Journal of Earth Sciences and Geotechnical Engineering, vol. 3, no. 1, 2013, 55-71
ISSN: 1792-9040 (print), 1792-9660 (online)
Scienpress Ltd, 2013

Soil Friction Angle as an Instability Factor in Landslide Susceptibility Modeling

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Abstract

Landslide susceptibility mapping and modeling is critical in the understanding and consequent management of land resources. A study was conducted to ascertain the effect of an intrinsic soil property on landslide susceptibility mapping. Soil friction angle was added as instability factor in the form of PFAS (Peak friction angle – Slope) and RFAS (Residual friction angle – slope). These novel parameters replaced two traditional parameter; lithology and slope. Results indicated that PFAS and RFAS were significant additions and increased the predictive capabilities of the model.

Keywords: Soil friction angle, susceptibility mapping, Trinidad soils.

1 Introduction

Landslides are considered to be one of the most hazardous natural disasters, resulting in continuous road obstruction, infrastructural damage, loss of agricultural land, loss of buildings and in some cases loss of lives (Nandi &Shakoor, 2006) [1.]. The cumulative damage caused by landslides is far more widespread and poses greater total financial loss than any other geological calamity (Schuster and Fleming, 1986) [2.].De Graff et al. (1989) [3.] indicated thatannually the estimated cost of repairing landslide damage to roads throughout the Caribbean amounts to 15 millionUS Dollars. They further estimated the annual cost of landslide investigation, repair, and maintenance for Trinidad and Tobago tobe 1.26 million and $0.96 million US dollars, respectively. Hazard and risk analysisof landslides, through identification of vulnerable areas, can significantly reduce both the economic and social impairment.

Landslide susceptibility mapping is a key component in the prediction and management of landslides. It depicts the likelihood of an occurrence based on local conditions. The accuracy of this approach depends on the amount and quality of available data, the

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selection of the appropriate methodology and modeling (Yalcin, 2008) [4]. Although researchers have employed different models and methods over the years, to date there is still no consensus as too which is most applicable (Vahidnia et. al 2009) [5]. Generally all methods can be classified intoqualitative and quantitative or direct and indirect (Vahidnia et. al, 2009) [5]. Qualitative methods are mostly subjective and descriptive in nature. Quantitative methods generate numerical estimates (probabilities) of the occurrence of landslides in any hazard zone. Direct methods consist of the geomorphological mapping of landslide hazard (Verstappen, 1983) [6]. whilstindirect methods involves a series of steps. Guzzetti et al. (1999) [7].outlined these steps and stated that these methods firstrequires the recognition and mapping of landslides over a study area or a subset of it (trainingarea.), identification and mapping of a group of physical factors which are directly or indirectly correlated with slope instability (instability factors), followed by estimation of the relative contributions of instability factors to slope failure/instability. Ercanoglu (2008) [8]. concluded that the current trend of landslide assessments favors the utilization of quantitative methods specifically, GIS based ones. The ability of GIS to combine information from a variety of sources is a useful tool in identifying the probable locations of landslides. GIS has been the major tool adopted by researchers to map susceptibility (Nagarajn et. al, 1998) [9].. It is a practical technique for spatial analysis of a multidimensional phenomenon, such as landslides (Carrara*et al.,* 1999[10].; van Westen*et al.,* 1999[11].; Lan*et al.,* 2004[12].).

Complimentary to the range of susceptibility mapping approaches numerous approaches have been applied in the analysis and modeling of landslide data to determine susceptible zones. Selection of appropriate analytical methods is also influencedby the scale of analysis, the availability of input data and the required details of the hazard map (Sarkaret al., 1995) [13]. Most methods integrate spatial distribution and slope instability factors.

Mantovaniet, al. (1996) [14] categorized the major approaches to landslide susceptibility analysis into three categories; deterministic, heuristic and statistical. Deterministic approaches utilize numerical models and produces detailed descriptions of hazards in either an absolute form or engineering based safety factor. This approach requires extensive data for individual slopes and are often most effective in mapping only small areas (Ayalew et al. 2004) [15]. The heuristic approach requires the researcher's input in determining the degree of hazard within an area. This takes the form of either direct mapping in the field or indirect mapping utilizing remotely sensed data. Statisticalmethods involve the use of either bivariate or multivariate analyses of landslide conditions at known landslide sites. This approach combines past landslide conditions and instability factors to predict areas of susceptibility. Guzzetti et al. (1999) [7].recommended statistical approaches to analyze the link between landslide instability factors and the distribution of landslides. Bivariate statistical analyses (BSA) involves comparing a landslide inventory map with maps of landslide influencing parameters in order to rank the corresponding classes according to their role in landslide formation. Ranking is normally carried out using landslide densities. This approach results in reasonably accurate outcomes as seen in the works of Marhaento (2006)) [16]. andMagliulo et al. (2008)) [17]. .

Despite the model or approach, the choice of instability factors plays a major role in the relative accuracy of the outcomes. Limited emphasis has been directed towards selection. The literature indicates that the most common instability factors are; lithological formation/parent material, tectonic features, slope angle, proximity to road networks, proximity to drainage network, landcover and rainfall distribution(Anbalagan, 1992[18].;Donati and Turrini, 2002[19].; Guzzetti et al., 1999[7].; and Zhou et al., 2002[20].). All of these factors are considered to be related to instability.However, there are additional contributors to instability that may be arguable more influential. Intrinsic soil properties such as apparent cohesion pore- pressure and soil friction angle, all of which are known to be highly influential on slope stability has not been included as instability factors. The use of these variables may be limited by high spatial and in some cases temporal variability.

