting	Standardization
Hazard				Direct	
0.8	**Condition**				
		0.50	*Slope angle*	Direct	Concave
		0.20	*Landuse*		Ranking
		0.30	*Geology*		Ranking
0.2	**Factors**				
		0.90	*Rainfall*	Pairwise	Maximum
		0.10	*Earthquakes*		Maximum
Constraint for hazard map, areas with slope angle 3 degrees or less.					
Vulnerability					
0.256667	*Housing*			Rank. Expected value.	Maximum
0.090000	*Transportation*				Maximum
0.456676	*Population*				Concave
0.156667	*Production*				Maximum
0.040000	*Protected areas*				Ranking

The standardisation process is different if the indicator is a 'value' map with numerical and measurable values (interval and ratio scales) or a 'class' map with categories or classes (nominal and ordinal scales). For standardizing value maps, a set of equations can be used to convert the actual map values to a range between 0 and 1.

The class maps use an associated table for standardisation where a column must be filled with values between 0 and 1. The standardization is summarised in Table 4.2 (right column). In section 4.3, a detailed description of the indicator maps and their standardisation is given. The next step is to decide for each indicator whether it is favourable or unfavourable in relation to the intermediate or overall objective. For example, for the intermediate objective of vulnerability, all indicator maps of which higher values show an increase in the overall vulnerability were considered as favourable. In this study, all indicators were organised to have positive contribution (being favourable), except the housing condition index whose values were inversely calculated as explained in section 4.3.3 to the overall vulnerability and risk.

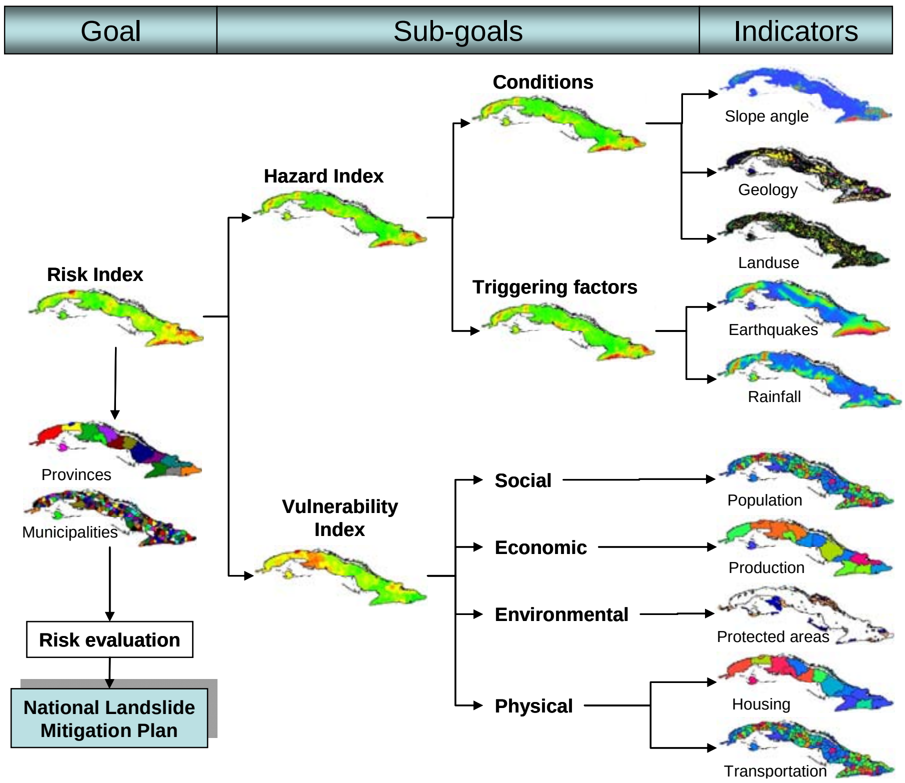

Figure 4.3. Landslide risk assessment model at national level in Cuba using spatial multi-criteria evaluation.

Another aspect considered in the model design was the use of constraint indicators. Constraint indicators are those that mask out areas and assign particular values to the resulting risk map, irrespectively of the other indicators. The most important constraint indicator used for the national landslide risk assessment is the slope angle. In areas that have very gentle or flat slopes, landslides are not expected or only occur under very specific conditions. From an analysis of the slope angle histogram made from the digital elevation model of Cuba, we found that 80.14% of the land surface has slope angles between 0 and 3°. Based on the analysis, a slope angle threshold of 3° was applied to mask out the areas without landslide risk.

After selecting the appropriate indicators, defining their standardisation and the hierarchical structure weights were assigned to each criteria and intermediate result. For weighting, three main methods were used: direct method, pairwise comparison and rank order methods (Table 4.2).

Before running the script in GIS, the entire model was implemented in a spreadsheet in order to test the model's performance using the extreme values for each indicator. When all indicators have their maximum values, they are standardised to 1, and the final risk index value is also 1. When all indicators have their minimum values, not all standardised values will be 0 and, as a consequence, the minimum risk index value that was possible was 0.00367. This is because some indicators could never be 0, as their lowest performance may indicate a landslide risk, e.g. geology, rainfall and housing as consequence of the ranking method used. Another analysis that was undertaken was to identify the performance of the model when all the indicators are in their measure of central tendency.

4.3. Indicator analysis

4.3.1. Landslides in Cuba

No landslide studies are available from the period before the revolution in Cuba in 1959, although there are some older publications with general geographic descriptions of landslide processes. In Figure 4.4 an overview is given of the most important known landslide events in Cuba in the last fifty years. The most catastrophic landslide happened in the Sierra de Caujerí scarp (Figure 4.4, number 1); specifically in the locality of Los Jagüeyes. This landslide occurred after three days of heavy rain during the passing of cyclone Flora on October 8 1963, which was the most devastating meteorological event that ever affected Cuba. During this event, a total amount of 1,100 mm of rainfall in three days was recorded in the Sierra de Caujerí region (Trusov, 1989). The successive rotational rockslide occurred in two pulses with about forty-five minute intervals, which allowed some of the inhabitants to escape, whereas five to ten others were killed. Although a technical report was not available directly after the incident, some data was recorded in 1999 with interviews of the survivors (Castellanos and van Westen, 2001a).

The highest landslide risk in Cuba related to a continuous slow landslide movement is located in Mariel municipality in Havana province (Formell and Albear, 1979; Díaz et al., 1983; Pacheco and Concepción, 1998). Mariel hill (Figure 4.4, number 2), the site of the old Navy Academy, is located over a slip surface which has moved intermittently. Recordings show 19 cm movement for 99 hours (in 1979 after hurricane Frederic) and 32.5 cm for 51 hours (in 1985 after 115 mm rainfall in three days). According to the reports, small movements have been recognized since 1918 and the crown of the landslide is about 40 m wide. The site is continuously monitored because, in case of a complete collapse, a large number of people may become victims.

The most comprehensive scientific publications about landslides in Cuba are related to those in the Eastern part of Cuba, such as the coastal landslides from Baitiquirí up to Maisí (Figure 4.4, number 3), in Guantánamo province (Magaz et al., 1991) and the ones in the Sierra Maestra (Iturralde-Vinent, 1991). The Baitiquirí-Maisí landslides are associated to the marine terraces, and may be considered as paleo-landslides since there is no historical record of movements. Besides, some of these paleo-landslides have been sealed in the front part by a coral reef ring which is also uplifted in the lowest marine terrace level. This is an indication that the landslides occurred in submarine conditions and that the area was subsequently uplifted. Large gravitational landforms were described in the southern slope of the Sierra Maestra (Figure 4.4, number 4) mountain system by Iturralde-Vinent (1991), and Orbera (1996). They were mapped as rotational rock slides, and although they are considered old, some of them have been re-activated during rainy periods, and have interrupted the single coastal road in the Southern Sierra Maestra.

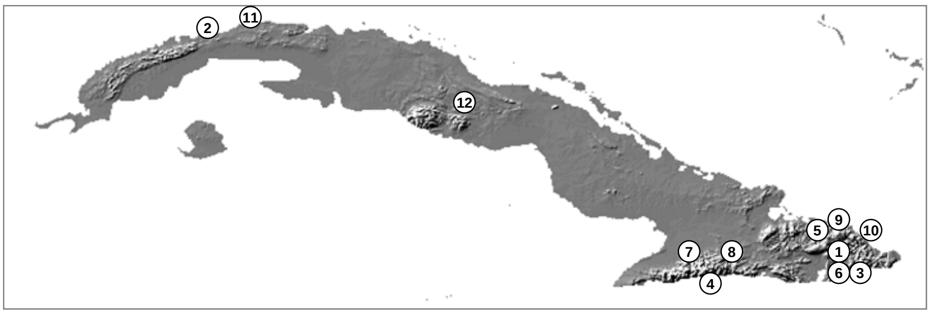

Figure 4.4. Location of landslides in Cuba, according the existing publications. Refer to the text for the numbers and landslide description.

In Moa-Baracoa and the Sierra del Purial mountain system (Figure 4.4, number 5) multiple old and recent landslides have been surveyed (Castellanos et al., 1998a). The landslides, located in highly dissected mountains, were identified in aerial photographs from 1974 and digitized in a GIS. A statistical analysis was carried out comparing the landslide frequency with different environmental parameters, and a landslide susceptibility map was made at 1:100 000 scale in an area of 14,000 km². A landslide hazard assessment at a more detailed scale (1:50,000) has been carried out in the San Antonio del Sur municipality (Castellanos, 2000; Castellanos and van Westen, 2001a; Castellanos and van Westen, 2001b). More than fifty landslides were recorded in a database (Figure 4.4, number 6).

Unstable slopes have been found in the northern slope of Sierra Maestra mountain system, specifically in Guisa Municipality (Figure 4.4, number 7), San Ignacio locality (Viña et al., 1977). On 10 June 1977 a landslide occurred in this region, which was measured at about 350 m long and 100 m wide. The vegetation and constructions on the landslide were relatively intact after being displaced for about 80 to 100 metres. Prior to the landslide there was an intense drought and later during May rainfall reached 737,2 mm, and 106,8 mm on 8 June (two days before the event). The 1977 landslide was a re-activation of an older one with reported activity in 1951 and 1960.

During geological mapping at 1:250,000 scale carried out in the Eastern part of Cuba small and medium size rockfalls and slides type of movements were reported (Pérez, 1983). They were located mainly along the rivers and happen mostly during the rainy season. Examples areas are Guanábana, close to Solongo, in Sierra Maestra (Figure 4.4, number 8) and the highland Yuraguana, close to La Tagua.

Some landslides occurring in the mountain areas are due to road construction in unstable or marginally stable slopes. Mining activity has also triggered different types of landslides as the one described in the Punta Gorda Nickel ore deposit (Guardado and Almaguer, 2001a; Almaguer and Guardado, 2003). A remarkable event was the landslide in the Cromite ore deposit in Merceditas (Figure 4.4, number 9), located 8 km from the La Melba locality in Sierra Cristal. A translational rockslide occurred with a width of 100 metres, due to underground mining activity, generating large chambers close to the slope. Although the landslide blocked the Jaraguá River, a lake was not formed due to the presence of large size rocks without soil materials.

Close to the Baracoa village (Figure 4.4, number 10), specifically 500 m from the airport an earth-rock slide occurred in 1997 (Castellanos et al., 1998b), blocking the road that connects the town with the airport. The landslide seems to be rotational over marls and limestone. The main factors involved may be the continuous rainfall, the cut at the foot of the slope for road construction and the construction of a tunnel inside the mountain.

There are other studies about landslides in Cuba such as the one related to the Via Blanca geological formation (Figure 4.4, number 11) in Havana City (González et al., 1994), the radiometric age dating of landslide zones (Chang et al., 2003), landslide hazard analysis in Sancti Spiritus (Figure 4.4, number 12) province (Reyes and Quisbert, 1998) and general publications about the landslide conditioning and triggering factors in the country (Rocamora, 1994; Guardado and Almaguer, 2001b; Rocamora, 2001; Rocamora, 2003).

In order to have up-to-date information about landslide occurrence in Cuba, a national landslide inventory system was designed. The landslide inventory was co-ordinated with the National Civil Defence and the Ministry of Science, Technology and Environment. Its design is based on collecting landslide information at the local level in the 169 municipalities prepared by the local staff of both organizations. A simple landslide reporting form has been designed, and workshops are conducted in order to train staff and make them aware of the procedure. Once the local officers report a landslide, a landslide expert from the

Institute of Geology and Palaeontology will visit the site and complete the questionnaire with more technical details. The initial report form only has three sections: location (date, place, duration, etc.); classification (material, type of landslide, activity, cause, etc.) and damages (materials, human and economic damages). Two extra pages were designed for explaining each entry and the landslide typological classification. The inventory was tested in ten municipalities of Guantánamo province and twenty-three events were reported by the local civil defence staff. Such a system for landslide data collection might not be very effective in other countries, due to lack of commitment of the reporting staff at the local level. However, in Cuba the Civil Defence is well organized, and very effective as can be concluded from a comparison of disaster related casualties in Cuba with those of neighbouring countries such as: Haiti or Dominican Republic (Thompson and Gaviria, 2004).

4.3.2. Hazard indicators

As mentioned above, the hazard indicators were separated into two groups: conditional factors and triggering factors. In the initial model development, a total of eight conditional factors were taken into account in order to estimate the intermediate hazard component of the national landslide risk index: slope angle, land use, geology, soil, geomorphology, slope length, drainage density and internal relief. These factors are generally considered as appropriate factors for landslide susceptibility assessment at a general scale (Soeters and van Westen, 1996). The last five indicator maps were later removed for different reasons, mostly related to data redundancy and the availability of data with inappropriate format or legend structure. The morphometric parameters slope length, drainage density and internal relief could be obtained from digital elevation values by processing SRTM data as explained below. The slope length parameter for landslide hazard was estimated from the base of the slope to the top instead of downhill calculation implemented in many GIS for other reasons such as soil erosion (van Remortel et al., 2001). The drainage network derived from the digital elevation model shows a disordered pattern in the low-land areas producing wrong density values. It was found that even after improving the raw data, the radar-generated relief data are not reliable enough for hydrological parameter derivation. The internal relief had a strong positive correlation (+0.8463) with the slope angle and therefore was considered to be redundant.

The geomorphological map of Cuba (Portela et al., 1989) was used initially as an indicator map as well. This map was designed on the basis of a physiographic legend rather than on a genetic legend of the landforms. As a consequence, the legend is actually a combination of geological and morphometric information. After a detailed analysis of the map and its legend, we concluded that the same information could be obtained by combining the geological map with the slope map, and that the geomorphological map contained redundant information. If the geomorphological map with its current legend would have been included in the analysis, this would have lead to overemphasizing the effect of geology and slope angle. Although the geomorphological map was removed as a hazard indicator, it could be used in future studies to produce a landslide hazard map through direct reclassification of the geomorphological units, when a good landslide inventory would be available. Furthermore, the soil type indicator map, derived from (Mesa et al., 1992) was discarded after careful analysis. Although the soil map contained a large number of legend units, most of the detail was in the flat or low-lying areas, where landslides are not occurring. Because a clear relation with landslides was absent, it was not possible to properly standardize the indicator map, and therefore it was not used in the analysis.

As a result, only three maps were considered relevant at this scale of analysis to be used as conditional factors for the generation of the intermediate hazard indicator map: slope angle, land use and geology. This is in accordance with other regional studies on landslide susceptibility mapping like the ones presented by Brabb (1984) and Dymond (2006).

Processing SRTM data for Cuba

The digital elevation model used for this study, was acquired by the from Shuttle Radar Topography Mission (SRTM) data (NASA-JPL, 1998; NASA-JPL, 2000), with a cell size of 90 m. There has been some research carried out with SRTM mostly regarding accuracy (Koch and Heipke, 2000; Koch and Lohmann, 2000; Koch et al., 2002; Miliaresis and Paraschou, 2005; Ludwig and Schneider, 2006; Pierce et al., 2006); but also related to practical applications (Murphy and Burgess, 2006; Verstraeten, 2006; Grohmann et al., 2007; Hubbard et al., 2007; Rossetti and Valeriano, 2007). The editing of SRTM data for Cuban Archipelago was explained in Castellanos (2005) and a brief summary is explained below.

The SRTM data that covers Cuba at 90 m resolution (0.0008333 degrees) has 6,002 rows by 13,202 columns created with 33 tiles of SRTM-3 data with 1,201×1,201 pixels for each one. These tiles were imported in ERDAS IMAGINE 8.7 (Leica Geosystems, 2003) with the WGS84 Geoid. The initial statistics obtained have a minimum value of -120 m, which is clearly an error. Besides, 1.40% of the pixels were 'voids' or undefined values including those on land and sea. However, the maximum value was 1970 m, which is only 4 m less than the maximum height measured in Cuba (Díaz et al., 1990). Since there are not any known inland areas which have an altitude below the sea level, all the negative values inland were also converted into undefined values. For masking the land from the sea, a coastline digitalized from a Landsat TM mosaic at 30 m spatial resolution in WGS84 geoid was used (Reyes, 2004). After masking the land area, the undefined values obtained (including voids and negative pixels) were the 0.83 percent of the Archipelago (114,444 pixels).

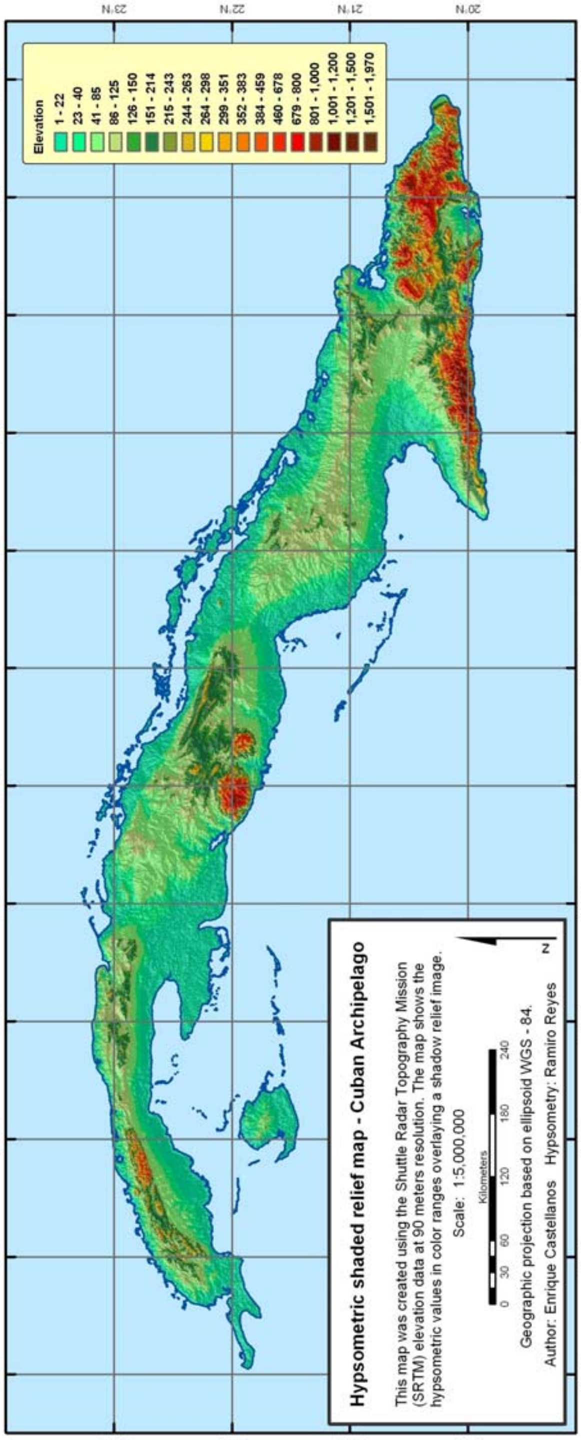

Figure 4.5. Hypsometric shaded relief map of Cuba using SRTM elevation data.

The undefined values are generally produced by three main causes: shadows, water bodies and instrument noise. By analyzing the voids in the Cuba Archipelago, these three main causes were found. The water surface generally produces very low radar backscatter. Undefined values were located in small inland water bodies (mostly reservoirs or artificial lakes), lowland coastal areas (usually swamp or marsh zones) and steep slopes in mountain areas (certainly due to shadows). The undefined values were located in a total of 13,916 isolated areas; where the largest area is 18.6 km^2, but almost half of those areas (6,749) only have one pixel. Another interesting feature is that the negative values and voids did not appear together.

Different approaches available (Koch et al., 2002; Ludwig and Schneider, 2006; Pierce et al., 2006) for eliminating the undefined values were tested and the better results were found when applying an 'iterative' average filter (Castellanos, 2005). In this method, an average filter is applied as many times as needed to 'close' the undefined areas. For Cuba STRM data, thirteen neighbourhood averaging iterations were needed to complete the filling of inland areas. Once the undefined values were removed the final SRTM DEM was used to produce a hypsometric shaded relief map in WGS84 at 1:1,000,000 scale (Figure 4.5). The map was produced using ArcGIS 9 and was used as the base georeference for all other indicators and results maps in this study. The hypsometric limits were defined by Reyes (2004) based on the histogram changes in the elevation data. The results identify the main mountain systems within Cuba where landslide are most likely to occur as explained later. It is also recognizable the relationship between the current relief and the previous geological processes. The DEM derived from SRTM data in the Cuban archipelago provide possibilities in many geomorphometric applications besides landslide hazard.

Slope angle indicator

Slope angle values were calculated from the SRTM data with a 90-m spatial resolution using the maximum downhill slope angle method (Hickey, 2000), which constrains the slope angle calculations to one cell length (or 1.4 cell lengths in the diagonal) in a downhill direction. The maximum slope angle obtained was 70°, and the mean value was 3.16 (5.54 SD). The slope angle histogram shows a break in the shape after 3°, and 80.14% of the land surface has a slope angle between 0 and 3°. The areas with higher values, about 22,016 km^2, represent the main mountain systems and isolated hills spread over the plains. For standardizing the slope angle values between 0 and 1, a concave curve equation was estimated from the original values. The mid point of the curve was created at 35 degrees, corresponding to 0.667 in the 0 to 1 scale. The resulting standardized map is shown in Figure 4.6a.

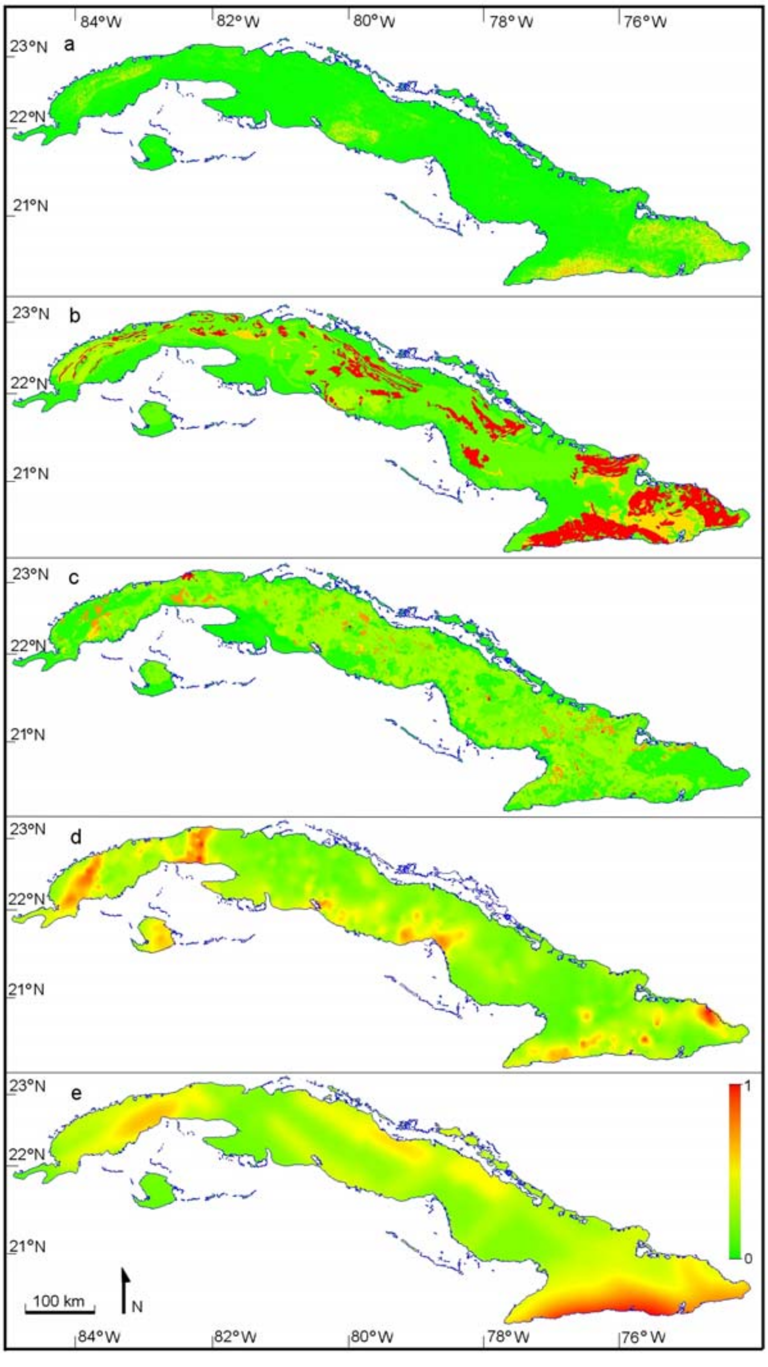

Figure 4.6. Hazard indicators standardised to 0–1 range: a slope angle, b geology, c land use, d maximum rainfall expected in 24 h and e maximum peak ground acceleration.

Land use/cover indicator

The land use map used in this study was digitised from the National Atlas of Cuba at 1:1,000,000 scale (Rodríguez, 1989). The three main land use types of Cuba are forest, uncultivated land and sugar cane crops (Table 4.3). Forests occupy most of the mountainous areas and are often full with minor crops, coffee-cacao plantations and cultivated pastures. Unfortunately, the most recent available data are from 1989, and land use percentages will have changed since then. However, the main trends have remained the same. Only the percentage of the area with sugar cane crops has changed significantly since 1989 because of the official closure in May 2002 of about 70 out of 154 sugar cane mills in the country. Because of that, a substantial part of the land was re-oriented to pastures or minor crops, but the new land use distribution map has not yet provided by the physical planning organisation. The extension (26%) of the uncultivated shrubland, which is susceptible to erosional and gravitational processes, is remarkable. For assigning weights the land use classes were ranked according to their susceptibility to landslide (Table 4.3) without taking into account any other aspect such as slope angle. The ranking considers the urban area as the most important and then the other land uses where the soil may be more exposed to superficial processes such as minor crops, tobacco and uncultivated land. The ranking order was based on discussion with experts and on the known occurrence of landslides. The standardisation values are produced by the rank ordering method (Janssen and Van Herwijnen, 1994) implemented in the SMCE module provided by ILWIS. The resulting standardized map is shown in Figure 4.6c.

Table 4.3. Land use classes, their percentage of coverage and the values assigned for standardization Land use data from the National Atlas of Cuba at 1:1,000,000 scale (Rodríguez, 1989).

Landuse	Percentage	Standardization values
Urban area	0.2	1.0000
Minor crops	3.3	0.6990
Tobacco crops	0.4	0.5480
Rice crops	1.6	0.3720
Sugar cane crops	22.1	0.3120
Uncultivated shrubland	26.3	0.2620
Citric Fruit orchards	1.2	0.2190
Pasture	7.9	0.1810
No citric fruit orchards	0.5	0.1470
Henequen	0.1	0.1170
Coffee-Cacao crops	1.1	0.0900
Forests	26.4	0.0650
Water bodies	0.5	0.0420
Swamps	8.4	0.0200

Geological indicator

The geological and structural setting of Cuba is rather complicated, and still much research needs to be done to achieve a complete understanding of its evolution. The region records, in a relative small area, several geological and structural environments, which range from the Late Jurassic to recent times. In general, the geology of Cuba has been subdivided into two principal groups of geological units: a foldbelt and a neoautochthon (Iturralde-Vinent, 1996), which unconformably overlies the foldbelt. The neoautochthon contains mainly sedimentary rocks, which are horizontal or gentle dipping with erosional 'windows' where the foldbelt outcrops. The foldbelt has sedimentary, volcanic and metamorphic rocks in different structural settings like volcanic arcs or ophiolites. They also have diverse weathering conditions and surface processes like karstification.

The geological map used for the generation of the geological indicator was published in the National Atlas of Cuba at a scale of 1:1,000,000 (Formell, 1989) with sixty-eight geological units, which was compiled from a series of maps at a scale of 1:250,000. These sixty-eight units were classified into five levels of landslide susceptibility. The following aspects were taken into account for the classification: known landslide occurrences within geological units, the lithological composition, weathering processes and structural arrangement. The highest landslide-prone units were found in the Eocene (Lower and Middle) with terrigenous and less carbonated materials, a Cretaceous unit with conglomerates and metavolcanogenic material and the ophiolite complex composed mainly by serpentines and peridotites. Weights ranging between 0 and 1 were assigned to the five units using the rank-ordering method (See Table 4.4 and Figure 4.6b).

Table 4.4. . Geological complexes, their descriptions and the values assigned for standardization.

Geological complex	Number of geological units	Description	Standardization values
A	5	Highly weathered and fractured rock formations including ophiolites.	1.00000
B	5	Middle Eocene units with sandstones, conglomerates, clays and marls weathered and fractured.	0.56522
C	6	Utramafic rocks tectonically affected, lutites, calcarenites and aleurolites	0.34783
D	36	Diverse lithologies in rock formations well preserved and less influenced tectonically.	0.19565
E	16	Massive and compact units, quaternary deposits in flats areas. Highly resistance volcanic rocks.	0.08696

Triggering factors: precipitation and seismicity

Apart from the three aforementioned conditional factors, also two triggering factors were taken into account: precipitation and seismicity. Precipitation is the main triggering factor for the landslides recorded in the landslide inventory database. Precipitation in Cuba is often caused by extreme events such as hurricanes or tropical storms. For that reason, we analysed two datasets: the storm tracks for the period 1851–2003 (NOAA, 2006) and the raster map of the probabilistic maximum daily rainfall expected within a 100-year return period. From the storm tracks, it is possible to recognise spatial patterns in coastal zones where most of the tropical storms have their landfall, which are mostly in the south and southeast. The probabilistic estimation of the maximum expected rainfall used 835 rainfall stations with data from 1970 up to 1990 (Planos et al., 2004). The values range from 126 to 846 mm as the maximum rainfall expected over a period of 24 h for a 100-year return period. There is strong spatial relationship between storm tracks zones and maximum rainfall expected, with the exception of the south-eastern part of Cuba. In this region, the most devastating historical hurricane Flora had its landfall in 1963. However, in contrast, the north-eastern corner of the island has the highest values of expected rainfall but without storm tracks, and the rainfall in this area (around Baracoa) has a strong relief control. For the standardisation of the rainfall values to the range of 0 to 1, the maximum linear method was used, which standardizes the input values by dividing them by the maximum value possible (846.32 mm in this case; see the output map in Figure 4.6d).

The seismic hazard in Cuba and its surrounding areas was characterised in detail by García et al. (2003). Although there are no seismically induced landslides recorded in the incomplete national landslide inventory, previous research had mentioned the relationship between old landslides and seismic activity (Portela et al., 1989). The maximum peak ground acceleration (PGA) with a 100-year return period was used as an indicator map in this study (Figure 4.6). Because of the tectonic plate boundary at the southeast to Cuba, this area presents the highest seismic hazard. Other important zones are located in the south-eastern part of Pinar del Río province (western Cuba) and in the north central part of the archipelago. The PGA values obtained for Cuba ranges between 0.064 and 0.423 g with a mean of 0.17 (0.06 SD). For standardizing the PGA map, the maximum linear method was used. The resulting map is shown in Figure 4.6.

4.3.3. Vulnerability indicators

The selection of vulnerability indicators was made after analyzing similar work in literature (Coburn et al., 1994; Leone et al., 1996; International Federation of Red Cross and Red Crescent Societies, 1999; CEPAL and BID, 2000; Commission on Sustainable Development, 2002; Manoni et al., 2002; van Westen, 2002; Barbat, 2003; Glade, 2003; UNPD, 2004). Initially, a total of forty-three vulnerability indicators were considered at the national level in this study, and the Cuban National Statistics Office (ONE) was asked to provide information on these indicators. However, because of the fact that not all information could be provided by the ONE office and the high correlation between several of the initially selected indicators, the total number was reduced to five key indicators: housing condition and transportation (physical vulnerability indicators), population (social vulnerability indicator), production (economic vulnerability indicator) and protected areas (environmental vulnerability indicator). The indicators are based on polygons related to political-administrative areas, which are mostly at the municipal level.

Housing condition indicator

The housing condition is a major problem in Cuba mainly because of the low level of maintenance, and in 2003, about 40% of the houses were estimated to be in bad or poor condition (INV, 2005). Because the number of houses has a high correlation with population (which is already used as the social vulnerability indicator), we found it more relevant to use the annual data about housing conditions. Unfortunately, data on housing condition was only available at the provincial level, and it was not possible to disaggregate these for the 169 municipalities. In this study, a housing condition index was developed with the following equation:

$$Housing\ Index = \frac{B_{Good}}{(B_{Regular} + B_{Bad})} \qquad \text{[eq.2]}$$

Where B_{Good}, $B_{Regular}$ and B_{Bad} are the number of houses in good, regular or bad condition according to the survey of 2003. The indexes close to '1' mean that half of the houses are in good condition. Table 4.5 gives the housing condition index for the Cuban provinces. The values were standardised inversely using a maximum linear method, in which provinces with a low housing condition index are more vulnerable than those with higher values. The resulting standardised map is presented in Figure 4.7d.

The values of the housing condition index in Table 4.5 reflect recent natural disasters that have impacted Cuba, and the provinces with higher indexes are those that suffered cyclone disasters in recent years and where many houses were completely rebuilt or repaired (e.g. hurricanes Michelle, Isidore and Lily, which affected the provinces of Matanzas, Pinar del Río and Isla de la Juventud in 2001 and 2002). On the other hand, the provinces with the lowest housing index, with less than 50% of their houses in good condition, are those located in the eastern part of Cuba (Granma, Holguin and Guantánamo provinces), which have not been recently affected by large scale disasters. The limited resources available for housing in Cuba are mostly directed to disaster recovery and not to a continuous housing development programme.

Transportation indicator

The national road and railway systems were digitised from the National Atlas of Cuba (Interián, 1989) and the density of road and railway lines per square kilometre was calculated in km/km^2. In the cities, only the main roads were taken into account, as the inclusion of all streets would lead to extreme density values.

The maximum road density was 4.093 km/km2, and as expected, the higher values are distributed close to the capitals of each province. Mountainous municipalities, with more potential landslide hazard, have lower values because they have fewer kilometres of road and railway with national relevance. An exception is the Guaniguanico mountain system in the western region of Cuba, where the municipalities have a more developed road system. For the national road network, the average is very low (21 km/km2), but when the whole road network of the country is included, this parameter increases considerably. All of the results were standardised using the maximum linear method. The standardised map is shown in Figure 4.7e.

Population indicator

Population density was selected as the main indicator for social vulnerability. Municipal population data were obtained from the ONE (2004). Population density in Cuba varies from two persons/km2 in Ciénaga de Zapata municipality up to 2,878 in Havana city, with an average of 119.34 persons/km2.

The municipalities can be separated into four groups based on their population density. Municipalities with a very low population density are usually associated with natural resource areas like swamps or marshy coastal zones (e.g. Ciénaga de Zapata, Río Cauto and Esmeralda). The largest group of municipalities has a population density ranging from 50 to 200 persons/km2, whereas the third group includes mainly the provincial capitals with densities of 200 to 600 persons/km2. The fourth group consists of the municipalities in Havana City with more than 2,000 persons/km2. To avoid the disproportionately large population density in Havana City, a concave curve-standardizing method was used, with an inflection point at 1,325 persons/km2. The standardised map is shown in Figure 4.7a.

Table 4.5. Vulnerability information at provincial level. Left: Housing condition index (based on data from INV, 2005). Right: Total production in 2003 per province (ONE, 2004).

Province	Housing Index	Total production (in million US $ in 2003)
Isla de la Juventud	3.18	164
Guantanamo	0.82	626
Santiago de Cuba	1.41	1100
Granma	0.73	1034
Holguin	0.82	2279
Las tunas	1.15	550
Camaguey	1.3	1234
Ciego de Avila	1.6	489
Sancti Spiritus	2.57	620
Cienfuegos	2.9	1033
Villa Clara	1.13	1505
Matanzas	2.92	1636
Ciudad de Habana	2.19	1747
La Habana	1.97	1604
Pinar del Rio	2.16	889

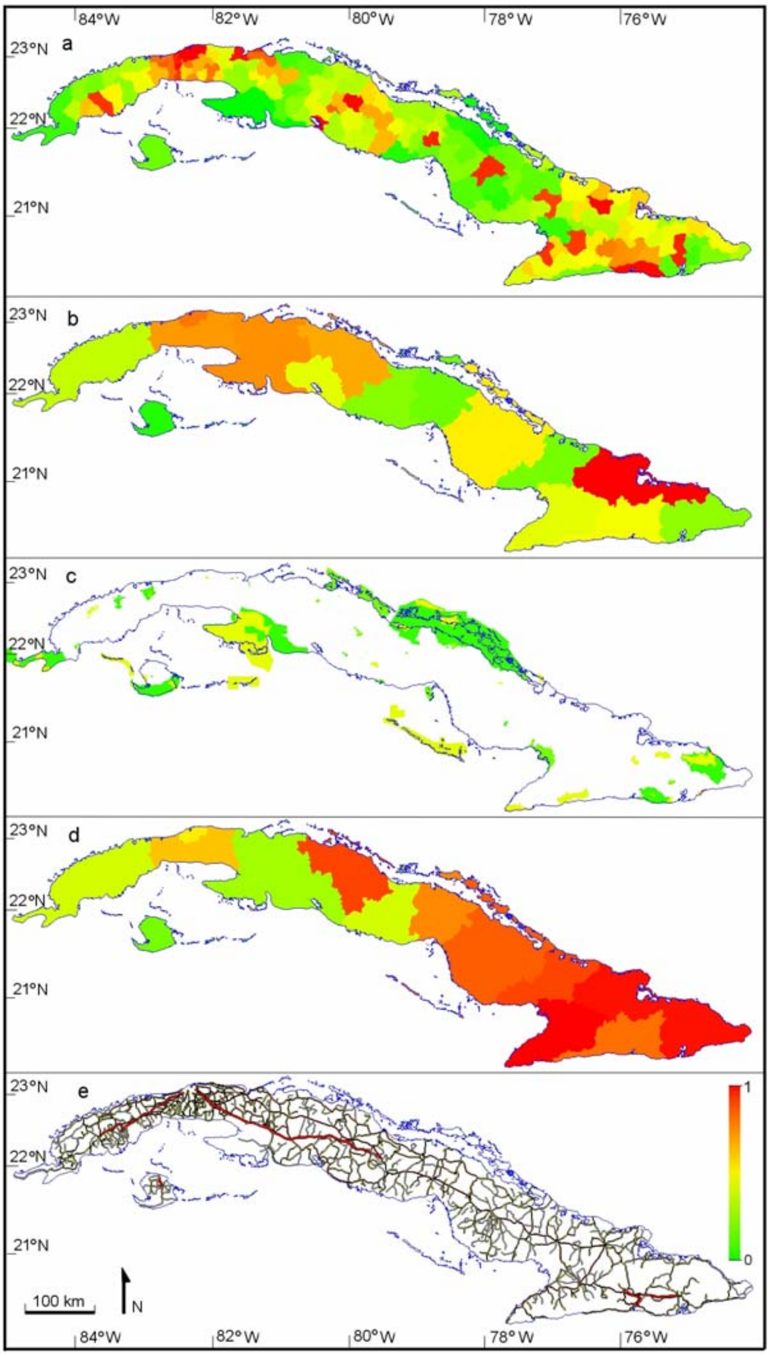

Figure 4.7. Vulnerability indicators standardised to 0–1 range: a population, b production, c protected areas, d housing condition and e road system (for clarity of this figure, the zero values are displayed in white in this figure).

Production indicator

According to the ONE, it was not possible to use the gross domestic product per municipality as indicator for economic vulnerability because of the lack of data. Furthermore, physical production values were not completely available, even at the provincial level. Instead, the total production (which include the market) indicator was used as an indicator in this study (ONE, 2004) at the provincial level (see Table 4.5). The production shows that provinces with important tourist resources like Matanzas or with principal industries like nickel in Holguin have higher values. The standardisation of this information was done using the maximum linear method. The standardised map is shown in Figure 4.7b.

Protected areas

The protected areas within the country were used as an indicator for the environmental vulnerability. The information on these areas was obtained from the World database on Protected Areas (IUCN, 2004). According to the World Conservation Union, protected areas are organised in seven management categories (IUCN, 2004), which represent their environmental significance from category Ia (Strict Nature Reserve) up to VI (Managed Resource Protected Area).

Cuba has eighty-one protected areas (SNAP, 2006), and most of them are in three main categories (Figure 4.7c): twenty-eight in category II (National Park), twenty-nine in category IV (Habitat/Species Management Area) and sixteen in category VI (Managed Resource Protected Area). Most of these protected areas are located in coastal zones. In the mountainous zones, there are several national parks, such as Viñales in the western part and Alejandro de Humbolt in the eastern part of Cuba, with a considerable number of recorded landslides. The areas were standardised using the ranking method with an expected value option. Through this method, the parks are linked according to their degree of environmental vulnerability, ecological uniqueness and fragility. The resulting standardised map is shown in Figure 4.7c.

4.4. Results and discussion

After the selection of the indicators, their standardisation and the definition of indicator weights, the analysis was carried out using an ILWIS GIS script to obtain the composite index maps and the final landslide risk index map (Figure 4.8). The summary statistics of the risk index map is highly influenced by the large number of pixels with zero values. Without considering zeros, the risk index values range from 0.022 to 0.620 with a mean of 0.18, a median of 0.170 and a predominant value of 0.097 (see Table 4.6). These values are low because of the multiplication of the intermediate maps of Hazard and Vulnerability, which were made using the weights as shown in Table 4.2.

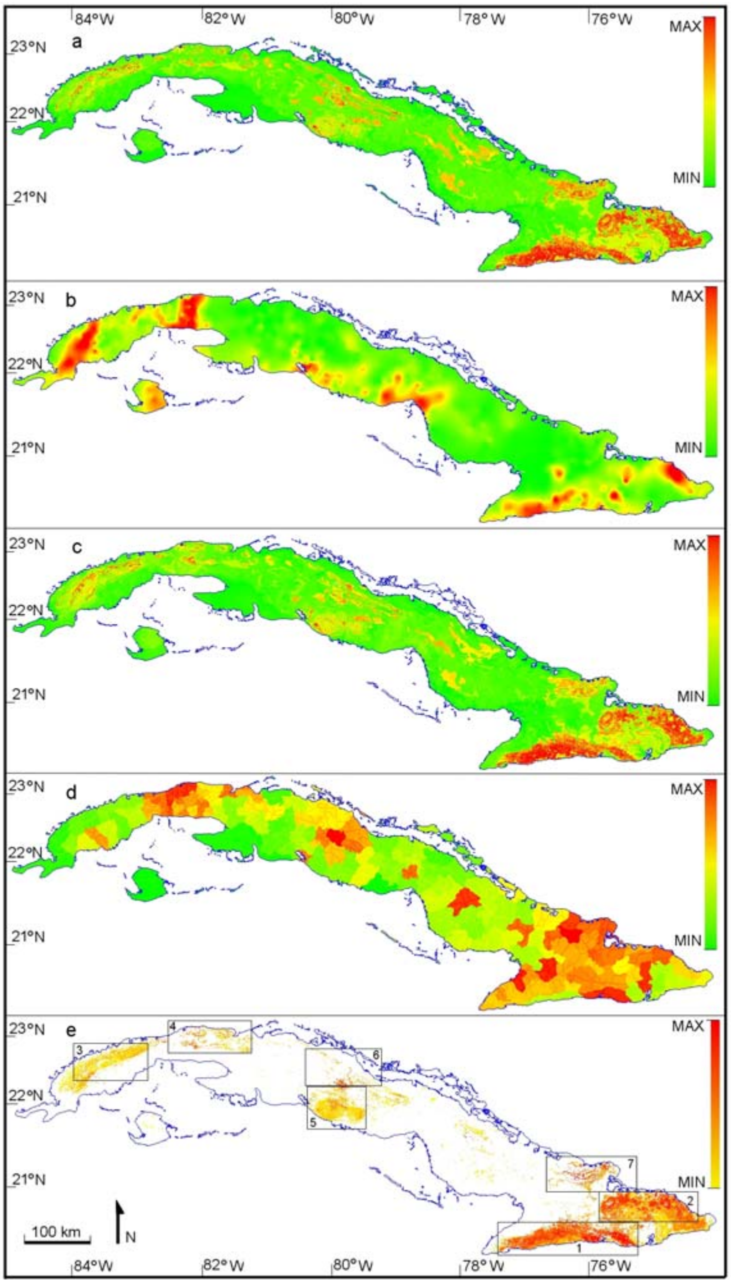

Figure 4.8. Maps used for calculation the landslide risk assessment. a Composite index map of conditions, b Composite index map of triggering factors, c Composite hazard index map, d Composite vulnerability index map and e final risk index map. All maps are represented from the minimum and maximum values according to Table 4.6.

The histogram, ignoring the zero values, which account for 80.14% of the total area of the risk index map, shows a bimodal pattern (Figure 4.9). By analysing each indicator and sub-goal in the model, we identified that the hazard component played more relevant role in the risk equation, specifically the conditions sub-goal. The boundary between the two modal curves is located approximately at 0.18. Below this number, conditions are mainly due to slope angle, and above this number, conditions are more due to geology and land use. In many areas, the highly susceptible land use types coincide with high susceptibility geological units, e.g. ophiolites and the forest.

The landslide risk index map shows the spatial distribution of the relative risk values for the entire country. It is possible to recognise the areas with higher values and to query the database of indicator maps to search the causes of these higher values as a backwards analysis. Because of the characteristics of the available datasets, it is not possible to avoid polygon boundaries especially with the vulnerability indicators related to administrative units, the geological units and the land use types. In order to conduct a more detailed study, the risk index values were analysed physiographically and administratively at provincial and municipal level.

Physiographic landslide risk analysis

As can be observed from Figure 4.8e, the landslide risk index in Cuba is the highest in seven physiographic regions. Indicated in order of decreasing landslide risk, these are: (1) Sierra Maestra–Gran Piedra, (2) Nipe–Cristal-Baracoa, (3) Guaniguanico, (4) Havana, (5) Macizo Guamuhaya, (6) Santa Clara and (7) Northwest of Holguin. Small isolated areas with higher risk index values were found in other places such as in the north of Camagüey province, but they do not actually represent a physiographic region, although they will be taken into account in the provincial and municipal analysis. A brief explanation of each region is given below.

Table 4.6. Summary statistics of the landslide risk index map and the intermediate maps of vulnerability and hazard values.

Maps	Summary statistics					
	Minimum	Maximum	Mean	Median	Predominant	Std. Dev.
Risk	0.0(0.022)	0.620	0.04(0.18)	0.0(0.170)	0.0(0.097)	0.08(0.09)
Vulnerability	0.172	0.940	0.45	0.421	0.210	0.15
Hazard	0.0(0.102)	0.848	0.07(0.36)	0.0(0.353)	0.0(0.281)	0.15(0.13)
Factors	0.170	0.946	0.35	0.321	0.269	0.11
Conditions	0.026	0.896	0.18	0.124	0.134	0.14

The values between brackets are based on exclusion of zero values.

The Sierra Maestra mountain system (area 1 in Figure 4.8e) is the largest area in Cuba with high landslide risk values. This is mainly caused by the very high hazard values of the hazard indicators, such as steep slope angles, sedimentary and volcanic rocks highly susceptible to landslides combined with a high earthquake hazard. The vulnerability indicator values are low for this region, as compared with other areas, although they increase in the vicinity of Santiago de Cuba because of increasing population density and economic activities. The region also contains many (pre-) historic landslides that are mainly rotational rock slides with large volumes (Iturralde-Vinent, 1991).

The Nipe–Cristal–Baracoa (area 2 in Figure 4.8e) is a large geological and tectonic complex consisting of ophiolite and metamorphic rocks with intense weathering processes. This region has the highest risk values in the Sierra de Nipe and Sierra Cristal, caused by both high values for hazard and vulnerability. The steep slopes in serpentinites or peridotites and the high rainfall amounts are responsible for high hazard index values, whereas the high economic value is due to the nickel mining industry, and the presence of environmental protected areas make this region more vulnerable. The landslides in this region are due to mining activity and poor land use practices and are associated with intensive rill and gulley erosion.

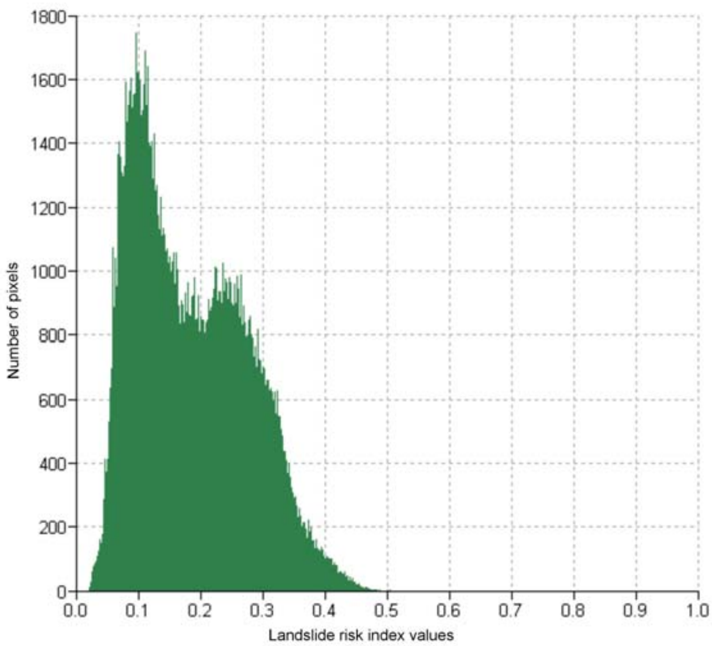

Figure 4.9. Histogram of landslide risk index map ignoring zero values.

The Guaniguanico mountain system (area 3 in Figure 4.8e), in western Cuba, has also a considerable area with high landslide risk index values, but they show a more disperse spatial pattern as compared with the two regions presented above. High risk values are concentrated on steep slopes of the most western part, and they are more disperse in the eastern part, where susceptible lithological units are occurring on steep slopes and in regions with fairly high rainfall amounts. In this region, intensive karstification occurs in different types of limestones and carbonated sandstones, which often leads to toppling, rockfall and subsidence features.

Although Havana city (area 4 in Figure 4.8e) is not located in a mountainous region, it still contains a number of areas with high landslide risk values. This is mainly because of the combination of moderate hazard values with very high vulnerability values, caused by the high highest population density and concentration of economic activities. Landslides in this region are normally small because of the geomorphological conditions, but their consequences can be significant.

The Macizo Guamhuaya region (area 5 in Figure 4.8e) has also some areas with high landslide risk index values, which are mainly located close to a large dam (Hanabanilla). The high values here are due to the presence of weathered metamorphic rocks and steep slopes. Another zone with higher risk index values is the region of Villa Clara province (area 6 in Figure 4.6e), which is another region with more economic activities and higher population densities, especially in Santa Clara and the surrounding municipalities of Placetas and Camaguaní.

The northwest of Holguín province (area 7 in Figure 4.8e) has concentrations of higher landslide risk values. The risk values are dispersed according to the geomorphology of the region. Although the geological units here are considered to have moderate landslide susceptibility, the steep slope angles and higher vulnerability values, caused by the more densely populated Holguín municipality result in moderate to high risk index values.

Provincial analysis

Figure 4.10 displays the final landslide risk index map as it was presented to the National Civil Defence in Cuba. It also contains information of risk index levels for different administrative units. As disaster management in Cuba is normally carried out by administrative units, the landslide risk index values were analysed also for the provinces and municipalities. For that, the risk index map was classified in three classes to make the analysis simpler for the Civil Defence. Based on the analysis of the histogram and on the spatial distribution of the risk index values, three classes were selected: low risk (with index values of 0); moderate risk (with index values between 0 and 0.18) and high risk (with index values larger than 0.18). These threshold values were derived in an interactive way, by evaluating the areas classified under different thresholds and comparing these with the known landslides and with the knowledge of the authors on main landslide regions. Table 4.7 provides the percentage of each province covered with different landslide risk index values.

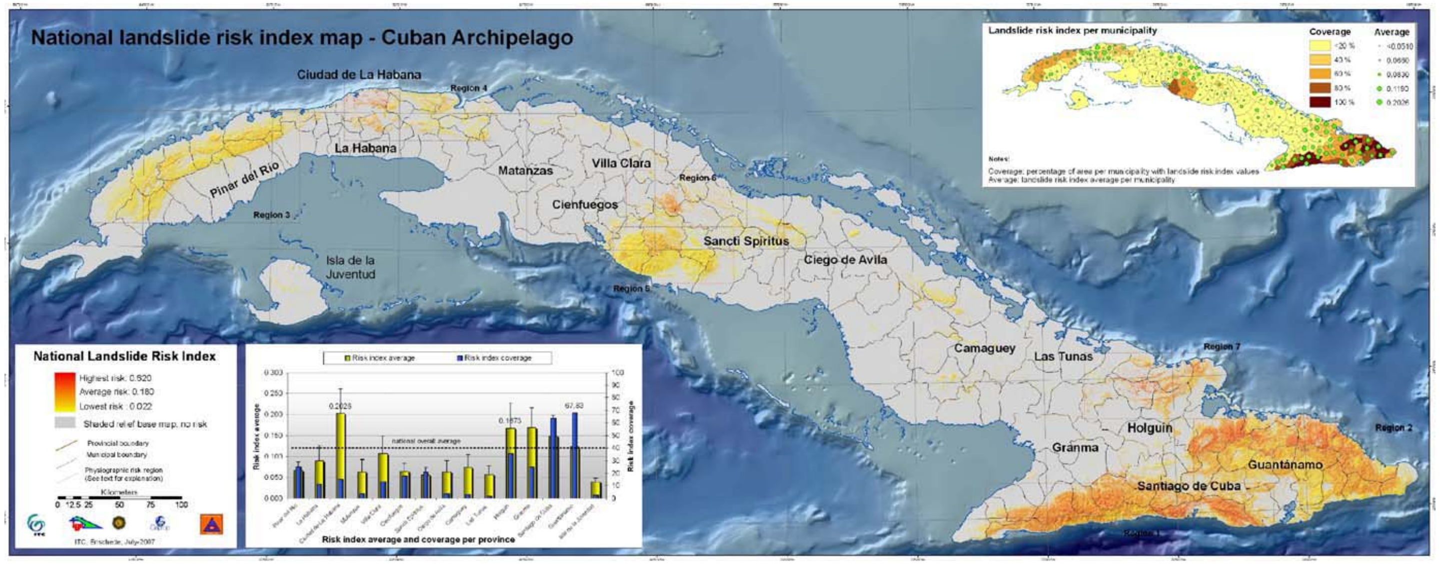

Figure 4.10. Final landslide risk index map, as presented to the National Civil Defence authorities. Inset map in the upper right corner indicates the landslide risk index per municipality, both as the percentage of area with landslide risk index larger than 0 (coverage) as well as the average landslide risk index. The bar chart shows the landslide risk index values per province.

In Table 4.7, it can be observed that four provinces have more than 20% covered with high risk values: Holguin, Granma, Santiago de Cuba and Guantánamo. They are all located at the eastern part of Cuba. It is also remarkable that the Ciudad de La Habana province has more than 10% of high risk index values. These provinces should be a priority for developing detailed studies of landslide hazard and risk. In the eastern provinces the risk index values are dominated by the hazard component, while in the capital, the risk is more due to the vulnerabilities indicators. It is also important to recognise that in the eastern part, the risk index values also relate to the percentage of mountainous area. For example, Guantanamo province has a 31% of high risk index values but also has large flat areas like Guantánamo valley surrounding the main bay. Furthermore, Granma has a large area that belongs to Cauto river floodplain.

Table 4.7. Percentage of each province with low, moderate and high landslide risk.

