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Likelihoods of Flood Hazards and Risks Using GIS-Based Analytical Hierarchy Process (AHP)

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Abstract: *Flood, as a hydrological phenomenon caused by a significant surge in the runoff water that overwhelms and overflows a drain, river, or stream, usually after heavy rainfall, tropical storms, and cyclones, has various impacts on Caribbean islands. Its adverse impacts include loss of human and domestic life, deteriorating public health, and damages to properties, and croplands. The Caribbean island of Jamaica is located in the geographical area where the current and forecasted hydrological, physical, climatic, and human conditions are set for probable flood hazard occurrences. Therefore, this study aimed at estimating the likelihood of flood hazard occurrences, and associated risk for Saint James Parish, Jamaica, and its port city of Montego Bay. It deployed a rather simple but robust method involving the Geographic Information Systems (GIS)-based Analytical Hierarchy Process (AHP) of multicriteria analysis. The AHP enlisted, prioritized (ranked), and weighed the criteria (i.e., land cover, soil, drainage density, elevation, slope, rainfall, land use, and population data) and integrated with the Weighted Sum Model (WSM) to arrive at the estimation. Accordingly, 36% of the study area is assessed to experience a very high and high probability of flood hazard occurrences. On the other hand, 25% of the study area is subjected to risks of high and very high exposure and vulnerability to the hazard. Wetlands are the most adversely impacted land-use and landcover types (i.e., 100%) followed by Built-up areas (i.e., 74%) and agricultural croplands (24%), indicating the unique vulnerability of the area to the hazards, and damages thereof. The GIS-based Multicriteria Analysis of flood risk factors of Montego Bay and surrounding areas revealed varying likelihoods of flood hazard occurrences, exposure, and vulnerability warrants policy-making attention. The expansion of public education on flood hazard areas—that is, areas where there is a 1 percent chance of a flood occurring in any given year (a 100-year flood)—efficiency in response time, knowledge of flood control regulations, planning, and preparedness—is also advised in-order-to enforce citizens' environmental responsibilities.*

Keywords: *Analytical Hierarchy Process (AHP), Flood Hazards, Flood Risk Factors, GIS, Multicriteria analysis, Risk Assessment*

1. Introduction

According to the US Federal Emergency Management Agency, a flood is a natural hazard when the water level in the rivers, lakes, or seas rises and overflows onto the surrounding drylands, banks, shorelines, or coastal lines. Such phenomena are caused by the combination of various hydrological, physical, climatic, and human factors [1,2]. For example, rivers and flash flooding are caused by heavy rainfall, and severe storms, whereas coastal and shoreline floods are caused by rising waves and tides, which occur when sea-level rise by the surge of storms, hurricanes, or winds. Moreover, rapid and excessive rainfall combined with poor soil drainage, and deforestation realize various forms of inland flooding. Other contributing factors are also increased population settlement in flood-prone areas (i.e., coastal areas and floodplains); adverse human modification of the river channels, and changing climate [3].

Floods, as natural hazards, cause widespread destruction to humans, domestic animals, and properties [4,5]. According to the global database of worldwide natural hazards (i.e., Emergency Events Database (EM-DAT)), accounting for 43% of all-natural hazards, floods affected nearly 2.5 billion people around the world and killed 224,000, between 1994 and 2013 [4]. The estimated worldwide damage to the economy is worth US$936 billion. According to Chan et al. [5], the average one-year flood damage in North and South American, Southeast Asian, and African economies amounts to US$5 billion. In the

Caribbean region, where the Jamaican island is located, 198 food events were recorded between 1990 and 2017 [4], more than 6 million people were impacted, and economic damage worth USD 1.5 billion was caused.

The situation in Jamaica itself is not any different [6,7,8,9]. Jamaica endured serious social and economic devastation from the recorded 119 flood events during the same time. Accordingly, damages worth US585 million to roads and bridges, US351 million to housing US235 million to agricultural croplands, and US48 million in electrical installations have occurred [7]. The 2017 flood in Saint James Parish, Jamaica (i.e., the study area), destroyed roads and bridges, drowned homes and swept away cars and other locomotives [10]. Also, the recent April 2022 flood in Montego Bay City left a record of devastating harm to the low-lying city's infrastructures, residences, and other sectors of the economy.

The projected climate change and population growth of the region also dictate a gloomy future outlook [6]. The forecasted change characterized by an increase in rainfall intensity, violent storms of tropical cyclones, and deforestation of the mountainous landscape, is expected to generate a large volume of runoff that would further overwhelm the existing draining system and heighten the likelihood of devastating flood hazards. Besides, urbanization is converting the natural ground into hard surfaces, pushing settlements into flood-prone areas (i.e., floodplains), and exposing more population to risks of flood hazards. Moreover, inappropriate solid waste disposal is restricting the volume as well as the ease of runoff flow, exacerbating the risk of flood hazards in the region [8].

