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Spatial landslide risk assessment in Guantánamo province, Cuba

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ABSTRACT: Within the Cuban national system for multi-hazard risk assessment, landslide hazard and risk have not been properly addressed thus far. This paper focuses on a method for landslide susceptibility assessment, its conversion into hazard, and the combination with elements at risk data for vulnerability and risk assessment. The method is tested in Guantánamo province, one of the areas with the highest incidence of landslides in Cuba. The GIS-based assessment was carried out with input maps at 1:100,000 scale or larger resulting in digital maps with 50 m pixel resolution. For the susceptibility analysis 12 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. The relationship between these factor maps and the landslide inventory was analyzed using a combination of heuristic and statistical methods (Artificial Neural Network analysis and Weights of Evidence method). Five different landslide types were analyzed separately (small slides, debrisflows, rockfalls, large rockslides and topples), resulting in five susceptibility maps. Success rate curves were generated and analyzed to evaluate the predictability and to classify the maps. The susceptibility maps were converted into hazard maps, using the event probability, spatial probability and temporal probability. Return periods for different landslide types were estimated based on the main triggering events and geomorphological reasoning. The vulnerability analysis started with the generation of a provincial database with five elements at risk maps: number of inhabitants per house, essential facilities and non-residential buildings, roads, agricultural landuse and natural protected areas. The spatial landslide risk assessment was conducted by analyzing the 5 hazard maps and the 5 vulnerability maps. A qualitative risk assessment was carried out using Spatial Multi-Criteria Evaluation. Semi-quantitative risk assessment was done by applying the risk equation in which the hazard probability is multiplied with the number of exposed elements at risk and their vulnerabilities. In this paper only the results of the semi-quantitative assessment of population risk are presented and briefly discussed. The study was able to identify high risk areas and the main causes derived either from high landslide hazard or from high spatial concentration of element at risk in Guantánamo province. In order to derive a quantitative estimation of risk more information should be available on temporal probability and vulnerability. Both of these require an extensive landslide database which should be implemented and maintained at the national level.

1 INTRODUCTION

Landslides are one of the hazard types occurring in Cuba. Local authorities have recognized the need for assessing the hazard and risk due to landslides, and incorporate these into a multi-hazard risk assessment. In Cuba, most of the reported landslides are associated with hurricanes, tropical storms or prolonged periods of rainfall (Pérez, 1983, Iturralde-Vinent, 1991, Pacheco & Concepción, 1998, Castellanos, 2000). Landslide damage is normally not recorded separately from the main disaster, so there is no historical landslide database available that could serve as the basis for a landslide risk study.

This research is intended to increase the awareness about landslide problems in Cuba by developing a method for GIS-based landslide risk assessment at different scales, taking into account the specific situation with respect to data availability and landslide types in Cuba. Various methods for landslide hazard and risk assessment have been applied in other countries (e.g. Cruden & Fell, 1997, Dai et al., 2002, Glade et al., 2005), but they need to be translated to the Cuban situation. Results on landslide risk assessment at the national and municipal scale were reported by Castellanos and Van Westen (2007a, 2007b). Here some results of the provincial scale are presented.

2 CASE STUDY AREA

The method for landslide risk assessment at a provincial scale was developed and tested in the province of Guantánamo (see Figure 1), the most eastern province of Cuba with a surface area of 6186 km^2, comprising 5.5 percent of the national territory. The population is 511,224 (ONE, 2007), which is 4.6 percent of the national population. About 75 percent of the area is mountainous with the highest point at 1,181 m. The southwest is covered by the large valley, which also forms a separate hydrographic basin. Guantánamo contains both the most humid (in the North) and driest (in the South) zones of Cuba. The province has 10 municipalities (indicated with large dots in Figure 1) and 386 settlements from where 18 are considered urban. Agriculture is the most important economic income for the province which is based on sugar cane, coffee, cacao, wood and coconut. The last four are cultivated in mountainous regions. The industries include an iron foundry, and factories for coffee, agricultural tools, furniture, food, sugar cane and salt. Guantánamo has the national record of 49 devastating hurricanes measured over the period 1789–2003, which are more frequent in September and October. Since 1997 to 2002 there were 93 forest fires reported, affecting an area of 3043 hectares. The landslides resulting from these other disasters are rarely recorded in the official statistics. The province also has a substantial earthquake hazard, due to the presence of the Caribbean-North American plate boundary in the south.

