Using Carrying Capacity and Multi-Criteria Analysis to Proactively Manage Floods in the Caribbean

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Abstract
Flooding is the most common hazard that affects Caribbean territories, Trinidad included, leading to economic losses and death. This paper promotes a Geoinformatics founded methodology for mapping areas that have the potential to flood 'flood prone areas' using Binary Logistic Regression to identify the carrying capacity of watersheds for flooding. The geophysical terrain characteristics such as slope, elevation, geology and rainfall for these susceptible areas for flooding were used. Binary Logistic Regression was used in determining the significant characteristics in predicting the flooded watersheds in comparison to the non flooded watersheds. It was found that the characteristics of the watersheds by themselves were not significant in predicting floods, but when interaction between these characteristics were considered it was possible to predict floods at approximately 83% accuracy. The developed model is useful for proactively managing floods, identifying flood prone watersheds, establishing flood insurance premium rates, and identifying areas having unique, natural and beneficial functions.

1. Introduction

During the past 87 years carrying capacity has evolved into many fields of study including: the fields of economics, ecology and ecosystems by examining the maximum population level that can be sustainably supported given available resources in a particular locale (Monte-Luna et al, 2004), in tourism, by examining the maximum number of people that may visit a destination without causing destruction of the physical, economic and socio-cultural environment leading to an unacceptable decrease in the quality of life (PAP, et al., 1999) and in the field of watershed management and natural hazards by defining carrying capacity to be the tolerable levels of development and changes to land use/cover that can take place within a watershed before the threshold for the triggers for floods are reduced (Baban and Aliasgar, 2008). Despite varying definitions across fields of study there appears to be a similarity in assessing a tipping point for an event to occur. In previous studies indicators have been examined and assessed in the context of the carrying capacity defined to determine its contribution to the tipping point (Dame and Prins, 1998, PAP et al., 1999 and Kammerbauer et al., 2001). In Honduras, landscape and soil fertility indicators were developed to be used for natural resource planning, amongst others, and each indicator was assessed according to its (+) positive, (-) negative or (+-) neutral contribution to sustainability (Kammerbauer et al., 2001). Applying this concept to flood management and development in watersheds is critical to maintain development at a sustainable level i.e. not resulting in physical changes leading to a watershed reaching its tipping point and inevitable floods. For the purpose of this paper carrying capacity has been defined in the context of watershed management and attempts to highlight the tolerable levels of development and changes that can take place within these watersheds before predefined thresholds for the trigger for floods are reduced. As focus is on the tolerable levels of changes before thresholds are lowered, the only interrelated dimension considered is the intensity/duration threshold for floods. This is predefined and applies as a constant to each watershed. A similar approach can be used when developing the carrying capacity for hydrological catchment management in the context of floods in Trinidad. Indicators can be those characteristics of the watersheds which contribute to its susceptibility to floods i.e. those characteristics or combination of characteristics which makes the watershed more vulnerable. Previous research in the Caribbean revealed that Slope, Elevation, Area, Land use/cover, Geology and Soil characteristics can be used to determine susceptibility to flooding (Baban and Francis, 2008 and Baban and Aliasgar, 2008). The aim of this paper is to identify the carrying capacity of watersheds in Trinidad by statistically analysing the indicators of carrying capacity in order to assess probability of flooding in Trinidad.

2. Study Area

Trinidad is the most southerly of the Caribbean islands, and is located 10^0-11^0N and 61^0-62^0W (**Error! Reference source not found.**). The island is about 4824 Km² and the highest elevation point is about 940m (Macpherson, 1984). Land use/cover is changing rapidly and research indicates that areas which are developed or partially developed are prone to floods (Baban and Aliasgar, 2008). Land use/cover practices in Trinidad such as slash and burn, illegal quarrying, illegal logging and forest fires have added to flooding process by increasing usual runoff and sedimentation (Ramlal, 2008). The Northern Range is made of low grade, regionally metamorphosed rocks which include limestone, shaley phyllites, shales and quartzites. Trinidad is annually affected by floods resulting from heavy and prolonged rainfall (Macpherson, 1984 and Baban and Aliasgar, 2008). Data collected in previous studies have led to the development of an inventory for floods from 1986 to 2006 and a flood prone map for Trinidad (Baban and Francis, 2008). This map was developed using Geoinformatics to identify areas which frequently flooded during the time investigated and by determining the physical characteristics of slope, elevation, geology, Land use/cover and soil in these areas. A deductive approach was then used to identify areas susceptible to flooding.

