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Modeling Flooding as a Consequence of Climate Change Dynamics in Abuja Municipal Area Council (AMAC), Abuja, Nigeria

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ABSTRACT

Globally, vulnerability to flooding is influenced by climate change dynamics, especially in regions that are undergoing rapid urbanization. The dynamics are manifested in the alteration of precipitation patterns, rises in sea levels, and increases in extreme weather events, to mention just a few. Research efforts therefore should be focused on assessing the risks of flooding, understanding the processes involved in climate change adaptation and resilience, making innovations in the ways water resources are managed, and refining disaster response and recovery protocols. The current study models climate-change-driven flood risks, using a multi-criteria analysis approach based on the Analytical Hierarchy Process and integrating geospatial data. The study analyzed several climate-related factors, including land use/land cover changes, topographic wetness index, elevation, precipitation patterns, drainage density, proximity to water bodies, and normalized difference vegetation index. Findings reveal that increased rainfall intensity and urban expansion have amplified flood susceptibility, with low-lying and poorly drained areas at the highest risk. The analysis also revealed that Topographic Wetness Index and Precipitation are the most significant determinants of flood vulnerability, indicating that areas with high potential for water accumulation and intense rainfall are most susceptible to flooding. To translate research into mitigation and adaptation strategies, the study recommends enhancing urban flood resilience through improved drainage infrastructure, enforcing sustainable land-use policies, and integrating climate risk data into urban planning. By modeling climate change dynamics, this research provides actionable insights to policymakers and disaster management agencies, emphasizing proactive adaptation measures to build climate-resilient cities and minimize flood-induced socio-economic losses.

INTRODUCTION

Flooding and flood-related menaces have continuously plagued the world annually. Of all the natural disasters, flooding has offered the most devastating impact on human existence in recent times (Matgen *et al.*, 2007). Flooding affects approximately 170 million people annually and has accounted for around 8 million deaths in the past 30 years (Adebayo, 2016; Tiepolo *et al.*, 2019; UN-Water, 2011). Approximately 2.3 billion lives have been affected by flood impacts, resulting in about USD 386 billion in economic depletion worldwide (Hussain *et al.*, 2021).

Flooding can be described as the overflow of water onto dry land, often due to excessive rainfall, storm surges, or rapid snowmelt that exceeds drainage capacity (Smith & Ward, 1998). There are various types of flooding, distinguished by Ologunorisa (2004) and Egbisola *et al.* (2017) as river flooding, coastal flooding and urban flooding, being the major types of flooding. River flooding occurs where a river bursts or overtops its banks and inundates the areas around it, and is more common than coastal flooding. Coastal flooding results when heavy storms or extreme weather conditions combined with hightides causing sea levels to rise above normal, forcing seawater to the land. Urban flooding happens in

a relatively short period and can inundate an area as a consequence of human activities such as deforestation, unplanned urban development, unwise use of land, etc. The main problem with urban flooding is the fact that they may occur in highly populated areas, which can lead to loss of lives, destruction of properties and social infrastructure.

Flooding is a direct consequence of climate change which exacerbates the impacts, accounting for the high severity and prevalence of tropical cyclones, typhoons, and hurricanes, as well as various other water-related severe weather spectacles (Buba *et al.* 2021; Hall *et al.*, 2014; Ouma & Tateishi, 2014). Extremely high global temperatures facilitate the formation of convection currents, which produce excessive precipitation as its end-product. Global warming is responsible for the continuous melting of ice caps in the polar regions of the world and the consequent global increase in sea levels which contributes to coastal and river fooding (Deepak, 2020).

Nigeria is one of the most affected developing countries in Africa regarding flooding incidences. There is virtually no state in the country that does not experience one or two flooding incidences annually. Over the last ten years, reported flooding cases in Nigeria showed that virtually

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all the thirty-six (36) States within the country are susceptible to flood disasters (NiMET, 2021). A total of 1550 people died from flooding in 2010, while the disaster displaced approximately 258,000 people (Agboola *et al.*, 2012; Oluwaseyi, 2017). In 2012, 361 lives were lost due to flooding, and 3.8 million people were displaced, costing a total of US\$ 6.5 billion in damages (Amangabra, 2015; Tokunbo & Ezigbo, 2012). 2015 to 2021 witnessed a far more devastating flooding menace than the previous years, primarily due to the failure of governments and policymakers to learn from past flooding occurrences and the inability to put proper flood forecasting and disaster management systems in place.

In 2020, the country experienced the devastating impact of extreme flood events. The flood affected 36 States of the Federation and the Federal Capital Territory (FCT), 349 Local Government Areas (LGAs) within the 36 States were affected and over 2,353,647 people were displaced with a record of 69 deaths. Kebbi and Jigawa States were worst hit with regards to agricultural lands and houses destroyed. Apart from the physical damages, other indirect losses are often overlooked. These indirect and intangible impacts are generally associated with disruption to normal life, as well as long term health issues and stress-related illnesses (NHSA, 2021).