3 LANDSLIDE INVENTORY

The provincial landslide hazard, vulnerability and risk assessment started with a detailed landslide inventory. Landslides were photo-interpreted from 300 aerial photos (format 23 × 23 cm) from the year 2000 at 1:25,000 scale, covering the entire Guantánamo province. The photo-interpretation was transferred from the photos to base maps which were later scanned and digitized. The landslides boundaries were cross-checked using band 8 (15 m) of a Landsat ETM+ satellite image. A spatial database was created with attributes for the size and type of landslide. The database also included only 12 historically reported landslides. Unfortunately no multi-temporal image interpretation could be carried out, which made it difficult to establish the age of the landslides. In total 281 landslides were identified covering an area of about 19.92 km^2. From this inventory, four main types of landslides were determined: rockfalls, debrisflows, topples and slides. Landslides identified as topples were considered in those areas where a number of subsequent detachment blocks could be identified without major downslope movement. A toppling movement may culminate in an abrupt falling or sliding but the form of the movement is tilting without collapse.

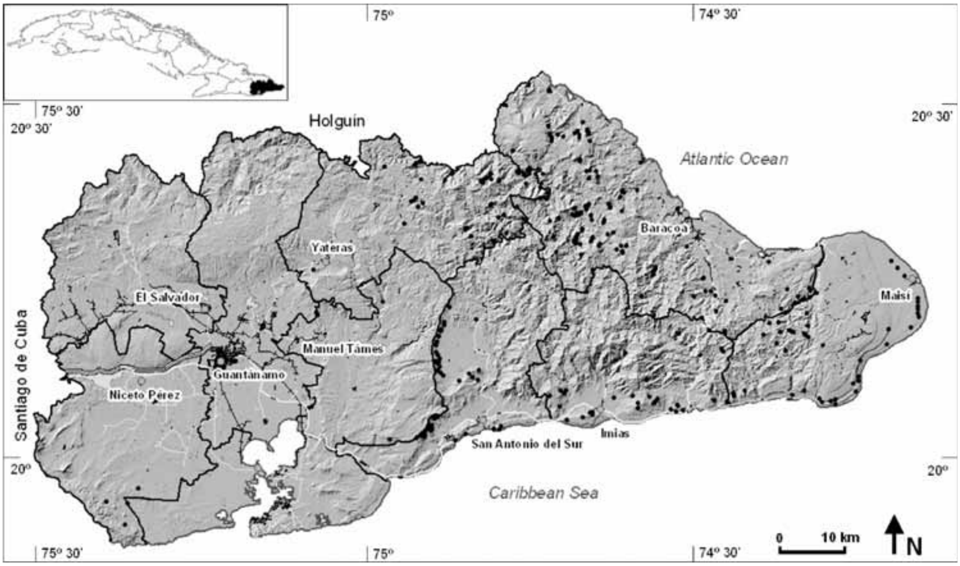


Figure 1. Hillshading map the study area, with municipalities, main urban centers and landslides (indicated as black dots).

Further analysis showed that slide-type movements were basically of two genetically and morphometrically different types: a group of 29 larger landslides located in a high tectonically affected area in the San Antonio del Sur area, and a group of 186 smaller landslides dispersed all over the province. The results are given in Figure 1 and Table 1.

