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Mapping landslide susceptibility for the Caribbean island of Tobago using GIS, multi-criteria evaluation techniques with a varied weighted approach

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ABSTRACT. **A GIS based methodology for evaluating landslide susceptibility for the Caribbean island of Tobago using GIS, multi-criteria evaluation techniques with a varied weighted approach using Boolean overlay is presented. The degree of susceptibility was weighted based on the prevalence of the condition of aspect, geology and slope in terms of acreage. The outcomes are presented as low, medium, high and severe susceptibility of areas to landslides. The areas to the south and west of Tobago were of either low or medium susceptibility to landslides. The northeast facing slopes along the Main Ridge of Tobago were of severe susceptibility. The outcomes are compared to previous research using an even weighted approach on landslides. The largest difference occurred in the medium susceptibility range followed by the high, low and severe ranges. In both cases, the susceptibility increased from the southwest part of the island of Tobago towards the Main Ridge area and the north-eastern part of the island. The landslide susceptibility map produced is a valuable tool, providing a basis for conducting detailed site-specific investigation on areas with high and severe susceptibility to landslides, which already have or plan to have infrastructure development.**

1. INTRODUCTION

Landslides are a part of the natural erosive process, and occur naturally and as a result of man's interaction with the environment. Landslides result in loss of property, loss of opportunity and loss of life. Although not all landslides result in catastrophe, the damage from many small landslide events can add up and exceed the impact of a single major failure (OAS, 1991).

The absence of a national landslide inventory system has impeded the investigation of landslide susceptibility in many Caribbean Island States (Ahmad and Calpin, 1999; Baban and Sant, 2004). This in turn has had a negative influence in the formation of proper national planning policies and property insurance systems. In the worst case scenario, development has been permitted on slopes that may be prone to failure and that lack adequate slope stabilization work. In such a case, homeowners are made to shoulder a disproportionate level of insurance premiums that were based on averaged liability as opposed to the actual degree of landslide vulnerability that their properties may be subjected to.

Landslides occur as a result of a number of determining and triggering factors. Therefore, landslide susceptibility analysis will invariably require the identification and quantification of these factors (Varnes, 1978; Van Westen, 1993a). In practice, any single, or combination of, technique(s) may be employed for landslide hazard analysis and there is generally no accepted single technique that can be applied to all situations and environments. The selection of an appropriate landslide hazard modelling technique is therefore dependent upon the management scale, site-specific conditions and data availability (Carrara *et al*., 1999). In this context, the uses of Geographical Information Systems (GIS) in carrying out landslide susceptibility analyses are numerous in scientific literature (Carrara *et al*., 1991; Van Westen, 1993b, Van Westen *et al*., 2003; Sarkar and Kanungo, 2004).

This paper aims to develop and implement a GIS assisted method for landslide susceptibility analysis using a varied weighted method. The results will be compared with the outcomes from a previous landslide susceptibility map generated using an evenly weighted method.

2. APPROACHES TO LANDSLIDE HAZARD ANALYSIS

The assessment of landslide hazards requires the development of a landslide inventory (maps or tables) from a variety of sources including, direct field measurements/observations, remotely sensed data, historical records and existing disaster maps (Baban and Sant, 2004). This type of data is frequently conveyed to users in a map format.

Soeters and van Westen (1996) categorized the major approaches to landslide susceptibility analysis as follows:

i. Deterministic approaches. These are dependent on utilising numerical models for slope stability analysis at large scales. Furthermore, they require a large amount of detailed parametric data, such as geotechnical and groundwater condition as inputs. The outcomes from analyses are often detailed expressions of the hazard either in an absolute form or as engineering based safety factor for slopes. This approach does not seem to be well suited for regional analyses due to its requirements for large amounts of parametric data that are often unavailable and economically prohibitive to acquire.

ii. Statistical approaches. These are generally grouped into either bivariate or multivariate analyses. The combination of landslide conditions at known landslide sites is statistically analyzed using large amounts of data and predictions are generated for areas currently free of landslides. In this approach, past landslide conditions are utilized to provide an indication for forecasting potential landslide sites in the future. In most cases, this approach seems to be well suited to analysis at medium scales (1:25,000 to 1:50,000) due to the approaches adapted as well as the availability of required data sets.

iii. Heuristic or an expert driven approach. This approach requires a geomorphologist's input into determining the type and degree of hazard within an area either by direct mapping in the field or indirect mapping often based on utilizing remotely sensed data.

