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GIS-based Flood Susceptibility and Risk Mapping Trinidad Using Weight Factor Modeling

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ABSTRACT. Flooding is a major concern in Small Island Developing States (SIDS), particularly the Caribbean region due the tropical climate. Flood susceptibility and risk mapping has proven to be a critical tool in modern natural hazard analysis. It provides geospatial representations of hazard susceptibility and risk, which has become vital in land use management and planning. This paper reports on the use of model builder application within ArcGIS 9.3 to develop a flood susceptibility and risk map of the island of Trinidad utilizing traditional inundation factors to determine flood susceptibility and then combined with population and building density to determine flood risk. Results indicated that rainfall was the most influential inundation factor followed by slope, elevation and drainage density, with the most susceptible areas being low lying coastal regions. Cross validation utilizing intersect analysis and field verification revealed 91% and 100% accuracy. Quantitative analysis of risk showed that 23% of the country's landmass can be considered to be at high risk with concentrations in the urban and suburban centres of the country. Utilization of the information provided can inform future planning and management strategies and consequently mitigate potential threats associated with flooding. The methodology also allows for uncomplicated replication and application in other Caribbean islands, where data limitation may prevent use of more complex models.

Keywords: Flood Susceptibility Mapping, Flood Risk Assessment, Flooding in Trinidad.

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1. INTRODUCTION

Mitigation and management of natural hazards are a concern for Small Island Developing States (SIDS), which are vulnerable to climate variability and change (**Eudoxie and Wuddivira, 2014**). Unplanned development, increasing urbanization, changes in land use and climate change have induced changes in the spatial and temporal patterns of natural hazards and intensified the associated effects. Flooding is one of the major natural hazards affecting SIDS, resulting in displacement of people, damage to property and are amongst the most frequent and costly natural hazards (**Ramroop, 2005**; **Canisius and Nancy, 2009**; **Pradhan, 2010**). The intensity of flooding events can be exacerbated by anthropogenic factors such as drainage, settlement, deforestation and cultivation (**Tollan, 2002**; **Kwak and Kondoh, 2008**; **Balabanova and Vassilev, 2010**). Inappropriate changes of the aforementioned factors alter watershed hydrological dynamics, largely by increasing runoff rate and quantity while decreasing infiltration capacity, soil porosity and evapo-transpiration. The result is increased susceptibility to frequent and severe flood events.

The Caribbean region is highly prone to natural disasters, mainly tropical depressions, storms and hurricanes (**Carby, 2011**). All of these significantly increase the occurrence of flood events and associated damages. In Trinidad, flood is one of the major natural hazards affecting the country (**Ramroop, 2005**; **Canisus and Nancy, 2009**). Estimated flood damage for flood events in the years 1993, 2002 and 2006 were US$580,000, US$3,300,000 and US$2,500,000, respectively (**Carby, 2011**). Therefore it is imperative that management and mitigation measures be employed forthwith.

Mitigation and management of natural hazards focuses on modifying or reducing the impacts on the human use system (**Collymore, 1995**). It seeks to accelerate the evolutionary process of adaptation and protection based on an understanding of known natural hazards, impacts and effects (**Schramm, 1984**). Assessing losses, the scope of effects and the nature of the phenomena are essential components in formulating mitigation and management programmes. There are two main approaches to mitigation and management of all natural hazards; structural and non-structural (**Florey, 1986**). Structural approaches deal with physical fortification of buildings and construction of protective structures, whilst non-structural approaches address the institutional framework of the areas at risk through governmental policies, laws, public education and land use management. In both approaches it is imperative that vulnerable areas along with the associated risk be identified.

Risk assessments are used in different fields, to investigate the probability that a negative event or condition will affect an individual in a given time and space. Within this framework and in the context of this paper, flood risk is defined as the probability of the occurrence of a flooding event in combination with its negative consequences (**UNISDR, 2009**). The flood risk assessment in this study involves the identification of susceptible areas based on correlations of flooding occurrence with inundation factors in combination with vulnerability. Susceptibility is defined as the likelihood of a dangerous event occurring in an area on the basis of local terrain conditions (**Santangelo et al., 2011**). In determining susceptibility temporal variability is not considered, however this method can provide useful baseline data that can direct future monitoring programs towards facilitating more extensive analysis. Resultant susceptibility classes are then analysed in conjunction with all elements of the human system, the built and natural environment, economic activities and ecosystems (vulnerability). A similar approach was used by **Pradhan** (**2010**).