Several studies have been devoted to flood hazard mapping, forecasting, and risk assessment in Jamaica [11, 12, 13, 14, 15, 16]. For instance, Nandi et al. [6] mapped flood hazard areas for Jamaica using combined principal component analysis and logistic regression; while Glas et al. [12] assessed flood damages for Annotto Bay, Jamaica using GIS. Similarly, Wilson et al. [14] predicted exposed and vulnerable areas of Negril, Jamaica to flood risk under projected climate change scenarios; while Glas et al. [13] conducted nationwide mapped forecasted flood areas and risks. Although the studies were consequential, they were not specific to St. James Parish and the utility of the Analytical Hierarchy Process (AHP) of Multi-criterial Analysis (MCA) presents a reliable approach for assessing flood hazards and risk for the region.

Therefore, the main goal of this study is to assess the likelihood of flood hazard occurrences, exposure, and vulnerability in Saint James Parish, Jamaica, and its Port city of Montego Bay. It is to help the local and regional government's efforts to reduce flood hazards and impacts by controlling flood patterns and distribution. This kind of study can assist in the adoption of policies that regulate the use of flood-prone areas; reduce the probability of flood occurrences, and hazard preparedness. GIS-based AHP of MCA is the widely used approach for modeling flood hazards and risk assessment ([e.g. 17, 18, 19,]). The approach is also credited for its capability to evaluate the region's environmental and socioeconomic vulnerability to the risks of flood hazard events [20, 21, 22, 23].

2. Materials and Methods

2.1. Overview of the Study Area

The study area, Saint James is one of the 14 Parishes of Jamaica, the third-largest island in the Caribbean Sea (Fig., 1). It covers a 4,244 mi ²land area with 146 miles in length and 22 to 51 miles in width. It is situated 100 miles west of Haiti and 90 miles south of Cuba. St. James Parish and its port city Montego Bay is one of the most beautiful parishes in Jamaica and is widely considered the country's tourist capital. It is home to some of the most beautiful beaches and resorts as shreds of evidence of its great potential destination for international tourism.

Climatically, surrounded by the warm waters of the Caribbean Sea and its latitudinal location, St. James experiences a tropical climate. The average annual temperature is 27 ℃, although mountains create local variability such that mountain peaks experience minimum temperatures as low as 4 ℃, while the low-lying areas and beaches experience as high as 32 ℃. There is a minimal variance in temperature from season to season. The Rainfall is moderated by the trade winds, which are predominant throughout the year. It receives rainfall ranging from 750mm in the hot and dry savannas in the northwest area to 2500mm in the south and southwestern highlands. The mountain peak areas may receive as high as 3,300mm of rain. The rainy season is between October and May, while tropical cyclones and hurricanes can bring severe storms anytime in the summer months of June to September.

Generally, the cumulative effect of the precipitations and intense storm surges from hurricanes are

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determinants for the occurrence of flood hazards in the region. Additionally, the mountain topographies, accelerate the drainage of excess runoff water to the low-lying settlement areas exposing sections of the Parish and its port city to the likelihood of frequent flood hazards.

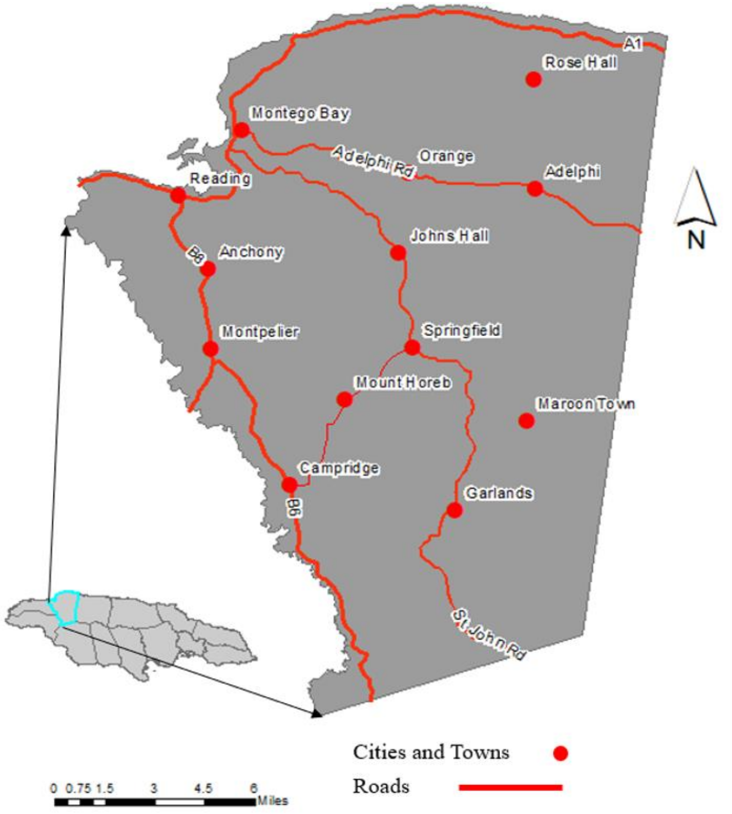

Figure 1: Geographical location of the study area

2.2. Data acquisition and description

Flood hazard zones are areas where a 1% chance of the probability for the occurrence of flood hazards of varying levels in any given year (100 years of flood). Several studies have identified factors contributing to flood hazards in a given area (e.g., [21,24]). These are Land Use/Land Cover (LULC), soil types, drainage density, elevation, slope gradient, rainfall, and population density factors.