Flooding, therefore, poses significant threats to life, property, and the environment globally. In urban areas, the impacts of flooding are often intensified by factors such as rapid urbanization, insufficient infrastructure, and climate variability (Sharma *et al.*, 2018). The leading mechanisms for flooding in Nigeria include lack of proper drainage systems, inundation of drainage channels because of obstructions, emergency dam releases, and heavy precipitation. Further, rapid population growth, urbanization, and rising sea-levels are the key factors responsible for floods in Nigeria and globally (Cirella & Iyalomhe, 2018; Echendu, 2020)

LITERATURE REVIEW

Flooding in urban areas like Abuja is driven by a complex interplay of natural and anthropogenic factors. Heavy rainfall, often associated with tropical climates, is the primary cause of floods. Abuja's climate, characterized by a distinct rainy season, frequently experiences intense and prolonged rainfall that exceeds the capacity of local rivers and drainage systems, leading to overflow and surface runoff (Opere, 2013). Climate change has intensified this pattern by altering precipitation regimes, leading to more frequent and severe rainfall events (Buba *et al.* 2021; John-Nwagwu *et al.* 2014). Empirical studies, such as the one by Nkwunonwo *et al.* (2016), have used hydrological models to demonstrate the increasing trend of heavy rainfall in Nigerian cities, and its direct impact on flooding frequency and severity. Their findings highlight a significant correlation between climate change indicators and flood occurrences, underscoring the importance of integrating climate models into flood risk assessments.

Urbanization significantly contributes to flood vulnerability by altering the natural landscape and

increasing impervious surfaces, such as roads, pavements, and buildings. These surfaces prevent water from infiltrating the ground, leading to higher surface runoff and overwhelming drainage systems (Douglas *et al.*, 2008). In Abuja, the rapid and often unregulated expansion of urban areas has led to the encroachment of natural floodplains, further increasing flood risks (Adelekan, 2011). A study by Abah (2013) used GIS to empirically analyze the impact of urbanization on flood risk in Makurdi, Nigeria, finding that unplanned urban expansion significantly increased surface runoff and flood risk due to the reduction of permeable surfaces. Moreover, deforestation in and around Abuja for development purposes has reduced vegetation cover, which naturally absorbs rainfall and reduces runoff, thus contributing to more severe flooding (Ologunorisa, 2009).

Poor waste management practices compound the problem, as solid waste often clogs drainage systems, impeding the flow of water and causing localized flooding during heavy rains. The improper disposal of waste in Abuja, particularly in informal settlements, has been identified as a major factor exacerbating urban flooding (Aderogba, 2012). Soil erosion due to poor land management practices and construction activities further degrades the land's capacity to absorb water, leading to increased runoff and sedimentation of water bodies, which reduces their capacity to channel floodwaters effectively (Adeoye *et al.*, 2019).

Remote sensing involves the use of satellite or aerial imagery to monitor and assess environmental conditions. In flood vulnerability assessments, remote sensing can be used to track changes in land cover, detect areas of water accumulation, and assess the extent of flood events (Seneviratne *et al.*, 2012). In Abuja, remote sensing has been employed to monitor urban expansion and its impact on natural drainage systems, providing critical data for flood risk assessments (Adeoye *et al.*, 2019). An empirical study by Said *et al.* (2016) used remote sensing data to analyze flood-prone areas in Cairo, Egypt. The study utilized satellite images to detect changes in land cover over time and assess their impact on flood risk. The findings indicated a significant increase in flood risk due to urban expansion and reduced natural vegetation cover, highlighting the importance of integrating remote sensing data into flood vulnerability assessments.

Hydrological models simulate the movement of water through the environment, allowing for the prediction of flood events under different conditions. These models can be used to assess the impact of changes in land use, climate, and infrastructure on flood risk (Youssef *et al.*, 2016). In Abuja, hydrological modelling could be particularly useful for assessing the impact of future urban development on flood risks and for designing effective flood mitigation measures. An empirical study by Adeoye *et al.* (2015) applied hydrological modelling to predict flood risks in the Osun River Basin, Nigeria. The study used rainfall data, river discharge records, and land use information to simulate flood scenarios and assess the impact of different land use changes on

flood risk. The findings demonstrated the importance of incorporating hydrological models into flood risk assessments, particularly in regions undergoing rapid urbanization.

From the foregoing, flooding has become a recurring and devastating phenomenon in the Abuja Municipal Area Council (AMAC), located within the Federal Capital Territory (FCT) of Nigeria. The city's vulnerability to flooding is exacerbated by several interconnected factors, including the complex types of settlements, significant infrastructure deficits, and inappropriate land use and land cover (LULC) practices. AMAC is characterized by a mix of formal and informal settlements, ranging from well-planned urban areas to poorly developed, densely populated informal communities. These settlements often lack adequate drainage systems and other essential infrastructure, making them highly susceptible to flooding during heavy rains (Oladokun and Adebayo, 2021). The informal settlements, in particular, are often situated in flood-prone areas, such as riverbanks and low-lying regions, where the risk of flooding is inherently higher (Buba *et al.* 2021; Adewuyi and Badiora, 2020; John-Nwagwu *et al.* 2014).

Moreover, the infrastructure deficits in AMAC, including inadequate stormwater management systems, further contribute to the region's flood vulnerability. The existing infrastructure is often overstretched or poorly maintained, leading to frequent overflow of drainage systems and subsequent flooding (Olorunfemi *et al.*, 2022). The absence of a comprehensive urban planning strategy that incorporates flood risk management has led to uncoordinated development, which exacerbates the impact of floods.

From 2019 to date, AMAC has experienced a significant number of flood events, with reports indicating at least seven major occurrences that have caused widespread damage to property, displacement of residents, and loss of lives (NEMA, 2023). These frequent flood events, exacerbated by climate change, underscore the urgent need for effective flood risk management and mitigation strategies tailored to the specific challenges of the area.

