Qualitative landslide hazard and risk assessment using multicriteria analysis; a case study from San Antonio del Sur, Guantánamo, Cuba.

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Abstract

This paper presents the results of a study on the use of geomorphological information combined with decision support tools for multicriteria analysis in a landslide hazard and risk assessment. The heuristic model was applied in San Antonio del Sur, a rural municipality in the province of Guantánamo, Cuba. The study is based on the generation of a Terrain Mapping Units (TMU) map at 1:50,000 scale, generated through the interpretation of aerial photos and satellite images, and field data collection. Information on 603 units was collected and a database was prepared describing each terrain unit. A more detailed mapping was done for the landslide areas, in order to classify the different landslide types and components. In the case study area three major landslide regions are recognized: coastal hills with rockfalls, shallow debris flows and old rotational rockslides, denudational slopes in limestone, with very large deep-seated rockslides related to tectonic activity and the Sierra de Caujerí scarp, with large rockslides. Among them, the Caujerí scarp presents the highest hazard with recent landslides and various signs of active processes. The different landforms and the causative factors for landslides were analyzed and used as the basis for the development of 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. With these variables a hierarchical heuristic model was applied in which three levels of weights were designed for classes, variables and criteria. The model combines all weights into one single hazard value in each pixel of the landslide hazard map. Later, the hazard map was classified using two scales; one with three classes for disaster managers and one with 10 detailed hazard classes for technical staff. For each class, the range of weight values and the number of existing landslides is registered. The result indicates that the landslide density increases with higher hazard classes, and as such can be considered a good indication of the reliability of the output map. The landslide hazard map was used in combination with existing information on buildings and infrastructure to prepare a qualitative risk map. One of the major difficulties in a landslide hazard and risk study in areas, such as San Antonio del Sur is the complete lack of historical landslide information, as well as geotechnical data which would allow the use of deterministic or probabilistic models.

Keywords:
Landslide susceptibility, geomorphological mapping, heuristic analysis, multicriteria analysis

1. Introduction

Similar to most developing countries, landslide inventory maps are still very scarce in Cuba, due to the limited resources for research. Most of the conventional landslide studies in Cuba are descriptive in nature, and a limited amount of studies focuses on landslide susceptibility assessment. Moreover, most of the quantitative landslides risk assessment methodologies that have been developed elsewhere are very case-specific and require many types of data, on landslide occurrences and impacts, most of which are not available in Cuba.

There is a general consensus on the classification in four different approaches for landslide hazard: a landslide inventory-based probabilistic approach, a heuristic approach (which can be direct Geomorphological mapping, or indirect qualitative map combination), a statistical approach (bivariate- or multivariate statistics) and a deterministic approach (Soeters and Van Westen, 1996; Aleotti and Chowdhury, 1999; Guzzetti et al., 1999). The landslide risk assessment methods are classified into three groups, as qualitative methods (probability and losses expressed in qualitative terms), semi-quantitative methods (indicative probability, qualitative terms) and quantitative methods (probability and losses quantified)(Lee and Jones, 2004).

In the Cuban situation, the heuristic approach is considered to be a useful method for obtaining qualitative landslide risk maps for large areas, in a relatively short period of time. It does not require the collection of extensive geotechnical data, although detailed geomorphological mapping is required. It may result in more reliable susceptibility maps than using statistical methods, where always a considerable amount of generalization needs to be accepted in the analysis. This is particularly relevant in Cuba, where the geomorphological setting exhibits a high spatial variability. In many countries qualitative risk assessment procedures have been implemented, which are based on heuristic approaches, e.g. in

Switzerland (Lateltin, 1997). The qualitative approach is based on expert opinion and the risk areas are categorized with terms as “very high”, “high”, “moderate”, “low” and “very low” risk. The increasing popularity of Geographic Information Systems over the last decades has lead to a majority of studies, mainly using indirect susceptibility mapping approaches (Aleotti and Chowdury, 1999). As a consequence there are less publications in which GIS is used in combination with a heuristic approach, either Geomorphological mapping, or index overlay mapping (e.g. Barredo et al., 2000;Van Westen et al., 2000; Van Westen et al., 2003).

Nowadays new decision support tools are available that may support GIS-based heuristic analysis. They allow to better structure the various components, including both objective and subjective aspects and compare them in a logical and thorough way (Saaty, 1980). The application of decision support tools such as (spatial) multicriteria analysis has not been very popular up to now in the field of landslide susceptibility assessment.

This research aims at combining geomorphological information with GIS-based decision support tools for the development of a heuristic landslide hazard assessment model in San Antonio del Sur, Guantánamo, Cuba at 1:50,000 scale.

2. The study area

The study area, within the San Antonio del Sur municipality, is located in the eastern part of Cuba (See Figure 1) at 60 kilometers 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 Imías, Baracoa and Maisí.

The geology and tectonic setting of the eastern part of Cuba is rather complicated, and contains several geological and tectonic environments in a relatively small area. The different tectonic and structural processes have been overlapping 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 evidenced by many neotectonic features and by the continuous general uplift of the area. In general the geology of Cuba has been subdivided in two principal geological units: a foldbelt and a neoautochthon (Iturralde-Vinent, 1996), which unconformably overlies the foldbelt (See Figure 1). Geological studies for the eastern part of Cuba and the study area have been made by Nuñez, et al. (1981), Nagy et al. (1983), Millán and Somin (1985) and Franco et al. (1992).