2.2.1. Digital Elevation Model (DEM)

The Digital Elevation Model (DEM) of the St. James Parish, Jamaica, is obtained from the national map viewer (https://apps.nationalmap.gov/viewer/) of the United States Geological Survey (USGS). The USGS delivers high-quality DEMs, geo-rectified, and at the spatial resolution of 1 arc-second (30*30m). The Shuttle Radar Topography Mission (SRTM) acquired the DEMs and spatially referenced to the geographic coordinate system on the NAD 83 datum at the time of delivery. The DEMs were then subsetted into the boundary of the study area before being used for indexing flood hazard factors such as elevation, slope gradient, and drainage density. Indexing the data is a pre-processing operation conducted to prepare factors (criteria) that are inputted into the model.

2.2.2. Elevation

Elevation influences the amount of precipitation received and EvapoTranspiration (ET) lost from a given area and hence controls the likelihood of flood hazards in the region [25, 26]. Additionally, lowland areas are more vulnerable to flood hazards compared to highland areas. The study area has an elevation ranging from 0 to 750 m above sea level (Fig., 2). The elevation data was classified into 5 elevation categories for ranking and indexing using the natural-break classifying algorithm. The algorithm categorizes based on the natural groupings found in the distribution of the data such that index 1 represents uplands with a very low probability of flood hazards rank, while 5 is bottomlands with a very high probability rank (Table 1; Fig., 3).

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2.2.3. Slope gradient

The slope gradient influences the surface run-off portion of precipitation. It determines the size of the rainwater that would be partitioned into runoff water. A Steeper slope gradient partitions more rainfall into surface runoff and also drains it quickly downslope compared to a gentle slope gradient. Flatter lands, on the other hand, are areas where the surface runoff ponds bring about floods. Hence, areas with a low percent slope gradient are more prone to flood hazards compared to areas with a steep slope gradient [e.g., [26, 27]].

The slope gradient was calculated as a function of the rate of change in the elevation values over a distance and is given by:

$$\text{Slope (radian)} = \text{ATAN}\left(\sqrt{\left([dz/dx]^2 + [dz/dy]^2\right)}\right)$$

Where ATAN is the Arc tangent function; dz/dx is horizontal distances and dz/dy is the vertical direction distances from the center cell.

The slope gradient of St. James Parish ranges from 0 – 73.3% (Fig., 2), and it was categorized into 5 classes using the natural-break classifying algorithm for ranking and indexing. The indexing was made such that 1 represents areas with a very low slope gradient rank, while 5 represents areas with a very high slope gradient (Table 1; Fig., 3).