Geographic Information Systems (GIS) and Remote Sensing have become an integral component in risk assessment and mapping of natural hazards particularly flooding and landslides (e.g., **Pradhan et al., 2008**; **Roopnarine et al., 2013**; **Lawal et al., 2014**). Two main methods are used to map flooding; flood hazard mapping (FHM) and flood susceptibility mapping (FSM). FHM is used to provide detailed flood estimation (extent and height) and hydraulic modelling of floods of specified return periods. This technique relies on high resolution data on rainfall, geometry of the drainage channels and is data and computationally intensive. Contrastingly FSM relies on qualitative data. FHM methods are therefore more accurate, however cannot be developed unless extensive data is available. Regardless of the method, whether hazard or susceptibility of natural disasters, various types of risk modelling can be employed. Probabilistic (e.g., **Pradhan and Shafie, 2009**) and logistic regression models (e.g., **Ohlmacher and Davis, 2003**; **Pradhan et al., 2006**) are more conducive to FSM where quantitative data is lacking. Hydrological and stochastic rainfall models (e.g., **Ebisemiju, 1986**; **Nageshwar and Bhagabat, 1997**; **Yakoo et al., 2001**; **Cunderlik and Burn, 2002**) are utilized where quantitative data is accessible. Some researchers have employed case study approaches in order to develop FHMs, where macro scale data was not obtainable (e.g., **Townsend and Walsh, 1998**; **Knebl et al., 2005**; **Ramlal and Baban, 2008**; **Merwade et al., 2008**). In each circumstance, the method and approach adopted is reliant on the quality and the nature of the available data.

The twin island republic of Trinidad and Tobago is plagued by perennial flooding, associated with increased rainfall during the wet season. The coastlines experience seasonal storm surges, which combined with climate associated sea level rise has exacerbated flooding and salt water intrusion in low lying regions (**Eudoxie and Wuddivira, 2014**). Drainage systems, particularly those in the capital city have been altered in the past 30 yrs primarily by urban development and land reclamation works (**Osuji, 2013**). Flood prone areas remain attractive for socio-economic reasons (accessibility, agriculture, commerce and housing) and thus it is likely that the damage potential will continue to increase. Consequently, identification of susceptible areas and their associated risks is paramount to effectively manage and mitigate these effects. This paper reports on risks associated with flooding in Trinidad, using a semi quantitative, frequency analysis approach.

2. METHODOLOGY

2.1. Flood Susceptibility

GPS coordinates of past flood occurrences were sourced from the Office of Disaster Preparedness and Management (ODPM) of Trinidad and Tobago. Point source data was obtained which did not reflect dimensions or intensity of flood occurrences. A total of one hundred (100) points were acquired and digitized as a point layer. Occurrence data was divided into two equal groups, by random selection of data points, using geo-statistical analyst extension of ArcGIS 9.3. The first group was used to develop the susceptibility model whereas the second was used for validation of the model.

Inundation factors were chosen based on available data supported by previous research. Six factors were chosen including: elevation, slope (length), road density, drainage density, land use, and rainfall. Similar factors were used by **Umitsu et al.** (**2006**) and **Pradhan** (**2010**). **Table 1** shows the source of all data utilized.

Each inundation factor was classified into five classes using Jenks Natural Breaks. This determines the best arrangement of values into various classes by reducing the variance within classes whilst maximising the variance between classes (**Roopnarine et al., 2013**). Numerical values from 1-5 were allocated to each of the five susceptibility classes as follows: Very Low-1, Low-2, Moderate-3, High-4, and Very High-5 (**Table 2**). Rainfall was ranked according to distribution, with areas receiving greater amounts, being assigned higher susceptibility. Elevation was ranked according to distance above sea level with lower elevations assigned higher susceptibility. Slope was ranked based on length, with the longer slopes being assigned a lower susceptibility. Drainage density was ranked based on percentage coverage of the watershed where areas with lower percentage coverage were assigned lower susceptibility. Road density was ranked in a similar manner to drainage density, with areas containing smaller percentages being assigned lower susceptibility. Land-use was ranked based on theoretical infiltration and absorption rates, with forested areas being considered the most likely to promote infiltration and hence the least susceptible, while developed land, wet lands and water bodies (rivers, lakes) were assigned higher susceptibility as they more conducive to extensive surface runoff and water logging. Similar methods of classification were used by **Pradhan** (**2010**) and **Forkuo** (**2011**).