The San Antonio del Sur area contains geological units from both the foldbelt and from the neoautochthon. The foldbelt is consisting of a Northern Ophiolite belt, a Cretaceous Volcanic arc, a Paleocene Middle Eocene volcanic arc and a Late Middle Eocene piggyback basin (See Figure 1). The ophiolites are represented in the study area by a hilly zone in the

Southeast called "Sierra del Convento" (see Figure 3). It is the surface expression of a larger body considered as a relic of the basement, which emerged due a spreading of the oceanic crust, pushed from the south by tectonic forces (Chang and Suarez, 1998). Volcanic rocks of the Cretaceous volcanic arc belonging to the Formation Sierra del Purial underlie the eastern part of the study area. Volcanic deposits with low grade metamorphism from the Paleocene volcanic arc, belonging to the El Cobre Formation, can be found in the north of the area (See Figure 1). The piggyback basin corresponds to Paleocene-middle Eocene volcanic arc. The formations Charco Redondo, San Ignacio and San Luis represent this basin in the study area. These formations cover the Northeast up to central part of the study area, 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 is underlain by the “Neoautochthon”, recent geological units formed in situ, and which are represented in the study area by geological formations from three transgression-regression phases which occurred since the Late Eocene (Iturralde-Vinent, 1996). The first transgression-regression cycle is from Late Eocene to Oligocene and consists of alternating layers of sandstone, mudstone and calcareous clay. The second cycle is from Early Oligocene – Late Miocene, and is characterized by alternating layers of clastic, bioclastic and biogenic limestone. The third cycle is Late Pliocene to recent and is characterized by algae-bearing bioherm limestones, with corals, and recent marine sediments.

Although the neoautochthon is characterized by transgression/regression movements, the main feature throughout this time is the overall uplift of the area. The Paleocene volcanic arc and its piggyback basin was cut through and displaced since the Oligocene-Miocene, and the entire southern part is now separated from Cuba into the island of La Española (Haiti and Dominican Republic Island). This displacement took place by the sinistral strike-slip Oriente fault, which passes along the coast and has many secondary faults inland. The Oriente fault slope length is almost 8 km; 6 km below sea level and 2 km above. Tectonically the area can by subdivided in three main fault systems: SW-NE, N-S and NW-SE. The first two systems show large scarps with abundant landslides.

3. Geomorphology

The geomorphology of the study area is conditioned by the Caribbean-North American inter-Plate zone, and the paleoclimatic oscillations during the Quaternary period. Figure 2 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.

A geomorphological map at scale 1:50.000 was prepared based on the interpretation of two sets of aerial photographs (of 1:25,000 and 1:37,000 scale) and fieldwork. In the interpretation the area was subdivided in 603 Terrain Mapping Units (TMU). A TMU can be considered a homogeneous mapping unit on the basis of geomorphologic origin, physiography, lithology, morphometry, and soil geography (Meijerink, 1988). The resulting geomorphological map is presented in Figure 3. The area has been subdivided into the following geomorphological complexes (See Figure 2):

- Denudational hills (in metamorphic rocks, terrigenous rocks, and in limestone) (A, B and C In Figure 2)
- Alluvial units and accumulational slopes (D and E in Figure 2)
- Coastal hills (F in Figure 2)
- Puriales de Caujeri depression (G in Figure 2)

3.1 Coastal hills

The coastal hills in the study area are isolated hills parallel to the coastline (See Figure 2, 3 and 4), with variable length and a width between one and two kilometres. Three coastal hills can be differentiated, one between El Naranjo and Baitiquirí Bay, one between the Baitiqurí bay and Sabanalamar Bay (Loma Los Aposentos) and the last one between Sabanalamar Bay and Macambo town. The lithology in the coastal hills is different in the southern (coastal) side than in the northern side. The north side is totally covered by the Maquey formation, consisting of mudstone and calcareous clay susceptible to landslides. The coastal slope, characterized by marine terraces is composed of the Maya formation, which is consisting of recent (Holocene) marine deposits. These recent marine deposits act as “rings” of the coastal hills and are uplifted between 5 and 10 meters from the current sea level.

The different material and morphometrical characteristics on both sides of the coastal hills also result in different landslide types. The northern slopes of the coastal hills are characterized by the occurrence of frequent, but small debris flows. 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 m^3 can be found as part of the rockfalls. 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 (West of Baitiquirí and East of San Antonio del Sur) because the lower terrace was formed on top of the landslide toe. The third landslide in Los Aposentos coastal hill (Figure 4) is more recent than the others are since the lower terrace (Holocene) was also destroyed.

3.2 Accumulational slopes

The Geomorphological complex of the accumulational slopes is located on the northern part of the coastal hills (See figure 2 and 3). It is an intra-mountainous fluvio-marine plain with deltaic origin and a width of approximately 2 kilometers. This complex is slightly sloping to the south (sea) side with angles between 5 and 15 degrees. The materials range from colluvial, close to the mountains, to fluvio-marine. This complex seems to belongs to an old planation surface, which collected all the sediments coming from the upward area, what is now Sierra de Mariana, during the Pleistocene. The extension and volume of the Quaternary sediments reveals that the rainfall at that time was larger 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 to erode the sediments to 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 meters above the current erosion levels, and around ten new channels have eroded the old plain and generated erosional scarps with the same high differences.

3.2 Denudational hills

A large part of the area consists of denudational hills, which can be separated according to the underlying lithology into a limestone plateau, metamorphic hills and terrigeneous hills. The limestone plateau is a monoclinal plateau with an average altitude of 500 meters, composed mainly of limestone from the Yateras formation with extensive karst processes and additional erosional processes in those places where the underlying materials from the Maquey formation are exposed. The area is dominated by neotectonic processes and a number of large and deep-seated mass movements are observed which could be considered as a mix between gravitational and tectonic movements (See Figure 2). The landslides are more concentrated in the north part of Baitiquirí and El Naranjo. As the area is strongly affected by active tectonic faults the landslides are located in three main "steps" from the limestone hills toward the coast. In the upper part the landslides occur in the limestone rocks from the Yateras formation (Figure 3). In the next two steps the landslides occur over terrigenous materials from the Maquey, Cilindro and San Luis formations (Figure 1). 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. In some of the upper portions of the large landslide masses the total amount of displacement has not been more than a few meters. Displacements were more in the lower steps of the terrain 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 landslide 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, associated with the activity of the faults, and probably with relatively minor individual displacements per event. The most recently known landslide was in a locality known as El Naranjo, which occurred in 1997. Although it occurred during an intensive rainy season it was probably caused by a leaking water pipe, and destroyed a mini-hydroelectric power plant.