Province	Low risk	Moderate risk	High risk
Pinar del Rio	74.77	24.07	1.16
La Habana	88.58	8.37	3.05
Ciudad de La Habana	84.83	4.47	10.70
Isla de la Juventud	97.37	2.63	0.00
Matanzas	96.50	2.97	0.52
Cienfuegos	81.95	17.75	0.30
Villa Clara	86.68	8.56	4.76
Sancti Spitritus	79.05	20.47	0.48
Ciego de Avila	96.51	3.19	0.30
Camaguey	96.89	2.94	0.17
Las Tunas	98.46	1.40	0.14
Holguin	64.30	9.57	26.13
Granma	74.68	3.58	21.75
Santiago de Cuba	35.89	14.26	49.84
Guantánamo	31.61	37.24	31.15

Municipal analysis

The analysis at municipal level reflects, in more detail, the results of the provincial analysis. Following the same classification of low, moderate and high risk, the landslide risk index map was combined with a map of the 169 municipalities. Because of the scale of analysis and the small area of the fifteen municipalities in Ciudad de La Habana, they appear in the map as one polygon. Figure 4.10 shows the risk index values displayed together with the municipal boundaries. There are thirty-six municipalities without high risk values, eighty-three municipalities with 0 to 10% high risk, thirty-eight with 10 to 50% and twelve municipalities with more than 50% of high landslide risk.

Furthermore, here it is clear that the eastern part of Cuba is occupied by moderate and high risk index values. Ciudad de La Habana municipalities and the centre of the country have moderate risk index values. The municipalities with more than 50% of high risk values are listed in Table 4.8. They are the primary targets for carrying out landslide risk assessments at local level.

4.5. Conclusions

Only a few examples have been presented in the literature of landslide risk assessments at a national scale. On the other hand, several countries have published national landslide susceptibility maps that are based on their national landslide inventory (Brabb et al., 1999; Guzzetti, 2000). However, in Cuba these activities are still in an initial stage, and as such a landslide inventory covering the entire country is not available. Therefore, it is not possible to re-classify the landslide inventory map according to municipalities, provinces or physiographic units, to obtain the landslide hazard map, which is one of the two required components of the national landslide risk map.

The starting point for the design of the national landslide risk assessment methodology was the consideration of the user's needs. The main user in Cuba is the National Civil Defence, who would like to have information at different administrative levels (i.e., municipal, provincial, national) of the level of landslide risk and information how this varies through time, in order to define areas for further more detailed studies.

Table 4.8. Ranking of the 12 municipalities with the highest percentage of landslide risk.

Municipalities with more than 50 % of high risk	Percentage
III Frente	89.46
Guisa	79.96
Buey Arriba	76.88
Santiago de Cuba	70.86
Moa	68.69
Baracoa	66.00
Bartolomé Masó	65.34
Guamá	62.57
Pilón	60.83
Imías	55.16
Sagua de Tánamo	53.96
Mayarí	53.88

The following elements were identified as most relevant for designing a landslide risk assessment model at the national level: analysis of the existing landslide inventory, the selection of the most relevant factors for a hazard assessment, the selection of the most relevant socio-economic indicators for the vulnerability assessment, the availability and reliability of data on these indicators and the overall objectives of the risk assessment (Figure 4.1).

The model for the generation of a national landslide risk index for Cuba was made following an iterative semi-quantitative procedure, based on an expert-based SMCE. Due to the absence of a reliable landslide inventory (which would allow the use of a statistical method and the fact that running physical models at a national scale is not feasible) weights were selected based on expert opinion. Although this method is subjective, it allows the incorporation of expert opinion and the use of group decision making, and therefore leads to reliable results, given the scale.

Semi-quantitative indicators were found to be more suitable, with the indicators and the resulting landslide susceptibility, vulnerability and risk maps all expressed in a scale from 0 to 1, to allow better representation of the spatial variability in the data. Only the final risk map was classified into qualitative classes of high, moderate and low. In order to prevent confusion with probabilities obtained in the quantitative approach, the estimated risk value was called 'landslide risk index'.

The spatial multi-criteria analysis started with an initial large number of forty-three indicators, which was narrowed down to ten in the final analysis. For many of the initially selected indicators, the data were insufficient or incomplete at the required level for the entire country. The spatial units for which the indicators were collected also varied, from individual cells of 90×90 m, in case of morphometric information, related to the resolution of the SRTM digital elevation model, to thematic units, in the case of geology or land use, or municipalities and provinces in the case of the socio-economic data. For example, information on the housing conditions was only available at the provincial level, whereas the best would be to have this available at municipal level or even linked to polygons defining the villages and towns.

A number of indicators were removed from the analysis because they showed very high correlation with others, which would complicate the analysis as similar patterns in different indicator maps would be amplified and the result would become exaggerated. An example of this is the use of both a population density as well as a housing density indicator. Careful analysis of every indicator leads to a better understanding of its contribution to landslide risk assessment. A good example of this was the analysis of the spatial relationship between the cyclones paths and the rainfall intensity.

The resulting landslide risk index is not a static one, as a number of indicators have a temporal variability, and the landslide risk index map should therefore be updated regularly. Similarly, the model equation could be improved by adding new indicators, once more data becomes available, and by fine tuning the standardisation and weight values. Depending on further requests from the end user, the model can also be made more complex and made at a higher spatial resolution.

Nevertheless, it is important to mention that much more research still needs to be done related to the visualisation of the risk and the measurement of its effectiveness for the decision makers. However, it is the view of the authors that studies like this with few modifications can be developed in many other countries as an initial screening process in order to analyze landslide risk at the national level.

Analysis of the results allows to evaluate landslide risk according to physiographic or administrative units.

The use of landslide risk index statistics for provinces and municipalities is useful for ranking them in order of importance for landslide risk reduction measures. The method allows evaluating which of the indicators is responsible for high risk index values. Local (provincial and municipal) authorities can now be warned about the landslide risk that their areas are facing, and because they are part of the civil defence system in Cuba, they can also allocate resources for a local landslide mitigation programme. The city of Santiago de Cuba ranks at the top of the landslide risk index list of municipalities as this densely populated area is located along the Sierra Maestra mountainous system.

Finally, this study was one of the first steps in the national landslide risk assessment programme of Cuba, and it is necessary to follow it up with larger scale studies. Among the highest priorities are the establishment and maintenance of a national landslide database and a national landslide mitigation plan. The national landslide mitigation plan sets the research priorities in landslide mapping, monitoring and assessment and proposes the guidelines for awareness, education and capacity building.

CHAPTER 5

Provincial landslide risk assessment

Based on:
Castellanos Abella, E.A., van Westen, C.J., Melchiorre, C. 2008. Combining computational models for landslide hazard assessment of Guantánamo province, Cuba. Geomorphology (accepted – on review)

Cited as:
Castellanos Abella, E.A. 2008. Provincial landslide risk assessment. In: Castellanos Abella, E.A., Multi-scale landslide risk assessment in Cuba, Utrecht, Utrecht University, 2008. ITC Dissertation 154, 101-152 p. ISBN: 978-90-6164-268-8

5. Provincial landslide risk assessment

5.1. Introduction

Landslides are one of the most hazardous types of events occurring in the Guantánamo province of Cuba. Unlike other mountainous areas in Cuba (where landslides often remain unnoticed) the authorities in Guantánamo are very well aware of the threat that landslides pose in their province. However, their perception of landslides is still limited, as hazard, vulnerability and risk assessments have not yet been undertaken. Since hurricanes over the last two decades have mainly affected the western part of the country, the hazard awareness in the eastern part has been low. Fortunately, the national civil defence organization enforces a yearly review (and updating) of disaster reduction planning and evacuation exercises. Risk analysis is however only performed intuitively by the authorities through a very basic overlay of hazard zones with areas that have important economic activities and population densities. In order to provide a better tool for disaster risk management a more comprehensive landslide risk assessment at 1:100,000 is proposed herein.

The proposed method starts with a comprehensive landslide inventory, then analyzes in detail the hazard and vulnerability indicators before carrying out the assessment. The diversity and complexity of geomorphic processes in the province made the analysis much more complicated from a hazard point of view. Different spatial analysis techniques were applied in GIS to generate hazard maps for the various landslide types, and specific risk maps were made for specific combinations of hazard type and elements at risk. The resulting 'specific risk maps' were combined in two ways: using spatial multi criteria analysis, and using the risk formula.

As with the other scales, the objectives for risk assessment at the provincial level have to be taken into account from the beginning. The management of a province is regarded as a 'middle level' responsibility in the political and administrative framework of Cuba, as its disaster risk management responsibilities are a combination of co-ordinating and executing tasks. At provincial level, there are a number of resources (in terms of materials, finances, equipments and human capacity) which the authorities can employ for disaster risk management. Almost all national ministries have some form of representation at provincial level, such that there is representation both at central level and at provincial government. Considering this framework and existing regulations, the objectives of the civil defence for landslide risk assessment at provincial level are:

1. Identify areas where landslide events have occurred and characterize them with as much detail as possible.
2. Locate areas in a provincial territory with a higher risk, and identify the main causes in terms of hazard and vulnerability indicators.

3. Inform provincial representatives of national ministries and municipal civil defence authorities about the potential landslide risk in their respective areas, with the aim that they include landslide risk in their disaster risk reduction plans.

4. Make agreements with provincial representatives of national ministries, industries, enterprises and social institutions, on the required measures of prevention and preparation, in order to cope with the identified risk in their respective areas.

5. Approve and implement (in agreement with all parties) a disaster reduction plan at provincial level which includes plans for detailed studies in the identified areas of higher risk, and the implementation of measures to reduce the risk..

Considering these objectives and the theoretical background explained in Chapters 2 and 3, the purpose of the study at a provincial scale was to design a method for landslide risk assessment that takes into account the requirements and available data at this level, such that it may be tested in the Guantánamo province. The framework of the method is presented in Figure 5.1.

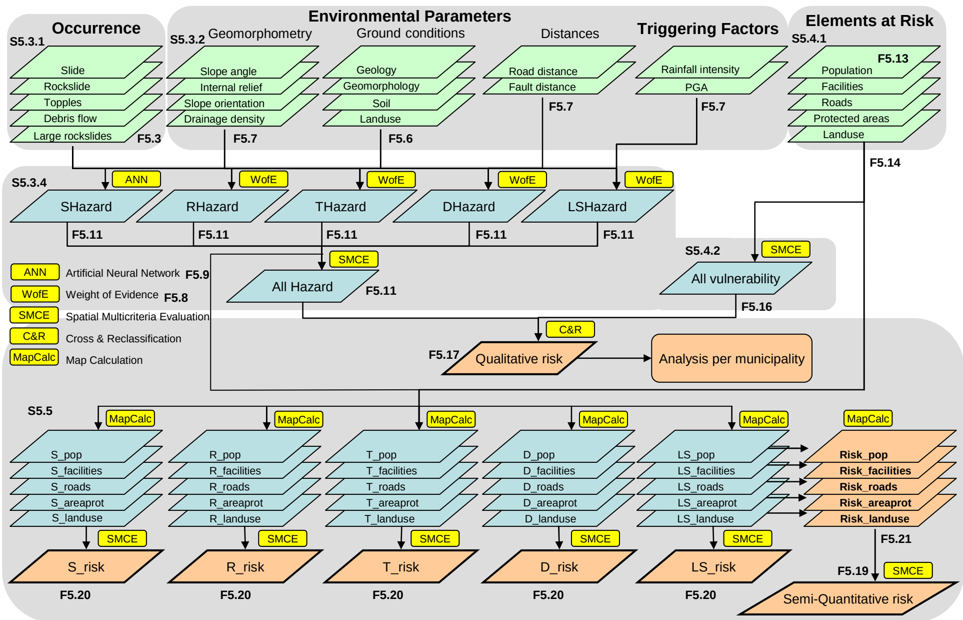

Figure 5.1. Flowchart for landslide risk assessment at provincial level. The abbreviations in the figure refer to the following aspects: D: Debrisflows, R: Rockfalls, S: Slides, ST: Large rock slide and T: Topples. ANN: Artificial Neural Network, WofE: Weight of Evidence, C&R: Map crossing and reclassification. The numbers in the figure starting with 'S' refer to the sections and with 'F' refer to figures in this chapter.

Since the risk assessment started from the data collection for hazard and vulnerability assessment, many steps were carried out as illustrated in Figure 5.1.

The upper part of Figure 5.1 represents the data collection for this study (data collection for landslide inventory is treated in section 5.3.1). The description of both the environmental factors and triggering factors, which together determine the hazard are treated in section 5.3.2, whereas the vulnerability indicators are discussed in section 5.4.1. The middle part of the figure shows the hazard, vulnerability and qualitative risk assessment procedures. Hazard assessment is carried out individually for each landslide type, either using Artificial Neural Network analysis, or Weights of Evidence Modelling (see section 5.3.4). Vulnerability indicators presented in section 5.4.1 are integrated using spatial multi criteria analysis (discussed in section 5.4.2). The semi-quantitative risk assessment is represented in the lower part of the figure. The resulting specific risk maps were combined in two ways: using spatial multi criteria analysis and using the risk formula (see section 5.5). The study was based on raster analyses at 50m resolution taking into account the cartographic rule of a maximum detail of 0.5 mm at the scale of the final map (1:100,000 scale in this case), resulting in maps with 2475543 pixels. However, before describing those sections, a short explanation about the Guantánamo province is given.

5.2. Case study area: Guantánamo province

Guantánamo (which means 'the land of the rivers' in the pre-colonial language) is the most eastern province of Cuba with a surface area of 6186 km^2, comprising 5.5% of the national territory. The population is 511,224 (ONE, 2004), which is 4.6% of the national population (Figure 5.2). Guantánamo is surrounded by the provinces of Santiago de Cuba, and Holguin (in the western and northern part) and by the Caribbean Sea and the Atlantic Ocean in the South and East. About 75% of the area is mountainous with the highest point of 1,181m, located in the Maisí municipality in the East. Most of the northeast part is mountainous while the southwest is covered by a large valley, which also forms a separate hydrographic basin draining into Guantánamo bay. The northeast basin is drained by the Toa River, which has the highest discharge in Cuba. Other physiographic characteristics are discussed in section 5.3.1 and 5.3.2. In terms of climate, Guantánamo contains both the most humid (in the North) and driest (in the South) zones in the Country (see section 5.3.2).

The province has 10 municipalities (represented with green dots in Figure 5.2) and 386 settlements from where 18 are considered urban (see section 5.4.1). Almost half of the population (49.4%) is female, and the working population is 28.7% of the total population. The infant mortality rate is 7.9% and life expectancy from birth is 77.59 years for females, and 74.13 years for males (ONE, 2004). Healthcare and education in the Guantánamo province is widely available, as with the rest of the country. There are 210 inhabitants per doctor, and the province has 17 hospitals. Around 99.5% of the children in the age group of 6-14 years are in one of the 859 schools, many of which are rural and located in hilly areas with very small class sizes. For example, during primary school the average number of students per teacher is 9 (ONE, 2004).

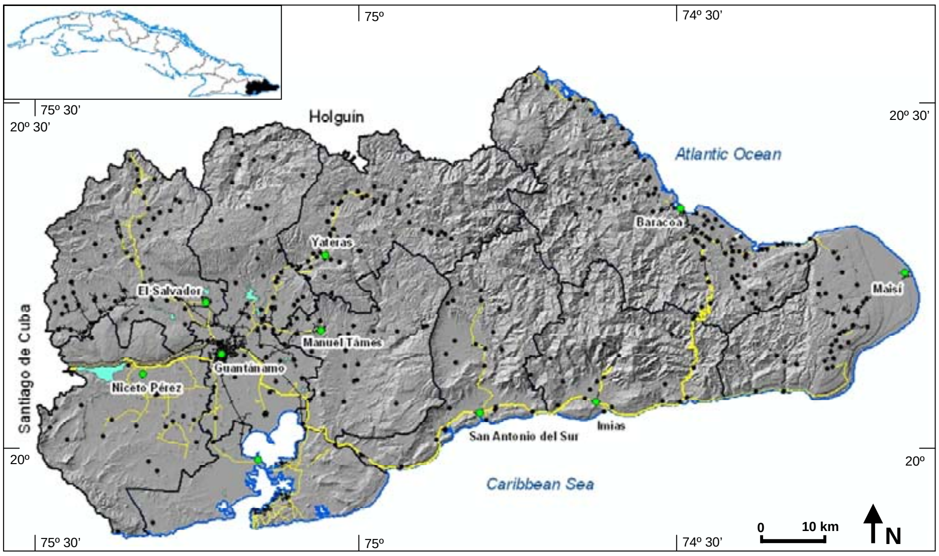

Figure 5.2. Location map of Guantánamo province, where the green dots are the head of the municipalities, and the black dots are other settlements. All black lines denote municipality boundaries, whereas all yellow lines denote main roads.

Agriculture is the most important economic income for the province and is based on sugar cane, coffee, cacao, wood and coconut. The last four are cultivated in mountainous regions, and there are 258 economic entities in the province (ONE, 2004) including 99 enterprises. The industries include an iron foundry, and factories for coffee, agricultural tools, furniture, food, sugar cane and salt.

Regarding disasters, Guantánamo has the national record of 49 devastating hurricanes measured over the period 1789-2003, which are more frequent in September and October (ONE, 2004). Natural and man-made forest fires are also a major concern. Since 1997 to 2002 there were a total of 93 fires that were reported, which affected an area of 3043 hectares. Other disasters, like landslides are rarely recorded in the official statistics.

5.3. Landslide hazard analysis

5.3.1. Landslides in Guantánamo province

The provincial landslide hazard, vulnerability and risk assessment started with a detailed landslide inventory. At the beginning of this study there was no specific record on any landslides in the area, although the disastrous landslides in Jagüeyes de Caujerí during hurricane Flora in 1963 is well known. In 1991, a book was published that contained one chapter with an inventory of landslides in the sea-facing slopes of the coastal hills in the South by the Institute of Tropical Geography of Cuba (Magaz et al., 1991). In this research, the different geomorphological characteristics of the area were revealed and the landslide types occurring in the marine terraces were described. For the landslides surveyed, six morphometric measurements were recorded that included: length of the head scarp, maximum depth, average width, average slope, total volume and number of marine terraces destroyed. As a conclusion, the authors associated the landslide occurrence in the coastal hills to the Pliocene-Quaternary earthquakes, but did not explain how they reached this conclusion.

In 1998, a research project (at a scale of 1:100,000) was undertaken in order to map the principal hazardous geological processes in the eastern part of Cuba (Castellanos et al., 1998). In the framework of the project, the main types of landslides were identified, and inventory and hazard maps were produced. The hazard map was made using multivariate statistical analysis also indicated as a 'data driven method' (Soeters and van Westen, 1996). Lack of experience in landslide photo-interpretation, and problems associated in having a complete causal factors dataset, made a review of the results necessary.

For the present study, landslides were photo-interpreted in 300 aerial photos (format 23 x 23cm) from the year 2000 at a scale of 1:25 000 that covered the entire Guantánamo province. The photo-interpretation was transferred from the photos to base maps and then digitized. The landslide boundaries were crosschecked using two Landsat ETM+ satellite images from 2001-03-08 (path 010, row 046) and 2001-02-27 (path 011, row 046). The information from band 8 (with 15 m spatial resolution) was used as it provided the highest spatial resolution and contrast of the sensor. The crosscheck made it easier to differentiate landslides that were showing signs of activity (mainly presented by unvegetated surfaces) from the ones that were completely vegetated. Unfortunately no multi-temporal image interpretation could be carried out, which made it difficult to establish the age of the landslides. A spatial database was produced including information on size and type of the landslides. The database also contained twelve landslides that were reported by the local civil defence authorities during the fieldwork campaign. Other characteristics of the landslides (e.g., activity) were not described, as it was not possible to identify at this level of analysis during the photo-interpretation. Finally, a map was produced that included the landslides, the two orthorectified Landsat TM images, and several cartographic elements such as roads, topographic names, etc. This map (see the supplementary CD-ROM) was presented to the provincial authorities as the first step in reducing landslide disaster risk.

Due to the large size of the province, the small scale of the study, and the relatively small size of most of the landslide events, the actual landslide area could not always be digitized to scale. This was especially true in the case of rockfalls, topples and debrisflows events, as the source and depositional areas could not always be separately displayed. Also, some landslide events were very small and difficult to map while others were very large and could even be subdivided into smaller units. The representation of landslides which have been active over various time periods also posed a problem at this scale. This had some implications during the analysis which will be discussed later.

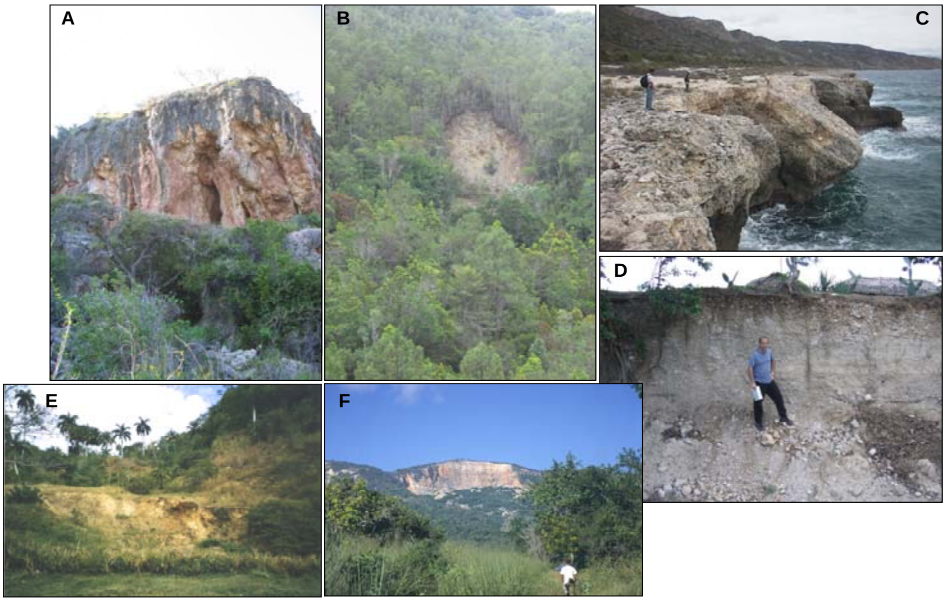

Figure 5.3. Examples of landslides in the Guantánamo province. A: marine terraces with rock fall in the southern coast. B: translations rockslide in Sierra del Purial. C: Coastal rockfall in San Antonio del Sur. D: debris flow in Caujerí valley. E: Rockslide in Baracoa, F: Jagüeyes landslide in Sierra de Caujerí.

Figure 5.3 shows some examples of landslides in the Guantánamo province. In total, 281 landslides were identified covering 7971 pixels (about 19.92 km^2). From this inventory, four main types of landslides were determined including 22 rockfalls (517 pixels), 26 debrisflows (501 pixels), 18 topples (510 pixels) and 215 slides (6443 pixels). Further analysis showed that slide-type movements were basically of two genetically and morphometrically different types: a group of 29 larger rockslides (3356 pixels) located in a tectonically affected area in the Sierra de Caujerí, and a group of 186 smaller slides (3087 pixels) that were all dispersed over the province. Although topples are defined as a landslide type (IGME, 1987; UNESCO-WP/WLI, 1993) and some other research has been conducted on this type of movement (Nichol et al., 2002; Parise, 2002; Tamrakar et al., 2002; Andriani et al., 2005; Duman et al., 2005), it may also be considered as an initial step towards a rock fall. In this study, toppling events were considered separately as they are can be identified by a series of detached blocks on a slope, separated by tension cracks or small scarps without necessarily fell down. A toppling movement may culminate in an abrupt falling or sliding but the type of the movement is tilting without collapse (Varnes, 1978; Dikau et al., 1996). Statistical analysis revealed that the size of all landslides varies from 7982 m^2 up to 941,142 m^2 with an average of 70989 m^2. The frequency distribution of landslide area by landslide type (Figure 5.4) shows a distribution similar to other landslide inventories (Malamud et al., 2004). Due to the small number of events per type (except for slides) the dataset was not sub-divided into events with different magnitude.

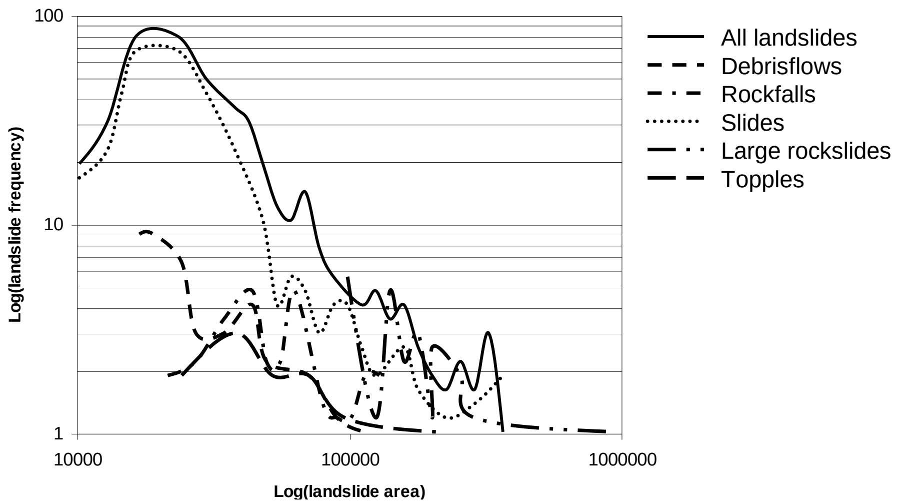

Figure 5.4. Graph for area and frequency of landslides in the Guantánamo province. Area in m^2.

5.3.2. Indicators for landslide hazard

A total of twelve potential causal factors were selected, after evaluating the literature (Carrara et al., 1991; Soeters and van Westen, 1996; Guzzetti et al., 1999) and the data available in Cuba. They were divided into fours main groups: ground condition factors, distance related factors, geomorphometric factors and triggering factors. These factors are presented in Figure 5.5 and Figure 5.6 and their location in the methodology in Figure 5.1.

Landuse as an indicator is used for both the hazard assessment (as it is considered one of the important causal factors) and the vulnerability analysis (to evaluate the damage caused by landslide to different crops). As there are five types of landslides the relationship between each indicator and landslides is very diverse. Therefore, this relationship is explained in section 5.3.4 per specific landslide type. In order to find the relationship between distance (such as distance to road) and geomorphometric indicators (such as slope) with landslides, classes maps where created using the quantiles classification in ten classes. This classification is exploratory and assumes no previous knowledge between the indicator and the landslide.

Ground condition factors

Ground condition factors are those that represent characteristics of the ground condition in which landslides might take place, related to the geomorphology, geology, soils and landuse.

- The geomorphological map at a scale of 1:100 000 was created from the national geomorphological map at 1:1,000,000 of the National Atlas of Cuba (Portela et al., 1989). The digital boundaries were superimposed on stereo-images generated from the digital elevation model and different band combinations from satellites images. Interactively, these boundaries were adjusted, and in some cases more detailed units were made, based on the same legend. The geomorphology of the Guantánamo province is very diverse (Figure 5.5A). The map contains ninety seven areas within thirty four legend units of mountains, hills and plains of different types and genesis (Annex 5.A in the supplementary CD-ROM). The mountains are the most extensive, as they cover 64% of the surface. According the classification of Cuban relief the mountains have been divided in low mountains (1,000-1,500m), small mountains (500-1,000m), pre-mountains, and sub-mountains (300-500m) (Portela et al., 1989; Díaz et al., 1990).
- The geological factor map was obtained from the Institute of Geology and Palaeontology (IGP). The map was supplied in CARIS GIS format (CARIS GIS, 2007) with legend and styles according to the Geological Information System of Cuba called SIGEOL (Castellanos et al., 2003). In order to mosaic the ten maps covering the province, editing and polygonization was carried out in the ILWIS, and then the whole map was exported to ArcGIS. The Guantánamo province has 44 geological units (Annex 5.B in the supplementary CD-ROM) distributed in 621 polygons (Figure 5.5B). A total of 45.5% of the province is only covered by three units: San Luis Formation with 1051.6 km^2 distributed mainly in the western part, Sierra del Purial Formation with 907 km^2 mostly located in the east, and Maquey Formation with 860.1 km^2 mainly outcropping in the central part of province. Each of the other units covers less than 6% percent of the territory.
- The landuse map was obtained from the Institute of Physical Planning (IPF). It was digitized, edited and polygonized in ArcGIS. The Guantánamo province has 16 landuse types distributed in 633 polygons (Figure 5.5C). A total of 55% of the territory is covered by natural forest and 14% by natural pasture. The rest of the territory is covered by sugar cane, coffee and cultivated pasture and grassland as shown in Table 5.1. The landuse does not show very dynamic changes, but there is a tendency is to gradually increase the forested area. Besides, the sugar cane lands have largely been decreased after many sugar factories were closed in the middle of the 90s.
- The soil map used was obtained from the Soil Institute (Mesa et al., 1992). It was digitized, polygonized, and linked to a database. Each unit is classified by a combination of a Group, a Sub-Group, and parent material ('genus'). The Guantánamo province has 45 unique combinations of soil map units distributed in 101 polygons (Figure 5.5D). The predominant soil map unit (21% of the area) is the Tropical Greyish Calcareous formed from limestone, marls, and carbonated detrital material. No other soil map units cover more than 10% of the area; those with most area are the 'Typical Greyish Tropical

Saline', the 'Greyish-Red Calcareous' and the 'Typical Saline'. Most of the soils are less than 30cm deep, which is relevant for landslide occurrence.

Table 5.1. Landuse types in the Guantánamo province. Further explanation of the column 'Vulnerability weight' will be given in section 5.4.1.

Landuse	Area (km^2)	%	Vulnerability weight
Natural pasture	875.02	14.14	0.1810
Fruit orchards	59.58	0.96	0.1470
Natural forest	3426.45	55.37	0.0650
Different crops	112.49	1.82	0.6990
Pastures and grassland	424.44	6.86	0.1810
Sugar cane crops	472.80	7.64	0.3120
Fallow land	181.48	2.93	0.2620
Coffee plantations	376.64	6.09	0.0900
Citric orchards	43.22	0.70	0.2190
Cacao plantations	114.95	1.86	0.0900
Lake or water body	32.35	0.52	0.0420
Urban areas	56.00	0.90	1.0000
Newly developed urban area	2.84	0.05	0.9889
Forest plantations	4.33	0.07	0.0650
Tobacco crops	5.52	0.09	0.5480
Banana plantations	0.78	0.01	0.0200

Distance related factors

Another group of potential causal factors are those that relate to the distance of a feature that might have influence on landslide occurrence. Two of these were taken into account: roads and faults.

- As road construction in hilly or mountainous terrain is often a causal factor for landslide occurrence, a buffer map was created showing zones adjacent to roads. The road map was obtained from the digital topographic map at a scale of 1:100,000, which was produced by the national cartographic agency, Geocuba. The edited vectors include: highways, first and second order roads, streets in populated zones, unpaved and enhanced-unpaved roads, trails and tracks, wide and narrow railways (Figure 5.6H).
- Tectonic factors play relevant role in producing landslide in some cases. In order to explore the spatial relation with landslide the fault map of the province was used. The faults were obtained from the Geological Information System of Cuba (SIGEOL) recently designed and implemented (Castellanos et al., 2003). Different faults types were used including: inferred faults, certain faults, supposed faults, thrust faults and reversed faults. A distance map was created (Figure 5.6G).

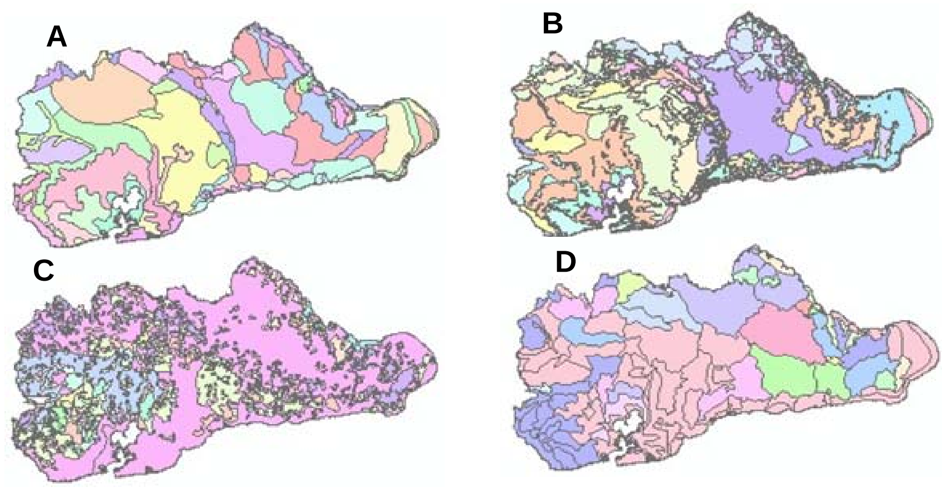

Figure 5.5 Hazard indicators. A: geomorphology, B: geology, C: landuse, D: soil. Due to size of the area and the complexity of the legends the maps are represented out of scale (see text for explanation).

Geomorphometrical factors

The digital elevation model (DEM) of the province was created in ArcGIS using the tool 'topo to raster', which considers different data sources in the interpolation process such as: elevation points (usually geodetic points), contours lines, drainage network, sinks, lakes or water surfaces and the limit of the area. During the process, sinks were identified and those erroneously created were removed interactively until the process was successfully completed. From the DEM, with a spatial resolution of 50 metres, 4 geomorphometric parameter maps were extracted: slope steepness, slope orientation (aspect), internal relief (vertical dissection), and drainage density.

- The slope angle map was divided into ten classes by quantiles. Due to the large pixel size and the slope calculation algorithm used, the maximum slope angle was 48 degrees (Figure 5.6D), which occurs in the side slopes of the marine terraces in the coastal zone of Maisí, the main river valleys and the ridges of some mountain system such as the Sierra de Caujerí.
- The slope orientation (Aspect) map contains eight classes representing the main compass directions (north, northeast, east, etc), and one class for flat areas. The slope direction classes have more or less the same frequency with a slight tendency for south facing slopes (Figure 5.6A).
- Internal relief or vertical dissection considers the height difference per unit area. This map (Figure 5.6B) was created in ArcGIS by first obtaining the minimum and maximum elevation per hectare using a 'moving filter'. Then the height difference was calculated for each pixel. The maximum internal relief in the province was 636.6 m/ha and the average was 152.2 m/ha (105 SD). The areas with higher values are located at the edge of the terraces and in the

mountain ridges. The Sierra del Purial was the physiographic region with highest internal relief values.

The drainage density map was obtained from the detailed drainage vector map that was made by the EMPIFAR Company, including all natural and artificial drainage networks. The length per unit area of drainage lines that fall into a specific search radius of one square kilometre for each pixel was calculated. The drainage density map (Figure 5.6C) shows concentrations of high values in specific zones, especially in the eastern part of Sierra del Purial and other mountain zones. The average value was 2.94 km/km² (0.97 SD) and the maximum was 6.7 km/km².

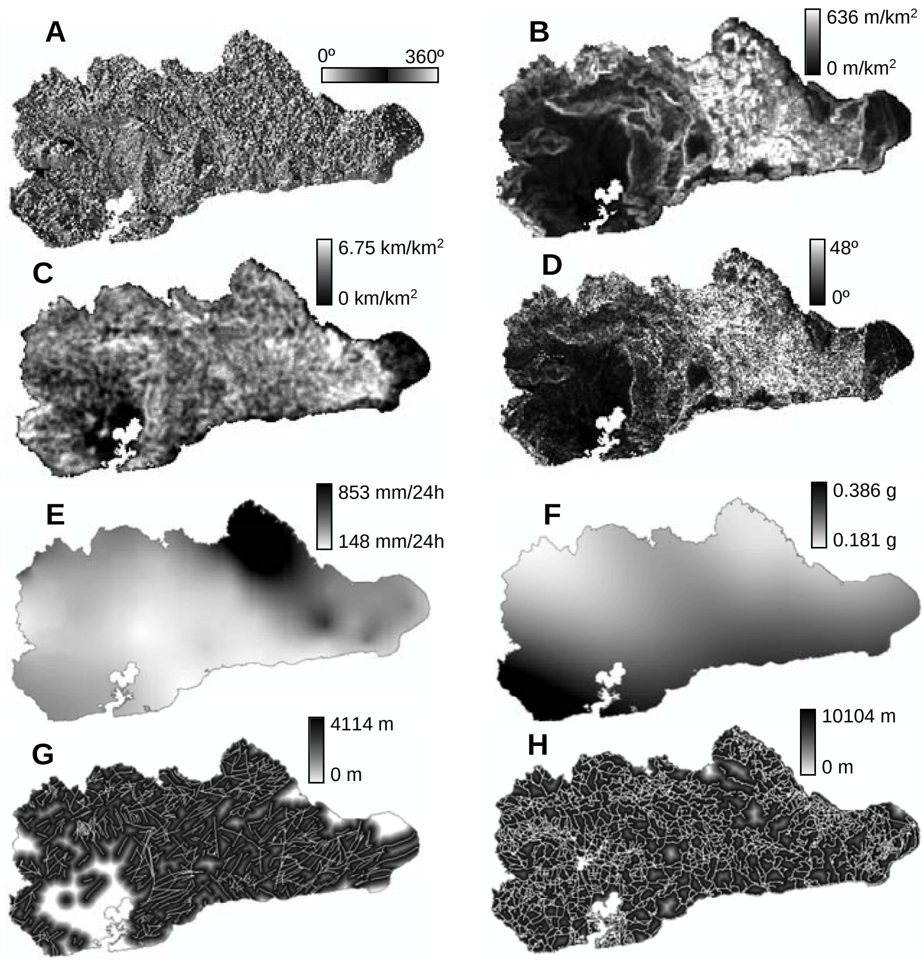

Figure 5.6. Hazard indicators. A: aspect, B: internal relief, C: drainage density, D: slope angle, E: rainfall intensity, F: ground peak acceleration, G: fault distance and H: road distance.

Triggering factors

Apart from the aforementioned environmental factors, the spatial variation of two triggering factors was used in the landslide hazard assessment: rainfall and earthquakes.

- A raster map of maximum expected rainfall in 24 hours for a 100 year return period was obtained from Planos et al. (2004). This map was made for the whole country, but for the provincial analysis it was cut and resampled. The values range from 148.6 to 853.96 mm/24h with an average of 301.6 mm/24h (127.77 SD). Figure 5.6E shows a high contrast between the northern and southern parts of the province. Rainfall in the northern part, close to Baracoa, usually comes from the northeast (Atlantic region) and is controlled by the relief. The mountains in the central eastern part serve as a barrier for rain clouds and the area south of that is a semi-arid zone.
- The second triggering factor was a map of the peak ground acceleration (PGA) with 100 years return period obtained from García (2003). In this region, the PGA values (Figure 5.6F) are highly influenced by the Caribbean-North American plate boundary located south of the province and by the high seismic activity zone south of Santiago de Cuba city. Intra-plate seismic activity has also been recently detected in the mountainous part of the Guantánamo province.

5.3.3. Methods for susceptibility and hazard analysis

As part of the hazard analysis, two methods were applied for estimating the spatial probabilities of landslides occurrence: Weights of Evidence (WofE) modelling and Artificial Neural Networks. Before selecting these methods, a detailed heuristic analysis was carried out in order to recognize the spatial relationship between the factors and the landslides. The authors do not intend to give a comprehensive explanation on these methods since there are many publications on these subjects (Bonham-Carter, 1996; Arora et al., 2004; Lee et al., 2004; Kanungo et al., 2006; Neuhauser and Terhorst, 2007). In this section the reasoning behind the selection of the methods and the data preparation are briefly explained.

Basic estimation of weights and heuristic analysis

The first step was to estimate the prior probabilities of each specific type of landslide in the province. Guantánamo province has an area of 6188.85 km^2, corresponding to 2 475 543 pixels of 50 by 50 m. The calculated prior probability values were very low, due to the very large area of the province as compared to the relatively small area of the landslides. For example, the prior probability for rockfall is only 0.0002088. Other landslide types have similar low prior probability values: 0.0002060 for topples, 0.0002024 for debrisflows, 0.001247 for slides and 0.0013557 for large rockslides.

The second step was to prepare the twelve factors maps for the analysis, which were described above. The factor maps with classes (geology, geomorphology, landuse and soil) were rasterized at 50 m per pixel. The continuous value maps (slope angle, aspect, internal relief, drainage density, fault distance, road distance, maximum rainfall, and maximum acceleration) were converted into ten classes maps using statistical quantiles. After this, the map with the five landslide types was overlaid (crossed in ILWIS terminology) with the twelve factor maps. As a result of each overlay operation a joint frequency table (or crosstable) was obtained with the areas occupied by each landslide type for all factor classes. The statistical processing of these tables allowed the extraction of the density of each of the five landslide types for each of the classes of the twelve factor maps, which were used as the basic information for the susceptibility analysis, and which were compared with the prior probabilities discussed above. For example, the density of rockfall events in geological unit 13 (Fm. Rio Maya) was calculated (see Annex 5.C in the supplementary CD-ROM) by dividing the number of pixels of rockfall events in this unit by the total number of pixels in this unit (in this example 256/73 145=0.00349, which is almost 17 times higher than the prior probability). This calculation allowed us to evaluate the importance of each of the classes of the twelve factor maps, for the spatial prediction of the five landslide types. See the supplementary CD-ROM for a list of results for all five landslides types.

After generating the landslide density, relative weights were calculated, expressed as the ratio between landslide density in the class and the landslide density in the entire map. All classes with density ratios substantially higher than 1 were considered relevant for the analysis, because they have higher frequency than the regional average. The higher the ratio, the higher is the weight of the class in the susceptibility model. For the example of rockfall and the Fm. Río Maya the resulting density ratio is 0.00349/0.00021 = 16.76. After calculating this weight value for all classes, two estimators were applied to quantify the importance of the factors, namely the 'accountability' and the 'reliability' (Greenbaum et al., 1995a; Greenbaum et al., 1995b). The former calculates the percentage of the total landslide population accounted by each factor as:

$$Accountability = \frac{\sum Npixsld1}{\sum Npixsld} \quad \text{[eq.1]}$$

Where *Npixsld1* are the landslide pixels in those classes of the factor map having weight values larger than 1, and *Npixsld* are the landslide pixels over the entire study area. The reliability is defined as the percentage area of the variable corresponding to landslides, and it is computed for each variable as:

$$Reliability = \frac{\sum Npixsld1}{\sum Npixcls} \quad \text{[eq.2]}$$

Where *Npixels* are the landslide and non-landslide pixels in the classes with weights larger than 1. Both indicators provide different but relevant results to predict landslides, although reliability is more important (Greenbaum et al., 1995a; Greenbaum et al., 1995b). Based on this type of analysis, it is possible to recognize the relevance of the individual factor classes as possible contributors to landslide occurrence.

The next step is to make a selection of important factors for each type of landslide, by evaluating the weights, accountability and reliability values for each factor and their classes. After analyzing the importance for the occurrence of the five types of landslides, the actual landslide susceptibility assessment was carried out. Two specific methods were used: weights of evidence modelling and artificial neural networks

Weights of evidence (WofE) modeling

The weights of evidence (WofE) modelling (Bonham-Carter, 1996) is a well proven technique for landslide susceptibility assessment, and therefore only a short explanation is given here. Many landslide susceptibility studies have been carried out using this method (van Westen, 1993; Fernández, 2003; van Westen et al., 2003; Lee and Choi, 2004; Lutfi and Doyuran, 2004; Suzen and Doyuran, 2004; Neuhauser and Terhorst, 2007). Essentially, the WofE method is a bivariate statistical technique that calculates the spatial probability and odds of landslides given a certain variable. The method was very well explained with GIS examples by van Westen (1993) and Bonham-Carter (1996). The weight of evidence values estimated for each class are calculated by two weights: the positive weight (W^+) gives the importance of the presence of the class for prediction landslides, and the negative weight (W^-) gives the importance of the absence of the factor for landslide prediction. The positive and negative weights (Wi^+ and Wi^-) are defined as:

$$W_i^+ = \log_e \frac{P\{B_i \mid S\}}{P\{B_i \mid \bar{S}\}} \qquad \text{[eq. 3]}$$

and

$$W_i^- = \log_e \frac{P\{\bar{B_i} \mid S\}}{P\{\bar{B_i} \mid \bar{S}\}} \qquad \text{[eq. 4]}$$

Where,

B_i = presence of a potential landslide conditioning factor,
$\bar{B_i}$ = absence of a potential landslide conditioning factor,
S = presence of a landslide, and
$\bar{S_i}$ = absence of a landslide

The contrast factor, *Cw*, was also calculated. It is expressed as the difference between the weights *W*+ and *W*- and quantifies the predictability of each class. Finally, the positive weights calculated for all the classes of the factor maps that occur simultaneously in a certain location (raster cell), and all negative weights of all the other classes, that do not occur at that location, are added in order to produce the final weight, *Wmap*. The main steps in the GIS-based WofE analysis, which was carried out in a script file, are presented in Figure 5.7.

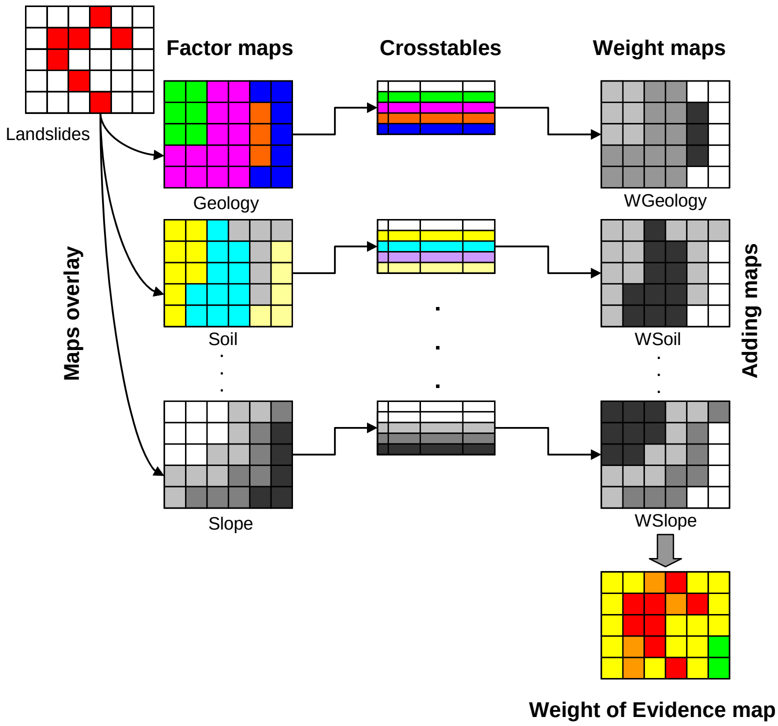

Figure 5.7. Schematic representation of weight of evidence method implemented in GIS.

The landslide inventory map was overlain with each factor map (geology, soil, etc.) to produce joint frequency tables with the number of pixels in each combination of the two maps. Some table calculations need to be accomplished to estimate the weights of evidence for each class and produce the weights maps corresponding to each factor. Finally, the weight maps were added in order to obtain the final weights of evidence map. This map is then again crossed with the initial landslide map in order to calculate the success rate (Chung and Fabbri, 1999).

The method WofE has shown good success rates in many applications including mineral exploration (Carranza, 2002). However, the main drawback of the WofE is that the method assumes conditional independence between variables, which may lead to relatively higher weights in certain areas that do not fit with the landslide data perfectly. However, as mentioned by Bonham-Carter (1996), this method provides a simplification that, when used carefully, is useful for evaluating the relative contributions of the separate factor classes, and allows a good selection of the most relevant factors to be used in the analysis.

Artificial Neural Network (ANN)

One of the relatively new methods applied to landslide hazard and susceptibility assessment is the artificial neural network (ANN). Lee at al. (2003a; 2003b) present examples of case studies in Korea. They also show a combination of ANN for determination of weights used with spatial probabilities to create a landslide susceptibility index map (Lee et al., 2004). Rainfall and earthquake scenarios as triggering factors for landslides have been used in hazard assessment with ANNs (Lee and Evangelista, 2006; Wang and Sassa, 2006). Several studies recognize ANN as a promising tool for these applications and most of them use a Multi-layer Perceptron (MLP) network and a back-propagation algorithm for training the network (Arora et al., 2004; Ercanoglu, 2005; Ermini et al., 2005; Gomez and Kavzoglu, 2005; Wang et al., 2005).

More critical analyses compare ANN techniques with other methods such as logistic regression, fuzzy weighing and other statistical methods (Lu, 2003; Miska and Jan, 2005; Yesilnacar and Topal, 2005; Kanungo et al., 2006). Melchiorre et al. (2006) did further research on the behaviour of a network with respect to errors in the conditioning factors by performing a robustness analysis. While the aforementioned studies used ANN in landslide hazard or susceptibility zonation, Neaupane and Achet (2004) applied ANNs for monitoring the movement.

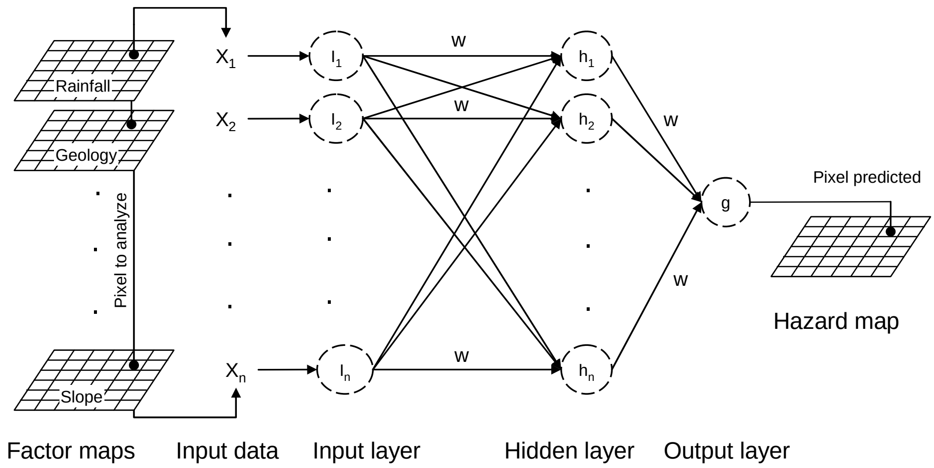

Figure 5.8. Spatial implementation of generalized multi-layer feed-forward ANN scheme. X_1-X_n are input maps for the analysis, I_1-$I_n$are neurons in the input layer, W are weight values, h_1-h_n are neurons in the hidden layer and g is goal neurons or pixel predicted.

ANN is defined as a non-linear function approximator extensively used for pattern recognition and classification (Bishop, 1995; Haykin, 1999). Neurons are the basic units of a neural network. They are organized to compute a non-linear function of their input(s). A neuron receives input(s) with an assigned weight (s), which influence the overall output of the neuron. It is possible to allocate more than one layer of neurons and pass the information and weights from one layer to the next one. The structure of layers, the weights and the connections, known as network topology, determine the behaviour of a network precision (see Figure 5.8).

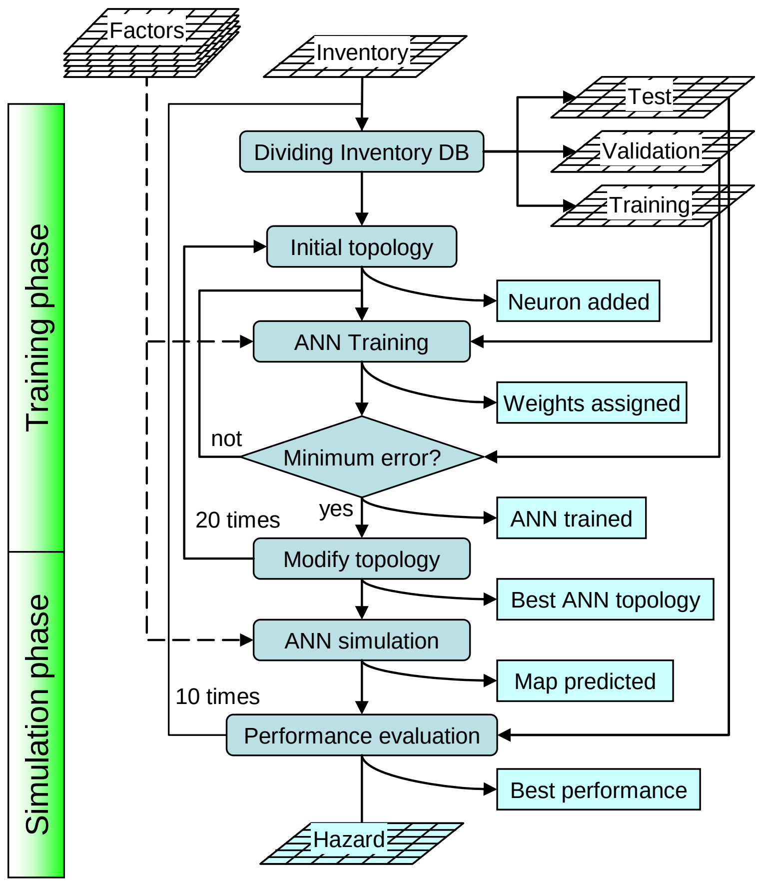

Figure 5.9. General flow-chart for spatial landslide hazard assessment with ANN.

There are several possible network topologies. Figure 5.8 shows a multi-layer feed-forward (i.e., no loops are present) with a 3-layer structure. This topology can approximate any non-linear continuous function and so it is considered to be suitable to evaluate landslide susceptibility. In order to make a spatial assessment of landslide susceptibility, the analysis was carried out using a pixel-based approach. Where, a vector of factor values (x) for each pixel is the input of the network. Initially, the network needs to be trained. During the training phase, the weights are optimised to minimize an error function by applying any back-propagation algorithm (Rumelhart et al., 1986), standard optimization techniques (Press et al., 1992), or a randomized algorithm (Montana and Davis, 1989).

The topology is crucial for the training capabilities: simple topologies make it more difficult to approximate complex functions, whereas an increase of complexity leads to a reduction of generalization capability. There are some techniques used to estimate the appropriated topology and improve generalization. In this study, we used the early stopping technique (Caruana et al., 2000).

Preparing the factors maps is also a relevant task, as ANNs can work with different types of variables such as class maps (like geology) and continuous data (like rainfall) in the same dataset. Since ANNs can approximate any non-linear function, thematic maps such as geology, geomorphology or soil, do not need to be ranked, which is a clear advantage over the WofE method. However, it is recommendable to use some ranking relationship with respect to landslide occurrence (Melchiorre et al., 2007). Another advantage with respect to the weights of evidence method is the possibility to work directly with continuous maps without any need of reclassification. The network is forced to find de relationship between the given classes, or continuous variables and the landslide occurrences. Therefore, the whole process could be divided into two phases: training and simulation (Figure 5.9).

In this study, the analysis was performed by using the Levenberg-Marquardt algorithm (Marquardt, 1963; Hagan and Menhaj, 1994) to train the Multi-Layer Perceptron (MLP) network and the early stopping technique to improve its generalization capability. The landslide inventory database was randomly divided into three subsets: a training set (75% of the landslides) used to optimize the weights, a validation set (12.5%) used to stop the network algorithm before the network starts learning noise in the data, and a test set (12.5%) to evaluate the prediction capability of the network. An equal number of samples were also randomly selected from non-landslide areas. In order to obtain results that were representative of the whole data and not conditioned by a specific subdivision of the dataset, a '10 cross-folder validation procedure' was introduced into the analysis. This procedure consisted of dividing the landslide inventory database ten times in training, validation, and test set. The initial topology (with only one neuron in the hidden layer) and the training set went into the training process. The training was stopped when the error rate on the validation set started to increase. This process was repeated twenty times, increasing one neuron in the hidden layer each time. The ANN topology with minimum error was used in the simulation phase to produce a predicted landslide map.

The ANN performance measurements, used to estimate the prediction capability on the test set, are: sensitivity, specificity, and overall accuracy. The sensitivity is the percentage of correctly classified landslides (i.e., true positive); the specificity is the correct samples classified as 'no landslide' (i.e., true negative); the accuracy assesses the goodness of the classification, since it evaluates the correct samples classified as a landslide or no landslide.

5.3.4. Landslide susceptibility and hazard

The results of accountability and reliability for each indicator are shown in Table 5.2. Geomorphology and geology are predominant factors in most of landslide types. Regarding triggering factors, large rockslides, topples and slides are more associated to PGA values, whereas rockfalls and debrisflows are better predicted by rainfall. The weights of the classes of the twelve factor maps were used to analyze the role of each factor map in predicting the occurrence of the five different landslide types (see the supplementary CD-ROM). For each type, the factors and classes to be included in the analysis were selected, and the best methods (e.g., ANN and WofE) were chosen for the susceptibility assessment. The following sections describe the conceptual models for each landslide type (also see Figure 5.3 for some illustrations of the types).

Table 5.2. Accountability (A) and reliability (R) for each indicator and landslide type in Guantánamo.