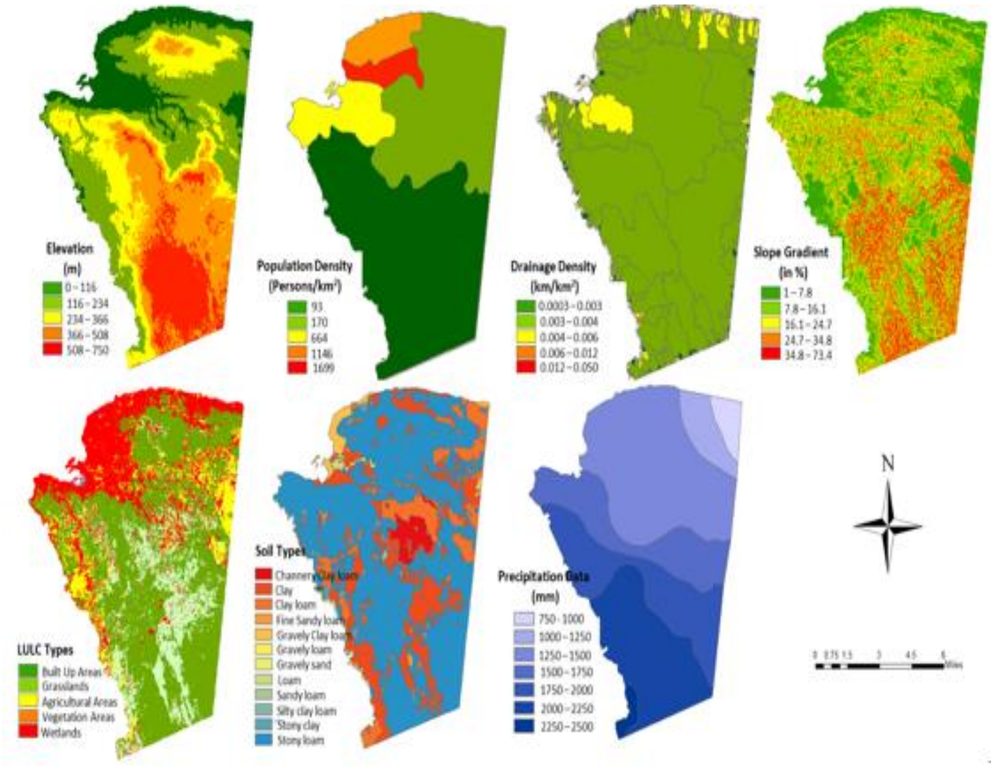

Figure 2: The factors affecting the occurrences of flooding hazards

2.2.4. Drainage Density

Drainage density affects flood hazard occurrence such that higher density implies a higher probability of flooding [17, 21, 28]. Drainage density (Dd) is calculated from the DEM using the hydrologic modeling tool in ArcGIS. It is then determined by dividing the unit length of the streams in the watersheds by the areas of the corresponding watersheds, which is given by:

$$Dd = \frac{\sum L}{A_{watersheds}}$$

Where Dd is Drainage density, L is the unit length of the streams in the watersheds and Awatersheds is the area of the watersheds in square units.

The study area has drainage densities ranging from 0 to 0.52 km/km^2 (Fig., 2). It is classified into 5 classes for ranking and indexing, where index 1 represents areas with very low drainage density rank, and 5 is the areas with very high drainage (Table 1, Fig, 3).

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2.2.5. Rainfall Data

Rainfall partitions into surface runoff and infiltration. Surface run-off, which causes flooding, occurs when the soil is saturated or is falling at a rate that exceeds soil infiltration. The rainfall data of the study area was obtained from the State of the Jamaican Climate [29] (Climate Studies Group, Mona (CSGM), 2017). Generally, the rainfall in the study area ranges from 750mm to 2500mm (Fig., 2). Higher rainfall is associated with the likelihood of Flood hazards occurrence and hence the rainfall data is classified into 5 categories for ranking and indexing. Index 1 represents the areas of very low rainfall rank, whereas 5 is the areas of very high rainfall (Table 1; Fig., 3).

2.2.6. Soils Data

Soil properties such as thickness, permeability, water-holding capacity, and moisture content influence the rainfall-runoff process [30]. These properties are mainly controlled by the soil textural classes. Generally, coarse-textured sandy soils have a bigger pore space, which allows higher soil permeability or drainage versus fine-textured clayey soils with low soil permeability. Low soil permeability is associated with high surface runoff and a very high vulnerability to flooding compared to high-permeability soils. The soil textural class data of the study area was obtained from ArcGIS online. It was produced by an anonymous GIS group and 13 soil texture classes were identified for the study area (Fig., 2). Accordingly, the textural classes were indexed such that Gravely sand soils are indexed 1; Stony loam, gravelly loam, and sandy loam are indexed 2; Fine sandy loam and Loam are indexed 3; Silty clay loam, Channery clay loam, and Gravely clay loam are indexed 4; and Stony Clay, Clay, and Clay loam are indexed 5. The ranked soil map was rasterized in preparation for integration into modeling the flood hazard and risk assessment in the region (Fig., 3; Table 1).

2.2.7. Land Use/Land Cover (LULC) Data

The LULC data is developed after acquiring the raw Landsat Thematic Mapper TM satellite image from the Earth Explorer (https://earthexplorer.usgs.gov/). The Earth Explorer is a data portal developed by the USGS to provide downloadable satellite data (including the Landsat TM), free of charge, online. The Earth Explorer delivers the image that is corrected for its systematic as well as terrain distortions, and spatially referenced on the Universal Transverse Mercator (UTM) coordinate system. An attempt was made to select legacy imagery in the interest of obtaining a quality image over currency. The image was clipped to the bounds of St. James Parish, Jamaica, in preparation for the supervised image classification exercise to produce the LULC data.

Five LULC categories were classified, (Fig. 3) namely: vegetation areas, grasslands (fields), agricultural areas, built-up areas, and wetlands [31,32]. Literature informed the ranking of the categories in the order of their vulnerability to the impacts of flood hazards [20, 21]. Accordingly, the wetland was ranked very highly vulnerable LULC followed by Built-up areas, which ranked highly vulnerable, and the Agricultural lands, which are moderately vulnerable. The vulnerabilities of Grasslands and Vegetation areas were ranked low and very low; respectively (Table 1). These vulnerability rankings were then indexed with numbers from 1 to 5, where 1 represents Vegetation areas with very low vulnerability and the wetlands with very high vulnerability.

2.2.8. Population Density (Pd)

Population data was acquired from the Statistical Institute of Jamaica (STATIN). The STATIN is an agency run by Jamaica’s Ministry of Finance and Public Services to collect, compile, analyze, and publicize statistical information related to the activities and conditions of the Jamaican people. District boundary data was obtained from the Electoral Commission of Jamaica (ECJ). Population Density (PD) for the districts was calculated as follows.

$$Pd = \frac{P}{A}$$

Where P is the number of people living in a district of the Parish and A is the corresponding area of the district.