Soil friction angle, unlike pore pressure and apparent cohesion, is not temporally variable and is a derivative of the measurement of soil shear strength. It is a measure of the ability of a unit of soil to withstand a shear stress. The angle measured between the normal force (confining stress) and the resultant force within the soil column that is attained when failure just occurs in response to a shearing stress (Coulomb, 1776)[21]. Peak soil friction angle refers to the initial angle attained from the initial shearing phase, while the residual friction angle refers to the angle obtained following the initial failure of the soil sample and is important in cases of reactivated landslides or areas that have undergone previous forms of mass movement (Skempton, 1964) [22]. Roopnarine et al., (2012) [23] emphasized the importance of soil friction angle as a component of mass movement and slope instability and classified the soils of Trinidad into friction angle categories for both peak and residual friction angle. This paper reports onthe inclusion of soil friction angle as an instability factorto investigate the effect of an inherent soil property on the accuracy of susceptibility mapping and modeling.

2 Methodology

Figure 1 illustrates the chronological series of activities that were employed in the development of the susceptibility model.

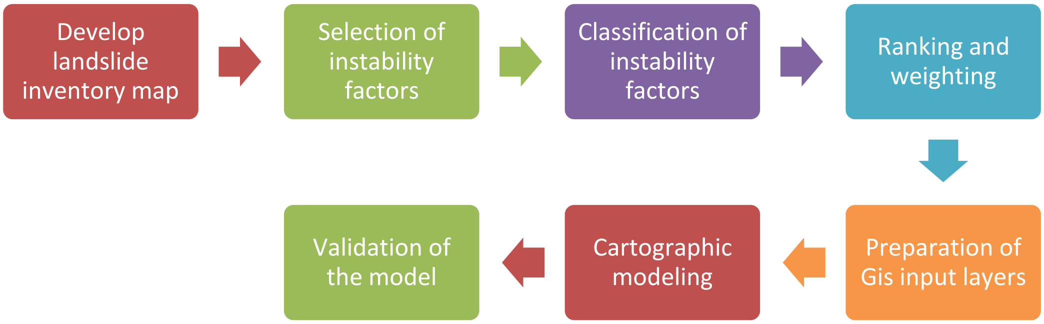


Figure 1: Sequence of activities involved in development of the landslides susceptibility model

2.1 Landslide Inventory Map

GPS coordinates of landslide occurrences as point data was sourced from the office of disaster preparedness and management (ODPM) of Trinidad and Tobago. The data did not reflect extent or dimensions of the landslide occurrences and was consequently digitized as a point layer. The resultant inventory map represented the spatial distribution of documented landslide occurrences but did not distinguish among landslide type. A total of one hundred points were used.Occurrence data was divided into two equal groups, by random selection of data points, using geostatistical analyst extension of ArcGIS 9.3. The first group was used to rationalize the weighting of the instabilityfactors (model development data) and the second group was used in model validation (model validation data) Figure 2 shows the landslide occurrences.

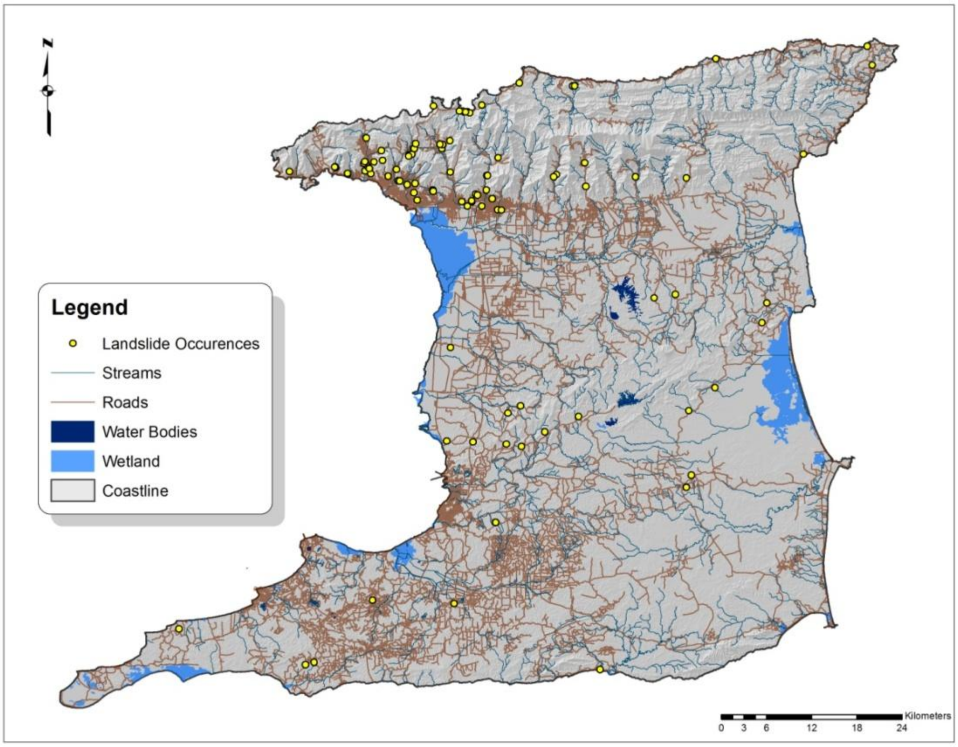


Figure 2: Landslide Occurrences

2.2 Selection of Instability Factors

Instability factors were chosen based on available data. Lithological formation, tectonic features, slope gradient, proximity to road network, drainage network, land use, and rainfall distribution were used consistent with Lan*et al., (*2004) [24]; Liu *et al., (*2004); [25] Guthrie & Evans, (2004)[26]; Ayalew&Yamagishi(2005) [27].; Duman*et al., (*2005) [28]; Moreiras, (2005) [29]; andRemondo*et al., (*2005)[30]. Two addition instability factors were included, which combinedslope and soil friction angle; peak friction angle minus slope (PFAS) and residual friction angle minus slope (RFAS).

2.3 Classification of Instability Factors

Table 1 shows the classifications for each instability factor, with corresponding susceptibility levels and rank.

