Mapping Critical Slopes To Landslide Occurrence In A Tropical Environment Using Geographic Information Science: Examining The Case Of Tobago

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Due to land space and economic limitations, the effects of natural disasters such as landslides have a significant impact upon the economies of small mountainous tropical islands such as Tobago. This is mainly due to the existing favorable physical conditions for landslides and their triggers, coupled with the increasing demands of development, tourism and population growth.

This paper presents a GIS based methodology to define the factors influencing landslide occurrence as well as mapping critical slopes to landslide occurrence in tropical mountainous environments. In addition, the sources of raw data, including ortho-imagery and field surveys are identified and techniques to capture, validate and convert the required data into usable digital format are described.

A landslide susceptibility approach is presented for Tobago and the results are represented as a landslide critical slope map. This outcome can is useful in guiding future developments, the formulation of disaster response and mitigation plans as well as the formulation of landslide insurance guidelines.

Key Words: Landslides, Tropical, Slope Risk Map, Geographic Information Science, Tobago

1. Introduction

Of all geological hazards, landslides are amongst the most predictable as slope failure tend to affect discrete areas of land and are therefore amenable to avoidance, prevention and mitigation. *Landslide hazard* refers to the probability of a landslide of a given size occurring within a specified period of time within a particular area (Bell, 1999). Varnes (1984) noted that landslides are not as spectacular or as costly as floods, earthquakes and other natural hazards, but are more widespread.

Landslides are considered complex phenomena and have generated much research from the academic and commercial spheres. Landslide causes are normally separated into three types: preparatory, sustaining and triggering (Terzaghi 1952; Crozier 1986; Hansen 1984). *Preparatory causes* are those events that prepare the slope for failure but do not necessarily initiate movement. *Sustaining causes* are those that keep the slope in motion, either intermittently or continuously, once initial movement has been commenced. *Triggering causes* are those that initiate landslide movement.

Landslides are not currently amenable to risk assessment since there is no reliable basis to determine the probability of landslides occurring within a given time period. Hazard assessments are possible and can be used in place of risk assessments (Wu, Tang and Einstein, 1996). Hazard assessments are estimations of an area's susceptibility to landslides based on a few key factors such as

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topography, geology and land use/cover (Baban and Sant, 2004b). These are each capable of being mapped and allow land areas to be evaluated on their relative susceptibility to landslides. The number of conditions present in an area can then be factored together to represent the degree of potential hazard present (Baban and Sant, 2004a). Generally, three principles guide *landslide hazard assessment* (Varnes, 1984):

- Landslides in the future will most likely occur under geomorphic, geologic, and topographic conditions that have produced past and present landslides.
- The underlying conditions and processes which cause landslides are understood.
- The relative importance of conditions and processes contributing to landslide occurrence can be determined and each assigned some measure reflecting its contribution (Varnes, 1984).

The use of Geographic Information Science (GIS) in landslide susceptibility mapping provides a valuable input into the decision making process with respect to natural hazard management (Carrara *et al.*, 1999). The GIS is able to manage the myriad of spatially related factors that influence landslide occurrence and coupled with a landslide inventory it can be used to extract geo-environmental indicators at known landslide locations (Soeters and van Westen, 1996; Baban and Sant, 2004a, 2004b).

In fact, GIS has become a promising tool in the effective analysis of landslides (Brabb, 1984; DeGraff *et al.*, 1989; Ahmad and McCalpin, 1999; Carrara *et al.*, 1999; Sakellariou and Ferentinou, 2001; Griffiths *et al.*, 2002; Baban and Sant, 2004a, 2004b). The GIS facilitates modeling through its ability to handle large data sets, providing an efficient medium for analysis and display of results, with a powerful series of tools that allow the collection, retrieval, manipulation and display of spatially referenced data representing the real world. The system allows the integration of qualitative and quantitative through their spatial distribution that may not be evident otherwise (Frost *et al.*, 1997).

This paper aims to develop a GIS based approach to locate and map critical slopes in mountainous tropical environments, examining Tobago as a case study, using factors (geology, slope, soil, rainfall and land use) that positively influence landslide occurrence.

