Landslides
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E. A. Castellanos Abella · C. J. Van Westen

Generation of a landslide risk index map for Cuba using spatial multi-criteria evaluation

Abstract This paper explains the procedure for the generation of a landslide risk index map at national level in Cuba, using a semi-quantitative model with ten indicator maps and a cell size of 90× 90 m. The model was designed and implemented using spatial multi-criteria evaluation techniques in a GIS system. Each indicator was processed, analysed and standardised according to its contribution to hazard and vulnerability. The indicators were weighted using direct, pairwise comparison and rank-ordering weighting methods, and weights were combined to obtain the final landslide risk index map. The results were analysed per physiographic region and administrative units at provincial and municipal levels. The Sierra Maestra mountain system was found to have the largest concentration of high landslide risk index values while the Nipe–Cristal–Baracoa system has the highest absolute values, although they are more dispersed. The results obtained allow designing an appropriated landslide risk mitigation plan at national level and to link the information to the national hurricane early warning system, allowing also warning and evacuation for landslide-prone areas.

Keywords Landslide risk index · Spatial multi-criteria evaluation · Indicators · Vulnerability · Hazard · Cuba

Introduction

Although individual landslide events are less significant in terms of damage than other hazardous events in Cuba, which are often related to the occurrence of hurricanes (such as flooding or windstorms), they cause considerable damage in the mountainous parts, which forms around 25% of the country. The recently initiated national landslide inventory shows a significant number of people affected and economic losses for landslide disaster events recorded, even though the data is still incomplete (Castellanos and Van Westen 2005). Although the Cuban system for natural disaster management is recognised by international organisations as a good example, worth to be followed by neighbouring countries (ISDR 2004), the economic losses of disasters in Cuba still continue to 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). 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 a multi-hazard risk assessment at all management levels.

Up to now, only a limited amount of research has been carried out on landslide risk assessment in Cuba. Most landslide studies in Cuba that have been published thus far concentrate on landslide inventory mapping, landslide descriptions and qualitative hazard assessment and do not cover the entire country (Viña et al. 1977; Formell and Albear 1979; Iturralde-Vinent 1991; Magaz et al. 1991; Castellanos et al. 1998; Guardado and Almaguer 2001). Most of the investigations were carried out in the southeastern part of the country. To include also the landslide risk in the multi-hazard risk assessment for the national system of disaster management, the National Civil Defence organisation of Cuba initiated a national landslide risk assessment project together with the Institute of Geology and Palaeontology. As a component of this, a research project for the development and implementation of a suitable methodology for landslide risk assessment from national to local level started in 2004.

Unlike landslide hazard, landslide risk assessment has been receiving only full attention by the international scientific community in the past decade (van Westen et al. 2005). One of the most useful definitions of risk is presented by Varnes (1984) as "the expected number of lives lost, persons injured, damage to property and disruption of economic activity due to a particular damaging phenomenon for a given area and reference period." When dealing with physical losses, (specific) risk can be quantified as the product of vulnerability, cost or amount of the elements at risk and the probability of occurrence of the event with a given magnitude/intensity (van Westen et al. 2005).

For large-scale landslide risk assessment, a range of methodologies have been published (Bonnard et al. 2004; Lee and Jones 2004; Eberhardt et al. 2005; Glade et al. 2005), but only limited 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 to produce a landslide risk index, which makes it possible to zoom in on 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, b). 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, allowing also warning and evacuation for landslide-prone areas.

The main goal of this research was to design a methodology for the assessment of a nationwide landslide risk index for Cuba taking into account the limitations in data availability and detail. This risk index does not intend to quantify the risk according to the definition of Varnes (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. Given these limitations, it was decided to derive 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 should use indicator maps collected from a variety of national information sources. The methodology should allow 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 that could be regularly updated based in the new statistical records such as population or economic production.

National landslide risk assessment model

Design issues and objectives

The landslide risk index method started with the selection of indicator maps, the way the criteria are going to be structured and the selection of standardisation and weighting methods. Figure 1 presents an overview of the various components of the landslide risk index method. Although the method does not produce the quantitative results according to the equation of Varnes (1984), in the design of the landslide risk index the general structure of the equation was used in which risk is a function of both hazard and vulnerability of the elements at risk. Therefore, the indicators were subdivided into hazard indicators and vulnerability indicators.

An important source for the hazard indicators is the analysis of an existing landslide inventory (Fig. 1). There are good examples in the literature of the use of landslide inventories for hazard assessment (Guzzetti et al. 1994; Guzzetti 2000; Chau et al. 2004; Guzzetti and Tonelli 2004). However, the existing landslide databases often present several drawbacks (Guzzetti 2000; Ardizzone et al. 2002; Guzzetti and Tonelli 2004) related to the completeness in space and even more so in time and the fact that they are biased to landslides that have affected infrastructures such as roads.