Table 1. Input data sources utilized in developing the susceptibility model

Data Theme	Date Limitation	Scale Limitation	Source
Past landslides	2002 -2014	Unknown	ODPM
Past floods	2002-2014	Unknown	ODPM
Contour	1994	1:10,000	Land and Surveys Division
Slope	1994	1:10,000	Derived from contour datasets
Roads	1994	1:10,000	Land and Surveys Division
Rivers/Streams	1994	1:10,000	Land and Surveys Division
Land Cover	2007	1:10,000	Derived for IKONOS imageries
Buildings	1994	1:10,000	Derived for IKONOS imageries
Lithology	1984	1:50,000	Ministry of Energy and Energy Industries
Tectonic features	1984	1:50,000	Ministry of Energy and Energy Industries
Rainfall	2010		Water Resources Agency
Population	2000		Central Statistical Office

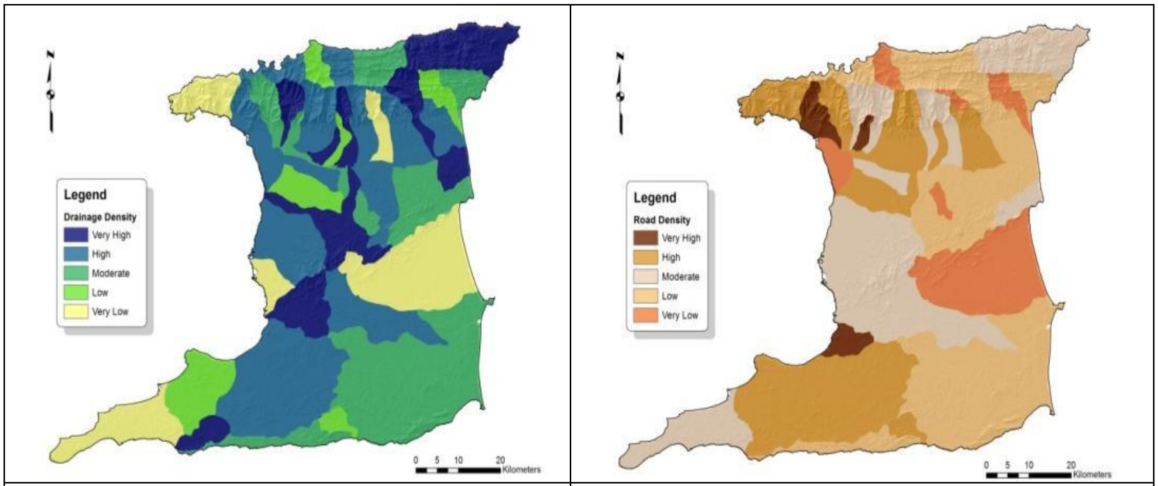
A weighted factor model approach was used to determine the overall susceptibility index of each land unit (**Dai et al., 2002**; **Roopnarine et al., 2013**). Weights were assigned to inundation factors according to frequency distribution of the model development data set of flood occurrence across susceptibility classes of each inundation factor. Assigned numerical weights were determined based on frequency analysis, that is, the percentage of flood occurrence in the each susceptibility class. This is a modified approach to that used by **Lee and Dan** (**2005**).

GIS vector layers were prepared, classified, ranked into raster grids with 10-m resolution for each inundation factor (**Figure 1**). Using ArcGIS, a cartographic model was developed for an additive weighted overlay of the input GIS layers. Transformation functions within ArcGIS were employed to convert the input layers into intermediate layers and later into an output: flood susceptibility map.