2. The Study Area

The islands of Trinidad and Tobago form the two most southerly islands of the Caribbean's Lesser Antilles chain. The island of Tobago is situated approximately 12 km to the northeast of Trinidad (at I1°N longitude and 62°W latitude) and is approximately 292km^2 (Fig 1) in area. Tobago has a low central coral limestone plateau to the southwest and relief increases on moving towards the middle and northeastern sections of the island which is dominated by igneous geology. The island's core is marked by a northeast-southwest ridge, the Main Ridge, with a peak elevation of some 560m. The north facing slopes of the Main Ridge are generally steeper than the south facing ones and valleys are frequently bisected by small steep flowing rivers (Baban and Sant 2004a, 2004b). The island has an agricultural history, but its main source of income is tourism, which is driving the development process.

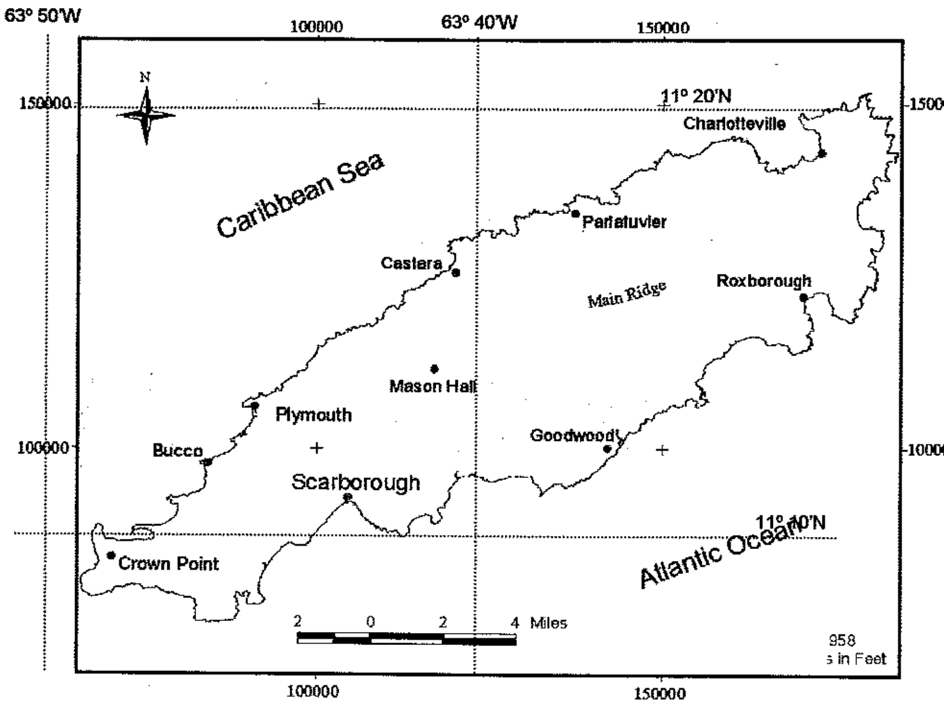

Figure 1: *Study Area, the island of Tobago*

3. Methodology

This paper is based on advancing a deductive approach for studying landslides founded on the concept that *conditions at known landslide sites within an area are reliable indicators of where future slope failures might occur* (Baban and Sant (2004a).

The initial stage of determining the favourable factors influencing landslide occurrence was conducted via site visits to various areas affected by landslides. We have used the Trinidad and Tobago National Emergency Management Authority's Disaster Response Map (NEMA, 1994) was useful for facilitating landslide site selection. The field data collection included the spatial distribution of landslides, landslide types, slope characteristics, geology, soil and land use/cover) and where possible the trigger. The identified factors (or parameters) that affect landslide occurrence in the study area were slope, aspect, rainfall, and land use/cover (Baban and Sant, 2004a, 2004b).

3.1 Data collection and Development

Governmental and private institutions in Trinidad and Tobago were inventoried to ascertain the location of data sources for the factors identified as affecting landslide occurrence within the study area. Table 1 shows the relevant data layers available for the study area. These data sets formed the basis for developing the necessary data themes. In the case of maps, the source map was scanned, georeferenced and digitized to yield a GIS based data layer. Then topology was built and the attributes attached to the digitized feature using a relational database.