Table 1: Classification of instability factors with susceptibility levels and ranking

Instability Factors	Classifications	Susceptibility Level	Rank
Lithological Formation	Formations		
	Alluvium, Navet, Palmiste	Very High	5
	Moruga, Lengua, Brasso, Manzanilla, Maracas, Galera, Cipero, Karamat	High	4
	Toco, Maraval, Rio Seco, Springvale, Nariva, Chaudiere, MorneL'Enfer, MudVolcanoesCones and Flows, San Fernando, Talparo, Concord, Cruse	Moderate	3
	Cedros, Diorite, Laventille, Guayamara, Tompire, Chancellor, Guayamara, Lopinot, Cushe, Cunapo, Gautier, Naparima, Lizard Springs, Chaudiere, Erin, Mayaro, GrosMorne	Low	2
	Sans Souci, Arima, Water, Pointe-a-Pierre	Very Low	1
Land Cover	Classes		
	Barren land	Very High	5
	Urban or built-up land	High	4
	Rangeland	Moderate	3
	Agricultural land	Low	2
	Forest land, Wetland, Water	Very Low	1
Instability Factors	Classifications	Susceptibility Level	Rank
Tectonic Features	Proximity (m)		
	0-100	Very High	5
	101-200	High	4
	201-400	Moderate	3
	401-500	Low	2
	501-600	Low	2
	> 600	Very Low	1
Slope Angle	Angles (degrees)		
	49 – 87	Very high	5
	28 – 48	High	4
	16 – 27	Moderate	3
	6 – 15	Very Low	2
	0 – 5	Low	1
Road Network	Proximity (m)		
	0-100m	Very high	5
	101-200m	High	4
	201-400m	Moderate	3
	401-600m	Low	2
	>600m	Very Low	1
Drainage Network	Proximity (m)		
	0-100m	Very high	5
	101-200m	High	4
	201-400m	Moderate	3
	401-700m	Low	2
	>700m	Very Low	1
Rainfall	Classes (mm)		
	207 – 225	Very High	5
	193 -206	High	4
	181 – 192	Moderate	3

Instability Factors	Classifications	Susceptibility Level	Rank
	167 – 180	Low	2
	143 -166	Very Low	1
Instability Factors	Classifications	Susceptibility Level	Rank
PFAS	Classes		
	< -5	Very High	5
	-5-10.7	High	4
	10.7-22.76	Moderate	3
	22.77-36.96	Low	2
	36.96-57.20	Very Low	1
RFAS	Classes		
	< -12	Very High	5
	-12.1-4.36	High	4
	4.37-14.6	Moderate	3
	14.7-37.95	Low	2
	37.96-45.9	Very Low	1

The lithological formations were classified based on their geotechnical characteristics - following Alger (1993)[31] modified from Kugler (1961)[32] and Cart- Brown and Frampton (1979) [33] The level of cohesiveness was based on the general lithological description of each formation in the study area. However, the susceptibility level was based on the cohesiveness and the nature of the material that exists for each formation. Tectonic features were classified based on the distance from tectonic features with increasing distance resulting in lower susceptibility levels. Classification was similar to that of Donati and Turrini, (2002) [19] and Zhu and Huang (2006) [34]

Slope angles were classified into various ranges as indicated in Table 1 where higher susceptibility levels were attributed to slopes with higher angles. Roadways were classified based on proximity with increasing distance receiving lower susceptibility levels. Drainage network was classified in similar fashion to tectonic features, with areas closer to rivers and streams considered more susceptible to landslides. Land cover was classified based on vegetation density with barren land being considered the most susceptible, similar to classification schemes used by Zhu and Haung(2006) [34].Rainfall was classified based on distribution where areas with greater amounts were assigned the higher susceptibility level. Classification of PFAS was based on the resultant value of rasterized analysis of Peak Friction angle-Slope, where the lower values were attributed greater susceptibility; the same was done for RFAS. The combination of the friction angles with slope is based on the relationship established in the Mohr Columb failure criterion, which indicates that soil friction angle is a component of shear strength such that:

$$\tau f = \sigma \tan\varphi + c \tag{1}$$

Where

Tf is the shear strength

σ is the applied normal stress

φ soil friction angle

c is apparent cohesion.

According to the aforementioned relationship, soils with greater friction angles will have greater shear strength. However instability/slope failure only occurs when shear strength is exceeded by shear stress. Thus it is impractical to classify instability zones based solely on soil friction angle, as there will be soils with low friction angles and relatively low shear strength but these may occur on shallow slopes and thus shear strength may not be exceeded. Similarly there may be soils on very steep slopes that possess very high friction angles, but depending on the steepness of the slope the shear strength may not be exceeded. PFAS and RFAS provide a simplistic relationship between two of the static properties of shear strength and shear stress. The slope angle for each polygon was subtracted from the friction angle value for the corresponding polygon. The resultant values were classified based on magnitude with higher values analogous to lower susceptibility.

2.4 Ranking and Weighting

A weighted factor modeling approach was used to determine the overall susceptibility index of each unit of land (Dai and Lee, 2002) [35].For application of the model, numerical values were assigned to each of the five susceptibility levels for each factor as follows: Very low=1, low=2, Moderate=3, High=4 and Very High=5.Weights were assigned to the instability factors based on the frequency distribution of the model development dataset of landslide occurrencesacross susceptibility levels of each instability factor. Factors with greater than 60% of the landslide occurrences falling in the moderate to very high susceptibility classes were given weights of 2. All other factors were given a weight of 1.

2.5 Preparation of GIS-Input Layers of Instability Factors

GIS vector layerswere prepared, classified, ranked, and converted into raster grids with 10 meter grid resolution. Figure 3 A-I shows the nine raster grids used in the analysis.