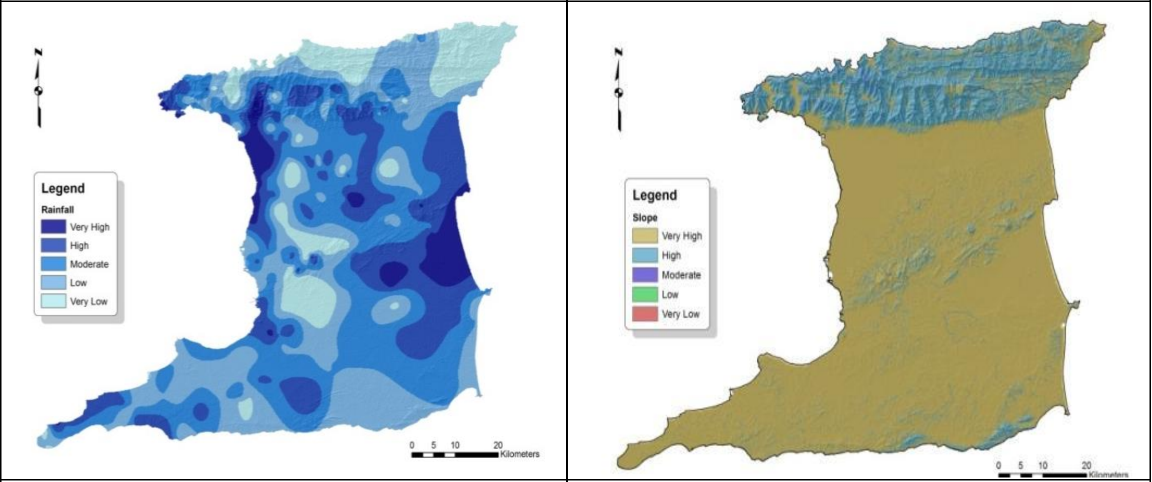
The resultant susceptibility maps were validated using intersect analysis of the flood occurrences validation data set and the five flood susceptibility classes. Intersect analysis calculates the geometric intersection of any number of feature classes and feature layers. The features or portion of features that are common to (intersect) all inputs will be written to the output feature class resulting in only areas of overlap being reflected. Additionally, 15 randomly selected sites with very-high and high susceptibility classes were field checked for any visible or community confirmed evidence of past floods. Evidence of current or past occurrences was documented through interviews. Similar methods of cross validating of susceptibility models were used by **Roopnarine et al.** (**2013**) and **Jiménez-Perálvarez et al.** (**2009**) in validation of landslide susceptibility models.

Table 2. Classification scheme, susceptibility classes and numerical ranking for all parameters included

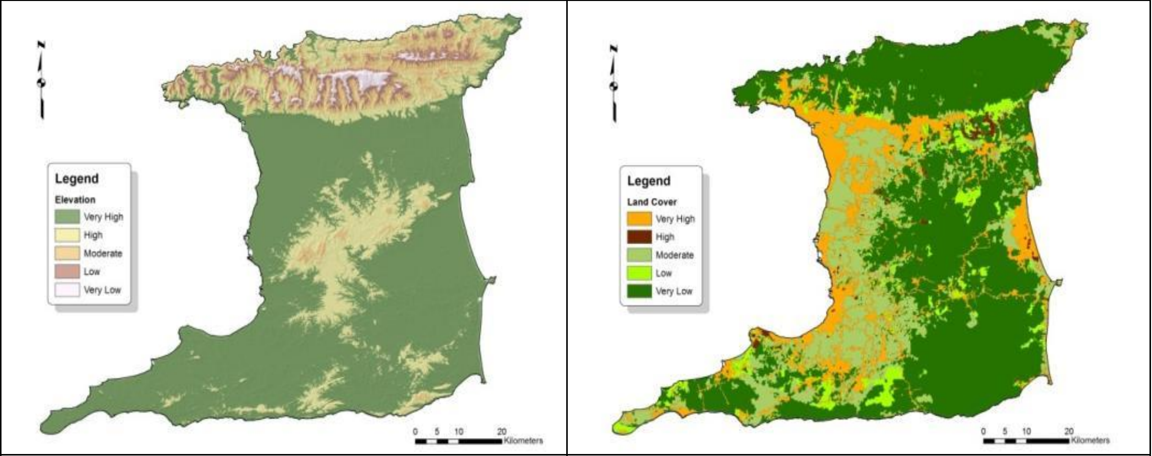
Factors	Classification scheme	Susceptibility Class	Rank Numeric Value
Monthly Rainfall (mm)	143 -166	Very Low	1
	167 – 180	Low	2
	181 – 192	Moderate	3
	193 -206	High	4
	207 – 225	Very High	5
Elevation (m)	477.1 – 931.4	Very low	1
	286.5 – 477.0	Low	2
	147.2 – 286.4	Moderate	3
	55.6 – 147.1	High	4
	0 – 55.5	Very High	5
Slope (lenght) (m)	569.2– 2748.7	Very low	1
	257.8– 569.1	Low	2
	86.0– 257.7	Moderate	3
	21.6 – 85.9	High	4
	0 - 21.5	Very High	5
Drainage density (% each watershed)	0 – 0.004674	Very low	1
	0.004675 – 0.006769	Low	2
	0.006770 – 0.0083	Moderate	3
	0.0084 – 0.009508	High	4
	0.009509 – 0.020628	Very High	5
Road (% each watershed)	0.000194 – 0.004626	Very low	1
	0.004627 – 0.009335	Low	2
	0.009335 – 0.018198	Moderate	3
	0.018199 – 0.039249	High	4
	0.039250 – 0.071101	Very High	5
Land Cover (related to water absorption and drainage capacities)	Forest	Very Low	1
	Rangeland	Low	2
	Agricultural land	Moderate	3
	Barren land	High	4
	Built-up land, Wetlands, Water bodies	Very High	5