4 METHODOLOGY

A schematic overview of the methodology is given in Figure 2. The method started with a comprehensive landslide inventory, and the collection of input data on landslide causal factors and elements at risk, represented in the upper part of Figure 2. The next step was to generate a number of landslide susceptibility maps for the five different landslide types described above, using a combination of a heuristic approach, and of several statistical methods, such as the Weights of Evidence Modeling and Artificial Neural Network analysis. The susceptibility maps were converted into hazard maps, based on the landslide densities of the susceptibility classes and the temporal probability of landslide occurrence. This resulted in five hazard maps (H_slide to H_rockslide), indicated in the middle part of Figure 2.

Table 1. Number of landslide events and areas for different landslide types mapped from photo-interpretation and fieldwork in Guantanamo province.

Type	Number	Area (m^2)
Small landslides	186	7.72E+06
Large landslides	29	8.39E+06
Topples	18	1.28E+06
Rockfalls	22	1.29E+06
Debrisflows	26	1.25E+06
Total	281	1.99E+07

Elements at risk (EaR) data were collected for population, roads, essential facilities and non residential buildings, agricultural land use, and protected areas. In order to estimate the risk to these elements by the five different landslide types, each of the five hazard maps was overlain with the elements at risk maps to calculate the number of elements per hazard class. In the lower part, the method for the risk assessment is presented. Two approaches have been used: qualitative and semi-quantitative methods. A qualitative risk assessment was carried out using Spatial Multi-Criteria Evaluation. Each EaR map was standardized to values between 0 and 1, and weights were assigned to each of the maps, depending on their importance, and their estimated vulnerability to the particular landslide types. These maps were integrated into a single vulnerability map, which was combined using a two-dimensional matrix with the 5 hazard maps. This resulted in five qualitative specific risk maps (R_slide to R_rockslide). The semi-quantitative risk assessment method is based on the calculation of specific risk as the multiplication of hazard, vulnerability and amount of elements at risk that are exposed. This is indicated by the two maps at the bottom right part of Figure 2. Semi-quantitative assessment was only carried out for population and roads, as there was no cost information available for the other 3 types of elements at risk. The study was based on raster analyses using IL WIS and ArcGIS© GIS software at 50 m resolution taking into account the cartographic rule of a maximum detail of

