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A MULTICRITERIA GIS-BASED ANALYSIS MODELLING AND ANALYTICAL HIERARCHICAL PROCESS (AHP) FOR FLOOD RISK MAPPING IN THE DELIMI CATCHMENT, JOS, PLATEAU STATE, NIGERIA

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ABSTRACT

This study identified and mapped areas vulnerable to flood risk in the Delimi River Catchment of Jos area, Nigeria. The ALOS-PALSAR DEM (12.5m) from the Alaska Satellite Facility downlinks was employed to generate relevant morphometric parameters namely corridor, slope, and elevation which are identified drivers of floods in the catchment, while the area coverage of each soil type within the study catchment was sourced from FAO Digital Soil Map of the World (DSMW) and Building Form shapefile from Eagle Eye Geographics. The multi-criteria Analysis model and the Analytical Hierarchical Process (AHP) were employed in a Geographical Information system (GIS) environment using the ArcMap 10 Software to map and synthesize these drivers. The hierarchy ratings of the drivers for the catchment based on expert opinions are corridor, slope, elevation, and soil type (38, 37, 21, and 4 percent respectively), and a consistency ratio of 0.06. Results showed that about 9.3 km^2 (5.7%) of the catchment area is at risk of flooding. This at-risk area accommodates 5,306 buildings out of which 445 buildings are within the Very High-Risk zone. At the end of the study, the area at risk of inundation was delineated and the number of buildings within the risk zone was ascertained. This information will assist decision-makers and watershed managers in effectively developing strategies for the control and mitigation of future flood occurrences in these areas of the catchment.

Keywords: Multi-Criteria Analysis, Analytical Hierarchical Process, Flood Risk, Delimi Catchment.

INTRODUCTION

According to Mokhtari, Faridi, Masoodi, & Ahmadi (2023), Floods are disasters prevalent in many countries of the world; often occurring on an annual basis with significant human and economic losses. They are perhaps the biggest challenge that needs to be examined at all scales (global, regional, and local). They are natural processes that can happen at any time in a wide variety of locations and cannot be entirely prevented. While the major driver of floods is excess rainfall, many other drivers from human activities such as land degradation; deforestation of catchment areas; sprawl, and increased population density along riverbanks, rapid urbanization of flood-prone sites exacerbate floods leading to a general modification of urban stream basins (Odufuwa et al., 2012)

Mans 'quick-fix' developmental practices of the past and some uncontrolled practices of the present have resulted in undesirable alterations to the hydrology, morphology, and ecology of urban watersheds and streams. As these urban sheds become further urbanized, they grow more hydrologically active. The resultant effect is that natural flows that occurred during pre-development periods will become more frequent and severe, thereby altering the natural flow regime and floodplain extent of streams; invariably imposing greater risks of flooding on surrounding riparian inhabitants (Ciszewski & Grygar, 2016). Munich (2002), Pelling (2003), and Guarín, Westen, and Montoya (2004) acknowledged that the problems relating to flooding and the vulnerability of a population are on an upward increase in recent decades due to several factors including climate change, changes in land use, urbanization of flood-prone sites, squatter settlements and sub-standard constructions, and increased household density.

Urban areas, which are located within catchments, are more frequently exposed to flooding, especially in developing countries (Laka & Dabi, 2021). As urbanization intensifies, natural surfaces are replaced by buildings, paved roads, and concrete surfaces, which do not allow water to percolate readily into the ground. The effect is that a large proportion of rainfall that should normally infiltrate into the soil or be intercepted by the vegetation may be delayed for some time before running off into the immediate environment as surface runoffs, invariably, the rivers swell and flood their banks (NEST, 1991). These problems have put and increased the variety of exposures at risk of floods within urban flood plains. Also, demographic increases combined with rising land prices due to shortages of building areas, have led to disorder and indiscriminate land use along river corridors, with different kinds of installations and infrastructures being built in areas at high risk of flooding (Ciaravino and Ciaravino, 2015). To, therefore, ameliorate these problems, there is a need for risk assessments.

The need for flood risk assessments has induced continuous scientific research both in the areas of methodologies and applications (Odufuwa et al., 2012; Adewunmi et al., 2017). Foremost are hydraulic-based assessments that employ river-gauged data and hydrological-based assessments that transform rainfall amount into quantity of runoff (Laka, 2023). Where gauged data are not available, or alternative methodologies such as Multi-Criteria Analysis (MCA) are applicable. River-gauged records are absent for the Delimi catchment, therefore necessitating the use of an alternative methodology, in this case, the MCA in a Geographical Information System (GIS).

GIS and Remote Sensing (RS) can be very effective in identifying the spatial component of flood and are used to measure and monitor the extent of flooded areas and provide a quantifiable estimate of the land area and infrastructure affected by flooding, and erosion (Adewunmi *et al*, 2017; Izinyon and Ehiorobo, 2011). According to Rahmati *et al*.(2016), Multi-criteria analysis (MCA) in a GIS/RS environment has been recognized as an important tool for analyzing complex decision problems, that often involve incommensurable data or criteria, they further hinted that these methods can be employed to integrate technical, environmental, and socio-economic objectives to achieve an optimal decision. These assertions are supported by Danumah *et al.* (2016) and Guarín *et al*. (2004), who hinted that this approach has in recent times become widely used to solve complex problems and to assess flood risk in particular. Examples of works done on flood risk assessment using MCA include those by Prinos (2008), Meyer et al, (2008), Musungu et al. (2012), Ismail and Saanyol (2013), van Westen (2015), Ashwajit *et al*. (2015), Rahmati et al. (2016), Danumah et al. (2016) and Samanta et al. (2016) amongst many others.