The landslides that occur in the denudational hills underlain by metamorphic rocks and terrigenous rocks 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 hillslopes or along the river incisions.

3.3 Puriales de Caujerí depression

By far the most striking geomorphological feature in the study area is the large oval shaped depression in the center (Puriales de Caujeri depression), which is considered to be a structural depression of the graben-type with high elevation differences up to 500 meters. The valley is limited in the west by a large scarp of the Sierra de Caujeri, with active retrogressive mass movements. On the southern and northern parts the valley is also surrounding by major fault scarps. The origin of the Puriales de Caujeri depression can be interpreted as a combination of tectonic and mass wasting processes. The main fault systems (Mariana and Caujeri) started to generate a graben depression after the Second Transgression-Regression period (Lower Miocene to Late Miocene). Later, the 15 kilometer long N-S oriented Sierra de Caujeri scarp, with a height difference between 300 and 400 meters, has been the main area for landslide activity. In the North the scarp ends 3 to 5 kilometers north of Mameyal and has less recent landslides. In the South the scarp intersects with the fault-controlled Sierra de Mariana scarp creating another area with large landslides. Figure 4 shows some of the landslides in the Caujerí scarp.

The most catastrophic landslide in the Sierra de Caujerí scarp 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 (See Figure 4). During this event a total amount of 1,100 mm of rainfall in three days was recorded in the Sierra de Caujerí area (Trusov, 1989). The successive rotational rockslide occurred in two pulses with about 45 minute intervals, which allowed some of the inhabitants to escape, whereas 5-10 others were killed. There is no technical report made directly after the event although some data were recorded during the fieldwork when a number of interviews were held with some of the survivors of the 1963 event. However, due to the long time since the occurrence of the landslide this information might not be very reliable anymore. Most of the landslides in the Sierra de Caujerí scarp consist of a large scarp in the upper part, often up to 100 meters high, which has cut almost vertical the limestone layer of the Yateras formation, and the underlying Maguey formation. This scarp is actually the back-scarp of multiple landslides, which change from rockslide to debris flows. Around 150 different landslide events have been mapped along the Sierra de Caujerí scarp (See figure 2, 3 and 4).

4. Landslide hazard assessment

The geomorphological mapping provided a more in-depth knowledge of the causal factors for landslides in the study area and was used as the basis for the landslide susceptibility assessment. The qualitative weighting method, one of the heuristic methods (Soeters and Van Westen, 1996), was selected as the best method for landslide susceptibility assessment, given the scale, the available data, and the characteristics of the study area.

The analysis has been carried out using different steps following the decision support system (DSS) methodology, according to the Analytic Hierarchy Process (AHP) (Saaty, 1980; Saaty and Vargas, 2001). First the various components (causal factors) that are used in the model were selected, and their hierarchical relation was designed. After that, weights were assigned to these maps, in a standardized way. After assigning weights a combination formula was used to integrate the weights and produce a final map, which was classified into a number of classes (Bonham-Carter, 1996).

The components were organized in a tree-shaped structure and ranked according to their importance to generate landslides (See Figure 5). The upper level of the components is called *criteria*, and consisted (in ranked order) of Geomorphology, Topography, Geology, Tectonics, and Hydrology. Several of the criteria were further subdivided into *variables* related to specific components, such as slope, internal relief and slope shape for the criteria Topography. The variables used are described in Table 1. The *relation* of each variable with respects to the landslide occurrence can either be a benefit (meaning that it is favorable to the occurrence of landslides) or a cost (unfavorable). The class boundaries in case of numerical *variables* were selected by taking the 25-cumulative percentage intervals of the histogram.

Once all the variables were characterized and classified in four classes the weights were assigned in the three corresponding levels: the criteria, the variable and the classes. Using a

GIS application all the criteria, variables and classes and their weights were listed in tables and a simple weight summation formula was applied to interactively evaluate the effect of the weights on the overall weight of the landslide susceptibility map. Weights were assigned using three different methods: a direct method by expert opinion, a pairwise comparison matrix method and a ranking method. For checking the weight assignment a decision support system called Definite was used (Janssen and Herwijnen, 1994). The pairwise comparison matrix is a matrix where each variable (or criteria) is compared to all other variables 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. The ranking method simply means that the variables are ranked according to their importance as landslide controlling factors. It is assumed that the ranking can be considered as units on a ordinal scale. Consequently the weights can be found by standardizing the rank order (Voogd, 1983).

The three methods gave comparable results, as can be seen from Table 2. For the pairwise comparison matrix method the inconsistency value was 0.08, demonstrating that the weights are reliable enough. The inconsistency is a parameter to measure how randomly the expert judgments are, and has a range from 0 to 1. As a conclusion the initial weights assigned by expert opinion were taken for the analysis.

As the weights were assigned in three levels the weights of the two upper hierarchical levels (*criteria* and *variable*) were multiplied by those of the lowest level (the *classes*) in order to get one final weight per class. For example, the slope class “shp4” (>20.37 degrees) has a weight of 50, which was multiplied by the weight of the “Slope” variable (0.7) and by the weight of the “Topography” criteria (0.3), so that the final weight was 10.5. The final weights of the resulting maps ranged from 0.500 to 47.100. This map was classified into 10 classes in an interactive way, during which the relation with existing landslide areas and geomorphological units was evaluated. Although the map gives a good indication of the landslide susceptibility in the study area, the use of many classes might make it difficult to use by decision makers for development planning. Therefore, the final map is presented with ten classes, which are grouped into three simplified ones: high, moderate and low. (See Figure 6)

The final hazard map was combined with the TMU map-database in order to obtain the information about the attributes per hazard class. Table 3 show the legend of the final landslide hazard map with statistical information related to the number of landslides and landslide density per class. Also the geomorphological information in the TMU map was used to define two classes with high and moderate flood hazard.