As mentioned above, in Cuba, the landslide inventory is still under development and does not have a full national coverage yet. The current national landslide database only contains those landslides where major damage has been reported and is therefore not complete both in space and time. Furthermore, quantitative damage information is not available for most of the landslides in the database. For that reason, in this study, the national landslide database was used with caution as it does not give a complete picture for the country yet. If a complete landslide database would have been available, it could have served as the main input in the landslide risk index, as landslide density of landslides per municipality could then have been used as the main hazard indicators and the landslide damage per municipality as the main vulnerability indicator. As part of the national landslide risk assessment project for the National Civil Defence, also a research project was initiated to improve the national landslide inventory, making use of local Civil Defence personnel that are trained in reporting the occurrence of new landslides, combined with multi-temporal landslide maps based on Remote Sensing (Castellanos and Van Westen 2005).

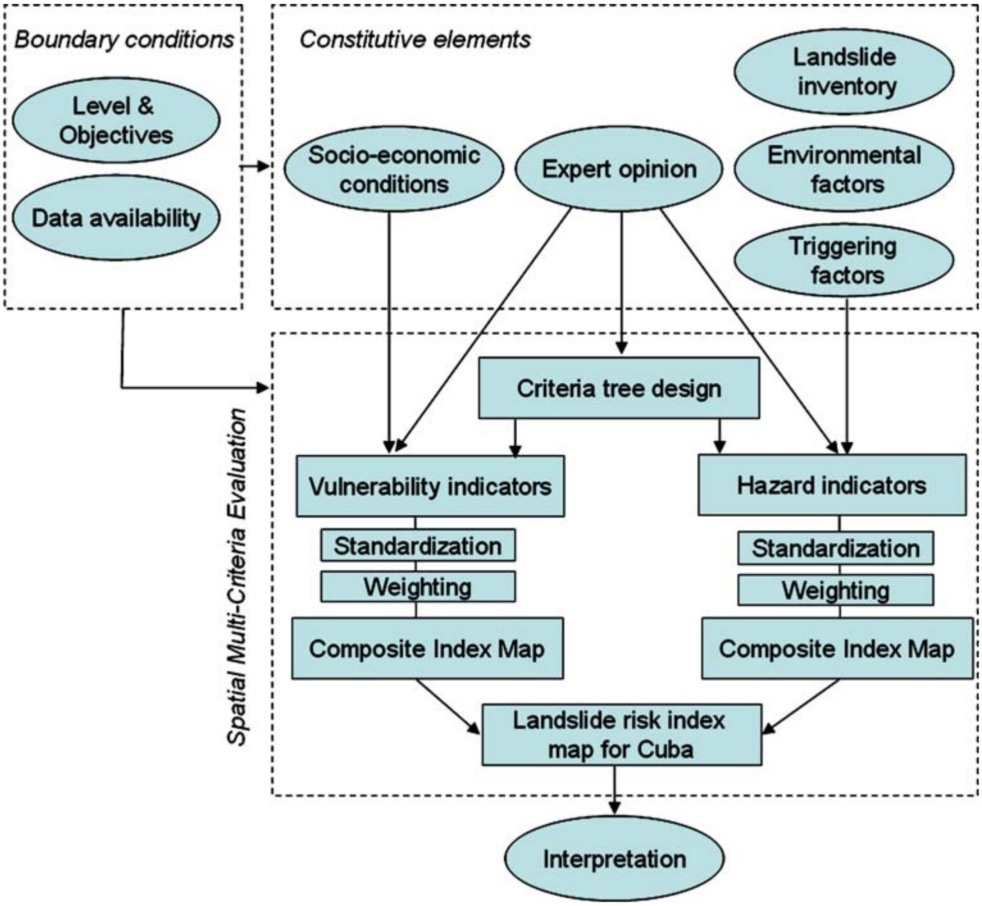


Fig. 1 General framework for building the landslide risk assessment model

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. 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 (van Asch et al. 1999; Zaitchik et al. 2003; Schmidt and Dikau 2004; van Beek and van Asch 2004). Combining inventory analysis (empirical modeling) and physical rules established in the deterministic models provide a better understanding for designing appropriated hazard indicators.

For designing the 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 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 are dealing with large-scale studies or 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. They are therefore not specific for landslide vulnerability and could also be used to assess vulnerability to other hazardous phenomena at a national scale.

Two interrelated boundary conditions have a high influence in designing a model for the national landslide risk index assessment: the data availability and the level of analysis (Fig. 1). Data availability is especially relevant in developing countries, where data is scarce, disperse or not in the appropriate format. Furthermore, the level of analysis is relevant as it determines the quantity of data, in terms of area coverage and detail. National level assessment involves small-scale input data, which is generalised and which determines the type of analysis method that can be used. That issue, along with the funding, can overrule all others aspects explained for designing the model. In practice, there is always a discrepancy between the desired and available information. If the desired type of information is available, it may still be in the wrong format or level of detail.