In addition to settlement patterns and infrastructure

issues, the improper use of land use and land cover (LULC) significantly heightens flood risk in AMAC. Rapid urbanization has led to the conversion of natural vegetation into impervious surfaces, such as roads and buildings, which reduce the land's natural ability to absorb rainwater, thus increasing surface runoff and the likelihood of flooding (Nwankwoala, 2016). Furthermore, the encroachment on floodplains and wetlands, often driven by the demand for land in urban areas, has disrupted natural water flow, contributing to more severe and frequent flood events (Onyekuru and Marchant, 2017).

Existing studies often focus on either the impact of informal settlements, infrastructure deficits, distance to stream, precipitation, or LULC changes in isolation, leaving a gap in understanding how these elements collectively contribute to flood risk in AMAC. This study attempts to provide further information on the leading causes of flooding in the Abuja Municipal Area Council of FCT and their impacts on the vulnerable environment by analyzing the factors responsible for flooding, not in isolation of each other, but bringing them together in a framework. A comprehensive assessment is necessary to address these challenges, inform policy and planning, and support sustainable development and disaster risk reduction in the area.

MATERIALS AND METHODS

Study Area

Abuja Municipal Area Council (AMAC) is one of the six (6) Area Councils within Abuja. Geographically, it is located between longitudes 7° 5' 00" and 7° 40' 00" East of the Greenwich Meridian and latitudes 8° 35' 00" and 9° 10' 00" North of the Equator. It is bordered by Bwari to the north, Kuje to the south, Gwagwalada to the west, and Karu Local Government Area (LGA) in Nasarawa State to the east. The mean elevation of the Abuja Municipal Area Council (AMAC) is approximately 840 meters (2,755 feet) above sea level. This elevation contributes to the region's temperate climate and its suitability for various forms of urban development and agriculture (Olayemi, 2021).

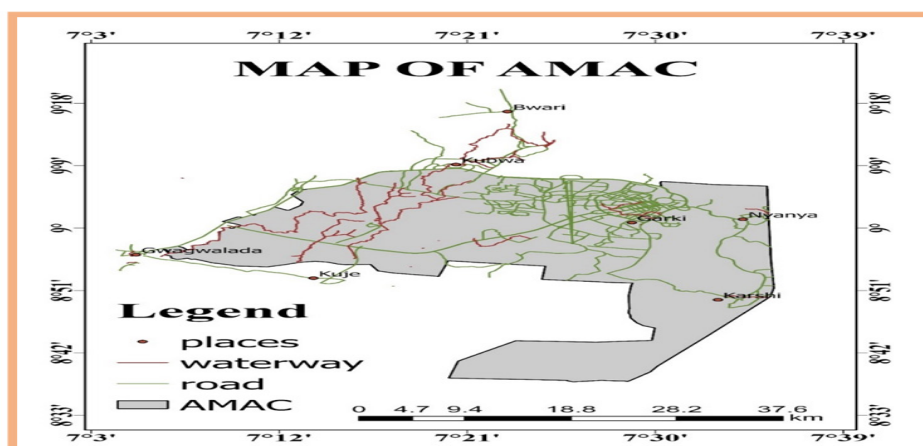


Figure 1: Map of the Study Area

Data Type and Sources

Primary data used consisted of locations of the places that have experienced flooding within AMAC which were collected using coordinates from Google Earth Pro. While secondary data used included Digital Elevation Model (DEM), precipitation data, and SENTINEL 2A Multispectral Instrument (MSI).

Data Analyses

Eight flood-control parameters were identified and considered significant triggers of flooding in the study area. They include; slope, elevation, topographic wetness index (TWI), normalized difference vegetation index (NDVI), precipitation, distance to stream, drainage density, and land use/land cover (LULC). The study then conducted a multi-criteria evaluation (MCE) which considers different options of a decision problem employing the analytical hierarchy process (AHP) methodology to determine the relative importance of the different criteria. The main use of the AHP is the ranking and prioritization of multi-criteria parameters using the pairwise comparison technique. The comparisons are made using a scale of absolute judgments that represent how much more one criterion or factor dominates another with respect to a given attribute (Saaty, 2008). These comparisons are used to obtain the weights of importance of the decision criteria.

The calculation of the ranking of each factor was conducted

by using pairwise comparison and reclassification of the factors was carried out into appropriate classes using the AHP. All the weighted factors were integrated in ArcGIS environment to produce the flood vulnerability map using the weighted overlay technique. All parameters were reclassified into five common measurement scales, ranging from 1 (extremely low susceptibility to flooding) to 5 (very high susceptibility to flooding). A higher classified ranking value of (5) indicates that an area is more vulnerable to flooding, whilst a lower value of (1) indicates that an area is less vulnerable to flooding. The classifications of all flood-controlling elements were established based on the evaluation of earlier research.

RESULTS AND DISCUSSION

Results

Elevation

Elevation is a factor in determining flood hazard. Because lower elevated areas have a higher river discharge and flood more quickly from high water flows, they generally have a higher probability of experiencing floods than higher elevated areas (Das, 2019 and Khosravi *et al.* 2016). Figures 2a and 2b show that over 25% of the studied area likely to be moderately vulnerable to flooding, while 21% of the studied area are in low lying area and likely to be highly vulnerable to flooding because of their low elevation above sea level. The other classification and areas of influence are shown in Table 1.