Adewunmi *et al.* (2017) and Rahmati *et al*. (2016) stated that the result of any GIS-based MCA is a map that allows for the ranking of risk areas, reveals the exposures vulnerable to flooding, and therefore, presents a useful tool for flood management, mitigation and planning the future direction of city growth. The approach localizes flood risk assessment following a general framework but in such a way that it allows for the main drivers of floods unique to a particular environment (or factors that may influence runoff and hence allow floods) to be broken down into criteria or parameters for which experts carry out paired comparisons and assign weight using the Analytical Hierarchy Process (AHP) developed by Saaty (1980) amongst other plausible processes. Danumah *et al.* (2016), Orencio and Fujii (2013), and Yahaya *et al.* *(*2010) indicated that the AHP is one of the best-known and most widely used MCA approaches and it is described as an understandable, cost-effective, and convenient method for flood risk assessment. The AHP assumes complete aggregation among several criteria and develops a linear additive model. Its uniqueness is its application in different studies in modelling situations of uncertainty without losing the subjectivity and objectivity of any evaluation measure.

Broadly speaking, the purpose of a flood risk assessment is to establish where and when risk is unacceptably high; and where and when mitigation actions would be necessary (Ntanganedzeni & Nobert, 2021). This would allow for the determination of the extent of damages if a flood hazard were to occur. Achieving this purpose will entail mapping out and quantifying zones and exposures at risk to floods in an area. The actual and potential damages and spatial extents of floods within the drainage basin of the Delimi area are yet to be determined. To reduce large-scale damages/losses arising from floods, to adequately plan for flood control/mitigation, and to plan the future direction of city growth in the study area, there is a need for a risk assessment that will map out flood risk zones. Thus, the general research concern of this study is to assess flood risk areas in the Delimi River basin of the Jos Plateau, Nigeria.

1) MATERIALS AND METHODS

2) The Study Area

The Delimi River is the headwater of the Delimi-Bunga river system, a sub-system of the Chad drainage basin. It originates from the rocky terrains of the Jos Plateau and traverses through four Nigerian states (Plateau, Bauchi, Yobe, and Borno) where it has acquired different names such as Delimi, Bunga, Jama’are, Hadija, and Kamadougou Yobe (Laka & Dabi 2021, Shettima, 1997), before finally emptying into Lake Chad (Figure 1 & 2). The river network presents a dendritic pattern and takes its source some 10 km southeast of Jos flows through the city, then north-eastwards through the Bauchi plains into the Jama'are - Komadugu Yobe river system. The catchment lies between latitudes $9^{O}52'$ N and 10^{O} $50'$ N and longitudes 8^{O} $45'$ E and 9^{O} $37'$ E (Figure 3). The spatial coverage of the basin area of study as generated in ArcMap GIS using the ALOS PALSAR Digital Elevation Model (DEM) is about 163.00 km^2. The source of the river is at a height of about 1,310 meters and the basin length is about 31.15km (Laka, 2023). The climatic conditions of the area are influenced by relief, latitude, and winds, giving lower temperatures and higher rainfalls compared to other places on equivalent latitudes. The catchment experiences the Koppen A_w climate, with an annual mean temperature of about 23.7°c; monthly temperature is highest in March and April with average temperatures reaching about 31°c while the coldest months are in December and January with average monthly temperatures sometimes dropping to below 20°C (Laka & Dabi 2021). The basin experiences two seasons: the wet, from April to October, and the dry, from November to March.