	Rockfall		Topples		Debris flow		Slide		Large slide	
Variables	A	R	A	R	A	R	A	R	A	R
Geomorphology	100.00	0.23	100.00	9.02	93.01	3.71	82.44	10.31	97.20	67.80
Slope	92.26	0.02	79.61	1.64	69.66	1.41	80.63	10.05	82.60	11.20
Aspect	76.21	0.02	77.84	1.61	52.69	1.07	57.73	7.23	72.35	9.84
Internal Relief	83.95	0.02	99.41	4.15	83.83	2.10	91.32	12.50	81.76	13.74
Drainage density	97.49	0.07	79.22	2.02	68.46	1.54	60.45	7.54	75.00	11.23
Road distance	89.56	0.02	76.08	1.92	39.32	0.80	69.97	8.73	63.92	8.66
Geology	100.00	0.23	97.06	4.66	85.63	2.19	66.70	8.82	86.86	27.78
Faul distance	70.99	0.01	80.20	1.99	57.29	1.26	93.26	12.68	96.99	15.81
Landuse	99.61	0.03	93.33	1.70	98.00	2.41	92.78	13.18	77.68	12.54
Soil	95.16	0.07	100.00	5.62	94.21	3.44	67.18	10.61	96.90	37.32
Rainfall	100.00	0.05	91.96	4.59	73.45	1.87	64.17	8.00	100.00	43.74
PGA	79.50	0.03	100.00	10.48	66.67	1.35	71.75	8.95	100.00	34.20

Rockfalls

Rockfall events are mostly located in the east, southeast and along the south coast of the Guantánamo province. They are associated with different types of marine terraces, and biodetritic limestones of Jaimanitas, Río Maya and Cabo Cruz formations, but also to small outcrops of marble and crystallized dolomites of the Chafarina formation. The relationship between rockfalls and slope angle is three times higher in slopes with more than twenty three degrees. The internal relief did not show the expected relation, due to the fact that it was created in GIS using a neighbourhood operation with a window of 1 km and therefore the local terrace scarps, where landslides are most frequent were not adequately represented. Rockfalls are also associated with a low drainage density (< 2.58 km/km^2) as they occur in a semi-arid environment mostly due to the physical weathering. Initially, it was considered that rockfalls may be associated with roads cuts, but the analysis showed no statistical relationship. It was also not possible to find a clear relationship with fault distance.

As far as triggering factors are concerned, rockfalls are associated with relatively low values of maximum daily rainfall intensity ranging from 225 up to 300 mm in 24 hours, indicating that sporadic rainfall (chemical weathering) and long dry periods with high solar radiation (physical weathering) play an important role in the limestones for rockfall occurrence. The most important relationship was found with high values of peak ground acceleration, as the area where rockfalls occur is close to the Caribbean/North American plate boundary, which implies a periodical shaking and a slow but continuous uplifting.

Topples

Toppling features exhibit similar relationships as rockfalls, but they predominately occur in the south, along the coast on uplifted fluvio-marine terraces, tectonic-erosive small mountains, with folded and monoclinal structures, with karst phenomena. They are associated with the following geological formations: Cabo Cruz, Río Maya, Yateras and Maquey, composed of detritic, biodetritic and biogenic limestones, marls and, in less proportion, sandstones, clays and limonites. The area is mostly covered by red limestone soils, with natural forest and pastures. For toppling features, the relationship with slope angles is not straightforward. Although the densities increase with higher slope values almost all classes of slope angle have toppling events. The internal relief shows a clear increase in weights with values higher than 211 m/km^2. They are also associated with very low rainfall (0 to 225 mm/24h) and high PGA values (0.2755 to 0.2900 g) which can be explained by their geographic location along the south coast. The drainage density, and roads distance were not considered relevant factors, based on the statistically derived weights, and expert knowledge on their occurrence. The derived weights didn't support the expert assumption that toppling phenomena are very closely related to faulting, probably due to the generalization of the fault types in the buffer zone creation.

Debrisflows

Debris flow features are distributed over several different geomorphological units in the Guantánamo province, but happen most frequently in structural-tectonic hills and mountains with horst and graben structures. Obviously, the accumulational zones of debris flows appear often on alluvial fans. Debrisflows are strongly related to colluvial deposits and also to mafic, ultramafic and granodiorite lithological complexes. The soil relationship was rather diverse with predominant occurrence in tropical black soils and the greyish tropical latosols. The prominent landuse types are natural pasture and natural forest. A positive relationship was found with slope angles (> 18 degrees), with slopes facing east and southeast, and with high values of internal relief. Debrisflows are also associated with moderate values of drainage density and road distance. There was no relationship with the distance to faults, maximum daily rainfall and PGA. Debrisflows events were encountered in very high dry areas as well as in areas with high rainfall amounts.

Slides

Slide type movements, further on referred to as slides, are the most abundant type of mass movements and are distributed throughout the study area. Therefore, their spatial pattern related to geology, geomorphology, soil and landuse is not well defined, which indicates that the same landslide type occurs under different conditions. As a consequence, one single model could not be defined for all cases, and therefore only the main controlling factors are mentioned herein. Many slides are located in small massive mountains or pre-mountains and less common in structural-tectonic hills. The main lithologies related to slides were the ophiolite complex, but they are also found in marine-palustral deposits from Middle-Late Pleistocene. The soils in these lithologies are typical latosols and less evolved latosolic soils on basic and ultrabasic igneous rocks as well as greyish tropical saline and greyish limestone rich tropical soils. The slides happen most predominantly on landuse types such as natural forest and partially cacao plantations. The slides occur in slopes steeper than fourteen degrees with an increasing relationship in higher slopes classes. The slopes facing north to southeast have an increasing amount of slides, and there is a positive correlation between slides and internal relief. However, drainage density, fault distance and road distance do not show any clear relationships with slides. Slides were mostly found in areas with either very high or very low values of maximum daily rainfall, which could be due to two different types of slides. One based mostly on dry conditions with sporadic precipitation and other type characteristic of high rainfall expectance. Regarding PGA, there is no relationship with this type of event.

Large rock slides

Large rockslides were considered as a separate group because they occur under different environmental conditions as small landslides. The rock slides in the Guantánamo province are predominantly related to landforms in the Caujerí fault scarp and in the northern part of Baitiquirí. They contain alluvial and colluvial deposits originated from limestones of Yateras formation located in an area with natural pasture and forest cover. Although large volumes of colluvial materials are present, related to older landslides, the soil formation in this area is shallow and very limited. These slides are strongly related to the highest slope classes facing east and southeast and also to the highest internal relief classes. The large slides are located in areas with low drainage density probably due to the presence of old landslides and karstic phenomena. There are hardly any roads in this area, so these are not considered to be a contributing factor. Although tectonic movements play an important role in the occurrence of these slides, there are many minor faults in the area. However, since no distinction was made in separating the fault types with respect to the distance fault map, no clear relationships have been found. Large rock slides predominantly occur in areas with high PGA values and low values of maximum daily rainfall, even though, they are known to be caused by extreme rainfall during hurricanes, as was the case with the Jagüeyes landslide (see Chapter 7).

Generation of susceptibility maps

Once the contributing factors were analyzed for each landslide type a decision was made to use one of the two methods for susceptibility assessment (WofE or ANN). The weights of evidence method was selected for the generation of the susceptibility maps for debris flows, rockfalls, topples and large rock slides, because for each of them it was possible to outline the main controlling factor classes, and define the conditions under which they occur. However, for slide movements, no clear sets of conditional factors classes could be differentiated. Since the analysis for slides was more complicated it was decided to use ANN for this type of landslide. After the generation of the resulting weight maps for the five landslide types, success rate curves were generated. These curves were also used to classify them into four classes: no susceptibility, low, moderate and high susceptibility. The susceptibility maps are presented in Figure 5.10, and the success rates for each landslide type are shown in Figure 5.11. The numbers of pixels with and without landslides per class are shown in Table 5.4. The success rate for rockfalls, topples and rock slides show very good results, as less than ten percent of the susceptibility maps with the highest scores contain over eighty percent of the existing landslides. This is due to the fact that these events occur under specific conditions in the area, which can be identified clearly based on the combination of specific classes of the causal factor maps.

Table 5.3. Performance measurements and number of neurons obtained.

Database Subdivisions	Number of Neurons	Performance		
		Sensitivity	Specificity	Accuracy
1	11	86.22	82.88	84.26
2	12	89.47	70.47	78.93
3	16	91.72	76.42	84.67
4	11	86.25	72.48	79.07
5	8	72.16	73.94	72.91
6	8	86.05	73.7	79.32
7	13	87.25	82.88	84.92
8	10	82.15	83.87	83.1
9	14	89.58	82.83	85.52
10	10	85.04	82.38	83.67

Regarding the slide type movements, the susceptibility was carried out by means of weights of evidence and ANNs. ANNs were used in order to improve the prediction capability of the models. According to accountability and reliability values, several combinations of factors were tested in the weight of evidence analysis. We chose to perform the analysis by means of ANNs using two sets of data: the first one contained class and continuous variables, the second one only class factors. In general, the models obtained by ANNs showed better performance, as the success rate curve was much steeper (see Figure 5.11).

Between the two models carried out by using ANNs, the one obtained with both class and continuous variables has a higher success rate. When the continuous variables are classified, ANNs are forced to find relationship between those classes and landslide occurrence, but those classes can not be optimal for the modelling. This can explain the better results when using continuous variables. Table 5.3 shows the performance measurements and the selected number of neurons in the hidden layer for each of the ten subdivisions of the landslide inventory database. Taking into consideration the accuracy, a network with fourteen neurons was chosen (Melchiorre et al., 2007). Using this network, the whole study area was classified and the map of Figure 5.10E was obtained. The regional influence of geology, rainfall and more locally the slope angle can clearly be noted.

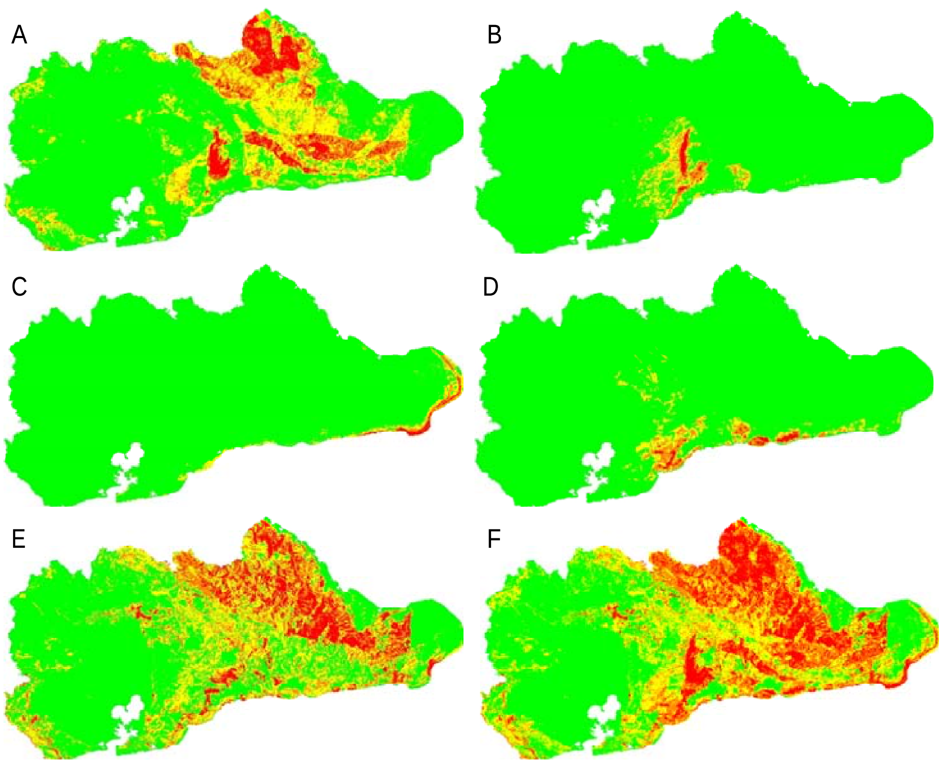

Figure 5.10. Landslide susceptibility maps. A: debris flow, B: large rockslides, C: rockfalls, D: topples, E: slides and F: all susceptibility maps. Legend: green is no susceptibility, yellow is low susceptibility, orange is moderate susceptibility and red is high susceptibility.

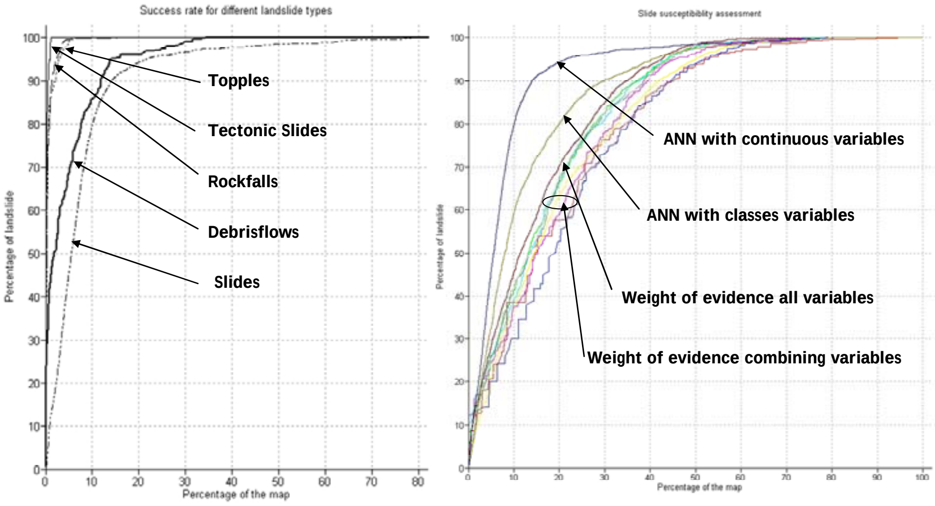

Figure 5.11. Success rates for all landslide types (left) and for slide type movements with different methods (right). ANN: artificial neural network.

As provincial authorities needed a single map for management and planning, the five individual susceptibility maps were combined in an overall susceptibility map (see Figure 5.10F), by selecting the highest susceptibility class for each pixel among the five maps.. As a result, 12.88% of the province was classified as having high susceptibility of at least one landslide type, 17.45% were classified as moderate and 23.98 % of the area as low.

From susceptibility to hazard

The analysis presented so far only resulted in landslide susceptibility maps, which indicate the relative likelihood of an area for landslide occurrence. However, in order to be able to use these maps for landslide risk assessment, information on the spatial and temporal probability should also be included. Unfortunately, no temporal information was available on the landslide occurrences, either through historical records or multi-temporal image interpretation. Therefore a simplified procedure was followed, in which the hazard is calculated by multiplying three probabilities (see below).

$$H = P_E * P_S * P_T \quad \text{[eq. 5]}$$

Where:

- H is hazard;
- P_E is the event probability, defined as the probability that if a landslide occurs of a given type, it happens in the particular susceptibility class.

- P_S is the spatial probability, defined as the probability that if a landslide occurs within a given susceptibility class, a pixel in this class might be hit.
- P_T is the temporal probability, defined as the annual probability of occurrence of a particular landslide type.

The calculation was made based on the combination of the landslide inventory map (with five landslide types) and the five susceptibility maps, classified in four classes (low, moderate, high, very high). This method is selected because the output of a heuristic approach or a WofE approach is a susceptibility map with scores that are not considered to be spatial probabilities. The values resulting from ANN are considered to be spatial probability values. However, for uniformity, the five maps were analyzed in a similar fashion. The hazard only considers the landslide initiation. Runout is not considered given that this study is done on a regional scale. The event probability is calculated as follows:

$$P_E = \frac{Npix(sld,cls)}{\sum Npix(sld,cls)} \qquad \text{[eq.6]}$$

In which *Npix(sld,cls)* refers to the number of pixels of landslides of a certain type within a particular susceptibility class. The event probability assumes that the landslides happening in the various susceptibility classes have more or less the same dimensions. The event probability is directly related to the success rate, and normally the high susceptibility class has an event probability of 0.8 or higher. The spatial probability is calculated using the following equation:

$$P_S = \frac{Npix(sld,cls)}{Npix(cls)} \qquad \text{[eq.7]}$$

In which *Npix(cls)* refers to the number of pixels of a susceptibility class. Susceptibility maps having a very steep success rate, like the ones shown in Figure 5.10 will have high values for both the event probability as well as the spatial probability.

The temporal probability could not be obtained statistically, due to the lack of sufficient temporal landslide data. Therefore, an estimate was made based on detailed photointerpretation and on field observation using geomorphological evidence. Debris flow events happen frequently, but their depositional features are more easily masked out by vegetation growth, and human intervention. Small debris flows and slides occurring in the heavily forested wet part in the north of the province are more difficult to recognize by photointerpretation, since after about twenty years the vegetation has recovered again. In the southern part with dry condition and scarce vegetation, erosional processes will affect the landslide features and make them less visible over time. The scarps remain visible for a longer time, especially in bedrock and can still be identified after twenty years. Rockfalls that occur along the marine terraces in the south remain clearly visible for a large number of years, whereas the ones occurring along road cuts are more rapidly modified. Large rock slides occur with very high magnitude and their features remain clearly visible over very long periods. These events are related to weak tectonic areas and to extreme rainfall events or even earthquakes. Topples are also associate with tectonic areas but they have a higher frequency than the rockslides.

Table 5.4. Landslide hazard estimations per landslide susceptibility class.

Susceptibility	Area in pixels	Perc area	Slides in pixels	Event probability	Spatial probability	Temporal probability	Hazard X10^{-4}
Rockfalls							
None	2414586	97.54	0	0.0000	0.0000	0.02	0.0000
Low	37200	1.50	22	0.0448	0.0006	0.02	0.0005
Moderate	15587	0.63	81	0.1650	0.0052	0.02	0.0171
High	8158	0.33	388	0.7902	0.0476	0.02	0.7517
Total	2475531	100.00	491	1.0000	0.0002	0.02	0.7693
Large rockslides							
None	2358294	95.26	12	0.0036	0.0000	0.01	0.0000
Low	79118	3.20	267	0.0797	0.0034	0.01	0.0027
Moderate	28156	1.14	711	0.2122	0.0253	0.01	0.0536
High	9963	0.40	2361	0.7046	0.2370	0.01	1.6697
Total	2475531	100.00	3351	1.0000	0.0014	0.01	1.7259
Topples							
None	2346673	94.79	3	0.0059	0.0000	0.02	0.0000
Low	77146	3.12	48	0.0941	0.0006	0.02	0.0012
Moderate	41658	1.68	120	0.2353	0.0029	0.02	0.0136
High	10054	0.41	339	0.6647	0.0337	0.02	0.4483
Total	2475531	100.00	510	1.0000	0.0002	0.02	0.4630
Debris flows							
None	1642390	66.34	1	0.0020	0.0000	0.0500	0.0000
Low	491839	19.87	25	0.0499	0.0001	0.0500	0.0001
Moderate	211754	8.55	125	0.2495	0.0006	0.0500	0.0074
High	129548	5.23	350	0.6986	0.0027	0.0500	0.0944
Total	2475531	100.00	501	1.0000	0.0002	0.0500	0.1019
Slides							
None	1377092	55.63	61	0.0198	0.0000	0.0500	0.0000
Low	569395	23.00	94	0.0305	0.0002	0.0500	0.0003
Moderate	327319	13.22	773	0.2504	0.0024	0.0500	0.0296
High	201725	8.15	2159	0.6994	0.0107	0.0500	0.3743
Total	2475531	100.00	3087	1.0000	0.0012	0.0500	0.4041

Based on geomorphological reasoning and by using the triggering factors of rainfall and PGA for different return periods, this study assumed a temporal probability of 1/100 years for large rock slides, 1/50 years for rockfall and topples and 1/20 for debris flows and slides. For the calculation of the hazard using equation [5] this means that the landslide area of the small slides used to calculate the event probability and spatial probability has originated in a twenty year period, and the one for rockslides in a one hundred year period. Table 5.4 shows the calculation of hazard for the five landslides types. The highest hazard values were obtained for large rockslides mainly due to the large size of these events, and the concentration of these events in clearly defined areas, making the spatial and event probability very high.

The results obtained for the hazard analysis allowed us to characterize the landslides problems in the Guantánamo province for each type of landslide. However, a complete quantitative hazard assessment can only be carried out if good historical records are available of landslide occurrences, coupled with analyses of triggering events. As both types of data are not sufficiently available for Cuba, the hazard, and therefore the risk can only be expressed semi-quantitatively.

5.4. Landslide vulnerability analysis

In order to be able to calculate the expected number of elements at risk that might be affected by landslides in the Guantanamo province, it is important to select the elements at risk that will be included in the assessment, and quantify these spatially. The qualitative risk assessment procedure used in this method does not allow the specification of vulnerability as a function of the characteristics of elements at risk and the magnitude of the landslide features.

5.4.1. Defining elements at risk

In spite of efforts by many organizations throughout the world, there is still no general consensus about which elements at risk should be selected and how their vulnerability should be assessed. UNDP proposes to group vulnerability in four components physical, economical, environmental and social (UNPD, 2004b). This implies that elements at risk should be selected that reflect these four different aspects.

A selection of possible elements at risk, and their characteristics for landslide vulnerability that could be used in landslide risk assessment at provincial level was made considering literature sources (Barbat, 2003; Dao and Peduzzi, 2003; UNPD, 2004b), the experience of the researcher in previous work (Castellanos et al., 1998; Castellanos and van Westen, 2001) and the availability of cartographic and statistical information produced in Cuba (Oliva, 1989; ONE, 2001; ONE, 2004) at provincial level.

Unlike the analysis at the national level, where vulnerability indicators were used in order to prepare risk indices (Castellanos Abella and Van Westen, 2007) the aim at provincial level is to quantify the elements at risk located in high hazard zones, for the different types of landslides defined earlier on in this chapter. Initially, it was considered using the municipalities as a spatial unit in order to collect the elements at risk. A total of forty three different characteristics of these municipalities, related to population, housing, infrastructure and economy were collected from the Territorial Statistics Office (OTE in Spanish) of Guantánamo. However, during the spatial analysis it was proved evident that the integration of the relatively large polygons related to the municipalities with the highly detailed landslide hazard maps, did not give satisfactory results, as it did not allow evaluation as to whether the areas of the highest hazard coincided with the built-up area within the municipality. For that reason, this information was not directly used in the analysis, although it provides a general understanding of the vulnerability in the province.

In order to be able to have more spatial detail, the main elements at risk were derived from the available digital maps in AutoCad format, based on 1:100,000 scale topographic maps. From this data the following types of elements at risk were derived: buildings, population, facilities, roads agricultural land and natural protected areas. In the following sections the procedure for the extraction of these elements at risk is further explained.

Table 5.5. Settlement classification in Guantánamo

Category	Minimum population	Maximum population	Number of settlements in Guantánamo	Classification
City				
City, 1st order	100,000	499,999	1	Urban
City, 2nd order	50,000	99,999		
City, 3rd order	20,000	49,999	1	
Town				
Town, 1st order	10,000	19,999		Urban or Rural
Town, 2nd order	5,000	9,999	5	
Town, 3rd order	2,000	4,999	14	
Village				
Village, 1st order	1,000	1,999	15	
Village, 2nd order	500	999	37	Rural
Village, 3rd order	200	499	116	
Hamlet	1	200	197	
Total			386	

Houses and population

Unfortunately no data was available on the number of people per house, distributed over the entire province. In order to quantify the spatial distribution of people over the province in a detailed level, three data sources were used. The first dataset, provided by the National Statistics Office (ONE) contains information about the number of houses and people per municipality (see Figure 5.12B). The second data set, from the same source has information on the number of houses and inhabitants per settlement. For each settlement, the coordinates of the centroid were also available (Figure 5.12D). The other dataset consisted of the digitized locations of all 21,591 houses and 1529 residential populated areas (Figure

5.12A and C). These data were extracted from the digital topographic map at a scale of 1:100,000.

The spatial distribution of inhabitants per house was modelled using an estimated number of people per houses for the points and residential areas, and the calculated population density for the settlement area. Although this information was not exact, it gave a more effective approximation than if the number of inhabitant were estimated by municipality or province. Table 5.5 shows the classification of the 386 settlements in the Guantánamo province according to the number of inhabitants. From the second dataset, containing the number of houses and people per settlement it is possible to estimate the number of inhabitant per house for each settlement. These values range from 1.75 to 4.34 inhabitants/house, with an average of 3.2 and a standard deviation of 0.35. From the first dataset with housing and population statistics for the 10 municipalities, the values ranged from 3.31 and 4.20 inhabitants per house.

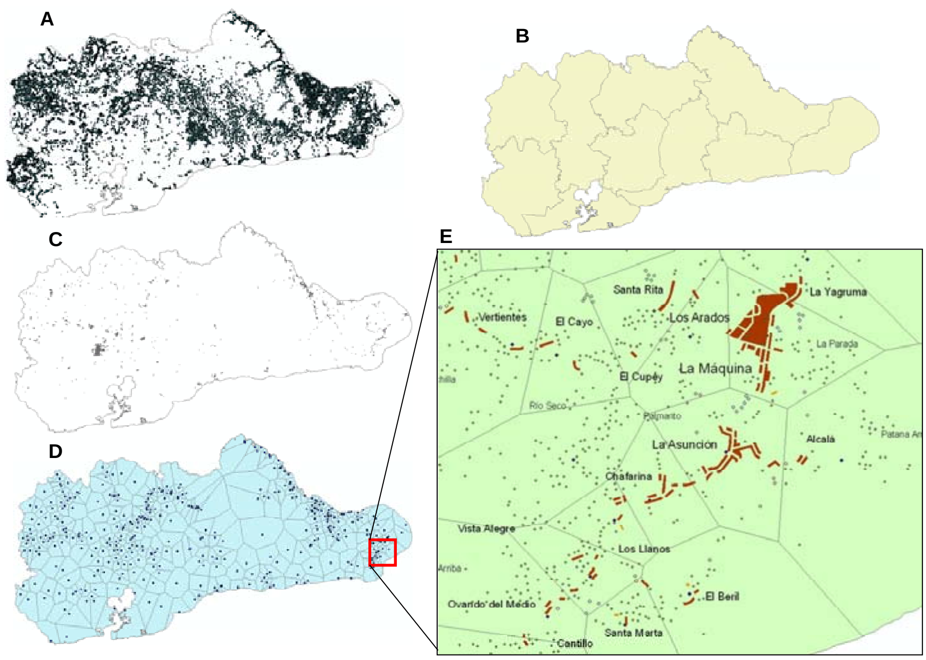

Figure 5.12. Maps used for estimating the number of inhabitants per house. A: houses, represented as points, B: 10 municipalities, for which building and population information is available, C: residential areas represented as polygons, D: Thiessen polygons generated from the centroids of the settlements with the number of people and buildings, used for defining the contributing area to each settlement E: Detail of an area with all layers.

In order to estimate the number of persons per building for the entire area, Thiessen polygons were constructed from the settlement centroids (Figure 5.12D). Then, the value of the average number of inhabitants per house calculated for the settlement was assigned to all houses falling in the Thiessen polygon. The fractional values were then rounded off to the next integer number. As a result, the average number of people per house varied between 2 and 5 and the total number of inhabitants in houses was 84,235. However, the people living in the houses located in residential areas, represented by 1529 polygons (19.84 km^2) must be added to the previous calculation. For this the population statistics of the municipalities were used and the difference between the total population per municipality and the sum of the people living in houses gave the level of population inside residential areas. The results were finally checked with the official statistics on the total population of the entire province for the year 2003 (510,225 persons in 136,272 houses) and turned out to be 96% correct. Taking into account all assumptions involved in this estimation and the level of analysis, this was considered to be adequate, especially as the population was now distributed at the same level of detail as the hazard information. Nevertheless, further studies should focus on obtaining better spatial distributions of population making use of a complete building footprint map.

Non residential buildings and essential facilities

For generating a map of non residential buildings and essential facilities many GIS operations were carried out, because the original data was grouped in different layers and represented differently in the digital maps. In total 1536 of such elements at risk were surveyed in the area, grouped in 32 types (

Table 5.6 and Figure 5.13B). Ideally, for vulnerability assessment each facility should have a monetary value representing the value of construction and the value of the production. This is because the value of construction of an agricultural product processing facility (e.g. for tobacco or sugar cane) may be much less than the value of its production. While the value of construction is in currency, the value of production is also in currency but only for a certain time period. As these particular values are not available, another option is to represent them using a relative monetary value per facility, ranging from 0-1 or to represent the number of certain facilities per hazard class.

Table 5.6 represents the estimated relative monetary values as weights. Shelters are named to relative large farm houses where workers stay during the harvest season.

The thirty two types indicated in Table 5.6 were sorted by relevance or importance and linearly weighted. This implies a level of subjectivity since each expert may provide different sorting order. Also, it is specific for this study area and it include not only elements with economic values but with social values too. For example, as coffee is one of the main economic sources in this area, the coffee processing facilities were ranked higher compared with other facilities that may be more relevant in other areas. Obviously, facilities such as schools and hospitals received the highest values.

Table 5.6. Facilities surveyed in the Guantánamo province.

Non residential buildings and essential facilities	Amount	Weight
School	520	1.0000
Hospital	23	0.9696
Shelter	189	0.9393
Shelter in construction	6	0.9393
Oil or gas well	5	0.9090
Factory	107	0.8787
Coffee house for production	3	0.8484
Coffee dryer	73	0.8181
Milk farm	4	0.7878
Dairy farm	179	0.7575
Pig farm	2	0.7272
Poultry farm	53	0.6969
Electrical Power plant	8	0.6666
Electrical distribution unit	3	0.6666
Deposit for cement	3	0.6363
Church	18	0.6060
Warehouse	29	0.5757
Water pump	26	0.5454
Wrecker for sugar cane	33	0.5151
Elevated water tank	125	0.4848
Oil storage	56	0.4242
Runway	6	0.3939
Radio/TV tower	17	0.3636
Chimney for industry	10	0.2727
Garage	1	0.2424
Cemetery	21	0.3030
Watch tower	1	0.1818
Weather station	1	0.1515
Monument	1	0.1212
Collection center for sugar cane	6	0.0909
Water pumping station	4	0.0606
Pick up point for personnel	3	0.0303
Total	1536	

Transportation network

All different roads types according to the classification in the topographic map provided by the cartographic agency in Cuba (Geocuba) were digitized for the study area. A total 4,482.5 kilometres for 10 types of roads (Table 5.7 and Figure 5.13C) were recognized, including two types of railways.

Table 5.7. Roads types in the Guantánamo province.

Road type	Length (km)	Cost/km	Weight
Highway	25.5	17000	1.0000
Urban street	537.0	*16000	0.6586
Paved road 1st order	151.3	15204	0.4879
Paved road 2nd order	382.8	12350	0.3741
Unpaved road (enhanced)	824.6	*8000	0.2887
Unpaved road	856.2	5100	0.2204
Path	235.3	*2000	0.1635
Trail	1,283.9	*1000	0.1148
Total	4,482.5		

* Estimate values. Cost/km in Cuban pesos

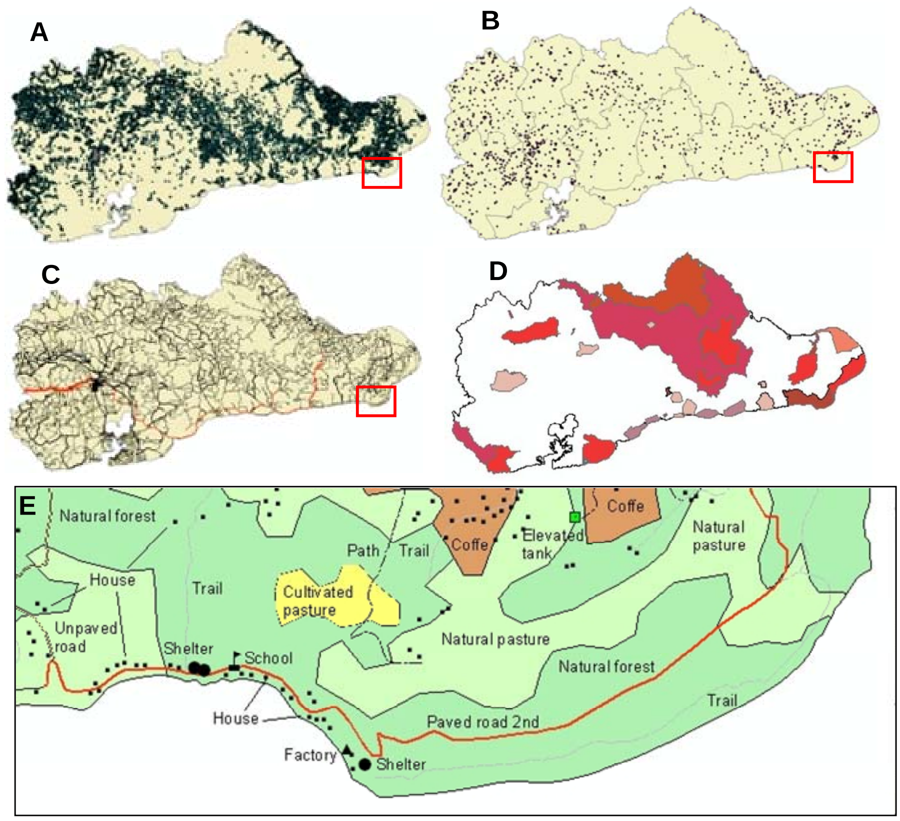

Figure 5.13. Elements at risk for vulnerability analysis. A: population in houses and residential areas, B: facilities, C: roads and railway, D: natural protected areas, E: enlarged zone with all elements combined except natural protected areas. The landuse map is shown in Figure 5.6.

Information on the construction costs per kilometre were obtained from the National Centre of Roads (CNV), although, their classification of road types does not completely match with the road types in the dataset. For some road types the construction costs were estimated, based on values of nearly similar road types. Nevertheless, for the qualitative analysis weight values were assigned using the raking method with the option of expected value. The ranking method assigns weights to a list of sorted factors from the most important at the top. The expected value option of this method assumes that each set of weights that fits the rank order of criteria has equal probability (Janssen and Van Herwijnen, 1994; ITC, 2001).

Land use and protected areas

The landuse map is used both as a factor map in the hazard assessment, as well as one of the elements at risk Figure 5.5C. As indicated earlier, the map was provided by the Institute of Physical Planning (IPF). As shown in Table 5.1, the Guantánamo province has 16 landuse types distributed in 633 polygons. Besides, more than a half of the province is covered by natural forest. A map of protected areas in the Guantanamo province was obtained from the national map provided by the National Center of Protected Areas (CNAP). There are 32 areas with some management category (Table 5.8 and Figure 5.13D) that cover 36 % of the surface of the province.

Table 5.8. Natural protected areas in the Guantánamo province. World Conservation Union (IUCN) categories explained in IUCN (1994).

Code	Management Category (CNAP)	Amount	Area (km^2)	Category IUCN	Weight
RN	Wilderness area	5	69.35	I	1.000
PN	National park	3	354.92	II	0.518
RE	Ecological reserve	8	521.99	II	0.518
END	Natural element highlighted	5	84.61	III	0.293
APRM	Managed resource protected area	2	1020.13	VI	0.197
PNP	Natural landscape protected	1	54.63	V	0.119
RFM	Flora managed reserve	8	145.51	IV	0.055
Total		32	2251.14		

Ecological relevance of natural protected areas is already established by categories (IUCN, 1994). Although there is a relationship (as shown in Table 5.8), Cuba has some modifications of these categories. With comprehensive studies is possible to assign monetary values per km to certain natural protected areas based on the environmental assets in the area. Since CNAP has not yet calculated these values for Cuba, areas (for the purposes of the study present herein) were ranked and weighted using the ranking method with the expected value option. Cuba has two types for Category II of UICN (Table 5.8) and the ranking method applied allowed to consider then in the same level with the same weight.

5.4.2. Landslide vulnerability assessment

Before actual spatial assessment of landslide vulnerability, different analyses were carried out for the Guantánamo province in order to get better insight of their main problems with regard to disasters. First at all, a provincial database of disaster events was analyzed as explained in section 3.2.3. After this (as housing is one of the main elements at risk in Guantánamo) the housing typologies and conditions were analyzed as explained in section 3.3.5. Moreover, generic vulnerability indicators per municipality were standardized and examined as explained earlier. Later, the spatial vulnerability assessment was carried out for the whole territory.

Vulnerability assessment in landslides is still an issue under research in most countries. A detailed discussion on this issue can be found in the literature (Glade, 2003; Glade et al., 2005; van Westen et al., 2005). The expression of vulnerability on a scale of 0 to 1 expressing the degree of damage to an element at risk requires detailed information on the expected landslide magnitude and its interaction with the elements at risk. As it is not possible at this scale of analysis to predict for a particular location what the magnitude of landslides will be, including both the components of landslide initiation and landslide runout, the generation of actual vulnerability values will be extremely difficult and highly uncertain. Therefore it was decided to use the 'elements at risk' as indicators, in a similar way as in the national level, and to assign weight values that give an approximation of the vulnerability. At this level of analysis, and considering the data available for this study, vulnerability values were estimated for population and roads based on literature and expert opinions as explained below. In order to be able to calculate the risk in terms of expected monetary losses, information about replacement costs should also be available, which is only the case for the transportation network. Therefore it was decided to use weight values that give a relative indication of the importance of the elements at risk. Spatial multi-criteria evaluation (SMCE), was used as the main tool for the landslide vulnerability and risk assessment. The method was already explained in detail in Chapter 4 for the national assessment.

Generic non spatial vulnerability analysis

Generic non spatial vulnerability analysis was carried out for the Guantánamo province in order to get a better insight into the vulnerability components. A set of vulnerability indicators was analyzed per municipality in order to recognize relevant aspects for landslides. As the selection of vulnerability indicators is very much related to the objectives of the particular level of analysis, this study focused on the priorities of the civil defence at provincial level. The selection of indicators was based on existing international studies on disasters (Coburn et al., 1994; International Federation of Red Cross and Red Crescent Societies, 1999; CEPAL and BID, 2000; Commission on Sustainable Development, 2002; Barbat, 2003; Dao and Peduzzi, 2003; UNPD, 2004a; UNPD, 2004b; Douglas, 2007), particular studies on landslides (Leone et al., 1996; Manoni et al., 2002; Glade, 2003) and the availability of data in Cuba both in tabulated (ONE, 2001; ONE, 2004) and spatial form (Oliva, 1989). Following the same approach as used in the national assessment, the vulnerability indicators were divided into four major types: physical, social, economic and environmental indicators. The social indicators were later divided in those related to inhabitants (social I) and those related to public facilities (social II).

It is important to take into account that many of the indicators can actually be include in different types of vulnerability, depending on the spatial attributes. For example, an industry has its construction facilities that can be physically damaged by a landslide, but also the economic value of the production can be heavily affected. In this case, the same spatial object can have two attributes to be considered for different vulnerability types and they may be correlated. To give another example: the density of electricity and communication networks per spatial unit can be used for analyzing the physical vulnerability as these networks may be impacted by landslides. However, they also have an influence on the social vulnerability, as part of the economic and cultural development of certain area or to estimate the amount of population that can be part of the early warning system. Deciding how to classify the indicator depends on the scale of assessment and its objectives.

Initially, forty three indicators were defined and the Territorial Statistics Office (OTE) was requested to provide these for the ten municipalities of the Guantánamo province. OTE supplied many more indicators which were basically disaggregating those requested. It was impossible to deliver some indicators, for example the number of inhabitants with disability, or some indicators which are intrinsically spatial such as the area of productive soils. The indicators used in this studied and their values for the ten municipalities obtained from OTE are presented in annex 5.D in the supplementary CD-ROM. As seen, many of these indicators are valuable not only for landslide events but for many other natural or not natural disasters as well. Therefore, they can be part of a more comprehensive multi-hazard risk assessment or taken from exiting risk assessment for other hazards.

A graphical analysis was carried out to compare the indicator values in the municipalities. In order to make their values comparable all indicators were standardized from 0-1, by dividing the values by the maximum. No weights were applied by indicator this time in order to make a graphical analysis as real as possible. Figure 5.14 shows a selection of indicators in radar graphs. The geographic locations of the municipalities are shown in Figure 5.2. Most of the physical indicators show a similar pattern where the municipalities of Guantánamo and to a lesser extend Baracoa and Imías have predominant values with the exception of roads which are almost equally distributed into four municipalities. The social indicators related to population are highly concentrated in the Guantánamo municipality. The exception here is the amount of tourists mostly due to camping facilities located in Imías. The social indicators related to facilities and services show a more equal distribution over the various municipalities. As these facilities and services are free in Cuba, they are designed proportionally to the population in every territory especially for education and health system. Moreover, provincial facilities, like maternity hospitals or Universities are concentrated in the Guantánamo municipality. The unemployment rate and the percentage of cultivated land show different patterns as compared to the other economic indicators. The El Salvador municipality produces mainly sugar cane, while Baracoa is much more diverse producing coconut, cacao and coffee. The largest natural protected and forest areas in the province are in Baracoa and in Yateras, although forests also cover large parts of other municipalities.

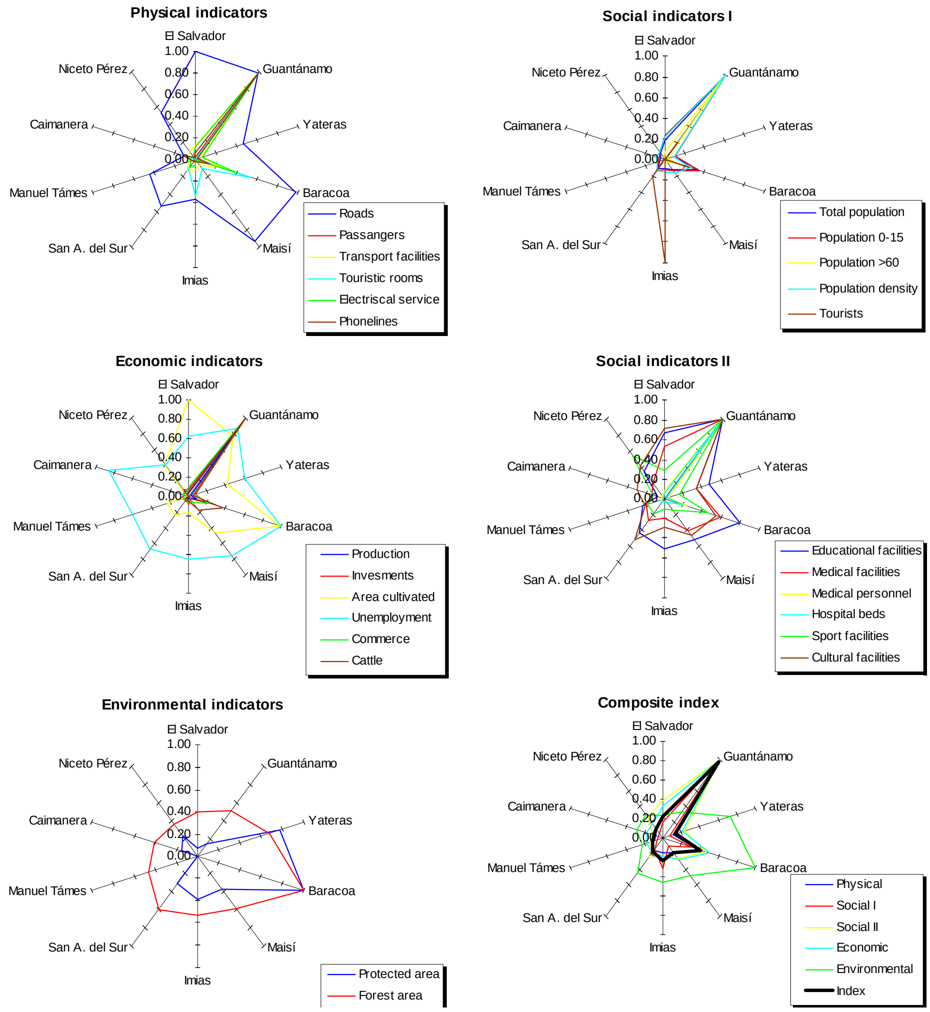

Figure 5.14. Radar graphs representing selected vulnerability indicators for ten municipalities in the Guantánamo province. All indicators are standardized from 0-1.

A composite vulnerability index was needed for an overall assessment of the province (Figure 5.14, lower right graph). In order to create a composite index for a provincial analysis the standardized values of the indicators belong to the same group (Physical, social 1, social 2, economic, and environmental) were added, and the resulting values were multiplied by a weight according to the priorities of Civil Defence authorities. The following weights were used: 0.34 for physical vulnerability, 0.4 for population vulnerability (social I), 0.05 for vulnerability of social facilities (social II), 0.15 for economic vulnerability, and 0.04 for environmental vulnerability. The composite index was derived by adding up the five individual indexes, multiplied by the above mentioned weights. As expected, the Guantánamo municipality presents the highest value for most indicators types and for the composite index. The environmental indicators show a different pattern, they are more distributed with predominance in Baracoa and Yateras. These analyses allowed a first examination of the relative degrees of vulnerability for the municipalities in the province. It is important to mention that no connection was yet made with landslides, and that the vulnerability values cannot be represented as a single value per municipality. Therefore, in order to carry out a spatial vulnerability assessment for landslides a different approach was followed.

Spatial landslide vulnerability analysis

For the spatial landslide vulnerability analysis only five types of elements at risk (population, facilities, roads, protected areas and landuse), described in section 4.1 were used. Also here the approach was to combine them using spatial multi-criteria evaluation (SMCE). As explained before, since it was not possible to obtain monetary values for all elements at risk the vulnerability was carried out using relative weight values. For standardization of the maps, different options were applied depending on the type of element at risk and on the number of classes (Table 5.9). The standardization of each map was explained in the section of vulnerability indicators. In the section of risk assessment, elements at risk are also counted by hazard classes for the five hazard type maps.

Table 5.9. Landslide vulnerability model applied to the Guantánamo province

Indicator	Description	Weight	Standardization
Population	21591 points and 1529 polygons	0.457	Maximum
Facilities	1536 points and 324 polygons	0.257	Maximum
Roads	10 types, 4482 km	0.090	Ranking
Protected areas	7 types, 32 areas, 2251 km^2	0.040	Ranking
Landuse	16 types, 633 areas	0.157	Ranking

Weighting vulnerability indicators were carried out by using similar weights of the national landslide vulnerability assessment. But here, at provincial level, the landuse areas were interpreted by their relative importance, such as production of coffee or fruit, since the areas at this level represent different sectors of the economy. Another difference with the method at the national scale was that the weight for housing at national level was used here as the weight for non residential buildings and essential facilities, as the houses were analyzed along with the population.

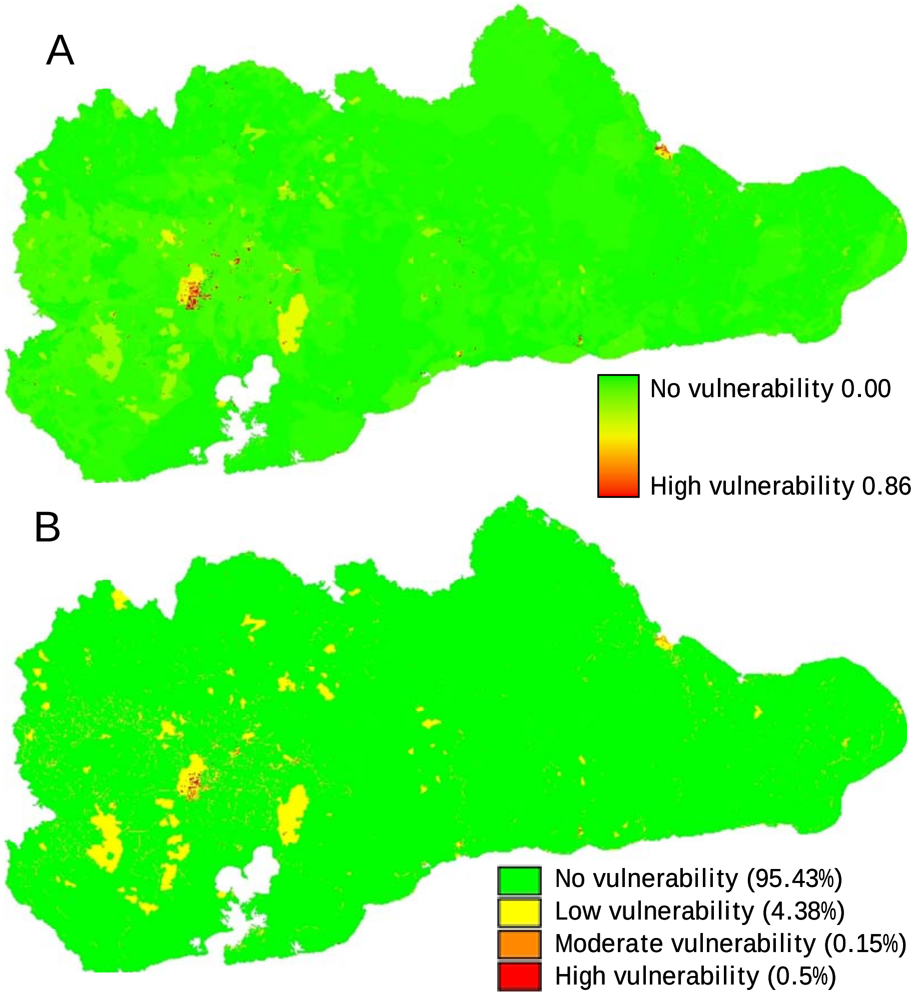

Figure 5.15. Generic landslide vulnerability maps. A: value map (0-1) scale. B: class map.

Vulnerability is considered as 'degree of loss' which implies determining the impact of a certain hazard over each element at risk. Its evaluation at this scale over a large area with little available data, (like in this research) does not lead to many other options, other than considering it as the exposure and assuming maximum loss (1) whenever an element at risk is located in a hazard area. In this way, for example, all of the population is equally considered vulnerable but areas with higher numbers of people will have a higher 'vulnerability value' and higher risk for an equal hazard. That allows authorities at this level to prioritize disaster reduction measures in those areas with higher exposure. In order to produce such a 'vulnerability map', all elements at risk can be combined by their relative weight and standardization. The map of landslide vulnerability produced by SMCE had a mean of 0.03 with values ranging from 0 to 0.86. This asymmetry (positive skewness) is mainly due to large area without any houses, facilities or roads which results in 0 values in the standardization. Based on this fact, and on the analysis of the table of frequencies, a class map was produced with 0.05, 0.25 and 0.5 class boundaries for no vulnerability, low, moderate and high vulnerability areas.

In Figure 5.15 the value and class vulnerability maps are shown. It is recognizable that urban areas have higher vulnerability since they concentrate the most relevant element at risk: population and infrastructure. Besides, they are located mostly in low lands as settlements were historically preferentially positioned in flood plains. When creating the class map the road network becomes more visible because all land uses with low values were classified as areas with no vulnerability. There are small zones dispersed all over the territory with high and moderate vulnerability. The visualization effect (such as stretch maps values) makes the same data set look different by the representation used, as shown in Figure 5.15. These maps as well as the individual elements at risk maps were used for landslide risk assessment.

5.5. Landslide risk analysis

After the hazard and vulnerability analysis the risk assessment was carried out using both qualitative and semi-quantitative methods as explained in Figure 5.1. The landslide hazard and vulnerability maps, discussed in the previous sections, were used for the qualitative assessment. For the semi-quantitative assessment a more detailed analysis was made by using each type of landslide hazard and each type of element at risk. This allows a more detailed interpretation of the risk and more precise planning for disaster risk reduction.

5.5.1. Qualitative assessment of landslide risk

The qualitative landslide risk assessment initiated by overlaying the composite hazard map with the composite vulnerability map. The map resulting from the overlaying was reclassified considering the hazard and vulnerability classes. In order to be more conservative with the vulnerability assessment, ‘expert-based’ rules were applied to create the qualitative landslide risk map. The rules used for the combination of hazard and vulnerability classes are given in Table 5.10. With this approach, the areas with low or even no vulnerability but certain hazard, were still considered as risky areas. This classification was adopted taking into account the subjectivity and the data problems involved in the analysis. This method resulted in 41.86 % of the area which has neither hazard nor vulnerability.

The qualitative landslide risk map of the province is shown in Figure 5.16. The areas classified as ‘no risk’ (45.70 %) are predominately in the western part of the province. Low risk areas (41.23%) are located in three main regions: in the mountain range northwest-southeast, in the centre of the province and in the coastal zones associated with terraces. The moderate risk areas (13.01 %) are always surrounded by low risk areas and are located in the same three regions. In the mountain range, they appear more scattered while in the central part (Sierra de Caujerí) and the southeast coast they are more grouped. The high risk areas occupy only 0.06 % (3.71 km²) of Guantánamo and they are located in some spots inside the moderate regions, or in road sections either in the coastal area or in the mountain range. The meaning of these qualitative risk classes at this level is only as an initial screening process in order to explore the risk distribution in the province. As this qualitative assessment included all landslide types and all elements at risk, it is not possible to characterize specific causes of the risk, but it is very relevant to recognize the target areas for disaster risk reduction.

Table 5.10. Qualitative landslide risk matrix applied in the Guantánamo province. The percentage of the total area for each combination is given in brackets.

Vulnerability	High	No risk (0.05)	High risk (0.00)	High risk (0.00)	High risk (0.00)
	Moderate	No risk (0.12	Moderate risk (0.02)	Moderate risk (0.01)	High risk (0.00)
	Low	No risk (3.67)	Low risk (0.48)	Moderate risk (0.17)	High risk (0.06)
	Not	No risk (41.86)	Low risk (23.48)	Low risk (17.27)	Moderate risk (12.81)
		Not	Low	Moderate	High
		Hazard			

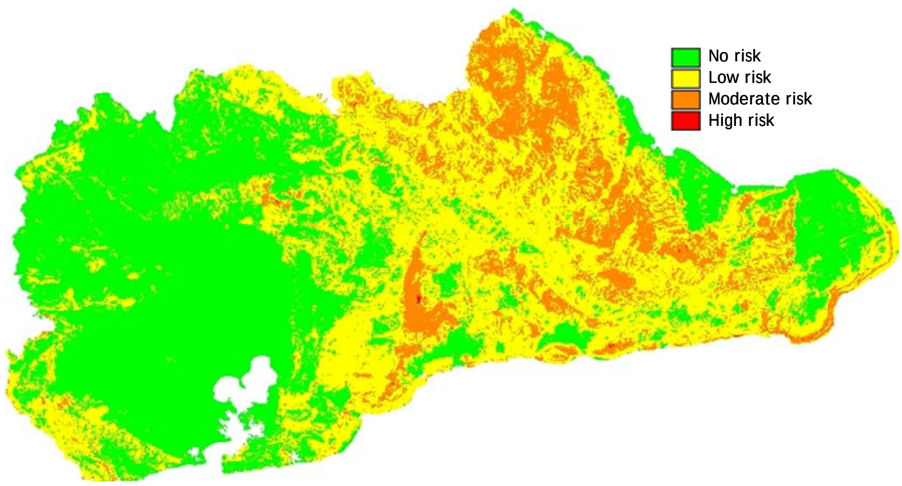

Figure 5.16. Qualitative landslide risk map of the Guantánamo province with municipalities boundaries.

For effective planning of disaster risk reduction, it is useful to recognize the spatial distribution of risk at lower management units: municipalities. Figure 5.17 shows the percentage of area per municipality occupied by the various qualitative risk classes. The municipalities of El Salvador, Guantánamo and Caimanera do not have any high risk areas. Other municipalities have such small high risk areas that they could not be proportionally represented in the graph. At first sight, it can be recognized that the safer municipalities (from a landslide risk point of view) are El Salvador, Guantánamo and Niceto Pérez, as each one has 10% or more of the province and 90% or more of their area classified as no risk. The municipality with the highest risk is Baracoa, which also counts for almost 16% of the province, followed by Yateras and San Antonio del Sur, although the last one has more moderate risk areas. One characteristic of the moderate risk of San Antonio de Sur is that it appears to be concentrated in specific areas while in Baracoa moderate risk is dispersed. During the municipal risk assessment, the municipality of San Antonio de Sur will be studied in more detail.

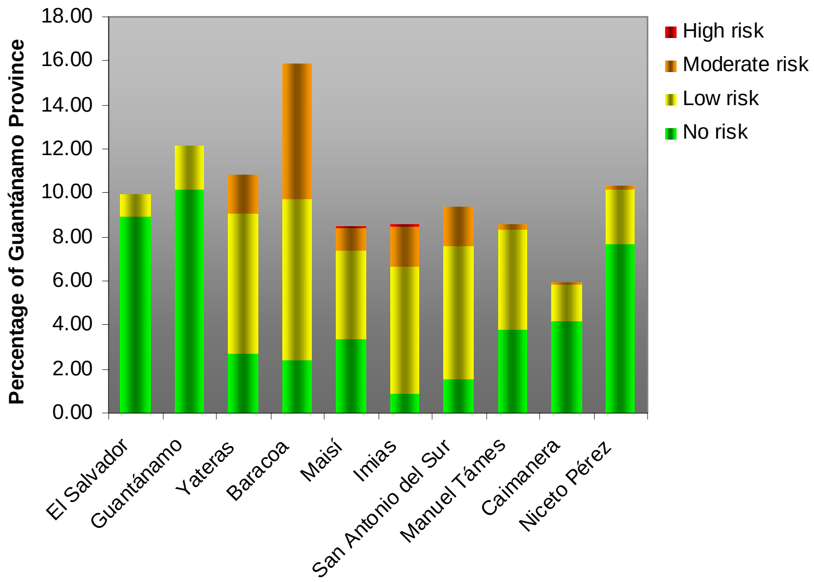

Figure 5.17. Spatial distribution of qualitative landslide risk per municipalities in the Guantánamo province.