Table 1: Elevation area of coverage

Elevation (m)	Vulnerability rank	Area (km ²)	Percentage (%)
641 – 935	1	63.35	4.29
520 – 641	2	306.44	20.77
430 520	3	382.43	25.92
347 – 430	4	421.66	28.58
178 – 347	5	301.79	20.45

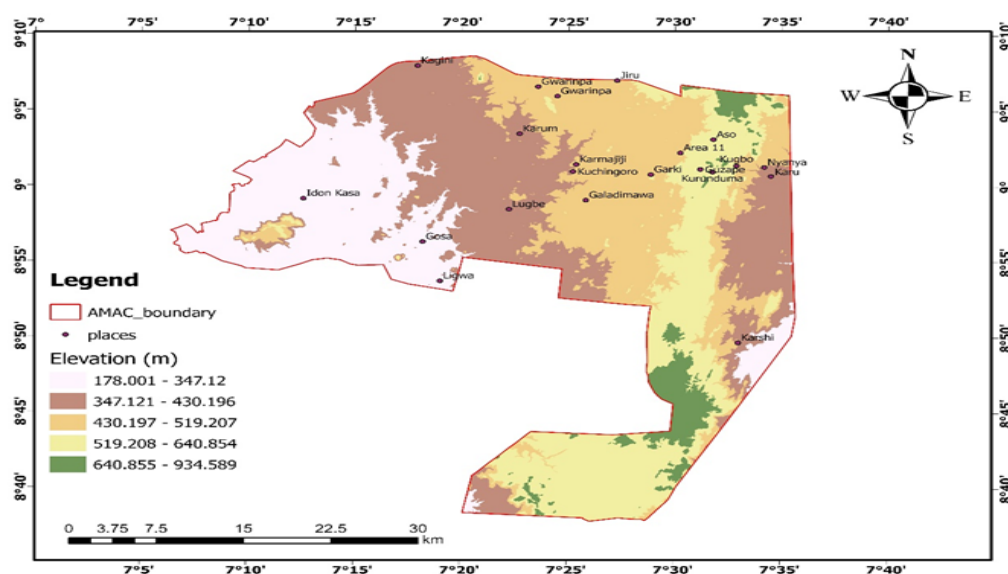


Figure 2: Map of Elevation of the Study Area

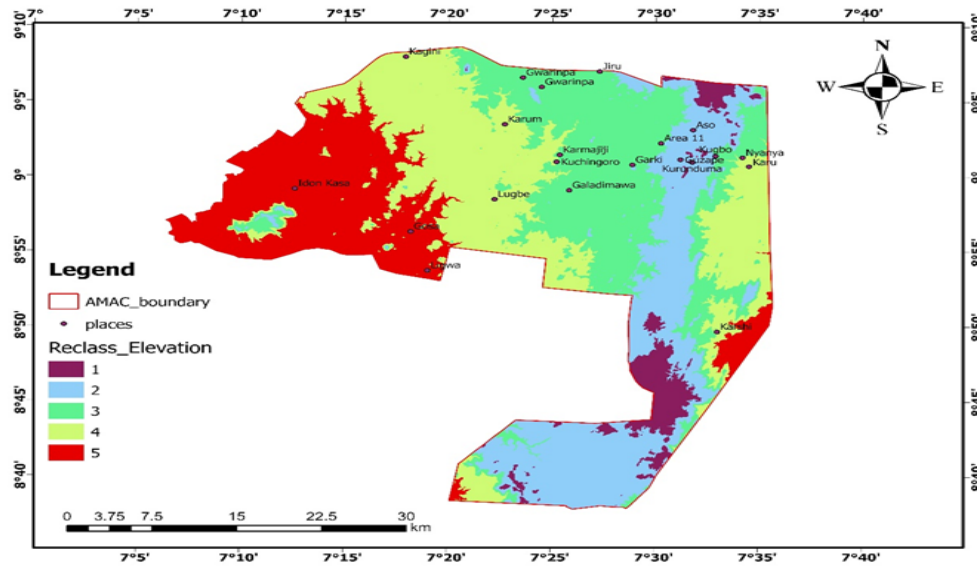


Figure 3: Map of Elevation of the Study Area (reclassified)

Slope

The speed at which surface water flows is determined by the slope of the land. The volume of water covering the land and the likelihood of a flood rise when the slope declines and surface water flow velocity drops (Astutik *et al.* 2021; Das and Gupta 2021; Zzaman *et al.* 2021). Lowlands and flatlands with mild slopes are more likely

to experience flooding than mountainous places, which often have steeper slopes that prevent water from collecting (Wang *et al.* 2015). Slope map shows the area in AMAC has lower of 3.5 to higher of 65-degree slope (Figure 3a). The higher the value the lesser the flood possibility because of the high flow velocity in the steeper zone.

Table 2: Slope gradient Area of Coverage

Slope (degree)	Vulnerability rank	Area (km2)	Percentage (%)
24.7 - 64.2	1	24.73	1.69
15.4 - 24.7	2	64.51	4.4
8.3 - 15.4	3	120.76	8.23
3.5 - 8.3	4	373.98	25.49
0.0 - 3.6	5	883.69	60.22