3. Methodology

Watersheds were selected as a basic unit for analysis as in mountainous areas watersheds represent a clearly defined unit in the water regime as well as being an indicator for allocation of space for agriculture or human settlements (Kammerbauer et al., 2001). An initial study by Baban and Aliasgar (2008) attempting to develop carrying capacity indicators for flooding in Trinidad watersheds (Table 1) showed that the possibility of flooding increases if the % slope in the 0^0-10^0 (SL0to10) range were to increase above 72%, if the percentage elevation in the range 0-100m (EL0to100m) were to increase above 59% and if the Land use/cover of mainly forest and natural vegetation (LUL) falls below ~65%. These variables were chosen for this study together with Soil and Compactness Ratio (CR) (Table 2) which is the ratio of the watershed perimeter to the circumference of a circle whose area is equal to that of the drainage basin (Figure 2). Compactness Ratio is indicative of the shape of the watershed to the flooding process as a low ratio indicates that there is more rapid discharge from the basin (Bell, 1999). The primary objective of the analysis was to build a predictive model for the probability of a watershed being subjected to flooding.

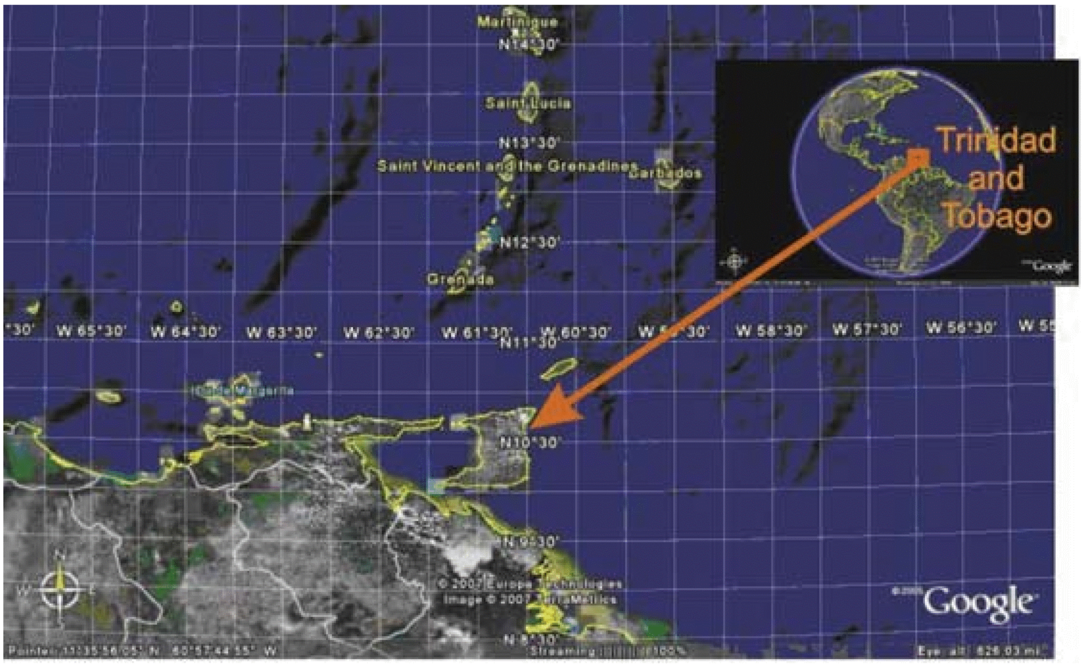

Figure 1: Map of Trinidad and Tobago (GoogleEarth 2005)

Table 1: Indicators used in defining the Carrying Capacity (Baban and Aliasgar, 2008)