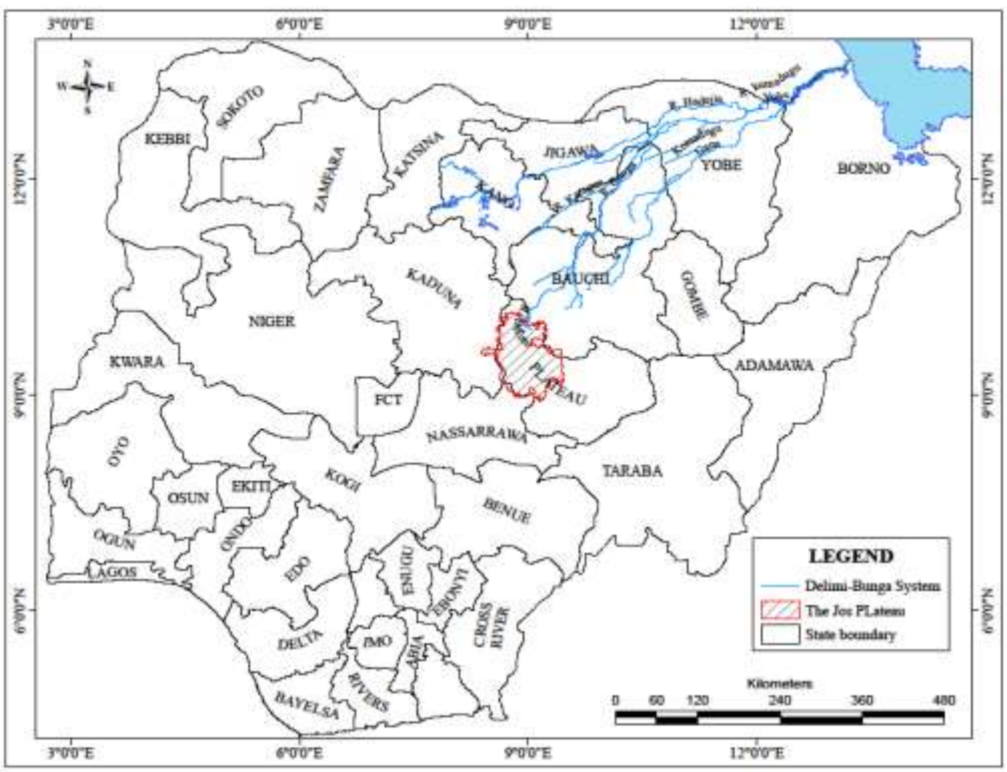

Figure 2: Delimi-Kumadugu River System, Nigeria

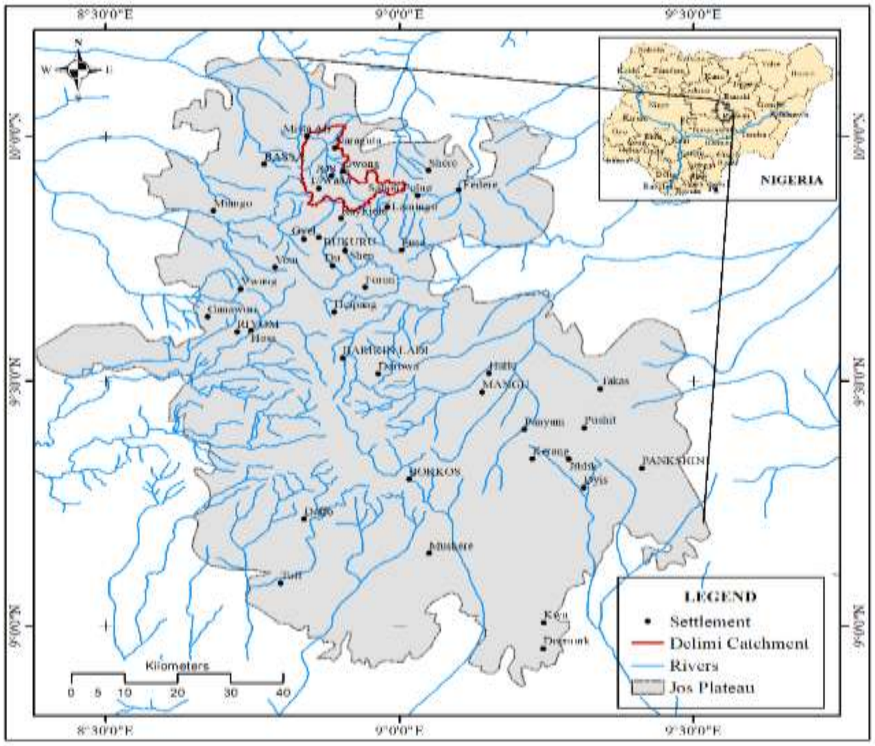

Figure 3: Delimi Catchment on the Jos Plateau

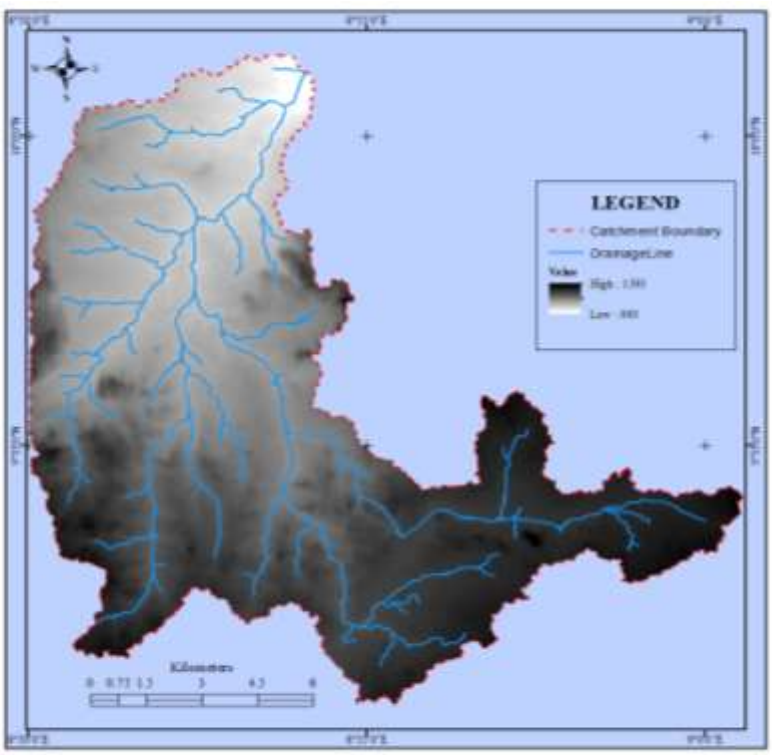

Figure 4: The Delimi Catchment on DEM

Rainfall in the catchment increases from 26mm in March peaks at about 286mm in August and gradually dips to almost zero in December. The catchment is situated in the northern Guinea Savannah vegetation zone of Nigeria. This zone is characterized by open woodland and tall grasses and is often referred to as parkland vegetation; however, the relief of the catchment modifies its vegetation to allow for montane vegetation with fringing woodlands or gallery forests found along some river valleys (Laka & Dabi, 2021) Anthropogenic pieces of evidence in terms of the morphology of built-up land cover, presents radiation of buildings from about the catchment centre to all directions.

3) Multi-Criteria Analysis in ArcGIS

The weighted criteria are synthesized in a GIS environment to generate flood risk zone maps. After which exposures within the high-risk zones can be ascertained and the elements at risk can be quantified for individual and aggregate values. Further explained as regards the analysis flow in multi-criteria are as follows:

- **Hazard Criteria (HC_i):** Since the flood is the hazard of study, the criteria or factors that influence flood potential in any study area are considered. No exact agreement exists on which drivers should be applied in an MCA flood assessment, however, some geomorphological characteristics used by numerous researchers (Ashwajit *et al*., 2015; Danumah *et al*., 2016), Samanta *et al*., 2016; Rahmati *et al*., 2016) indicates drivers important in flood hazard mapping as slope percentage, drainage density, soil types, distance from rivers, land use/land cover, altitude, the size of the watershed and the gradient of the primary drainage channel amongst others. It ought to be noted that criteria selection is to be restricted to very few numbers of independent parameters that uniquely relate to a particular environment and will yield the best results.

- **Elements at Risk (ERi):** Van Westsen (2015), defined elements at risk as all objects, persons, animals, activities, and processes that may be adversely affected by hazardous phenomena, in a particular area, either directly or indirectly. These include buildings, facilities, population, livestock, economic activities, public services, and the environment. Elements at risk are exposure to the hazard (in this case floods). For this study, the high-resolution satellite image was employed to take an inventory of exposures within high-risk zones ascertained earlier; this was supported by field data captured for both validation of risk zones and to ascertain asset types (Adewunmi *et al*., 2017). What is where and what services are being provided is assembled according to buildings, how many people live and work there; how they move under flood conditions are ascertained; and what are those essential facilities (lifelines, services, and emergency response units) that are within the risk zones.