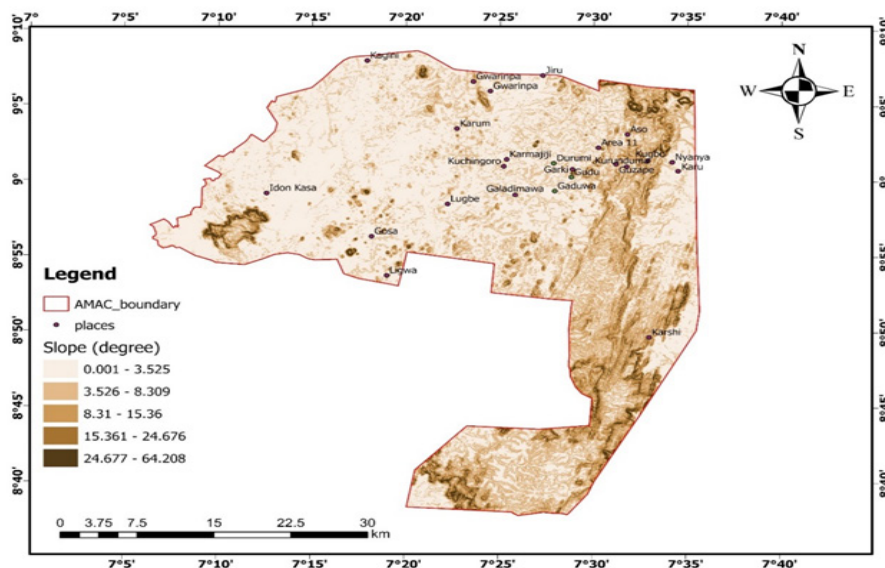


Figure 4: Slope Map of the Study Area

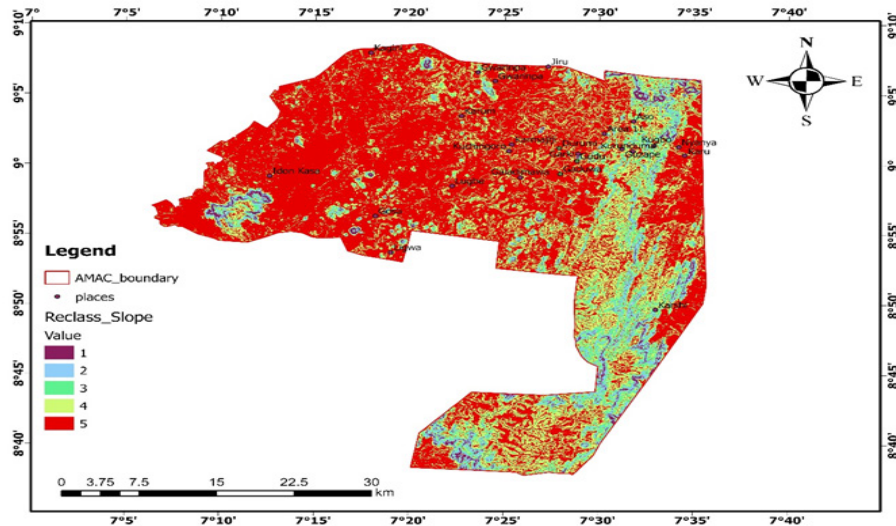


Figure 5: Slope Map of the Study Area ((reclassified))

Precipitation

Since we cannot imagine a flood occurring without precipitation, it is imperative that precipitation be taken into account as a component in flood susceptibility studies. Flood inundation is caused by a massive volume of runoff flows as a result of overly heavy precipitation

or protracted precipitation, making it the most important element that triggers the occurrence of floods (Allafta and Opp 2021; Hong *et al.* 2018a, b). The mean annual precipitation value in Figure 4a ranging in between 1270mm to 1440 mm.

Table 3: Precipitation Distribution in Area of Coverage

Precipitation (mm)	Vulnerability rank	Area (km2)	Percentage (%)
1278 – 1324	1	203.17	13.77
1324 – 1352	2	195.48	13.25
1352 – 1373	3	288.63	19.56
1373 – 1392	4	498.36	33.77
1392 – 1437	5	289.96	19.65