Characteristic	Effects on flooding
Soil	Amount of water absorbed depending on soil porosity which will determine how quickly the rain fall will seep through the underlying bedrock.
Geology	The harder the geology, the less water is absorbed.
Land use/cover	The presence of trees usually increases the thresholds for floods as the trees absorb some of the precipitation, on the other hand, agricultural practices tend to loosen the soil hence increasing the process of infiltration and run off.
Slope	The slope can give an indication of the speed at which the water will run off into rivers and lakes and can affect the lag time for the floods
Area	Can have an impact on the lag time as the rain fall has to travel further to get to the rivers and lakes.
Elevation	An indication of speed at which the rain fall will travel and can give an indication of the areas which will flood i.e. areas of low elevation usually flood.

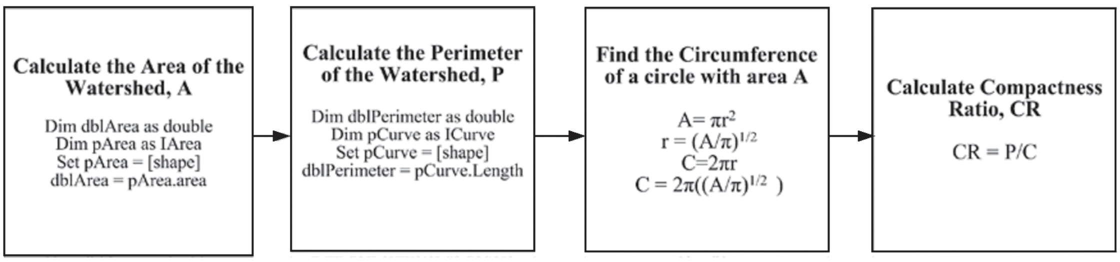

Figure 2: Steps in Calculating Compactness Ratio

Table 2: Description of Variables used in the analysis

Variable set	Number of variables	Description	Chosen subset for entry into	Name used in model
Slope	9	% of watersheds area in the categories 0-10°, 10-20°,…, 80-90°	Slope 0-10°	SL0to10
Elevation	10	% of the watersheds area in Elevation 0-100m, 100-200m,…,900-1000m	Elevation 0-100m	EL0to100m
Land Use	5	% of watersheds area in the categories Low, Low-Medium, Medium-High,	Land Use Low	LUL
Soil	3	% of watersheds area in the categories Low, Medium and High	Soil High	SH
Compact Ratio	1	The Compactness Ration of the Watershed	CR	CR
Flooded	1	Binary response to flooding in a watershed. 1=flooded 0=not flooded	Flooded	-

Variables in the BLR

SL0to10 –% of watershed whose slope in the range of 0 to 10 degrees
EL0to100m - % of watershed whose slope is in the range of 0 to 100m
LUL - % of watershed whose Landuse use was reclasses as Low (this is in terms of infiltration)
SH - % of watershed whose soil was reclassed as HIGH (this is in terms of runoff)
CR – the compactness ratio