5. Qualitative landslide risk assessment

Unfortunately too limited information was available to carry out a proper landslide risk assessment. In particular there is not enough information on the probability of landslides with different magnitudes in order to make a (semi) quantitative risk assessment. Therefore only a basic qualitative analysis was carried out through the combination of the landslide susceptibility map with basic elements at risk. During the fieldwork information was collected on buildings and roads. As the study area is in a rural environment, most of the buildings are isolated farmhouses, and also a number of small schools and medical centers can be identified. Most of the roads in the study area are unpaved country roads, except for the main road in the south of the study area, which runs along the coast, mostly on the landside of the coastal hills. The roads and buildings are indicated in Figure 6. No intend was made to evaluate the potential losses of crops. In the study area there are a few settlements, of which San Antonio del Sur is the biggest village. Other villages and hamlets are Puriales de Caujerí, Baitiquirí, Macambo, Guaibanó, and El Naranjo.

Most of the 3317 buildings in the study area are made of wood over a concrete base, and a smaller amount are masonry buildings or RCC buildings, which are nearly only found in the settlements. There are 88 small schools spread out over the area, 6 medical centers and 4 small cemeteries. Building density is highest in the central-north part of the Caujerí depression, which a significant amount of buildings at risk in case a large landslide is originated from the Caujerí scarp.

For analyzing the qualitative risk level of the buildings an overlay was made between the building map and the hazard map. The result is shown in Table 4. Most of the buildings, and all of the small schools are located in low and moderate landslide hazard zones. In the highest hazard zones there are currently no buildings. A similar analysis was made for the road network (See Table 4). The provincial and national roads do not cross the high hazard areas, although quite some roads are in the moderate hazard classes.

In future, more data related with the elements at risk should be collected, including population distribution, and the replacement value of buildings and roads, as well as the value of the different agricultural crops.

6. Discussion and conclusions

Detailed geomorphological mapping provides information on the very site-specific conditions under which different landslide types occur in different parts of the area. Landslides in the study area are concentrated along the Caujerí scarp, but also in the coastal hills and in the northern part of the Baitiquirí area. In these areas the landslides have different characteristics and causative factors. The subdivision of the terrain in 603 so-called Terrain Mapping Units, which can be considered as individual homogeneous polygons, allowed for a more detailed characterization of the terrain, than would be possible through conventional map overlaying of main factor maps. The boundaries of different landslide parts were surveyed using photointerpretation, and landslides were described in the field using a checklist in detail, where information was collected related to landslide type, subtype, relative age, and depth.

The collection of this data allowed to generate a heuristic model, using multicriteria analysis, which was quite successful in classifying the area in different susceptibility classes, which can be displayed either in 10 more detailed or 3 generalized classes, depending on the user of the map. Improvements in the method could still be made if different weight maps were produced for different landslide types. However, since the geomorphological units are one of the main variables in the heuristic analysis, this could partly be taken into account, by assigning weights to each individual unit.

The overall landslide susceptibility can be considered rather low, with the exception of a number of specific areas, such as the Caujeri scarp, and the area directly below. However, due to the absence of a sufficient landslide record with age information, it was not really possible to convert the susceptibility map into a hazard map, in which indicative probabilities are assigned to the 10 classes. Historical landslide information is not available, except for a few isolated landslides. It is known that large landslide can happen along the Sierra de Caujeri, similar to the one that occurred in 1963 during the passing of a hurricane. 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 geological, geomorphological, tectonic and hydrological conditions of landslide areas is still limited. Recently, however, the National Civil Defense 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 and Van Westen, in press).

One very important component of this system will be the involvement of local staff of the Civil Defense at the 169 municipal centers, including San Antonio del Sur. A simple landslide reporting form has been designed, and workshops will be conducted to train the staff and make them aware of the 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 not be very effective in other countries, due to lack of commitment of the reporting staff at the local level. In Cuba, however, the Civil

Defense is well organized and very effective as can be concluded from a comparison of disaster related casualties numbers in Cuba with those of neighboring countries such as Haiti or Dominican Republic (Thompson and Gaviria, 2004).

Acknowledgements

We would like to thank Koert Sijmons for his assistance in generating the cartographic output. The research is coordinated with the National Science and Technological Innovation Program for Civil Defense (PNCIT) in Cuba and with the National Headquarters of the Civil Defense (EMNDC) in Cuba. The Institute of Geology and Paleontology (IGP) is carrying out this research project since January 2004 for the four case study areas with a duration of 3 years. This research is carried out as component of the ITC SLARIM research project: Strengthening Local Authorities in Risk Management.

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Figures

Figure 1: Above: Location of the case study area in Cuba. A = outcrops of the foldbelt, B = Eocene to Recent neo-autochthonous deposits, C = Main faults, D = Study area. Below: general geological map of the San Antonio del Sur municipality, Guatánamo province, Cuba. The map is north oriented and the area is 20 by 30 kilometers.

Figure 2. Anaglyph Image of the study area. For viewing in 3-D red-green glasses are required. 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

Figure 3: Geomorphological map.

Figure 4. Different landslides from the study area. A and B: typical rotational landslide in the coastal hills; C,D, E: large landslide movements in the Sierra de Caujeri scarp.