The population density ranged from 93 - 1699 people per km2 (Fig., 2). Exposure to flood hazards is more significant when the hazard occurs in densely populated districts than in sparsely populated districts. Therefore, the density data were classified into 5 categories, where rank 1 represented very sparsely populated districts, while 5 is very densely populated districts (Table 1; Fig., 3).

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Table 1: Parameters (elements) of the flood factors and associated ranks in the order of their relative importance to flood hazard occurrences

Factors	Weight	Result of classification based on Natural Break	Ranking	Hazard Levels
Drainage Density (km/km^2)	0.08	0.00 - 0.12	1	Very Low
		0.12 - 0.31	2	Low
		0.31 - 0.41	3	Moderate
		0.41 - 0.48	4	High
		0.48 - 0.52	5	Very High
Elevation Data (m)	0.35	0.00 - 116	1	Very High
		116 - 234	2	High
		234 - 366	3	Moderate
		366 - 508	4	Low
		508 - 750	5	Very Low
LULC Types	0.05	Vegetation Areas	1	Very Low
		Grasslands (Field)	2	Low
		Agricultural Areas	3	Moderate
		Built-Up Areas	4	High
		Wetlands	5	Very High
Precipitation (mm)	0.14	750 - 1000	1	Very Low
		1000 - 1250	2	Low
		1250 - 1750	3	Moderate
		1750 - 2000	4	High
		2000 - 2500	5	Very High
Slope Gradient (%)	0.35	0 - 7.78	1	Very High
		7.78 - 16.11	2	High
		16.11 - 24.75	3	Moderate
		24.75 - 34.82	4	Low
		34.82- 73.38	5	Very Low
Soil Types (Texture)	0.04	Gravely sand, Stony loam	1	Very Low
		Gravely loam, Sandy loam	2	Low
		Fine sandy loam, Loam	3	Moderate
		Silty clay loam	4	High
		Channery clay loam, Gravely clay loam, Stony Clay, Clay, Clay loam	5	Very High

2.3. Research Methodology

2.3.1. Integration of Analytical Hierarchy Process (AHP)

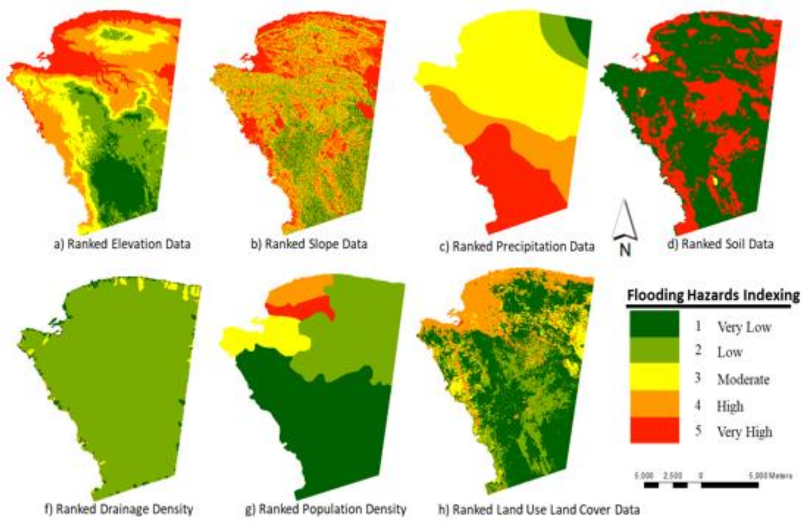

Figure 3: Map showing the ranking of the flooding hazard factors

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The AHP is a multicriteria decision-supporting approach that uses a hierarchical structure of criteria (factors) to address the decision-making endeavors of competing interests [33, 34]. The approach allows users to establish an indexed hierarchy of criteria (factors), and determine literature, expertise, and local knowledge-supported prioritization of the factors affecting flood hazards, and risk assessments [17, 20, 21, 24]. Accordingly, elevation data and slope gradient are prioritized (ranked) on top followed by precipitation, drainage density, LULC, and Soil types, in the orders of their importance.

The weights associated with ranked (prioritized) factors were estimated based on the standard 9-point pairwise comparison scale developed by Saaty, [35.36]. The scale has 5 categories in the order of the factor's (criterion's) importance. Accordingly, scale 1 means both factors are equally important, while scales 3, and 5 mean that one factor has moderate and strong importance over the others; respectively. Likewise, Scale 7 and 9 are when one factor is very strong and extremely important influences as compared to the others, respectively (See Table 2). A decision rule is the end product of the pairwise comparison. The modeling of the probability of flood hazard occurrences and risk assessment was made by applying the decision rule, (i.e., Weighted Sum Model (WSM) given by:

$$V = \sum_{j} W_j R_{ij}$$

Where: V is the total score of an area with regards to vulnerability to flooding hazards and risks, W_j is a relative weight of the j_{th} factors and R_{ij} is the indexed factors.