Some other data themes, such as slope and aspect were derived from available topographic maps at a scale of 1:10,000 scale on the Cassini Projection (Tobago Topographic Maps, 1962). Table 1. These were scanned georeferenced and digitized to yield secondary data themes of contours, coastline, rivers and watersheds. The contours, watersheds, coastline and rivers were used to generate a Triangulated Irregular Network (TIN) surface from which the slope and aspect data themes were generated within the GIS. The contours formed the input for elevation data while the themes of watersheds, rivers and coast were used as break-line features to improve the quality of the TIN surface (Baban and Sant 2004a). The slope and aspect themes were reclassified into ranges and attributes were nominally coded as shown in Table 2.

The absence of a recent land use map for Tobago necessitated the development of a provisional land use map. The non-availability of cloud free remotely sensed imagery for the study area at the time of analysis led to the development of this data theme from an alternative source. The 1:10,000 scale topographic maps (Tobago Topographic Maps, 1962) contained inherent land cover/use information, which was created from aerial photo interpretation of the source stereo imagery. These maps were scanned, georeferenced and the land cover/use features (e.g. vegetation types, urban areas and settlements) were digitized to develop a land cover/use inventory for Tobago at the time of the mapping. These features were then encoded with the relevant attribute and used to generate the provisional land use map for the study area within the GIS. The GIS was used to generate Thiessen polygons around each point feature digitized and similar coded Thiessen polygons were subsequently dissolved to yield coded land use polygons (Fig 2).

The development of a landslide inventory was based on a 1994 published NEMA Disaster and Response map for Tobago (NEMA, 1994) that indicated the location of landslide locations within the study area. To support this inventory, a field survey was conducted in May of 2002 to determine the location of recent landslides within the survey area. This survey utilized GPS, compass bearings and distance measurements from a GPS station, to quantify the location, orientation and planimetric extent of landslides. The landslide inventory was also supplemented by using orthorectified aerial photography to identify and measure landslide locations. These three data sources formed the basis for the landslide inventory data theme developed in this analysis (Figure 3). The field inventory incorporated all landslide types (debris flows, shallow slides and rock falls).

Table 1: *Summary of available data sets, sources and scales for landslide analysis*

DATA SET	SOURCE	MAP SCALE	DATA TYPE
Geology	Tobago Geology Map (1997). By W.A. Snoke and Colleagues. Ministry of Energy and Mines, Government of the Republic of Trinidad and Tobago.	1:100,000	Polygons & Lines
Soils	Tobago – Soils (1974), Compiled jointly by Land Capability Survey, Ministry of Agriculture and U.W.I. Published by the Lands and Surveys Division, Ministry of Agriculture, Lands and Marine Resources, Government of the Republic of Trinidad and Tobago.	1:25,000	Polygons
Rainfall	Rainfall Map (1990). Water and Sewerage Authority, Water Resources Agency.	Unknown	Polygons
Land Use	Tobago Topographic Map series (1962)	1:25,000	Polygons
Slope & Aspect	Digital Terrain Model, University of the West Indies.	Not Applicable	Polygons
Landslide Inventory	NEMA (1994) Disaster and Preparedness Map, Prepared by NEMA & Lands and Surveys Division, Ministry of Agriculture, Lands and Marine Resources, Government of the Republic of Trinidad and Tobago.; Field surveys (April 2004); and remotely sensed ortho imagery (1994).	1:75,000	Polygons

Table 2: *Reclassification of Slope and Aspect Themes*

Slope Angle Range	Slope Code	Aspect Angel Range	Aspect Code
0° - 10°	1	Flat	0
10° - 20°	2	315° - 45° (North)	1
20° - 30°	3	45° - 135° (East)	2
30° - 40°	4	135° - 225° (South)	3
40° - 50°	5	225° - 315° (West)	4
50° - 60°	6		
60° - 70°	7		
70° - 80°	8		
80° - 90°	9		