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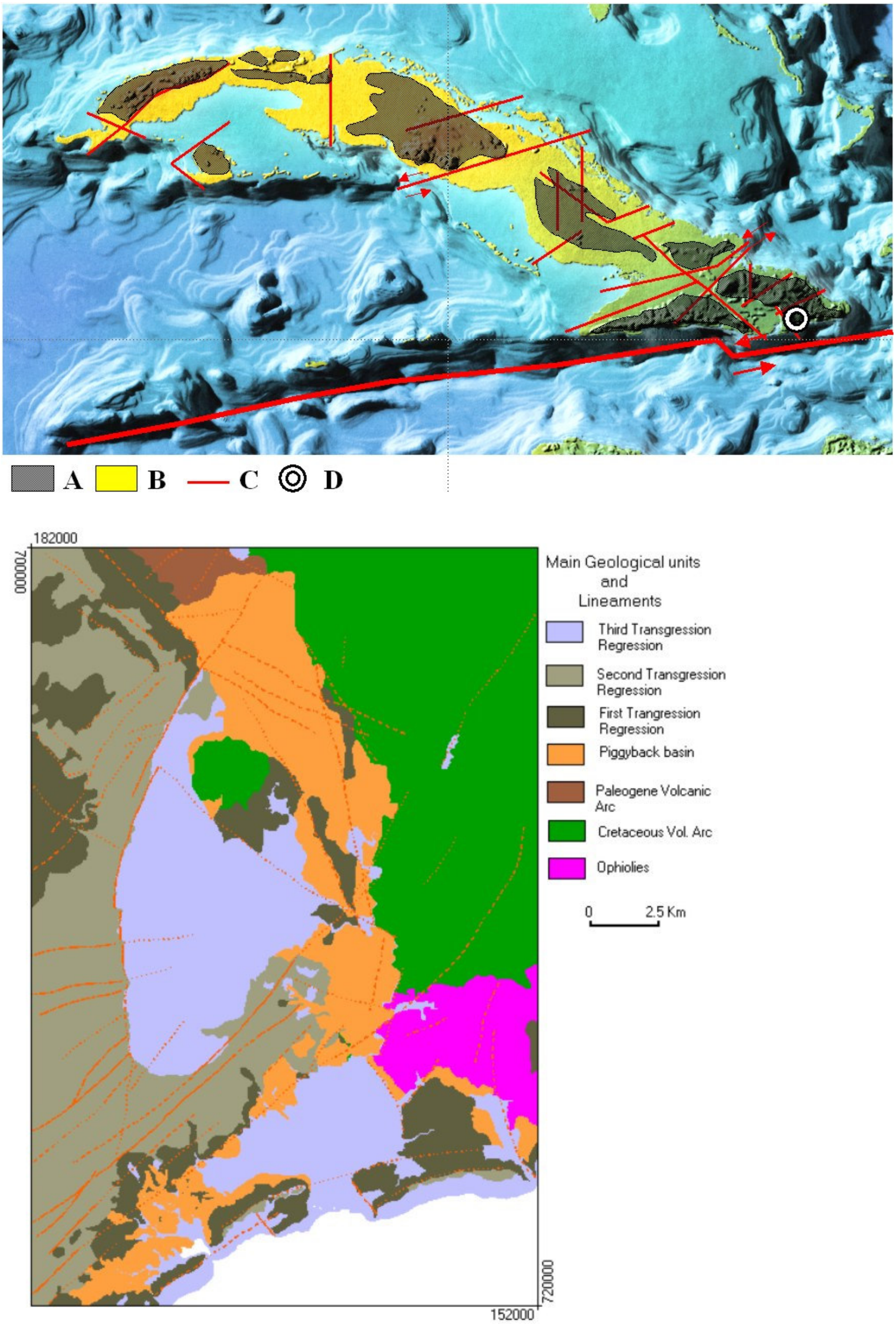
Table 2. Weight for criteria and variables using three methods

Table 3: Characterization of the 10 hazard classes using in the hazard map (See Figure 6)

Table 4: The number of buildings and length of roads per hazard class. The small difference between the total and the actual number is due to processing errors in the rasterization procedure.



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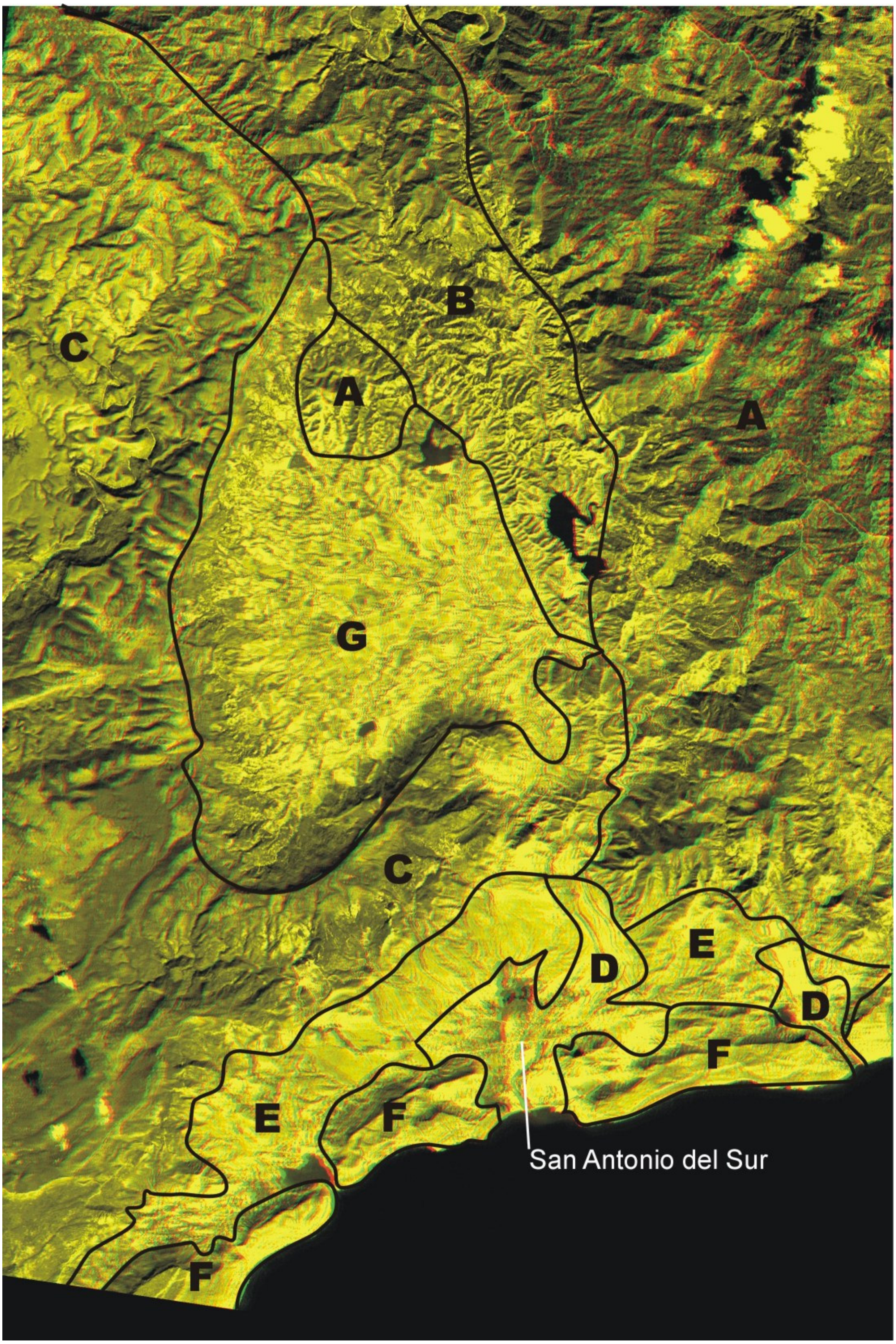