The management level determines the objectives of the risk assessment (Fig. 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 the 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, enterprises and social institutions, on the required measures of prevention and preparation, 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 with the aim to study in more detail the identified areas of higher risk, its causes and the implementation of measures to reduce the risk

Multi-criteria analysis and analytic hierarchy process

Considering the abovementioned 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 under 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 (Australian Geomechanics Society and Sub-committee on landslide risk management 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 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).

For implementing the semi-quantitative model the SMCE module of ILWIS-GIS was used. SMCE application assists and guides users in doing multi-criteria evaluation in a spatial manner (ITC 2001). The input is a set of maps that are the spatial representation of the criteria. They 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) made multivariate statistical processing 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.

From a decision-making perspective, multi-criteria evaluation can be expressed in a matrix (Triantaphyllou 2000; see Table 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_n). 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 is filled, the

Table 1 Multi-criteria decision matrix

	C_1	C_2	C_3	$\cdots$	C_n
	$(W_1W_2W_3$	$\cdots$	$W_n)$		
A_1	a_{11}	a_{12}	a_{13}	$\cdots$	a_{1n}
A_2	a_{21}	a_{22}	a_{23}	$\cdots$	a_{2n}
•	•	•	•	•	•
•	•	•	•	•	•
•	•	•	•	•	•
A_m	a_{m1}	a_{m2}	a_{m3}	$\cdots$	a_{mn}

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 need to be considered: decomposition, comparative judgement and synthesis of priorities (Malczewski 1996). The first one decomposes the problem (and the weights) in 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 A_j (Malczewski 1996). The notion of alternative is different in this context. The alternative here is not a choice of action but a different spatial realisation of the final goal (e.g. landslide risk). This implementation is better explained in Fig. 2. The goal (landslide risk index) has been decomposed in 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. 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 are consisting of raster maps, their spatial performance (a_{ij}) and the alternative (A_i) will be identified for particular raster cells.

The composite index map 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. The performance of every element in the matrix (a_{ij}), however, is obtained in a different way:

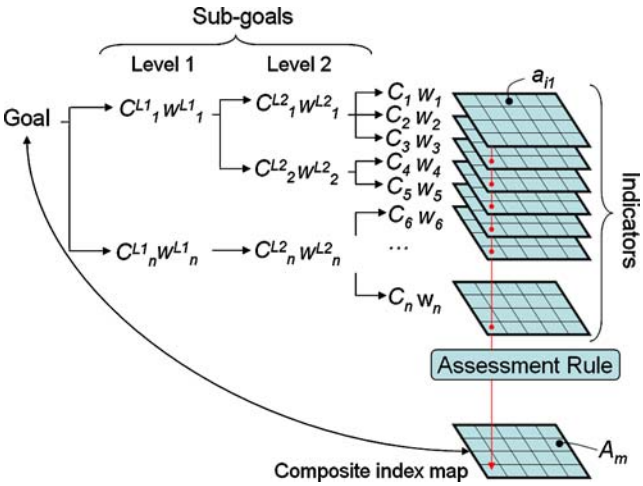


Fig. 2 Schematic procedure for spatial multi-criteria evaluation based on analytical hierarchical process

$$a_{ij} = v^*_{ij} \prod_{L=0}^{h} w_j^L \tag{1}$$

In this equation, v_{ij} refers to the standardised value of criterion (C_j) for alternative (A_i), and weight w_j^L refer 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_j^L) 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 behavior 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 is high only if both the hazard and vulnerability index maps are high. The hazard component in fact 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 happen. The intermediate map of *Vulnerability* is generated by combining the four vulnerability types mentioned earlier. A schematic representation of the landslide risk assessment model is given in Fig. 3.