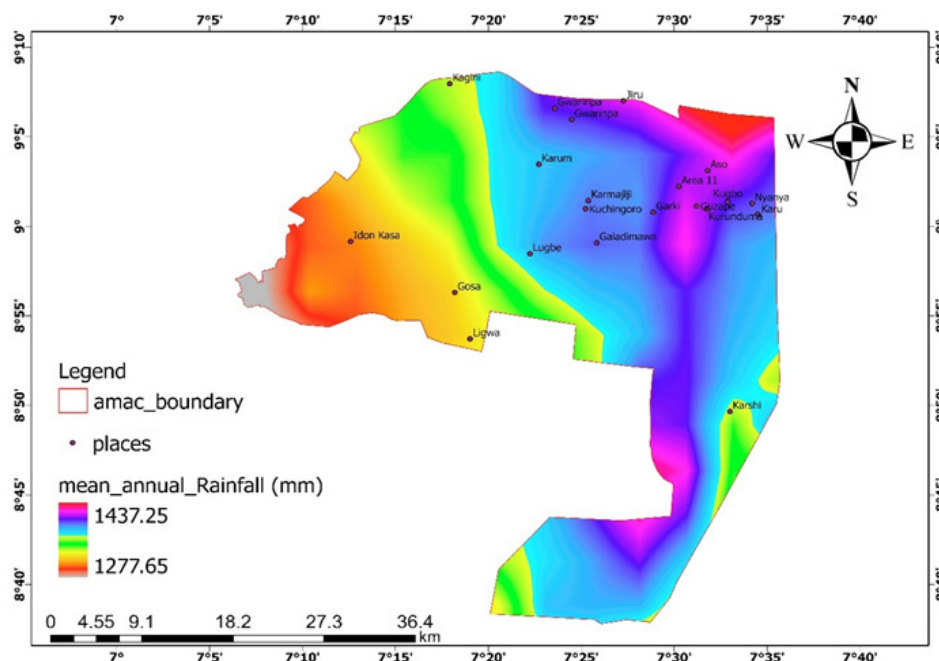


Figure 6: Map showing Precipitation Distribution of the Study Area

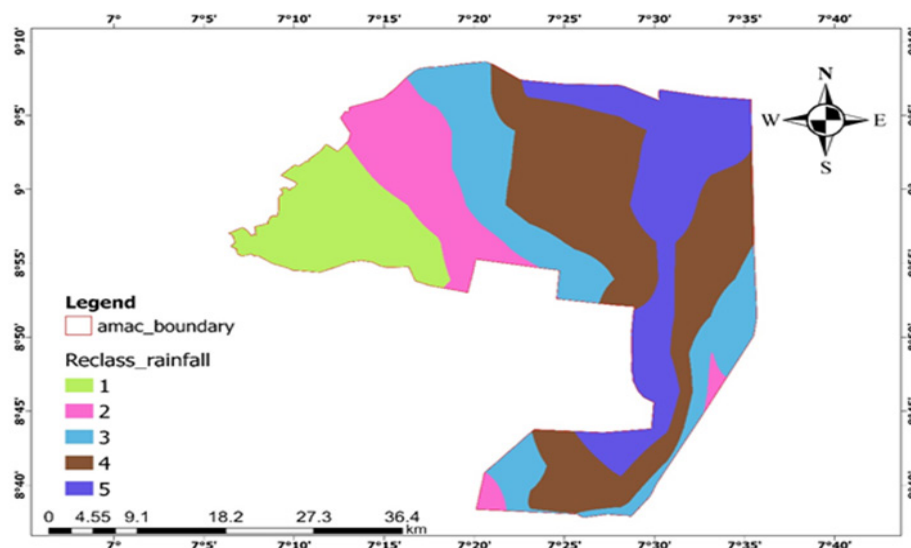


Figure 7: Map showing Precipitation Distribution of the Study Area (reclassified)

Proximity to Water Body

In order to ascertain if and to what degree a region may be impacted by flooding, it is crucial to consider its distance from the stream. A region is less likely to be harmed by flooding if it is farther from a river (Figure 5a). Studies

indicate that because of overflow, the regions closest to these rivers are most impacted by floods. From the map, areas less than 550m from the stream are likely to be flooded and are classified as 4 and 5 on the vulnerability scale (Figure 5b).

Table 4: Distance to Stream Area Coverage

Dist. to stream (m)	Vulnerability rank	Area (km ²)	Percentage (%)
1203 – 2475	1	63.04	4.27
835 – 1203	2	218.37	14.8
544 – 837	3	331.88	22.49
262 – 544	4	416.86	28.25
0 – 262	5	445.48	30.19

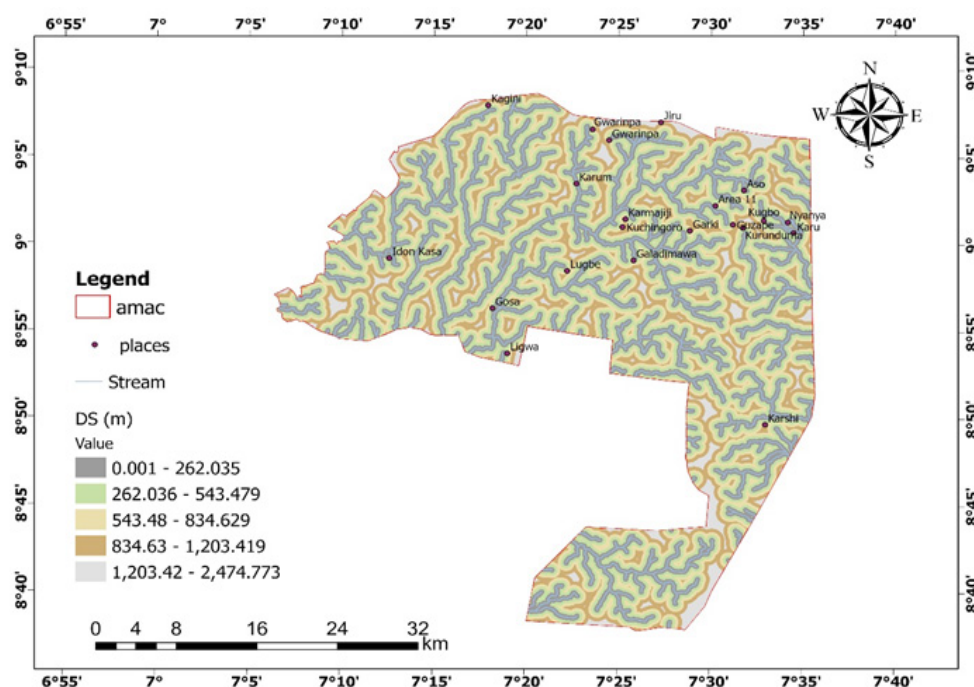


Figure 8: Map showing Distance from Water Body



Drainage density can be defined as the ratio of the total length of streams in a given region to the area's size (Rahmati, 2019). It has a direct relationship with flooding. A higher likelihood of flooding is directly linked to higher drainage density as it indicates a higher surface runoff (Paul *et al.*, 2019). A drainage density map was produced

for the study area and the layer was further reclassified (Figure 6b) in five preference classes. Areas with very low drainage density (≤ 0.000556 km/km²) are dry areas which were ranked as 1 and those with very high drainage density are wet areas, which were ranked with a value of 5 as depicted in Figure 6b and Table 5.