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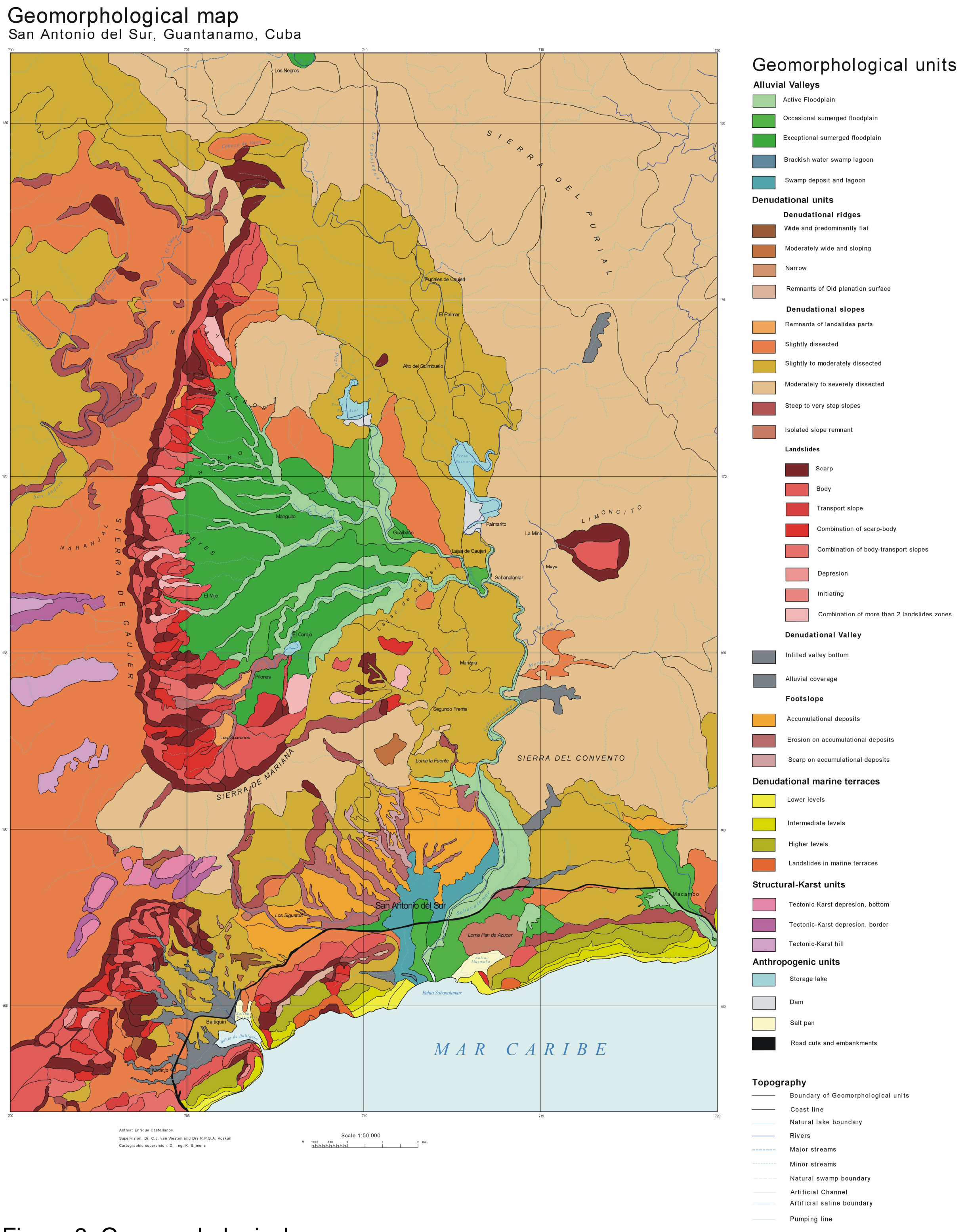