3. Role of GIS in Landslide Susceptibility

A Geographic Information System (GIS) may be defined as "A powerful set of tools for collecting, storing, retrieving at will, transforming and displaying spatial data from the real world for a particular set of purposes" (Boroughs, 1986). Therefore, GIS is well suited for the systematic estimations leading to slope stability evaluation and landslide hazard mapping by handling and analyzing various associated spatial data sets (Boroughs and McDonald, 1998; Baban and Sant, 2004). The GIS allows for the storage and manipulation of information concerning the different terrain factors as distinct data layers and thus provides excellent tools for slope instability zonation. Further, a GIS contains effective tools for examining spatial variability.

The main advantages of using a GIS in assessing landslide hazard include:

• Improving the hazard occurrence model in slope stability analysis by varying the input parameters and evaluating the results in an iterative process of trial and error.

• Rapidly updating input maps derived from field observations in the course of a landslide hazard assessment project. Upon completion of the project the final data (digital) can be used by others in an effective manner.

• Improving modelling outputs by evaluating their results and varying the input variables to achieve an optimum result by a process of trial and error, running the model several times, where as it is difficult to run a model even once in conventional techniques.

• Making hazard analysis techniques attainable by providing means for, as well as combining spatial and temporal analysis and the speed of computations.

The main disadvantages of using a GIS in assessing landslide hazards are:

• A large amount of time is needed for data entry, when data is not available in a digital format, scanning and digitizing existing of maps is especially time consuming and costly.

• There is a danger of placing too much emphasis on data analysis at the expense of data collection and manipulation based on professional experience. GIS contains large numbers of theoretical techniques that can be used for assessing landslides, but often the required data are missing (i.e., although the tools are there the required data is not). This creates a temptation to place unrealistic emphasis on the usage of various data analysis algorithms.

4. The Study Area

The island of Tobago lies at Latitude 11ºN and Longitude 60ºW. It is approximately 41.5 km long, 12 km wide at its centre and has an area of approximately 292 km^2. The island forms part of the Republic of Trinidad and Tobago and is located 32 km northeast of the island of Trinidad.

As the most easterly island of the Lesser Antilles, Tobago is more closely related geologically to South America than the other islands (DeGraff *et al*., 1989). The island has a ridge of Cretaceous metamorphic rocks passing through the central part along the Main Ridge. The Main Ridge is oriented E-NE–W-SW and has steep abrupt slopes frequently intersected by small streams. Diorite, ultramafics and basic extrusive rocks crop out to the south and southeast of the Main Ridge. Tertiary and Quaternary coral limestones and interbedded marls and clays form a series of low terraces in the southwest part of the island (Snoke *et al*., 1998).

In general, the northern side of the Main Ridge is steeper than the southern side. Almost 80% of the island exceeds 150 m in elevation. The northern and central parts of Tobago are mountainous in comparison to the southern portion. Furthermore, the lowest 'plain' area is located on the south-western side