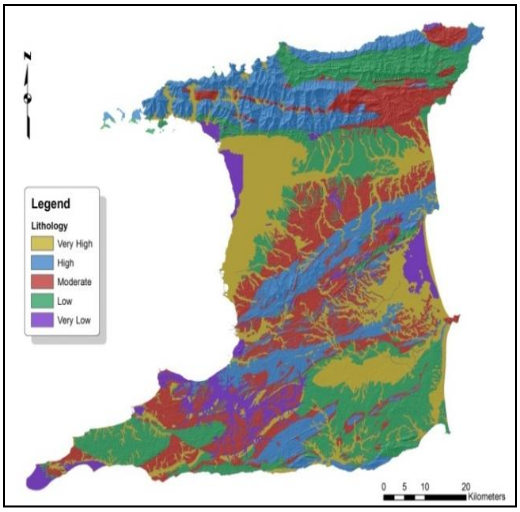


Figure 3- A

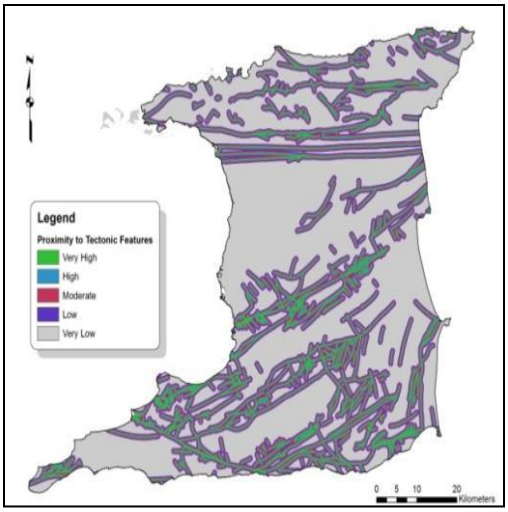


Figure 3-B

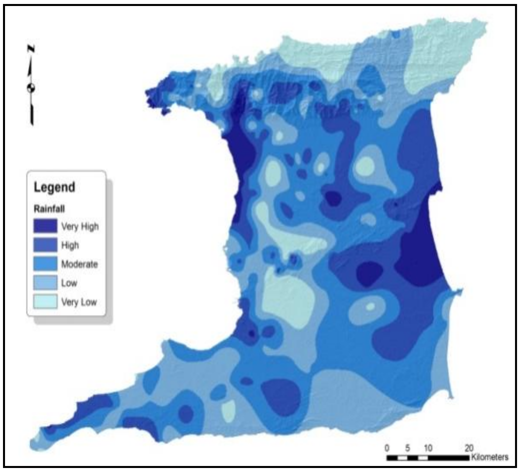


Figure 3- C

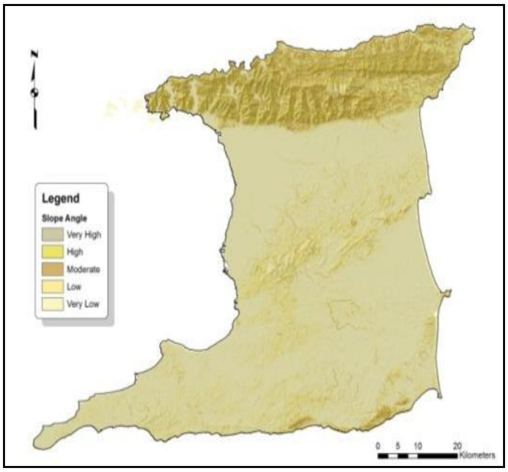


Figure 4-D

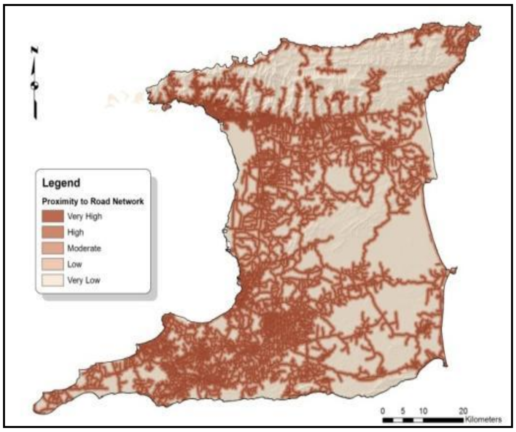


Figure 3-E

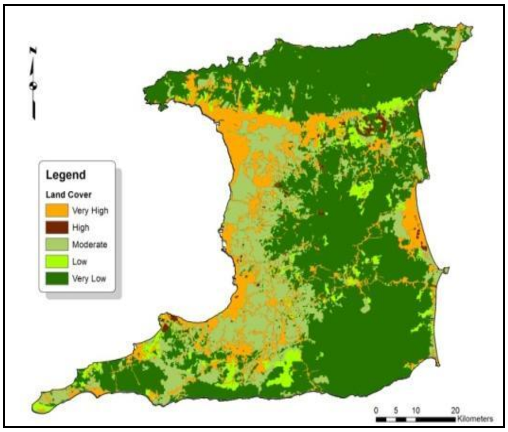


Figure 3-F

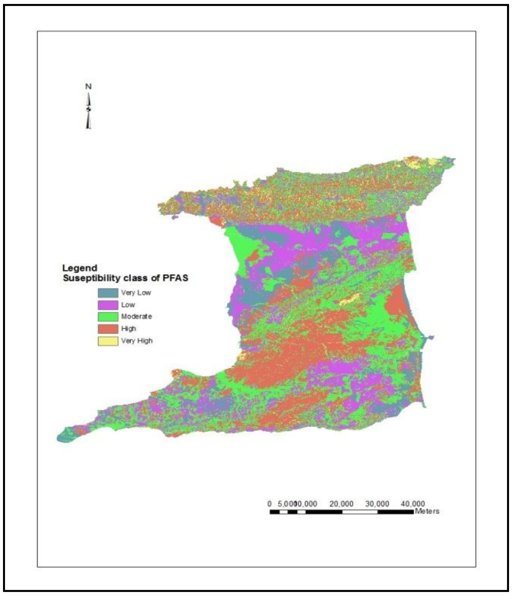


Figure 3-G

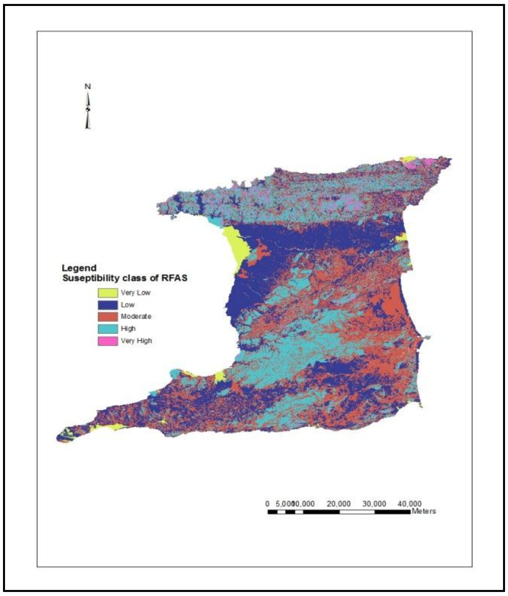


Figure 3-H

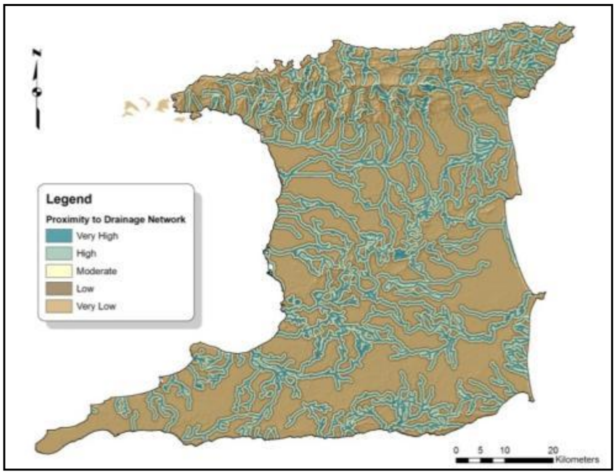


Figure 3-I

Figure 3 A-1: 9 input layers of instability factors; A- lithology, B-Tectonic activity, C-Rainfall, D-Slope, E- Road networks, F-Land cover, G- PFAS, H-RFAS, I-Drainage networks.

2.6 Cartographic Modeling

Using ArcGIS software, a cartographic model was developed for an additive weighted overlay of the input GIS layers. The model was run three times with different instability factors being used in each instance resulting in 3 outputs (scenario 1, 2 and 3) (Table 2). In each instance the overall susceptibility class was determined and classified into very low, low, moderate, high and very high susceptibility classes within Arc Gis 9.3 , using Jenks natural breaks, which determines the best arrangement of values into different classes by reducing the variance within classes and maximizing the variance between classes.

Table 2: Input factors used in the model for the three scenarios

Instability Factors	**Scenario 1**	**Scenario 2**	**Scenario 3**
Tectonic Features	Yes	yes	yes
Lithological Formation	Yes	yes	yes
Slope Angle	Yes	**Not included**	**Not included**
Land cover	Yes	yes	Yes
Drainage Network	Yes	yes	Yes
Road Network	Yes	yes	Yes
Rainfall	Yes	yes	Yes
PFAS	**Not Included**	yes	**Not included**
RFAS	**Not Included**	**Not included**	yes

2.7 Validation of the Landslide Susceptibility Model