The production of a flood risk map involves the generation of thematic layers and according to de Brito and Evers (2016), there is no consensus on the criteria that should be included in a flood susceptibility mapping when using an MCA. However, four causative factors - Corridor (distance to Streams), Slope, Elevation, and soil in this order of priority were considered salient causal drivers of floods for the study area. They are defined as follows:

Corridor (Distance to Streams)

The measure of distance to stream plays a very important role in defining areas susceptible to flooding. Zones closest to rivers are most affected by floods. To obtain this distance, the ALOS PALSAR DEM (12.5m) of the Delimi catchment was first converted to a point feature class using the *Conversion Tools: From Raster>To Points* with the raster as input while the output point feature class was named *DEM to Point.* Next, the distance of all points from the mainstream network was generated using the *Analysis Tools: Proximity>Near* on the Arc Toolbox with the *DEM to Point* as input and the river network for the catchment as the Near feature; generating method was left as the default planar method. The distances were generated in meters and the attribute table of the point DEM was populated accordingly. This was converted to raster using *Point to raster* tool and named *Distance to River*. After which it was reclassified into a corridor layer. The reclassification was based on a nine-class domain (See Table 1, Figure 4) with a value of 9 allocated to areas nearest to the streams and 1 to areas furthest from the stream.

Table 3: Reclassed Distribution of Flood Drivers

Class	Corridor	Slope	Elevation	Soil
9	< 30	< 3	< 1030	
8	30 - 60	3 - 6	1030 - 1070	
7	60 - 100	6 - 12	1070 - 1100	
6	100 - 150	12 - 15	1100 - 1140	
5	150 - 500	15 - 20	1140 - 1180	
4	500 - 1000	20 - 25	1180 - 1220	
3	1000 - 2000	25 - 30	1220 - 1260	
2	2000 - 3000	30 - 45	1260 - 1320	I-c
1	> 4000	> 45	> 1320	Af12-2b

Catchment Slope

The catchment slope was obtained in percentage from the DEM. This was generated in the ArcMap environment using the spatial analysis tool (*Spatial Analyst>Tools>Surface>Slope with Delimi_DEM* as the input raster while the output raster Delimi_*slope).* The slope was then filtered using the filter operation in *spatial analyst >Neighbourhood* tools, this was then re-classified into nine domain groups to accommodate for the varying mountainous terrain of the Jos Plateau. The point feature class was named DEM to Point. Next, the distance of all points from the mainstream network was generated using the Analysis Tools: Proximity>Near on the Arc Toolbox with the DEM to Point as input and the river network for the catchment as the Near feature; generating method was left as the default planar method. The distances were generated in meters and the attribute table of the point DEM was populated accordingly. This was converted to raster using the Point to raster tool and named Distance to River. After which it was reclassified into a catchment slope layer. The reclassification was based on a nine-class domain (See Table 1, Figure 5) with a value of 9 for areas with lower slopes in the catchment and 1 for areas with higher slope values.

- **Catchment Elevation**

The Elevation layer was also generated from the Alos Plasa DEM of the catchment. Randomly sampled elevation information obtained from the field served as a guide for the re-classification of the DEM into nine domain groups based on their respective elevations above mean sea level (a.m.s.l.). The domain groups are as presented in the point feature class named DEM to Point. Next, the distance of all points from the mainstream network was generated using the

Analysis Tools: Proximity > Near on the Arc Toolbox with the DEM to Point as input and the river network for the catchment as the Near feature; generating method was left as the default planar method. The distances were generated in meters and the attribute table of the point DEM was populated accordingly. This was converted to raster using Point to raster tool and named Distance to River. After which it was reclassified into an Elevation layer. The reclassification was based on a nine-class domain (See Table 1, Figure 6) with a value of 9 allocated to areas of lowest elevations and 1 to those of highest elevations.

- **Soil Layer**

The soil layer polygon shapefile for the Delimi River catchment was extracted from the Digital Soil Map of the World (DSMW) and converted to raster using the polygon to raster conversion tool and added to the model. Two soil layers with distinct characteristics were extracted and rated averagely as shown in the point feature class named DEM to Point. Next, the distance of all points from the mainstream network was generated using the Analysis Tools. The distances were generated in meters and the attribute table of the point DEM was populated accordingly. This was converted to raster using Point to raster tool and named Distance to River (Table 1, Figure 7). The reclassification maintains the two distinct soil types in the catchment namely 1. Ferric Acrisol soil (Af12-2b) and 2. Lithosols (I) soil types.

4) Criterion Weights using the Analytical Hierarchical Process (AHP)

MCA was carried out to establish a relationship between all flood causative drivers which had been modelled as thematic maps. The inter-relationships between these layers as well as their respective attributes were derived using the Saaty (1980) AHP.

As stated earlier, the four (4) thematic maps (Corridor, Slope, Elevation & soil) that were reclassified formed the network for the pair-wise comparison in the AHP premised on Saaty’s 1-9 scale shown in Table 2. The respective associations of proximity (corridor), slope, elevation, and soil with flood occurrence were used as a guide for the derivation of the relative importance matrix.

Table 4: Saaty's 1-9 scale of pair-wise comparisons

Scale	Intensity of importance Definition
1	Equal Importance
2	Weak Moderate
3	Importance
4	Moderate Plus
5	Strong Importance
6	Strong Plus
7	Very Strong
8	Very, very Strong
9	Extreme Importance

The perceptions used were based on a literature search, field experience, and the assessment of their respective measures of association with flood occurrence. The method of Eigenvector estimation was used to estimate the respective weights of the various criteria. The pair-wise comparison was checked on Saaty's Consistency Ratio (CR)

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

Where:

CI = Consistency Index which reflects the consistency of the judgment

RI = Random Inconsistency Index dependent on the sample size

The Consistency Index, *CI* was calculated using

$$CI = \frac{\lambda_{\max -} n}{n - 1}$$

Where λ is the average of the value of the consistency vector (calculated factor weight).