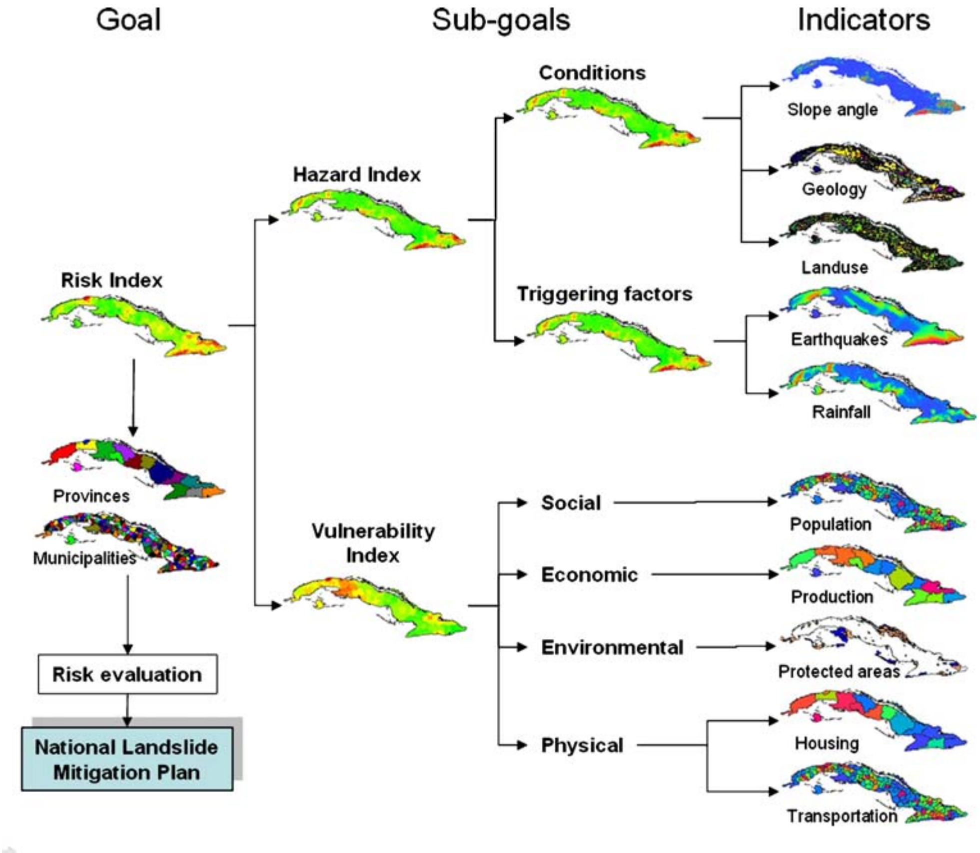
Theoretically, we found, when starting the analysis, a total of 43 potential indicators to be considered for the generation of the risk index at national level in Cuba. However, for different reasons that will be explained in the Section Indicator Analysis, the final model was simplified up to the ten indicators given in Fig. 3.

Standardisation, weighting and evaluation rules

To make spatial multi-criteria analysis possible, 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 into account these elements, different standardisation methods provided in the SMCE module of ILWIS (ITC 2001) were applied to the indicators.

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.

Fig. 3 Landslide risk assessment model at national level in Cuba



The class maps use an associated table for standardisation where a column must be filled with values between 0 and 1. The standardisation is summarised in Table 2 (right column). In Section Indicator Analysis, 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 (see below) whose values were inversely calculated to the overall vulnerability and risk.

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,

Table 2 Overview of indicators (italic), intermediate maps or sub-goals (bold), with their corresponding weight values

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

The weighting and standardization method is indicated in the right columns landslides are not expected or occur only 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 with not 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 2).

One limitation of the SMCE software used in ILWIS is that all indicators and sub-goals can only be added. Therefore, the model was implemented in the SMCE, but the actual calculation was run in a separate script.

Before running the script in GIS, the entire model was implemented in a spreadsheet to test the model 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, in consequence, the minimum risk index value 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 was to identify the performance of the model when all the indicators are in their measure of central tendency.

Indicator analysis

In this section, the indicator maps used in the landslide risk index will be presented including their method of standardisation and weighting.

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 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 removed later for different reasons, mostly related to data redundancy and availability of data with inappropriate format or legend structure. Slope length, drainage density and internal relief are morphometric parameters that could be obtained from digital elevation data.

The digital elevation model, which was used as the basis for this analysis, was made from Shuttle Radar Topography Mission (SRTM) data, with a cell size of 90 m. The process carried out during the editing of SRTM data for the Cuban Archipelago was explained in Castellanos (2005). Calibration was necessary for the water bodies, shaded mountainous areas and in coastal zones where radar backscatter signal produces considerable erroneous values. A final mosaic at 90 m with 6,002 rows by 13,202 columns was created with 33 tiles of SRTM-3 data with 1,201×1,201 pixels for each one. This mosaic was used as the base georeference for all other indicators and results maps in this study.

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 like 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, this 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 was in fact containing 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 standardise 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).

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 standardised map is shown in Fig. 4a.

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 3). Forests occupy most of the mountainous areas and are often combined 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 is 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 landsliding (Table 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 standardised map is shown in Fig. 4c.