2.3.2. Validation Methods

The robustness of prioritization; the integrity of the pairwise comparison exercise; and the decision rules thereof, were checked through automated AHP and Consistency Ratio (CR). Automated AHP is a software that is developed to implement Saaty's pairwise comparison, online [37], whereas CR is an index used to determine whether the output of the calculated pairwise comparison matrix is consistent. CR is given by:

$$CR = \frac{CI}{RI}$$

Where CI represents the consistency index and RI is the random index. It is the tabulated indices whose values vary according to the number of criteria involved in the decision rule [38] (Table 2).

$$\mathrm{CI} = {(\lambda_{maz} - n)}\Big/{(n - 1)}$$

Where λ_{maz} is the sum of the product of the column of the comparison matric and the corresponding weight, whereas n is the number of factors considered. The decision rule is robust if the CR is ≤ 0.1 and the CR is $\leq 10\%$ [21].

3. Results and Discussion

3.1. Decision rules and modelling flood hazard

The 9-point Saaty's scale for the factors affecting the chances of flood hazard events in St. James Parish, Jamaica determined. Accordingly, elevation and slope gradient were assumed to have an equally important influence on the likelihood of flood occurrence. Additionally, they are expected to exert an extremely important influence over the soil types and the LULC types; and moderately and strongly important influences over the precipitation and drainage density; respectively. This is even though rainfall and drainage density are directly responsible for runoff generation and flood hazards thereof, in the region. In Montano Bay city and surrounding areas, flood hazards often occur in low-lying and flat areas as compared with areas on hills as well as steeply slope gradients, regardless of the precipitation received. Additionally, the spatial variability of drainage density is marginal to explaining the patterns of flood hazards in the region. The scales applied to these factors in St. James Parish Jamaica corroborate the scales reported elsewhere [20, 21, 22].

The result of the pairwise comparison matrix is presented in Table 2. The average weights were calculated such that Elevation Data and Slope Gradient weighed 0.35, while Precipitation weighed 0.14. On the other hand, Drainage Density weighed 0.08, while the LULC and Soil Types weighed 0.05 and 0.04; respectively. The weighted sum model (WSM) applied to determine the flood hazard of the area is given by:

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Flood hazard = 0.35 [Slope] + 0.35 [Elevation] + 0.14 [Precipitation] + 0.08 [Drainage Density] + 0.05 [LULC Types] + 0.04 [Soil Types]

Table 2: Pairwise as well as average weights of Flood hazard factors as per AHP multi-criteria weight determination

Flood Hazard factors	Average Weight (Calculated)	Average Weight (online tool)	Difference
Elevation Data	0.35	0.35	0.0
Slope Gradient	0.35	0.35	0.01
Precipitation	0.14	0.14	0.0
Drainage Density	0.08	0.08	0.0
LULC Types	0.05	0.05	0.0
Soil Types	0.04	0.03	-0.01
Sum	1	1	0.0

The modeled areas with varying levels of the likelihood of flood hazard occurrences are shown in Fig. 4. According to Fig. 4, the parish experiences the likelihood of flood hazard occurrences ranging from very low to very high likelihood. The most common flood hazard probability level is low (i.e., 154 km^2) followed by very low (i.e., 140km^2) and moderate levels (i.e., 131km^2). These levels cover 23%, 21%, and 20% of the study area; respectively. Roughly, areas with a very low to low likelihood of flood hazard occurrences are found in the southern, central, and northeastern parts of the parish. On the other hand, a very high and high probability of flood hazard events occurring on 120 km^2 (i.e., 18%) and 115 km2 (i.e., 17.4%) of the study area, respectively. These are mainly located in Montego Bay city, other settlements, and areas along the Great River on the west side of the parish. In general, 36% of the study area experiences a very high and high probability of flood hazard occurrences; 45% of the study area experiences a very low or low probability of flood hazards.

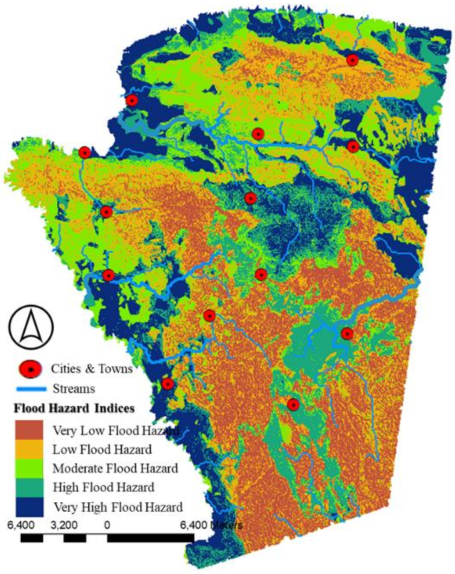

Figure 4: Map showing the probability of flood occurrences

3.2. Decision rules and modelling flood hazard

The validation of the modeled probability of flood hazard occurrences for Montano Bay city and surrounding areas was made with the Consistency Ratio (CR). It is also validated by comparing weights of factors obtained through calculated and automated AHP. The result of the Consistency Ratio (CR) is presented as:

$$\lambda_{max} = (2.79 * 0.35) + (2.79*0.35) + (8.36*0.14) + (14.3*0.08) + (21.78*0.05) +(27*0.04) = 6.44$$

$$CI = {(6.44 - 6)}/{(6 - 1)} = 0.088$$

CI = 0.08, is less than the threshold CI is ≤ 0.1, indicating that the pair-wise matrix scaling of the factors and their corresponding weights are robust.