The Random Inconsistency Indices, *RI* for respective sample sizes are presented in Appendix 13. The judgment would be accepted for $0 \leq CR \leq 0.1$ with a value of zero (0) being the most consistent. Any value outside this range would require re-visiting the assignment of the criterion weights.

5) Integration of Flood Driver Maps and Hazard Map Production

Weighted data sets were integrated into ArcGIS 10.3 to produce the flood Hazard map by weighted overlay in a model builder environment. The flood hazard map produced from the weighted overlay operation was then reclassified into five Hazard classes: 'Very High Hazard,' 'High Hazard,' 'Moderate Hazard,' 'Low Hazard' and 'No Hazard. The Very High Hazard and

High Hazard zones represent the extent of inundation of flood waters.

6) Flood Risk Mapping Procedure

Building-Form shapefile gotten from Eagle Eye Geographics LTD, Jos, Nigeria, based on a Quickbird high-resolution image for 2013 covering the study area and updated from the 2017 Google Earth map engine, was overlaid on the reclassified spatial extent map generated from the flood hazard map. The selection by location tool was then activated to isolate and quantify all buildings in the catchment and each mapped zone.

1 RESULTS AND DISCUSSION

MCA for floods in the Delimi catchment premised on four causal drivers - Corridor, slope Elevation, and soil carried out in an ArcGIS environment using the AHP according to sa'aty's scale are presented as follows:

2 Generation of Thematic maps for each driver in the Catchment

4 Corridor

The measure of distance to streams is shown in **Error! Reference source not found.**, it plays an important role in defining areas susceptible to flooding. The zones closest to rivers are the most affected by floods. The corridor layer shows the distance of respective points on the catchment to the Delimi River.

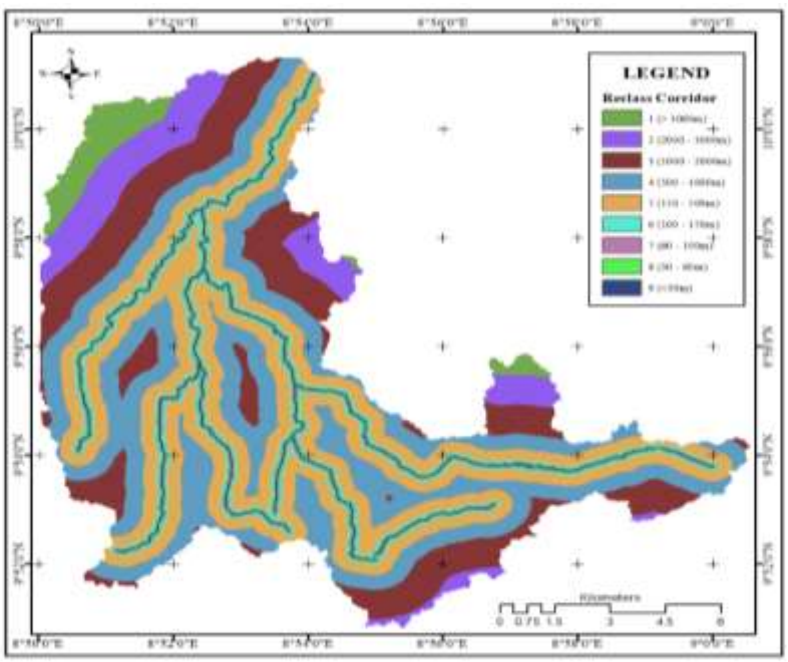

Figure 5: Corridor Layer for Multi-Criteria Analysis

5 Slope

Slope affects the velocity at which water is conveyed through a drainage channel and the catchment as a whole. It also accounts for the volume of runoff because the steeper the slopes, the higher the runoff, and consequently a higher peak discharge will be expected. The output slope layer is shown in **Error! Reference source not found.**. The c atchment is described as a predominantly undulating hilly and mountainous terrain with a percentage slope ranging from 0% to 88%.

6 Elevation

The elevation layer of the study area as extracted from the ALOS PALSAR DEM (12.5m) was also reclassified into nine classes of domain based on field experience and the need to accommodate for as much elevation variance as possible (**Error! R eference source not found.**). The general elevation range