5.5.2. Semi-Quantitative assessment of landslide risk

The semi-quantitative assessment is based on the standard risk formula where risk is obtained as the product of landslide probability (consisting of the spatial and temporal probability), the vulnerability and the amount of elements at risk. The analysis was carried out in two different ways, as illustrated in Figure 5.1: estimating the risk for each landslide hazard type and each landslide hazard class (shown as the columns below in Figure 5.1) and total risk for every type of elements at risk (shown as horizontal rows in the right part below in Figure 5.1). For the first method, all of the elements at risk are counted for each landslide hazard type, and each hazard class. They can be multiplied by the replacement costs and the landslide probability in order to obtain the specific risk per hazard class. In the second method, the number of elements at risk is multiplied with the cost and the hazard probability for all hazard types together. Both ways provide deeper knowledge about landslide risk and its spatial distribution as explained below.

Table 5.11. Results of specific risk calculation of population per hazard class by landslide type.

Rockfall	Low hazard	Moderate hazard	High hazard	Total
Hazard E-04	0.0005	0.0171	0.7517	
Vulnerability	0.6000	0.6000	0.6000	
Population	1616	522	200	2338.00
Risk E-04	0.5139	5.3700	90.2006	96.08
Large rockslides				
Hazard E-04	0.0027	0.0536	1.6697	
Vulnerability	1.0000	1.0000	1.0000	
Population	1265	453	184	1902.00
Risk E-04	3.4014	24.2712	307.2170	334.89
Topples				
Hazard E-03	0.0012	0.0136	0.4483	
Vulnerability	0.2000	0.2000	0.2000	
Population	2139	745	12	2896.00
Risk E-4	0.5010	2.0198	1.0758	3.60
Debrisflow				
Hazard E-03	0.0001	0.0074	0.0944	
Vulnerability	0.4000	0.4000	0.4000	
Population	22384	4717	2158	29259.00
Risk E-04	0.8954	13.9623	81.4861	96.34
Slides				
Hazard E-04	0.0003	0.0296	0.3743	
Vulnerability	0.4000	0.4000	0.4000	
Population	42620	22196	6045	70861.00
Risk E-04	5.11	262.80	905.06	1172.97

Table 5.11 shows the results of calculating the specific risk for population per hazard classes by landslide type. The hazard values were calculated as shown in Table 5.4. In this analysis the vulnerability was estimated depending on the type of hazard. The values presented were based on the literature (e.g. Glade et al., 2005) and expert judgment after many fieldwork campaigns in the study area. Further studies are required to produce vulnerability values for landslide based on historical information collected about landslide damage in the study area. Slides type of movement is, by far, the highest risk value for population and well as the highest number of inhabitants exposed. Rockfalls and debrisflows have a similar risk value, but the numbers of the population that are exposed is much higher for debrisflows. During the course of this research, we found that for all landslide

types the population decreases with the increase of the hazard, which could be an indication of appropriated physical planning as less people are exposed in high hazard areas. A similar calculation was made for specific risk on roads (see Table 5.12). In this case, the actual cost of the road (in Cuban Pesos) per kilometre was processed considering the 50 m pixel size of the map. The result of multiply the cost of every road type per the number of kilometres in each landslide hazard class was used for the risk calculation in each landslide type. Also here, the slides movements have the highest values of risk and elements exposed. However, in this case the rockfalls also have high risk values due to the roads constructed close the marine terraces where rockfalls events occur frequently.

Table 5.12. Results of specific risk calculation of roads per hazard class by landslide type.

Rockfall	Low hazard	Moderate hazard	High hazard	Total
Hazard E-04	0.0005	0.0171	0.7517	
Vulnerability	1.0000	1.0000	1.0000	
Cost*km	606726	155948	189812	952486
Risk E-04	321.55	2673.84	142676.33	145671.72
Large rockslides				
Hazard E-04	0.0027	0.0536	1.6697	
Vulnerability	1.0000	1.0000	1.0000	
Cost*km	258936	70731	17405	347072
Risk E-04	696.25	3789.69	29060.39	33546.33
Topples				
Hazard E-04	0.0012	0.0136	0.4483	
Vulnerability	1.0000	1.0000	1.0000	
Cost*km	217765	35962	100	253827
Risk E-04	255.05	487.49	44.83	787.36
Debrisflow				
Hazard E-04	0.0001	0.0074	0.0944	
Vulnerability	1.0000	1.0000	1.0000	
Cost*km	3742560	948703	410796	5102059
Risk E-04	374.26	7020.40	38779.14	46173.80
Slides				
Hazard E-04	0.0003	0.0296	0.3743	
Vulnerability	1.0000	1.0000	1.0000	
Cost*km	6695538	2575103	1200260	10470901
Risk E-04	2008.66	76223.05	449257.32	527489.03

Because all elements at risk could not be completely quantified, instead of cost or value, weights were used for non residential building and facilities, landuse and protected areas. In these cases, elements at risk multiplied by the weights were grouped by hazard classes as shown in Table 5.13. The weights were obtained by the ranking method using the SMCE module in ILWIS where users sort the classes, and the algorithm calculates the weights from 0 to 1. Even when this is a dimensionless number, it is possible to compare the frequency for different hazard classes and landslide types. If monetary value per square kilometre would be known, the weight value could be replaced by the actual cost per unit area and the risk could be calculated as expected losses within a given period of time. While for protected areas and landuse the number of square kilometres was considered, for facilities the number of facilities multiplied by its weights was used. Similarly for population and the roads, it can be said that for all cases the value of the elements at risk decreases when the hazard increases, and the slides and debris flows movements have the higher elements exposed.

Table 5.13. Elements at risk exposed in each hazard class of different landslide types. Rows 'Total at risk' show sum of low, moderate and high hazard.

Hazard classes	Debris flow at risk	Rockfall at risk	Slide at risk	Large rockslide at risk	Topples at risk	All hazard at risk	Exposed to different types of landslides
Facilities (weights *number of facilities)							
Not hazard	1345	1377	1249	1386	1392	1189	
Low hazard	45.15	11.12	127.54	5.55	4.67	170.02	
Moderate hazard	6	4.88	13.76	2.61	0	25.24	
High hazard	0	3.7	6.21	2	0	11.91	
Total at risk	51.15	19.7	147.51	10.16	4.67	207.17	26.02
Protected areas (weights*km2)							
Not hazard	510.06	708.03	399.53	752.14	695.36	255.87	
Low hazard	231.82	34.88	278.97	8.67	21.11	343.77	
Moderate hazard	21.48	13.56	59.57	2.55	30.08	115.23	
High hazard	0	6.9	25.3	0	16.83	48.51	
Total at risk	253.3	55.34	363.84	11.22	68.02	507.51	244.21
Landuse (weights*km2)							
Not hazard	770.88	844.2	720.9	821.87	830.76	644.27	
Low hazard	77.88	7.86	109.01	21.42	16.97	157.04	
Moderate hazard	8.59	3.82	18.91	9.92	8.06	39.99	
High hazard	0.22	1.68	8.75	4.35	1.77	16.25	
Total at risk	86.69	13.36	136.67	35.69	26.8	213.28	85.92

After estimating the specific risk for the population and the roads, and analyzing the frequency of the elements at risk per hazard class, the actual landslide risk values were calculated. The calculation was considered semi-quantitative because for three types of elements at risk it was not possible to obtain the actual costs. As there were five hazard maps and five elements at risks, twenty five maps were produced with all possible combinations. For producing these maps the hazard probabilities were spatially multiplied for each raster cell by the vulnerabilities and amounts of the elements at risk, and the cost or the weight values. The twenty five maps that were produced represented the specific risk of each landslide type for each element at risk analyzed (Figure 5.1). Ultimately, ten resulting intermediate risk maps were made before the final risk map: five considering the risk a particular group of elements at risk for all landslide types (Figure 5.1 bottom right) and five considering the specific risk of a particular landslide types for all elements at risk (Figure 5.1 lower row). The first set was obtained by adding the values of the specific risk for the same group of element at risk (e.g. population) for each the individual landslide types (e.g. slides, rockfalls, topples, debris and large rockslides). For example, in the case of population, the combination of the five specific risk maps gives the total population at risk for all landslide types. These five risk maps, for population, facilities, roads, protected areas and landuse, are useful in disaster risk reduction planning as they are focusing on the expected loss for a particular element at risk. Presenting the five maps full-size is not possible because the area is too large and individual elements are not fully visible. Instead, Figure 5.20 (A-G) shows a detailed area for risk map as well as for a composite landslide risk map. This composite landslide risk map was obtained by integrating the five specific risk maps into one map using a spatial multi-criteria evaluation model (Figure 5.18). For this model, the weights employed in the vulnerability assessment were used (Table 5.9).

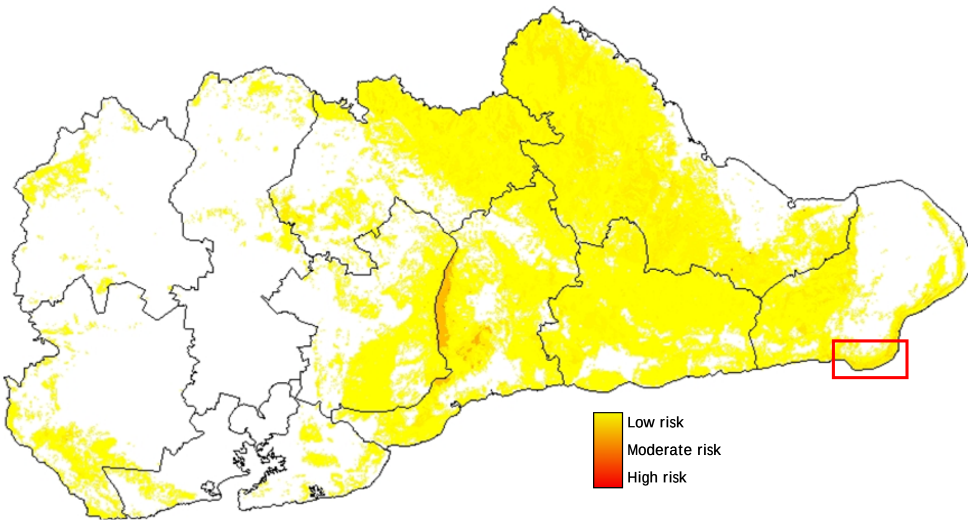

Figure 5.18. Composite landslide risk map obtained by SMCE of five elements at risk map. Representation is yellow to red, i.e., from minimum to maximum risk values. The area marked is represented in detail in Figure 5.20.

The landslide risk map that was obtained is shown in Figure 5.18, and the summary statistics, excluding the area without risk are shown in Table 5.14. Due to procedure that was carried out these values are dimensionless, but they can used for comparison among risk maps and also among different areas within each map. Like in the qualitative map (see Figure 5.16), areas in the western part of the province appear almost without landslide risk. In the north and northeast low to moderate values of risk were found distributed in several patches. The coastal area in the southeast contains zones with low to moderate risk while the San Antonio del Sur municipality has the highest landslide risk values.

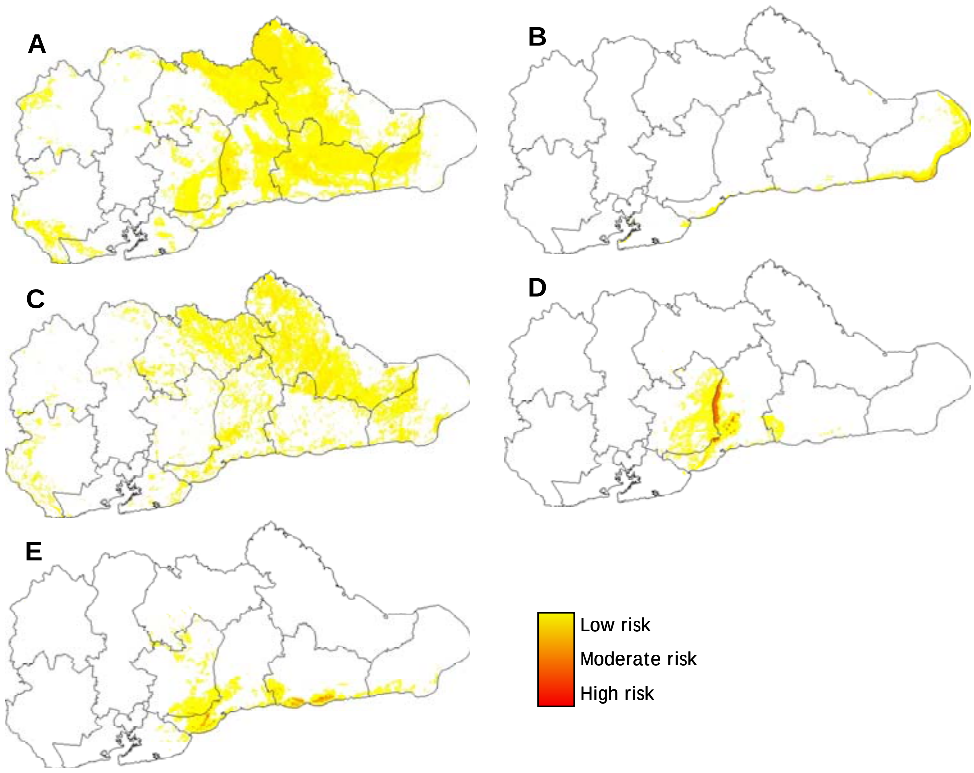

Figure 5.19. Risk maps for different landslide types. A: debrisflows risk, B: rockfall risk, C: slide risk, D: large rockslide risk and E: toppling risk.

Another set of five specific risk maps was made corresponding with each landslide type (Figure 5.1 bottom). Because specific risk to different elements at risk is combined, the weights used for vulnerability (Table 5.9) were also applied. Therefore a new spatial multi-criteria evaluation (SMCE) model was applied with the individual risk maps for each landslide type. The final five maps in scale 0-1 show the distribution of risk for specific types of movement which is more applicable from a physical planning point of view. In Figure 5.19 (A to E) the five risk maps are shown with the boundaries of the municipalities in the Guantánamo province and their statistics are given in Table 5.14. At this scale is not possible to see the isolated high risk values and only the low and moderate risk areas covering large regions are recognizable.

Table 5.14. Descriptive statistics of the landslide risk maps.

Maps	Min	Max	Mean	Median	SD	Figures
Debris flow risk	0.00053	0.50280	0.01061	0.00230	0.01258	Figure 5.19A
Rockfall risk	0.00003	0.53600	0.01420	0.00009	0.03726	Figure 5.19B
Slide risk	0.00010	0.53810	0.01257	0.00310	0.01623	Figure 5.19C
Large rockslide risk	0.00010	0.26110	0.01422	0.00020	0.04271	Figure 5.19D
Topple risk	0.00020	0.25816	0.08070	0.00073	0.02446	Figure 5.19E
Risk for facility	0.00023	0.84610	0.06760	0.06293	0.06255	Figure 5.20A
Risk for protected area	0.00010	0.03590	0.00114	0.00025	0.00321	Figure 5.20B
Risk for land use	0.00001	0.38854	0.01549	0.00727	0.02555	Figure 5.20C
Risk for population	0.00060	0.74860	0.32246	0.37230	0.13138	Figure 5.20E
Risk for road	0.00500	832.500	15.9500	1.88000	50.2100	Figure 5.20D
Risk total	0.01000	0.160000	0.02031	0.01000	0.02109	Figure 18 and Figure 5.21F

The comparison of the qualitative and semi-quantitative maps should be made carefully as both maps were made using different approaches. While in the semi-quantitative map, 43.2% of the province is covered with risk values, whereas the qualitative map has about 54.3% in one of the three risk classes. The main reason for this is the division of the classes based on expert opinion in the qualitative assessment. A possible solution could be a new reclassification to each hazard class for the five landslide hazard maps and to the vulnerability classes. On the other hand, the quantitative assessment uses a number of assumptions that could divert the analysis from the reality. In this case, weights were used, instead of actual monetary values, for facilities, protected areas and land uses. Because of the large difference between both maps and the different measurement scales, it was decided not to compare them quantitatively. Nevertheless, both risks maps were converted into binary maps, displaying risk and no risk areas, and overlaid to test if all areas with risk in the semi-quantitative map were also included as such in the qualitative map. As a result, only 0.38% of the area with risk values in the semi-quantitative map was not evaluate as risky in the qualitative map. Besides, visual comparison shows (Figure 5.20 F and G) that there is some degree of similarity between both maps, especially for the area with higher risk. While the semi-quantitative map shows more subdivisions in the higher risk areas, the qualitative map has more areas covered with lower risk values.

The qualitative landslide risk map is much more appropriate as a preliminary indication of risk in the Guantánamo province, and also be used to identify priority areas within the municipalities for further studies. The semi-quantitative landslide risk map was found to be much more appropriate for disaster management and disaster risk reduction planning until more quantitative risk value become available or more detailed studies can be used to update this map. With areas delimitated qualitatively authorities could define where research funding could be more usefully and outline strategies. With semi-quantitative risk values disaster managers and physical planners could make local decisions for specific areas. The validation of landslide risk maps is a worldwide issue not well defined yet. A disaster database of the Guantánamo province was created (explained in Chapter 3) with the intention to improve the landslide inventory, damage assessment and validation. The limited number of landslides described herein did not allow for accurate validation of the area. However, even when a landslide disaster occurred the reconstruction of both natural and social-economic environments at the moment of the disaster would be almost impossible. However, further investigation on this issue is required for improving existing methods.

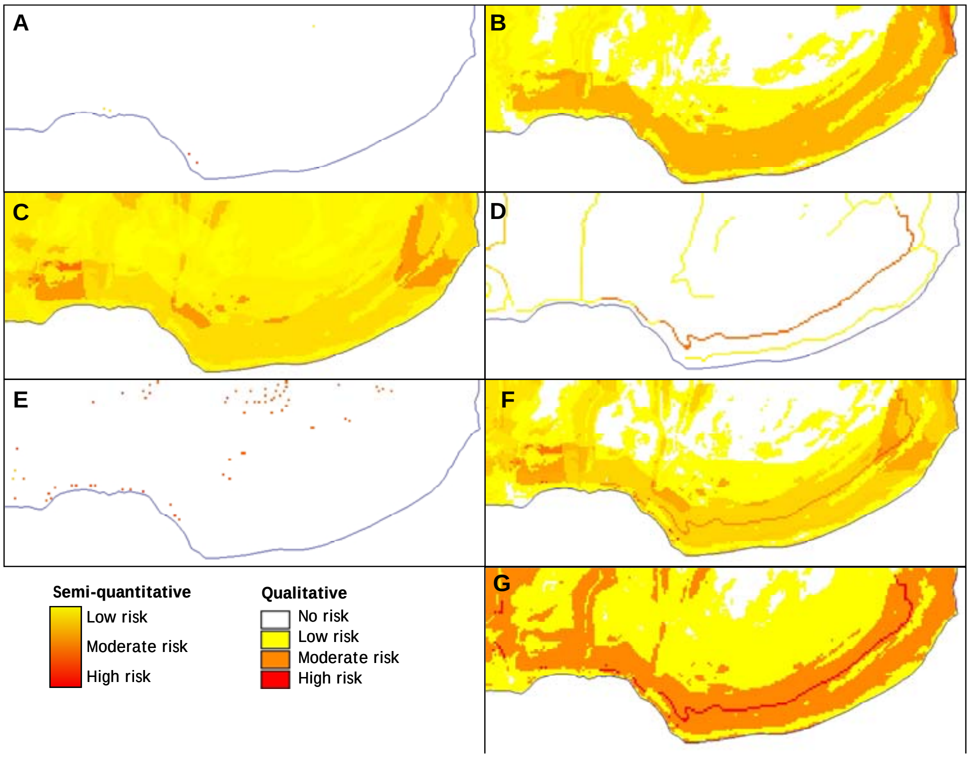

Figure 5.20. Detail of risk maps A: risk for facilities, B: risk for protected areas, C: risk for landuse, D: risk for roads, E: risk for population, F: total semi-quantitative risk, G: total qualitative risk. Maps A-F use (continuous) semi-quantitative legend with a representation from minimum to maximum of each map. Map G use class-based qualitative legend. The area is located in the southeast corner of the Guantánamo province.

5.6. Conclusions

A comprehensive landslide risk assessment study was carried out in the Guantánamo province at a scale of 1:100,000. The study started by analyzing the landslide inventory in the territory and the causal factor related to landslide hazard.

Also information for elements at risk was collected for five types (population, facilities, transportation, protected areas, and land use). This stage is relevant for any landslide risk assessment study as many important issues appear which guide the rest of the analysis. After this, both qualitative and semi-quantitative methods were applied to the hazard, vulnerability and risk assessments.

Guantánamo, one of the weakest economic provinces in Cuba, contains large natural reserves and protected areas in lowlands (25%) as well as in its mountainous regions (75%). The natural characteristics of the province makes landslide hazard assessment rather difficult since there is not a single set of environmental parameters to define a landslide model like other studies elsewhere. The landslide inventory allowed for differentiation of the five landslide types and therefore the whole hazard - vulnerability and risk analysis was then undertaken for these five types. However, temporal probability was assumed based on expert opinion (photo interpretation and fieldwork) and in the one hundred year return period of the triggering factors, rather than on actual frequency analysis of the landslide inventory. Each landslide type has its particular characteristics that need to be considered during the hazard and the risk assessment. This is often overseen in other landslide risk studies. The study did not take into account the expected landslide magnitude (or volume) due to the relatively small scale aerial photos that were available, and to the relatively small number of landslides for each landslide type. Based on the photo interpretation, fieldwork observations and the spatial correlation with the hazard indicators, each landslide type was described in as much detail as possible in order to create a descriptive model of the causal factors.

As the main focus of this research was risk assessment, testing several susceptibility methods that were already available was beyond the scope of the work presented herein. The weights of evidence (WofE) proved a useful first method for landslide susceptibility assessment as it allowed us to look in detail into the relationship between every class of every variable and landslides. Also in this study, the artificial neural network method (ANN) was applied to analyze the susceptibility of slides, since this particular type of landslide was dispersed over the whole territory and the weight of evidence values did not show clear relations with individual variable classes. This was an indication of the presence of more than one landslide generation model in the dataset. Better results were obtained as compared with those of WofE because ANN can be properly trained to cope with this problem. The ANN method with multiple training and included sensitivity analysis (Melchiorre et al., 2007) showed good results that could be replicated in other areas. Regarding the use of WofE, still more research needs to be done in other to recognize better possible effects on the output due in different characteristics of the data set such as factors classes and factors combination. Due to the scale of analysis, runout modelling was not included in this study.

Collecting information about the elements at risk was complex, mainly due to the lack of an appropriate geospatial data infrastructure and digital data available in the country. The most relevant example applied in the Guantánamo province was the estimation of inhabitants per house in the rural areas and in the residential areas within the settlements using the population density per settlement. Statistical information was linked with geospatial information disaggregating the population density. Even though this approach is an approximation, it shows a possible solution for risk studies over large areas where the number of inhabitants per house is not available.

One of the main limitations in the vulnerability and risk assessment is the use of weights instead of the actual replacement cost values or the production values, as these data were not available. The result is that the risk values can not be quantitatively estimated, and become only relative indications of risk levels. It is unclear in many risk studies how to quantify the social value of certain constructions such as: monuments, churches and cemeteries. This study introduces the commonly forgotten concept of environmental vulnerability by ranking the natural protected areas in the territory. The level of detail and the objectives of the provincial risk assessment did not allow for the construction of vulnerability curves for every single element at risk. Instead, the vulnerability for every element at risk was estimated based on literature and expert opinion, considering the "worst case scenario".

The hazard, vulnerability and risk assessments were carried out using both qualitative and semi-quantitative techniques, which showed advantages and disadvantages. In the qualitative assessments the results were more certain for the highest classes when compared with other approaches, while moderate and low classes could be overestimated. In the semi-quantitative assessment less area was covered with estimated values, but, a number of assumptions have always been applied in order to obtain a final map. In this case study, these assumptions included: unknown temporal probability, generalization for all range of magnitude, use of weights instead of monetary value for assessing vulnerability and on use of indirect cost or effect such as road blockage. Value maps are often wrongly considered as being better than class maps. However, one has to realize the amount of assumptions involved in the estimation and the (mis)interpretation for the final users on the meaning of the risk values. Commonly, the final users would only like to know about the spatial representation of risk into polygons with risk classes with a specific meaning and less frequently about of the actual risk values. For the risk analysis, these two types of maps were compared (Figure 5.20) and they were proposed for different types of users: disaster managers and physical planners. Nevertheless, much more research needs to undertaken in the field of risk visualization and its interpretation by the users. While the hazard assessment is validated by comparing with existing landslides, risk assessment is seldom validated. This is due to a non existing validation criterion, but also due to social characteristics of the risk assessment and evaluation. In this study, the results were presented to the national civil defence and provincial authorities for their evaluation. After extensive review, the authorities considered the findings to be satisfactory and subsequently ordered their inclusion into the disaster reduction plan for the Guantánamo province.

CHAPTER 6

Municipal landslide risk assessment

Based on:
Castellanos Abella, E.A. and van Westen, C.J. 2008. Qualitative landslide susceptibility assessment by multicriteria analysis: A case study from San Antonio del Sur, Guantánamo, Cuba. Geomorphology, 94 (3-4): 453-466

Cited as:
Castellanos Abella, E.A. 2008. Municipal landslide risk assessment. In: Castellanos Abella, E.A., Multi-scale landslide risk assessment in Cuba, Utrecht, Utrecht University, 2008. ITC Dissertation 154, 153-192 p. ISBN: 978-90-6164-268-8

6. Municipal landslide risk assessment

6.1. Introduction

The San Antonio del Sur municipality was selected in order to conduct landslide risk assessment at a municipal level. The selection was made based on the results obtained at provincial level (Chapter 5) and on the landslide inventory. Reported landslide occurrences (Castellanos Abella et al., 1998) highlighted that the municipality was one of the most problematic regions in the province for this type of disaster. Casualties from landslide disasters were known in different parts of the municipality and large landslides have been recognized in previous research (Magaz et al., 1991). Also, local authorities need to create a landslide risk reduction plan, but so far no landslide risk analysis has been carried out in this area.

For landslide risk assessment at this level, extensive use of detailed geomorphological mapping with photo-interpretation was utilized coupled with the results of an intensive fieldwork campaign previously carried out in his area (Castellanos Abella et al., 1998; Castellanos Abella, 2000). Geology, tectonic, geomorphology and landslides were analyzed in order to acquire deep knowledge of the problem before the hazard and risk assessment was undertaken. Figure 6.1 shows the main steps of the municipal assessment.

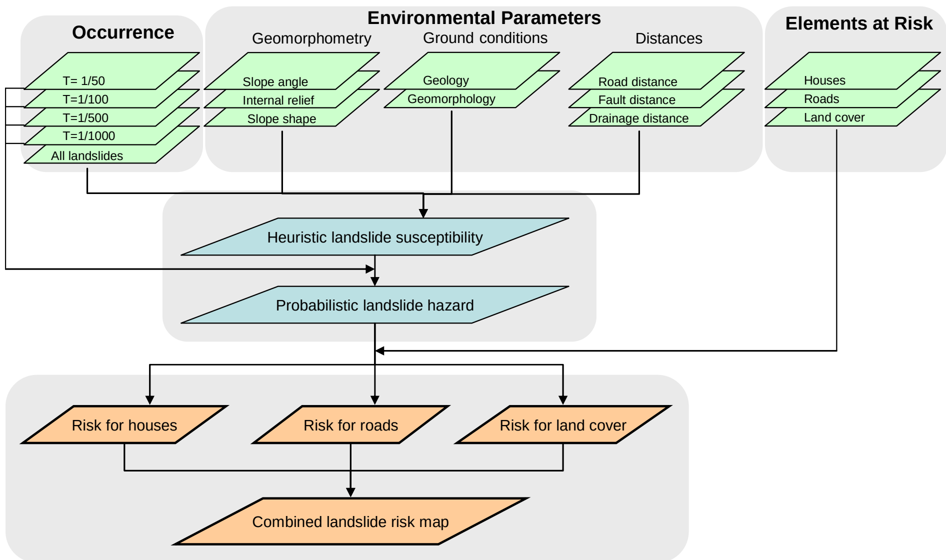

Figure 6.1. Flowchart for landslide risk assessment at municipal level.

The hazard assessment considered all landslides for susceptibility and four return periods for the probabilistic calculation of the hazard. Three elements at risk were considered: houses, roads and land cover. A landslide risk map for each element was made, as well as a combined landslide risk map.

While in provincial analysis statistical methods were employed for hazard assessment, at municipal level the analysis was mainly heuristic. The heuristic approach is considered to be useful for obtaining qualitative landslide hazard maps for large areas in a relatively short time (Soeters and van Westen, 1996; Barredo et al., 2000; Castellanos Abella and van Westen, 2001). It does not require the collection of geotechnical data, although detailed geomorphological mapping is essential. The heuristic approach may result in more reliable susceptibility maps than statistical methods, where a considerable amount of assumptions always need to be applied in the analysis.

Landslide risk assessment at municipal level is very important in Cuba as it is considered to be at a 'basic level' by the national multi-hazard risk assessment programme (AMA, 2007). The main objectives for carrying out landslide risk assessment at this level are:

1. Recognize landslides events and characterize their typologies and conditions in as much detail as possible.
2. Carry out landslide hazard, vulnerability and risk assessment identifying the areas where major landslide disasters are expected.
3. Inform municipal and local authorities about the areas at risk, including its characteristics and discussing possible countermeasures that can be implemented in order to reduce the risk.
4. Approve and implement (in agreement with all parties) a disaster reduction plan at municipal level considering existing resources or requesting support from upper levels.

The results obtained at this level allow us to recognise the distribution and magnitude of landslide hazard and risk for this particular area. Next sections describe details about the study area, its geology, tectonic, geomorphology and landslide problems; followed by hazard and risk assessment.

6.2. The study area: San Antonio del Sur

The study area, within the San Antonio del Sur municipality, is located in eastern Cuba (Figure 6.2) 60 km from the city of Guantánamo, the capital of the province with the same name. The main access to the area is by the coastal road connecting Guantánamo and the eastern municipalities. The population is mainly concentrated in the head of the municipality in the southern part or in settlements more inland. The other contingent of the population is dispersed in isolated houses represented as black dots in Figure 6.2. The area is widely covered by roads of different types which are generally in bad condition due to continuous rainfall and poor maintenance.

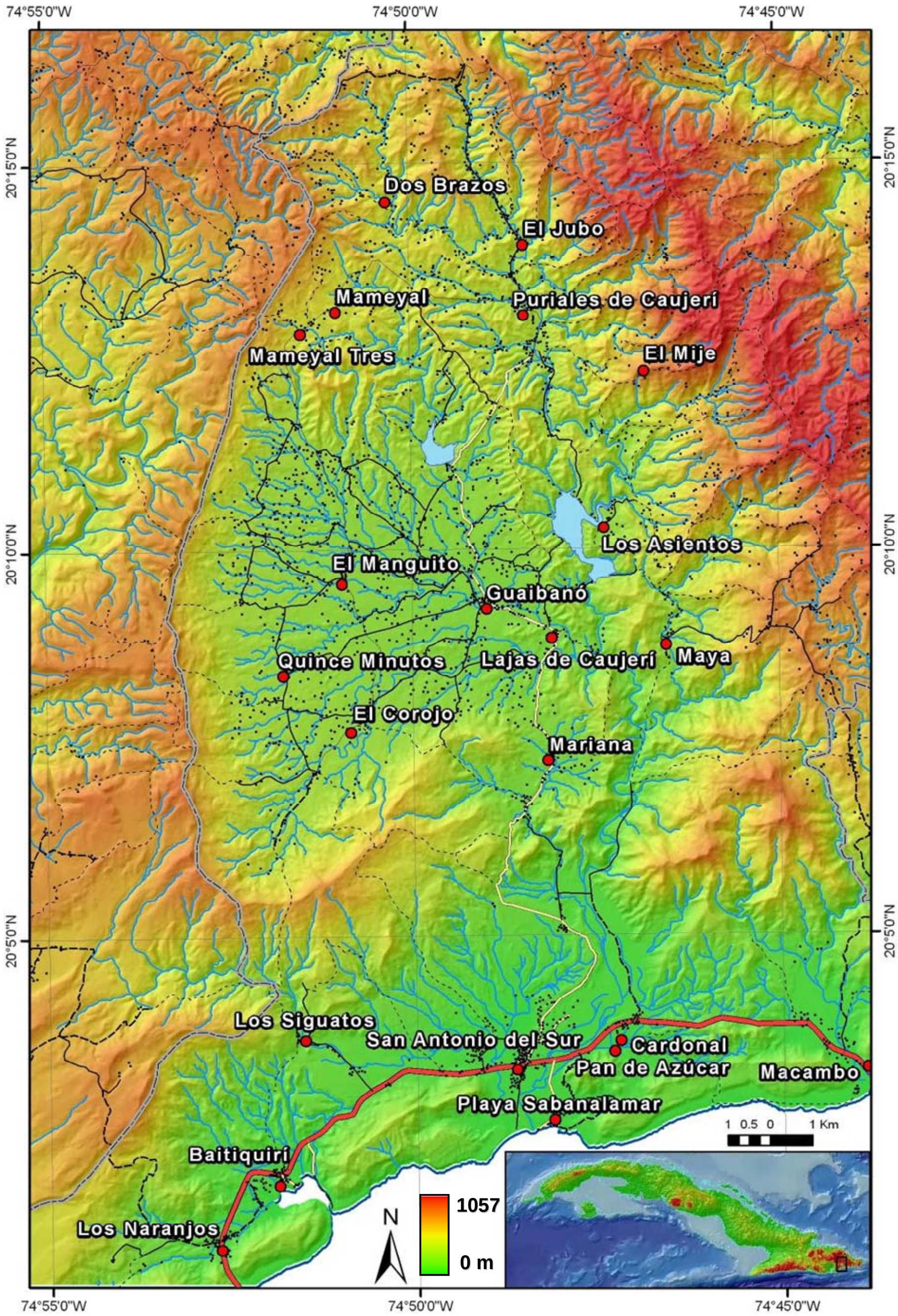

Figure 6.2. Location map with the shaded relief of San Antonio del Sur municipality. Main roads, houses and settlements named.

Natural processes are very different in this region due to geologic and climatic conditions. While the northern part is very humid, the southern part is very dry. Similarly, in the western part the limestone rocks control the landforms and process and in the eastern part weathered metamorphic rocks are more predominant. These features rule the natural processes including landslides. The area has an inner valley and a complex drainage system, as water is collected from both the valley as well as from the surrounding mountains in the north and the east (Figure 6.2) and is passed into a tectonic gorge that flows into the sea. More characteristics of the area are explained in the hazard and risk sections.

6.3. Data preparation and processing

Digital elevation model (DEM)

The digital elevation model was created using a vector dataset (elevation points, contours, lakes and streams) made available by the Sustainable Development Mountain Office of the Nipe-Sagua-Baracoa region. Some editing was required such as connecting and orienting the stream vectors downstream. The interpolation at 25 m resolution was carried out in ArcGIS by using a 'Topo to Raster' tool. DEM derivative maps including slope angle, internal relief and slope shape were also produced with ArcGIS tools. This resolution (25 m) was used for all other maps including the final results. It represents 0.5 mm at a scale of 1:50,000 - the scale at which the final map was presented to the local authorities. A shaded relief coloured with elevation values is shown in Figure 6.2.

Earth observation data

Different types of earth observation products including satellite data and aerial photos were used for various purposes such as interpreting the landslides, geology, tectonic and geomorphology. Table 6.1 shows a summary of available satellite data for the entire study area. Where, all satellite data were imported and georeferenced in ERDAS. Statistical analysis for each band of each sensor was undertaken in order to discriminate and therefore recognize features in the images. Several colour composites were also tested and the better results were obtained with 457 and 321 (RGB) for Landsat TM.

Table 6.1. Satellite data used in San Antonio del Sur

Satellite	Sensor	Date	Time	Spectral resolution	Spatial resolution
Landsat	TM	01/15/1985	14:51:03	Multispectral 7 bands	30 meters
Landsat	ETM+	08/03/2001	15:11:03	Multispectral 7 bands	30 meters
Terra	ASTER	25/10/2001	15:49:27	Multispectral 3 bands	15 meters
Terra	ASTER	14/02/2002	15:45:51	Multispectral 3 bands	15 meters
SPOT	PAN	28/12/1994	15:40:45	Panchromatic	10 meters
JERS-1	SAR	01/05/1994	15:27:39	Radar HH (L-Band)	12.5 meters

The Spot PAN was very useful for mapping the terrain units by creating the anaglyph image, as shown in Figure 6.7. The Spot PAN was also used in multiple data fusion techniques such as SPOT-DEM, SPOT-Landsat and SPOT-Geology. Details on these methods can be found in Castellanos (2000).

Table 6.2. CORINE classes and number of pixels for land cover.

CORINE Code	Class	Pixels
3.1.3	dense forest	15343
3.3.4	burnt areas	680
3.2.0	shrubs	2224
3.3.3	sparsely vegetated areas	1857
5.1.2	water bodies	17363
3.3.2	bare rock	1814
Mixed	bare rocks and shrubs	2521
4.1.0	wetland	108
2.0.0	agricultural land	11755

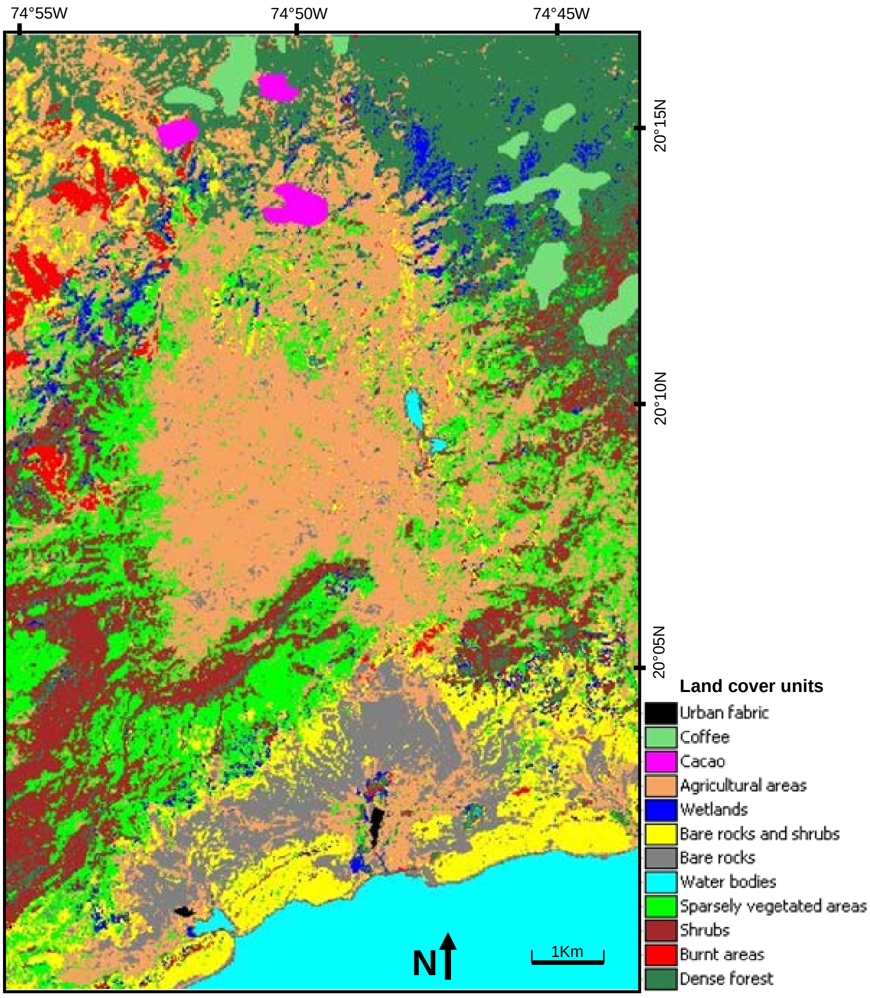

Figure 6.3. Land cover map obtained by image classification.

Landsat ETM+ was used for mapping land cover according to CORINE standards for land cover classes (EEA, 1999). The processing was carried out in

ENVI 4.2 and nine classes were selected for supervised classification as shown in Table 6.2. The overall accuracy was 90.71% with a Kappa coefficient of 0.8806. After that, based on provincial landuse map, image interpretation and fieldwork checking three classes were aggregated on the area: cacao and coffee plantations and urban fabric areas. The final land cover map is presented in Figure 6.3.

Geomorphological photointerpretation

A geomorphological map, including the landslide inventory, (Figure 6.6) at a scale of 1:50,000 was prepared from interpretation of two sets of aerial photographs (of 1:25,000 and 1:37,000 scale) and fieldwork. Both photo sets correspond to a national aerial survey carried out at the beginning of the 1970s. The 1:37,000 scale photos (55 in total) cover the whole study area with four flight lines and were taken between 2-Feb-1972 and 19-Mar-1972. The 1:25,000 scale photos (46 in total) cover the south-west part of the study area in three flight lines and were taken between 5-Dec-1971 and 21-Dec-1971. In these cases, the SPOT PAN and Google Earth high resolution images were used. Aerial photos were the main source for mapping the landslides and the terrain units. The photos were interpreted with a TOPCON stereoscope on transparent paper and transferred to digital format by onscreen digitizing using other image products for double checking (anaglyph, shaded DEM, Landsat TM true colour composite and digital topographic map). The photo-interpreted units were checked in the field by three people during a fieldwork campaign which lasted for three weeks.

Landslide database

For those areas, which were recognised as landslide parts, a different checklist was filled recording data for type, subtype, zone, subzone, age, depth, name and phase. The classification was made using the literature (Varnes, 1978; Varnes and IAEG, 1984; IAEG-Commission on Landslides, 1990; UNESCO-WP/WLI, 1990; UNESCO-WP/WLI and Cruden, 1991; UNESCO-WP/WLI, 1993; UNESCO-WP/WLI, 1994). The landslide types and subtypes are according to the classification as described by Varnes. The subtype actually is classified by type of material: rock, debris or soil. In some classifications the term 'soil' is substituted with 'earth', but with the same meaning (Table 6.3).

Table 6.3. Landslide types and subtypes using in the geomorphological survey.

Type	Subtype
Unknown	
Fall	Rock fall, debris fall, soil fall
Topple	Rock topple, debris topple, soil topple
Slide, Rotational	Rock slide, debris slide, mud slide
Slide, Translational	Rock slide, debris slide, mud slide
Spread, lateral	Rock spread, debris spread, soil spread
Flow	Rock flow, debris flow, soil flow
Creep	Soil creep
Complex	

The zone and subzone are in relation with the landslide parts. Table 6.4 shows the landslides zones and subzones surveyed for a final scale of 1:50,000 using the aerial photographs at a scale of 1:37,000. Because in some cases it was difficult to subdivide different landslides zones, 'mixed' zones were necessary like 'Scarp-Body' and 'Body-Transport' for those areas where the boundaries are not totally recognisable at this scale or where there is not an exact boundary to be mapped. Table 6.4 shows the subzones and a qualitative criterion about the activity. The Scarp subzones were classified according to the spatial location although the 'Tectonic scarp' was also surveyed as a one possible subzone. The tectonic scarp in the study area is a scarp created by tectonic movement, specifically a normal fault, where the foot-wall fault block goes up hence creating a scarp. Some areas have a combination of 'Tectonic scarp', which is a genetic classification and any of the other: Back, Side or Intermediate scarp. In a case like this the predominant was used.

Table 6.4. Landslide zones and subzones surveyed for a mapping scale of 1:50,000

Zones	Sub Zones and activity
Scarp	Back scarp, with recent activity
	Back scarp, with no-recent activity
	Side scarp, with recent activity
	Side scarp, with no-recent activity
	Intermediate scarp, with recent activity
	Intermediate scarp, with no-recent activity
	Tectonic scarp, with recent activity
	Tectonic scarp, with no-recent activity
Transport	Upper part, with recent activity
	Upper part, with no-recent activity
	Lower part, with recent activity
	Lower part, with no-recent activity
Body	Side slope on the body, with recent activity
	Side slope on the body, with no-recent activity
	Blocks on the body
	Normal body
	Remain body surface
Depression	With transversal cracks
	Slightly undulate
Initiating	Slope on depression
Scarp-Body	With recent activity
combination	With no-recent activity
Body-Transport	With recent activity
combination	With no-recent activity
All-mixed	With recent activity
(undifferentiated)	With no-recent activity

It was only possible to classify the transport zone into 'Upper' and 'Lower' parts, as this zone is strongly related to the flow landslides where the transport zone is still recognisable. A subzone was called 'Blocks on the body' only when close to the head of the landslide an area with large blocks was recognisable and could be separated from the rest. In others parts there are some areas which belong to former landslides bodies, but because a number of successive and multiple landslides cover the same area, a small surface remains and was called 'Remaining body surface' (Table 6.3). It is important to note that these classified areas are highly dependent on the scale of mapping, especially because at more detailed scale other landslides may be recognised within areas that now have other classification.

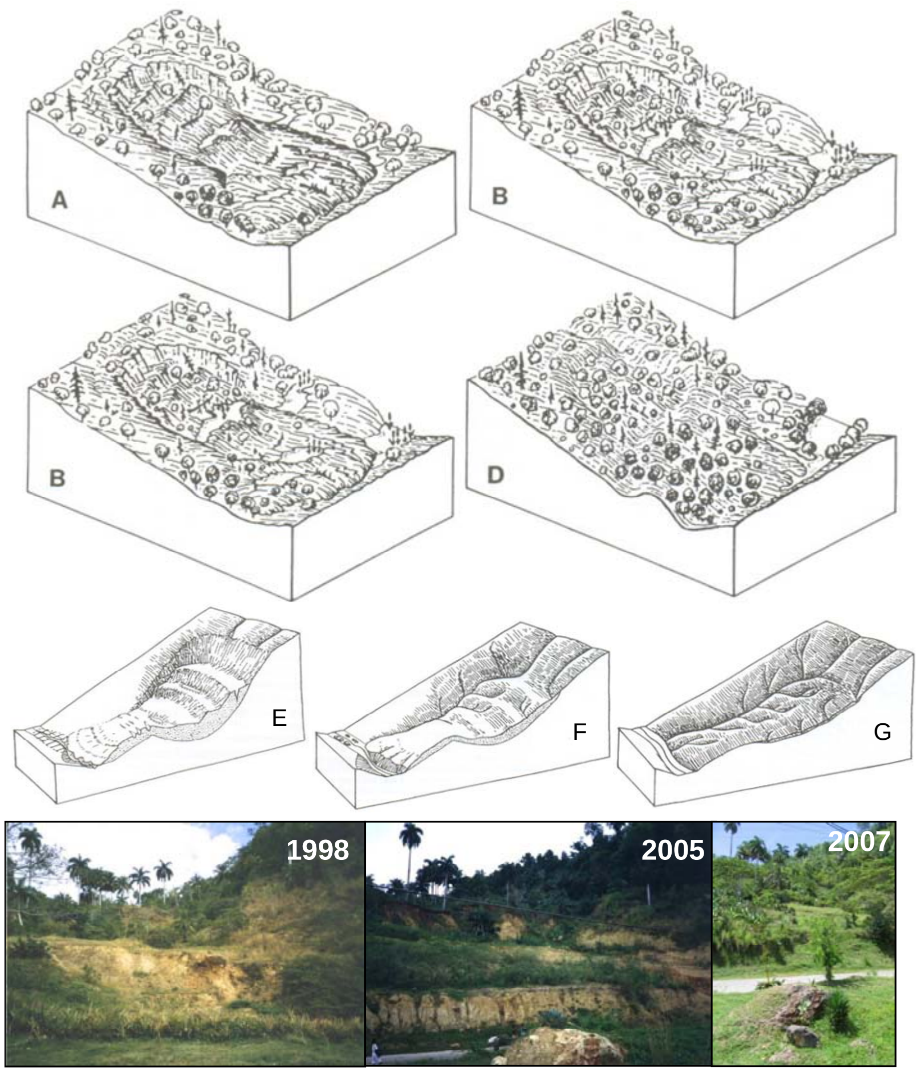

Figure 6.4. Geomorphological evidence for dating landslides. Diagrams A-D for humid climate (after Wieczorek, 1984), diagrams E-G for arid or semiarid climate (after McCalpin, 1984). In the lower part are photos from a single landslide in different years.

Since information about landslide date was incomplete, age classification was made based on geomorphological evidence recognised in aerial photos and checked during the fieldwork. The removal of landslides features after certain period is related to climate and lithological conditions. Figure 6.4 shows a schematic representation of this process for humid and arid climate. Although some authors recommend certain landslide ages (such as McCalpin, 1984; Wieczorek, 1984), they could not be directly applied worldwide due to the particular combinations of the conditions. In the study area, the climate and lithology change substantially from less preserved landslide features in the northern part to more preserved features in the southern coastal part. Earth observation data from different periods was analyzed in order to compare the preservation of landslides features along the time for particular litho-climatic condition. Based on these criteria, landslides were classified into four age classes: '1963 event landslides' with 1/50 years return period for 6 units, 'historic' landslides with 1/100 years return period for 19 units, 'old landslides' with 1/500 years return period for 157 units and 'very old' landslides with 1/1000 years for 113 units. The 1963 event, landslides are mapping units that were part of landslide that occurred during Flora hurricane in 1963. Figure 6.8 and Figure 6.9 show different landslides in the study area and the remains of their geomorphic features. The subjectivity in age classification of landslides makes the temporal statistics processing limited, but provides an approximation of the temporal component in the hazard and risk assessment.

All these information is attached to each landslide part in a GIS context where the Terrain Mapping Units (TMU) map is linked with the landslide database. The management and analysis was made in CARIS GIS in both directions: from map to database (spatially) and from database to map (by the attributes).

Other data

Other types of information useful for landslide risk assessment were mainly obtained from topographic maps, fieldworks campaigns and statistical offices. This information include: 3317 houses, 123 springs, 88 schools facilities and the road system. The digitalization was carried out in ILWIS with a CALCOMP 3400 A0 Format digitizing table. After digitizing, the data was imported in CARIS (CARIS GIS, 2007), where the hazard assessment was carried out. Details on this data are provided in the following sections.

6.4. Assessment of landslide hazard

6.4.1. Geology and tectonic

The geology and tectonic setting of the eastern part of Cuba is rather complicated, and includes several geological and tectonic environments in a relatively small area. The different tectonic and structural processes have overlapped over geological time in such a way that it is difficult to separate them spatially and temporally. Moreover, the area remains an active tectonic zone on the northern boundary between the Caribbean and North American plates, as can be seen by many neotectonic features and by the continuous general uplift of the area. The general geology of Cuba is divided into two principal units: a foldbelt and a neoautochthon (Iturralde-Vinent, 1996), which unconformably overlies the foldbelt (Figure 6.5). The eastern part of Cuba and the study area have been studied by (Nuñez et al., 1981; Nagy et al., 1983; Millán and Somin, 1985; Franco, 1992). Detailed information about the geology and tectonic setting of San Antonio del Sur can be found in Nuñez Cambra (2000).

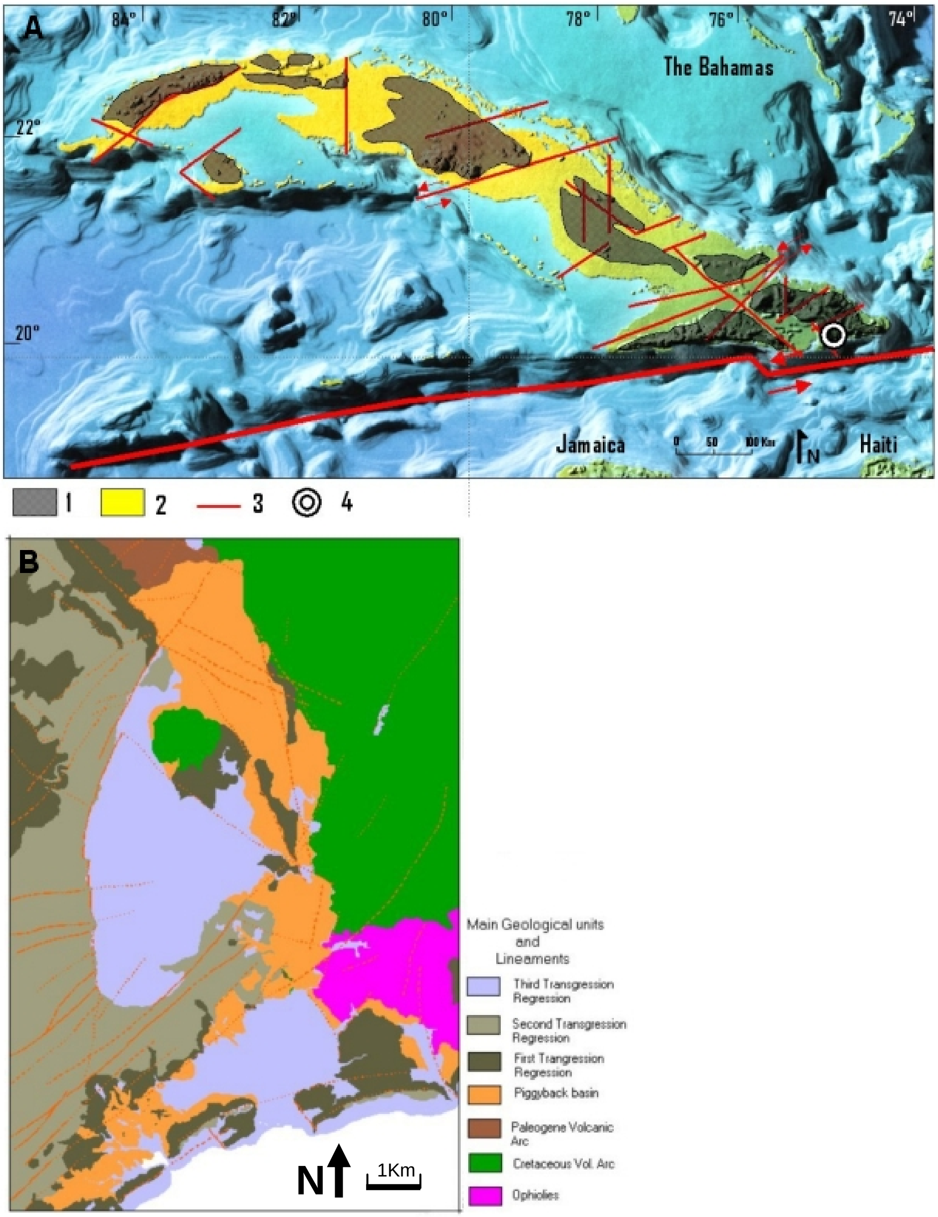

Figure 6.5. A: Main geological units of Cuba. 1 = outcrops of the foldbelt, 2 = Eocene to Recent neo-autochthonous deposits, 3 = Main faults, 4 = Study area. B: general geological map of the San Antonio del Sur municipality, Guantánamo province, Cuba.

The study area contains geological units from both the foldbelt and the neoautochthon. The foldbelt consists of a Northern Ophiolite belt, a Cretaceous Volcanic arc, a Paleocene Middle Eocene volcanic arc and a Late Middle Eocene piggyback basin (Figure 6.5). The ophiolites are represented in the study area by a hilly zone in the southeast called 'Sierra del Convento' (Figure 6.6). It is the surface expression of a larger body considered as a relic of the basement, which emerged due to spreading of the oceanic crust, pushed from the south by tectonic events (Chang and Suarez, 1998). Rocks of the Cretaceous volcanic arc belonging to the Sierra del Purial Formation underlie the eastern part of the study area with low grade and high pressure metamorphism. Deposits from the Paleocene volcanic arc, belonging to the El Cobre Group, can be found in the north of the area (Figure 6.5). The piggyback basin corresponds to the Paleocene–middle Eocene volcanic arc. The Charco Redondo, San Ignacio and San Luis formations represent this basin in the study area. These formations cover the northeast up to the central part, and consist of polymictic sandstones, mudstones, marls, clays, limestone clays, bioclastic limestone, sandy limestone and polymictic conglomerates.

The western and central part of the study area is underlain by the 'Neoautochthon', recent units formed in situ, and which are represented in the study area by formations from three transgression–regression phases which occurred since the Late Eocene (Iturralde-Vinent, 1996). The first such cycle is from Late Eocene to Oligocene (Phase1) and consists of alternating layers of sandstone, mudstone and calcareous clay. The second cycle is from Early Oligocene–Late Miocene (Phase2), and is characterized by alternating layers of clastic, bioclastic and biogenic limestone (Figure 6.5B). The third cycle is Late Pliocene to recent (Phase3) and is characterized by algae-bearing bioherm limestones, with corals, and recent marine sediments.