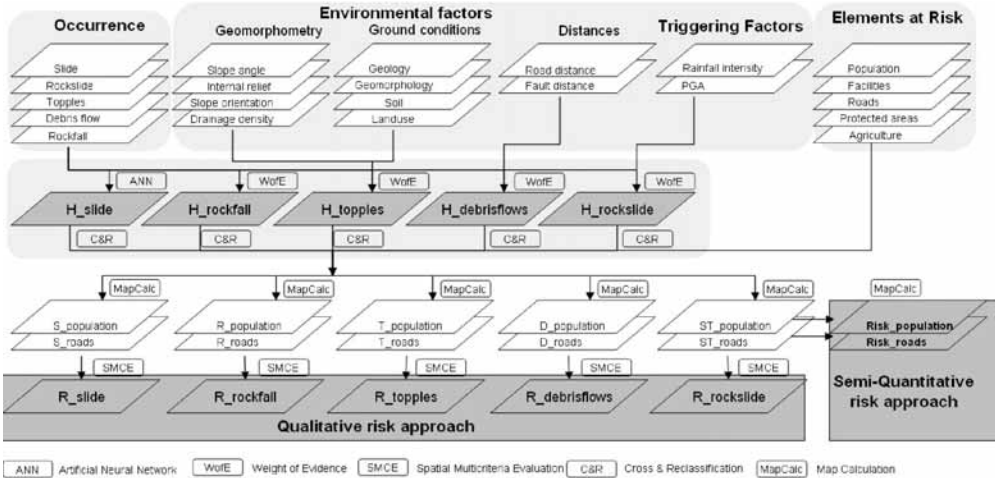


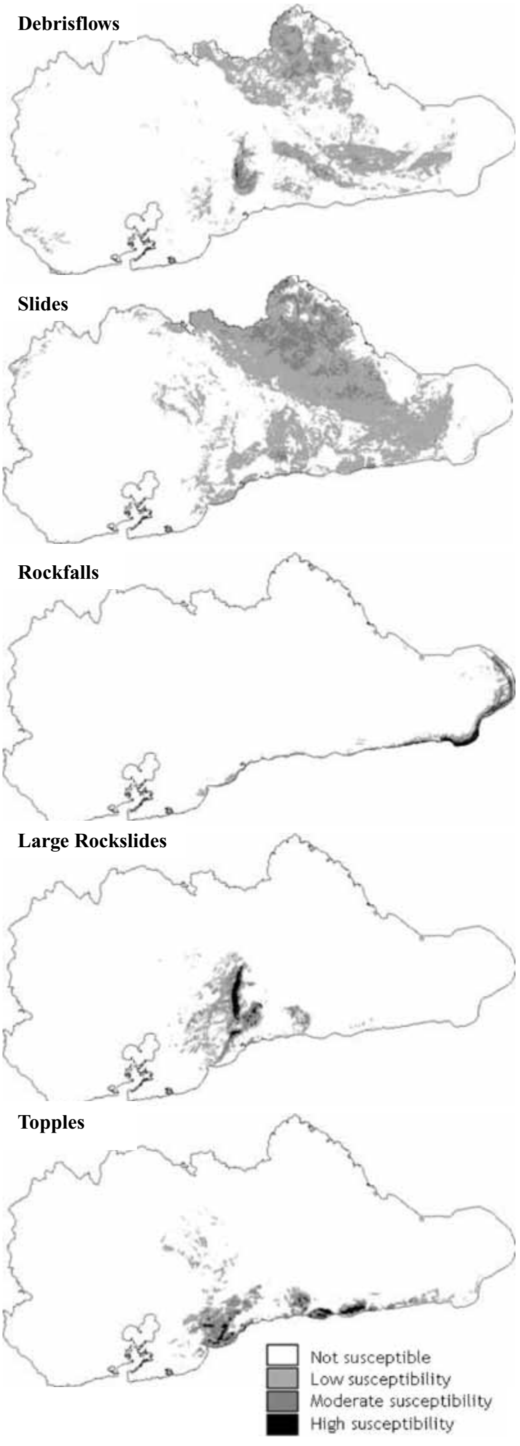
Figure 2. Flowchart of the method used for landslide risk assessment at the provincial scale. See text for explanation.

0.5 mm at the scale of the final map (1:100,000 scale in this case), resulting in maps with 2475543 pixels.

5 HAZARD ASSESSMENT

The casual factor maps were selected based on literature (Carrara et al., 1991, Soeters & van Westen, 1996, Guzzetti et al., 1999) and on the data available in Cuba. They were separated into 3 groups: morphometric factors, ground conditions, distance related factors, and triggering factors. A DEM was created using the ArcGIS© "topo to raster" tool, and four morphometric parameter maps were extracted: slope steepness, slope orientation (aspect), internal relief (vertical dissection) and drainage density. Existing geological, geomorphological and soil maps were used and reclassified by reducing the number of legend units to only those that were considered relevant for landslide susceptibility assessment. The landuse map, which was also obtained from existing maps, was used both as potential causal factor, and as element at risk for estimating the impact of landslides on agricultural production. Two buffer maps were used: distance to main roads in sloping areas, and distance to active faults. Also two triggering factors were used in the landslide hazard assessment. The first of these was a raster map of maximum expected rainfall in 24 hours for a 100 year return period (Planos et al., 2004), and the was a map of the peak ground acceleration (PGA) with a 10 percent exceedance probability in 50 years (García et al., 2003).