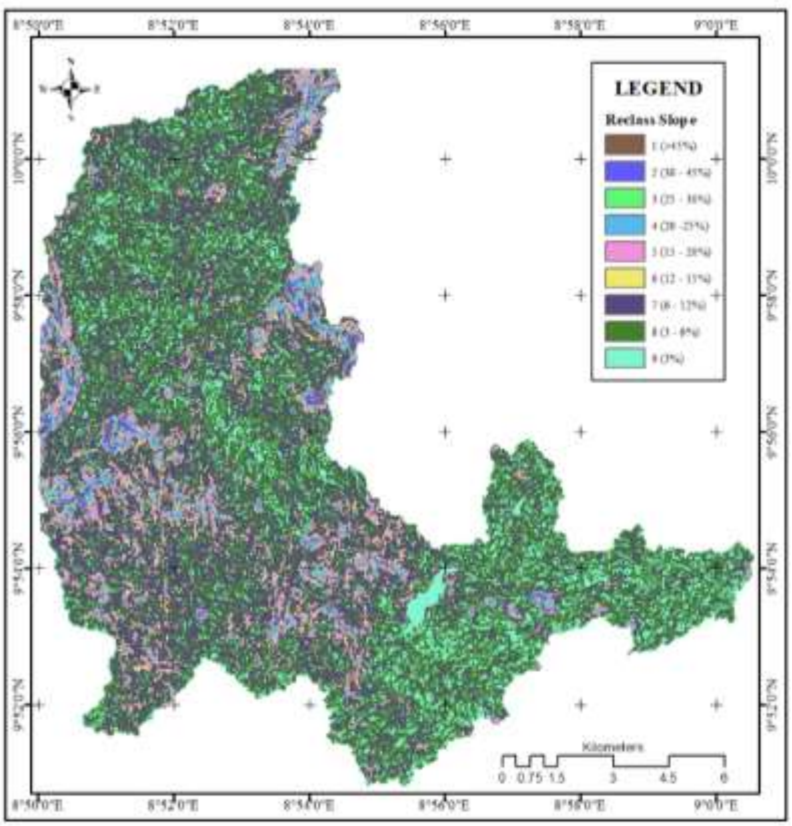

Figure 6: Slope Layer for Multi-Criteria Evaluation

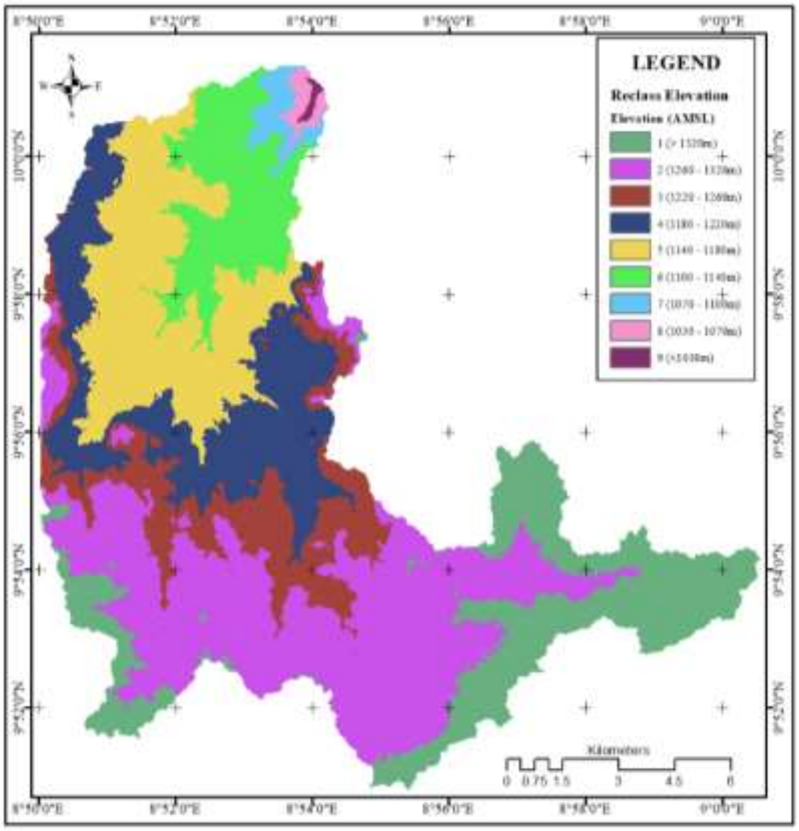

Figure 7: Elevation Layer for Multi-Criteria Evaluation

was from 933m to 1393m (AMSL). Low elevations are seen to the northeast of the map and gradually increase to the southeast.

7 Soil

The soil distribution map for the study area was extracted from the digital soil map of the world (DSMW) and reclassified to maintain its two distinct types namely the 1. Ferric Acrisol soil (Af12-2b) and 2. Lithosols (I) soil types. See **Error! Reference source not found.**.

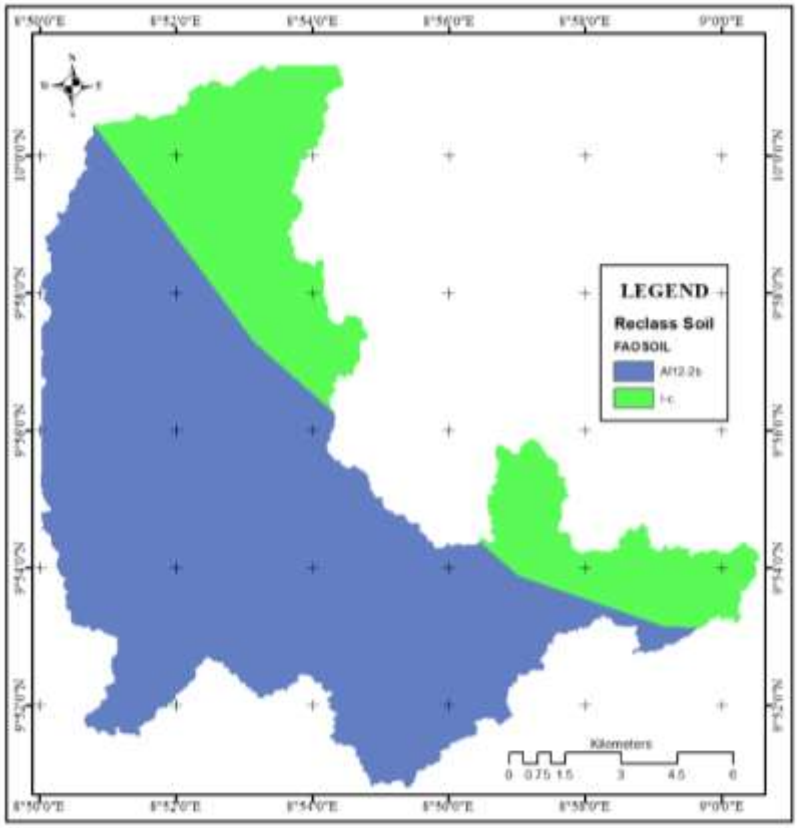

Figure 8: Soil Layer for Multi-Criteria Evaluation

3 Criterion Weights for Flood Drivers in The Delimi Catchment

The pairwise comparison of four flood drivers using the (AHP) is presented in

Table 5. For the catchment, Corridor and Slope rank first and second with a weight of 38 and 37 percent respectively, followed by elevation with a weight of 21% while soil ranked lowest with a weight of 4%. A consistency ratio of 0.06 was obtained for the pair-wise comparison and accepted since it was less than a CR of 0.1. Based on the criterion weights derived, the four thematic raster maps of flood for the catchment were integrated and modelled in the ArcMap model builder and output hazard map presented in **Error! Reference source not found.**. The output map) was reclassified based on natural breaks into Very High Hazard, High Hazard, Moderate Hazard, Low Hazard, and no hazard' with the very high and high hazard classes representing the

extent of inundation due to possible flood waters (Figure 9).