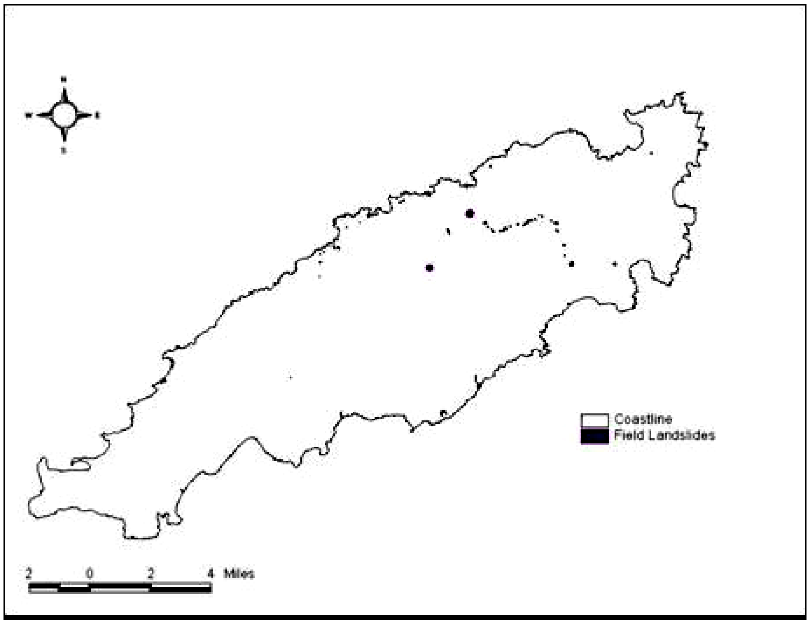

Figure 1. Landslide inventory theme developed from field surveys and RS imagery

of the island. This south western area is also the most urbanized (Baban and Sant, 2004).

Much of the interior of the island of Tobago is undeveloped due to the rugged terrain. This area remains in natural forest and much of the Main Ridge is a State Forest Reserve. The last officially published land use map for Tobago was in the 1970's (Brown *et al*., 1965) and is no longer current with the existing levels of land use. Agricultural and residential developments have in the main been limited to a narrow coastal belt and tourism has been intensively developed in the southwest third of the island.

Rapid economic/physical development within the past three decades has led to increased human activity in areas that were previously considered pristine. The increased demand for land has resulted in illegal development of spot squatting in mountainous and hilly areas that are predominantly State owned (Driver, 2002). Increased real estate development has caused a construction boom in Tobago, resulting in increased infrastructure and general development works. The development of sites for residential, tourism and agricultural purposes has fuelled the clearing and construction of roads around the island. This increased construction on slopes has altered the natural state of the environment thereby contributing to increases in the level of deforestation and potential increased rates of landslide occurrence (Baban and Sant, 2004). Available estimates indicate an average annual landslide damage cost to Trinidad and Tobago of US$1.5 Million (or TT$9.45 million) over the period from 1982 to 1986 (DeGraff *et al*., 1989). No costing estimate was available for the island of Tobago. The upwards tend in spending indicates further increases in this level of expenditure. There was an absence of an official recording system for landslide events in Tobago. The Hazard and Response map published at a scale of 1:75,000 by National Emergency Management Authority in Trinidad was not used because the mapped landslides did not agree well in spatial extent and distribution with field visits to verify landslide locations. As a result only field surveyed landslides and those discerned from remotely sensed imagery were used to develop a landslide inventory (Fig. 1). The developed landslide inventory has since been entered and stored within the GIS database.

5. METHODOLOGY AND DATA DEVELOPMENT

Governmental and private institutions in Trinidad and Tobago were inventoried to ascertain the location of suitable data sources for data layer development. Table 1 includes the various GIS data layers developed for this study. A landslide inventory was developed using a combination of three data sources – (1) Field based GPS data and terrestrial surveys; (2) Digitizing landside events discernable from panchromatic 1994 Ortho-imagery of the island accessed at the Lands and Surveys Division of the Government of Trinidad and Tobago; and (3) Previous geotechnical report (Earth Systems, 1999). The landslide inventory comprised the full spectrum of landslide categories.

The need for slope and aspect data layers necessitated the development of a Terrain Surface Model (TIN). Several data layers are required for developing a surface model, these included digital contours, coastline, roads, watersheds and Trigonometric and Traverse Control Stations. These

Table 1: Developed GIS data layers for Tobago

GIS DATA LAYER	TYPE	COMMENT/USE
Contour Data Layer	Input	Generate TIN
Roads	Input	Landslide inventory
Rivers	Input	Hard breaklines in generating TIN
Coastline	Input	Hard clip polygon in generating TIN
Trigonometric and Control Stations	Input	TIN verification
TIN	Derived	Used for slope and aspect generation
Slope	Derived	From TIN and converted to polygons
Aspect	Derived	From TIN and converted to polygons
Field Survey Landslide Inventory	Input	From field surveys and ortho-imagery
Parametric Data Matrix	Derived	Merged from slope, aspect and geology intersects by watersheds
Landslide Conditions	Derived	From clip of parametric data matrix using landslide polygons
Landslide Condition Occurrence	Derived	From classification of parametric data matrix using Landslide Conditions (value of 1 or 2)
Landslide Susceptibility TIN	Derived	Generated surface of susceptibility from management grid centroids

data layers serve as boundary polygons, elevation data sources and points for testing the degree of representativeness of the Surface Model. The island of Tobago has been mapped in both the Cassini and UTM projection systems. However, detailed topographic mapping (1:10,000 scale, 25 foot contour interval) used in this study was only available on the Cassini system. As many of the GIS data layers were developed from published topographic maps, an imperial (feet) unit of measurement was adopted for this analysis. The derived data layers were digital datasets and are therefore scale-less.