Drainage Density **Road Density**



Rainfall **Slope**



Elevation **Land cover**

Figure 1. Input raster layers used for flood susceptibility modelling

2.2. Flood Risk Mapping

Flood risk modelling involved combining susceptibility classes with vulnerability assets. Two vulnerable assets were considered in this case study: population and building density. The denser the population or buildings in a community the higher the risk factors for that community. The population (POP) risk to flooding (FD) was computed using Equation 1:

$$\mathbf{POPRiskFD = SusceptibilityFD + VulnerabilityPOP} \qquad \textbf{.... 1}$$

The building (BUD) risk to flooding was computed using Equation 2:

$$\mathbf{BUDRiskFD = SusceptibilityFD + VulnerabilityBUD} \qquad \textbf{.... 2}$$

The input data layers required were: flood susceptibility maps, population spatial distribution, and building spatial distribution. Polygons of the build-up areas were generated and used to derive the Areal Population Density (APD) in each Enumeration District (ED), as shown below:

$$\mathbf{APD = (Population)/\ (Areal\ Area\ of\ the\ ED)} \qquad \textbf{.................... 3}$$

Where:

$$\mathbf{Areal\ Area\ of\ ED = (ED\ Area) - (Area\ of\ Built\text{-}Up\ in\ ED)} \quad \textbf{.. 4}$$

The Areal Building Density (ABD) was similarly evaluated using the Equation 5:

$$\mathbf{ABD = (No.\ of\ Buildings\ in\ an\ ED)/(Areal\ Area\ of\ ED)} \qquad \textbf{... 5}$$

2.3.Cartographic Models for the Flood Risk Mapping

Two cartographic models were built for the evaluation of the risk using ArcGIS Model Builder. The modelling essentially involved the weighted sum additive overlay of all the ranked input risk factors (flood susceptibility, population/building vulnerability) to produce the risk map.

3. RESULTS AND DISCUSSION

The majority of recorded flood events occurred on the western side of the island (**Figure 2**). This side of the country is significantly more developed and is adversely affected by land use changes that reduce infiltration rates and increase surface runoff, thus increasing the potential for flood occurrence. Although, the eastern portion of the country receives more rainfall (**Figure 1**) it consists of significantly more forested areas with lower surface runoff rate and quantity and contrastingly higher infiltration rate. These increases lag time and thus reduce the number of flood occurrences.

Classification and ranking resulted in the data presented in **Table 2**. Rainfall ranged from a maximum of 225 mm/month to a minimum of 143 mm/month across the country. Higher rainfall amounts were found to be associated with the mid eastern and north eastern portion of the country. This is due to moisture rich clouds brought in by the north east trade winds. Elevation ranged from sea level (0 m) to a maximum of 931.4 m and slope (length) from 0 m to 2748.7 m indicative of the presence of northern and central ranges intermingled with the northern, central and southern basin (**Suter, 1960**). Drainage density and road density were variable throughout the country. Road density was generally higher on the western side of the island consistent with the presence of urban centres. Drainage density was generally higher in the northern half of the island. Land cover ranged from built-up land, wetlands and water bodies to agricultural land and forests emphasizing the diverse nature of land use. The western side of the country contains significantly more developed areas containing both major cities and thus more built up areas. This results in reduced infiltration capacity and increasing surface runoff increasing the susceptibility of these areas.