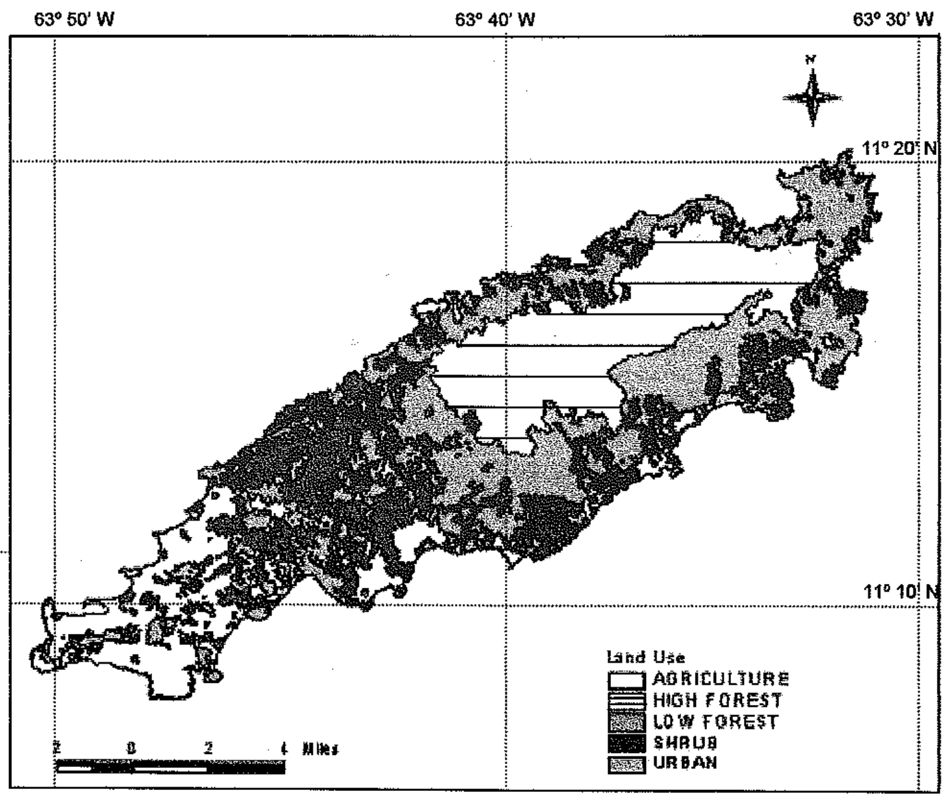

Figure 2: *Provisional Land Use/Cover map derived from 1962 Topographic Map Series at 1:25,000 scale*

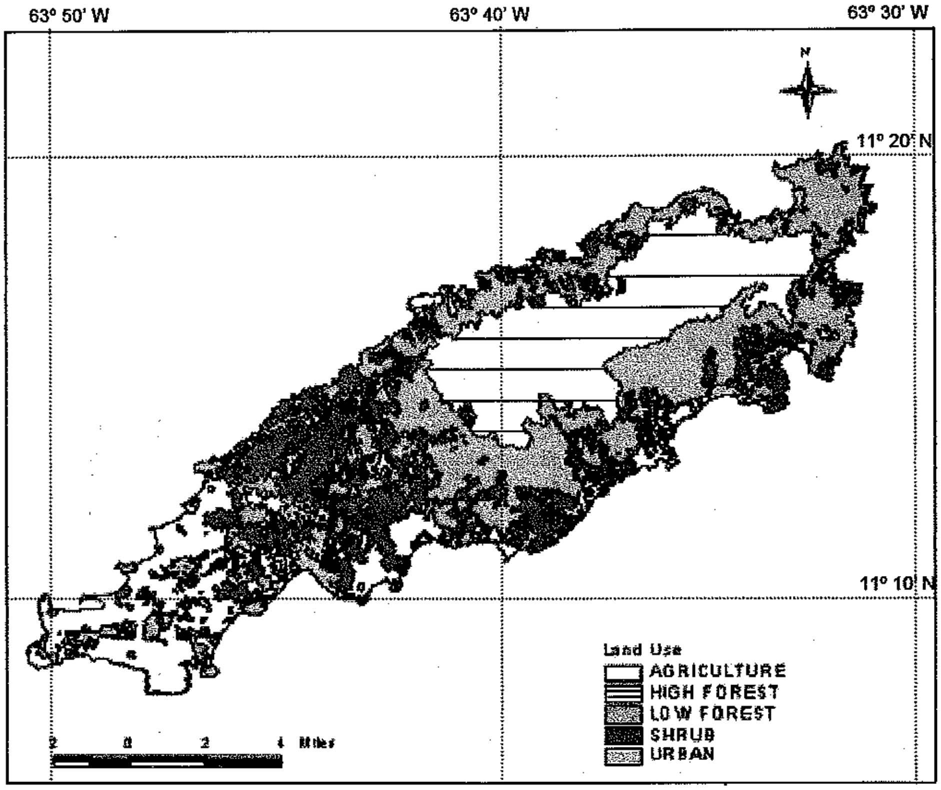

Figure 3: *Developed landslide inventory map for Tobago (after Baban and Sant, 2004a)*