As part of the hazard analysis two methods were applied for estimating spatial probabilities: Weights of Evidence (WofE) modeling (Bonham-Carter, 1996) and Artificial Neural Network (ANN) analysis (e.g. Lee et al., 2004). The selection of the relevant causal factor maps for each of the five landslide types was made based on initial results of WoE modeling, and expert judgment. The susceptibility maps for 4 out of 5 landslide types were generated using WoE modeling (See Figure 3), as for each of these the main casual factors could be clearly separated, and also because the number of events for each of these was relatively small (See Table 1). For the generation of the susceptibility map of slide-type movements it was decided to use the ANN method, because there were several different causal mechanisms for this landslide type, that were difficult to separate, and also because the number of events was substantially larger than for the other types. The landslide inventory database was randomly subdivided in 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 from noise in the data, and a test set (12.5%) to evaluate the prediction capability of the network. An equal number of samples was


Debrisflows

Slides

Rockfalls

Large Rockslides

Topples

Figure 3. Susceptibility maps for five different landslide types.

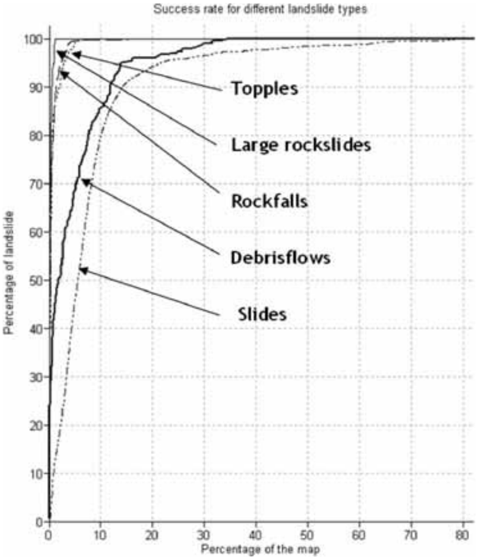


Figure 4. Success rate curves for the five landslide susceptibility maps.

also randomly taken in non-landslide areas. Due to the small scale of the study and the relatively large pixel size it was decided not to include a runout analysis as part of the landslide susceptibility assessment. The five susceptibility maps (See Figure 3) were validated using the landslide inventory and success rate curves were generated (See Figure 4). The results showed generally a very good fit, especially for the topples, large rockslides and rockfalls that occur under very specific conditions. The success rate curves were also used to classify the susceptibility maps with approximately equal percentages of the total number of landslides (e.g. ∼70% of all landslides in the highest class).

The next step in the analysis was the conversion of the susceptibility maps into hazard maps. For this three probabilities were calculated for pixels belonging to each hazard class within the five maps:

- Event probability, P(E), defined as the probability that if a landslide occurs of a given type, it happens in the particular susceptibility class.
- Spatial probability, P(S), defined as the probability that if a landslide occurs within a given susceptibility class, a pixel in this class might be hit.
- Temporal probability, P(T), defined as the annual probability of occurrence of a particular landslide type.

The event probability and spatial probability were calculated based on the area of landslides within each susceptibility class, in relation to either the total area of landslides (for P(E)) or the total area of the class (for P(S)). Temporal probability was the most difficult to estimate, also in the absence of a historical landslide database. Therefore, based on geomorphological analysis and comparison with return periods for the main triggering events, a return period (RP) of 100 years was selected for large rockslides, a 50 years RP for rockfall and topples, and a 20 year RP for debrisflows and slides. The resulting hazard probability values calculated for each class of the 5 maps are given in Table 2.

Table 2. Results for the annual hazard probability calculated as product of event probability P(E), spatial probability P(S), and temporal probability P(T).