The resulting contour data was used in conjunction with the watersheds, roads, coastline and river data layers (breakline features) to improve and generate a terrain surface model (TIN). The local trigonometric stations as well as traverse control stations were used to evaluate the degree of representativeness of the TIN to the actual ground surface. Once the TIN was validated, two grid layers of slope and aspect were generated. These grids were at a 100 foot by 100 foot pixel sized grid. This value ensured that no two landslides could exist within one grid cell.

In the development of required datasets, the topographic maps at 1:10,000 scale were scanned, georeferenced, digitized and elevation attributes attached. The necessary slope and aspect data layers for Tobago were developed as grid data layers covering a nominal size of 30.5 m by 30.5 m in extent. The geology data layer was digitized from a scanned geology map for Tobago developed by the Ministry of Energy and Energy Resources in 1997 (Snoke *et al*., 1998) and the relevant attributes attached to each polygon.

5.1. Multi-Criteria Evaluations

Constructing a 'suitability' map using weighted Boolean overlay requires converting the data layers into a binary digital map of 1/0 or 'yes'/'no' data. Then using Boolean operators (such as AND and OR) a final Boolean map of suitable locations is produced. In using a criteria combined with an AND operator, any single 'no' value in a criteria will result in a decision of 'unsuitable', while if an OR operator is used, any 'yes' value will result in a decision of 'suitable'. Therefore, the AND case is risk-averse whilst the OR case is very optimistic about suitability. These operators are invoked in vector GIS using Merge, Clip, Union and Intersect operators.

A weighted Boolean approach imposes a rather strict form of selection where only those satisfying all the conditions will progress to the next Boolean query. In practice, certain factors within a data theme may be of more significance than others and it is desirable to differentiate between the locations of possible landslide sites based on how they meet specific criteria of conditions (Jones, 1997). Accordingly, each condition within a data theme can be assigned a numerical weight based on the prevalence of the condition at landslide sites. A weighted overlay data theme combination would evaluate intersected regions by a weighted sum of the scores so that each resulting region was characterized by a score measuring its suitability to landslide occurrence.

The difficulty in assigning numeric weights lay in deciding on the appropriate weight for a condition within the data theme. The process may be subjective (based on expert inputs) or be impartial (based on the prevalence of the condition by frequency or extent of occurrence) or a matrix of pair-wise comparisons (Eastman *et al.*, 1993). The varied weighted approach adopted in this paper assigned numeric weights, varying from 0 to 1, to each condition within a data theme depending on the existence and prevalence (by acreage) of the condition at known landslide sites. Locations assigned a value of "0" meant that the

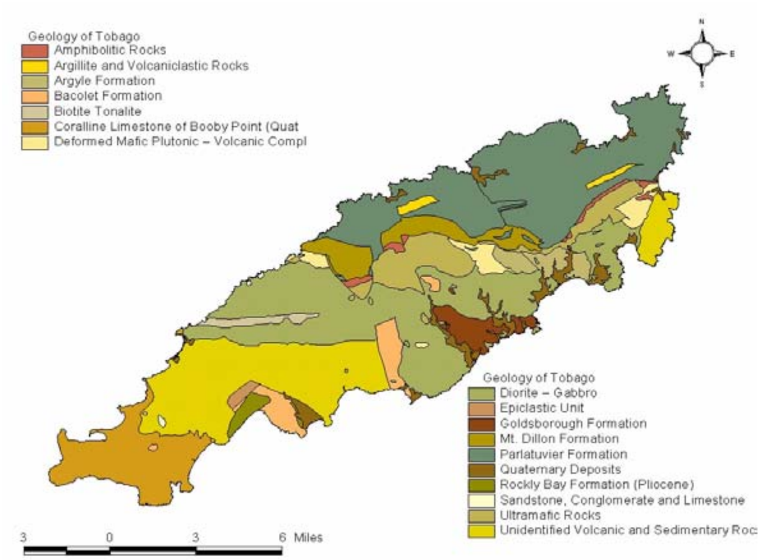

Figure 2. The Developed Geology Data Layer for Tobago (after Snoke *et al*., 1998).

particular condition combination did not occur at any of the known landslide sites. Whilst a weight of "1" meant that the combination of conditions did exist at a known landslide site.