The susceptibility maps were validated usingintersect analysis ofthe landslide occurrence validation data set and the landslide susceptibility classes resulting from each of the three scenarios. Intersect analysiscalculates the geometric intersection of any number of feature classes and feature layers. The features or portion of features that are common to (intersect) all inputs will be written to the output feature class.

3 Results and Discussion

Landslide occurrence frequency distributions across all instability factors indicated that the most influential factors were RFAS, PFAS and proximity to road network with more than 60% of the landslide occurrences falling in the moderate to high susceptibility classes, whilst the least influential were slope angle and proximity to tectonic activity with less than 25% (Figure 4). Accessibility and consequent sampling bias may account for the high correlation between proximity to road networks and landslide occurrences. PFAS and RFAS reflect the interaction between soil friction angle and slope angle and are therefore directly related to instability based on the Mohr failure criterion. Peak friction angle and residual friction angle are intrinsic soil properties directly related to stability and when combined with slope is theoretically a very good predictor of areas of instability (Roopnarine et al. 2012) [23]. Slope angle as an independent instability factor assumes that the steeper the slope the greater the potential for instability, however in most cases soils that populate steep slopes usually posses a particle size distribution dominated by larger particles such as gravel and sand as opposed to silt and clay for soils in lower elevation (Parkinson and Gellataly, 1991)[36]. In such cases high internal friction angles will exist leading to lower potential for slippage.