6.4.2. Geomorphology and landslides

The geomorphology of the study area was conditioned by the Caribbean–North American inter-Plate zone, and the paleoclimatic oscillations during the Quaternary period. Figure 6.7 presents an overview of the study area as an anaglyph image, generated from a digital elevation model and a SPOT-PAN image. For 3-D viewing of the image, red–green glasses are required. In the annexes in the supplementary CD-ROM this image can be found at higher resolution. The inter-Plate boundary consists of a strike–slip fault system (Figure 6.5) of which secondary faults has topographic effects inland (see Figure 6.7, complexes C and B). The Quaternary sea-level oscillations left coastal hills with marine terraces and abandoned valleys (see Figure 6.5, complexes D, E and F).

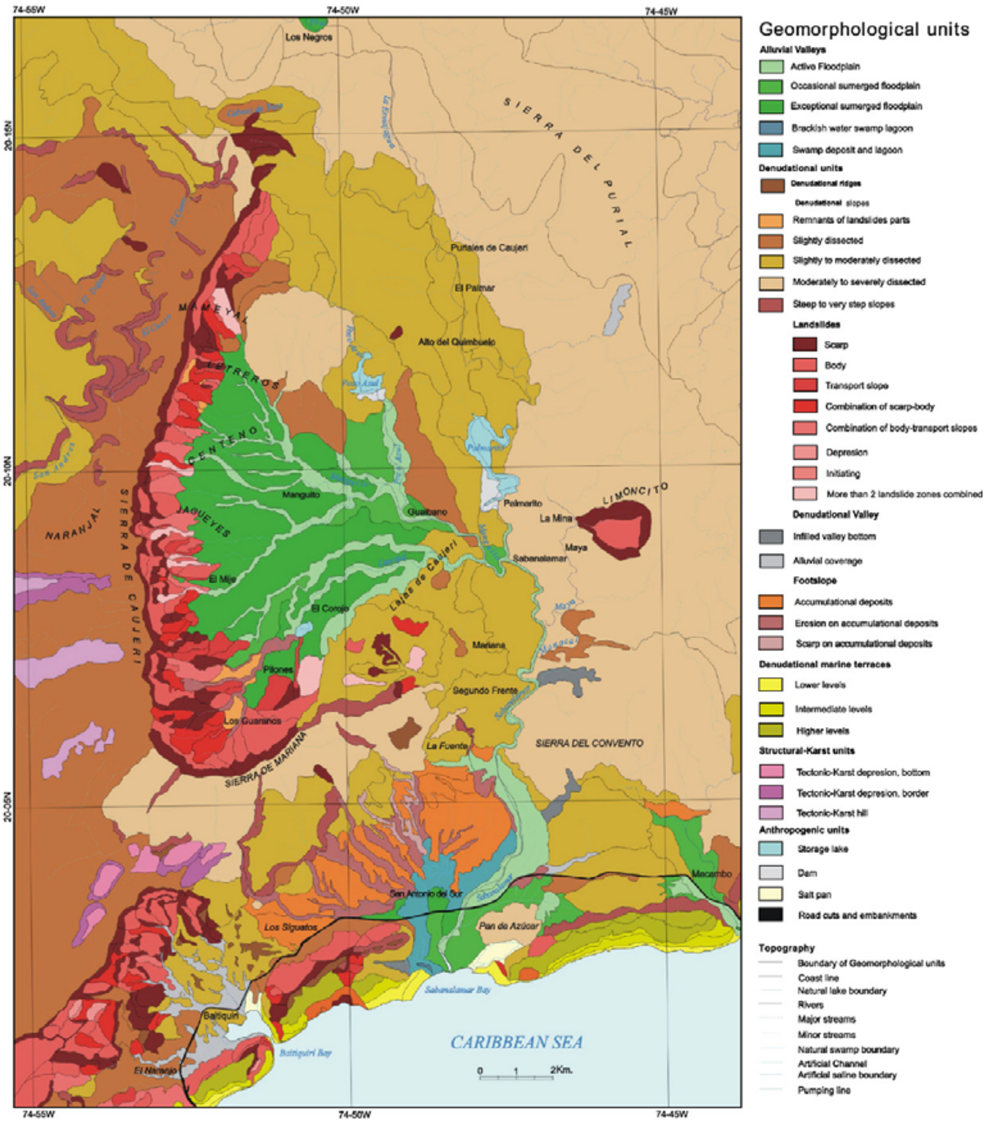

Figure 6.6. Geomorphological map. San Antonio del Sur, Guantánamo Province, Cuba. See annexes for full scale map.

The area was divided into 603 terrain mapping units (TMU). A TMU can be considered as a homogeneous mapping unit on the basis of geomorphologic origin, physiography, lithology, morphometry, and soil geography (Meijerink, 1988). Normally, a single landslide was considered as an individual TMU. In certain cases, when the size was large enough, landslide zones such as scarps, bodies and depressions were also considered as separate TMUs. The units have been combined into the following geomorphological complexes:

– Denudational hills (metamorphic rocks, terrigenous rocks, and limestone) (A, B and C in Figure 6.7)
– Alluvial units and accumulational slopes (D and E in Figure 6.7)
– Coastal hills (F in Figure 6.7)
– Puriales de Caujerí depression (G in Figure 6.7)

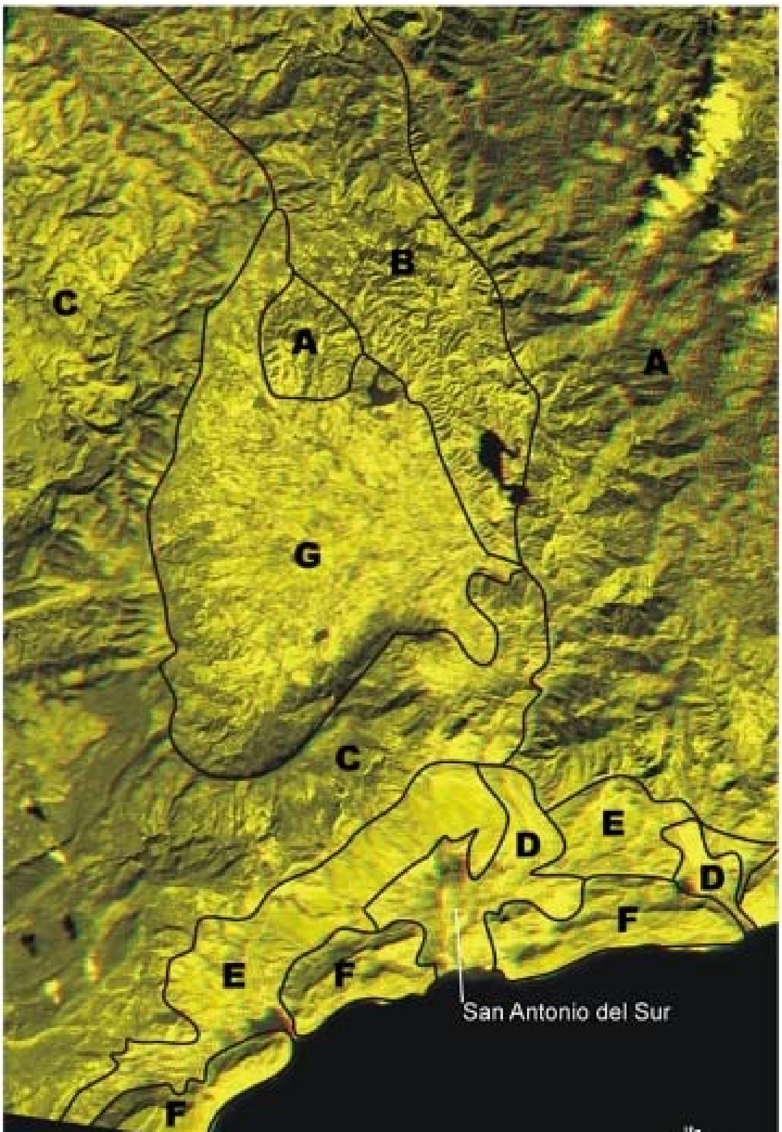

Figure 6.7. Geomorphic complexes of the study area: A, B, C: denudational hills in metamorphic rocks, terrigenous rocks, and in limestone respectively; D: Alluvial units; E: Accumulational slopes; F: Coastal hills; G: Puriales de Caujeri depression. This anaglyph image requires red–green glasses for viewing in 3-D.

Denudational hills

Denudational hills can be separated by the underlying lithology into a limestone plateau (C in Figure 6.7), metamorphic hills (A in Figure 6.7) and terrigenous hills (B in Figure 6.7). The plateau is a monocline at an average altitude of 500 m, composed mainly of limestone from the Yateras formation (Phase2) with extensive karst processes and additional erosion where the underlying mudstone and calcareous clay from the Maquey formation (Phase3) are exposed. The area is dominated by neotectonic processes such as faulting, and a number of large deep-seated mass movements are observed which could reflect a mix of gravitational and tectonic movements (Figure 6.7). The landslides are concentrated in the northern part of Baitiquirí and El Naranjo (Figure 6.8). As the whole area is strongly affected by active faults the landslides are located in three main 'steps' from the limestone hills toward the coast (Figure 6.8A). In the upper part the landslides occur in limestone rocks of Yateras formation (Figure 6.6). In the next two steps the landslides occur over terrigenous materials (Figure 6.8, B and C). All the main landslide features are aligned with the major faults in the directions SW–NE, N–S and W–E, and they occur often where the faults are converging (Figure 6.8). In some of the upper portions of the large landslide masses the total amount of displacement has not been more than a few metres. Displacements were greater on the lower steps and individual landslides are more difficult to delimit because they occurred in a multiple and successive way, often one on top of another. The main types in this area are rotational rockslides in the upper part, often with multiple scarps and debris slides in the lower parts, combined with extensive rill and gully erosion. It is difficult to define the age of the landslides, but the multiple and complex landslide forms indicate that mass movements have been active over a long period of time, and are associated with the activity of the faults - probably with relatively minor individual displacements per event. The most recently known landslide occurred in 1997, during an intensive rainy season, but was probably caused by a leaking water pipe (it destroyed a mini-hydroelectric power plant). Landslides in the denudational hills underlain by metamorphic and terrigenous rocks (Figure 6.7, A and B) are generally smaller than those in the limestone hills, and are not so related to tectonic lineaments. Most of them are shallow rotational landslides occurring rather at random on the steep hill-slopes or along river incisions.

Alluvial units and accumulational slopes

The Alluvial valley complex is related to recent sediments accumulated by the principal river systems (Figure 6.7D and Figure 6.6 for names). Sabanalamar river floodplain, Macambo river floodplain and the most recent fluvial channels in the Caujerí valley are part of this complex. They are composed of alluvial and swampy deltaic deposits where the rivers end in submerged valleys, due to tectonic uplift. This complex is essentially a fluvial plain with a combination of erosive and accumulation processes. Accumulation prevails in the Sabanalamar and Macambo floodplains and erosion in the Caujerí valley. Three floodplain levels are recognizable: active, occasionally submerged and exceptionally submerged floodplains. The area is regularly inundated during intensive rain. Close to Sabanalamar Bay and in the surroundings of San Antonio del Sur town, there are brackish water lagoons and swamps. Also, Mangrove vegetation is abundant only in the mouth of the Sabanalamar River.

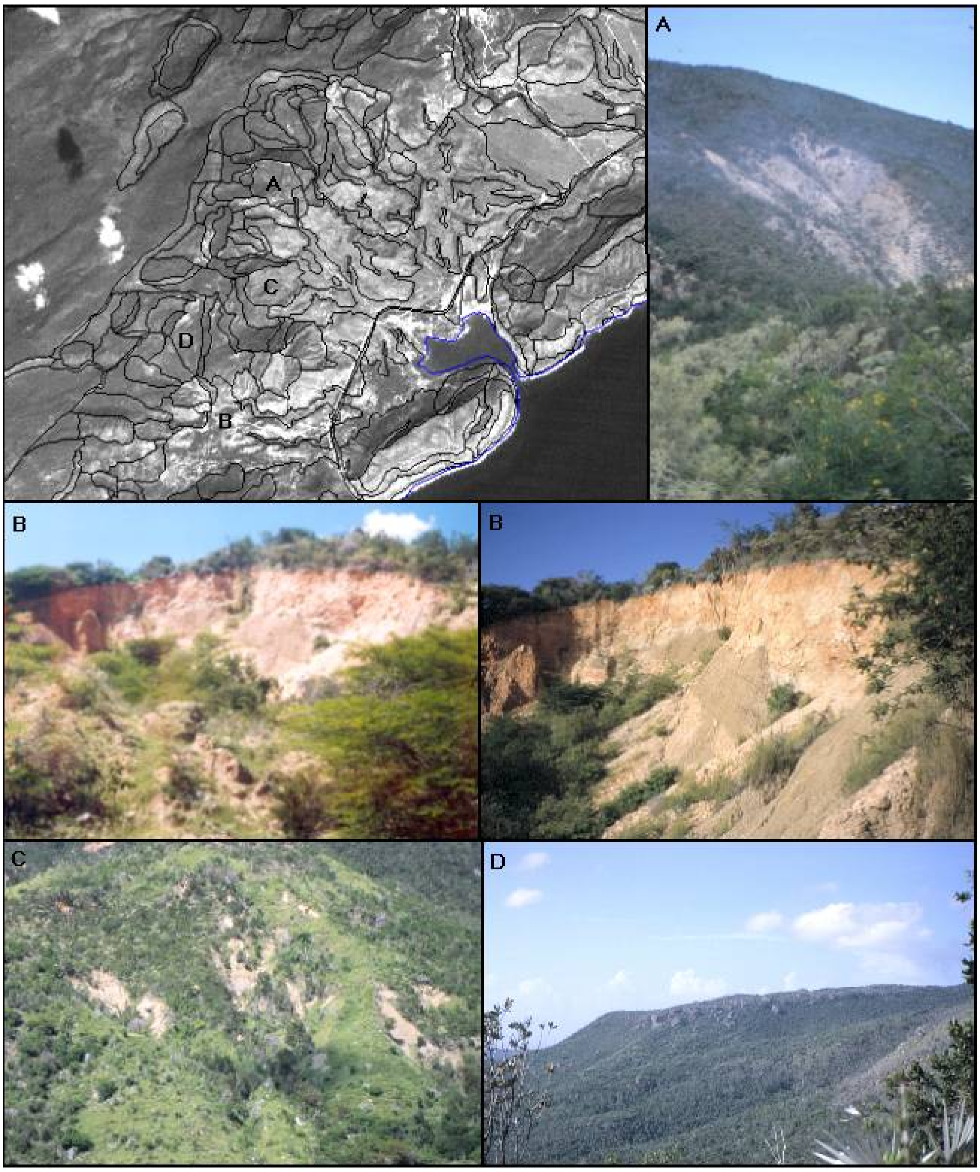

Figure 6.8. Landslides in denudations hills (see text for an explanation).

The accumulational slopes are located in the northern part of the coastal hills (Figure 6.7). It is an intra-mountainous fluvio-marine deltaic plain approximately 2 km wide, sloping slightly to the south (sea) side at 5 to 15°. The materials range from colluvial, close to the mountains, to fluvio-marine. This complex seems to belong to an old planation surface, which collected all the sediments coming from the upward area, in what is now Sierra de Mariana (Figure 6.6), during the Pleistocene. The extension and volume of the Quaternary sediments reveals that rainfall at that time was higher than currently. This might be true considering the fact that in the northern border of the Sierra de Mariana the drainage seems to be cut-off due to large mass movements. In both the western and eastern sides of the area, the Pleistocene sediments are not present. In the western side the drainage system was sufficiently strong enough to erode the sediments into the Baitiquirí Bay, besides this part appears to be slightly more uplifted. In the eastern part the pre-Quaternary formation overlies the ophiolites and the area has an irregular relief. The planation surface is raised 10 to 30 m above the current erosion levels, and around ten new channels have eroded the old plain and generated erosional scarps with the same height differences. The alluvial unit and accumulational slopes do not contain any major landslide features.

Coastal hills

These hills parallel the coastline (Figure 6.7), with variable length and a width between 1 and 2 km. Three coastal hills can be differentiated, between El Naranjo and Baitiquirí Bay, between the Baitiqurí bay and Sabanalamar Bay (Loma Los Aposentos) and between Sabanalamar Bay and Macambo town (see names in Figure 6.6 and relief in Figure 6.7F). The north side is totally covered by the Maquey formation (Phase1), mudstone and calcareous clay susceptible to landslides. The coastal slope (characterized by marine terraces) is composed of the Maya formation (Phase3) consisting of recent (Holocene) marine deposits. These deposits act as 'rings' of the coastal hills and are uplifted between 5 and 10 m from current sea level.

The different material and morphological characteristics on both sides of the coastal hills also result in different landslide types. Northern slopes are characterized by frequent, but small debris flows (Figure 6.9C). On the coastal side, rockfalls occur in the marine terraces, caused by a combination of karstic dissolution and physical weathering processes and triggered by wave erosion. Large blocks with volumes between 15 to 40 m3 can be found as part of the rockfalls (Figure 6.9D). On top of the cliff various cracks delimit the boundaries of future rockfall events. Magaz et al. (1991) mapped three large rotational and two translational rockslides in the marine terraces, covering the entire seaward side of the coastal hills. Two of the large rotational landslides are pre-Holocene because the lower terrace was formed on top of the landslide toe (Figure 6.9A). The third landslide in Los Aposentos coastal hill (Figure 6.9B) is more recent than the others, since the lower terrace (Holocene) was also destroyed.

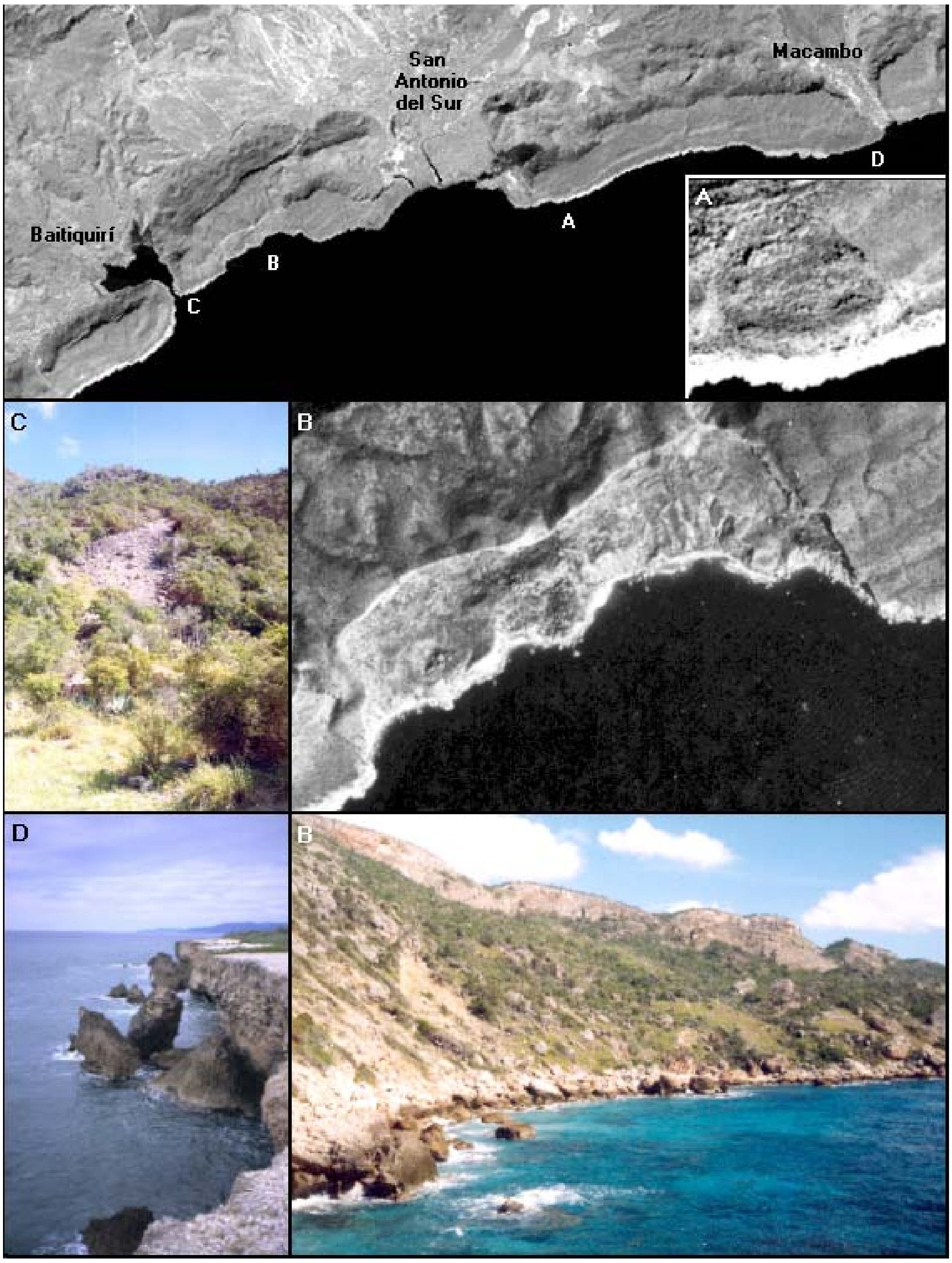

Figure 6.9. Various coastal landslides (see text for an explanation).

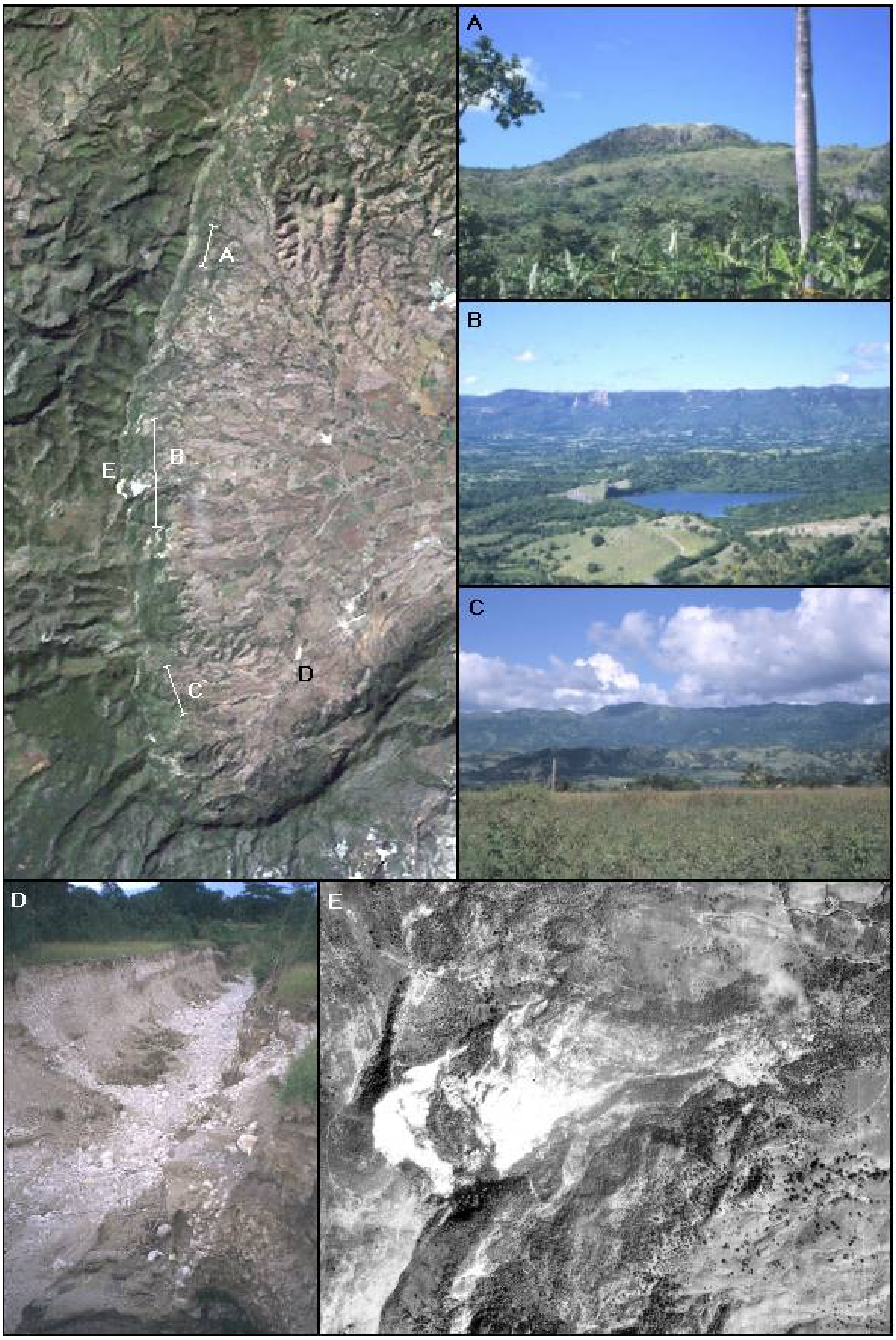

Figure 6.10. Landslides in Caujerí Scarp (see text for explanation).

Puriales de Caujerí depression

By far the most striking geomorphological feature in the study area is the large oval shaped depression (Puriales de Caujerí valley), which is considered to be a graben with elevation differences up to 500 m. The valley is limited on the west by a large scarp of the Sierra de Caujerí, with active retrogressive mass movements. On the southern and northern parts the valley is also surrounded by major fault scarps. The origin of the Puriales de Caujerí depression can be interpreted as a combination of tectonic and mass wasting processes. The main fault systems (Sierra de Mariana and Sierra de Caujerí) started to generate a graben depression after the second Transgression–Regression period (Lower Miocene to Late Miocene). After that, the 15-kilometer-long N–S oriented Sierra de Caujerí carp, 300 to 400 m high, has been the main area of landslide activity. In the north, the scarp ends 3 to 5 km north of Mameyal and has less recent landslide activity (Figure 6.10). In the south the scarp intersects the fault-controlled Sierra de Mariana scarp creating another area with large landslides (Figure 6.10C). Due to the long period of the occurrence of landslides in the area, they occasionally can be found in current agricultural land large gully and ravine erosion (Figure 6.10D).

The most catastrophic landslide in the Sierra de Caujerí scarp occurred during the passing of cyclone Flora on October 8, 1963, the most devastating meteorological event known that affected Cuba (see Figure 6.10E). Detailed information on this event is given in Chapter 7. Most of the landslides in the Sierra de Caujerí scarp consist of a large scarp on the upper part, often up to 100 m high, which almost vertically cut the limestone layer of the Yateras formation (Phase2), and the underlying Maguey formation (Phase1). This scarp is actually the back-scarp of multiple landslides, which changes from rockslide to debris flows. Around 150 different landslide events have been mapped along the Sierra de Caujerí and Sierra de Mariana scarp (Figure 6.6 and Figure 6.7).

6.4.3. Heuristic hazard assessment

The geomorphological mapping provided in-depth knowledge of the causal factors for landslides in the study area and was used to assess landslide susceptibility. Qualitative weighting, one of the heuristic methods (Soeters and van Westen, 1996), was selected, given the relative small scale, the available data, and the characteristics of the study area. Besides, the TMU mapping may produce biased results when using a statistical method due to the high spatial correlation between the landslides inventory and some units in the TMU map. Also, deterministic models required data that was not available for the whole area such as soil depth and geotechnical parameters.

The analysis was carried out in different steps following the spatial multi-criteria evaluation module of ILWIS (ITC, 2001), according to the analytic hierarchy process (Saaty, 1980; Saaty, 1996; Saaty and Vargas, 2001). First the various components (causal factors) in the model were selected, and their hierarchical relationships determined. Weights were then assigned to these maps, in a standardized way. A combination formula integrated the weights in order to produce a final map, which was divided into a number of classes (Bonham-Carter, 1996).

Detailed explanation about the analytic hierarchy process and multi-criteria evaluation was given in Chapter 4 for the national landslide risk assessment. In this section, only the issues concerned with this case study are explained. The design of a heuristic landslide hazard model requires thorough analysis of the causative factors and their relationships in the study area, which was made based on the geological and geomorphological interpretation along with the fieldwork campaign. The selection of the model components was organized in a tree-shaped structure (Figure 6.11). The uppermost general level of the components is called criteria, and consists (in ranked order) of Geomorphology, Topography, Geology, Tectonics, and Hydrology. These criteria were further subdivided into nine variables, specific attributes, such as slope, internal relief and slope shape for Topography. The variables are described in Table 6.5. The relation of each to landslide occurrence can either be favourable or unfavourable.

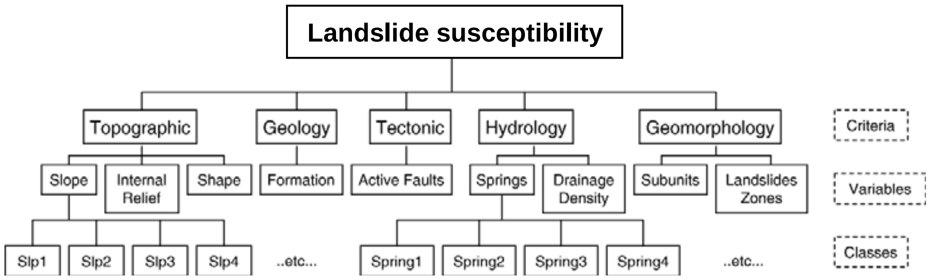

Figure 6.11. Components of the heuristic landslide hazard model.

Table 6.5 Variables for the heuristic model. See text for explanation. (N/A – Not applicable)

Variable	Origin	Scale	Units	Relation
Slope	From the original DEM	Interval	Degrees	Favourable
Internal Relief	From the original DEM	Ratio	Meters/ hectares	Favourable
Shape	From the original DEM	Ratio	N/A	Favourable
Geology	By reclassifying the TMU map	Categorical	N/A	N/A
Faults	Calculating a distance from the fault map and dividing into four classes	Ratio	Meters	Unfavourable
Springs	Calculating a distance from spring points and dividing into four classes	Ratio	Meters	Favourable
Drainage Distance	Calculating a distance from the drainage map and dividing into four classes	Ratio	Meters	Favourable
Geomorpho logical Subunits	By reclassifying the TMU map	Categorical	N/A	N/A
Landslides subzones	By reclassifying the TMU map	Categorical	N/A	N/A

(N/A – Not applicable)

The variables selected needed to be standardized in order to properly compare them. The values of the variables were converted into a number of classes, depending on the type of variable. Every class received a value between 0 and 100, considering that the value of all classes in one variable needed to add up to 100. Class boundaries for numerical variables were selected from the 25-cumulative percentage intervals of their histogram. The classes of the categorical variables (e.g. geology) were 'weighted' according to a ranking method (see below).

Once all the variables were standardized, weights were assigned to the corresponding levels of criteria and variables in three different ways: directly by expert opinion, by pairwise comparison matrix and by ranking. The weight values range between 0 and 1 and need to add up to 1 among the variables within a criterion and among the criteria. For checking the weight assignment the decision-support system called DEFINITE was used (Janssen and Van Herwijnen, 1994). In the first method the weights of the criteria and variables were assigned directly based on expert opinion and field experience. For the pairwise comparison matrix, each variable (or criterion) is compared to all others in pairs in order to evaluate whether they are equally significant, or whether one of them is somewhat more significant/better than the other for the goal concerned. In the ranking method, the criteria and variables are simply ranked according to their importance as landslide controlling factors, where the rankings can be considered units on an ordinal scale. Consequently, the weights can be found by standardizing the rank order (Voogd, 1983). The values for criteria, variable and classes were tabulated using Microsoft Excel and a simple summation formula applied to interactively evaluate the effect of the weights on the overall weight of the qualitative landslide hazard.

Table 6.6. Weight for criteria and variables for three methods

Components	Direct Method		Pairwise Matrix		Ranking method	
Topography	0.3		0.224		0.257	
Slope		0.7		0.7		0.7
Internal Relief		0.2		0.2		0.2
Shape		0.1		0.1		0.1
Geology	0.2		0.131		0.157	
Formation		1		1		1
Tectonic	0.05		0.040		0.065	
Active faults		1		1		1
Hydrology	0.05		0.038		0.065	
Springs		0.5		0.5		0.5
Drainage distance		0.5		0.5		0.5
Geomorphology	0.4		0.566		0.457	
Subunits		0.4		0.4		0.4
Landslides zones		0.6		0.6		0.6
Total for criteria	1		0.999		1.001	

Analyzing Table 6.6, it can be seen that the three weighting methods gave comparable results. For the pairwise comparison matrix method the inconsistency value was 0.08, demonstrating that the weights are sufficiently reliable. The inconsistency parameter measures randomness of the expert judgments, and ranges from 0 to 1. As a conclusion the initial weights that were assigned by expert opinion were taken for the analysis.

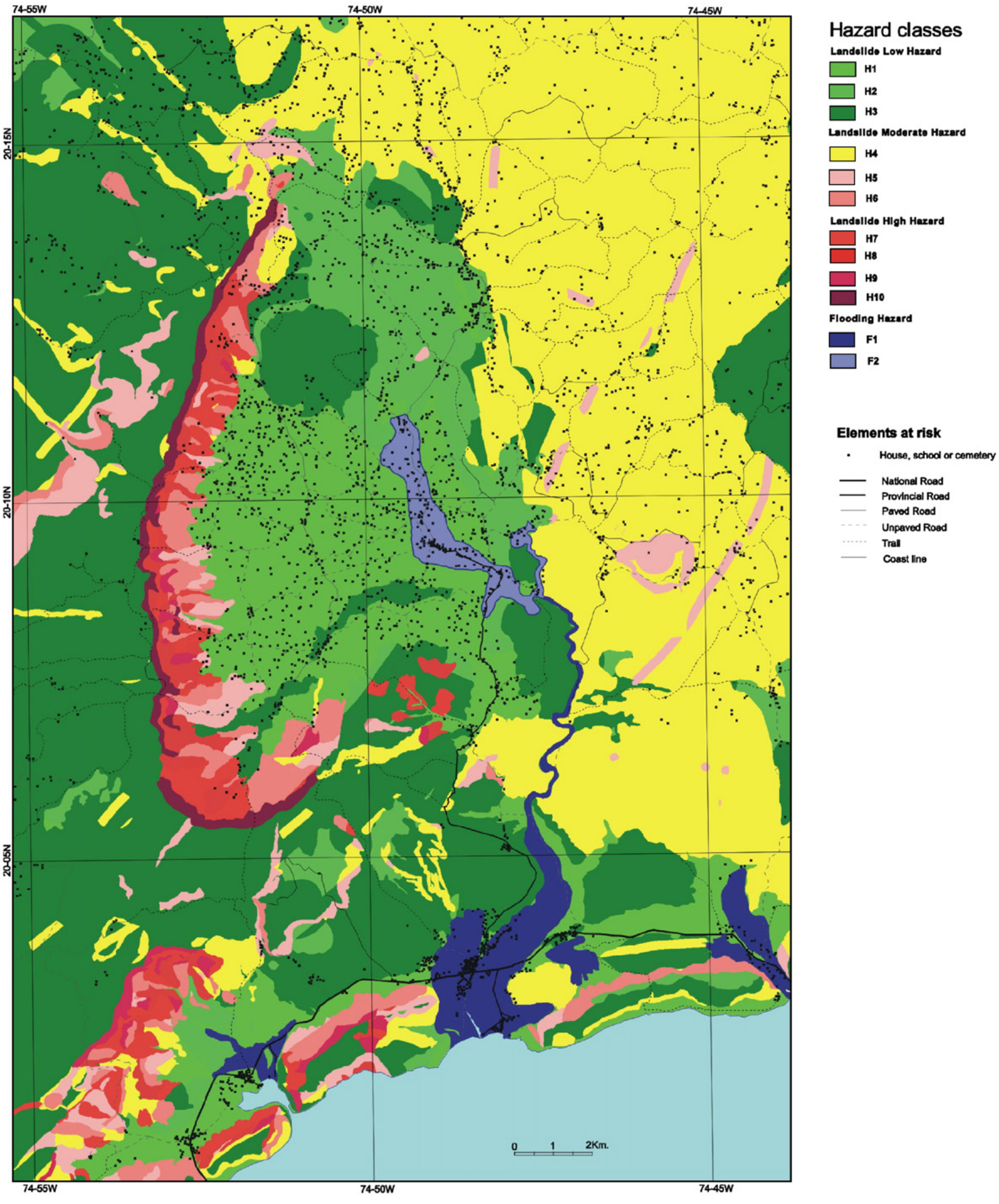

Figure 6.12. Qualitative landslide hazard map. San Antonio del Sur, Guantánamo, Cuba. See Table 6.7 for explanation of the legend.

Table 6.7 Characterization of the ten landslide hazard classes and two flooding hazard classes.

Hazard	Overall class	Hazard Class	Weight range	Area (ha)	Number of TMU units	Number of landslides	Area of landslides (ha)	Landslide density (%)
LANDSLIDES	LOW	H1	0.50-5.16	8,669	88	0	0	0
		H2	5.17-9.82	4,176	40	0	0	0
		H3	9.83–14.48	18,107	125	8	210	1.1
	MODERATE	H4	14.49–19.14	18,361	94	22	338	1.8
		H5	19.15 – 23.80	2,013	85	46	901	44.7
		H6	23.81 – 28.46	1,702	87	79	1,428	83.8
	HIGH	H7	28.47 – 33.12	969	77	76	963	99.3
		H8	33.13 – 37.78	719	59	59	715	99.5
		H9	37.79 – 42.44	291	36	36	289	99.4
		H10	42.45 – 47.10	439	24	24	438	99.8
FLOODS	-	F1	N/A	1325	15	0	0	0
		F2	N/A	503	6	0	0	0

In order to calculate a ‘final weight’ for a single pixel the weights of the three components (class value, variable and criterion) were simply multiplied together. For example, the slope class ‘shp4’ (>20.4°) has a weight of 50, which was multiplied by the weight of the ‘Slope’ variable (0.7) and by the weight of the ‘Topography’ criterion (0.3), so that the final weight was 10.5. Final weights were calculated for each variable and resulted in separate layers, which are generated with the CARIS GIS software package (CARIS GIS, 2007) for the spatial overlay analysis. In this GIS, each class is created in raster format by different options according to the map characteristics: by buffering (e.g. distance to faults), by selecting polygons (e.g. TMU subunits) and by reclassifying pixel values in a raster image (e.g. slope angle values). All weight maps were added into a layer with final weights.

The final weights of the resulting map ranged from 0.5 to 47.1. This map was classified into ten divisions interactively, during which time the relationships with existing landslide areas and geomorphological units was evaluated. Although the map gives a good indication of the qualitative landslide hazard in the study area, too many classes might make it difficult to use by decision makers for development planning. Therefore, the susceptibility map has ten classes, which are grouped into three simplified categories: high, moderate and low (Figure 6.12 and

Table 6.7). The final susceptibility map was combined with the TMU map-database in order to obtain information about the attributes for each hazard class.

Table 6.7 shows the legend of the final landslide susceptibility map with statistical information related to the number of landslides and landslide density per class.

Considering the characteristics and conditions of every overall hazard class the following description was supplied to the local authorities together with the hazard map:

- Low landslide hazard (H1, H2 and H3). No landslides expected. Areas can be corridors for mudflows or other intensive mass wasting processes. In some parts small landslides can happen in extreme conditions. The areas are suitable for development projects.
- Moderate landslide hazard (H4, H5 and H6). Moderate to high possibility of landslides occurrence during intensive or prolonged rainfall. These areas contain most of the existing landslide zones. Most of the landslide materials are unconsolidated and susceptible to being reactivated in smaller proportions. More studies are required for development of the area. Land use changes should be previously studied in relation to landslide hazard problem.
- High landslide hazard (H7, H8, H9 and H10). High to very high landslide hazard areas. A high possibility of landslide occurrence during rainy conditions. No development is recommended in these areas. Possible relocation of land for agricultural use. Highly recommended re-allocation of existing population in these areas
- Flooding areas (F1) up to five years return period taken from local civil defence authority and updated yearly. Appropriate warning system needs to be maintained. The area could be used for seasonal agricultural products. Land-use planning should consider flooding hazard limits to re-allocated existing infrastructure and avoid new developments.
- Dam break flood limit (F2) taken from dam project report. Engineering conditions of the dam should continuously be checked. The area could be used for agricultural products. Land-use planning should consider this hazard limit to re-allocated existing infrastructure and avoid new developments.

Additionally, in the final hazard map the flooding areas were included with two categories: flooding zones (F1) and dam break zones (F2) (Figure 6.12 and

Table 6.7). Flooding zones were primarily acquired from a disaster management plan used by the local civil defence authority. The flooding boundaries were corrected by photo-interpretation, DEM analysis and fieldwork. Dam breaks zones were obtained from the dam project reports made by the Institute of Water Resources for the Guantánamo province. The two areas mapped are related to Pozo Azul and Palmarito dams. Dam location and names appear in Figure 6.6. More detail information about the flooding zones was available, but could not be displayed at a scale of 1:50,000.

From susceptibility to hazard

Once the hazard classes were obtained, the next step was to assign a probabilistic value to each class. Table 6.8 show the results of probabilities obtained with the following equation:

$$H^t = P_e^t \times P_s^t \times P_t^t \quad \text{[e.q.1]}$$

Where P_e^t, P_s^t and P_t^t are event, spatial and temporal probabilities for return period of '*t*' years. They are calculated as explained in Chapter 5. Because in each hazard class there are landslides with different return periods the hazard probability was calculated for each return period and then added up. In order the homogenized the four return periods the temporal probabilities were estimated for a period of fifty years. New probabilities were calculated using the following equation:

$$P = 1 - \left(1 - \frac{1}{R}\right)^N \quad \text{[e.q.2]}$$

Where R is the return period for the different landslides and *N* is the number of years to be considered. The following values were obtained: 0.64 temporal probability for landslides of 1/50 years return period, 0.39 temporal probability for 1/100 years return period, 0.09 for 1/500 and 0.05 for 1/1000. Due to the fact that in areas where landslides of older return period (e.g. 1/1000) can also include more recent return period (RP) events (e.g. 1/50), the number of pixels was aggregated. Therefore, number of landslide pixels per class (Sld^t) for t=100 contain also Sld^t for t=50. The event probability (P_e^t) and spatial probability (P_s^t) were estimated in the same way as explained in Chapter 5 for provincial assessment. The hazard probability is calculated as the product of event, spatial and temporal probability (P_t^t). The final probabilistic landslide hazard map is shown in Figure 6.14 with the risk calculation for houses.

The total landslide probabilistic hazards calculated on Table 6.8 shows increasing probabilities of landslide occurrence for the higher hazard classes. However, for the specific return periods results are slightly different. For example, for the 50 years return period, class H5 has 0.00068 probabilities of landslide occurrence because there 193 pixels with landslide in this class and H6 and H7 do not have any probabilities. Also for other return periods, it is possible to see higher hazard classes with slightly lower occurrence probability. This is due to the fact that the susceptibility was estimated for all landslides together and that some classes have much more pixels than others. Despite this observation for particular classes of some return periods the estimation allowed to include in the landslide hazard and risk assessment different temporal probabilities.

Table 6.8. Probabilistic hazard calculation (see text for an explanation)

RP	Hazard	Npix	Sld^t	P_e^t	P_s^t	P_t^t	H^t	Total
Return period of 50 years	H1	108795	0	0.0000	0.0000	0.64	0.00000	
	H2	75355	0	0.0000	0.0000	0.64	0.00000	
	H3	275814	0	0.0000	0.0000	0.64	0.00000	
	H4	294236	0	0.0000	0.0000	0.64	0.00000	
	H5	32479	193	0.1776	0.0059	0.64	0.00068	
	H6	27701	0	0.0000	0.0000	0.64	0.00000	
	H7	15431	0	0.0000	0.0000	0.64	0.00000	
	H8	11302	209	0.1923	0.0185	0.64	0.00228	
	H9	4714	105	0.0966	0.0223	0.64	0.00138	
	H10	6987	580	0.5336	0.0830	0.64	0.02835	
Return period of 100 years	H1	108795	0	0.0000	0.0000	0.39	0.00000	
	H2	75355	0	0.0000	0.0000	0.39	0.00000	
	H3	275814	0	0.0000	0.0000	0.39	0.00000	
	H4	294236	0	0.0000	0.0000	0.39	0.00000	
	H5	32479	193	0.0504	0.0059	0.39	0.00012	
	H6	27701	475	0.1240	0.0171	0.39	0.00083	
	H7	15431	749	0.1955	0.0485	0.39	0.00370	
	H8	11302	545	0.1423	0.0482	0.39	0.00268	
	H9	4714	609	0.1590	0.1292	0.39	0.00801	
	H10	6987	1260	0.3289	0.1803	0.39	0.02313	
Return period of 500 years	H1	108795	0	0.0000	0.0000	0.09	0.00000	
	H2	75355	1	0.0000	0.0000	0.09	0.00000	
	H3	275814	2992	0.0625	0.0108	0.09	0.00006	
	H4	294236	4578	0.0957	0.0156	0.09	0.00013	
	H5	32479	8480	0.1772	0.2611	0.09	0.00416	
	H6	27701	8720	0.1822	0.3148	0.09	0.00516	
	H7	15431	5733	0.1198	0.3715	0.09	0.00401	
	H8	11302	4939	0.1032	0.4370	0.09	0.00406	
	H9	4714	5062	0.1058	1.0738	0.09	0.01022	
	H10	6987	7347	0.1535	1.0515	0.09	0.01453	
Return period of 1000 years	H1	108795	0	0.0000	0.0000	0.05	0.00000	0.00000
	H2	75355	1	0.0000	0.0000	0.05	0.00000	0.00000
	H3	275814	3201	0.0378	0.0116	0.05	0.00002	0.00008
	H4	294236	5507	0.0650	0.0187	0.05	0.00006	0.00019
	H5	32479	11401	0.1346	0.3510	0.05	0.00236	0.00732
	H6	27701	17707	0.2090	0.6392	0.05	0.00668	0.01267
	H7	15431	13226	0.1561	0.8571	0.05	0.00669	0.01440
	H8	11302	13360	0.1577	1.1821	0.05	0.00932	0.01833
	H9	4714	7814	0.0923	1.6576	0.05	0.00765	0.02726
	H10	6987	12487	0.1474	1.7872	0.05	0.01317	0.07918

6.5. Assessment of landslide risk

During the fieldwork, information was collected on buildings and roads. As the study area is a rural environment, most of the buildings are isolated farmhouses; a number of small schools and medical centres were also identified. The landslide risk assessment was carried out for houses, roads and land cover types.

6.5.1. Risk for houses

It was not possible to map the daily movement of the population or even the number of inhabitants per house at this scale, therefore risk assessment was carried for houses and not for population. Nevertheless, houses recognized as 'at risk' could be the focus for a more detailed survey about their inhabitants in order to reduce the risk. San Antonio del Sur municipality has six popular councils: Yateras, San Antonio del Sur, Guaibanó, Maya, Puriales de Caujerí and Viento Frío. Inside these councils there are twenty five settlements (Table 6.9 and Figure 6.2).

The population density of these settlements range from 2.50 up to 3.76 people/house, and gender is equally distributed. Children between 0 and 14 years old represent the 25.5 percent of the population, and 57.3 % of the labour force, are people of working age (Villalón Semanat, 2007). More than the 60% of the population is distributed in the head of the municipality (San Antonio del Sur) or in the central valley (Guaibanó). The proximity to coastal areas, the road access, the existence of natural sources of water and the location of very fertile lands are the most important factors that can be related to the formation of settlements (Villalón Semanat, 2007). For example, the settlements in the southern part are generally located in flat terrain, some of them, even in current flood plains which are very flood prone areas. More inland the settlements are mostly located in road junctions surrounded by agricultural land. Only the head of the municipality is considered as 'urban' and as for the rest, only basic services and infrastructure are provided. Settlements are classified by the number of inhabitants according the National Institute of Housing in Cuba as shown in the last column of Table 6.9.

Housing, as one of the main concerns in Cuba and closely related to disaster losses, is also a problem in the San Antonio del Sur municipality. Table 6.10 shows the summary statistics for housing inventory considering house condition (good, regular and bad in columns 3 to 5) and typology (from I-VII in column 1) for the entire municipality according to provincial authorities. Description of each house typology can be found in annexes in the supplementary CD-ROM. Analyzing the findings, it can be concluded that 60 percent of the houses are in regular or bad condition, and that 2436 houses in the lowest typology are in bad condition.

Table 6.9. Population and houses per settlement and council in San Antonio del Sur (ONE, 2004; INV, 2005; ONE, 2007).

Council	Settlement	Houses	Population	Classification
San Antonio del Sur			**8193**	
	San Antonio del Sur	1413	4549	Town, 3rd order
	Baitiquirí	267	851	Village, 2nd order
	Cardonal	86	268	Village, 3rd order
	Macambo	145	484	Village, 3rd order
	Pan de Azúcar	97	332	Village, 3rd order
	Playa Sabanalamar	119	394	Village, 3rd order
	Los Siguatos	78	274	Village, 3rd order
	Los Naranjos	122	388	Village, 3rd order
Yateras			**3276**	
	Tortuguilla	132	425	Village, 3rd order
	Yateritas	552	1945	Village, 1st order
	El Acueducto	171	580	Village, 1st order
Guaibanó			**8146**	
	Guaibanó	605	2124	Town, 3rd order
	Mariana	141	472	Village, 3rd order
	Laja de Caujerí	27	76	Hamlet
	El Manguito	92	334	Village, 3rd order
	El Corojo	198	675	Village, 2nd order
	Quince Minutos	13	49	Hamlet
	Mameyal Tres	15	52	Hamlet
Maya			**1602**	
	Maya	27	81	Hamlet
	Los Asientos	42	105	Hamlet
Puriales			**4670**	
	Mameyal	20	71	Hamlet
	Puriales de Caujerí	650	2181	Town, 3rd order
	El Mije	25	74	Hamlet
	Dos Brazos	12	27	Hamlet
	El Jubo	77	238	Village, 3rd order
Viento Frío			**622**	
Total in Settlements		**5126**	**17049**	
Total in the municipality		**6372**	**26509**	

Table 6.10. Summary of housing evolution 2004/2005 for San Antonio del Sur municipality. 'R & B' regular and bad.

	Total	Good	Regular	Bad	R & B	% R & B
Initial inv.	6369	2574	1006	2789	3795	59.59
I	653	419	186	48	234	35.83
II	65	40	17	8	25	38.46
III	1667	1267	313	87	400	24.00
IV	990	527	308	155	463	46.77
V	523	327	186	10	196	37.48
VI	2436	0	0	2436	2436	100.00
VII	37	0	0	37	37	100.00
Final inv.	6372	2580	1010	2782	3792	59.51
Relation	3	6	4	-7	-3	
Relation %	100	100.2	100.4	99.7	99.9	
Evolution %	0	0.2	0.4	-0.3	-0.1	

Most of the houses are one-story buildings and only very few two-story building are found in the head of the municipality (Villalón Semanat, 2007). Un-reinforced masonry and wooden buildings are predominant, whereas asbestos sheets and palm leaf are widely used as roof materials. However, in the head of the municipality reinforced concrete houses are predominant. Figure 6.13 show some typical houses in the municipality. It was observed a significant urban growing in flood zones where many houses have been constructed in areas yearly inundated. Although less frequent, in mountainous areas there are also new developments in landslide prone zones.

In San Antonio del Sur, 1649 out of 6372 (25.8%) houses were identified as belonging to some sort of landslide hazard class. Table 6.11 (upper part) show the statistics of theses houses per typology and condition. Also for these houses at risk, there are many in the lowest typology and in the worst condition. The vulnerability should be expressed in relation to the landslide type and magnitude. In real case studies it is needed to assume an average value and literature recommend some vulnerabilities for particular conditions (Leone et al., 1996; AGS, 2000; Glade, 2003; Bell and Glade, 2004; NGI, 2006; Fuchs et al., 2007). Considering the characteristics of landslide occurrence in the study area and the literature on this topic vulnerability values were assigned to each house type and condition (Table 6.11 middle part). Vulnerability values were distributed between 0.3 up to 1 as recommended by the literature taking into account the six house typologies and the three structural conditions. Besides, average house construction cost was also determined based on the common house size in the study area and the procedure established in Cuba for calculation of house cost. At this scale it was not possible to calculate the specific cost of an individual building.

Figure 6.13. Typical houses in San Antonio del Sur. (Clockwise from left to right: wooden house in bad condition, wooden house in good condition, un-reinforced masonry house and reinforce concrete house in good condition (Villalón Semanat, 2007).

Table 6.11. Amount of houses, vulnerability and cost of houses in hazards areas.

Amount					**Vulnerability (0-1)**			
		Condition					Condition	
Type	Good	Regular	Bad	Totals	Type	Good	Regular	Bad
I	72	20	76	168	I	0.3	0.4	0.5
II	15	2	13	30	II	0.4	0.5	0.6
III	179	65	185	429	III	0.5	0.7	0.7
IV	96	31	118	245	IV	0.6	0.8	0.8
V	55	19	53	127	V	0.8	0.9	0.9
VI	250	93	307	650	VI	1.0	1.0	1.0
	667	230	752	1649				
Cost (in Cuban pesos)								
I	10000	9500	9000					
II	8500	8000	7500					
III	7000	6500	6000					
IV	5500	5000	4500					
V	4000	3500	3000					
VI	2500	2000	1500					

The attributes of vulnerability and cost were assigned to each house of a specific category/condition and they were multiplied with the hazard probability to calculate the risk according to the standard equation established by Varnes and IAEG (1984). There are 1499 houses with landslide risk lower than 1 Cuban peso, 90 houses with landslide risk between 1 and 10 and 60 houses with landslide risk higher than 10 Cuban pesos. This risk values represent annual expected loss for a fifty year return period. The low risk values obtained respond to both the low hazard probabilities values and the estimation of cost per house. Spatial distribution is according to what was expected as shown in Figure 6.14. Most of the houses with higher risk are located in high hazard areas of Caujerí Scarp. These houses were analyzed in more detailed for the next level of analysis, as explained in Chapter 7.

6.5.2. Risk for roads

The road map digitized from the topographic map at a scale of 1:50,000 had five road types in the study area: A highway crossing the southern part with 21.9 km; a second order paved road connecting the highway with the central valley (27.9 km); unpaved normal roads (56 km) and enhanced (143 km) inside the valley and connecting small settlements; and trails (347 km) and paths (47 km) also distributed in the mountainous areas. The last two, in spite of their low cost, are very relevant for local farmers in order to transport any agricultural production in mules, oxen or horses. Considering the characteristics of each type of road, landslides in the study area and other similar studies (AGS, 2000), vulnerability values from 0.5 up to 1 were assigned to each road type as shown in Table 6.12. These values represent the financial loss if a landside were to hit the road. Normally speaking, 'high cost' roads (such as highways) have better designed 'engineering' slopes as well as protection against landslide occurrence. The costs of road per kilometre were supplied by the Research Centre of the Ministry of Transportation. Due to differences between raster and vector format of the road, the pixel's size (25m) was added to its squared root (5m), i.e. equal 30m. This calculation provided a better approximation in comparing the length between both formats, and also provided a better approximation in comparing the length of the road in vector and raster format. The risk was then calculated as the product value, hazard and vulnerability per road type in each hazard class. A summary for each hazard class and for each road type is provided in Table 6.12. The total risk per hazard class depends very much on the length of roads crossing the class. Thus, hazard class 8 has less total risk than lesser hazardous classes, as trails and enhanced unpaved roads are the most risky.