3.2. Data Analysis

A multi-factor layer combination sequence was used to effect the identification of critical slopes in the study area (Figure 4) within a vector GIS environment. The landslide inventory was used to extract the specific range of conditions at known landslide sites for each identified data theme/factor that could influence landslide occurrence. Extracted landslide prone conditions for each condition theme were then combined to determine the exact combination of conditions and the range for each condition that existed at known landslide sites (Table 3).

This process facilitated the determination of the unique combination of the landslide prone conditions. Thus the spatial distribution of landslide prone conditions could be determined by assigning a binary value to each individual polygon in each factor data theme. Binary values of either 1 or 0 were attached to each polygon of respective data themes to indicate either the presence or absence respectively of a landslide prone condition.

The combination of the six data themes classified into landslide prone and non-prone conditions through an overlay process resulted in a summary data theme reflecting the relative distribution of conditions. Only polygons with a sum of six (i.e. where all six conditions were found at landslide sites) were considered critical slopes (Figures 4, 5).

Table 3: *Prevalent parametric conditions at landslide locations*

Parameter Theme	Significant attribute occurrence
Soil (Tobago – Soils (1974))	Soil types – Bloody Bay clay loam (71), Hope clay (43), Concordia sandy clay loam (61), and Concordia sandy clay loam eroded phase (63)
Rainfall	1800, 2000, 1200, 1600 and 2200 mm
Land Use (Tobago Topographic Maps (1962))	Low forest, High forest and Shrub
Geology (Tobago Geology Map (1997))	Parlatuvier Formation (16), Diorite – Gabbro (6) and Unidentified Volcanic and Sedimentary Rocks (17)
Slope	Ranges 20°-30°, 0°-10°, 10°-20° and 30°-40°
Aspect	All classes with an approximately even occurrence

Note: Soil data developed from Tobago – Soils (1974); Geology developed from Tobago Geology Map (1997) DTM and land use/cover developed from Tobago Topographic Maps (1962)