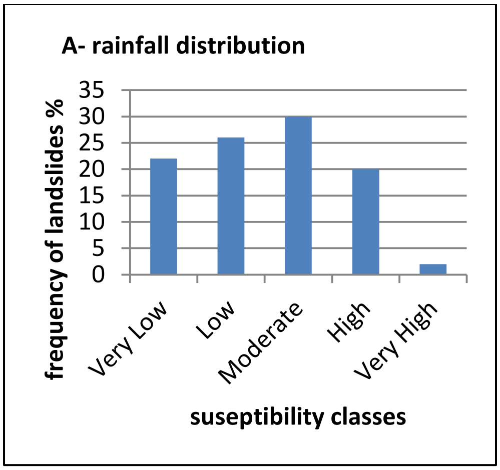
These high internal friction angles may not necessarily be superseded by the slope angle and hence if considered in isolation will not have a great potential for slippage. Similarly gentle slopes may have soils with very low internal friction angles which may be exceeded by the slope angle and hence have the potential to become unstable. Additionallyerosion is more prominent on steep slopes, which discourages the formation of deep profiles thus preventing large scale mass-movements such as landslides from occurring on these slopes. PFAS and RFAS can be considered more practical and precise instability factors, as it reflects the interaction between soil stability and slope angle as it pertains to instability. RFASoverestimates landslide susceptibility. It incorporates residual friction angle with slope which assumes that all the soils under consideration have undergone some previous form of mass movement. Residual friction angles are lower than peak friction angles for all soils thus there is a greater possibility that they will be exceeded by slope angles. Consequently it is expected that more areas will fall into higher susceptibility classes than with PFAS. The results did not indicate higher frequency of landslide occurrence in the moderate to high susceptibility classes; however landslide occurrence frequency distribution showed that there were no occurrences in the “very low” susceptibility class for RFAS while for PFAS contains 10%. This implies that the residual friction angles of soils due to previous mass-movement may be more pronounced in soils that have high peak friction angles than those with low peak friction angles. Tectonic features, although considered in most landslide susceptibility models, only has an effect if there is significant and frequent tectonic activity in respective study areas. Hence, proximity to tectonic features may not show any significant correlation with landslides and mass movement occurrences in cases where tectonic activity intensities are minimal and the occurrence infrequent.Based on the aforementioned results; proximity to road network, PFAS and RFAS were assigned weights of two (2).

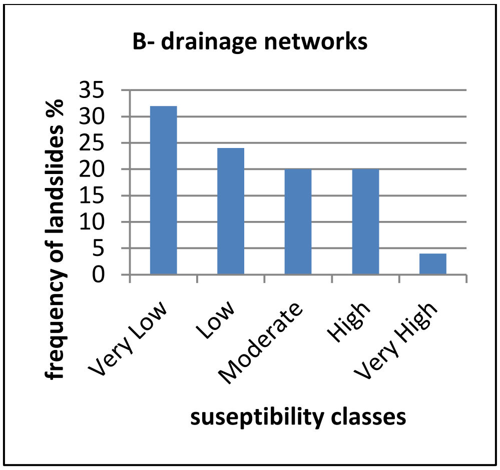
All other factors were given a weight of one (1) as frequency distribution resulted in less than 60% of landslide occurrences falling in the moderate to high susceptibility classes.

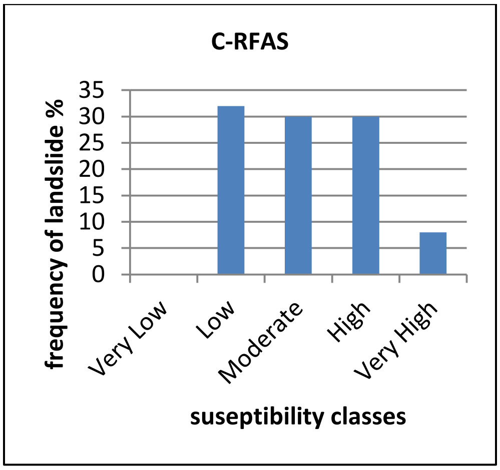
3.1 Landslide Susceptibility Model.

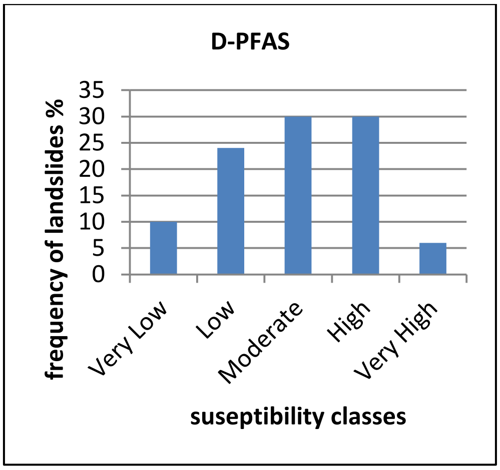
Table 3 shows the percentage landmass in each susceptibility class as well as the overall susceptibility class values. Figure 5 shows the frequency distribution of the model validation data set in the moderate to high susceptibility classes for each of the three scenarios. Differences in weighting of the factors resulted in dissimilar class values for scenario 1 when compared to scenarios 2 and 3. Class values were higher in the case of the scenarios 2 and 3 as two of the included factors were assigned weights of 2 (PFAS /RFAS and proximity to road network), whilst only one instability factor was assigned a weighting of 2 in scenario 1 (proximity to road network). Scenario one contained the largest % landmass in the moderate to high susceptibility classes with 60.9% whichmight be an overestimation as itassumes equal influencesacross instability factors and uses slope angle.Thus all area where slope angles are high will be considered susceptible to landslides. Scenarios 2 and 3 contained 54.7 and 55.2% respectively in the equivalent susceptibility classes. These scenarios incorporated soil friction angle and slope angle and as such not all areas with high slope angles were considered susceptible thus providinga more accurate representation of instability. This inference is supported by the frequency distributions of the model validation data set which indicates that scenarios 2 and 3 generated the best results, both containing 92% of landslide occurrences in the moderate to high susceptibility classes, whilst scenario 1 contained 88%. Scenario 1 did not include PFAS or RFAS which contributed to the lower percentage occurrence in the moderate to high susceptibility classes and emphasizes the significance of PFAS and RFAS as instability factors.