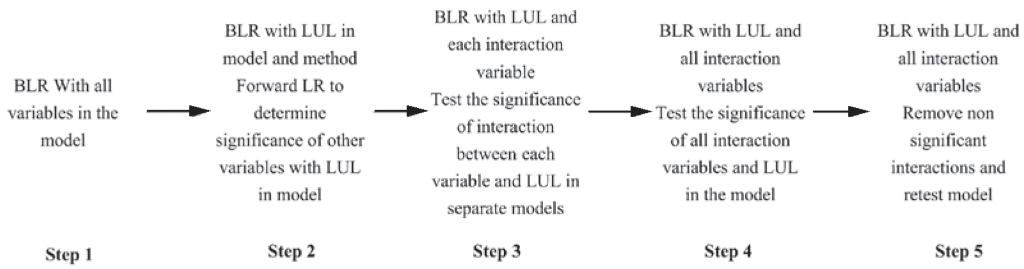

Figure 3: The steps chosen in determining model for Carrying Capacity

A multiple binary logistic regression model (Agresti, 2000, Hosmer and Lemeshow, 1989) was deemed appropriate for this purpose as the variable, Flooded, is a binary indication of a watershed which, in the past, has exceeded its carrying capacity. The available data were in several sets of potential explanatory variables, reflective of the characteristics of the watershed (Table 2). It was found that there was a high degree of correlation between the variable sets due to the inherent characteristics of the watersheds. It was also noted that variables in the each variable set was compositional; summing to 100%, leading to possible distortion in data distribution (Filzmoser and Hron, 2008). Thus before analysis, it was important to reduce the number of variables within each set. This not only reduced the effects of compositional data, but this assisted in creating a parsimonious model. The chosen subset for entry into the model was guided by previous work performed on Carrying Capacity (Baban and Aliasgar, 2008) (Table 1). For the regression a $p \leq 0.05$ for entry and $p \geq 0.10$ for removal was used. The analysis was divided into 5 steps. Step 1 entered all variables in the model to determine if any were significant. As Land use/cover was considered critical in this analysis, Step 2 involved entering Land use/cover in the model and using a step wise selection, for the remaining variables. Step 3 tested the significance of the interaction of the variables with Land use/cover individually. Step 4 used step wise selection to test the significance of Land use/cover with all interaction variables entered in the model. Finally, Step 5 removed the non-significant interaction variables to determine the best suited model fulfilling both statistical and managerial requirements (Figure 3).

4. Results and Analysis

The results of the statistical analysis are listed in Table 3. Step 1indicates that with all variables in the model, none was significant in predicting the binary response for floods (i.e. sig. >0.5). This means that when all the characteristics of the watershed were examined together none of them significantly contributed to the flooding process. Research reveals that the uncontrolled development of land in Trinidad, leads to increased runoff and increased sedimentation (Ramlal, 2008). Together with this the lack of land use policies in monitoring and controlling of such practices can be influential in the occurrence of floods in Trinidad (Baban, 2008). As a result, land use/cover was chosen as a new starting point in the BLR. By making LUL a mandatory variable in the model and performing a stepwise regression with the remaining variables, it was found that no additional variable was added to the model i.e. no characteristic of the watershed significantly contributed to flooding when effects of land use/cover was made compulsory to the flooding process (Figures 4, 5 and 6). Step 3 individually tested the interactions of each variable in combination with Land use/cover to determine its significance. It was found that only the combined effects of Land use/cover and elevation was significant in predicting floods. However when the model included all the interactive variables it was found that the combined effects of Land use/cover and elevation and the combined effects of Land use/cover and slope did not contribute significantly to the flooding process. Considering that elevation and slope themselves were not significant (from Step 1 and Step 2), they were removed to determine if the model could be improved, Step 5. It was found that by removing these two variables from the model, the significance of the interaction between Land use/cover and Soil and Land use/cover and Compactness Ratio was increased slightly. On the other hand, by removing the interaction with Elevation alone, there was no change in the accuracy of the model, but when both interactions with Elevation and Slope was removed, the accuracy of the model was increased from 81.5 % to 83.3%. This is not surprising as previous studies indicated that slope was the most influencing factor contributing to floods as more than 95% of flooded locations were located on a slope if <1.0% (Baban and Francis, 2008). As a result slope was not removed from the model. The interaction of Compactness Ratio and Land use/cover was indicated as significant. This meant that in Trinidad, the shape of the watershed together with the land use/cover of the watershed were important in determining floods. This can be seen in Figure 4 where the flood prone watersheds of the Northern Range tend to be long and narrow as well as being characterised by intensive unplanned housing and agriculture on the hillsides (Cropper, 2008). The interaction between Land use/cover and Soil was also significant. The original map obtained for Soil had 15 classes of soil. This was reclassed into categories which were meaningful in determining susceptibility to flooding by assessing the particle size and drainage of the Soil, Figure 4. The classes formed were an indication of the Soil's infiltration capabilities with the class High denoting the most infiltration capabilities with largest particle size and free drainage. Soil particle size and texture is a good indication of the infiltration capacity of the soil (Bell, 1999).