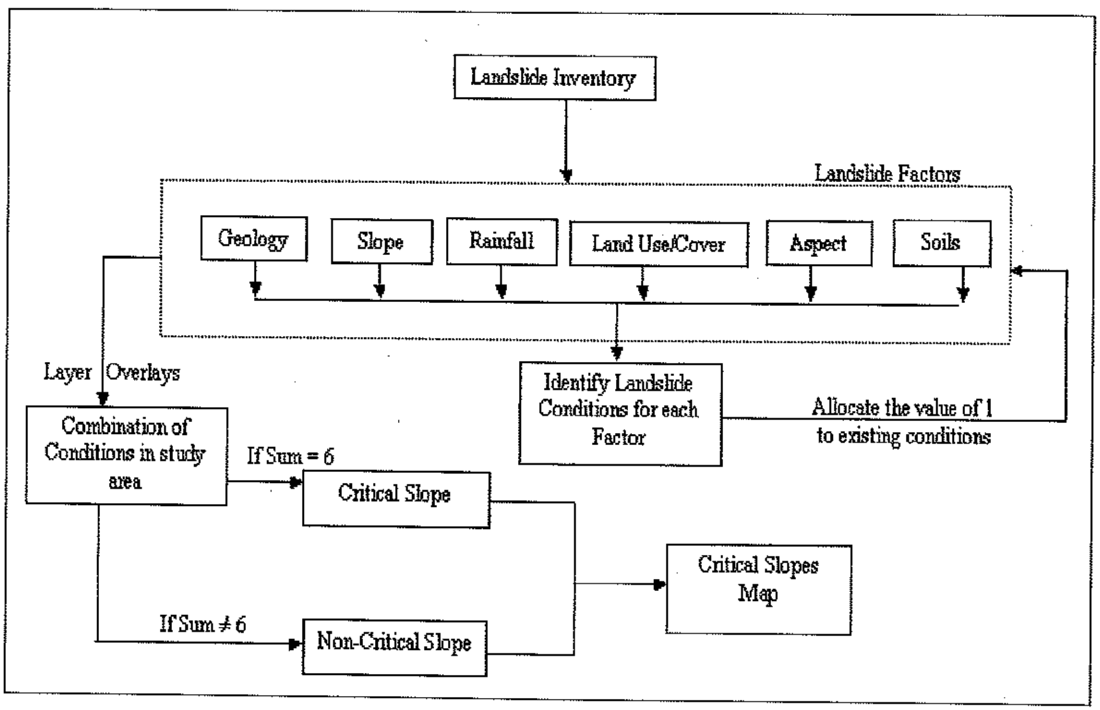

Figure 4: *The process for developing the critical slopes map for Tobago*

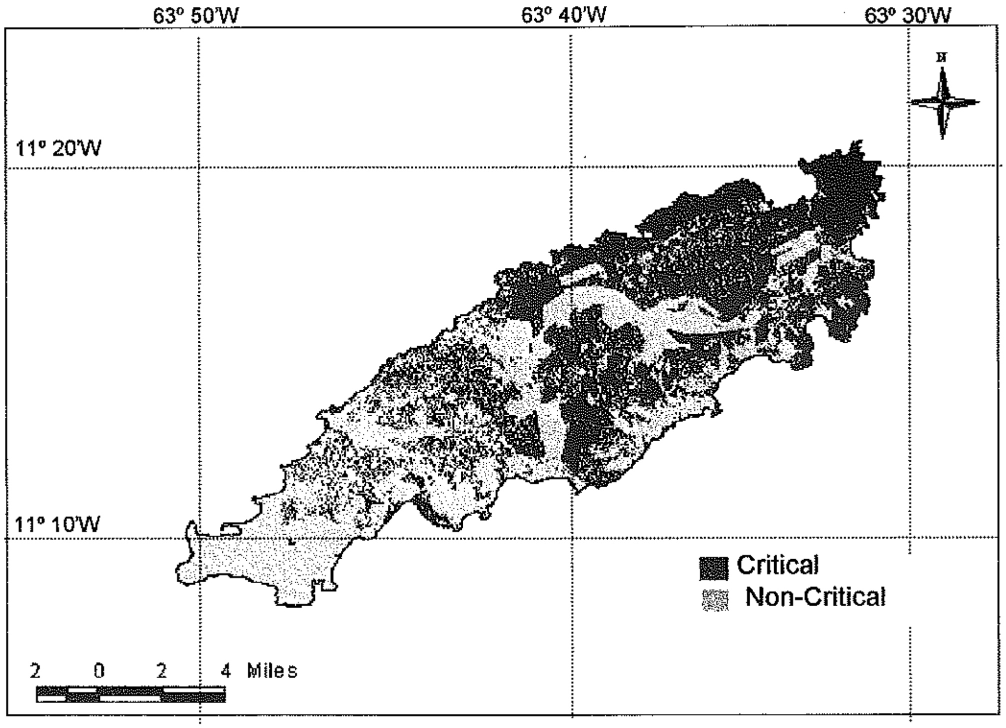

Figure 5: *Critical slopes to landslides in Tobago*

4. Results and Discussions

The developed landslide inventory located the spatial distribution and planimetric extent of 212 landslides, 51 of which were derived from the field surveyed landslide inventory and the ortho-imagery (Figure 3). The landslide inventory represented approximately 1.5% of the total land space of the study area.

The provisional land use theme was classified into five major land uses of agriculture (17.0%), high forest (22.5%), low forest (33.7%), shrub (18.0%) and umm (8.8%) (Figure 2). Each of the themes developed reflected the spatial distribution and quantification of the respective landslide parameters. The combination of these themes in the GIS, through an overlay process, yielded a theme representing distribution of combinations of factors for the entire study area. Additionally, landslide inventory polygon data theme provided the spatial distribution of landslide events within the study area.

By determining which combination of the parameters were present at known landslide sites a prediction of the location of potential landslides could be proposed by determining where similar combination of conditions were present within the study area. Landslide critical slopes showed a frequency of occurrence of some conditions above others within each of the parameter themes used in the analysis (Table 3).

The landslide critical slopes map (Figure 5) indicates that the southwest part of the island was devoid of critical slopes, and in moving from south towards the north east part of the island the frequency of critical slopes increased and became the prevalent slope type towards the north east of the island. There was a noticeable band of non-critical slopes across the Main Ridge area (middle) of the island and this was attributed to the spatial distribution patterns inherent within the rainfall and land use data themes.