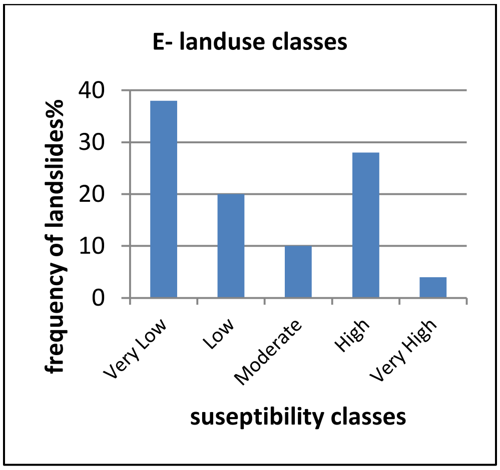
Overall results indicate that the use of an intrinsic soil property such as soil friction angle in the form of PFAS and RFAS provides improved predictive capabilities and enhances the accuracy of the landslide susceptibility model. In instances where comprehensive landslide inventory maps are available, PFAS and RFAS can be used in bivariate and logistic regression models which will allow for statistical quantification of its contribution to instability and lead to more precise and pragmatic landslide susceptibility models. A spatial representation of scenario 2 is shown in figure 6.

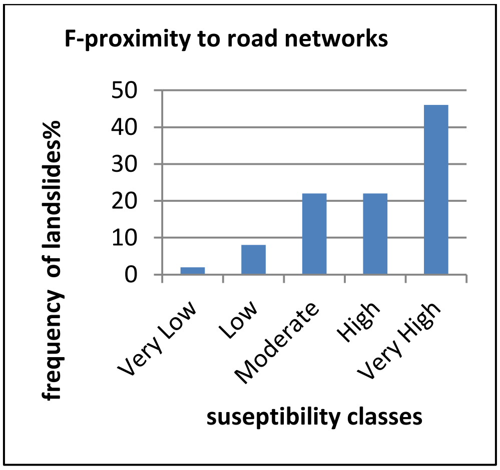

A- rainfall distribution
frequency of landslides %
35
30
25
20
15
10
5
0
Very Low
Low
Moderate
High
Very High
suseptibility classes


B- drainage networks
frequency of landslides %
35
30
25
20
15
10
5
0
Very Low
Low
Moderate
High
Very High
suseptibility classes


C-RFAS
frequency of landslide %
35
30
25
20
15
10
5
0
Very Low
Low
Moderate
High
Very High
suseptibility classes


D-PFAS
frequency of landslides %
35
30
25
20
15
10
5
0
Very Low
Low
Moderate
High
Very High
suseptibility classes


E- landuse classes
frequency of landslides%
40
30
20
10
0
Very Low
Low
Moderate
High
Very High
suseptibility classes


F-proximity to road networks
frequency of landslides%
50
40
30
20
10
0
Very Low
Low
Moderate
High
Very High
suseptibility classes

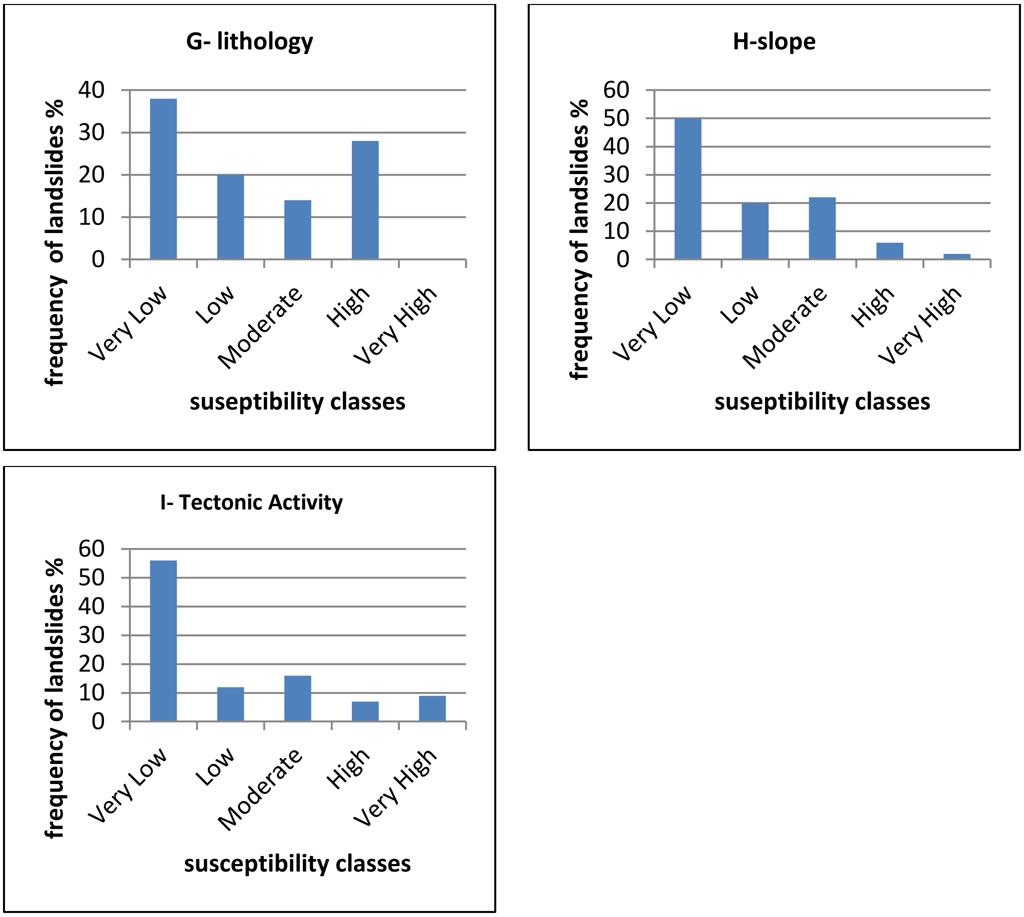


Figure: 4 Landslide occurrences across different susceptibility classes affected by Rainfall distribution (A), Proximity to drainage networks (B), RFAS (C), PFAS (D), Land use (E), Proximity to road networks (F), Lithology (G), Slope (H), Tectonic activity (I).