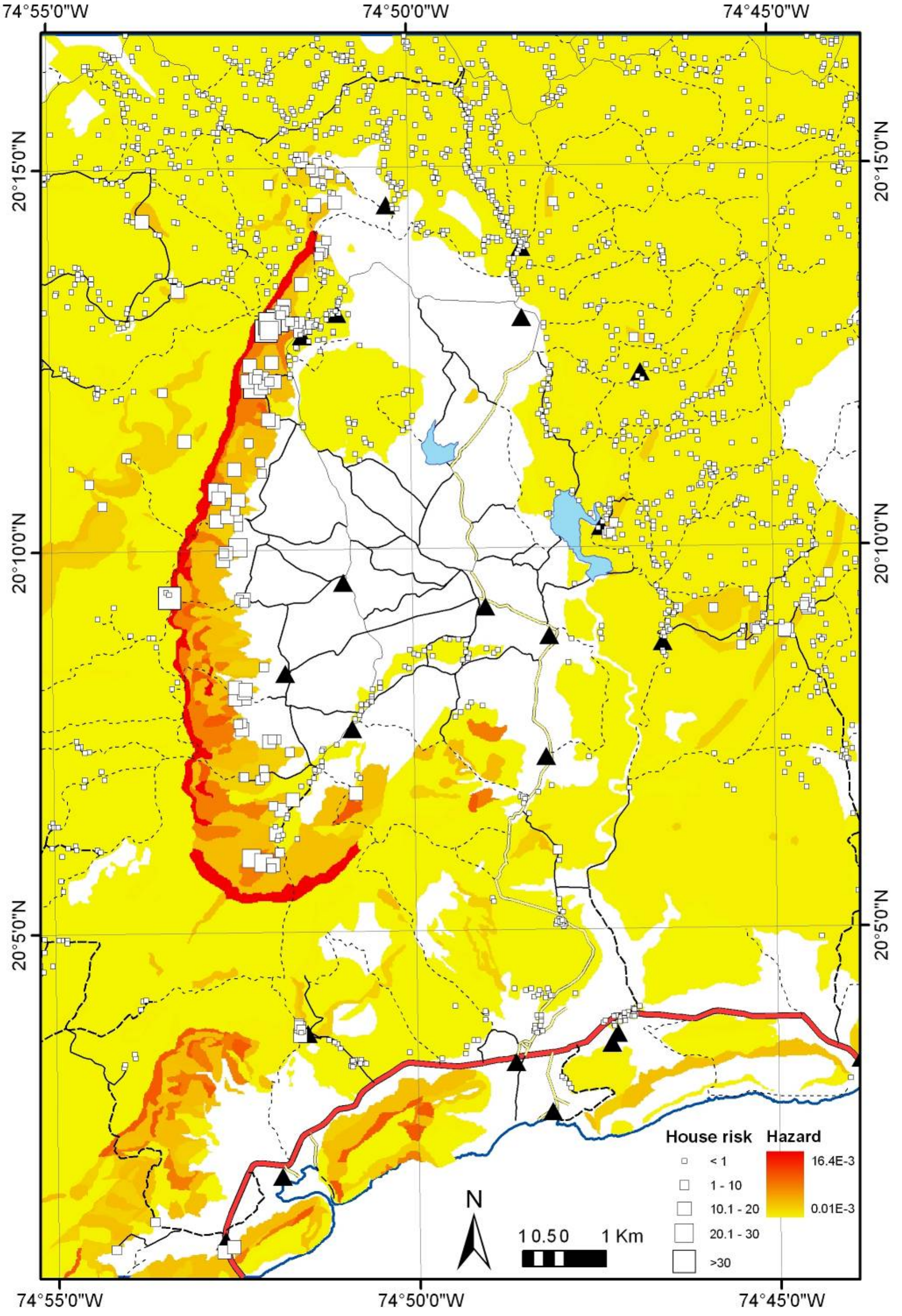

Figure 6.14. Risk for houses in pesos and probabilistic hazard map. Black triangle are the main settlements.

Table 6.12. Landslide risk calculation for roads (summary per type) in Cuban pesos. Hazard classes according to Table 6.7.

Hazard	Road type	Pixels	Cost/km	Value	Hazard	Vul.	Risk
Hazard3	Highway	93	17000	47430	0.00006	0.50	1.42
	Paved road 2nd	258	12350	95589	0.00006	0.70	4.01
	Unpaved road (enhanced)	995	8000	238800	0.00006	0.80	11.46
	Unpaved road	266	5100	40698	0.00006	0.80	1.95
	Path	545	2000	32700	0.00006	1.00	1.96
	Trail	3054	1000	91620	0.00006	1.00	5.50
	Total	*5211*		*546837*			*26.31*
Hazard4	Paved road 2nd	13	12350	4817	0.00012	0.70	0.40
	Unpaved road (enhanced)	911	8000	218640	0.00012	0.80	20.99
	Unpaved road	560	5100	85680	0.00012	0.80	8.23
	Path	377	2000	22620	0.00012	1.00	2.71
	Trail	4829	1000	144870	0.00012	1.00	17.38
	Total	*6690*		*476627*			*49.72*
Hazard5	Unpaved road (enhanced)	166	5100	25398	0.00248	0.80	50.39
	Path	36	2000	2160	0.00248	1.00	5.36
	Trail	255	1000	7650	0.00248	1.00	18.97
	Total	*457*		*35208*			*74.72*
Hazard6	Highway	2	17000	1020	0.00340	0.50	1.73
	Unpaved road (enhanced)	52	8000	12480	0.00340	0.80	33.95
	Unpaved road	14	5100	2142	0.00340	0.80	5.83
	Path	11	2000	660	0.00340	1.00	2.24
	Trail	168	1000	5040	0.00340	1.00	17.14
	Total	*247*		*21342*			*60.89*
Hazard7	Unpaved road (enhanced)	50	8000	12000	0.00371	0.80	35.62
	Path	36	2000	2160	0.00371	1.00	8.01
	Trail	128	1000	3840	0.00371	1.00	14.25
	Total	*214*		*18000*			*57.88*
Hazard8	Unpaved road	13	5100	1989	0.00781	0.80	12.43
	Path	7	2000	420	0.00781	1.00	3.28
	Trail	42	1000	1260	0.00781	1.00	9.84
	Total	*62*		*3669*			*25.55*
Hazard9	Unpaved road (enhanced)	2	8000	480	0.01025	0.80	3.94
	Trail	20	1000	600	0.01025	1.00	6.15
	Path	12	2000	720	0.01025	1.00	7.38
	Total	*34*		*1800*			*17.47*
Hazard10	Trail	*163*	1000	*4890*	0.01649	1.00	*80.64*
Total		*13078*		*1108373*			*393.16*

Table 6.12 Cont.

Summary	Highway	95	17000	48450		0.50	3.16
	Paved road 2nd	271	12350	100406		0.70	4.42
	Unpaved road (enhanced)	2176	8000	507798		0.80	156.34
	Unpaved road	853	5100	130509		0.80	28.43
	Path	1024	2000	61440		1.00	30.95
	Trail	8659	1000	259770		1.00	169.86
	Total	*13078*		*1108373*			*393.16*

6.5.3. Risk for agriculture and forest

The land cover map obtained (Figure 6.3) by classifying a Landsat ETM+ image (08/03/2001) was overlaid with the hazard map. The results show in Table 6.13 that the land cover areas generally decrease toward the higher hazard classes. The exception of this rule is class H9 when compared with H10, due to the actual area of the class (see

Table 6.7). In the high hazard classes (from 7 up to 10) are predominant shrubs, sparsely vegetated area and unfortunately, the agricultural land. Cacao, Coffee and Urban Fabric are only present in the moderate and low hazard classes. However, for the first two, more precise mapping would provide areas at risk (as was recognized in the fieldwork campaigns).

Table 6.13. Crossing hazard classes with land covers (all values in hectares).

Land cover	Corine Code	Area (ha)	H3	H4	H5	H6	H7	H8	H9	H10
Mixed forest	3.1.3	9441	17230	6377	244	68	15	27	6	66
Sparsely vegetated area	3.3.3	8897	3858	2405	433	401	325	250	97	129
Bare rocks and shrubs	Mixed	5249	1731	1510	266	367	138	52	76	4
Wetland	4.1.0	1492	371	821	68	41	23	14	6	3
Agricultural land	2.0.0	17361	4026	3912	525	436	241	202	36	99
Cacao	2.4.4	353	35	142	0	0	0	0	0	0
Coffee	2.4.4	1065	140	702	20	0	0	0	0	0

Quantitative landslide risk for land cover was estimated only for those types of land cover where its economic value was known. This includes mixed forest, agricultural land in general, cacao and coffee plantations. The economic values per hectare were obtained from specialists of the Agricultural University of Havana based on previous works. The most difficult type was agricultural land, since it is a very generic term. Thus, common crop types of Caujerí Valley were taken into account in order to create an average economic value per hectare. The risk calculation was as shown in Table 6.14. In this case vulnerability was considered as 1 assuming that wherever it would happen, the lost will be complete. It is known that the lower parts of a landslide like the toe could be partially recovered and used for crop again. However, at this scale, distinction of every landslide parts with different vulnerability values for crops was not possible due to the resolution. This issue show the dependence of how detailed could be the method applied with relation to the scale of the analysis for landslide risk assessment. The analysis of the results on Table 6.14 shows that by far, agricultural land is the most affected by landslide risk in the study area followed by the forested areas.

Table 6.14. Risk for land cover with economic value in Cuban pesos.

Land cover	Area (ha)	Value/ha	Value	Hazard	Vul.	Risk (pesos)
Mixed forest	1729.75	500	864875.00	0.00008	1	69.19
Agricultural land	4025.94	750	3019453.13	0.00008	1	241.56
Cacao	35.50	350	12425.00	0.00008	1	0.99
Coffee	139.69	1200	167625.00	0.00008	1	13.41
hazard3			*4064378.13*			*325.15*
Mixed forest	6377.63	500	3188812.50	0.00019	1	605.87
Agricultural land	3912.44	750	2934328.13	0.00019	1	557.52
Cacao	141.88	350	49656.25	0.00019	1	9.43
Coffee	701.81	1200	842175.00	0.00019	1	160.01
hazard4			*7014971.88*			*1332.84*
Mixed forest	243.75	500	121875.00	0.00732	1	892.13
Agricultural land	525.00	750	393750.00	0.00732	1	2882.25
Coffee	20.50	1200	24600.00	0.00732	1	180.07
hazard5			*540225.00*			*3954.45*
Mixed forest	68.00	500	34000.00	0.01267	1	430.78
Agricultural land	435.94	750	326953.13	0.01267	1	4142.50
hazard6			*360953.13*			*4573.28*
Mixed forest	14.69	500	7343.75	0.01440	1	105.75
Agricultural land	240.88	750	180656.25	0.01440	1	2601.45
hazard7			*188000.00*			*2707.20*
Mixed forest	27.56	500	13781.25	0.01833	1	252.61
Agricultural land	202.31	750	151734.38	0.01833	1	2781.29
hazard8			*165515.63*			*3033.90*
Mixed forest	6.19	500	3093.75	0.02733	1	84.55
Agricultural land	35.94	750	26953.13	0.02733	1	736.63
hazard9			*30046.88*			*821.18*
Mixed forest	66.31	500	33156.25	0.07918	1	2625.31
Agricultural land	98.56	750	73921.88	0.07918	1	5853.13
hazard10			*107078.13*			*8478.45*
Summary						
Mixed forest	8533.88	500	4266937.50			5066.19
Agricultural land	9477.00	750	7107750.00			19796.33
Cacao	177.38	350	62081.25			10.43
Coffee	862.00	1200	1034400.00			353.50
Total risk						25226.45

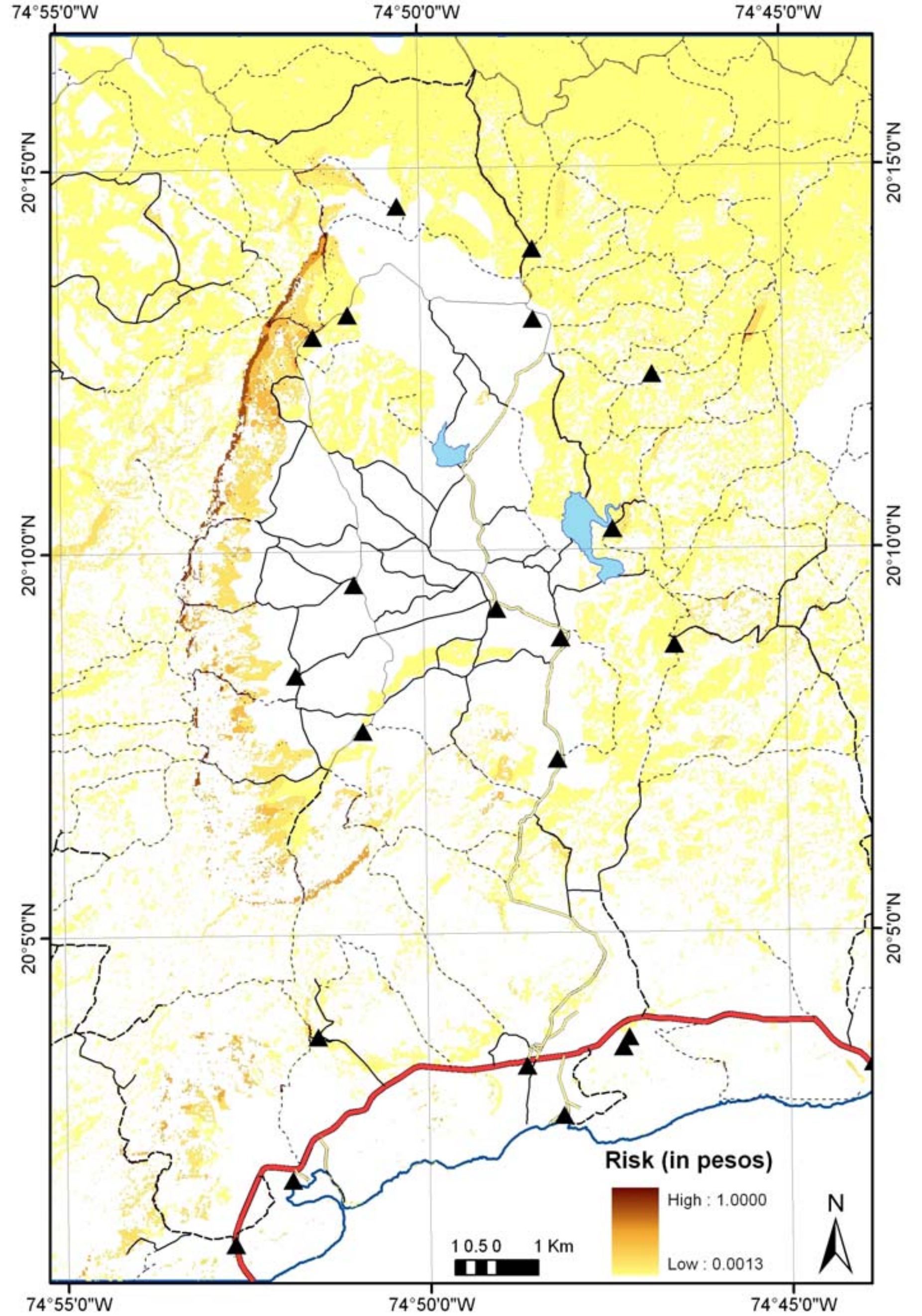

Figure 6.15. Final landslide risk map for houses, land cover and roads. Black triangle are human settlements.

A general risk map was created for San Antonio del Sur municipality considering the landslide risk for roads, land covers and houses. The value for roads was converted from a cost per kilometre to a cost per 30 m according to the spatial resolution. Similarly, the value of land covers was converted from cost per hectare to cost per 625 square meters (25 m x 25 m). Once all maps were prepared at the same spatial resolution they were added in order to obtain the final risk map (Figure 6.15). The final risk values that were obtained were fairly low (maximum of 176 Cuban pesos). This was due to i) the low temporal probability of the landslides in the area, ii) to the existing subsidised monetary system in Cuba and iii) to the limited spatial coincidence of high landslide hazard areas and high costly elements at risk.

In spite of these low values, spatial distribution of risk could be analysed in Figure 6.15. The final landslide risk map is included in the annexes in the CD-ROM. The non risky areas are either areas with no hazard probability (hazard class 1 and 2) or areas with no element at risk with any economic value, such as bare rock land cover. The highest landslide risk values are located in the top of the Sierra de Caujerí escarpment and in parts of the roads on the mountains. Although the middle part of the escarpment is more hazardous, the northern part has higher risk due to economic assess. The northern part is at risk with very low values due to the forest and low landslide hazard probability.

6.6. Discussion and conclusions

Detailed geomorphological mapping provides information on the site-specific conditions under which different landslide types occur in various parts of the study area. Landslides are concentrated along the Caujerí scarp, but also in the coastal hills and in the northern part of the Baitiquirí area. There, the landslides have different characteristics and causative factors. Subdivision of the terrain into 603 terrain mapping units, individual homogeneous polygons, allowed for a more detailed characterization of the terrain than would be possible through conventional map-overlay of main factor maps. The boundaries of different landslide parts were surveyed by photo-interpretation, and landslides were described in the field from a detailed checklist, where information was collected related to landslide type, subtype, relative age, and depth.

This data set enable us to generate a heuristic model, using multi-criteria analysis, which was successful in classifying the area into different hazard classes, which can be displayed either in ten more detailed or three generalized classes, depending on the user needs. Improvements in the method could be made if different weight maps were produced for different landslide types. The qualitative hazard assessment was converted into probabilistic values including event, spatial and temporal probabilities. The latest one was obtained based on the geomorphological classification of aging for the landslides during photo-interpretation and fieldwork. This approach, despite subjectivity, is a solution when landslide dates are not known. The situation in the study area can be considered as representative for the whole of Cuba, where due to the lack of a landslide inventory, the knowledge about landslide causative factors and mechanisms is still limited. Recently, however, the National Civil Defence and the Ministry of Science, Technology and Environment have decided to establish a system for landslide risk assessment in the Cuban Archipelago. The system will include the design and implementation of a national landslide inventory database and landslide risk-assessment procedures at different disaster management levels (Castellanos Abella and Van Westen, 2005). An important component of this system will be the involvement of local staff of the Civil Defence at the 169 municipal centres, including San Antonio del Sur. A simple landslide reporting form has been designed, and workshops will be conducted in order to train the staff and make them aware of the new procedure. Once the local officers report a landslide, a landslide expert from the central office will visit the site and complete the questionnaire in more detail. Such a system for landslide data collection might be less effective in other countries, due to insufficient reporting staff at the local level.

One issue that requires further improvement is landslide vulnerability assessment. In this study, vulnerability values were assumed based on the literature (see AGS, 2000; Glade, 2003) and on fieldwork experience with previous landslide disasters. Therefore, a much more credible landslide vulnerability assessment system needs to consider landslide magnitude and runout distance. However, in order to carry out a spatial landslide vulnerability assessment for an entire region at this scale, vulnerability values should be assumed, as no detailed information about impact for every single element at risk can be surveyed. Future research is needed in order to standardize vulnerability values according to houses and road typology in Cuba as well as in other countries.

The landslide risk values were low but show the distribution of risk along this rural municipality. In this case study, quantitative landslide risk assessment was carried out for roads, agricultural lands and houses. Although only three type of element at risk were taken into account in this assessment it allowed knowing the most risk zones for landslides at this scale. This information was used for municipal authorities in planning landslide disaster reduction and to locate zones for more detailed analysis at a larger scale as carried out in the next chapter.

CHAPTER 7

Local landslide risk assessment

Based on:
Castellanos Abella, E.A. et al, 2008 Characterization and runout modelling of Jagüeyes landslide. Landslide (in preparation)
Castellanos Abella, E.A. et al, 2008 Up-scaling landslide modelling for risk assessment. Engineering Geology (in preparation)

Cited as:
Castellanos Abella, E.A. 2008. Local landslide risk assessment. In: Castellanos Abella, E.A., Multi-scale landslide risk assessment in Cuba, Utrecht, Utrecht University, 2008. ITC Dissertation 154, 193-226 p. ISBN: 978-90-6164-268-8

7. Local landslide risk assessment

7.1. Introduction

Studies on local landslide risk assessments are more often reported in the scientific literature. During the nineties, when the landslide risk assessment framework started to take shape, the basic concepts were defined, but practical applications were still rare. Cruden and Fell (1997) compiled several papers on landslide risk illustrated with few case studies and since the beginning of the twenty first century practical case studies were gradually increasing (e.g. see Kong, 2002; Guzzetti et al., 2003; Bell and Glade, 2004; Cascini, 2004; Wong, 2005). The problem of data availability allowed researchers to develop risk studies only in limited regions compared with hazard studies that were commonly available in medium and large scales. Constraints on data availability are more related with surveying elements at risk and assessing its vulnerability. As a consequence, most of these studies are still qualitative (e.g. when selecting vulnerability values). Besides, at local scale the effect of runout distance is more notorious and the hazard assessment should consider it somehow. Some applications have been created in order to model runout for rockfalls (Guzzetti et al., 2002; Guzzetti et al., 2003) and for debris flows (Hungr, 1995). Still the link between runout modelling and risk assessment is not generally implemented. A possible explanation could be that the modelling procedure is still at a 'developing' stage.

In this study, local landslide risk assessment was carried out considering runout modelling in one historical landslide and subsequently up-scaling analysis. The study was made in the Caujerí scarp, in the San Antonio del Sur municipality, province of Guantánamo, where a series of landslide events have been photointerpreted (see Chapter 6) and where a landslide disaster including casualties occurred in 1963. A runout simulation (and calibration) was performed on the landslide called 'Jagüeyes' and the calibrated parameters were used to conduct runout simulations on twelve landslide zones along the Caujerí scarp. Before the start of the simulation, the Jagüeyes landslide was characterized as much as the available data allowed. Aerial photointerpretation, digital photogrammetry and geophysical surveys were carried out. Data before and after the occurrence facilitated the interpretation confirmed by various fieldwork campaigns. For the runout simulation the MassMov model (Beguería-Portugués and van Asch, 2008) implemented in PCRaster (PCRaster Environmental Software, 2008) was calibrated with PEST (Doherty, 2004). Difficulties were found defining the appropriate geotechnical parameters in order to adjust the simulation to the real situation. The result of the Jagüeyes landslide simulation was used to scale-up the simulation for the Caujerí scarp by assessing the risk for every house according to its typology, condition and replacement cost. Population risk was also considered for landslide risk assessment.

Local risk assessment in Cuba involves more practical and executive tasks as it is more focused on areas where existing landslide problems occur. This implies that target areas for this level of analysis are selected either by analysis carried out at upper levels or by recently reported landslides. The objectives for this level of assessment, according to the Civil Defence Authorities are to:

1. Map as precise as possible existing landslides boundaries and characterize their conditions in order to recognize main causes and consequences.
2. Map elements at risk and survey their typologies and conditions in as much detail as possible, including cost and vulnerability.
3. Estimate the risk of the infrastructure and population considering the potential impact of predicted landslides or the instability of recently failed slopes.
4. Inform and discuss, along with municipal authorities, to the local authorities and civil society the risk they are facing, focusing on possible solutions and identify any resources that may be required.
5. Approve and implement (in agreement with all parties) a disaster reduction plan at local level for the areas potentially affected.

Considering the aforementioned objectives the landslide risk assessment was carried out as explained in the following sections where the first part relates to the single landslide analysis and the second part deals with risk assessment along the scarp area. The study focused on the first three objectives while the last two are beyond the scope of this research.

7.2. Los Jagüeyes landslide

On 7 October, 1963, after three days of rain due to Hurricane Flora, a large landslide occurred in a location known as Jagüeyes in the Caujerí Valley, Guantánamo. The event caused human deaths and many cattle were lost as well as a considerable area of agricultural land. The occurrence of this event was not recorded by any media nor was a technical report carried out. Perhaps, because many more damages and deaths occurred at the same time by flooding in the neighboring province. By analyzing reports on hurricane Flora, interpreting pre and post event aerial photos and interviewing local, a reconstruction of the event was carried out.

Hurricane Flora was the seventh of nine tropical cyclones that occurred in the North Atlantic region in 1963. Flora was recognized as a tropical depression (<63 km/h wind speed) on 26 September, as a tropical storm (63-117 km/h) on 29 and as hurricane (>118 km/h) on 30 September when it crossed the Lesser Antilles over Trinidad and Tobago (Dunn, 1964). It moved northwestward approaching Haiti (3 Oct) and Cuba (4 Oct). After a loop over Cuba it changed direction heading off towards the northeast, crossing the Bahamas (8 Oct) and moving towards the Atlantic Ocean where became an extra-tropical depression on 12 October and disappeared next day. Flora was a major natural disaster in Caribbean history. The duration, extent of the damage and losses were significant as showed in Table 7.1. On 21 October, an official statement about the damages of Flora in Cuba was broadcast, reporting a death toll of 1157 persons, 10,000 houses destroyed, 20,000 houses affected and 175,000 persons evacuated (EMNDC, 2007).

Table 7.1. Estimated casualties and damage (USD), Hurricane Flora (Dunn, 1964).

Location	Killed	Damage (x 1000)
Tobago	24	30000
Trinidad	-	100
Grenada	6	25
Haiti	5000	125000
Dominican Republic	400	60000
Cuba	1157*	300000
Jamaica	11	11900
Bahamas	1	1525
Florida	1	-
Total	7186	528550

* Updated with Civil Defense report (EMNDC, 2007)

Trusov (1964) produced isohyets maps for each day of Flora Hurricane as well as cumulative rainfall for the period 3-8 October based on rainfall stations available in eastern Cuba. Figure 7.1 shows the distribution of rainfall, the track of Flora and the location of the Jagüeyes landslide in the Guantánamo province. A total rainfall of 1083 mm was recorded over this area distributed in 417.4 mm (Oct 4), 175.2 mm (Oct 5), 220.2 mm (Oct 6), 266.5 mm (Oct 7). As seen in the figure, the maximum precipitation did not occur over the landslide area, but in the southwestern part with almost 2000 mm.

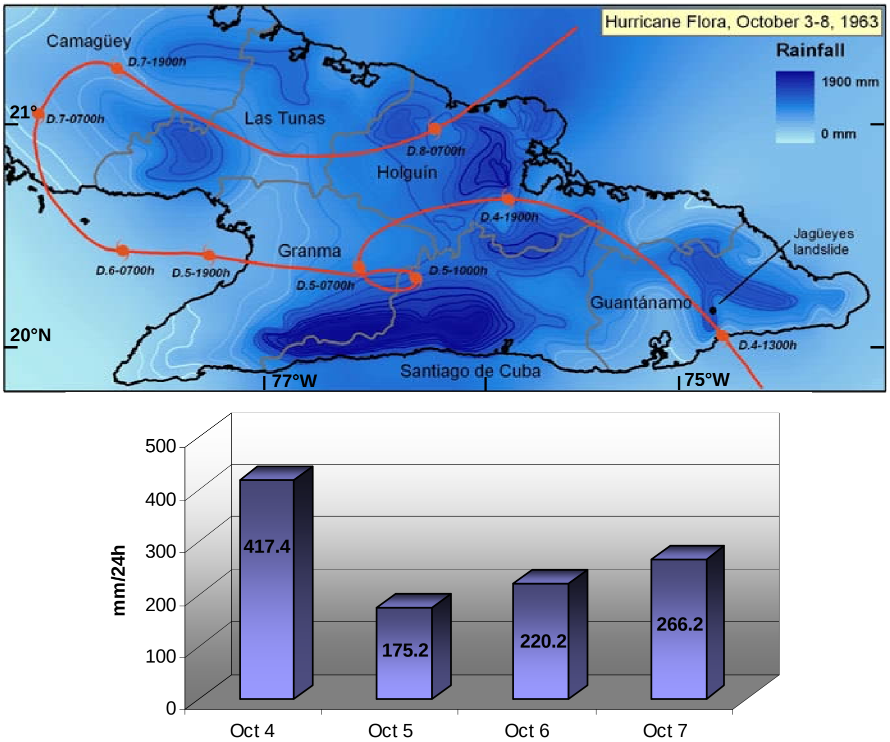

Figure 7.1. Rainfall during Hurricane Flora and the occurrence of landslide Jagüeyes.

By interviewing the survivors during several fieldwork campaigns from 1997 till 2006, the landslide occurrence was characterized. They described first hearing a strong blasting sound coming from the top of the mountain, which frightened them so that they started running down slope. After about forty-five minutes a second large noise started and persisted until they saw the mass movements approaching the foot of the slope. The interval between both 'pulses' allowed some of the inhabitants to escape, whereas five to ten others were killed. The houses of about fourteen families were complete destroyed and many animals, mainly from the valley areas, were buried by the landslide. Besides, agricultural lands, crops and roads in the zone were completely lost. Figure 7.2 shows three selected photos of the Jagüeyes landslide taken during a fieldwork campaign in 1999. The upper left photo was taken from the toe of the landslide showing the almost 2 kilometres length of the movement. The lower left photo was taken from the southern border of the scarp and shows the ancient landslides bodies toward the north that are now vegetated. The image on the right is a detail of the scarp which shows its steepness and sub-horizontal stratification. Inter-layering of predominant limestone and secondary marls is indicated as well as karstic features that can be observed at different levels.

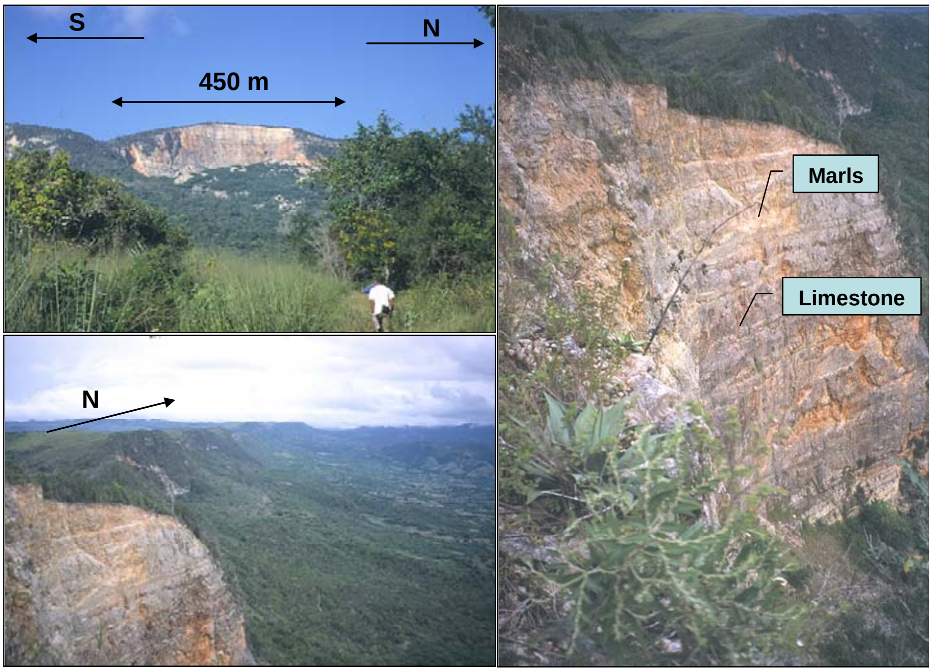

Figure 7.2. Fieldwork photos of Jagüeyes landslide.

7.2.1. Detailed photo-interpretation and geomorphological analysis

Most of the general geomorphological information of this area was already explained in the previous Chapter. For the analysis of the Jagüeyes landslide the data of several Earth Observation images were processed. Figure 3.5 (Chapter 3) shows eights views of this landslide from aerial photos and satellite images. For the geomorphological photointerpretation two pairs of aerial photos– before and after – were used. The pair before the event is from 13 January 1956 at a scale of 1:62,000 and the pair after is at a scale of 1:37,000 which was taken on 16 February, 1972. The interpretation was carried out both in analogue with a TOPCON stereoscope, and digitally with ERDAS Imagine 9.1 Leica Photogrammetry Suite (Leica Geosystems, 2006).

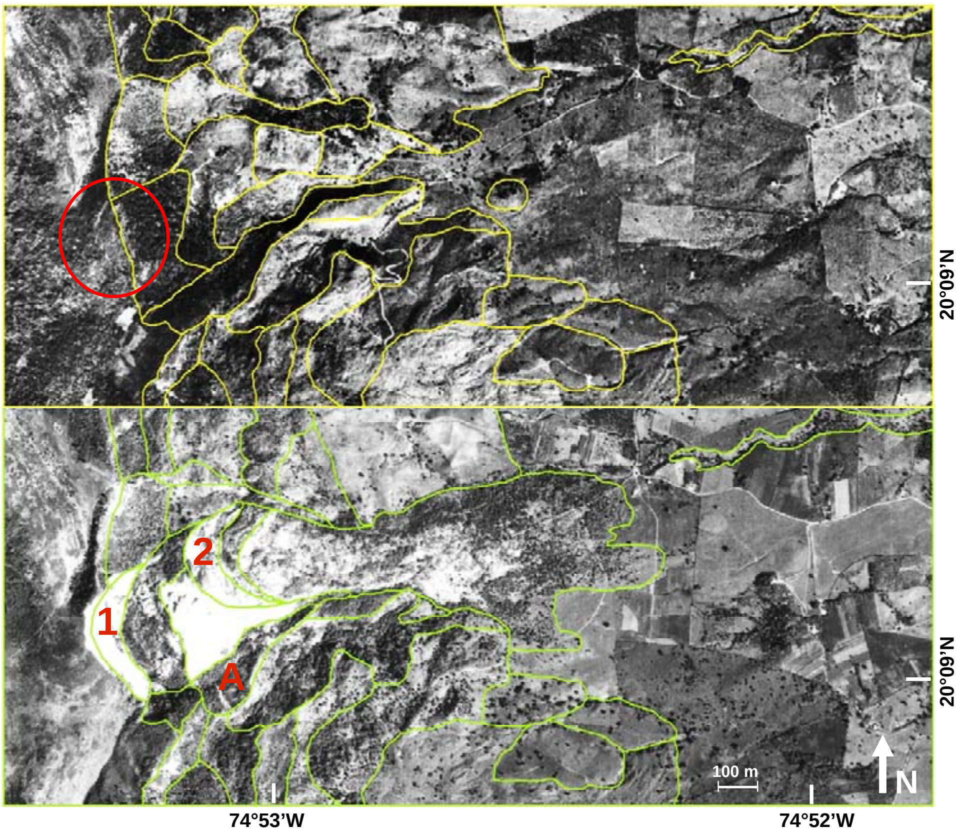

Figure 7.3. Aerial photos before (1956) and after (1972) occurrence of the Jagüeyes landslide.

Figure 7.3 shows a section of two aerial photos of the Jagüeyes area. The western section corresponds to the karstic limestone plateau, the middle is the escarpment with landslide bodies and the eastern sector is part of the Caujerí Valley with agricultural fields. In the upper photo, before the landslide occurrence, an existing crack was recognized (marked with a circle) as well as features from ancient landslides bodies. The lower photo (taken nine years after the landslide in 1963) shows non-vegetated parts of the body. There are two crowns and scarps (indicated with number 1 and 2) suggesting that there were actually two movements. The second one is inside the first one and its central axis is more oriented to the east, whereas the first scarp is oriented more to the northeast. The landslide body continues into a funnel shaped area in the middle where shrub type vegetation starts to grow. The toe of the landslide has a similar gray tone than the surrounding agricultural land, but the stereo capability of the photos allowed tracing its limits by height differences.

The features identified by photointerpretation and the type of materials were checked during several fieldwork campaigns. The first movement, with the larger scarp (1) in Figure 7.2 included coarser material with micritic limestone blocks (Figure 7.4 upper left) whose sizes ranged between 50 cm up to 3 m. In the central part of the body the block sizes and limestone content diminishes to 30 cm or less (Figure 7.4 right). Towards the lower part of the body the limestone content decreases and the percentage of clayey matrix increases until it get mixed with the soil on the valley. On the top of the scarp, we also found the same type of rock with many karstic features (Figure 7.4 lower left) where the water remained or infiltrated the rock.

Figure 7.4. Outcrop of material on the landslide body and karst feature on the top of the scarp (lower left).

7.2.2. DEM preparation pre- and post-event

In order to do a more quantitative analysis of the situation before and after the landslide, two digital elevation models (DEM) were created with digital photogrammetric processing. Detailed explanation about the process can be found in the ERDAS documentation for photogrammetry about orthorectification, automatic terrain extraction and terrain editor (Leica Geosystems, 2006). Here, only some particular relevant aspects to this case study will be explained. The general steps involve in this process are:

1. Establishing parameters of the camera, flight and aerial photos.
2. Collecting, measuring and verifying accuracy of ground control points (GCP).
3. Performing triangulation and orthorectification.
4. Extracting digital terrain model (DEM) automatically.
5. Editing the elevation values to obtain the digital elevation model (DTM).

The information about camera and flight for the 1972 photos (post event) were provided by Geocuba, the Cuban national topographic agency who carried out the photographic survey. For the 1956 photos they declared do not have that information as this flight was carried out by the American Survey Corporation (ASC) many years ago. Fortunately, the information was obtained from the USGS Optical Science Laboratory, department of Aerial Camera Calibration who maintains a database of camera calibration reports and offers this service on-line (USGS, 2008). They found the report for the ASC camera back in 1953 (National Bureau of Standards, 1953). After setting up the camera, flight and photographic information the interior orientation was successfully obtained with 0.47 and 0.27 pixels of root mean squared error (RMSE) for the photos of the 1956 flight, whereas for 1972 photos it was 0.38 and 0.42 pixels of RMSE respectively.

The selection of ground control points (GCP) was made interactively, by measuring the accuracy of every set of points and choosing better locations and distribution. Points were taken from the aerials photos as well as in digital topographic maps at scales of 1:25,000 and 1:10,000. After several tests the best combination obtained provide a total image unit-weight RMSE of 0.5962 for the triangulation of the photos of 1956 with 5 control points, 2 check points and 29 tie points. For the 1972 photos, the RMSE was 0.3925 with 4 control points, 3 check points and 23 tie points. After performing the triangulation, orthophotos were created with 2 metre resolution for the area of the landslide as shown in Figure 7.3.

A digital terrain model (DTM) was extracted from aerial photos at a 2 metre spatial resolution with the DTM Extraction tools in ERDAS (Leica Geosystems, 2006). The area close to the landslide was selected and appropriate parameters for the algorithm were tested until the best results were obtained. For measuring the accuracy of DTM generation all control, tie and check points were used. Table 7.2 shows the accuracy results for both stereo-pairs. 1972's photos have slightly better values, but both show good results. Although the mean error was very low, there were many points that could not be used directly as elevation values. This is partially because of the errors involved in the process and partially because of natural features altering the ground elevation such as trees and buildings. Depending on the purpose of the study, this problem is usually solved by editing these elevation values and producing the actual DTM or by editing contour lines created and producing the DTM supported with geodetics points. As DTM editing requires extensive time and the accuracy obtained was sufficient, the option of generating contour lines was selected.

Table 7.2. Accuracy results from DTM extraction of aerial photographs.

Accuracy parameters	1956 photos	1972 photos
Mass point quality (%)		
Excellent (1-0.85)	64.45 %	65.72 %
Good (0.85-0.70)	18.27 %	19.38 %
Fair (0.70-0.50)	0.00 %	0.00 %
Isolated	0.00 %	0.00 %
Suspicious	17.27 %	14.94 %
Vertical accuracy (m)		
Total of reference points	36	30
Minimum error	-9.83	- 7.39
Maximum error	8.29	6.55
Mean error	0.12	0.10
Mean absolute error	1.40	1.25
Root mean square error	2.61	1.98
Absolute linear error 90	2.55	1.94
NIMA absolute linear error 90	4.29	2.87

The final digital elevation models (DEM) were created with 10 m interval contour lines, 131 geodetic points and stream network in ArcGIS 9.1. Figure 7.5 shows both DEMs obtained and the vectors layers used for interpolation. The contours lines were edited in order to remove 'crisp turns', i.e. where elevation values were estimated incorrectly. Streams were then digitized from the orthophotos in both stereo-pairs. Some streams join to the river network while other disappears down slope. Higher topographic differences are shown in the scarp area and the contours outside of the landslide boundaries remain the same. Differences between both DEMs in the landslide area were calculated. The minimum value was -110.9 m located close to the scarp and the maximum was 29.3 m located in the central part, the mean was 0.29 m with a standard deviation of 7.72 m.

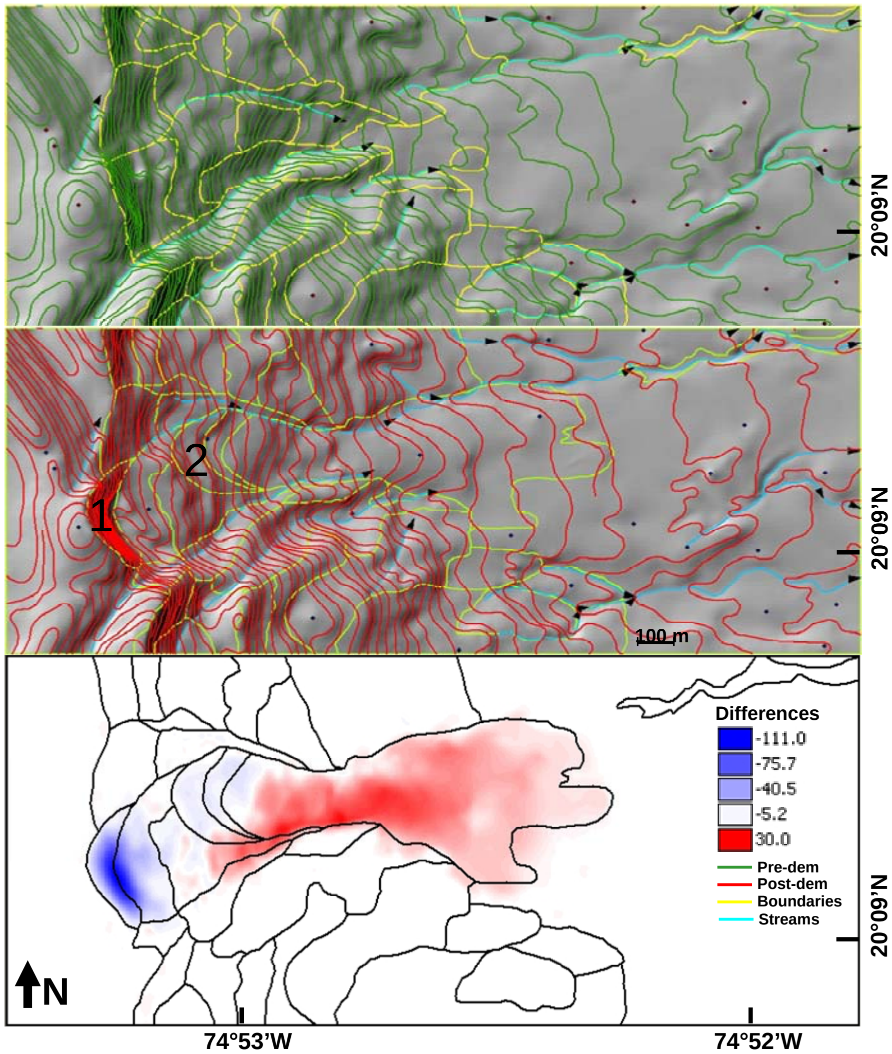

Figure 7.5. Shaped relief representation of the pre-and post DTM for Jagüeyes Landslide and relief differences. Contour lines, geodetic points, stream network and geomorphological boundaries are overlaid.

7.2.3. Geophysical survey

In order to be able to calculate the landslide volume, the pre and post landslide altitude differences derived from the DEM should be combined with the altitude of the failure surface. Geophysical surveys were carried out for this purpose.

Geophysical research for landslides started with the pioneer review publication of Bogoslovky and Ogily (1977). Later, more key research was published on this topic (McCann and Forster, 1990; Hack, 2000; Jongmans and Garambois, 2007) with an overview of the methods and the results expected. Other relevant studies showed specific cases where geophysics has been successfully applied to characterize landslides (Caris and Van Asch, 1991; Mauritsch et al., 2000; Israil and Pachauri, 2003; Donnelly et al., 2005; Sass et al., 2008). In almost all cases resistivity was the main method that was applied, as it showed the most relevant results.

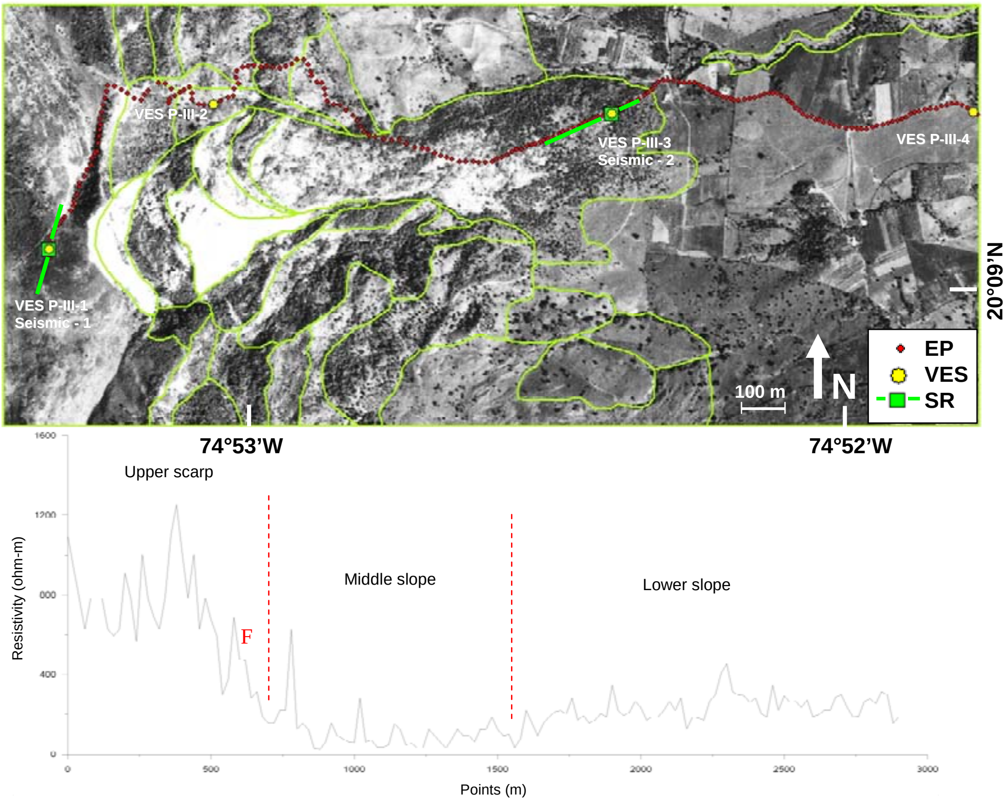

Figure 7.6. Location of geophysical methods (above) and results of electrical profiling (below). EP: Electrical profiling, VES: Vertical electric sounding and SR: Seismic refraction.

In order to recognize the characteristics of landslides along the Caujerí scarp a geophysical survey was carried out in the area by the department of Geophysics, at the Institute of Geology and Paleontology (IGP). Vertical electric sounding (VES), and electrical profiling (EP) as well as seismic refraction studies were carried out. Four profiles were made crossing the main scarp in east-west direction and two more were completed in the valley. In this section only the results obtained for the Jagüeyes landslide will be shown. For VES a Schlumberger configuration was used with maximum separation of electrodes (AB) of 700 m and measurement at intervals of 250 m. Some experimental VES were carried out first to select the best equipment and to check its calibration. For EP also a Schlumberger configuration with AB of 300 m and MN of 40 m was used with interval measuring of 25 m. In both methods, the digital geoelectrical system Geotron Ω-25 was used in order to record voltage and current independently. The calculation of apparent resistivity was made with RESIXP software. For seismic refraction, a 24 simultaneous channels OYO McSeis 170 unit from a Japanese manufacture was used. Geophones were spaced 5 m apart and three hammer shots (advance, central and match), plus intermediate shots in channels six and eighteen were applied. The data was processed using the generalized reciprocal method (GRM). All points were located in the field with a GPS Garmin 14 and transferred to a computer in order to create tables with the measured values. Figure 7.6 shows where the methods were applied in Jagüeyes landslide. Due to the current topography and vegetation it was not possible to access the upper part of the main body. The electrical profiling shows highest resistivity values (above 400 ohm-m) in the limestones rocks (clastic and bioclastic) in the upper part of the scarp and lowest values (less than 100 ohm-m) in the materials of the middle slope corresponding with the main body of the landslide. At the lower part of the slope the percentage of clay content increases the compactness and makes the zone more resistant although not as much as the primary limestone. The Caujerí fault which is the main culprit for the scarp was located about 500m from the beginning of the profile.

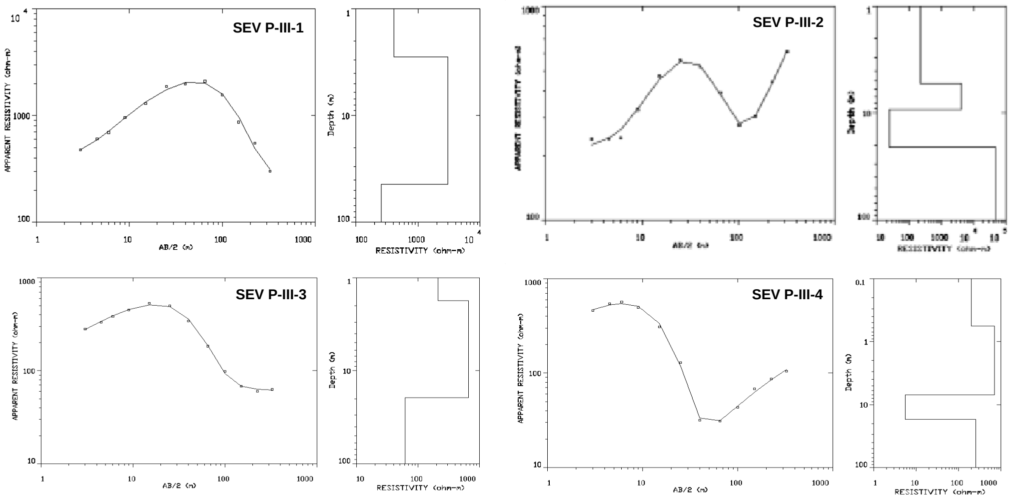

Figure 7.7. Vertical electrical sounding in Jagüeyes landslide.

The interpretation of the VES data provided more insight in the characteristics of the landslide. The first VES (SEV-III-1) on primary limestones shows an approximately depth of 2.7m of weathering crust and about 45m as the boundary between the limestone formation and the formation beneath with more claystone and marlstone. This could be recognized along the scarp as the limit where water was flowing from the slope during hurricane Flora. The second VES (SEV-III-2) was taken in similar material (at the upper part of the landslide body) and shows a change at 6 m depth, probably due to discontinuities in the mass; finally, the sliding surface was detected at 30 m depth in this location. For the third VES (close to the toe of the landslide) an upper boundary of 1.7 m indicated the depth of the landslide material while the 30 m limit is more probably the groundwater level at this point. The fourth and last VES, already in the valley, shows a well endured clay material until a depth of 8.5 m, and then a groundwater table with a clay layer around 17 m.

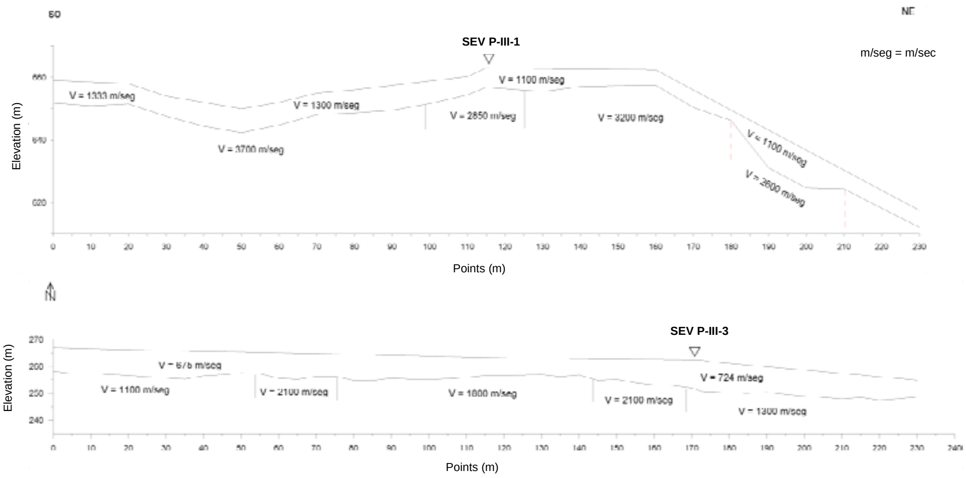

Figure 7.8. Seismic refraction profiles (location indicates in Figure 7.6).

Two seismic profiles were performed along the landslide, one on top of the scarp and one at the toe as shown in Figure 7.8. Due to use of a use of a hammer only shallow layers could be differentiated. The profile at the top of the scarp shows a thin layer of 7 to 5 metres depth, which corresponds to the weathering crust and soil, mixed with karstic cracks. Below this layer, the more endured homogenous limestone was expected but the results show discontinuities in different sections due to softer materials in wide cracks filled with sediments. These portions are more likely to be weakness zones of the next possible landslide. At the toe of the landslide two layers are also differentiated. The upper one, with a depth between 6 to 9 metres corresponds to the less endured sediments while underneath the material is more compacted although it is also part of the landslide deposit. Also in this profile, the materials have differences but they are less than the previous profile. Even tough very detailed geophysical surveys could not be carried out, the characterization obtained contributed to the understanding of the landslide. The location of the Caujerí fault, the sliding surface and the ground water surface were the main objectives reached. Besides, a less consolidated surface was recognized by the seismic profiles.

7.2.4. Profiling and volume calculation

The sliding surface was estimated with the DEM before and after the landslide. For doing this, 36 profiles were traced over both DEMs spaced every 20 m with points every 20 m as shown in Figure 7.9 summing 1404 points. The interpretation of the sliding surface in every profile was made considering the differences between DEMs and the geomorphic position at each specific location. Then, for every point, the depth of the sliding surface 20 m spaced was calculated. The maximum height difference obtained was 118 m close to the main scarp and this elevation was cross-checked with photogrammetric techniques. The estimated depth values were transferred from the profiles to a point map and an interpolation with 5 metres spatial resolution was made in order to obtain the sliding surface.

The volume of the landslide was calculated in two different ways, by the equation of a semi-ellipsoid and by the raster pixels with depth values. For the first method we used the equation that considers the displaced mass as half of an ellipsoid (UNESCO-WP/WLI, 1990) calculated in cubic metres as follows:

$$V = \frac{1}{2} \cdot \frac{4}{3} \cdot \pi \cdot \frac{1}{2} \cdot L_d \cdot D_d \cdot \frac{1}{2} \cdot W_d = \frac{1}{6} \cdot \pi \cdot L_d \cdot D_d \cdot W_d \qquad \text{[eq.1]}$$

Where, Ld is the length of the mass displaced, measured from the tip of the displaced material to its top. Wd is the width of the mass displaced, taken across the original ground surface in directions perpendicular to the length Ld; And the thickness of the displaced material, Dd, is measured perpendicular to the surface of the displaced material. The graphical representation of theses measures can be found in UNESCO-WP/WLI (1990). The shape of Jagüeyes landslide does not fit exactly into a semi-ellipsoid because its movement was diverted to the northeast, and it has a bottle neck in the middle and a spreading zone at the toe. Therefore these measurements were made considering the hypothetical location of an ellipsoid that better fits into this shape. The most difficult parameter to estimate was Ld since the total length of the landslide was about 1.7 km. But it is clear in the photointerpretation that the lower part of the movement is not a typical rotational slide. Thus, the values estimated for the parameters were 700 m for Ld, 410 m for Wd and 50 m for Dd. The volume of the landslide calculated by this method was 7,479,794 m^3.

The volume calculation with depth values of the pixels has the disadvantage that the surface is discretized (every 5 m in this case), but the advantage that it better fits any non-standard geometric shape. The volume was calculated by the following equation:

$$V = \sum_{Detph} PixSize^2 \cdot Depth \cdot Npix \qquad \text{[eq.2]}$$

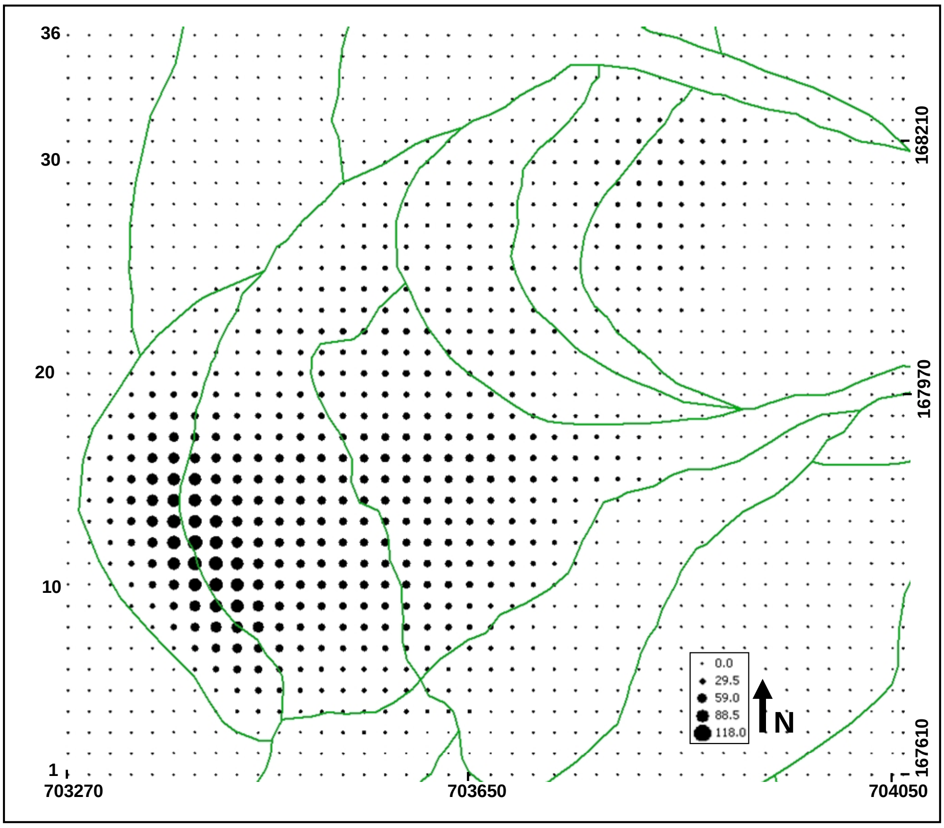

Figure 7.9. Profiles indicated on the left side and height (m) estimation for the sliding surface. Geomorphological boundaries are added for better recognition.