DD (km/km2)	Vulnerability rank	Area (km2)	Percentage (%)
≤0.000556	1	439.5	29.78
≤0.001047	2	394.03	26.7
≤0.001551	3	334.31	22.66
≤0.002159	4	216.43	14.67
≤0.003296	5	91.37	6.19



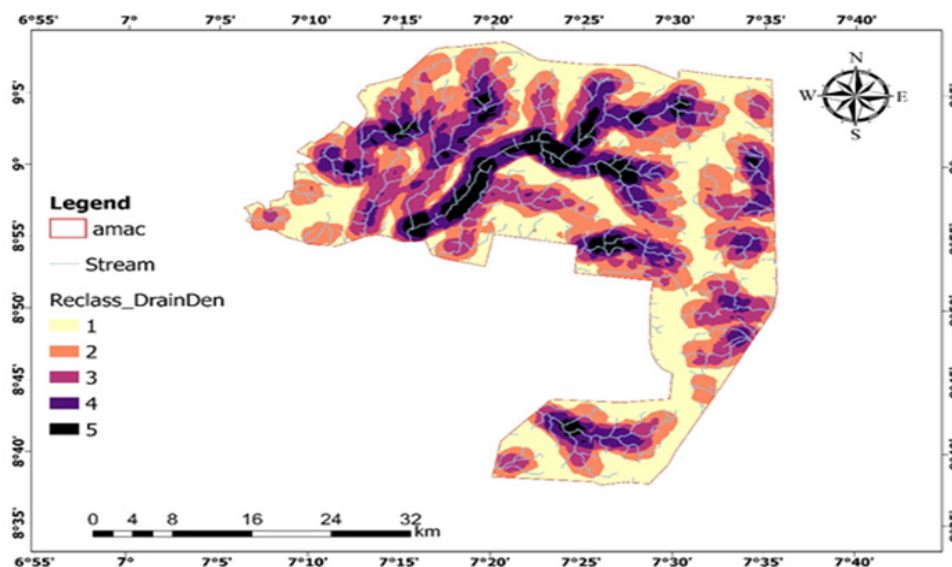


Figure 11: Map showing Drainage Density across the Study Area (reclassified)

Topography Wetness Index (TWI)

The Topographic Wetness Index quantifies the impact of topography on the volume of runoff generated and the accumulation of flow at a certain location. It illustrates how gravity pressure causes water to gravitationally pool at a certain location or flow downward (Lee and Rezaie 2022). The TWI has the ability to forecast regions that

might experience overland flow and those that are prone to saturated land surfaces (Hong *et al.* 2018a, b). The TWI and flood risk are tightly correlated; the higher the TWI value, the higher the chance of flooding (Das and Gupta 2021). Hence TWI of the present study is classified into five classes to denote the high to low possibility of flood (Figure 7b).

Table 6: TWI area coverage

TWI	Vulnerability rank	Area (km ²)	Percentage (%)
2.67 - 6.5	1	386.72	26.35
6.5 - 8.1	2	652.46	44.46
8.1 - 10.23	3	293.92	20.03
10.23 - 13.66	4	103.22	7.03
13.66 - 24.54	5	31.34	2.14