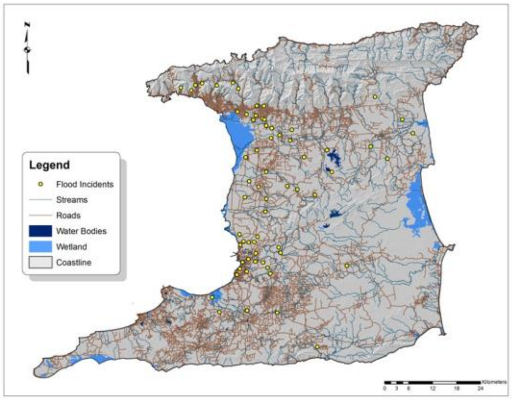


Figure 2. Flood occurrence inventory map

Frequency distribution (**Figure 3**) revealed that the most influential inundation factor was rainfall with more than 80% of past flood occurrences falling in the moderate to high susceptibility classes, followed by slope (length), elevation and drainage density each with over 60% of the past events occurring in the equivalent susceptibility classes. Road density and land use showed relatively lower influence on past flooding occurrence with just over 50% of the past flooding events occurring in the aforementioned susceptibility classes. Weights were assigned to susceptibility factors based on frequency analysis with more influential factors receiving higher weightings. Weighting were assigned as follows: Rainfall:3, Elevation:2, Slope:2, Drainage Density:2, Road Density:1 and Land Cover:1.

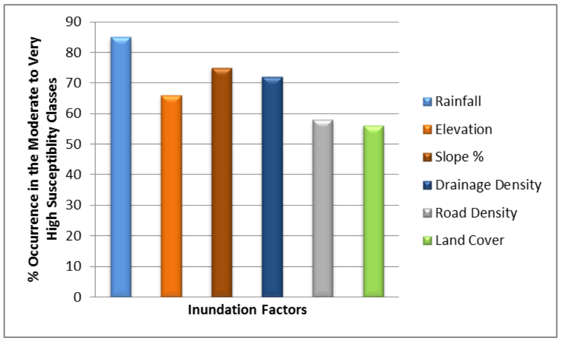


Figure 3. Frequency distribution of inundation factors

3.1. Flood Susceptibility Analysis

Table 3 provides the list of communities in Trinidad that are "Very highly" and "Highly" susceptible to flooding. Many of the highly susceptible areas occur in low lying coastal areas. The capital city of Port of Spain and the City of San Fernando, both fall within areas that are considered highly susceptible to flooding (**Figure 4**). In the case of Port of Spain, a significant percentage of the land is below sea level and in some cases reclaimed land. Additionally, the city receives surface water from a large area, with insufficient drains to accommodate surface runoff (**UN-Habitat, 2012**). The same can be said for the city of San Fernando which possesses similar features to the capital city although not dominated by reclaimed land. Areas along the east coast identified as being highly susceptible, apart from occurring on general flat land, face issues pertaining to sea level rise, inadequate drainage, and coastal erosion. Additionally, these areas receive significantly more rainfall (**Figure 1**). In order to validate flood susceptibility/risk models, two basic assumptions are necessary. Firstly, flooded areas are related to spatial information such as topography, soil and land cover, and secondly, future flooded areas will be affected by a specific factor such as rainfall (**Pradhan, 2010**). Both assumptions were satisfied in this study.

Validation of the flood susceptibility map based on intersect analysis revealed that 91% of past floods have occurred in the areas identified as moderate to highly susceptible supporting the predictive accuracy of the map (**Figure 5**). **Pradhan** (**2010**) reported an 84.76% predictive accuracy using the "Area Under Curve" method of validation, where each input factor and the logistic regression values are compared. This method along with others employed by researchers involving "failed/unfailed" cells and hit rate (e.g., **Santacana et al., 2003**), that are more statistically reliable could not be used in this study as flood extent data was unavailable. Intersect analysis follows a similar premise, but allows for point source occurrence data to be used and can provide reasonably accurate conclusions. Of the 15 randomly selected sites in the very high and high susceptibility classes visited, all had confirmed instances of flooding of various intensities. Overall the susceptibility map proved accurate based on the combination of validation criteria used.