The squared area of the pixel size (PixSize) is multiplied by the value of the depth and the number of pixels with the same depth value (Npix) in order to get the volume. This calculation provided a volumetric value of the displaced mass of the landslide. In the Jagüeyes landslide this value was 7,465,187 m³ with a difference of 1.2 % in comparison to the ellipsoid method. The similarity in the values obtained from both methods was more due to the compensation that occurs in the mass volume calculations than the actual geometrical matching among them. This is because areas not covered by one geometric model are covered by the other and vice versa.

7.2.5. Conceptual landslide model and runout simulation

The conceptual model of the Jagüeyes landslide was created by integrating the above results and fieldwork campaigns including interviews of the locals. As Figure 7.3 shows, in 1956 there was already a circular shaped crack at the top of the scarp. During Hurricane Flora around 1083 mm of rain fell in this area. The resulting groundwater pressure affected the Caujerí Scarp which in turn led to the infiltration of the plateau located in the west. After three days of raining the amount of lateral pressure was enough to detach the large rock block of limestone and marls corresponding to the cracked area. This was reported by locals as a huge blasting sound when they start running down slope. During this period of semi-stable condition, considerable amounts of water came out from the scarp and were embanked by the recently detached materials. After about 45 minutes, a second movement commenced with devastating consequences for the locals including casualties and loss of houses and agricultural land. Due the persistent daily heavy rain fall local farmers evacuated their cattle to higher areas of safety. Unfortunately, a majority of the cattle were buried alive in mud and debris when the landslide occurred. Locals also identified the toe of the landslide as a 'muddy area' with decreasing depth down slope.

The identification of two movements from different sources made the modelling more complicated, since it was not possible to reconstruct the surface from the photos in between both movements. The first movement was identified as a rotational rock slide and the blocks of rock up to 5 m wide can still be observed in the field (See Figure 7.2 upper left). The second movement could have started as a rotational slide but gradually was changing to end in a mud flow. It has a narrow 'neck' area in the middle from where the mud content was gradually increasing. Both movements can easily be identified in aerial photos in the lower part of Figure 7.3, denoted as 1 and 2; and their relief characteristics can be recognized in Figure 7.5. Considering the description of the landslide and the data produced from the DEMs, a simulation of its runout was carried out.

Runout analyses are used for risk assessment and design of remedial measures against rapid landslides (Hungr, 1995). Research on modelling runout has been reported in literature since the beginning of the nineties (e.g. Sousa and Voight, 1992). Hutter et al. (1994) and Iverson (1997) compiled a comprehensive review on methods and physics for modelling debris flows. In practice, different 2D models have been proposed with field case studies (Chen and Lee, 2000; Bertolo and Wieczorek, 2005; Savage and Wasowski, 2006). Differences exist between the type of rheology equations and the 2D computational implementation of such models. Rickenmann et al. (2006) made a comparison of three models concluding that they are all capable to simulate debris flows when appropriated calibration is applied. They also highlight the importance of accurate topography reconstruction in order to obtain good results.

For runout modelling a two dimensional finite differences code for mud and debris flow was applied. A complete description of the model can be found in Beguería-Portugués and van Asch (2008). The model named 'MassMov' is based on a depth-averaged form of the motion equation for a continuum fluid, and it can incorporate different constitutive relations for the flow resistance term such that it can adapt to materials with different rheologies. In this case, we use the version 6.5 of MassMov which simulates 2D transport of material over a DEM, typically for routing of debris flow originating from a landslide. It uses a simplified, depth integrated, form of Bingham rheology to calculate the relation between stress and velocity. The main parameters used are: bulk unit weight (Pa.m-1), apparent yield stress for pure Bingham (Pa), dynamic viscosity (Pa.s) and angle of internal friction (º). Besides it is possible to setup in the model the 'time slice' (sec) and number of 'time steps' of the simulation. The model was implemented in PCRaster, a dynamic modelling system for distributed spatial simulation (PCRaster Environmental Software, 2008). It uses a scripting language for constructing models describing processes through time with raster GIS functionality emphasizing on analytical capabilities. Besides de geotechnical parameters, the runout model requires some input maps. The elevation map (dem.map) over which the material moves was created by subtracting the initial volume (h_ini.map) estimated from the DEM before the landslide occurs (predem.map). MassMov also has the possibility to simulate situations where the material has upper and lower boundaries like outlets as well as channels.

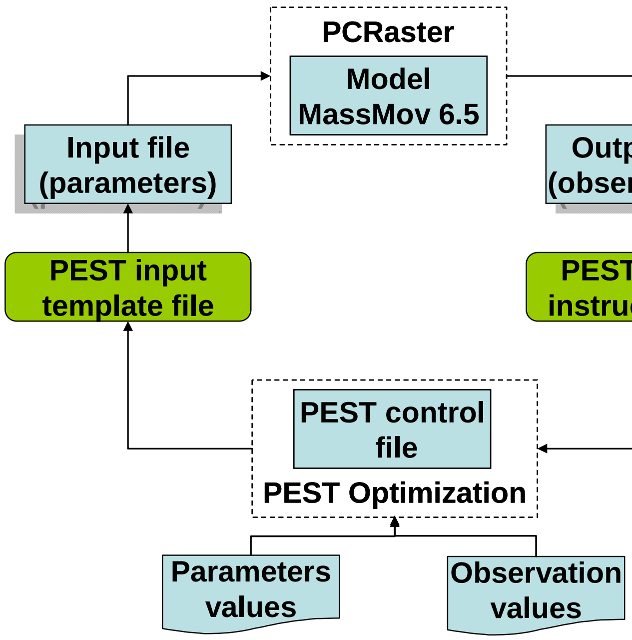

Figure 7.10. PEST flowchart with MassMov in PCRaster.

The fact that Jagüeyes landslide has two movements with different rheology was a drawback for the simulation with MassMov. The influence of rheology on debris flow simulation has been previously analyzed by Arattano et al. (2006). In this case, due to the large volume of initial material and the viscoplastic (Bingham) rheology of the model it was not possible to contain the mass at the early stage of the first movement into its original path. It always went out in the zone indicated as 'A' in Figure 7.3. One possibility was to simulate the runout for the second movement but, reconstructing the intermediate surface for the second movement was even more difficult and has much more uncertainties as far as mass balance is concerned. Actually, the chance to have a similar 'two-movements' event other locations along the Caujerí scarp is much less considering the morphology of area with a steep slope. One may expect either a single large movement from the top of the scarp up to the valley or a smaller movement occurring inside the colluvial material in the middle of the slope. As the original objective was to simulate a movement coming from the top of the scarp to assess the risk down slope; intent to generate a single movement covering the whole landslide area was made. The values of the parameters obtained could be then been used to simulated similar events in others part of the scarp.

The parameter values should be those that make the simulated mass movement depth similar to those obtained from the DEM overlay analysis. For finding the values with a better fit, the MassMov model in PCRaster was linked with PEST in order to simulate the Jagüeyes landslide. PEST is a model-independent parameter estimator used to set bounds on parameters while minimizing (in the weighted least squares sense) the discrepancy between model results and the observations(Doherty, 2004). It implements a particularly robust variant of the Gauss-Marquardt-Levenberg method of nonlinear parameter estimation. More details about the algorithm and the implementation can be found in the PEST user manual (Doherty, 2004).

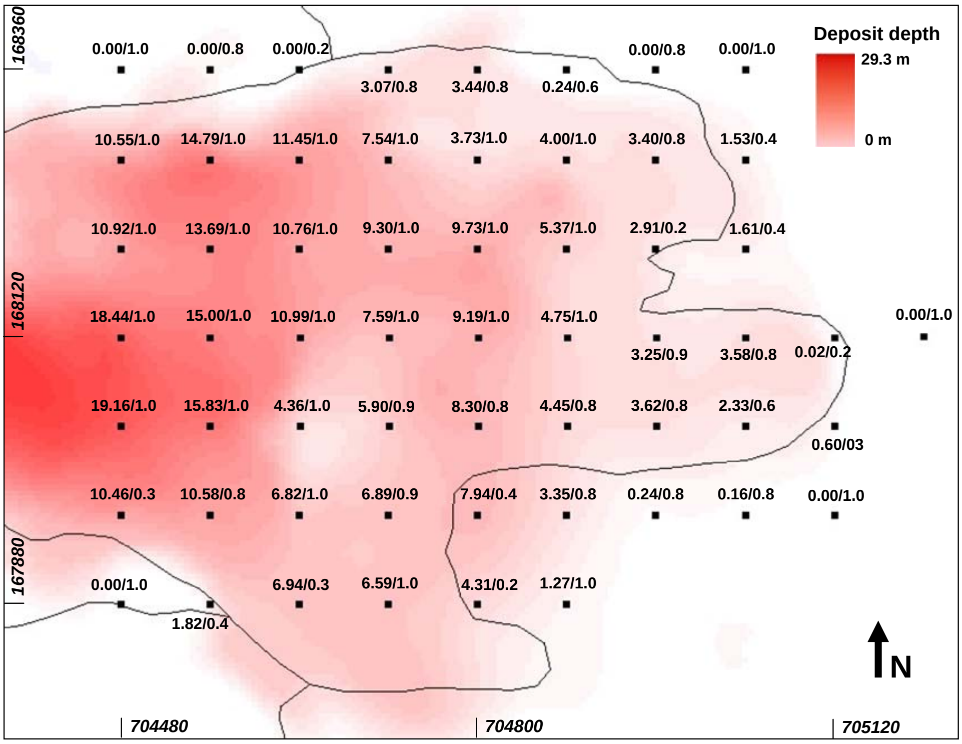

Figure 7.11. Observations points for calibrating the parameter at the lower part of Jagüeyes landslide. Each point has a measured depth&weight of the observation (see the text for an explanation).

PEST is configured with batch files and templates allowing the system to run in an iterative way as shown in Figure 7.10. A set of input parameters needed to run the MassMov in PCRaster are supplied to the model. The output result of the model is a file with model-generated observations. In this case it consisted of 58 points with depth values obtained after the simulation. The model-generated observations are read by PEST with an instruction file that 'translates' where and how to read these observations in the output file. Based on the differences between the model-generated observations and those measured by subtracting both DEMs, the optimization algorithm in PEST generated new values for the parameters of the model. Using a template the new parameters values are located in the input file and the MassMov model is executed again. The setting for the whole process is defined in a control file interpretable by PEST. For Jagüeyes landslide 58 observation points where located in a network of 80 x 80 m as shown in Figure 7.11. Each point has a measured observation of depth and a weight value related to the uncertainty of the point. As the landslide was interpreted in photos taken nine years after the occurrence, there were uncertainties about the location of the actual limit. Therefore, for each observation point an uncertainty or weight value was assigned ranging from 0-1. The weight values were estimated considering the distance of the points to the landslide boundary (Figure 7.11).

Table 7.3. Parameter values for simulating Jagüeyes landslide with MassMov in PCRaster optimized with PEST.

Parameter (unit)	Initial value	minimum	maximum	PEST result
Bulk unit weight (kPa.m-1)	18	10	50	18.03
Apparent yield stress (kPa)	0.5	0.1	5	0.505
Dynamic viscosity (kPa.s)	2.5	1.6	50	2.5
Angle of internal friction (º)	5	1	35	5.05

Establishing the landslide parameter values for runout modelling is still at an experimental stage. Results from calibrations and back analysis published for Bingham rheology the values shows large variations. Hungr and Evans (1996) carried out back analysis for twenty-three 'well documented case studies'. While the yield strength varied 16 kPa up to 400 kPa, the viscosity went from 1.6 up to 50 kPa.s. Bertolo and Bottino (2008) collected data from eight case studies, and found that unit weights values varied from 15.7 kPa.m-1 up to 22.5 kPa.m-1, yield strength varied from 0.038 kPa up to 4.794 kPa and viscosity varied from 0.0021 kPa.s up to 1.1 kPa.s. The differences in these parameters could be due to actual differences in the movements as well as due to the computational implementation of the modelling. For this case study the parameter values were established as shown in Table 7.3, the first three columns were the initial values established by testing the model and the range setup for PEST. The differences with the values reported in the literature reflect the experimental stage of the model. The last column has the best fit obtained with PEST calibration. Three steps of the simulation of the landslide occurrence with values are shown in Figure 7.12. The 3D view shows the area mapped as landslide and the simulated event. This result was obtained with a correlation coefficient of 0.7843 and the sum of squared weighted residuals was 759.1. The standard variance and error of weighted residuals were 14.06 and 3.749 respectively. A full report of the optimization process including the sensitivity analysis and some videos of different simulations are available on a supplementary CD-ROM. The MassMov model reports a lot of valuable information as maps or time series graphs, such as: velocity (m/s), momentum (m2/s), discharge (m3/s), total mass (m3), mass error, etc. These results are also presented in the supplementary CD-ROM. The parameter values obtained were later used for performing similar simulations in other parts of the scarp as explained below.

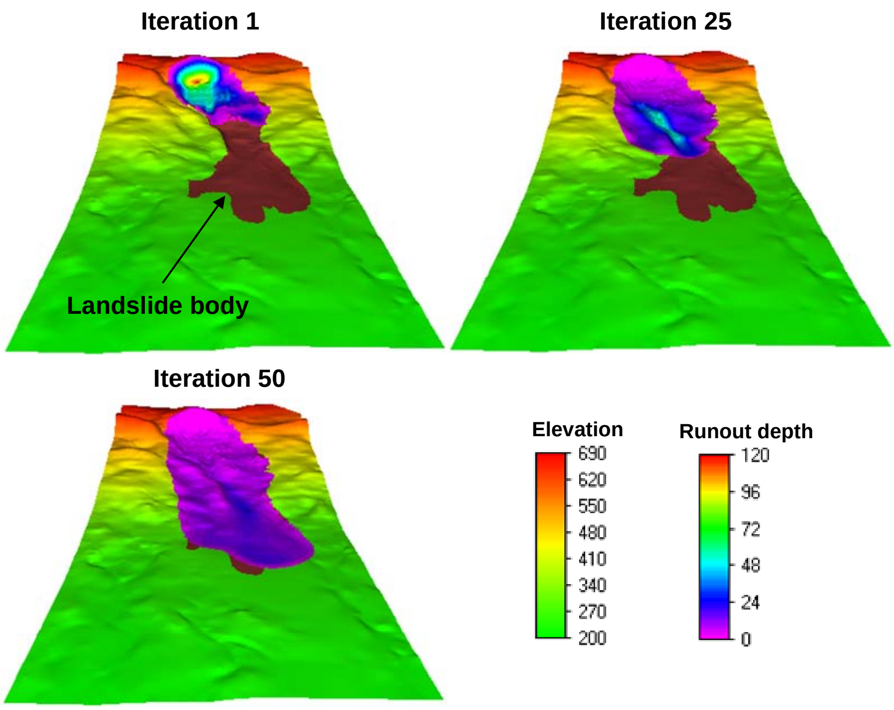

Figure 7.12. 3D views for the simulation of Jagüeyes landslide.

7.3. Caujerí scarp – up-scaling analysis

Based on the results obtained from the runout modelling of the Jagüeyes landslide, a quantitative landslide risk analysis was carried out for the whole escarpment. The mountain ridge, geographically named as Sierra de Caujerí, is located in the western border of the central valley of the San Antonio del Sur municipality – see Figure 7.13. It shows (in the aerial photos and fieldwork campaign) a series of complex mass movements that have occurred in a successive and regressive way. The re-activation of landslide areas is expected to be linked to intensive of prolonged rainy events. Due to the lack of historical records it was not possible to link the rainfall events to the landslides occurrence and therefore their return period and frequency/magnitude relationship could not be calculated. Based on the aerial photos from 1956, 1972 and 2000 a landslide type similar to Jagüeyes was estimated to occur along the Caujerí scarp every fifty years. Continuous monitoring carried out by the local authorities would certainly improve this prediction in the future.

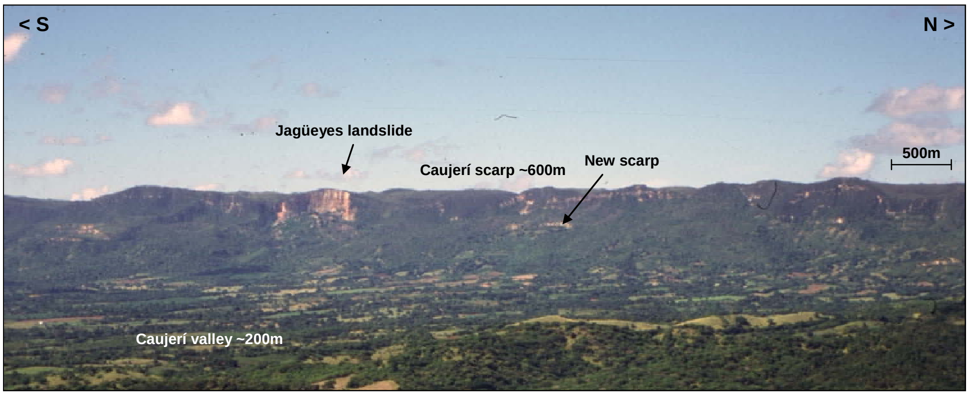

Figure 7.13. Central part of Caujerí Scarp (photo taken in 1998).

Before carrying out a runout and risk assessment it was necessary to recognize the areas along the scarp which are more likely for landslide occurrence. The analysis was based on the integration of different geological and geomorphological methods. First of all, the morphology of the scarp was characterized to evaluate new potential failure zones. Then (by profiling) the angle of reach was applied to delineate a new potential 'toe line'. The groundwater table was mapped considering the location of different spring along the scarp. These methods plus a more detailed geomorphological mapping were the main sources for an integrated zonation along the scarp. The houses and population as elements at risk were mapped in detail and some scenarios were used for carrying out the runout modelling in order to estimated the loss in case of new landslides. A detailed explanation is given the next sections.

7.3.1. Landslides and potential sliding surface

The first element for estimating new potential landslide zones was to make a geomorphological evaluation. For the entire scarp detailed geomorphological photo-interpretation was made to discriminate i) escarpment sections, ii) back scarp and iii) their likelihood to occur. The criteria used for the discrimination were the i) back slope steepness, ii) vegetation covers and iii) down slope steepness. Figure 7.14 shows on the left the delimitation of twelve potential sliding zones with their potential back scarps lines classified. On the right, two cross sections are shown as an example. As seen, cross section 2 is steeper on both sides than cross section 9. The last one has more of a plateau shape in the back slope and the valley slope is also less steep. Consequently the other ten potential surfaces were classified based on the aforementioned criteria.

The angle of reach method has been previously used (Scheidegger, 1973; Corominas, 1996; Hunter and Fell, 2003; Hungr et al., 2005) as a method to estimate the travel distance of a potential landslide. The method is based on the empirical relationship of the distance reached by previous events and its horizontal angle as shown in Figure 7.14 (right). Advantages and disadvantages have been mentioned and even though it is not directly based on physical laws the method have been recognized as a possible solution. In the Caujerí scarp, the angle of reach method was applied for the twelve potential sliding zones. Considering the new predicted travel distance for every cross section a reach line was drawn based on the topography. This line (based on this empirical method) delimited an important zone beyond which the landslide body was not expected to travel. In all sliding surfaces the predicted travel distances are inside the former landslides bodies as the analysis was made considering retrogressive movements.

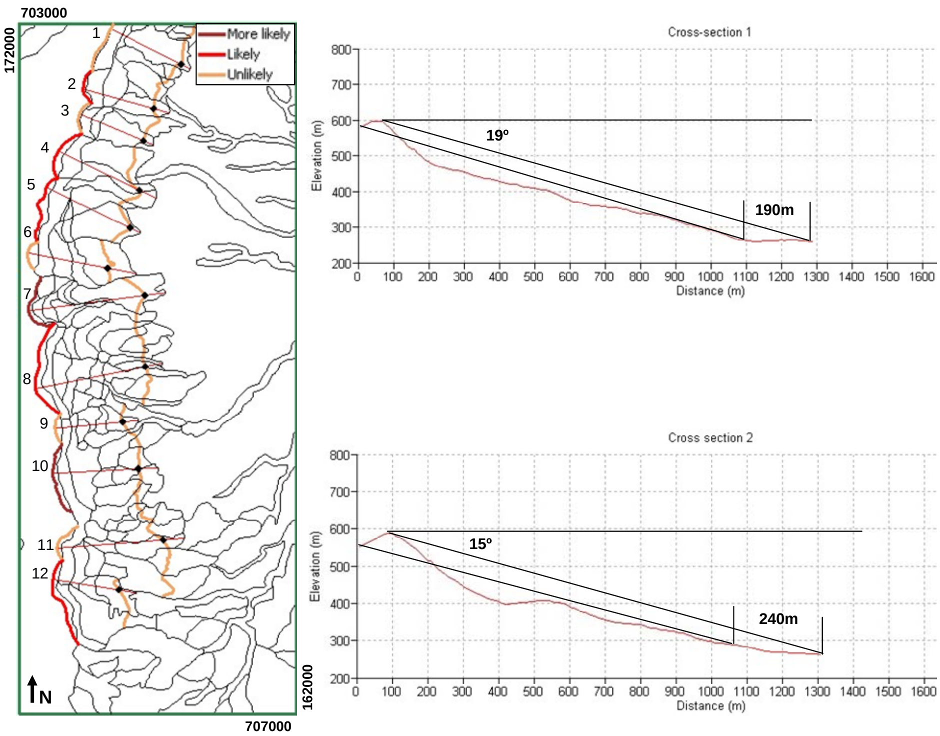

Figure 7.14. Potential back scarps and cross sections with the reach of angle method.

The contact between the groundwater table and the slope was mapped by locating the springs in the topographic maps at a scale of 1:25,000. Many of these springs were later verified during a fieldwork campaign. They are used by the local farmers to collect water by creating a small pond and transporting the water through pipes to their houses or crops. Figure 7.15 (left) shows the location of the springs and the drainage network with the geomorphological interpretation. In some areas more springs were found further down the slope but they were discarded. Besides, there were springs at higher elevation which only drain during rainy seasons. The superficial karstic phenomena identified in the limestone layers of the plateau are an indicator of the complexity of this aquifer which requires deeper analysis, especially regarding landslide generation.

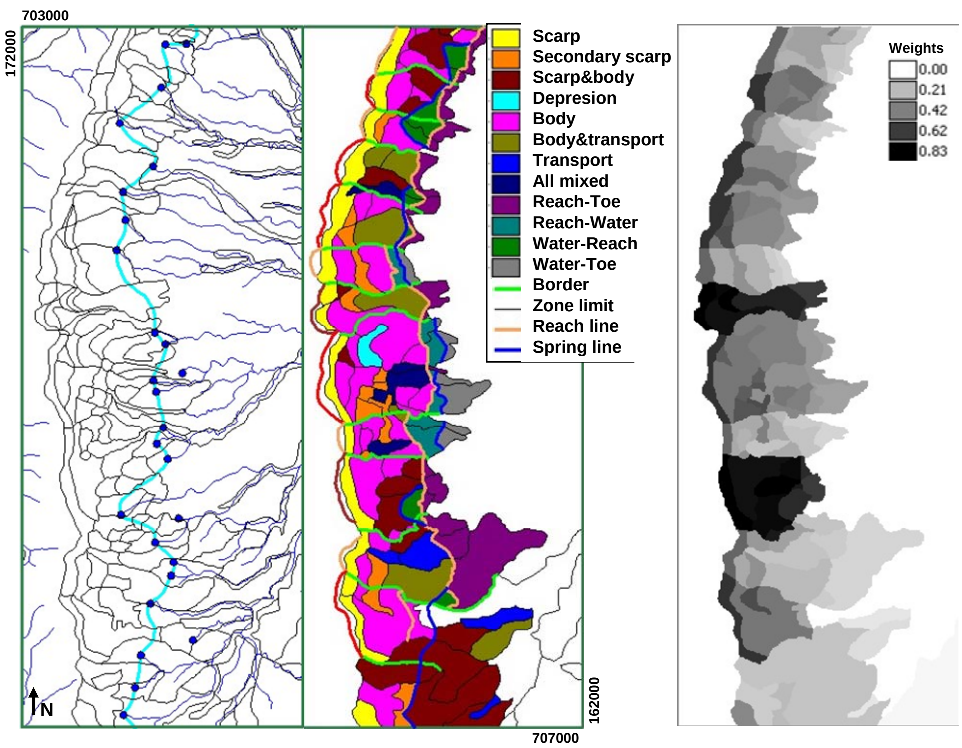

Figure 7.15. Location of springs (left), detailed geomorphological mapping (middle) and zonation (right). See the text for an explanation.

Integrating the above interpretation and the detailed photointerpretation the scarp area was divided up into geomorphological units shown in Figure 7.15 (centre). At the bottom of the slope, different new zones were created by combining the spring line, the reach angle line (Figure 7.14) and the toe of the former landslides. Depending on the position of these lines the zones were particularly named in Figure 7.15 and in Table 7.4, e.g. 'reach-water' when the reach angle line is topographically higher than the spring line. This map contains sufficient information to recognize different areas related to landslide occurrence.

The subdivision was made not only down the slope (west-east) but also along the scarp (south-north). The next step was to determine a weighted zonation for the different parts of the scarp. The zonation was made using three criteria i) the potential back scarps, ii) the detailed geomorphological mapping and iii) the hazard assessment carried out at municipal level. The last one was chosen because in the municipal assessment (Chapter 6) other geological and geomorphological factors were included. The assessment was made with the multi-criteria evaluation method as explained in detail in Chapter 4. The criteria with their weights and the standardization for the classes are shown in Table 7.4. The ranking method was applied with the variant of 'expected value' (ITC, 2001). Other data obtained were the area (in square metres) of every sliding zone, as shown in Table 7.6. The calculation was made from the scarp down slope up to the toe and border lines as shown in Figure 7.15. Besides, the spatial probability was calculated as the chance of a landslide occurring in every zone compared with the others.

Table 7.4. Weights used for Caujerí scarp zonation.

Criteria	Classes	Standardization
Break zones (w=0.61)	More likely	1.000
	Likely	0.455
	Unlikely	0.182
Geomorphology (w=0.28)	Scarp	1.000
	Secondary scarp	0.678
	Scarp&body	0.517
	Depression	0.329
	Body	0.404
	Body&transport	0.264
	Transport	0.210
	All mixed	0.164
	Reach-Toe	0.056
	Reach-water	0.088
	Water-reach	0.124
	Water-toe	0.027
Previous hazard (w=0.11)	Low H1	0.034
	Low H2	0.072
	Low H3	0.115
	Moderate H4	0.164
	Moderate H5	0.220
	Moderate H6	0.289
	High H7	0.374
	High H8	0.488
	High H9	0.659
	High H10	1.000

The result (Figure 7.15 (right)) shows different zones in the scarp with a final weight. As expected, the upper parts of the slope have more weights and the Jagüeyes landslide was also highlighted as it is considered: as an unstable zone where more small movements could occur. Although, these values are not in probabilistic terms they facilitate recognition of the hazardous situation of the buildings and population according to this qualitative assessment. For example, as shown in Table 7.5, there are 33 houses out of 90, and 188 people out of 371 are located in non hazardous areas according to this estimation. However, some people are double counted as some buildings are used as schools or local grocery stores as explained below. This preliminary assessment allows local authorities to focus prevention measures – at first – to the 38 people located in 13 buildings with the highest weights. A more quantitative estimation was carried out based on runout modelling as described in the next section.

Table 7.5. Buildings and people at risk by qualitative estimation.

Weights	Buildings	People
0.00	33	188
0.01	5	10
0.03	1	4
0.14	2	6
0.15	9	38
0.17	7	27
0.19	6	20
0.20	1	3
0.32	2	6
0.33	8	25
0.35	2	3
0.46	1	3
0.65	13	38

7.3.2. Scenarios for runout modeling

Based on the parameters obtained from runout modelling of the Jagüeyes landslide (Table 7.3), a runout simulation was carried out for the twelve potential zones along the Caujerí scarp. As explained in the municipal assessment (Chapter 6) this scarp had movements estimated with different return periods of 1/50 years, 1/100 years and 1/500 years. Considering the characteristics of existing landslides and in order to analyze the runout with different magnitudes, sliding surfaces were three-dimensionally delimitated for three potential initial volumes representing aforementioned return periods as simulation scenarios. The volumes in cubic metres are shown in Table 7.6 and are represented in Figure 7.16. Scenarios two and three were designed to be around 90% and 50% of scenario 1 respectively.

Table 7.6. Volume in cubic meters for the three magnitude scenarios.

Scarps	Scenario 1	Scenario 2	Scenario 3	Area (m^2)	P_{event}
1	6,262,650	5,668,620	3,131,260	881,100	0.069
2	5,105,210	4,637,890	2,552,610	706,600	0.055
3	3,144,490	3,060,670	1,572,210	567,200	0.044
4	9,842,100	8,961,030	5,497,710	868,500	0.068
5	8,779,450	7,890,220	4,730,680	943,100	0.074
6	6,378,070	5,779,400	3,519,110	759,900	0.059
7	6,246,920	4,788,970	3,315,070	840,500	0.066
8	19,153,850	17,396,440	9,576,890	2,471,400	0.193
9	4,788,470	4,345,600	2,571,350	874,300	0.068
10	15,526,280	14,139,640	8,542,190	1,286,800	0.100
11	6,135,570	5,523,610	3,282,430	1,493,300	0.116
12	20,099,380	18,385,850	10,049,660	1,130,700	0.088
	P_t=0.002	P_t=0.01	P_t=0.02		

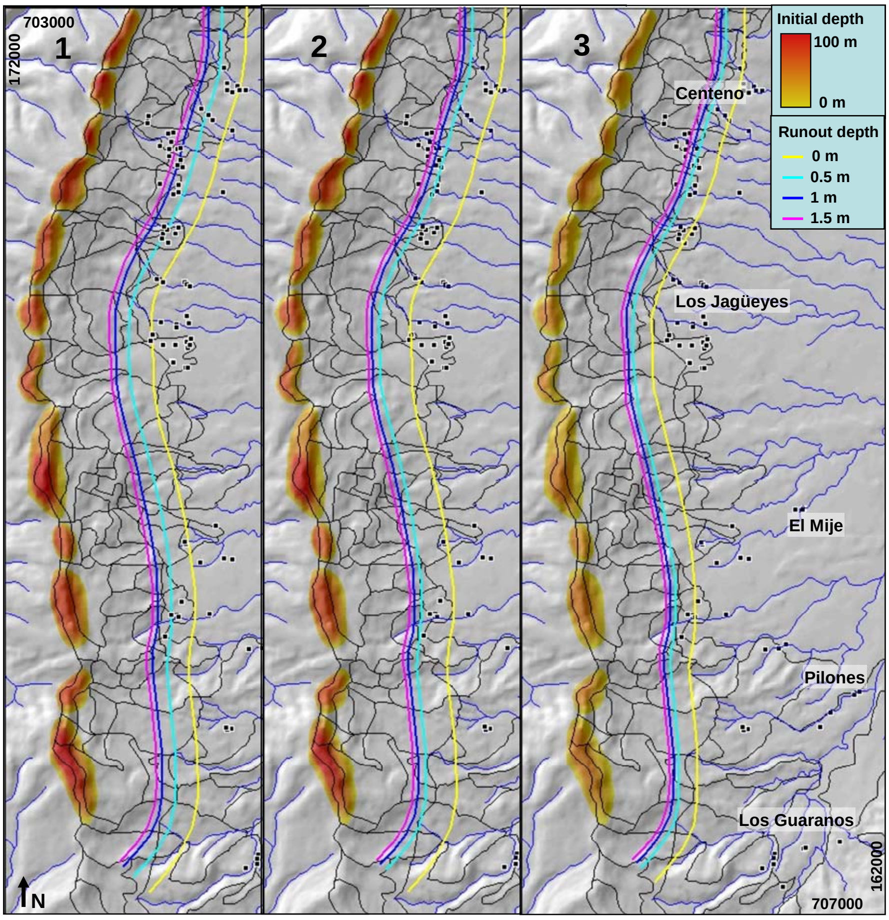

Figure 7.16. Initial volume and runout depth for three different scenarios. Black dots are buildings. Coordinates in Cuba Sur coordinate system.

The three scenarios were simulated for the twelve zones and the travel distance is represented as a yellow line (i.e. a depth of 0m) in Figure 7.16. The limits where the runout had 0.5m, 1m and 1.5m depths are also represented. Scenarios 1 and 2, had very similar maximum runout distance, but the 0.5m isohyets was different. As expected, scenario 3 had a shorter distance because less volume was released. With the MassMov model it is possible to generate multiple outputs maps and graphs such as velocity and momentum maps. For vulnerability and risk analysis the momentum map would be an optimum parameter, which represents the product of the mass and the velocity of the material at any given location. This could better indicate the impact of the materials to a building. The maximum and cumulative momentum maps were calculated for this case study. However, due to parameters values obtained the momentum values were not consistent with the literature values for potential damage estimation of buildings. Therefore, in this study, runout depth was used for vulnerability and risk assessment.

7.3.3. Elements at risk and vulnerability assessment

At this scale of analysis only population and buildings were considered as elements at risk for vulnerability analysis. Detailed information about these elements was surveyed in the field by Villalón Semanat (2007). This data were processed in order to assess the landslide vulnerability based on the runout modelling. Agricultural production is another important element a risk, but it was discarded as only limited information could be surveyed about the type and cost.

Buildings

The region of Caujerí scarp has ninety buildings from which eighty-two are single floor houses, two grocery stores, three rural schools, two churches and one power generator. They are located at the foot of the slope and in the valley either isolated or in five hamlets as indicated in Figure 7.16. Only two buildings have a foundation, and sixteen buildings have walls made with bricks or concrete blocks. The rest of the buildings (with the exception of one made from palm bark) are made out of wood. The roofs in this region are usually very weak with material such as asbestos sheets (for twenty-five buildings), metal sheets (twenty-five), palm leaf (thirty-seven) and other types (three). The buildings were constructed in different periods, counting only nine that are more than fifty years old. In fact, many owners, after some years, rebuild their houses with woods and palm leafs acquired in the nearby forests. In accordance with the building classification in Cuba (explained in Chapter 3) where the housing condition and typology were described, there are twenty-four houses classified as ‘good’, twenty as ‘regular’ and forty six as ‘bad’. In addition, every house has a replacement cost which was calculated according to its typology, condition, age and size.

Vulnerability curves for landslides are not very common in the literature such as for flood or earthquakes and only until recently some more results have been published. Based on previous experience some authors recommend vulnerability range values such as AGS (2000), Sterlacchini et al (2007) and Zezere et al. (2008). Five ranges of vulnerability for building were suggested by Glade (2003) modified after Leone et al (1996), considering five expected intensities of damage. Papathoma-Köhle et al. (2007) created a more comprehensive framework for assessing vulnerability based on weights and ranking. While these studies are applicable for qualitative assessment Remondo (2008) used previous losses per square metre in order to estimate the vulnerability for a specific landslide type. A more quantitative approach was presented by Fuchs et al (2007) where a polynomial vulnerability function was created for sixteen houses damaged by a debris flow in Germany. Neither the vulnerability value calculated nor the vulnerability function estimated reached a value of 1 (i.e. total damage) and houses covered up to 2.5 m only had 0.54 vulnerability. In spite of being the first work where a function was estimated, the results seem to require more refinement.

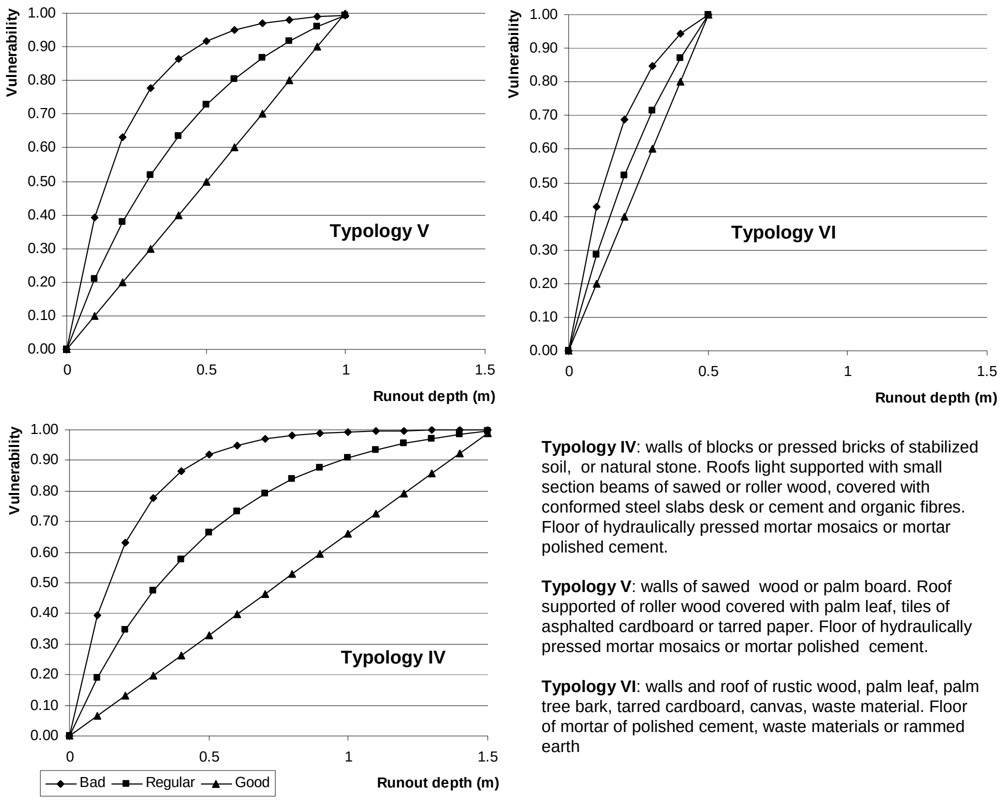

Figure 7.17. Vulnerability curves for building in Caujerí Scarp.

Considering aforementioned building characteristics and previous vulnerability studies, several runout vulnerability curves were created. The vulnerability functions were designed based on the following considerations:

i) Future landslides will have similar characteristics (i.e. depth, velocity, etc.) than those produced in the past.

ii) In the Caujerí scarp, although the movements commonly started as a rotational rock slide, they are transformed into debris flows, where half of their path ends in a mud flow at the toe. Thus, wooden houses were still standing or were partially destroyed (covered by mud) when the Jagüeyes landslide occurred.

iii) Previous studies and interviews with local people showed that with these types of house typologies, the vulnerability could be considered as 1 (i.e. total damage) after 1.5m of debris flow depth.

iv) The actual impact on building should be estimated by calculating the momentum. However, momentum equations require knowing the mass (volume time density) which was not discernable given the limitations of the modelling.

v) By analyzing the runout simulations we found very low velocity (less than 1 $m.s^{-1}$) when the deposit depth was less than 2m. This allows us to use only the runout depth in order to estimate the vulnerability.

The vulnerability curves shown in Figure 7.17 were created in relation to runout depths. Here, as similar to other studies, depth is considered as intensity (see Fuchs et al., 2007). The values 0.5m, 1m and 1.5m result in vulnerability 1 (total damage) for the typologies VI, V and IV respectively. Buildings in 'good' condition have a linear relationship while buildings with 'regular' and 'bad' condition have an exponential relationship using the same coefficients. The vulnerability functions were scripted in ILWIS and were executed depending on the building typology and condition. The three runout depth maps generated in PCRaster with MassMov were imported in ILWIS and the script for calculating vulnerability was applied in order to calculate the vulnerability value of every house.

Table 7.7. Results of building vulnerability

Parameters	Scenario 1	Scenario 2	Scenario 3
Buildings	41	41	35
Depth (m)			
Max. depth (m)	11.23	11.02	10.78
Average (m)	0.65	0.56	0.44
Standard dev. (m)	1.72	1.68	1.64
Vulnerability (0-1)			
Average	0.4287	0.373	0.201
Standard dev.	0.4769	0.430	0.359
With vulnerability 1	19	13	10
Total vulnerability	38.5843	33.561	18.116

Table 7.7 shows the results of vulnerability for building according to the three scenarios. Forty-one buildings had some vulnerability value for scenario 1 and 2 with 0.65m and 0.56m as average runout depth respectively. Figure 7.16 shows the location of every house and a runout depth line every 0.5m. For scenario 3, the number of buildings affected and runout depths are shorter. The average vulnerability is below 0.5 for the three scenarios, although a total of 19, 13 and 10 buildings are estimated to be totally damaged for scenarios 1, 2 and 3 respectively. Finally, adding up vulnerability values of each affected building can be used as a measure of vulnerability for every scenario. Because the scenarios represent different volumes (magnitude) related to temporal probabilities, the vulnerability values also show this difference. However, a detailed comparison is needed in order to analyze the landslide vulnerability. For example, although 41 buildings have been affected by landslides for 1/100 and 1/500 years return period, the total vulnerability was 13% less for the former one. More frequent events (1/50 years) have much less total vulnerability as shown in Table 7.7.

Population

Detailed information about the population in buildings was also recorded during fieldwork. Regarding the age composition the area has 275 inhabitants with 49 people who are 0-15 years old, 30 who are 12-18 years old, 167 who are 19-64 years old and 29 who are older than 65. Among them, 118 are female and 157 are male. There are three rural schools with ninety students in total, including children from the eighty-two houses and others from the surround areas. In the region there are twelve handicapped inhabitants which would require extra-help during an evacuation. Except for sixteen workers the rest of the people remain in the area permanently and have a low mobility. It is also remarkable that eighty women are housewives which is almost 70% of the total population. It was recorded that seventy-seven farm workers usually work in areas close to their houses.

For other disasters, like earthquakes, temporal presence in the house or other buildings like schools is a concern. Besides in other regions like Hong Kong, unexpected landslide may occur when people are at home. In Cuba, due to the disaster management system and particularly to the Early Warning System (EWS), any populations living at risk are normally warned and are helped several days in advance with their evacuation. Usually, three to five days before the tropical storms and at least 24 hours before prolonged precipitation. As all of the landslides reported herein were triggered by rainfall, it is expected that people who live in landslide prone areas will be warned when the EWS is activated by rainfall events. With the current level of landslide disaster awareness of municipal and local authorities, it would be very rare to have houses at risk in the Caujerí scarp that were occupied when a landslide occurred due to rainfall. Therefore actual vulnerability estimation, even though still qualitative in most studies (AGS, 2000; Glade, 2003), was considered to be applicable in this case study as well. Instead, since the worst exposed person is 100% present in the house and assuming his/her vulnerability 1, population for the 41 buildings at risk (see Table 7.7) was counted, being 138 people. Fortunately, none of the schools or grocery stores was among these buildings. This is relevant because during an evacuation it is common in these remote areas to use these facilities as shelters, as they are usually better constructed.

7.3.4. Landslide risk assessment

Estimating the landslide risk for the Caujerí scarp required a different approach than in the previous spatial assessment (Chapters 4-6). Here, although spatially distributed the risk is obtained for single houses that are points in the map. Therefore, the risk was first calculated in tabulated form and then cartographically represented. Based on the probabilities, vulnerability and cost values obtained for the three scenarios (or event) the specific risk ($Risk_S$) for every house was calculated as follows:

$$Risk_S = P_E * P_T * V_E * Cost \qquad \text{[eq.3]}$$

Where, P_E is the event probability, interpreted as the chance that if a landslide occurs in the scarp, a particular zone would be affected. The value calculated for every zone is presented in the right column of Table 7.6. A more quantitative assessment could be made if slope stability analyses were conducted for every slope zone at the scarp. However, due to the lack of data, this type of analysis would require large assumptions that would make the results less useful. The term P_T is the temporal probability already estimated for the three scenarios. The vulnerability, V_E was calculated as described in previous section for each scenario according to the building type and condition and the *Cost* was obtained for every house during fieldwork.

A table with the ninety buildings was constructed containing in columns the variables of the risk equation (Eq.3). A column multiplication allowed us to obtain risk values for the three scenarios as shown in Table 7.8. In this case every building was assessed for landslide risk and the scenario simulations were considered as intensity variants with different return periods. In this risk calculation there were two parameters that depend on the scenario: the vulnerability and the temporal probability. The former one is based on the runout depth which is different in each scenario. As expected, the results of the simulation in Table 7.8 and Figure 7.19 show the dependency of the risk with the initial volume with is related to runout length. However, the proportions of the scenarios are different. Approximately 90% and 50% of the proportion of the initial volume for scenario 2 and 3 as compared with scenario 1, was slightly reduced to 86% and 42% in vulnerability assessment and drastically reduced to 42% and 4% in the risk assessment. This difference was associated to the temporal probabilities P_T estimated for each scenario.

Table 7.8. Risk value in Pesos for the Caujerí scarp computed using equation 3.

Parameters	Scenario 1	Scenario 2	Scenario 3
P_t	0.002	0.01	0.05
Buildings	41	41	35
Minimum*	1.3200	0.6600	0.0011
Maximum	5.8200	2.7030	0.3520
Average	1.3320	0.5680	0.0546
Standard Dev.	1.6563	0.7185	0.0993
Sum (pesos)	119.8780	51.1194	4.9151

Without considering 0 value.

The total risk is represented in Figure 7.18 by the area under the curve using these three scenarios. Although less frequent events have larger consequences, the risk curve does not follow the ideal concave shape. This is due to number of assumptions involved in the calculation previously explained. This graph is useful in order to estimate the landslide risk at any given return period for this particular area.

Figure 7.19 shows the risk value obtained for every building in the three scenarios. A three dimensional animation was created in ArcScene allowing for the visualization of any of the three scenarios, the software also allowed for the rotation of the location of the viewer over the whole area for better visualization. Thus, as seen in Figure 7.19, buildings with no risk value are represented in lighter tones and lines represent runout depth as in Figure 7.16. The red bars over the buildings represent the risk illustrating that, according these assessments the northern part of the scarp has buildings with higher risk values. A small area in the mid-south has eight buildings at risk.

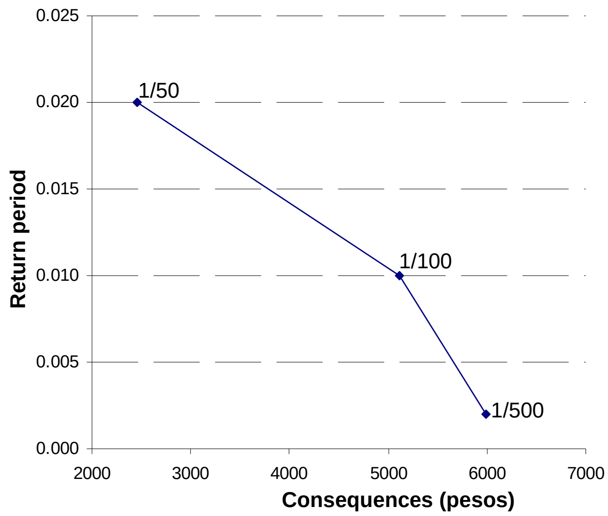

Figure 7.18. Total risk of landslide in the Caujerí Scarp.

Even tough the area has experienced large landslides the annual risk, as shown in Figure 7.18 and Figure 7.19, is very low. This is due i) the temporal probability and the cost of 'elements at risk' is low, ii) not all type of elements at risk were considered and those used (the buildings) were only low in number.

As far as population at risk is concerned, the same 138 people from the 41 buildings considered as 'vulnerable' were taken into account for being at risk in case of landslide occurrence. In principle, the 138 people at risk should be first priority in the case of an emergency evacuation. According to the survey carried out, among this population, there were six handicapped people who required extra help during the evacuation. Also, it was found that most of the population tend to remain in the area close to their houses or in agricultural fields nearby. However, as mentioned earlier, it is expected that when the early warning system is activated for heavy rainfall, this population is evacuated to safer areas far away from the scarp.

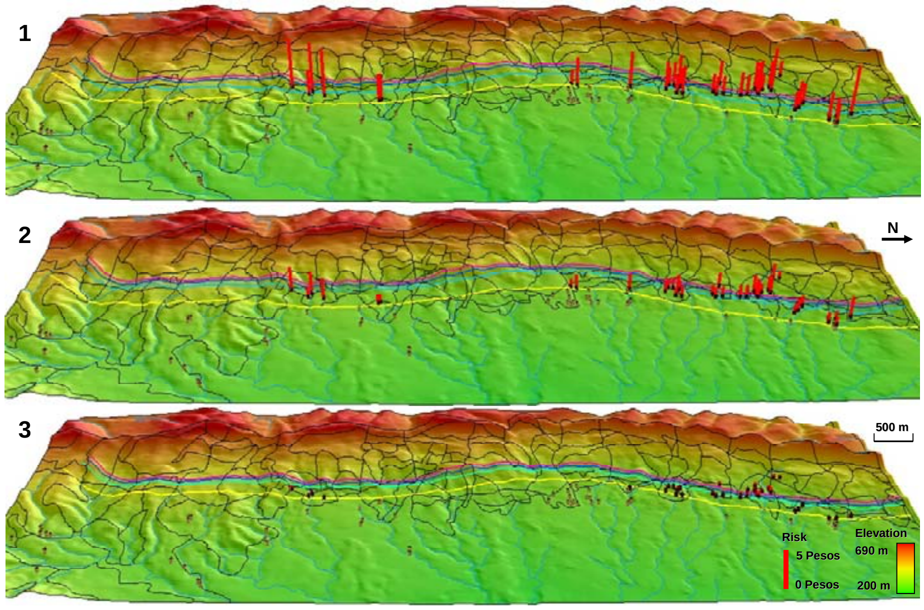

Figure 7.19. Three dimensional representations of the houses in the Caujerí scarp and their annual risk in Cuban Pesos.

7.4. Conclusions

Landslide risk assessment was carried out at local level considering runout modelling and up-scaling of the runout parameters. The use of runout modelling for landslide risk assessment is new. Detailed quantitative results obtained by the runout simulation allowed us to obtain many parameters, such as depth, velocity, momentum, etc. for every location in the study area. This approach substitutes the empirical relationship with runout distance or the empirical estimation of damage based on previous disasters. Still there is a gap with civil and structural engineering in modelling the impact of landslides on buildings or other types of infrastructure. Due to the fact that the model used was still under development and cumulative or maximum momentum were not suitable for assessing vulnerability. Instead, runout depth was used with an estimation of the damage of a mudflow at 0.5m, 1m and 1.5m depending on the building typology and condition. Thus, the use of runout modelling for risk assessment opens new possibilities for quantitative landslide risk assessment. As in all numerical simulations, calibration for obtaining appropriate parameters is a key requirement. In this study, we used PEST in order to calibrate the model, but still there were many options in modelling and calibration that could be tested. As the study was on risk assessment, we considered not to divert the objectives and to obtain a set of parameter needed for this purpose.

In order to reconstruct an event that occurred forty-five years ago all available data was employed. A thorough analysis of the disaster and a detailed geomorphological photointerpretation are always indispensable in such studies. The author considers that 'stereo' interpretation is still more relevant for landslides than satellite images. Recent satellites with stereo capabilities may provide a solution, but still resolution has to be as high as comparable with aerial photos. A further step for deeper analysis is the creation of orthophotos and DEMs by digital photogrammetry. Stereo pairs, even from very old aerial photos could still be processed for landslide applications when information about the camera is available. However, this task requires appropriated skills, especially on locating GCP to reduce the error and on DEM editing.

Geophysical studies for landslide also offer many perspectives in local landslide risk assessment. Wrong selection of methods and incorrect location of measurements may provide useless or partially useful results. Deep-seated landslides such as Jagüeyes require geophysical methods that are able to go 'deep enough' in order to facilitate satisfactory analysis. Besides, when a landslide had occurred many years ago and the colluvial material is rather homogenous, the recognition of the underground surfaces is very complicated. Despite limitations encountered, the objectives of the geophysical surveys were accomplished. Based on the data obtained by the photointerpretation, the digital photogrammetry, the geophysical survey and the runout modelling it was possible to reconstruct the Jagüeyes landslide.

By using the parameters obtained with runout simulation on Jagüeyes, the landslide risk on the Caujerí escarp was assessed. The strength of geomorphological interpretation was also utilized. The results obtained of landslide risk for buildings were lower compared with other studies such as Sterlacchini et al. (2007), Remondo et al. (2008) and Zezere et al. (2008). When comparing with other studies we must also consider the differences in economy and development. The aforementioned studies were carried out in highly developed areas (Italian Alps, north of Lisbon and northern Spain, respectively) compared with the poorest municipality of Cuba (San Antonio del Sur) for the present case. Besides the fact that the these studies did not use runout depth for estimating the risk, the two main reasons for having low risk values were i) the conservative (and qualitative) way to estimate the temporal probabilities and ii) the subsidized system still in place in Cuba for replacement cost of buildings.

Visualization of risk at local level requires more research. At these scales, zoning risk areas are less practical than identifying the risk of individual objects. However, the representation of the risk for these objects could be made in several ways. That may be the reason why most local landslide risk assessment shows final results in tabulated form rather than in maps.

CHAPTER 8

Discussions, conclusions and recommendations

Cited as:
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8. Discussions, conclusions and recommendations

8.1. Introduction and problem statement

Despite many efforts in risk reduction landslide disasters continue to affect the economy and population. Landslide events, which are classified as a meteorological disaster by most international databases (OFDA/CRED, 2007), seem to have increased worldwide and the future trend appears to be rising considering the increase of hazard potential due to climate change and the increase of a vulnerable population (Hoyois et al., 2007). In Cuba, awareness concerning landslide disasters started in the beginning of the nineties and both the civil defence authorities and the scientific community have put tremendous effort into reducing landslide impacts. Landslides are an important problem in mountainous regions in Cuba, mainly due to tropical storms, but also during prolonged rainy periods (Castellanos Abella and Van Westen, 2005). Since the landslide damage is recorded as associated to the main disaster there is no information on how many landslides have occurred and where they are located. The historic record of landslides is incomplete and, before this research, there was no landslide inventory system. Studies of landslides in Cuba are limited and only few hazard, vulnerability and risk assessment have been made with outdated methods.

Cuba is considered a model in hurricane risk management by the United Nations (ISDR, 2004), because hurricanes in Cuba cause considerable less casualties as compared to neighbouring countries with a different economical, social and political context (Wisner et al., 2006). The National Civil Defence organization and the various government organizations at various administrative levels are the main organizations in Cuba that are responsible for disaster management. The country was able to setup a warning system for tropical storms, with a warning time ranging from three to five days, which reduced the human casualties to a very low level, although economic losses were still considerable (Rodríguez, 2004).

The role of the National Civil Defence is to identify and evaluate (in co-ordination with government organizations, enterprises and social institutions) the hazard, vulnerability and risk factors as well as to provide the planning needed to cope with them. Each territory should have a disaster reduction plan, as disaster reduction measures will be included in the social-economic plan every year. The Ministry of Science, Technology and Environment is officially responsible as the main co-ordinator for conducting multi-hazard risk assessment in every municipality (169 in all) of Cuba.

Therefore, within the planned system for multi-hazard risk assessment it is very important to know the potential areas for landslide occurrence and the risk of population, infrastructure and economic activities in those areas.

8.2. Reflections on main objectives

This research is intended to contribute in reducing the lack of knowledge about landslide problems in Cuba by designing and applying innovative spatial analysis methods for landslide risk assessment at different scales, taking into account the specific situation in Cuba. Various methods and models for landslide hazard and risk assessment have been applied in other countries, but they had to be translated into 'the Cuban' situation.

In this study, after a comprehensive review of theoretical background, best practices worldwide and a contextual analysis of Cuba, four case studies for landslide risk assessment have been carried out. The assessment was made at four different scales considering the data availability and the most appropriated methods as summarized in Table 8.1. The main uses of the results are described in the table, but other uses are also explained in every case study in previous chapters. The generalization of these cases nationwide would require some adaptation in the method especially for municipal and local levels.

Every level of disaster management requires specific landslide risk information that should match the objectives and needs at that level. Large scale risk maps require quantitative output, whereas at smaller scales qualitative maps are more suitable. This problem also depends on the data available for spatial and temporal hazard assessment and quantitative vulnerability assessment which is an impediment for many landslide risk studies.

Besides the specific problems related to Cuba, landslide risk assessment in other countries is also still in a developing stage (e.g. Glade et al., 2005; Guzzetti et al., 2005). Even in more developed countries, methods for landslide risk assessment are not fully implemented yet and there are just a few countries with a standardized landslide risk assessment programme such as Hong Kong (GEO, 1999), France (BRGM, 1997) and Australia (AGS, 2000).