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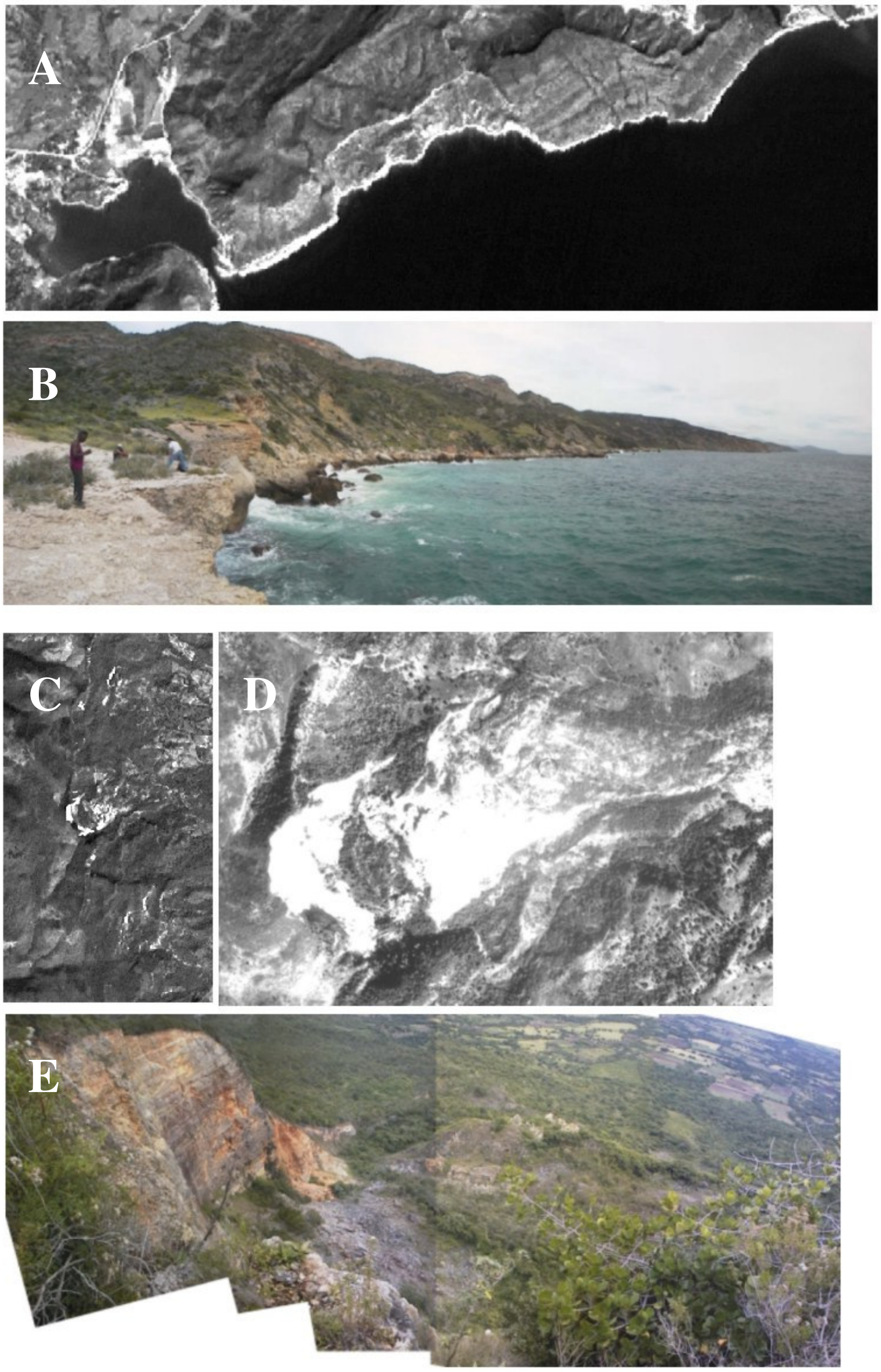

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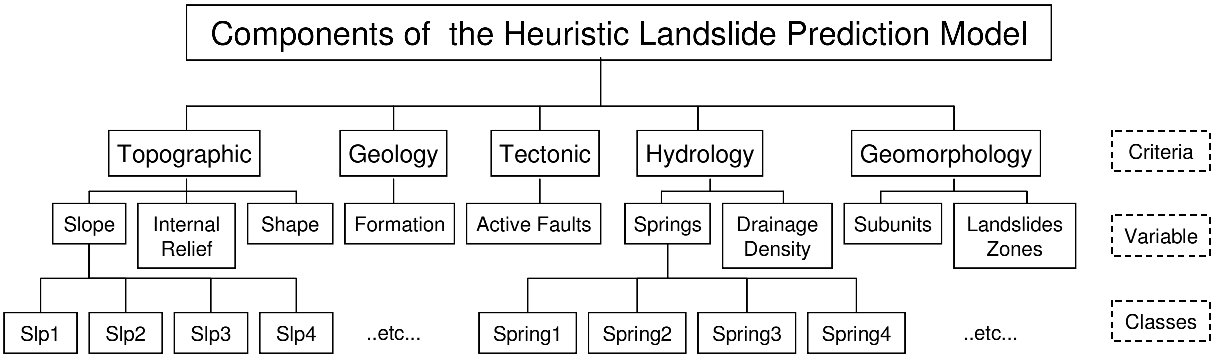