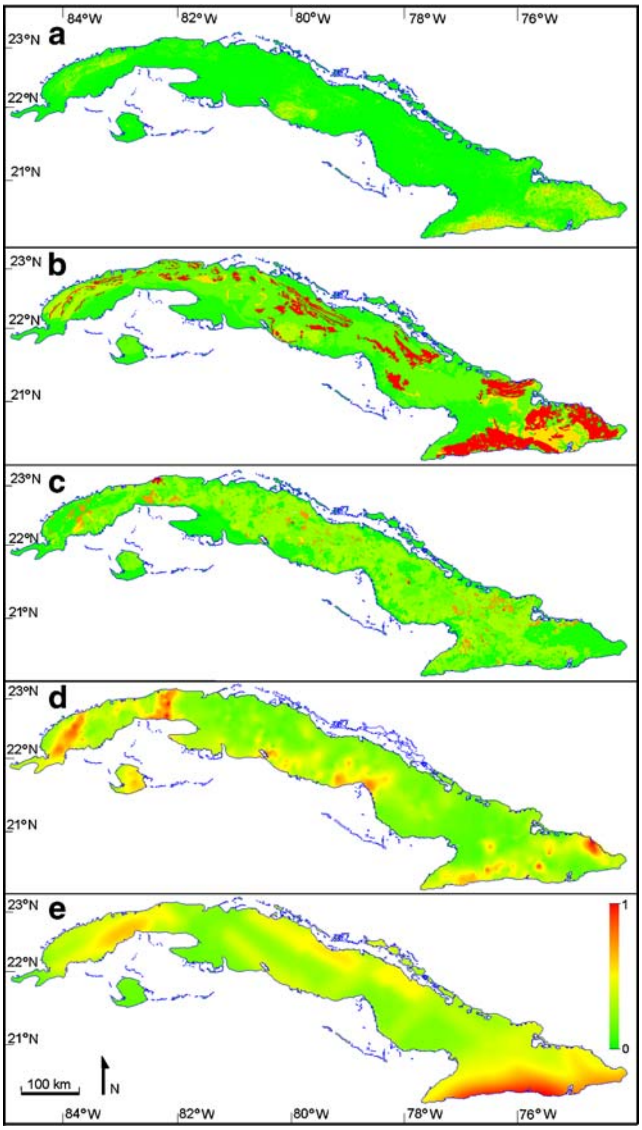


Fig. 4 Hazard indicators standardised to 0–1 range: **a** slope angle, **b** geology, **c** land use, **d** maximum rainfall expected in 24 h and **e** maximum peak ground acceleration

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 the 1:1,000,000 scale (Formell 1989) with 68 geological units, which was compiled from a series of maps at the 1:250,000 scale. These 68 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 and Fig. 4b).

Triggering factors

Apart from the three abovementioned 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 Coastal Services Center 2005) 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 southeastern part of Cuba. In this point, the most devastating historical hurricane Flora had its landfall in 1963. In contrast, the northeastern corner of the island has the highest values of expected rainfall but without storm tracks. 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 standardises the input values by dividing them by the maximum value possible (846.32 mm in this case; see output map in Fig. 4d).

Table 3 Land use classes, their percentage of coverage and the values assigned for standardization

Land use	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

Land use data from the National Atlas of Cuba at 1:1,000,000 scale (Rodríguez 1989)

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 (Magaz et al. 1991). The maximum peak ground acceleration (PGA) with a 100-year return period was used as an indicator map in this study (Fig. 4). 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 southeastern 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 Fig. 4e.

Vulnerability indicators

The selection of vulnerability indicators was made after analysing 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; United Nations Development Program 2004; UNPD 2004). Initially, a total of 43 vulnerability indicators were considered to be used in this study at the national level, and the Cuban National Statistics Office (ONE) was asked to provide information on these. 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 (Instituto Nacional de la Vivienda 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:

$$Housing\ Condition\ Index = B_{Good} / (B_{Regular} + B_{Bad}) \quad (2)$$

Where B_{Good}, $\mathrm{B}_{\mathrm{Regular}}$ 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 conditions. Table 5 gives the housing condition index for the Cuban provinces. The values were standardised negatively 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 Fig. 5d.

The values of the housing condition index in Table 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 disasters. The limited resources available for housing in Cuba are mostly directed to disaster recovery and not to a continuous housing development programme.

Table 4 Geological complexes, their descriptions and the values assigned for standardization

Geological complex	Number of lithological 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

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 of 4.093 km/km^2, and as expected, the higher values are distributed close the heads in 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 of Cuba where the municipalities have a more developed road system. For the national road network, the average is very low (21 km/km^2), but when the whole road network of the country is included, this parameter increases considerably. The results were standardised using the maximum linear method. The standardised map is shown in Fig. 5e.

Population indicator

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

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/km^2, whereas the third group includes mainly the provincial capitals with densities of 200 to 600 persons/km^2. The fourth group consists of the municipalities in Havana City with more than 2,000 persons/km^2. 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/km^2. The standardised map is shown in Fig. 5a.

Table 5 Vulnerability information at provincial level

Province	Housing Index	Total production (in million US $)
Isla de la Juventud	3.18	164
Guantanamo	0.82	626
Santiago de Cuba	1.41	1,100
Granma	0.73	1,034
Holguin	0.82	2,279
Las tunas	1.15	550
Camaguey	1.3	1,234
Ciego de Avila	1.6	489
Sancti Spiritus	2.57	620
Cienfuegos	2.9	1,033
Villa Clara	1.13	1,505
Matanzas	2.92	1,636
Ciudad de Habana	2.19	1,747
La Habana	1.97	1,604
Pinar del Rio	2.16	889

Left: Housing condition index (based on data from Instituto Nacional de la Vivienda 2005). *Right*: Total production in 2003 per province (Oficina Nacional de Estadísticas 2004)