5.2. Susceptibility Model Selection and Implementation

The Landslide Susceptibility Model developed by DeGraff and Romesburg (1980) may be classified as a hybrid between the statistical and heuristic approaches to landslide modelling. This method uses a matrix assessment approach to evaluate landslide susceptibility in a quantitative manner by combining parametric maps in a sequential manner utilizing a manual method. The basic assumption is that slope failure in the future will be most likely to occur under the conditions that led to past and present slope movements (Varnes, 1984). Although this method does not predict susceptibility in terms of probability and periods of occurrence, it allows relative potential susceptibility to be evaluated over large areas using three measurable attributes. These attributes are bedrock, slope and aspect and are assumed to reflect the five basic landslide conditions outlined by Varnes (1996).

1) The bedrock layer incorporates the lithologic conditions that favour landslides

2) Similarly, the bedrock layer also incorporates the stratigraphic conditions.

3) The slope layer inclination is normally classed into 5-10% bands and satisfies the basic landslide topographic condition.

4) The aspect layer is the compass direction of the slope face expressed in azimuth degrees and allows for the incorporation of the organic conditions. The organic condition incorporates the climatic factors such as rainfall distribution and slope drying characteristics on slopes.

5) The structural conditions are the bedding planes, fault planes and similar factors that influence sliding.

Through the Matrix Assessment Approach, potential landslide susceptibility can be determined by comparing the conditions involved in existing landslides to the conditions existing throughout the area of interest (DeGraff and Romesburg, 1980). In this study, the five determined landslide causal factors were accommodated within the analysis by utilizing the three parametric conditions of Slope, Aspect and Geology (Varnes, 1978), and the approach was also modified to facilitate incorporation within a vector GIS.

The classification for the slope, geology and aspect data layers are represented in tables 2a-c. The Slope layer was classified into nine equal ranges of 10º slopes each. The corresponding acreage for each slope class and weights were computed (Table 2a). The Geology layer comprised of seventeen (17) classes of geological formations within the study area (Fig. 2). The Aspect data layer was separated into five ranges, one flat and four representing the cardinal points of the compass. The island of Tobago is within the tropics and has a small azimuth variation of the sun year round. Further subdivision of aspect to reflect mid-cardinal directions would only serve to unnecessarily complicate the classification of the aspect theme. Therefore, four classes for aspect based on the cardinal directions of the compass were used.

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Table 2a. Computed weights for slope data layer

Slope Range (10º Class)	Slope Value	Acreage (Acres)	Proportional Acreage (PA)	Landslide Weighted Value (PA x 100)
0 -10	1	1,240,164.3	0.211	21.1
10 -20	2	820,750.0	0.139	13.9
20 - 30	3	1,629,275.9	0.277	27.7
30 - 40	4	1,241,464.9	0.211	21.1
40 - 50	5	603,465.5	0.103	10.3
50 - 60	6	290,900.7	0.049	4.9
60 - 70	7	48,686.6	0.008	0.8
70 - 80	8	10,000.0	0.002	0.2
80 - 90	9	0.0	0.000	0.0
	Totals	**5,884,707.9**	**1.000**	**100.0**

Table 2b. Computed weights for geology data layer (Snoke *et al.* 1988)