Table 3: Results of the Multiple Binary Logistic Regression Model

Step	Description	Variable	B	S.E.	Sig.	% Predicted
1	All Variable in the equation	SL0to10	-0.003	0.046	0.947	[redacted]
		EL0to100m	0.009	0.028	0.739	
		LUL	-0.019	0.014	0.187	
		SH	-0.017	0.026	0.519	
		CR	2.7	1.457	0.064	
		Constant	-2.262	4.504	0.616	
2	Test significance of variables with Landuse in equation using Forward likelihood ratio	LUL	-0.026	0.012	0.031	
		Constant	2.2	0.767	0.004	
3	Test for Interaction between Landuse and Slope	LUL	-0.105	0.066	0.109	
		SL0to10	-0.04	0.049	0.418	
		LUL by SL0to10	0.001	0.001	0.164	
		Constant	5.441	4.506	0.227	
	Test for Interaction between Landuse and Elevation	LUL	-0.111	0.052	0.034	
		EL0to100m	-0.055	0.04	0.169	
		EL0to100m by LUL	0.001	0.001	0.05	
		Constant	6.535	3.629	0.072	
	Test for Interaction between Landuse and Soil	LUL	0.007	0.016	0.67	
		SH	0.047	0.037	0.206	
		LUL by SH	-0.001	0.001	0.061	
		Constant	0.988	0.874	0.259	
	Test for Interaction between Landuse and Compactness Ratio	LUL	-0.145	0.079	0.066	
		CR	-2.063	2.542	0.417	
		CR by LUL	0.077	0.051	0.133	
		Constant	5.238	3.948	0.185	
4	Test model for significant variables when all variables including interaction variables are placed in the model	LUL	-0.228	0.1	0.023	
		SL0to10	0.068	0.061	0.262	
		EL0to100m	-0.01	0.045	0.829	
		SH	0.139	0.079	0.078	
		CR	-4.75	2.804	0.09	
		LUL by SH	-0.002	0.001	0.019	
		CR by LUL	0.169	0.071	0.018	
		Constant	1.564	6.273	0.803	
5	Test model for significant variables by removing non-significant variable from Step 4: Elevation removed	LUL	-0.222	0.096	0.021	81.5
		SL0to10	0.061	0.051	0.233	
		SH	0.142	0.079	0.071	
		CR	-4.662	2.768	0.092	
		LUL by SH	-0.002	0.001	0.02	
		CR by LUL	0.165	0.069	0.016	
		Constant	1.186	6.055	0.845	
	Test model for significant variables by removing non-significant variable from Step 4: both Slope and Elevation removed	LUL	-0.212	0.105	0.042	83.3
		SH	0.079	0.05	0.117	
		CR	-4.324	2.855	0.13	
		LUL by SH	-0.002	0.001	0.028	
		CR by LUL	0.156	0.074	0.036	
		Constant	7.01	4.297	0.103	