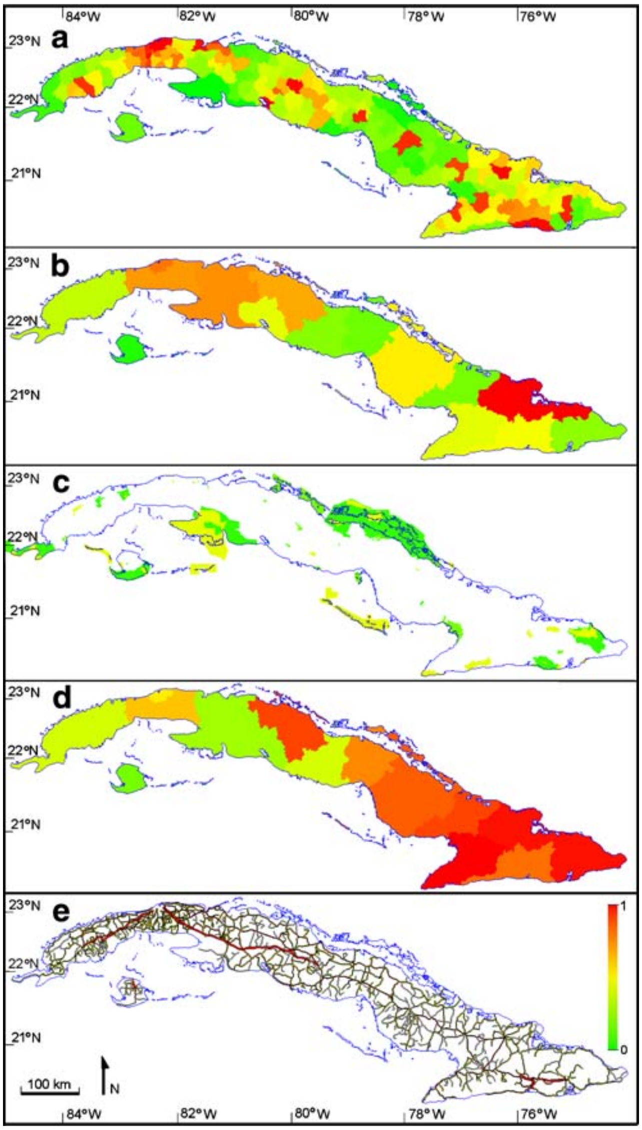


Fig. 5 Vulnerability indicators standardised to 0–1 range: **a** population, **b** production, **c** protected areas, **d** housing condition and **e** road system (for clarity of this figure, the zero values are displayed in *white* in this figure)

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 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 (Oficina Nacional de Estadísticas 2004) at the provincial level (see Table 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 Fig. 5b.

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 1994), which represent their environmental significance from category Ia (Strict Nature Reserve) up to VI (Managed Resource Protected Area).

Cuba has 81 protected areas (SNAP 2006), and most of them are in three main categories (Fig. 5c): 28 in category II (National Park), 29 in category IV (Habitat/Species Management Area) and 16 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 Fig. 5c.

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 (Fig. 6). 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 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 2.

The histogram, ignoring the zero values, which are 80.14% of the total area of the risk index map, shows a bimodal pattern (Fig. 7). By analysing each indicator and sub-goal in the model, we identified that the hazard component was most important and more specifically the conditions sub-goal in the equation. 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 high susceptible land use types coincide with high susceptibility geological units, e.g. ophiolites and 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. For a more detailed study, the risk index values were analysed physiographically and administratively at provincial and municipal level.