Table 3. Communities susceptible to flood hazard in Trinidad

Very Highly Susceptible		Highly Susceptible
Los Bajos	Santa Rosa	Icacos
Penal	Malabar	San Francique
Pluck	D'abadie	Bonasse
Barrackpore	Arouca	Palo Seco
Debe	Aranjuez	Siparia
Monkey Town	El Socorro	Point Fortin
Plaisance	La Florissante	Grande Terre
La Romain	Arima	Cipero
Duncan	Dinsley	Roussillac
Woodlands	St. Augustine	St. Margaret
Gulf View	Valsayn	Princess Town
Pleasantville	Mount Lambert	Pointe-A-Pierre
Ste. Madeline	Tacarigua	Gran Couva
San Fernando	Curepe	California
Mon Repos	Laventille	Preysal
Vistabella	Barataria	Montserrat
Marabella	Mt. Hope	Mac Bean
Rio Claro	San Juan	Freeport
Gasparillo	Port of Spain	Mundo Nuevo
Charuma	Gonzales	Chase Village
Brasso	St. Joseph	Waterloo
Couva	Woodbrook	Palmiste
Biche	St Clair	Edinburge
Poole	Belmont	Coryal
Carapichaima	St. Ann's	Talparo
Chandernagore	Cascade	Enterprise Montrose
Cumberbatch	Maraval	Chaguanas
Felicity	Las Cuevas	Manzanilla
Las Lomas		Cunupia
Brazil		Mon Plaisir
San Raphael		Guaico
St. Helena		Tamana
Sangre Grande		Caroni
Guanapo		Valencia
La Horquetta		Tunapuna
Golden Grove		Petit Valley
Oropouche		Salybia
Maloney		Maracas St. Joseph
		Caura

3.2. Flood Risk Analysis

Risk was evaluated using two independent vulnerability assets (population and building density). Geospatial representation of population and building density (**Figure 6**) revealed similar

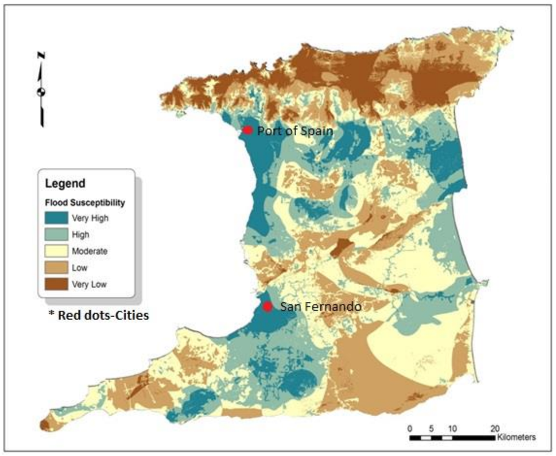


Figure 4. Flood susceptibility map of Trinidad

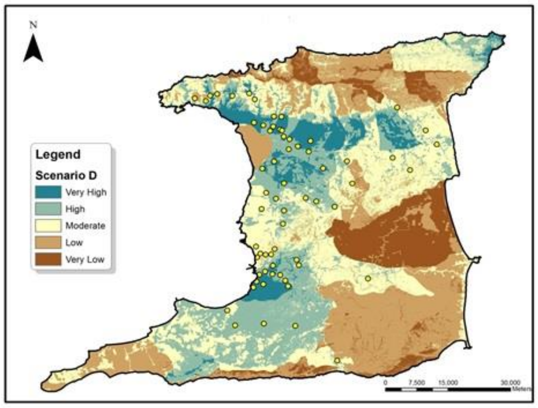
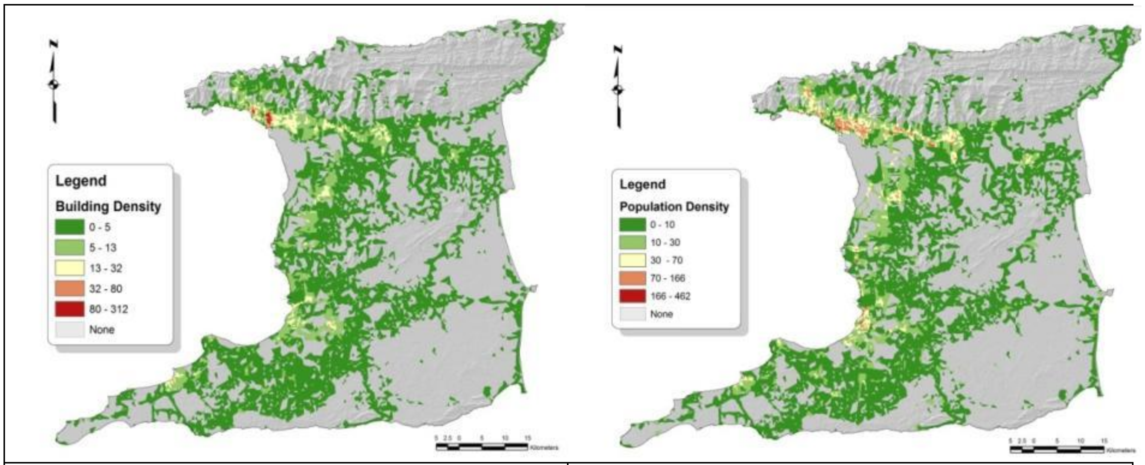