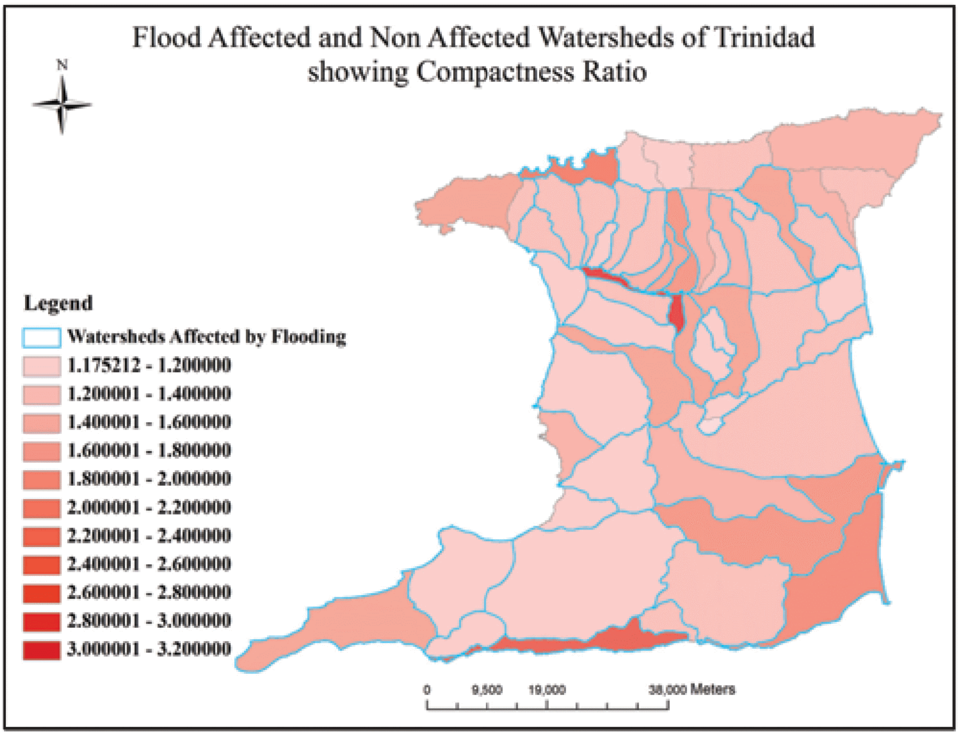

Figure 4: Flood affected and non affected watersheds in Trinidad

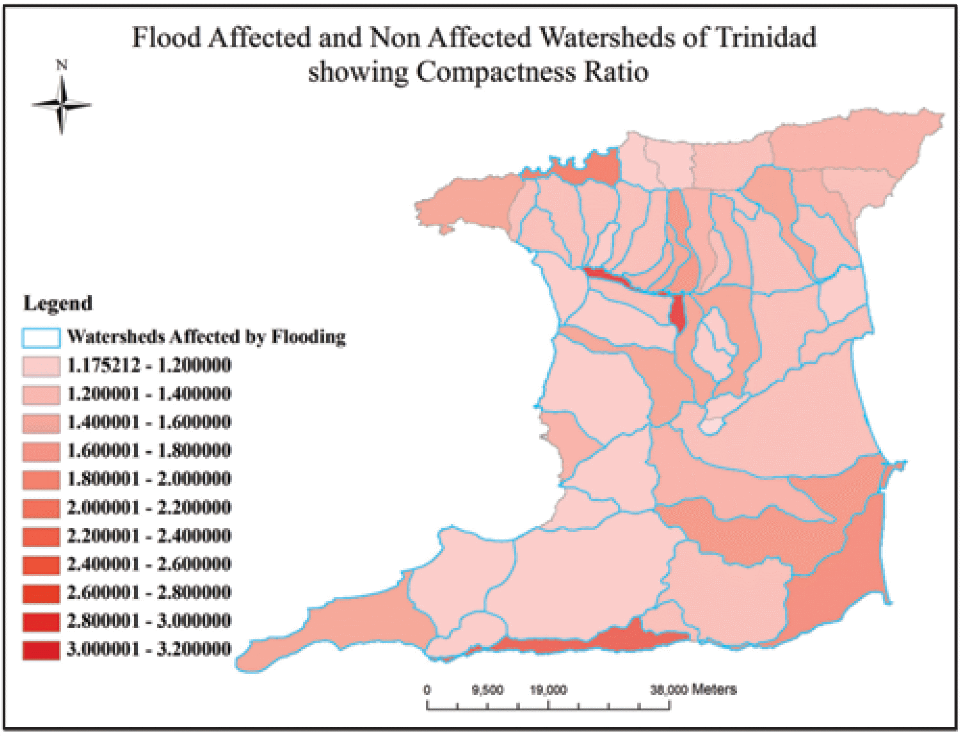

Figure 5: Flood affected and non affected watersheds in Trinidad showing Compactness Ratio