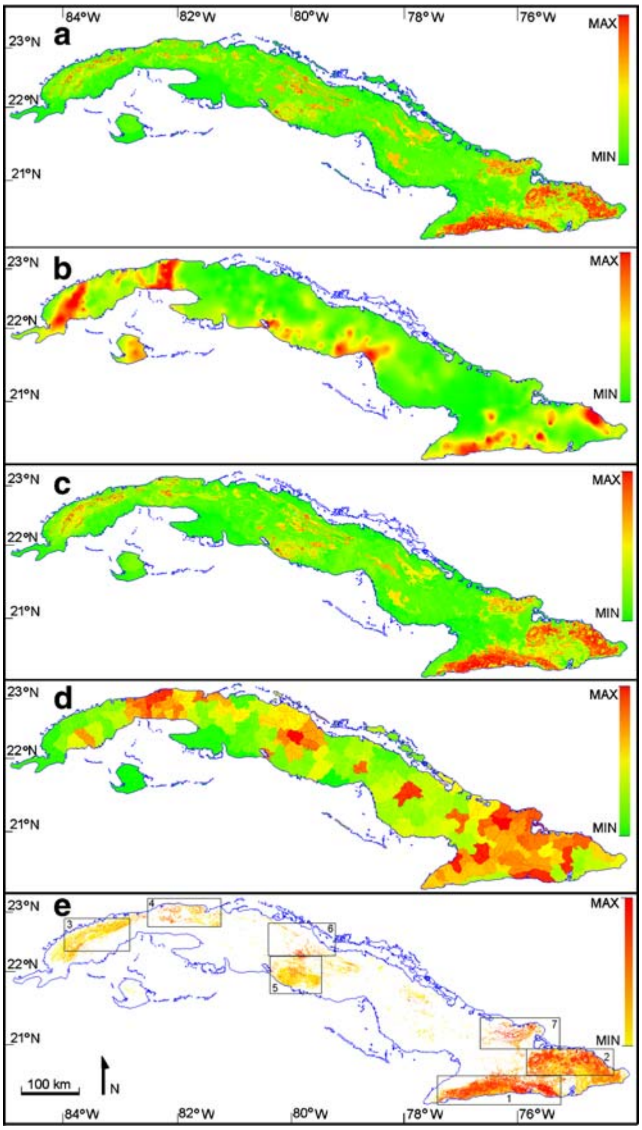


Fig. 6 Maps used for calculation the landslide risk assessment. **a** Composite index map of conditions, **b** Composite index map of triggering factors, **c** Composite hazard index map, **d** Composite vulnerability index map and **e** final risk index map. All maps are represented from the minimum and maximum values according to Table 6. Landslide risk index maps shows physiographic areas indicated by *rectangles*: *1* Sierra Maestra–Gran Piedra, *2* Nipe–Cristal–Baracoa, *3* Guaniguanico, *4* Havana, *5* Macizo Guamuhaya, *6* Santa Clara and *7* Northwest of Holguin

Physiographic landslide risk analysis

As can be observed from Fig. 6e, 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) Havana, (4) Santa Clara, (5) Macizo Guamuhaya, (6) Northwest of Holguin and (7) Guaniguanico. 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.

The Sierra Maestra mountain system (area 1 in Fig. 6e) 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).

Table 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	Standard deviation
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 Nipe–Cristal–Baracoa (area 2 in Fig. 6e) 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.

The Guaniguanico mountain system (area 3 in Fig. 6e), 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 Fig. 6e) 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.

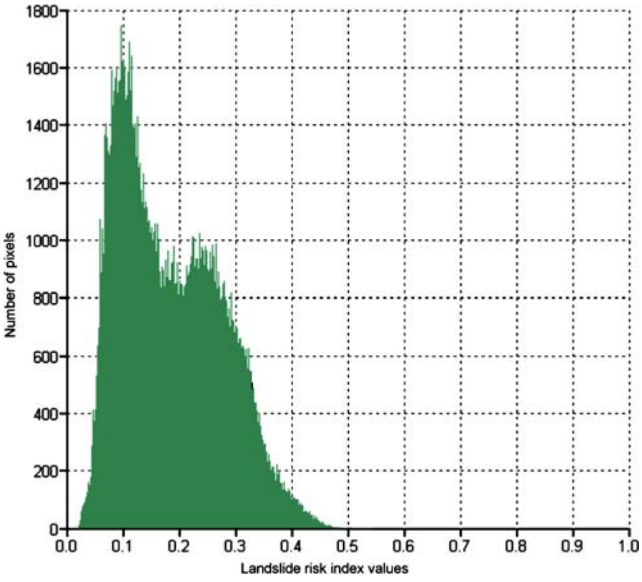


Fig. 7 Histogram of landslide risk index map ignoring zero values

The Macizo Guamhuaya region (area 5 in Fig. 6e) 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 Fig. 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 Fig. 6e) 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 8 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 carried out normally according to the 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 made: 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 7 provides the percentage of each province covered with different landslide risk index values.