Figure 5. Cross validation with intersect analysis (yellow dots represent past flood occurrences)

spatial trends, but with different numerical categories. Consequently the population flood risk and building risk map (**Figures 7**, **8**) illustrated similar patterns. Quantitative spatial analysis indicated that approximately 23% of the countries landmass occurred in the very high and high risk classes for both building and population density (**Tables 4, 5**). The majority of these areas occur in urban and suburban parts of the country that are densely populated. Additionally, the majority of areas identified to be at risk are on the western side of the country, as this side is considerably more developed. The results provide baseline data towards developing flood mitigation measures and land use planning. The information gathered also has the potential to inform newly developed national policies such as the National Spatial Development Policy (NSDS), which attempts to provide a framework for decision making regarding the use of national space. Site specific measures and policies may require additional investigation and analysis where geographic heterogeneity may exist. Additional factors such as transportation routes, food security (agricultural land), building types (governmental, security, housing) and environmental aspects (biodiversity, protected areas, reserves) can be included in a similar manner depending on the nature of risk assessment needed, once data is available.

4. CONCLUSION

The flood susceptibility and risk maps for the island of Trinidad were produced using existing data in a semi-quantitative model. Results, based on the intersect analysis indicated a 91% prediction accuracy. This was supported by field verification which revealed 100% prediction accuracy for the



A: Building Density | **B: Population Density**

Figure 6. Building and population density

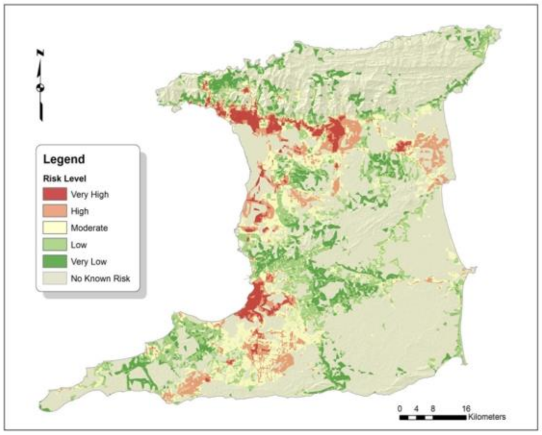


Figure 7. Map of population risk to flooding in Trinidad

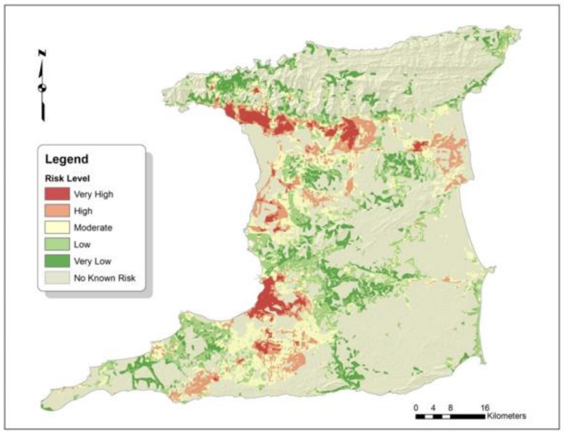


Figure 8. Map of building risk to flood in Trinidad

Table 4. Flood building risk (Sum of land area under each risk level)

Risk Level	Area (ha)	% of Trinidad Urban Land Mass
Very Low	36928.4	20.9
Low	47860.6	27.1
Moderate	50806.5	28.8
High	28597.0	16.2
Very High	12407.1	7.0

Table 5. Flood population risk (Sum of land area under each risk level)

Risk Level	Area (ha)	% of Trinidad Urban Land Mass
Very Low	37032.63	21.0
Low	48151.83	27.3
Moderate	50289.04	28.5
High	27925.3	15.8
Very High	13050.5	7.4

sites considered. The study provides a foundation on which further, more rigorous hydrological and statistical methods such as logistic regression can be developed. The causative model development can be improved with the inclusion of data on additional causative factors, flood extent and intensity data. As such the use of the maps developed in this study should not be used for the following purposes:

- Prediction of time or size of a landslide or a flood event
- Engineering designs of roadways, bridges, and buildings
- Selection of sites for the location for critical facilities
- Detailed land use planning
- Identification of most hazardous zones within the floodplain
- Detail site analysis and evaluation
- Property assessment
- Negotiating of insurance premiums

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