Table 5: Criterion Matrix and Weight for Flood Drivers

Drivers	Elevation	Slope	Corridor	Soil	Wc (%)
Elevation	1	0.5	0.5	7	21
Slope	2.000	1	1	8	37
Corridor	2.000	1.000	1	9	38
Soil	0.143	0.125	0.111	1	4
Total	5.14	2.63	2.61	25.00	100

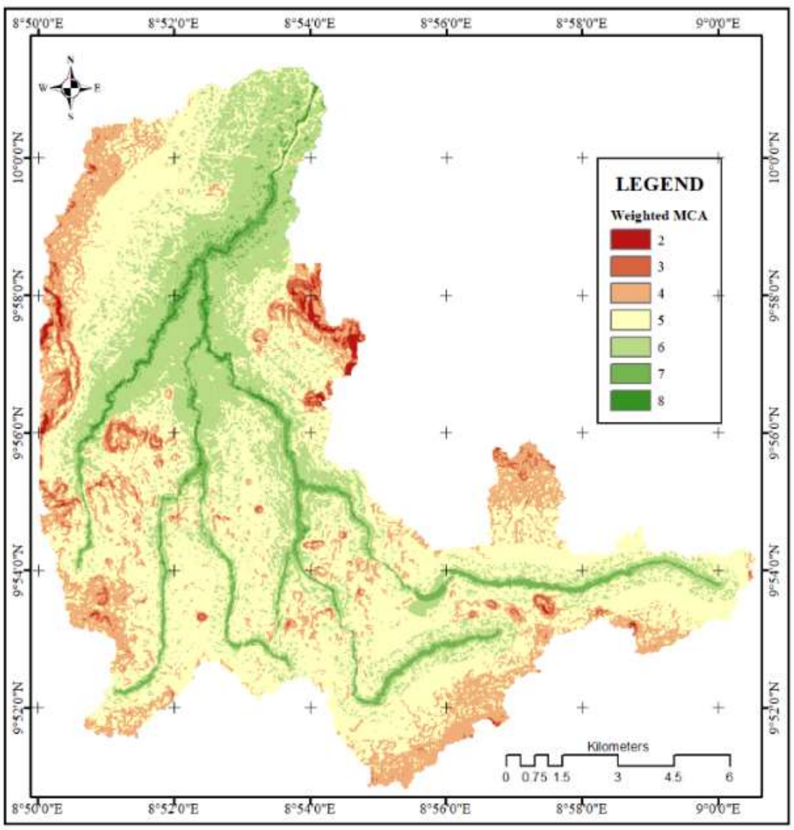

Figure 9: Output Hazard Map (Ranged 8 high to 2 low hazards)

The analysis revealed that areas having elevations of less than 1220 m, and gradients generally less than 12% but within a distance of fewer than 150m from the stream and have primarily Ferric Acrisol soil, are at very high risk of floods. This area covers a total of about one kilometre representing only 0.6% of the entire catchment (Table 4) but accommodating a high number of buildings. These represent areas from mid to downstream of the catchment. While the upstream is relatively devoid of floods. This result is in concert with the findings of Danumah *et al.* (2016) and Adewunmi et al., (2017), who both concluded, that the areas of high and very

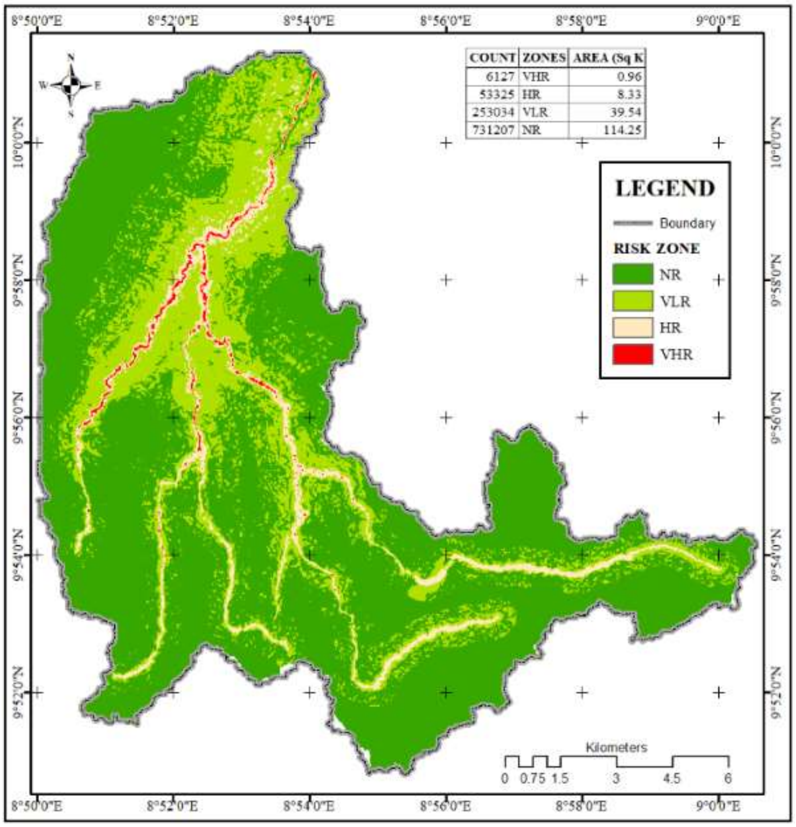

Figure 10: Flood Risk Hazard Zonation Map by Multi-Criteria Evaluation Method
(NR-No Risk, VLR-Very Low Risk, HR-High Risk, and VHR-Very High-Risk zones)

Table 6: Spatial Extent of Risk Zones

Zone	Area Km^2	Percentage	Area Sum	Percentage Sum
VHR	0.96	0.6	0.96	0.6
HR	8.33	5.1	9.29	5.7
VLR	39.54	24.2	48.83	29.9
NR	114.25	70.1	163.08	100
Total	163.08	100.0		

High hazards were areas dominated by low slopes and elevation.