In Table 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

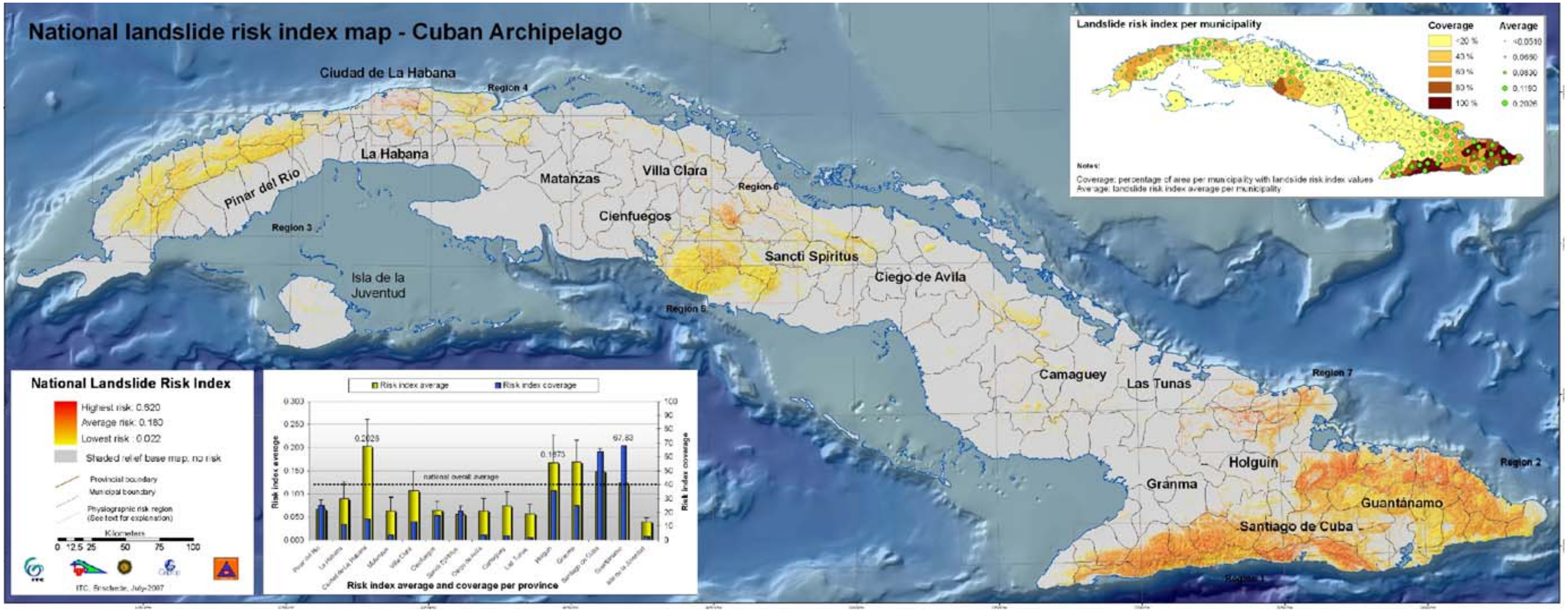


Fig. 8 Final landslide risk index map, as presented to the National Civil Defence authorities. *Inset map* in the *upper right corner* indicates the landslide risk index per municipality, both as the percentage of area with landslide risk index larger than 0 (coverage) as well as the average landslide risk index. The *barchart* shows the landslide risk index values per province

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 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.

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 15 municipalities in Ciudad de La Habana, they appear in the map as one polygon. Figure 8 shows the risk index values displayed together with the municipal boundaries. There are 36 municipalities without high risk values, 83 municipalities with 0 to 10% high risk, 38 with 10 to 50% and 12 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 8. They are the primary targets for carrying out landslide risk assessments at local level.

Conclusions

Only 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). In Cuba, however, these activities are still in an initial stage, and 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 needs. The main user in Cuba is the National Civil Defence, who would like to have information at different administrative levels (municipal, provincial, national) of the level of landslide risk and information how this varies through time, to define areas for further more detailed studies.

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 (Fig. 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. Because of 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 is leading 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. 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 43 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.

Table 7 Percentage of each province with low, moderate and high landslide risk

Province	Low risk (%)	Moderate risk (%)	High risk (%)
Pinar del Rio	74.8	24.1	1.2
La Habana	88.6	8.4	3.1
Ciudad de La Habana	84.8	4.5	10.7
Isla de la Juventud	97.4	2.6	0.0
Matanzas	96.5	3.0	0.5
Cienfuegos	82.0	17.8	0.3
Villa Clara	86.7	8.6	4.8
Sancti Spitritus	79.1	20.5	0.5
Ciego de Avila	96.5	3.2	0.3
Camaguey	96.9	2.9	0.2
Las Tunas	98.5	1.4	0.1
Holguin	64.3	9.6	26.1
Granma	74.7	3.6	21.8
Santiago de Cuba	35.9	14.3	49.8
Guantánamo	31.6	37.2	31.2

Table 8 Ranking of the 12 municipalities with the highest percentage of landslide risk

Municipalities with more than 50% of high risk	Percentage
III Frente	89.5
Guisa	80.0
Buey Arriba	76.9
Santiago de Cuba	70.9
Moa	68.7
Baracoa	66.0
Bartolomé Masó	65.3
Guamá	62.6
Pilón	60.8
Imías	55.2
Sagua de Tánamo	54.0
Mayarí	53.9

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.

It is important to mention, nonetheless, that still much research needs to be done related to the visualisation of the risk and the measurement of its effectiveness for the decision makers. We think, however, that studies like this with few modifications can be developed in many other countries as an initial screening process 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 studies at a larger scale. 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.

Acknowledgement

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E. A. C. Abella (✉)
Instituto de Geología y Palentología (IGP),
Vía blanca y Carretera Central, San Miguel del Padrón,
CP 11000 Havana, Cuba
e-mail: castellanos@itc.nl

C. J. Van Westen
International Institute for Geoinformation Science and Earth Observation (ITC),
P.O. Box 6, 7500 AA Enschede, The Netherlands
e-mail: westen@itc.nl