Geology Range	Geology Value	Acreage (Acres)	Proportional Acreage (PA)	Landslide Weighted Value (PA x 100)
Quaternary Deposits	1	27,984.492	0.005	0.5
Coralline Limestone of Booby Point (Quaternary)	2	0.000	0.000	0.0
Sandstone, Conglomerate and Limestone of Montgomery (Pleistocene –Pliocene)	3	0.000	0.000	0.0
Rockly Bay Formation (Pliocene)	4	161,418.997	0.027	2.7
Biotite Tonalite	5	0.000	0.000	0.0
Diorite – Gabbro	6	664,941.226	0.113	11.3
Ultramafic Rocks	7	1,162,592.730	0.198	19.8
Deformed Mafic Plutonic – Volcanic Complexes	8	3,942.075	0.001	0.1
Bacolet Formation	9	0.000	0.000	0.0
Epiclastic Unit	10	0.000	0.000	0.0
Goldsborough Formation	11	0.000	0.000	0.0
Argyle Formation	12	49,384.223	0.008	0.8
Amphibolitic Rocks	13	0.000	0.000	0.0
Mt. Dillon Formation	14	19,816.841	0.003	0.3
Argillite and Volcaniclastic Rocks	15	0.000	0.000	0.0
Parlatuvier Formation	16	3,784,952.008	0.643	64.3
Unidentified Volcanic and Sedimentary Rocks	17	9,675.327	0.002	0.2
	Totals	**5,884,707.92**	**1.000**	**100.0**

Table 2c. Computed weights for aspect data layer

Aspect Range (Compass Bearings)	Aspect Value	Acreage (Acres)	Proportional Acreage (PA)	Weighted Value (PA x 100)
Flat	-1	915,011.988	0.155	15.5
315º - 45º	1	1,469,011.640	0.250	25.0
45º - 135º	2	1,735,986.386	0.295	29.5
135º - 225º	3	917,459.361	0.156	15.6
225º - 315º	4	847,238.544	0.144	14.4
	Totals	**5,884,707.92**	**1.000**	**100.0**

this study, the five determined landslide causal factors were accommodated within the analysis by utilizing the three parametric conditions of Slope, Aspect and Geology (Varnes, 1978), and the approach was also modified to facilitate incorporation within a vector GIS.

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Table 3 – Reclassification of susceptibility and assignment of rating

Value Range	Reclass Value	% of Total Acreage	Number of Polygons	Rating
0.00 – 13.78	1	35.1	2148	Low
13.78 – 27.25	1			
27.25 – 40.71	2	41.9	1208	Medium
40.71 – 54.18	2			
54.18 – 67.64	3	16.6	5700	High
67.64 – 81.11	3			
81.11 – 94.57	4	6.4	11	Severe
94.57 – 108.04	4			
108.04 – 121.51	4			

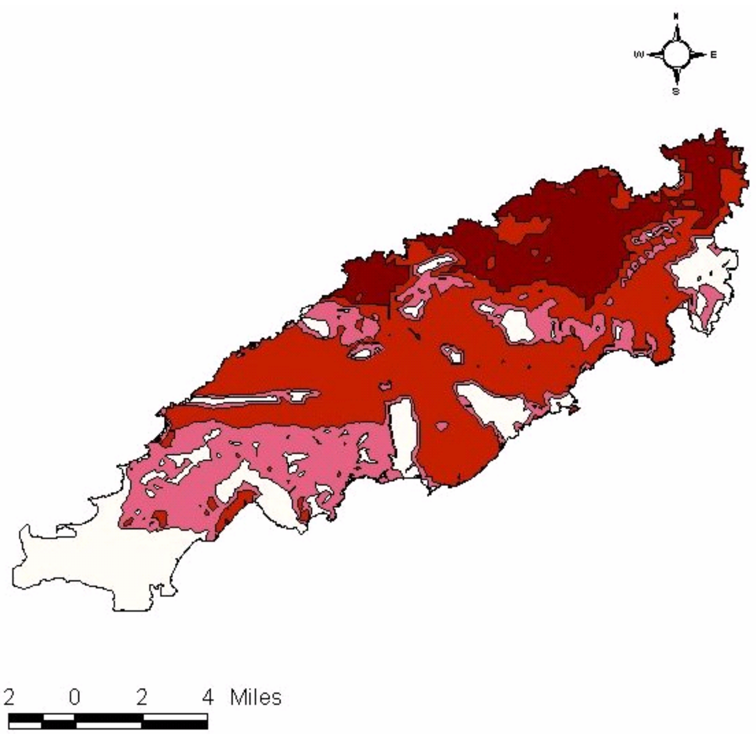

Figure 3. Landslide Susceptibility in Tobago using the Evenly Weighted Method (Baban and Sant, 2004)

and has a small azimuth variation of the sun year round. Further subdivision of aspect to reflect mid-cardinal directions would only serve to unnecessarily complicate the classification of the aspect theme. Therefore, four classes for aspect based on the cardinal directions of the compass were used.