The main objective of this research was to design a framework for spatial landslide risk assessment in Cuba, considering a multi-level approach and the specific characteristics of Cuba related to landslide types and distribution, availability of data and organizational structure. To do so, a set-up of a national landslide inventory database was made and landslide risk assessment methodology was worked out for four administrative levels and study areas, each one with a different scale, objectives, available datasets and analysis techniques.

The specific objectives were:

1. To design and implement methods for landslide inventory at different scales using the existing earth observation data in Cuba, and to propose a system for information collection about future events.
2. To design and apply appropriate indicators for landslide hazard and vulnerability at different scales in Cuba.
3. To propose, describe and implement spatial analysis models for landslide hazard, vulnerability and risk assessment.
4. To determine landslide hazard, vulnerability and risk assessment in four levels (scales) in Cuba with specific objectives and expected outputs.

Table 8.1. Method, organization involved and use of risk assessment in Cuba.

Level (scale)	Method	Organization	Use
National (1:1,000,000)	Semi-quantitative with SMCE Risk index by ranking and weighting	National Civil Defence	Locating priority areas for regional studies and guide national policy Periodic assessment to monitor local improvement
Provincial (1:100,000)	Semi-quantitative with SMCE Spatial model via Statistical method and weighting	Provincial government and civil defence	Provincial disaster risk reduction plan Locating landslides and priority areas for investigating causes and consequences
Municipal (1:50,000)	Quantitative TMU and expert judgment (adaptation needed for generalization)	Municipal government and civil defence	Municipal disaster risk reduction plan Estimating losses and delimitating areas for mitigation actions
Local (1:25,000)	Quantitative Runout modelling based on geotechnical parameters (adaptation needed for generalization)	Local and municipal government and civil defence	Local disaster risk reduction plan Identifying elements at risk affected by different scenarios and implementing mitigation actions

In the four case study chapters (from Chapter 4 to Chapter 7) the obtained results were discussed and several conclusions were achieved. In the next sections, the main discussions and conclusions are summarized which are related to the key points corresponding to the initial objectives of this research. Finally, some recommendations for further work are proposed.

8.3. Towards a national landslide inventory in Cuba

A landslide inventory is a cornerstone for landslide risk assessment. For all methods applied the hazard results can only be validated when a there is a record of historic landslides either by field description, archives, or by aerial photo interpretation. A comprehensive landslide inventory is also the basis for geomorphological or statistical analysis (Soeters and van Westen, 1996). Besides, if the inventory includes information about landslide damage it is very useful in estimating vulnerability (see Guzzetti, 2000) and to validate landslide risk nationwide.

Inventory of landslides in Cuba is at initial stages (Castellanos Abella and Van Westen, 2005). During the course of this research a national landslide inventory system was designed aiming at the collection of basic information in pre-defined forms by trained staff of local civil defence authorities. Reported landslide events could be verified later to complete the inventory by technical staff of national organizations. The maintenance of this landslide catalogue is vital to improve future landslide prediction and risk assessment at all levels.

In this study, landslide inventories were carried out at all levels with different degrees of detail. At national level, existing reports were collected and an inventory system was designed. In the provincial analysis landslides were mapped using photointerpretation, and descriptive models about each landslide type were built. Similar to mineral deposit models, landslide models are a valuable tool for recognizing landslide causes. They can be built by expert opinion, with the aid of bivariate analysis using with different environmental parameters. For certain areas, such as the Guantánamo province, particular landslide types (e.g. shallow slides) could be categorized by more than one landslide model. This means that the occurrence can be caused by different combinations of parameters. In the municipal analysis landslides were inventoried in more detail with terrain mapping units including a comprehensive description of each unit in a related database. At local level a refined analysis was made with digital photogrammetry, digital elevation models and geophysics.

8.4. Collecting hazard and vulnerability indicators

Data acquisition in the field or by earth observation is very expensive, sometimes unaffordable for developing countries (Van Westen et al., 2007). Except for the landslide inventory, many of the types of data needed for landslide risk assessment are also used for other purposes. Therefore it is often more affordable to collect existing data, especially because the costs of acquiring detailed data on elements at risk only for landslide risk assessment would not be cost effective. In fact most risk assessments are based on existing data rather than new data. In Cuba there are valuable data sets available for spatial landslide risk assessment at different levels, but major problems were found regarding data accessibility, format and quality. The situation is gradually improving after the generation of the national commission on spatial data infrastructure (Delgado Fernández, 2005) and the national multi-hazard risk assessment programme (AMA, 2007). The former one is working to nationally organize the policy regarding the use of data and the latter one is conducting a nationwide risk assessment using standardized approaches.

Recently new datasets have become available on the Internet that are suitable for landslide risk assessment at both national and provincial levels. For example, geomorphometric variables for hazard assessment could be created from digital elevation models from SRTM data, as explained in the chapter on the national level. For environmental vulnerability assessment maps of natural protected areas are now freely distributed by the World Conservation Union.

The indicators for landslide risk assessment must have coherence throughout all levels of analysis. In order to be consistent in modelling landslide risk, similar types of indicators are required at every level of the analysis (Figure 8.1) either for hazard or for vulnerability assessment. For example, consideration of the properties of the materials is essential for landslide hazard and thus it should be considered in the assessment. At large scales geotechnical parameters are used, whereas at smaller scales geological units (such as formations or periods) are more suitable. These could be made by data aggregation techniques or by surveying other data in more detail. Besides, some thematic layers (e.g. geology and geomorphology) are only available until a certain maximum mapping scale (e.g. largest scale is often 1:50000). The consistency in selecting indicators guaranties the comparability among the assessments at different levels.

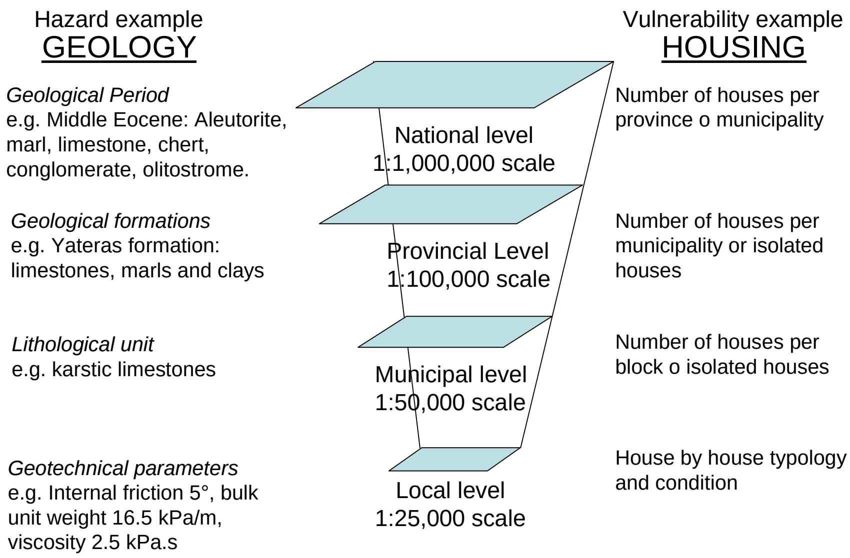

Figure 8.1. Two examples of data aggregation and consistence among scales. Left example is taken of geological data required at different levels, and right is an example of housing data for vulnerability assessment.

Regarding vulnerability indicators it was found that many indicators such as population, production, etc. can only obtained for particular administrative units (e.g. province and municipalities). That has a strong impact on the final output as theses units are the smallest areas for which the risk can be analyzed, even though the hazard information might be available at higher spatial resolution. For example in the national assessment, where municipal boundaries were used, conclusions about the risk distribution could not go into more detail. Regarding environmental vulnerability (which was introduced in this study) the indicator could not be applied at municipal and local levels, because there was no spatial representation at these levels.

Even when maintaining coherence among the levels of assessment and applying more quantitative methods going to larger scales, it is possible that the same areas are classified differently in the risk maps of the various levels. Figure 8.2 illustrates this issue, where an element at risk (e.g. a building) could be classified as low risk at a scale of 1:100,000, but at lower scales different scenarios could happen. At a scale of 1:25,000 the building could be located in a high risk area (see scenario 2a in

Figure 8.2), whereas the majority of the surrounding areas are low risk areas. This is the case for example, when there are local steep slopes with buildings that can only be represented at large scales, whereas at small scales the analysis is done for an entire municipality. Although this situation should not happen over large areas, the 'micro effect' of the indicators could occur. Two aspects previously mentioned should be considered to reduce this problem: i) the consistency of the indicators among the levels and ii) the interpretation of the results of every scale according to its objectives and scope. This aspect was explored among the levels in this research and no contradictory results were found. Although areas analyzed at more detailed levels were not always at the highest level of risk (as indicated in the maps of the generalized levels) their risk values were high enough to deserve a landslide risk assessment.

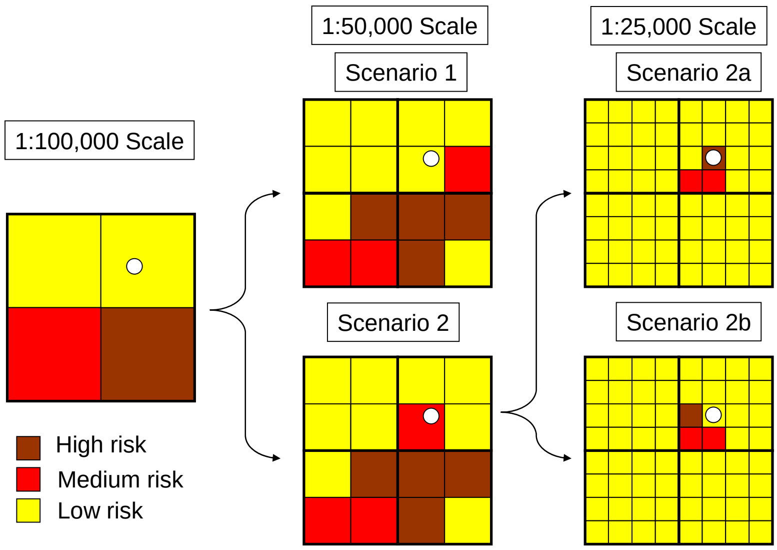

Figure 8.2. Assessing risk at different scales.

8.5. Multi-scale landslide risk assessment

Landslide risk assessment must be tailored to the objectives of the end users. Civil defence, local authorities or physical planers must state as clear as possible what they require from the assessment. Once the objectives are defined, the methods and data required to achieve these objectives can be identified. The objectives of the end users are related to the level of administration. National or upper levels have more 'co-ordinating' tasks whereas local and municipal levels have more 'executive' tasks. The specific objectives of every level were described in the introduction section of every case study. They follow four main elements i) landslide inventory, ii) data collection for hazard and vulnerability indicators, iii) hazard, vulnerability and risk assessment and iv) landslide risk reduction planning.

It is required that more detailed analysis needs to be more quantitative which also implies higher resolution and accuracy.

Careful analysis of each indicator is very relevant for a better understanding of its contribution to landslide risk assessment. Much of the earlier published work on risk assessment seems to be very straightforward in collecting data and assessing the risk without any preliminary analysis of these data. In this research, for every case study, hazard and vulnerability indicators were analyzed in as much detail as possible. Its examination allowed for the evasion of mistakes in the assessment and achieved much more credible conclusions when interpreting the results. For example, at the national level by analyzing the population density it was recognized that there are much more density in few municipalities than in the rest of the country. As a consequence, the standardization of population density was made with an exponential function rather than a linear function. Despite the time required for this task, the analysis of individual indicators is highly recommended for risk studies.

8.5.1. About the results of the assessment models

Qualitative, semi-quantitative and quantitative approaches were applied in the case studies of this research depending on the conditions (see Table 8.1). Ideally landslide risk should be quantified using the risk formula in which risk is defined as the multiplication of the hazard and its consequences. Or in other words the integration of the specific risk for individual types, and magnitudes of landslides with different return periods. These specific risks are obtained by the multiplication of temporal probability, spatial probability, event probability, vulnerability and cost. Of these the temporal probability was found to be the most difficult factor to evaluate, followed by the vulnerability.

Due to the lack of a historic landslide inventory and unavailability of sufficient multi-temporal images data sets, the return periods for landslides often had to be assumed based on Geomorphologic evidence only. Given this data limitation on temporal probability and vulnerability, often qualitative methods or at best semi-quantitative methods could be applied on the national, provincial and municipal scales.

In this research, spatial multi-criteria evaluation (SMCE) was extensively applied as a worthy solution to implement spatial landslide risk assessment semi-quantitatively. Similar spatial analysis methods have been used since the eighties for many other applications, e.g. geological exploration or waste disposal site selection analysis. The advantage of SMCE is that many intermediate steps such as standardization and weighting are integrated in a single GIS module. SMCE allows for the incorporation of expert opinion on landslide risk assessment using scientific tools such as a ranking method and pair-wise comparison. Besides, when no cost data are available but ranking of elements at risk is known, weights could be used for the risk equation. As found in this study, SMCE is a very good solution in order to estimate risk when no suitable quantitative method can be applied due to lack of data.

Expert opinion plays a major role in all approaches and scales for landslide risk assessment. In the qualitative approach all steps are based on expert opinion. Experts define the indicators, the standardization and the weights applied in Spatial Multi Criteria Evaluation. This is not necessarily limited to regional scales, as was demonstrated in this study, where heuristic methods were also applied at the municipal scale. In more quantitative approaches, although it could seem different, expert opinion also controls many parts of the assessment. Experts have to define which variables to use, how to collect them, how to classify the variables, how to use coefficients in many models, how to classify the final map and many other elements of the assessment. Even at local scale with the application of runout models, the experts decide many aspects of the modeling as explained in Chapter 7. While some methods have been implemented to collect expert opinions in qualitative approaches such as SMCE, few rules of thumb could be found to apply previous experiences in quantitative approaches. Most of the decisions taken in this research were taken after discussions with the Civil Defense and local authorities, considering their expertise in particular fields. With the aim of not diverting the main focus from landslide risk assessment, the process of collecting and processing those expert opinions was not fully described in the case studies. Besides, from the determination of who is the expert and the level of expertise up to the effect of his/her opinion the final results, there are many issues related with the use of expert opinions in risk assessment that require further research.

We found that in qualitative assessments the results were more reliable for high classes while for moderate and low classes the results may sometimes be overestimated. The results of the semi-quantitative approaches generally resulted in less area with higher risk, given a number of assumptions. These assumptions included estimation of temporal probability, estimation of the landslide magnitude and estimation of the monetary values of the element at risk. The decision on which approach to apply is ultimate based on the objectives of the assessment and the data available. In all cases low values of risk were obtained due to some reasons such as: i) a conservative (and qualitative) way to estimate temporal probabilities, ii) the economic and financial system in Cuba, with low values for replacement costs, iii) the low spatial probabilities for landslides in some areas, and iv) the relative low density of elements at risk in the highest hazard zones. Proper expression of the values of infrastructure with social meaning like churches or historical monuments is very difficult to obtain.

Validation of risk assessment is a problem reported in all cases in the literature (see Remondo et al., 2008; Zezere et al., 2008) and which is also the case in this study. The first problem relates to the difficulty in validating the landslide hazard maps, due to the lack of proper multi-temporal landslide inventories, which makes the generation of prediction rates impossible. Therefore, all work had to be based on the use of success rates only. Also the lack of target areas and existing damage information for comparing the estimated risk values is a drawback in most assessments. If damage data would exist, expected losses could be compared as a sort of validation. However, as the conditions have changed and new developments have taking place even this way of validation is doubtful. Moreover, new disasters may have other return periods than those used for the assessment. Another possibility for validation is to compare the estimated results with the 'expectations' of the end users, but so far no scientific method has been proposed for that. The absence of validation for landslide risk assessment remains a problem usually criticized by other disciplines.

In the following sub-sections the main conclusions from the national, provincial, municipal and local landslide risk assessment are summarized.

8.5.2. National assessment

There are few examples on national landslide risk assessment in the literature as presented in Chapter 4 (see Yoshimatsu and Abe, 2006). At national level the risk was estimated as a risk index, as an indication of the relative risk in the country and not an actual quantification of the risk. The landslide risk index can be compared to similar indices produced by international organizations (e.g. human development index). It was generated making use of data from national data providers such as the national statistics office, national housing institute and the national atlas of Cuba. In the literature some studies present indicators for producing risk indexes (Nadim et al., 2006; Carreño et al., 2007). Some are actually duplicating indicators which are usually highly correlated (e.g. population density and other social indicators). Therefore, in this study the number of indicators was limited to avoid such duplications, and main indicators were used as proxies for physical, social, economic and environmental vulnerability.

National authorities could evaluate the evolution of the landslide risk through time by regularly generating a landslide risk index based on updated information. Based on this, the National Civil Defence as a major disaster risk reduction stakeholder could focus its priorities on specific regions such as the eastern provinces or in particular issues such as housing. The landslide risk index map shows different ways to analyze the risk index tabulated for provinces and by average for municipalities. In future, with the development of a national landslide inventory, information on the landslide density should also be used as a main indicator, which would improve the landslide risk index substantially.

8.5.3. Provincial assessment

The provincial level is considered an intermediate level in Cuba, like in many other countries. In this research several types of spatial analyses were applied for this level, consisting of qualitative and semi-quantitative methods. However, once the nationwide multi-hazard risk assessment programme would be completed, at the municipal level, the provincial landslide risk map (Chapter 5) could be made by a re-classification and generalization of the results from the municipal level. Nevertheless, the provincial assessment that was carried out was useful in many aspects. First of all, the hazard assessment was based on the actual landslide inventory, in this case obtained through image interpretation and fieldwork. For the hazard assessment two methods were used (weights of evidence and artificial neural network) for five landslide types using qualitative and semi-quantitative assessment. While the former one was very useful to build the landslide descriptive models, the latter was valuable for susceptibility assessment of slides due to its complexity. The conversion from susceptibility to hazard at this scale involved the multiplication of event probability, based on the success rates, spatial probability, based on the landslide density in the susceptibility classes, and temporal probability, based on estimated return periods. It is a rather general way of obtaining the total hazard probability, as it is questionable whether these three probabilities can be treated independently. Nevertheless, the results give a reasonable indication.

Regarding elements at risk, problems were encountered to link population data available for administrative units, to other elements at risk data, available at larger detail. The spatial analysis allowed estimating the number of people per house based on the population density of the closest settlement where houses and population are registered. Such a technique could be applied to estimate population whenever the houses could be digitally mapped and the level of population registered at certain spatial unit. For the roads differences were found between the road types with cost per kilometre supplied by the ministry of transportation and the road types extracted from the digital topographic maps supplied by the national mapping agency. Future improvements in the spatial data infrastructure should cope with issues like this.

At provincial level, qualitative and semi-quantitative landslide risk maps were obtained. As five landslide types and five elements at risk were processed, specific risk maps were produced for each combination, resulting in twenty five maps. Based on this, it was possible to calculate the risk for each landslide type separately and for each element at risk as well as to integrate them all into a total landslide risk map. By using these outputs the end users can evaluate both the overall risk as well as the specific risk for particular landslide types and elements at risk. The risk assessment was limited to five elements at risk (population, buildings, infrastructure, essential facilities and agriculture), considering the direct risk only. Indirect risks, such as economic damage, as well as social vulnerability issues, were not considered at this scale. The inclusion of these would require other a combination with the spatial multi-criteria approach, similar to the one applied on the national scale, but would result only in qualitative risk maps.

8.5.4. Municipal assessment

The municipal level is considered the most important level for generating landslide risk maps in Cuba, as it will be incorporated in the nation wide multi-hazard risk assessment programme. Ideally risk assessment at this level should be quantitative and based on process modelling, which allows the inclusion of stability situation for different spatial and temporal triggering scenarios. However, due to the complexity of the landslide types in the study area, and the unavailability of geotechnical data, it was not possible to carry out such process based models in this case. Therefore, the municipal assessment carried out in this study (Chapter 6) was based on the outlining of terrain mapping units (TMU) which allowed us to incorporate a detailed description for every unit and landslide founding the area. Although a drawback of applying this method for susceptibility assessment in other municipalities is that it requires mapping experience with photo-interpretation and a detailed fieldwork campaign. Therefore, it is advised to combine this method with other more suitable methods, including process based modelling for shallow landslides, in other municipalities in Cuba that could be implemented by a trained specialist such that they could be more comparable.

Unavailability of temporal landslide information was also a major obstacle at municipal level. The landslide age could be estimated using geomorphological skills and in deep knowledge of the study area. Similar estimations are reported in the literature either for tropical (Wieczorek, 1984) or dry climate areas (McCalpin, 1984). We found however, that the age rates need to be customized for the Cuban environment because of rock types, vegetation and rainfall conditions. In consequence, through the analysis of landslides using different earth observation data four landslide return periods could be estimated.

The risk assessment at this level was made for houses, roads and agricultural lands. This is typical for most municipalities in Cuba which are located in rural areas with few industrial or commercial facilities. Information on building typologies and conditions was collected on a house-by house basis. The Housing Institute yearly collects this information but it does not have the geographic location of the houses. For the roads the landslide risk was assessed considering the type and cost per kilometre. The actual value for the roads should include somehow its usability that was missing in this case because of lack of data. For example, path and trails are very low-cost road types, but depending on their location they could result in higher risk values than unpaved roads. In many mountainous areas in Cuba, paths and trails are the only way to transport agricultural products from the various farms to the markets.

A combined landslide risk map was calculated by adding the risk for houses, roads and agricultural lands. This final map allows analyzing quantitatively the distribution of risk including the risk for point elements (houses), linear elements (roads) and polygon elements (agricultural lands).

8.5.5. Local assessment

A detailed analysis was carried out in Chapter 7 for a single landslide disaster (i.e. the 'Jagüeyes' landslide) using all available information. Digital photogrammetry, geophysical survey and runout modelling were successfully applied. The first two supported the characterization of the landslide event by creating the digital elevation model before and after and by reconstructing the sliding surface and geological features. The runout simulation successfully reproduced the conditions under which the Jagüeyes landslide occurred. The photogrammetry, geophysical and runout methods have been applied separately before (see Barlow et al., 2006; Bruckl and Bruckl, 2006; Otto and Sass, 2006) but not in an integrated way as presented here. It also demonstrated that in areas with limited information it is possible to reconstruct major landslide events successfully.

The application of these tools for landslide research should enhance the opportunities for quantitative landslide risk assessment as a way to improve the characterization of the landslide events.

The use of runout modelling for landslide risk assessment is new and still several issues need to be improved, such as the rheology computation and model calibration. For the first time a landslide runout simulation was calibrated spatially with the depth of the deposit. PEST, a model-independent parameter estimator (Doherty, 2004), was linked to the MassMov runout model (Beguería-Portugués and van Asch, 2008) running inside the dynamic modelling system PCRaster (PCRaster Environmental Software, 2008). The implementation could be undertaken in several possible ways leaving ample space for future research on this topic.

This is considered an innovative way to assess risk based on the parameters generated by the runout simulation like deposit depth, velocity or momentum. This approach substitutes the empirical relationship with runout distance or the empirical estimation of vulnerability based on previous disasters.

Landslide risk assessment for Caujerí scarp was carried out with the results obtained by simulating Jagüeyes landslide. The use of previous events to predict the future ones was made early through spatial analysis but not using runout parameters with up-scaling analysis, as was carried out in this study. The main difficulty in the up-scaling analysis was the estimation of potential landslide sites, and the relationship between volumes and possible return periods. The only way to properly address this would be the use of slope stability analysis for all potential landslide sites, which would need major financial investments in surveying and geotechnical testing.

The vulnerability and risk of ninety houses were assessed based on their typology and condition. The population living in the buildings at risk was simply counted as it was assumed that they will be evacuated during the onset of an intensive or prolonged period of precipitation before a landslide occurrence. For the same reason, the estimation of the population at risk for certain time of the day was dismissed. This analysis seems to be more effective for other disaster type such as earthquakes.

8.6. Risk mapping and visualization

While producing landslide risk maps for this research some visualization issues were raised. The lack of international and national standards for risk mapping in general or for landslide risk mapping in particular often results in the generation of maps that may be misleading for the end users. The topic on risk visualization for natural hazard assessment has not received ample attention in the literature and there is no analysis on the readability and effectiveness for risk mapping (Husdal, 2001; Fabbri et al., 2005). Risk can be reproduced in the form of general statistical information per administrative unit, or in the form of a map which shows the spatial variation of risk over an area. Important decisions will be taken by the end users based on the interpretation of this map. Therefore, risk visualization is considered important issue here and it is briefly discussed.

A risk assessment is done by a group of thematic experts (see Figure 8.3). The risk map is produced based on the interpretation and cartographic skills of these experts. However, the risk evaluation is carried out by policy makers (civil defence or government organizations) acting as map readers also with their interpretation and cartographic knowledge. Based on this interpretation, a risk reduction plan is produced and actions are taken over the initial risk scenario. If either the researchers, as map makers; or the policy makers, as map readers; perform erroneously, the risk reduction actions taken in the study area may have mistakes, which may lead to serious consequences. Risk visualization indeed requires an entirely other kind of research that goes beyond scope of this study, but its relevance is worthwhile mentioning.

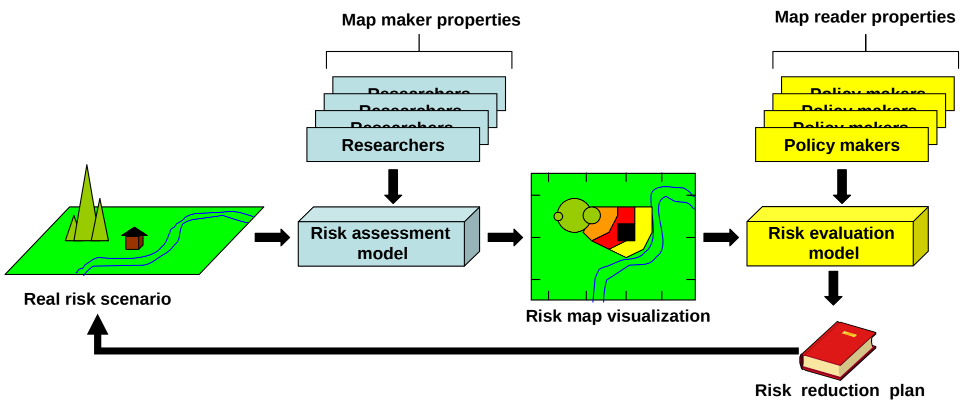

Figure 8.3. Risk visualization inside the risk assessment process.

Some issues with risk visualization are not totally considered wrong (like choosing the colour stretch methods), but others are mistakes indeed (like representing low risk in the colour green). The fact that risk maps represent 'areas at risk' is the main reason why most maps employ intensity scales in classes for one colour or traffic-light colours, in continuous ramps or in coloured patterns. The proper definition and representation of risk classes is an important issue. For example, when using gray tones for risk classes, the colour white should represent areas with no risk at all. Similarly, with traffic-light colours the colour green should represent safe areas with a negligible or zero risk. When all classes represent a certain level of risk then the lowest classes should be yellow. When colour ramps are utilized at least the minimum and maximum values of risk should be in the legends. While at national and provincial level risk maps could be presented by continuo values or classes, at municipal and local level the risk of individual objects is required to be visualized.

When the risk has been estimated quantitatively or semi-quantitatively and it is represented by a continuous ramp there are three main options by which these risk values could fit between the minimum and maximum intensity colour: by the standard deviation, by the histogram and by the minimum and maximum values. Figure 8.4 shows the visual effects of some of these options for the same area of the national landslide risk index map with the traffic-light representation (i.e. green-yellow-red). Risk values estimated in the model from 0 to 1 resulted in the following statistics: minimum (0.022), maximum (0.620), average (0.180) and standard deviation (0.09). The differences in visualization for the same risk values are quite remarkable. In risk maps with classes, similar problems arise since the number of classes and the break values between them should be decided by the researcher. The use of simple classifications with three classes is preferred for end user such as civil defence and local authorities. However, for physical planners or another researcher a higher number of classes could be required. For selecting the break values among classes, current GIS systems (the map maker) can select from many methods (e.g. equal intervals, defined intervals, standard deviation and natural breaks).

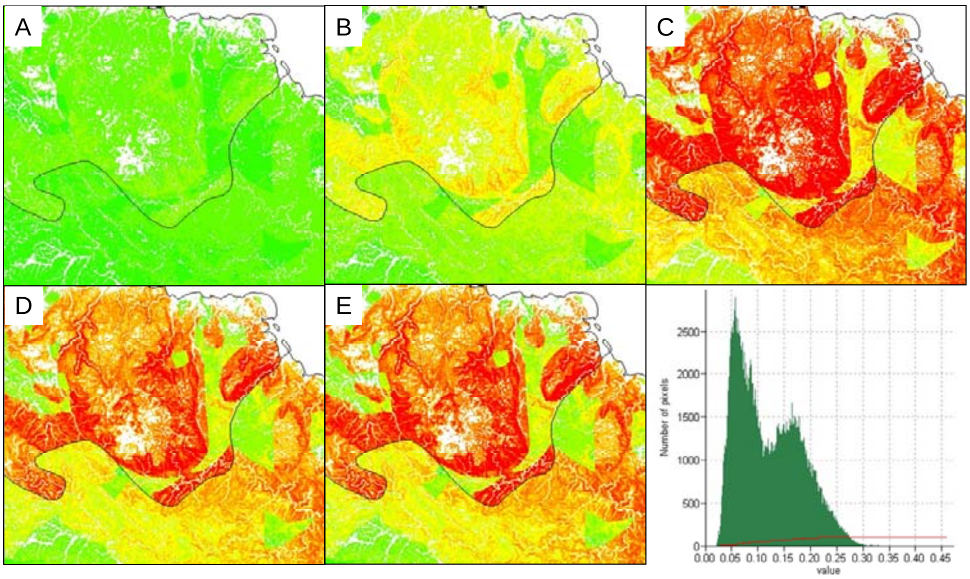

Figure 8.4. Risk representation of the same area with some stretch options and map histogram. A: risk values stretched between 0-1, B: between minimum and maximum risk values, C: between 2 times standard deviation, D: between 0.5 percentage of the histogram and D: between 1 percentage of the histogram.

8.7. Landslide risk assessment and disaster reduction in Cuba

In Cuba there is strong political willingness for reducing disasters integrating all possible means. The national civil defence, as the head organization for disaster reduction in the country, owns its success to a long term improvement process and a continuous adaptation to new conditions. Risk has been reduced throughout the years by social and infrastructural investments. Despite the recognized success of disaster management in the country, economic losses continue to increase, and are affecting the development. After the occurrence of natural disasters in 2004, a task force was installed with a mandate to carry out a multi-hazard risk assessment programme in Cuba. The programme aims to support the 169 municipalities with a standardized methodology for risk based mainly on existing data. Since 2005, the main priority was given to the assessment of risk of flooding, strong wings and sea surge. Also, beginning 2008 a start was made with the risk assessment for landslides. The methodology for landslide risk assessment is based on the results of this research, and the methods presented in this work have been applied to twenty municipalities with the highest landslide risk found during the national assessment of this research. It is expected that this work will be subsequently extended in order to encompass provinces with the highest landslide risk. The methodology that is applied nationwide will be an adaptation of the one used in this study at municipal level.

8.8. Recommendations for further work

Many issues could be recommended, based on the outcomes of this research, and considering the stage of development of landslide risk research and the amplitude of the topic. In this section, a number of the main recommendations are presented.

More research is needed on the optimal ways for generating landslide inventories, in particular to design different inventory systems based either on local reports or on periodical surveys. Existing landslide inventory databases could be enhanced by introducing time and scale dimensions. Time dimensions involve the linking of landslide records of the same movement across time, in order to properly address reactivation history. Scale dimension means the ability to change the representation of the landslide at different scales from a single point up to a set of polygons representing landslide features. Other aspects such as magnitude, time of occurrence, geometric dimensions are very valuable for statistical analysis of landslides and to predict expected magnitude and travel distance. Data about landslide damage is usually missing in landslide inventories and much research could be undertaken in order to link magnitude and damage for vulnerability assessment. The lack of the temporal component in the landslide inventory was a drawback in this research and in many other studies. A key recommendation for this problem is to establish a landslide inventory and to keep it updated.

The increasing availability of data through the Internet is very relevant for landslide risk assessment as data scarcity is one of the main limitations. Still most available data is only applicable at small scales, although more detailed data with higher resolution are gradually increasing. However, most of these datasets need to be validated as they are created with very general algorithms. This is the case (for example) of the Landscan project (see Rain et al., 2007) for population density information covering every 1km^2 for the entire World. For other datasets such as SRTM (Koch and Lohmann, 2000) there are many other techniques that are available in order to remove errors but they need to be improved. National or provincial landslide risk assessment could incorporate new datasets provided by international organizations, but more research is needed on the accuracy and validation of those data sets.

Selecting the indicators for hazard and vulnerability assessment requires more investigation on issues such as redundancy by measuring correlations and coherence by comparing assessment among different levels of analysis. Besides, based on the effectiveness of the results obtained, we encourage a preliminary analysis of the indicators involve in the risk assessment.

Housing as one the key elements for landslide vulnerability requires more examination. First of all, better methods for obtaining data about housing could improve and speed up recent vulnerability assessments. Secondly, vulnerability curves need to be created considering different scenarios of housing characteristics and runout depth, distance or momentum. There are many issues regarding landslide vulnerability that could be improved and more work is needed on this topic. For example, indirect cost and intangible cost are usually forgotten during the assessments undertaken by specialists in this field.

With spatial multi-criteria evaluation (SMCE) further work could be made to analyze the sensitivity of the indicators and the different combinations of variables and weights. It was the best way to carry out qualitative assessment, but several rules of thumb could be created to improve its performance and avoid mistakes. For quantitative approaches the quantification of the economic values of the elements at risk need to be improved. Studies would be required to complete all cost involved in the risk equation for different elements at risk and to discuss with the authorities the actual values. Similarly, the runout modelling still requires better linking with civil or structural engineering for actual calculation of landslide mass impacting infrastructure. Regarding validation of landslide risk assessment, because risk estimation is 'socially constructed' a bridge between social and natural sciences is required in order to implement a comprehensive validation method.

As previously discussed, there are many issues on risk visualization that require more research and standardization. Unfortunately, there is no single rule that specifies which option is the most appropriated and it is up to the map maker to make this decision. As a consequence, the actual risk values could either be over or under represented by the visualization method. Therefore map readers could easily make mistakes when interpreting the map and prepare an ineffective risk reduction plan. Besides, current web-mapping applications inherit these problems and include issues such as how to aggregate risk values when zooming in on the map.

Some countries have standardized some of the problems explained herein when implementing a nationwide multi-hazard risk assessment system. Thus, the number of classes, the colours and meaning of each class is sometime specified. In Cuba, risk visualization issues are still under research as part of the methodologies for risk assessment.

The objectives for landslide risk assessment at different levels could be analyzed in more detail. Experts on disaster management, physical planners, social and earth science scientists should be able to come up with better definition on what should be expected from the results on landslide risk assessment. Besides, social sciences could substantially improve current risk assessment methods, especially by evaluating the acceptance and tolerance of the risk by different stakeholders.

Investigations lines on disasters reduction are focusing more often on risk assessment in the last years. It is a step further in putting effort (and funding) in disaster avoidance rather than in disaster relief. As mentioned by Kofi Annan in 1999: "prevention is better than cure". Risk assessment not only shows the area where effort for disaster reduction must be concentrated but also the root causes why these areas are at risk. By analysing the theoretical background and the case studies implemented, we hope this research will contribute to this noble aim.

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Curriculum Vitae

Full name: Enrique Armando Castellanos Abella
Date of birth: March 1, 1970.
Place of birth: Camagüey City, Cuba
Higher education

- Geological Engineer. Universidad de Pinar del Río, Cuba (1994). Thesis: "An expert system for uranium exploration" (www.upr.edu.cu)
- Master of Science in Applied Geomorphological Surveys (with distinction). ITC (www.itc.nl), The Netherlands (2000). Thesis: "Design of a GIS-based System for Landslide Hazard Management San Antonio del Sur, Cuba, case study"

Current professional situation:

- Permanent work (since 1994): Institute of Geology and Paleontology (IGP). Address: Vía Blanca 1002 y Carr. Central, San Miguel del Padrón, CP 11000, Ciudad de La Habana. Cuba. Tel.: +53 (7) 696 7232, Fax: +53 (7) 696 7004, site: www.igp.cubaindustria.cu, e-mail: ecastellanos@igp.gms.minbas.cu
- Current position: geologist researcher, project manager. Nowadays carrying out PhD research at ITC, to be graduated on Utrecht University, Faculty of Geoscience - Physical Geography department. e-mail: castellanos@itc.nl

Professional and scientific activities:

- 1994, Sep-Dec: Introductory training at work.
- 1995-1996. Project: Tectonics and paleogeography of Eastern Cuba. Working in the geologic generalization and in the tectono-stratigraphic columns.
- 1996. Project: Applications of image processing and geo-referenced information methodologies to geology in Cuba. Three charters as a principal author and seven as a co-author.
- 1996. Project: Prospecting potential areas for location of auriferous placers in the basin of Pipian River. Working in the image processing and in the GIS methodology
- 1996-1997. Project: Environment impact assessment on mining: Sta. Lucia-Castellanos area. Working in impacts identification phase.
- 1997 Research to discover the burials remains of Che Guevara in Vallegrande, Bolivia. Working in remote sensing processing and modeling.
- 1997-1998. Project: Cartography of the principal hazardous geological processes in Eastern of Cuba. Working as project manager covering almost all technical aspects.
- 1998-2000. M.Sc. studies and thesis: Design of a GIS-based system for Landslide Hazard Management, San Antonio del Sur, Cuba, case study. ITC, Enschede.
- 2001. May-Aug. Project: Environmental line base of the mining project San Felipe Mining. Working in GIS design and implementation.

- 2001-2003. Project: Geological map of Merceditas Mine. Working as project manager covering almost all technical aspects except petrography analysis.
- 2002. Jun. Project: Study of the environmental line base of two marines areas of the petroleum exploration zone at the north of Pinar del Río, Havana and Matanzas. June, 2002. Working in the charter of geology, tectonic, geomorphology, sedimentology and paleogeography.
- 2002-2003. Project: Design of the Geological Information System of Cuba (SIGEOL) at 1:100 000 scale. Working as project manager and responsible for the geological data model.
- 2003. Project: Environmental factors and mental retard diseases. Working on geological and geophysical factors, on the spatial statistical analysis and on the final report.
- 2004 - . Project. Geological and geomorphological landslide hazard and risk assessment in the Cuban conditions. Working as project manager and involve in all topics.
- 2004 - . PhD research project at ITC: Multi-scale landslide risk assessment in Cuba.

Publications

See Http://eacastellanos.googlepages.com/publications

Postgraduate courses:

- 1995 Data Exploratory Analysis, IGA, Havana, Cuba (www.iga.cu)
- 1995 Geostatistical, ISCAH, Havana, Cuba
- 1995 Pattern Recognition, IGT, Havana, Cuba
- 1995 About new informatics-digital and digitized aerophotography technology in the environmental impact assessment, Cuba
- 1996 R&D project management, Higher School of MINBAS, Cuba
- 1997 Workshop: Use of Geographic information systems, Ecole Nationale Supérieur Agricolee Montpellier (INRA), Havana, Cuba
- 1998 Training at Universal Systems Ltd. company offices on GIS, titled as Authorized Trainer on CARIS GIS. New Brunswick, Canada
- 1998-2000 Master of Science in Applied Geomorphological Surveys (with Distinction), at ITC, Enschede, Netherlands (www.itc.nl)
- 2002 Integrated project management, GECYT, Cuba

Teaching experience:

- 1991-1993 Programming (Turbo Pascal, Basic, Databases) during undergraduate studies. University of Pinar del Río, Cuba
- 1995 Postgraduate course: Photointerpretation and Image Processing, IGP, Cuba
- 1995 Postgraduate course: Geographic Information System for Geology, University of Pinar del Río, Cuba
- 1995 Postgraduate course: Geographic Information System for Geology, IGP, Cuba
- 1995-2004: Teacher in several courses Introductory, Input and Editing, Advanced, Analysis and Modeling en CARIS GIS as Authorized CARIS Trainer (1998). (www.caris.com)

National and international congress participation:

I Iberoamerican workshop on informatics and geosciences, Havana, Cuba 1992
II Cuban Geological Congress, Santiago de Cuba, Cuba 1994
II Iberoamerican workshop on informatics and geosciences, Havana, Cuba 1994
Regional conference of latin american and caribbean countries International Geographic, 1995
Workshop on Mathematical modeling and GIS, Havana, Cuba 1995
First national workshop on geostatistics, Havana, Cuba 1995
III Iberoamerican Workshop on Informatics and geosciences, Havana, Cuba 1996
III Cuban Geological Congress, Havana, Cuba 1998
World GIS Conference, Rotterdam, The Netherlands 1998
The 2nd Int. Symposium on Operationalization of Remote Sensing, ITC, The Netherlands, 1999
IV Cuban Geological Congress, Havana, Cuba 2001
Geomatic Congress, Havana, Cuba 2002
V Cuban Geological Congress, Havana, Cuba 2003
International Conference on Landslide Risk Management, Vancouver, Canada. 2005
VI Cuban Geological Congress, Havana, Cuba 2005
ISPRS Mid-term Symposium: Remote sensing: From pixels to processes, ITC, The Netherlands 2006

Publications related to this research

2009

Castellanos Abella, E.A. and Carretero, D. 2009. Disaster management and multi-hazard risk assessment in Cuba. Disasters Journal. (Accepted with corrections)

Castellanos Abella, E.A., van Westen, C.J., Melchiorre, C. 2009 Combining computational models for landslide hazard assessment of Guantánamo province, Cuba, Geomorphology (Accepted with corrections)

Castellanos Abella, E.A. and van Westen, C.J. 2009 Landslide vulnerability and risk assessment of Guantánamo province, Cuba. (in preparation)

Castellanos Abella, E.A. et al, 2009 Characterization and runout modeling of Jagüeyes landslide. Landslide (in preparation)

Castellanos Abella, E.A. et al, 2009 Up-scaling landslide modeling for risk assessment. Engineering Geology (in preparation)

2008

Castellanos Abella, E.A. and Van Westen, C.J., 2008. Qualitative landslide susceptibility assessment by multicriteria analysis: A case study from San Antonio del Sur, Guantánamo, Cuba. Geomorphology, 94(3-4): 453-466p.

Castellanos Abella E.A. and Van Westen C.J., 2008. Spatial landslide risk assessment in Guantánamo Province, Cuba. In: Chen, Z., Zhang, J., Li, Z.,Wu, F., Ho., K. (Eds), Landslides and Engineered Slopes, From the Past to the Future, Taylor & Francis, London, Vol. 2, 1879-1885. ISBN: 978-0-415-411-97-7.

Castellanos Abella, E.A., van Westen, C.J., van Asch, T.W.J., de Jong, S.M., Begueria, S. and Jetten, V.G. (2008) Integrating methods for investigating a historic landslide : Jagüeyes landslide case study, Cuba : powerpoint. Geophysical Research Abstracts, Vol.10, EGU2008-A-11480. EGU General Assessmbly 2008

Castellanos Abella E.A. 2008. Evaluación de riesgo por deslizamientos de terreno en Cuba. Estado Actual y perspectivas. Revista Defensa Civil de Cuba. 7p. (Accepted)

Van Westen, C.J., Castellanos Abella, E.A. and Kuriakose, S.L., 2008. Spatial data for landslide susceptibility, hazard and vulnerability assessment: an overview. Engineering Geology, 2008 (Accepted): http://dx.doi.org/10.1016/j.enggeo.2008.03.010

Van Westen, C.J. and Castellanos Abella E.A. Development of a method for multi-scale landslide risk assessment in Cuba. . Proceeding of 2007 International Forum of Landslide Disaster Management, 10-12 December 2007, Hong Kong, 14p.

Van Westen, C.J. and Castellanos Abella E.A. 2008. Multi-scale risk assessment as a component to the national system for multi-hazard risk assessment in Cuba. Proceeding of First World Landslide Forum, 18-21 November, 2008 United Nations University, Tokyo, Japan.

2007

Castellanos Abella, E.A. and Van Westen, C.J., 2007a. Generation of a landslide risk index map for Cuba using spatial multi-criteria evaluation. Landslides, 4 (4): 311-325.

Melchiorre, C., Castellanos Abella, E. and Matteucci, M., 2007. Analysis of sensitivity in Artificial Neural Network models: application in landslide susceptibility zonation, Guantánamo Province, Cuba. 4th EGU General Assembly. April 15-20, 2007 Vienna, Austria. Geophysical Research Abstracts, 9: 10615.

Suárez Leyva, V. Chang, J. L. Stout Smith, R. Prieto Castro, F. Castellanos Abella, E. 2007 Aplicación de técnicas geofísicas para la caracterización de deslizamientos. Caso de Estudio: Valle de Caujerí, Guantánamo. III Congreso de Geofísica 2007 1p.

2006

Castellanos Abella, E., Cabrera, M. and González, B.-E., 2006. Deslizamientos submarinos en el talud insular como posibles generadores de tsunamis reportados en Cuba, MarCuba'06 - VII Congreso de Ciencias del Mar, La Habana, Cuba, pp. 1.

Castellanos Abella, E.A. Comparando indicadores de desarrollo sostenible e indicadores de reducción de riesgo de desastres a nivel internacional. Un análisis preliminar. (Comparing indicators of sustainable development and disaster risk reduction indicators at global level. A preliminary analysis.). Workshop: Indicadores de desarrollo sostenible. Perspectiva geoespacial, 9-10 March, 2006, Río de Janeiro, Brazil

Castellanos Abella, E.A. Indicadores de desarrollo sostenible y su perspectiva geoespacial para la cartografía subnacional. Ejemplo de Cuba (Sustainable development indicators and their geospatial perspective for subnational cartography. Example of Cuba. Workshop: Indicadores de desarrollo sostenible. Perspectiva geoespacial, 9-10 March, 2006, Río de Janeiro, Brazil

Castellanos Abella, E.A. (2006) National assessment of landslide risk in Cuba. 7Th International Congress on Disasters. June 13 – 16. 2006. Havana, Cuba.

Delgado Fernández, T. Castellanos Abella, E.A. 2006. Towards user-driven spatial data infrastructures. An approach oriented to sustainable development. GSDI-9 Conference Proceedings, 6-10 November 2006, Santiago, Chile

2005

Castellanos, E., 2005. Processing SRTM DEM data for national landslide hazard assessment. In: C. Centro Nacional de Información Geológica (Editor), VI Congreso de Geología, Geología' 2005. Sociedad Cubana de Geología, La Habana, Cuba, pp. 12.

Castellanos, E. and Van Westen, C.J., 2005. Development of a system for landslide risk assessment for Cuba. In: E. Eberhardt, O. Hungr, R. Fell and R. Couture (Editors), Proceedings, International Conference on Landslide Risk Management, May 31-Jun 3, 2005, Vancouver, Canada.

Abstract: Multi-scale landslide risk assessment in Cuba

Landslides cause a considerable amount of damage in the mountainous regions of Cuba, which cover about 25% of the territory. Until now, only a limited amount of research has been carried out in the field of landslide risk assessment in the country. This research presents a methodology and its implementation for spatial landslide risk assessment in Cuba, using a multi-scale approach at national, provincial, municipal and local level. At the national level a landslide risk index was generated, using a semi-quantitative model with 10 indicator maps using spatial multi-criteria evaluation techniques in a GIS system. The indicators standardized were weighted and were combined to obtain the final landslide risk index map at 1:1,000,000 scale. The results were analysed per physiographic region and administrative units at provincial and municipal levels. The risk assessment at the provincial scale was carried out by combining heuristic and statistical landslide susceptibility assessment, its conversion into hazard, and the combination with elements at risk data for vulnerability and risk assessment. The method was tested in Guantánamo province at 1:100,000 scale. For the susceptibility analysis 12 factors maps were considered. Five different landslide types were analyzed separately (small slides, debrisflows, rockfalls, large rockslides and topples). The susceptibility maps were converted into hazard maps, using the event probability, spatial probability and temporal probability. Semi-quantitative risk assessment was made by applying the risk equation in which the hazard probability is multiplied with the number of exposed elements at risk and their vulnerabilities. At the municipal scale a detailed geomorphological mapping formed the basis of the landslide susceptibility assessment. A heuristic model was applied to a municipality of San Antonio del Sur in Eastern Cuba. The study is based on a terrain mapping units (TMU) map, generated at 1:50,000 scale by interpretation of aerial photos and satellite images and field data. Information describing 603 terrain units was collected in a database. Landslide areas were mapped in greater detail to classify the different failure types and parts. The different landforms and the causative factors for landslides were analyzed and used to develop the heuristic model. The model is based on weights assigned by expert judgment and organized in a number of components. At the local level, digital photogrammetry and geophysical surveys were used to characterize the volume and failure mechanism of the Jagüeyes landslide at 1:10,000 scale. A runout model was calibrated based on the runout depth in order to obtain the original parameters of this landslide. With these results three scenarios with different initial volume were simulated in Caujerí scarp at the scale of 1:25,000 and the landslide risk for ninety houses was estimated considering their typology and condition. The methodology developed in this study can be applied in Cuba and integrated into the national multi-hazard risk assessment strategy. It can be also applied, with certain modifications, in other countries.

Samenvatting: Analyse van aardverschuivingrisico op meerdere schaalniveaus in Cuba

In de bergachtige gebieden van Cuba, die ongeveer 25% van het land beslaan, veroorzaken aardverschuivingen aanzienlijke schade. Toch werd er tot voor kort in Cuba weinig tot geen onderzoek gedaan naar de risico's van aardverschuivingen. Dit onderzoek presenteert een methodologie voor een ruimtelijke analyse van de aardverschuivingrisico's, en de toepassing ervan op meerdere schaalniveaus: op nationale, provinciale, gemeentelijke en lokale schaal. Op *nationale* schaal wordt een risico index gegenereerd op basis van een semi-kwantitatief model waarin 10 indicatorkaarten zijn opgenomen. Met behulp van een ruimtelijke multi-criteria evaluatie techniek, worden de indicatoren in een GIS gestandaardiseerd, gewogen en uiteindelijk samengevoegd tot een aardverschuivingrisico-index kaart op een schaal van 1:1.000.000. De eindresultaten zijn geanalyseerd per fysiografische regio en per bestuurlijke eenheid op provinciale en gemeentelijk niveau. Op *provinciaal* niveau is eerst een aardverschuivinggevoeligheidskaart gemaakt op basis van heuristische en statistische methoden, die vervolgens is omgezet naar een gevarenkaart en is gecombineerd met informatie over de kwetsbaarheid van het gebied om tot een risicobepaling te komen. Deze methode is toegepast voor de provincie Guantánamo op een schaal van 1:100.000. Voor de gevoeligheidsanalyse van aardverschuivingen zijn 12 factorkaarten gebruikt en vijf verschillende typen aardverschuivingen zijn afzonderlijk geanalyseerd (ondiepe aardverschuivingen, modderstromen, bergstortingen, gesteenteafglijdingen en zgn. overkieping fenomenen. Bij het omzetten van de aardverschuivinggevoeligheidskaart naar een gevarenkaart is zowel gebruik gemaakt van de kans dat een type aardverschuiving plaatsvindt, als mede de ruimtelijke en temporele waarschijnlijkheid. De semi-kwantitatieve risicobepaling is uitgevoerd door het toepassen van de risicodefinitie waarbij de kans op het voorkomen van een aardverschuiving wordt vermenigvuldigd met het aantal objecten/elementen dat is blootgesteld aan dit gevaar en met de kwetsbaarheid van deze elementen met betrekking tot aardverschuivingen. Op *gemeentelijke* schaal vormde een gedetailleerde geomorfologische kartering de basis voor de aardverschuivingsgevoeligheidskaart. Deze heuristische methode is toegepast voor de gemeente San Antonio del Sur in Oost Cuba. De studie is gebaseerd op een Terrein Eenheden Kaart (TEK), schaal 1:50.000, die is gemaakt met behulp van luchtfoto- en satellietbeeldinterpretatie en veldwaarnemingen. Informatie over 603 terreineenheden werd verzameld in een database. De gebieden met aardverschuivingen zijn gedetailleerd in kaart gebracht om de verschillende typen aardverschuivingen te classificeren op basis van de bezwijkmechanismen. De verschillende landvormen samen met andere factoren die tot aardverschuivingen kunnen leiden, zijn gebruikt om een heuristisch model te ontwikkelen. Het model is een aantal componenten opgedeeld waaraan gewichten

toegekend zijn op basis van expert evaluatie. Op *lokale* schaal zijn digitale photogrametrische en geofysische technieken gebruikt voor het karakteriseren van het volume en het bezwijkmechanisme van de Jagüeyes gesteenteafglijding op een schaal van 1:10.000. Een model voor het bepalen van het gebied dat getroffen kan worden door het transport and depositie van de materialen afkomstig van de gesteenteafglijding (zgn. run-out) is gekalibreerd op basis van de dikte van de afzetting van puinstroom materiaal om zo de oorspronkelijke parameters tijdens het bezwijken van de massabeweging te bepalen. Met deze resultaten zijn drie verschillende scenario's doorgerekend met verschillende initiële volumes vanaf de Caujerí steilrand op een schaal van 1:25.000. Voor negentig huizen is een risicoschatting gemaakt waarbij rekening is gehouden met het type gebouw en de staat van onderhoud. De methodologie die is ontwikkeld in deze studie kan worden toegepast in Cuba en kan worden geïntegreerd in een nationale risico analyse voor alle typen van natuurgevaren. Met enkele aanpassingen kan deze methodologie ook worden toegepast in andere landen.

Resumen: Evaluación multi-escala de riesgo por deslizamientos de terreno en Cuba

Los deslizamientos de terreno causan considerables daños en las regiones montañosas de Cuba, las cuales cubren cerca del 25 por ciento del territorio. Hasta ahora, pocas investigaciones se han llevado a cabo en el campo de la evaluación de riesgo por deslizamientos de terreno en el país. Esta investigación presenta una metodología y su implementación para evaluación espacial de riesgo por deslizamientos de terreno en Cuba, empleando un acercamiento multi-escala a nivel nacional, provincial, municipal y local. A nivel nacional se generó un índice de riesgo por deslizamiento, empleando un modelo semi-cuantitativo con 10 mapas indicadores usando técnicas de evaluación espacial multi-criterio en un sistema de información geográfica (SIG). Los indicadores estandarizados fueron pesados y combinados para obtener el mapa de índice de riesgo por deslizamiento a escala 1:1,000,000. Los resultados fueron analizados por región fisiográfica y por unidades administrativas a nivel provincial y municipal. La evaluación de riesgo a escala provincial se realizó combinando evaluación de susceptibilidad heurística y estadística, su conversión en amenaza, y la combinación con datos de los elementos en riesgo para la evaluación de vulnerabilidad y riesgo. El método fue probado en la provincia de Guantánamo a escala 1:100,000. Para el análisis de susceptibilidad se consideraron 12 mapas de factores. Se analizaron cinco tipos diferentes de deslizamientos (pequeños deslizamientos, flujos detríticos, caída de rocas, grandes deslizamientos de rocas y volcamientos). Los mapas de susceptibilidad fueron convertidos en mapas de amenaza empleando la probabilidad de evento, probabilidad espacial y probabilidad temporal. La evaluación de riesgo semi-cuantitativa se realizó aplicando la ecuación de riesgo en la cual la probabilidad de amenaza se multiplica con un número de elementos en riesgo expuestos y sus vulnerabilidades. A escala municipal, la base para la evaluación de susceptibilidad fue un mapeo geomorfológico detallado. Se aplicó un modelo heurístico al municipio San Antonio del Sur en Cuba Oriental. El estudio está basado en un mapa de unidades de mapeo de terreno (TMU), generado a escala 1:50,000 por medio de interpretación de fotografías aéreas e imágenes de satélite y datos de campo. Se creó una base de datos que colecciona información describiendo 603 unidades de terreno. Las áreas de deslizamientos fueron mapeadas en mayor detalle para clasificar los diferentes tipos de movimientos y sus partes. Para desarrollar el modelo heurístico, se analizaron los diferentes paisajes y factores causativos. El modelo está basado en pesos asignados por juicio de expertos y organizado en varios componentes. A nivel local el volumen y mecanismo de fallo del deslizamiento Jagüeyes a escala 1:10,000 se caracterizó empleando fotogrametría digital y levantamiento geofísicos. Para obtener los parámetros originales de este deslizamiento se calibró un modelo desplazamiento (runout) basado en el espesor del depósito. Con estos resultados se simularon tres escenarios con diferente volumen inicial en el escarpe de Caujerí a escala 1:25,000 y se estimó el riesgo para noventa casas considerando su tipología y estado técnico. La metodología desarrollada en este estudio puede ser aplicada en Cuba e integrada a la estrategia nacional de evaluación de riesgo multi-amenaza. También puede ser aplicada a otros países con ciertas modificaciones.

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