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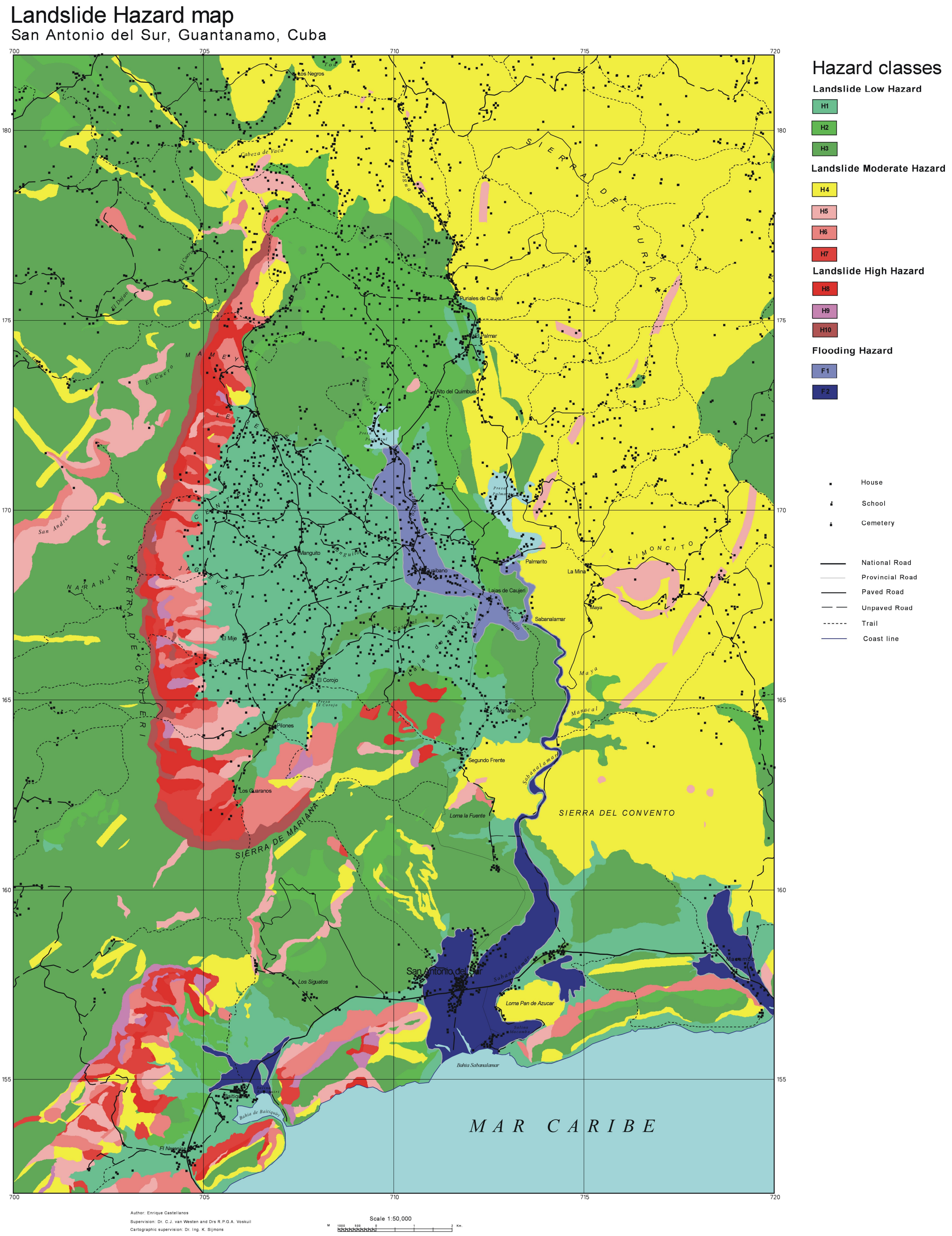

Figure 6: Landslide hazard map. See table 3 for explanation of the legend.

Tables

Variable	Origin	Scale	Units	Relation
Slope	From the original DEM using the methodology of ILWIS	Interval	Degrees	Benefits
Internal Relief	From the original DEM using the methodology of ILWIS	Ratio	Meters/hectares	Benefits
Shape	From the original DEM using the methodology of ILWIS	Ratio	No meaning. >o concave, 0 straight, >0 convex.	Benefits
Geology	By reclassifying the TMU map	Categorical	N/A	N/A
Faults	Calculating a distance from the fault map and classifying in four classes	Ratio	Meters	Costs
Springs	Calculating a distance from spring points and classifying in four classes	Ratio	Meters	Benefits
Drainage Distance	Calculating a distance from the drainage map and classifying in four classes	Ratio	Meters	Benefits
Geomorphological Subunits	By reclassifying the TMU map	Categorical	N/A	N/A
Landslides subzones	By reclassifying the TMU map	Categorical	N/A	N/A

Table 1. Variables used in the heuristic model. See text for explanation (N/A – Not applicable)

	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 density		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	

Table 2. Weight for criteria and variables using three methods

Overall class	Hazard Class	Weight range	Area (ha)	Number of TMU units	Number of landslides	Area of landslides (ha)	Landslide density (%)	General hazard description
LOW	H1	0.50-5.16	8669	88	0	0	0	No landslides expected in normal situation. 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. However, it is recommend take into account other natural hazards like flooding.
	H2	5.16-9.82	4176	40	0	0	0	
	H3	9.82–14.48	18107	125	8	210	1.1	
MODERATE	H4	14.48–19.14	18361	94	22	338	1.8	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 for being reactivated in smaller proportions. No recommended development project or a detailed study needs to be done in the design of the project.Land use changes should be previously studied in relation to landslide hazard problem.
	H5	19.14 – 23.8	2013	85	46	901	44.7	
	H6	23.8 – 28.46	1702	87	79	1428	83.8	
	H7	28.46 – 33.12	969	77	76	963	99.3	
HIGH	H8	33.12 – 37.78	719	59	59	715.88	99.5	High to very high landslide hazard areas. A high possibility of landslide occurrence during raining conditions. No development is recommended in these areas. Possible relocation of land for agricultural use. Highly recommended relocation of existing population in these areas
	H9	37.78 – 42.44	291	36	36	289	99.4	
	H10	42.44 – 47.10	439	24	24	438	99.8	

Table 3: Characterization of the 10 hazard classes using in the hazard map (See Figure 6)

Hazard classes	Buildings (nr)	Houses (nr)	Schools (nr)	Cemeteries	National roads (km)	Provincial roads (km)	Paved roads (km)	Unpaved roads (km)
H1	1370	1338	29	3	33.25	27.89	29.38	151.38
H2	381	367	13	1	2.44	0	17.55	48.92
H3	588	570	18	0	5.64	20.71	15.66	132.36
H4	947	919	28	0	0.09	1.24	7.41	120.62
H5	69	68	0	1	0.12	0	0	16.55
H6	36	36	0	0	0.55	0	0.89	5.83
H7	30	29	1	0	0	0	0	7.08
H8	14	14	0	0	0	0	0.72	0.8
H9	0	0	0	0	0	0	0	1.07
H10	1	1	0	0	0	0	0	0
Total	3436	3342	89	5	42.09	49.84	71.61	484.61
Actual nr.	3409	3317	88	4				

Table 4: The number of buildings and length of roads per hazard class. The small difference between the total and the actual number is due to processing errors in the rasterization procedure.