Rockfall	P(E)	P(S)	P(T)	Hazard
None	0.00	0.00	0.02	0
Low	0.04	6.00E−04	0.02	5.00E−08
Moderate	0.17	5.20E−03	0.02	1.71E−06
High	0.79	4.76E−02	0.02	7.52E−05
Rockslides	P(E)	P(S)	P(T)	Hazard
None	0.00	0.00	0.01	0
Low	0.08	3.40E−03	0.01	2.70E−07
Moderate	0.21	2.53E−02	0.01	5.36E−06
High	0.70	2.37E−01	0.01	1.67E−04
Topples	P(E)	P(S)	P(T)	Hazard
None	0.01	0.00	0.02	0
Low	0.09	6.00E−04	0.02	1.20E−07
Moderate	0.24	2.90E−03	0.02	1.36E−06
High	0.66	3.37E−02	0.02	4.48E−05
Debrisflow	P(E)	P(S)	P(T)	Hazard
None	0.00	0.00	0.05	0
Low	0.05	5.09E−05	0.05	1.27E−07
Moderate	0.25	5.92E−04	0.05	7.40E−06
High	0.70	2.71E−03	0.05	9.48E−05
Slides	P(E)	P(S)	P(T)	Hazard
None	0.00	0.00	0.05	0
Low	0.05	2.49E−04	0.05	6.24E−07
Moderate	0.25	2.08E−03	0.05	2.60E−05
High	0.70	8.73E−03	0.05	3.06E−04

6 RISK ASSESSMENT

The risk assessment was carried out for the 5 different landslide types and 5 types of elements at risk, using both a qualitative and semi-quantitative method. Here only results are presented for semi quantitative analysis of the expected number of people that might be killed by landslides annually in the province. This was

Table 3. Results for the specific risk for population calculated as the product of hazard, vulnerability, and number of persons within a particular hazard class for the 5 different landslide types.

Rockfall	**Low hazard**	**Moderate hazard**	**High hazard**	**Total**
Hazard	5.30E−07	1.71E−05	7.52E−04	
Vulnerability	0.6	0.6	0.6	
Population	1616	522	200	2338
Specific risk	0.0005	0.0054	0.0902	0.0961
Rockslides				
Hazard	2.69E−06	5.36E−05	1.67E−03	
Vulnerability	1.0	1.0	1.0	
Population	1265	453	184	1902
Specific risk	0.0034	0.0243	0.3072	0.3349
Topples				
Hazard	1.17E−06	1.36E−05	4.48E−04	
Vulnerability	0.2	0.2	0.2	
Population	2139	745	12	2896
Specific risk	0.0005	0.0020	0.0011	0.0036
Debrisflow				
Hazard	1.27E−07	7.40E−06	9.48E−05	
Vulnerability	0.4	0.4	0.4	
Population	8047	553	0	8600
Specific risk	0.0004	0.0016	0.0000	0.0020
Slides				
Hazard	6.24E−07	2.60E−05	3.06E−04	
Vulnerability	0.7	0.7	0.7	
Population	30490	2255	1465	34210
Specific risk	0.0133	0.0410	0.3133	0.3676

done by overlaying the hazard maps with a population distribution map, indicating the maximum number of persons in buildings per pixel of 50 by 50 m. Outdoor population and temporal variations of population density were not considered. This results in the number of persons per hazard class as indicated in Table 3. The next step was to estimate the vulnerability of people being killed by a landslide while being indoors, based on the type of landslide and the expected magnitude of the event. These values were based on literature (e.g. Glade et al., 2005) and expert judgment, in the absence of historical landslide damage information.

7 CONCLUSIONS

From Table 3 it can be concluded that the annual population risk for landslides in Guantanamo province is low (0.8 persons/year). As there are no official records available on landslide casualties it is difficult to validate these results. The method also allows to quantify the risk in monetary values for direct damage to roads, agricultural areas, facilities, and protected areas. The results allow a comparison of annual landslide risk with those from other hazard types, and can form the basis for planning risk reduction measures. In the estimation of the semi-quantitative risk it is important to keep in mind that there are a number of estimated factors that need to be quantified more in detail in future. These relate specifically to the estimation of temporal probability, and vulnerability. Both require the generation and maintenance of a landslide inventory for the province, which also includes actual damage information. Also a more detailed evaluation of the effect of different landslide magnitudes should be taken into account, as well the use of different return periods for the same landslide type and the inclusion of landslide runout assessment.

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