Sorting the landslide conditions within the MS Access database yielded a total of 833 unique combinations of landslide conditions of slope, aspect and geology. When the entire study area was classified into landslide conditions and non-landslide condition combinations it was found that landslide conditions accounted for a total acreage of 47,896.3 acres or 64.6% of the total study area.

The combination of the five conditions existing throughout the study area was determined by a map overlay process and effected within the GIS using a Boolean intersection function. The specific combination of conditions that existed at the known landslide sites was determined by clipping the parametric data layer using the landslide polygon data layer. The outcomes from this process were imported into a relational database program for additional manipulation and weighting computation. In other words, boundaries of existing landslides were used to extract information regarding all five conditions within these boundaries.

The approach used for the analysis was a varied weighted approach which assigned a weighting factor to areas that contained the same combination of parametric conditions (slope, geology and aspect) that existed at known landslide sites. The weighting was determined by the proportion of area occupied by each parametric condition in turn at known landslide sites. The process adopted was as follows:

• In the database, the total acreage of each landslide condition was totalled and the relative proportion by acreage computed (Tables 2a-c).

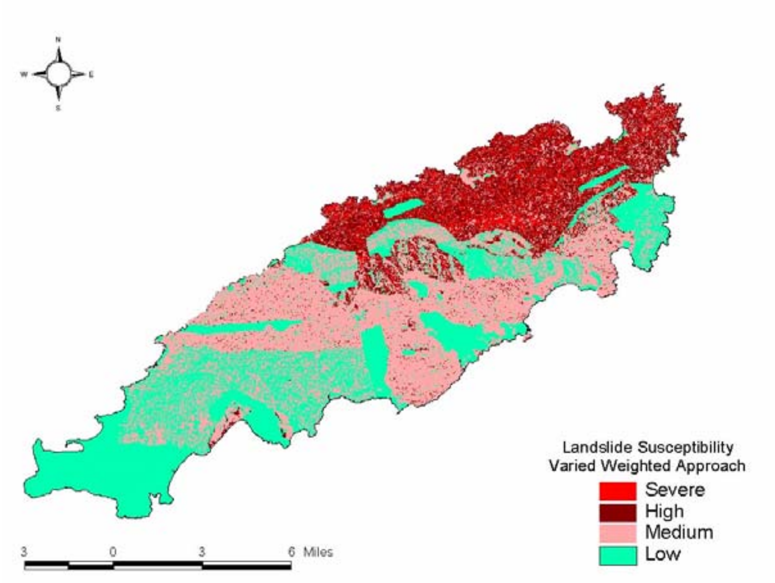

Figure 4. Landslide Susceptibility Distribution using a Varied Weighted Approach

• The proportion of acreage under each condition formed the basis for assignment of weights (as a percentage) and was applied using the formula:

Weighted Value of condition = Proportional Acreage of condition X 100

• The computed weights were assigned to each respective condition of Slope, Aspect and Geology and a total weight (sum of each of the three condition weights) computed for the combination of conditions for each polygon that constituted the study area.
• The weights were assigned to the centroids of each polygon in the data layer and a surface of susceptibility to landslides generated.
• The values for the Surface of Susceptibility were then classified into one Standard Deviation bands (Table 3) and assigned a rating of Low, Medium, High and Severe Susceptibility (Fig. 3).

The outcomes were compared to a previous study using an even weighted approach in ESRI's Arc View 3.2 vector based GIS (Baban and Sant, 2004). The even weighted approach assumes that all combination of parameters (slope, geology and aspect) carried an equal weight, regardless of their frequency or extent of occurrence. In this approach the unique combinations of parameters at known landslide sites (comprising all landslide categories) were located within the entire study area. A value of '1' was assigned to areas that had the combination of conditions at known landslide sites, whilst a value of '0' was assigned to those areas that did not contain the combination of parametric conditions. The resulting data layer was then intersected with a management grid (1 km^2) and the Susceptibility Index was computed as the proportion of landslide condition area to the grid area and assigned to each polygon as a centroid point. Subsequently, a surface of susceptibility was generated from the centroid points and reclassified into four non-hierarchical classes of Low, Medium, High and Severe Susceptibility based on the standard deviation within the values of the Susceptibility Index computed (Fig. 4).