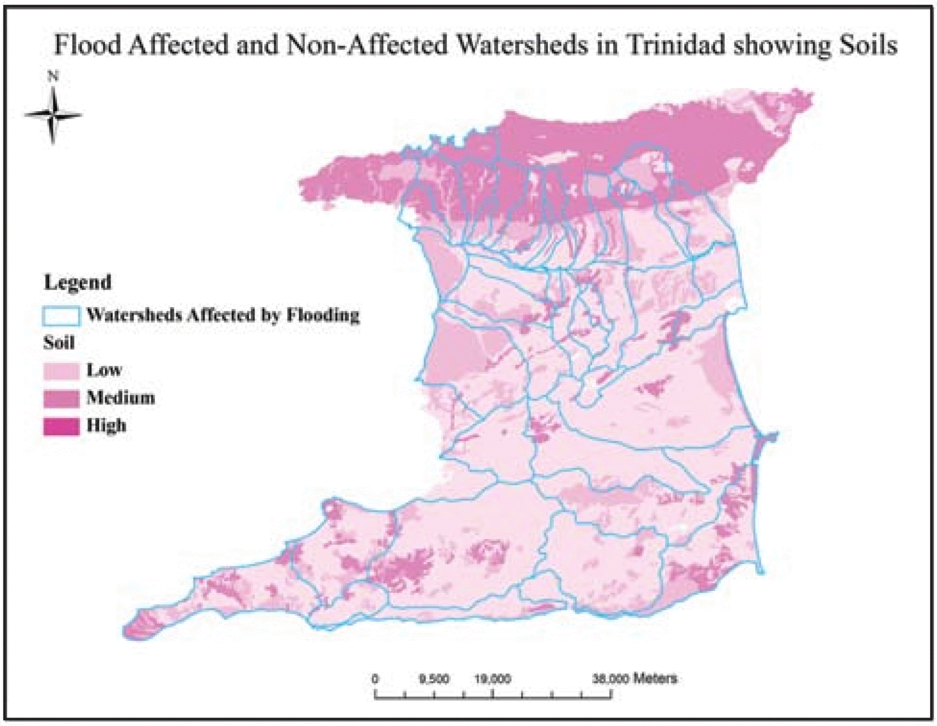

Figure 6: Flood affected and non affected watersheds in Trinidad showing Soils

It was found that on average the affected watersheds' had approximately three quarters (77%) of its soils belonging to the Low/Medium class (Figure 6). This indicates that the majority of soils in these catchments were clays or soils consisting of clays, peats, silts with little sands and gravels and with impeded to imperfect drainage. On the other hand, the watersheds which did not experience floods had on average approximately half of their soil in the class of Low/Medium. This signifies that 48% of the non-affected watersheds consisted of soils with largest particle size and free drainage i.e. sands, gravel, loams…etc. The interaction between Land use/cover and Soil is important as in some cases the soil may be permissive to high infiltration, but the Land use/cover may not be, thus enabling precipitation to become surface runoff before it has a chance to infiltrate into the soil, Figure 4. The following is the resulting equation for the probability of flooding in watersheds in Trinidad, Equation.

*Ln (#floods / #~floods) = 1.186 - 0.222Land use/cover + 0.061Slope + 0.142Soil - 4.662Compactness Ratio - 0.002(Land use/cover*Soil) + 0.165 (Land use/cover*Compactness Ratio)*

Equation 1

The changes to the probability of flooding when land use/cover low (forest) is altered can be calculated using this equation. This can greatly assist planners and government authorities in assessing the holistic effects of removing forest cover say to develop a housing project, so they do not only asses the local impact of the housing on the locale but can predict its effect on the entire watershed.

5. Conclusion

This study attempted to define the carrying capacity for watersheds in Trinidad to determine the limits of tolerable change before the intensity/duration thresholds of rainfall for triggering floods are reduced. This paper developed a Geoinformatics based methodology for mapping areas that have the potential to flood 'flood prone areas' using binary logistic regression to identify the carrying capacity of watersheds for flooding. BLR was used to examine the significant characteristics in predicting the flooded watersheds to the non flooded watersheds. The outcomes showed that the individual characteristics of the watersheds by themselves were not significant in predicting floods, but when interaction variables, Land use/cover and Soil and Land use/cover and Compactness ratio were considered it was possible to predict floods at approximately 83 % accuracy. The developed algorithm is useful for proactively managing floods, identifying flood prone areas, establishing flood insurance premium rates, and identifying areas having unique, natural and beneficial functions.

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