4 Flood Extent on Built Area

Individual building structures as digitized from Quickbird's high-resolution image for 2013 covering the study area and updated from the 2017 Google Earth map, gave a total of 95,999 building structures to be within the catchment (Figure 10). Out of which 5,306 building structures were found to fall within the high-risk and very high-risk flood-inundated areas, representing about 5.5%. It is worthy of note that 445 (0.6%) numbers of the 5,306 building structures are within the very high-risk zone as generated from the MCA model (Figure 11). Rahmati *et al.*, (2016) and Danumah et al (2016) were able to establish flood extent in built-up areas using a similar methodology; though, they did not specify the count of buildings at risk. These values are summarized in table 5.

Table 7: Percentage of building structures in high and very high-risk zones

Zone	Structure Count	Percentage	Count Sum	Percentage Sum
VHR	445	0.46	445	0.46
HR	4,861	5.06	5,306	5.52
Others	90,693	94.47	95,999	100
Total	95,999	100.00		

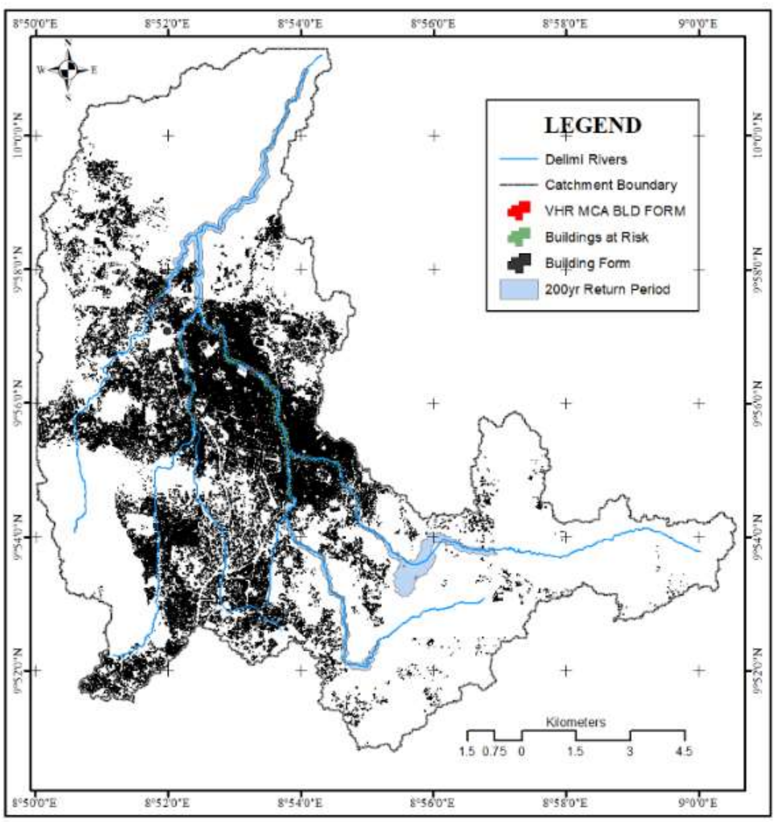

Figure 11: Building Structures in the Delimi Catchment (95, 999 forms).

1. CONCLUSION

Flood risk for the Delimi Catchment was assessed using the MCA in combination with the AHP approach. The analysis shows that 5.7% (9.3 Km^2) of the study area is within the very high and high flood risk zones, further analysis revealed that these areas accommodate a total of about 5,306 building structures with 445 (0.6%) of the building structures concentrated within the very high-risk zone. This implies that the area at risk is a densely populated and urbanized area with building structures made up of residential, commercial, and educational uses amongst others. The flood risk map reveals areas where planning, developmental control enforcement, and possible mitigations are to be implemented. It also will assist decision-makers and watershed managers in effectively developing strategies for the control and mitigation of future flood occurrences in these areas of the catchment.

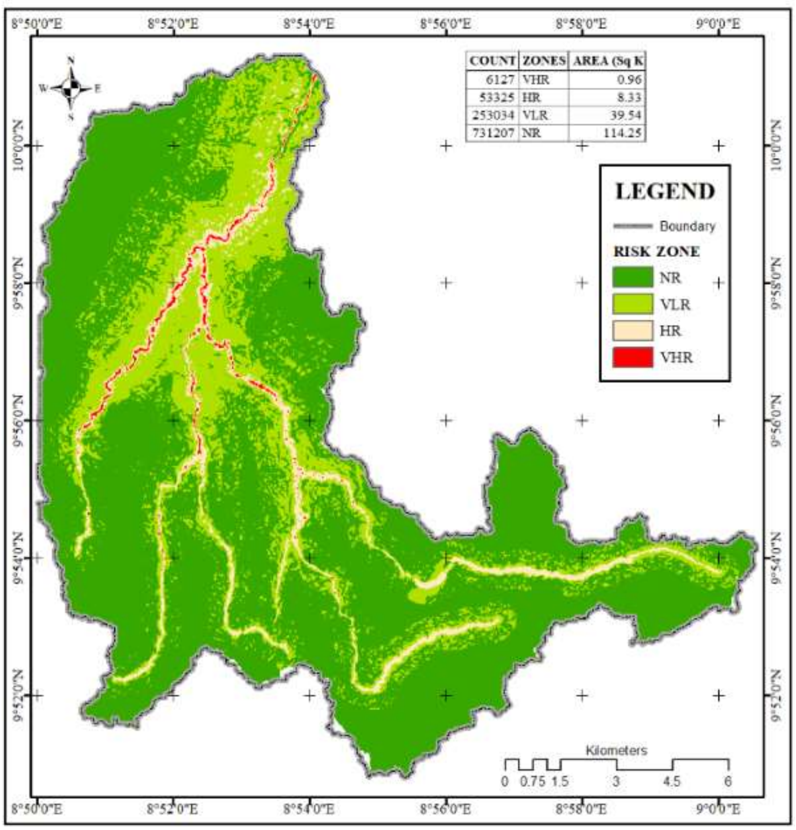

Figure 12: 5,306 Total Building at Risk; with 445 Buildings for Very High-Risk.

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