6. Results and Discussions

The even weighted approach yielded a classification of susceptibility over the study area. The Susceptibility Index was determined from the proportion of acreage within each Management Grid with landslide conditions, that is, Susceptibility Index = (Acreage with Landslide condition / Acreage of Grid). The Susceptibility Indices were assigned to each Grid's centroid and a surface of susceptibility was then generated. Finally, the Surface of Susceptibility was classified into four classes, based on the degree of difference between the attribute value (Susceptibility Index) and the mean of all of the values. The class break was set at one Standard Deviation with a mean value of 0.647 (Baban and Sant, 2004).

In the varied weighted approach, a total weight was computed from the sum of the three respective components for each polygon (Slope, Geology and Aspect) making up the study area. The total weights assigned to each respective polygon centroid were used to compute a surface of susceptibility. The surface was then reclassified using a one standard deviation criteria (Table 3). The mean of the total weights was 58.766 and the Standard Deviation was 13.446.

Figure 4 is a landslide susceptibility map for the study area using a weighted approach. Table 4 summarizes the differences between the Even Weighted Approach and the Varied Weighted Approach.

Table 4 – Summary of even and varied weighted susceptibility to landslide occurrence

Susceptibility Classification	Even Weighted		Varied Weighted		Difference in % Coverage
	% Coverage	Acreage (Ha)	% Coverage	Acreage (Ha)	
Low	19.6	63311.7	35.1	10592.3	+15..5
Medium	23.8	76749.0	41.9	12643.4	+18.1
High	39.7	127784.5	16.6	5003.8	-23.1
Severe	16.9	54390.7	6.4	1948.9	-10.5

The Landslidse Susceptibility Map zoned the study area into four areas of Low, Medium, High and Severe susceptibility to landslides. The areas to the south and west are generally either low or of medium susceptibility to landslides. The Northeast facing slopes along the Main Ridge of Tobago are zoned as being severely susceptible to landslides. Further, at the centre of the island, a zone of high susceptibility was noticeable. The disadvantage in the evenly weighted approach is that all combinations of landslide-prone conditions are treated evenly and errors in determining these conditions arising from the clipping process or positional errors in the digitizing of the source data are conceded in the analysis. The advantage of the weighted multi-criteria evaluation is that this approach facilitates minimizing the erroneous effects of modelling the landslide inventory, slope aspect and geology themes.

7. CONCLUSIONS

The myriad of conditions that influence landslide occurrence requires a multi-criteria approach to modeling landslides. Furthermore, as landslide conditions within one area will differ from those conditions in another, this factor will preclude the development of a general set of conditions that may be applied to all sites. This analysis is based on the premise that conditions at past landslide sites can provide a guide to those conditions that will exist at future sites. However, this approach does not attempt to provide a time period for when an event will occur in the future.

The landslide susceptibility zonation map for Tobago, based on all landslide types, produced as a result of this investigation was achieved using a Multiple Criteria Evaluation within a GIS. This evaluation was effected through a Boolean Map overlay process and the degree of susceptibility was weighted depending on the prevalence of the conditions of aspect, geology and slope in terms of physical extent. The result of this analysis in the form a landslide susceptibility map, is a valuable tool in providing a basis for site specific studies where more detailed investigation are warranted due to potential impacts on existing or planned infrastructure developments. Further, the development of this susceptibility map serves as a guide to planning policy formation for developers before development works are initiated.

The outcome when compared to a previously concluded research using an even weighted approach on landslides yielded differences between the acreage in the four susceptibility classes. The largest noticeable change occurred in the medium susceptibility range followed by the high susceptibility and then the low susceptibility ranges. The smallest change in susceptibility acreage occurred in the severe susceptibility range. In both the evenly and varied weighted cases, the susceptibility increased from the southwest part of the island of Tobago towards the Main Ridge area and the north-eastern part of the island. The weighted multi-criteria approach provided a level of refinement over the evenly weighted approach by minimizing the effects of misconstrued combinations of conditions due to modelling errors.

Given the finite and limited resources of the Trinidad and Tobago Government, this investigation can provide one of the useful inputs in development of new policies in respect of Disaster Management, Mitigation Works and overall Land Use allocation for future development.

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