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RI (Random Index) = the six flood hazard factors for which the pairwise comparison made is 1.24 (Table 3).

$$CR = \frac{0.08}{1.24} = 0.07$$

CR = 0.07, is less than the threshold CR is ≤ 0.1, again indicating that the pair-wise matrix and weight calculated thereof for the flood hazards factors for St. James Parish, Jamaica is robust.

Table 3: Table of the values of random indices to their corresponding number of factors considered for decision making.

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Additionally, Table 2 presented the comparison of the calculated and automated weights. The weights were more or less identical, again indicating the robustness of the prioritization, ranking, scaling, and the weight generated thereof. The only differences, which were in the order of 1%, are between the weights determined for the slope gradient and soil types.

3.3. Assessing the risks and impacts of the events of the flood hazards

Fig., 5 shows the assessed risks of exposure and vulnerability of people and properties to the high probability flood hazards. The WSM applied to develop the Flood Risk Assessment areas is given by:

Flood Risk Assessment areas = [0.33 x flooding hazard] + [0.33 x population density] + [0.33 x Land Use Types]

According to Fig. 5, the region is subjected to exposure and vulnerability ranging from areas with very low to very high risks. However, the majority of the study area (i.e., 199km^2), is subjected to low-risk exposure, followed by areas with moderate (i.e., 156km^2) and very low (i.e., 135km^2) risk. These risk exposures cover 30%, 24%, and 21% of the study area; respectively. Areas with a high and very high risk of flood hazards are 96 km^2 and 74 km^2, representing 14% and 11% of the study area; respectively. Therefore, 25% of the study area is exposed to a risk of high and very high flood hazards, corroborating the reports of flood hazards in the region [6,7,23]. For example, it is consistent with the reports [9], in which flood hazard events destroyed roads and bridges, washed away automobiles and other locomotives, drowned homes, and damaged croplands.

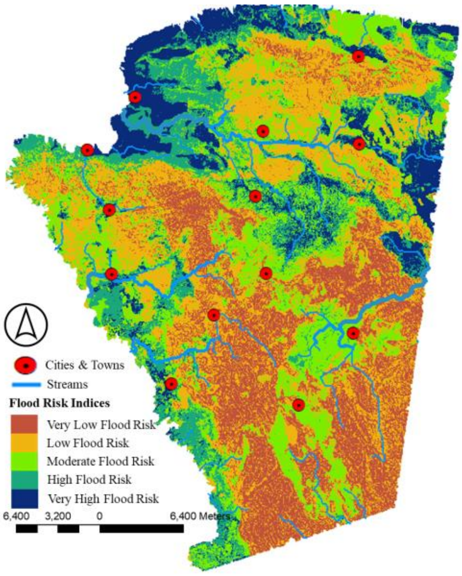

Figure 5: Maps showing varying adverse effects of flood hazards

Lastly, Fig., 6 shows the impacts of flood hazards on the region's people and properties. Accordingly, the largest impacted LULC type is the built-up and settlement areas, accounting for 74% of all affected areas in the Parish. This is 55 km^2 of the total 152 km^2 build-up areas of the region, indicating that 36% of the build-up areas are affected. Likewise, the second most impacted LULC type is croplands, representing 24% of the impacted land. This is again 18 km^2 of the total 115 km^2 of croplands in the Parish, showing that 16% of the croplands are impacted. Although wetlands encompass only 0.2% (i.e.,

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1 km^2) of the study area, all wetlands (i.e., 100%) are also damaged by the risk of flood hazards. These findings corroborate documented impacts of flood hazards in Jamaica, in recent years [7], where, flood events that occurred between 1988 and 2012 caused enormous economic damages to the country. The economic cost of damages to infrastructure (i.e., roads and bridges), housing, and agricultural lands amounts to USD1.171 billion. Additionally, it corroborates the budget announcement made by the government of Jamaica to earmark a billion USD for flood mitigation, prevention, and preparedness [39].

3.4. Implications of the impacts and recommendations

The modeled likelihood of flood hazard occurrences and impacts is significant in providing a baseline for more in-depth knowledge and understanding of what the region is up against. It is also critical in offering possible solutions to combat the harms of the hazard through management, preparedness, and reduction of the risk of flooding in the study area, and beyond. Risks of exposure and vulnerability to flood hazards are consequential for investors, developers, and planners across the region, especially for identifying high-risk areas for settlement, development, and structural installations. Therefore, the following recommendations were made.