The critical slopes map was compared to previous landslide susceptibility maps for Tobago that were developed using even and varied, weighted approaches (Baban and Sant, 2004a, 2004b). All three maps agreed well for the concentration of high landslide susceptibility in the north west facing slopes of the Main Ridge and a low susceptibility to the south west area of Tobago. The even weighted approach map agreed well with the critical slopes map for the central part of the island, but showed some differences (low susceptibility) with the varied weighted susceptibility map. This could be attributed to a combination of the variation in landslide factors used in the analyses as well as the difference in the spatial distribution and number of landslides within the developed inventories.

A landslide inventory map for Tobago has been prepared by combining published data, landslide mapping and remotely sensed imagery. A land use/cover map was developed based on a new approach of extracting land use/cover data from information inherent in topographic maps and engineered in a GIS environment.

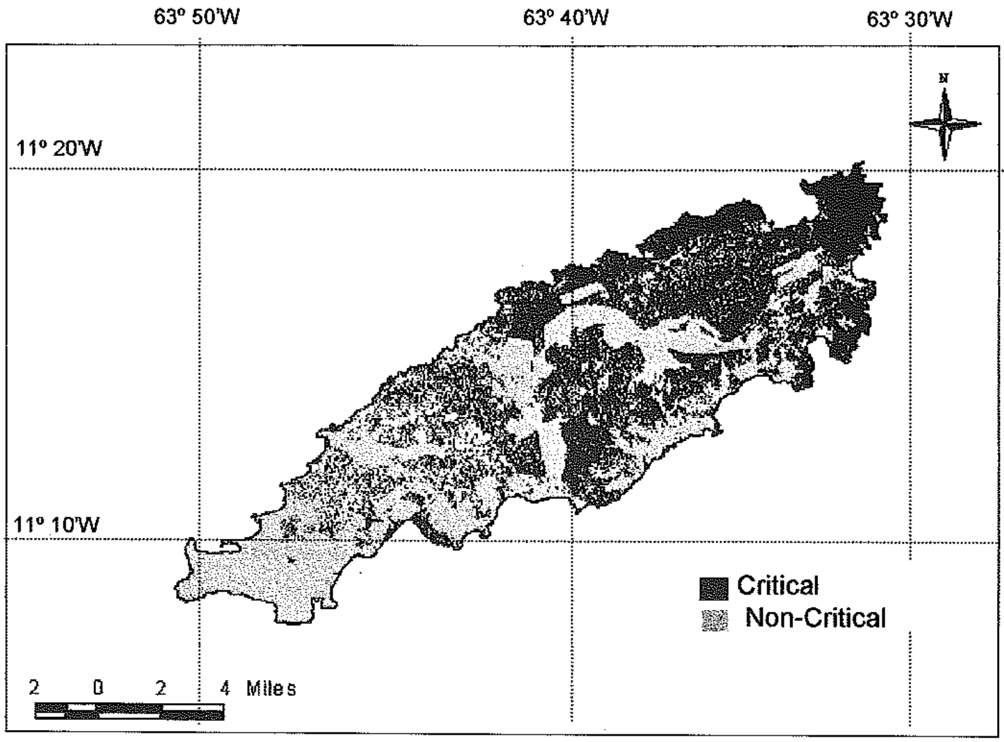

Figure 5: *Critical slopes to landslides in Tobago*

5. Conclusions

A methodology to discriminate landslide critical slopes was developed and presented. The methodology distinguishes between low, marginally and highly susceptible slopes to landslide occurrence by using the prevalence of landslide factors at known landslide sites.

The critical slopes map is in agreement with previous landslide susceptibility mapping for the study area (Baban and Sant, 2004a, 2004b). The frequency and spatial distribution of critical slopes classified in this analysis indicates that there exists a significant level of susceptibility to mass movements on the island of Tobago. Limited infrastructure and resource base makes it imperative that the new development projects, especially in the north east parts of the island and located on critical slopes identified herein, receive due consideration for slope movements.

The critical slopes map presented may be used for general planning purposes, formulation of disaster response and mitigation plans, and developing guidelines for landslide insurance.

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