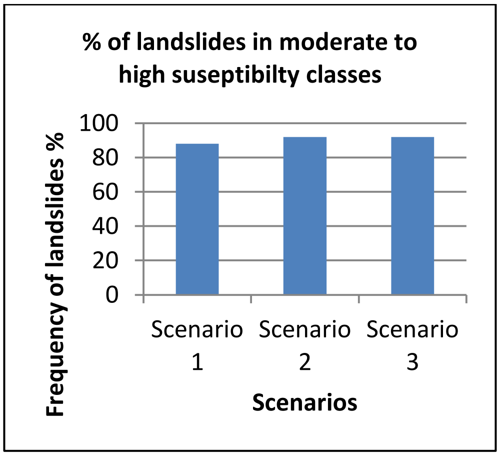


Figure 5: Distribution of landslide occurrences across the moderate to high susceptibility classes.

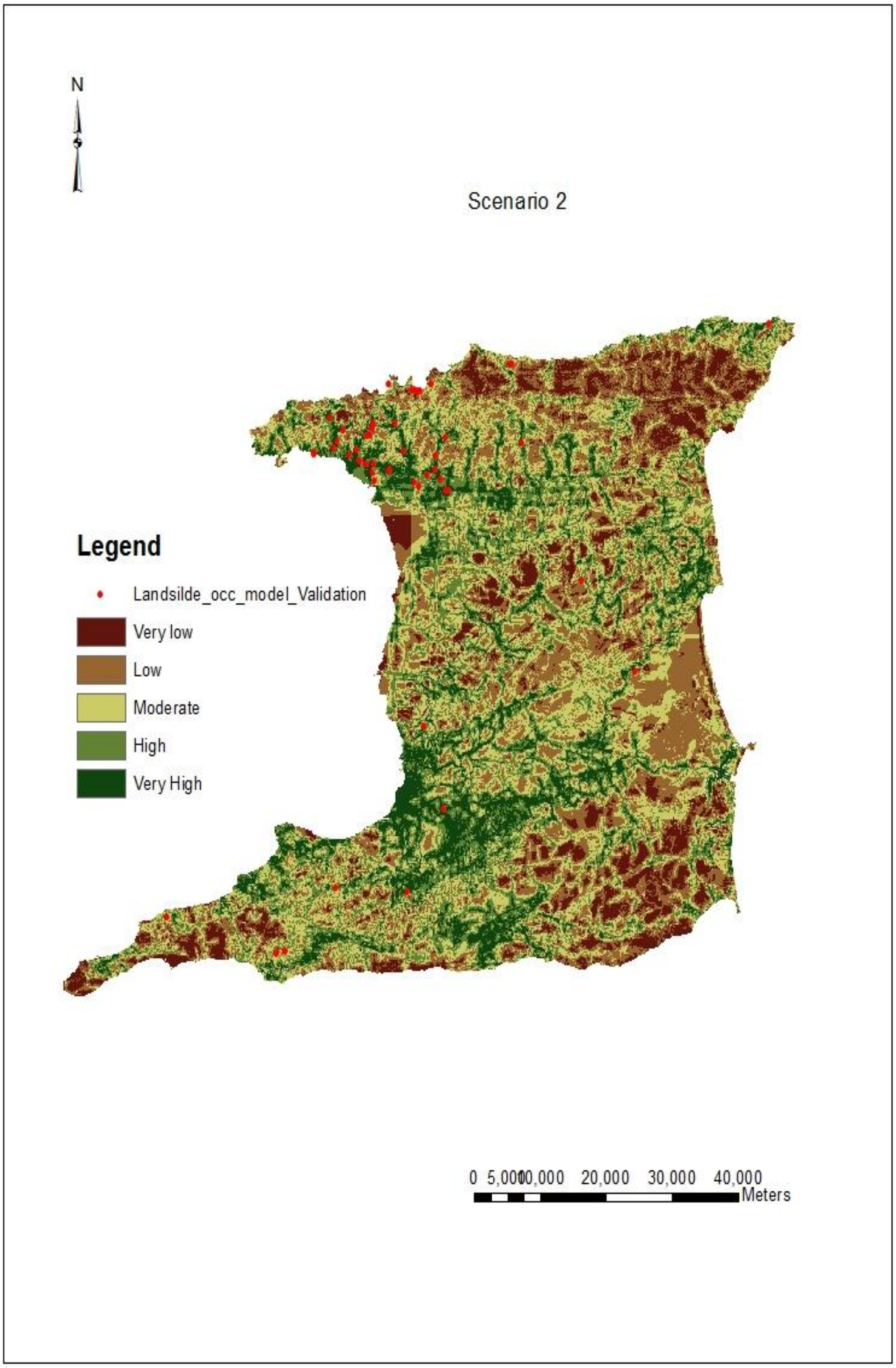


Figure 6 : Spatial distribution of landslide occurrences in scenario 2

Table 3: % landmass in each susceptibility class for all three scenarios

	Scenario 1		Scenario 2		Scenario 3	
Susceptibility Level	Class value	%land mass	Class value	%land mass	Class value	%land mass
Very Low	0-15	33.2	0-18	36.5	0-18	35.9
Low	15.1-19	5.9	18.1-22	8.8	18.1-22	8.9
Moderate	19.1-22	4.1	22.1-26	9.7	22.1-26	9.9
High	22.1-25	32.1	26.1-30	6.9	26.1-30	7.2
Very High	25.1-39	24.7	30.1-43	38.1	30.1-43	38.1

4 Conclusion

The use of GIS applications allowed for a simple logical weighted factor model of landslide susceptibility to be developed in three distinct scenarios using various instability factors. PFAS and RFAS were found to be significant additions to the model. The results indicated that there was increased accuracy in the predictive capabilities with the addition of PFAS and RFAS as instability factors, which empathizes that intrinsic soil properties, are critical in accurately assessing instability.

ACKNOWLEDGEMENTS: The authors would like to acknowledge the Office of Disaster Preparedness and Management (ODPM), of Trinidad and Tobago. 4A Orange Grove Road, Trincity, Tacarigua, Republic of Trinidad and Tobago.

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