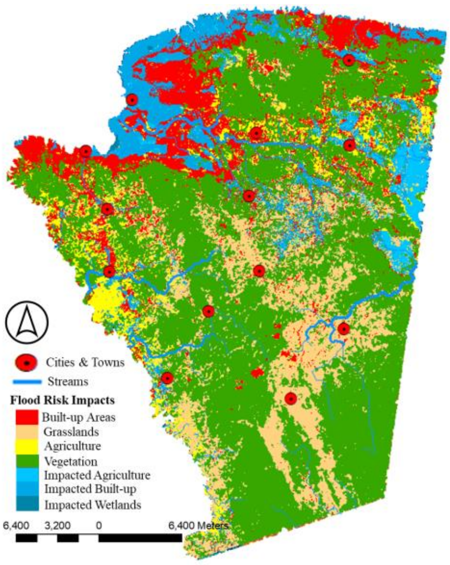

Figure 6: Maps showing the exposure and vulnerability risks of flood hazards

First, inadequate environmental responsibilities characterized by poor garbage and debris disposal and landfills in the river or gully course are characteristic of the region [40] (Rodriguez-Moodie, 2022). Consequently, channel morphology is modified to restrict the volume of runoff water the channel can carry thereby heightening the likelihood of flood hazard events. Therefore, appropriate solid waste management and sanitation practices, centralized garbage collection, and landfill mechanisms are recommended to alleviate the problem. Additionally, re-engineering of the gully infrastructure (i.e., including cleaning and freeing the gullies (channels)), before, major rainfall events can lessen the likelihood of flood hazard occurrences.

Secondly, the encroaching urban development in the natural areas, the conversion of the porous surface into pavement, and the increased inhabitance of the floodplains have risked the exposure and vulnerability of the population and properties to flood hazards. Therefore, apart from re-engineering the gully infrastructure, it is recommended to embark on the city's green area development and arrest the continued building of houses and commercial buildings along the flood-prone areas. It is also worthwhile to adopt relocation policies for the houses and businesses built on the floodplains.

Thirdly, to reduce damage to traffic, deploying an effective traffic early flood warning system is important. Similarly, paving roadways with permeable materials and increasing roadside storm drainage to ensure adequate removal of runoff water are advised to minimize damage to roads and bridges. Furthermore, constructing a street gutter to collect and divert rainwater that otherwise would be flash flooding on the roads is recommended.

Lastly, in response to the adverse impacts of floods, raising public awareness on the probability of flood hazard events (i.e., areas having a 1% probability of flood occurrence in any given year (100 years flood)), and risk areas of the region are critical. The population has to be educated with knowledge of quick responses, flood control regulations, prevention planning, and preparedness. It is also critical to enforce citizens' environmental responsibilities, especially on or along gullies and channels.

4. Conclusions

The assessment of the likelihood of flood hazard occurrences, exposure, and vulnerability has produced results that shed light on the problem and triggered expert recommendations. Firstly, the factors affecting the likelihood of flood hazard occurrences were determined. Accordingly, six outstanding factors were identified and then prioritized, ranked, and scaled such that elevation and slope gradient ranked on top followed by rainfall, drainage density, LULC, and Soil types, consecutively, in the order of their importance.

Additionally, the applied pairwise comparison matrix of AHP generated average weights for the factors ranging from 0.04 for soil types to 0.35 for the elevation data and slope gradient. The weight generated from AHP pairwise comparison and the resulting decision rules were consistent as evidenced by CI = 0.08 (i.e., CR is ≤ 0.1), CR = 6% (i.e., CR is ≤ 10%), and the marginal difference (i.e., 1%) between calculated and automated pairwise comparison matrices. The WSM of the factors affecting the likelihood of flood hazard occurrences found that the region endures varying likelihoods. Accordingly, while 44.5% of the study area experiences very low and low probability; 35.6% endures the high and very high odds of hazardous flood events. This finding is significant because the high probable flood hazard areas coincide with the populous port city of Montego Bay and other settlement towns of the parish.

Similarly, the assessed exposure and vulnerability of properties and life to flood hazards showed areas with varying risk levels. High and very high-risk levels were pronounced in 25% of St. James Parish. The majority of the study area (i.e., 51%), however, is marginally exposed to such risks. Wetlands are the most adversely impacted LULC types (i.e., 100%) followed by Built-up areas (i.e., homes, properties, and infrastructures) (i.e., 74%) areas and agricultural croplands (24%). Lastly, this study has also highlighted recommendations for flood mitigation, prevention, and preparedness to secure safer, and sustainable urban development in the region.

Although these are significant findings, the research has limitations that can be addressed by future works. First, there are various available approaches for flood hazard analysis and risk assessment, ranging from GIS and remote sensing-based modeling to hydraulic modeling and simulations. These mechanistic modeling approaches could improve the results; however, their successful utilization is contingent on the availability of quality and complex data, and extensive technical capabilities. The use of AHP, in this study, is a pragmatic response to its less data requirement, and simplicity while having a reputation for delivering reliable results. Secondly, the research used some published secondary data and high-resolution imagery for ground-truthing. Therefore, future studies with hydraulic modeling and simulations, and calibrations with ground truthing may improve the results of this study.

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