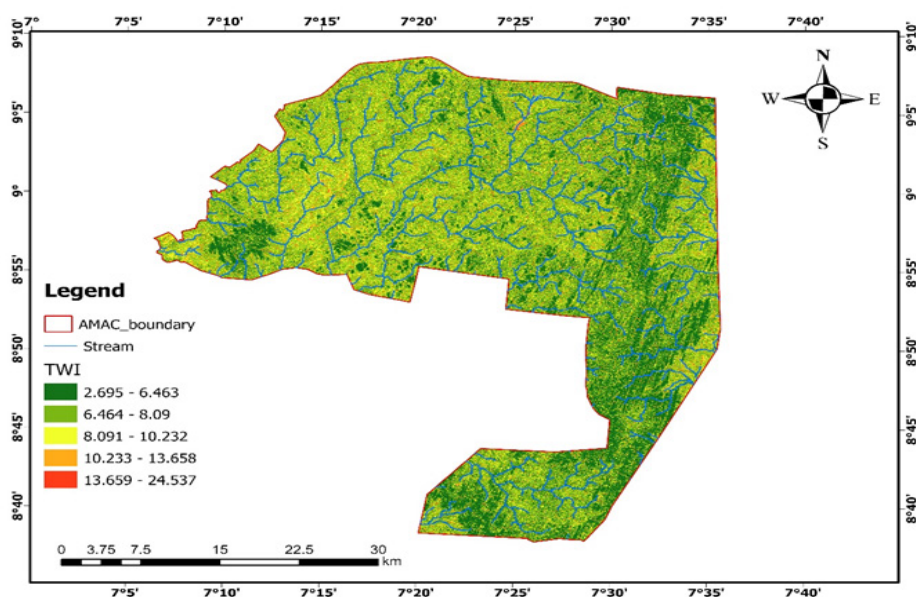


Figure 12: TWI Map of the Study Area

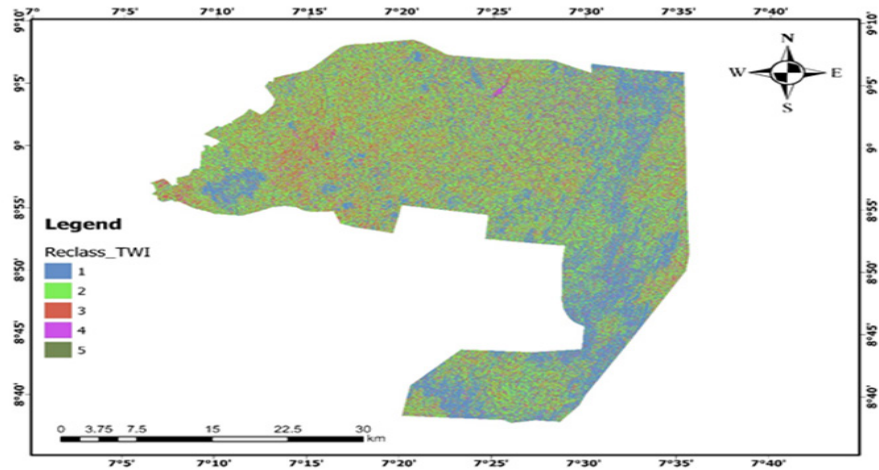


Figure 13: TWI Map of the Study Area (reclassified)

Normalized Difference Vegetation Index (NDVI)

NDVI map displays precise locations of areas with thriving vegetation and areas with little or no vegetation. This is important in food-risk assessment because vegetation influences water movements, making it a conservational property of flooding, which is useful

when assessing resistance to flooding (Alimi *et al.* 2022 and Pal *et al.* 2018). NDVI values generally vary between -1 and +1. Zero and negative NDVI values show water and barren land, NDVI values between 0.2 to 0.4 show grassland, while >0.5 represent forest land (Khosravi *et al.* 2019). NDVI map of AMAC is shown in Figure 8a.

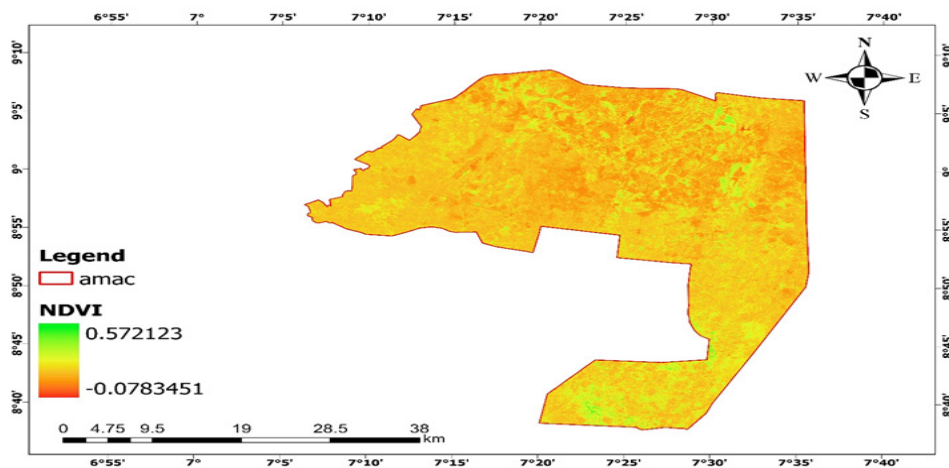


Figure 14: NDVI Map of the Study Area

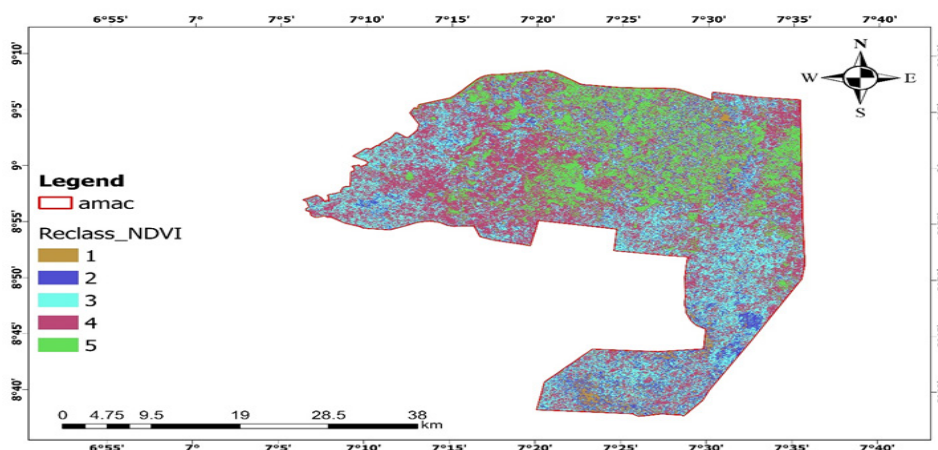


Figure 15: NDVI Map of the Study Area (reclassified)

Land Use and Land Cover (LULC)

Land usage and land cover are among the most significant variables influencing the likelihood of flooding. A high density of vegetation reduces the quick flow of water and increases infiltration, therefore regions covered by it are frequently less susceptible to flooding. Conversely,

impermeable surfaces and minimal infiltration cause runoff in residential and urban locations (Allafta and Opp 2021; Das and Gupta 2021; Kazakis *et al.* 2015; Zzaman *et al.* 2021). Seven features of LULC of the study area were derived; water, crops, tree, flooded vegetation, built-up, rangeland and bare land (Figure 9a).

Table 7: LULC area coverage

LULC	Vulnerability rank	Area (km2)	Percentage (%)
Water	5	3.5	0.24
Vegetation	1	102.12	6.92
Flooded vegetation	4	0.04	0.002
Crops	3	413.97	28.05
Built Area	5	469.36	31.81
Bare ground	4	0.15	0.01
Rangeland	2	486.48	32.97

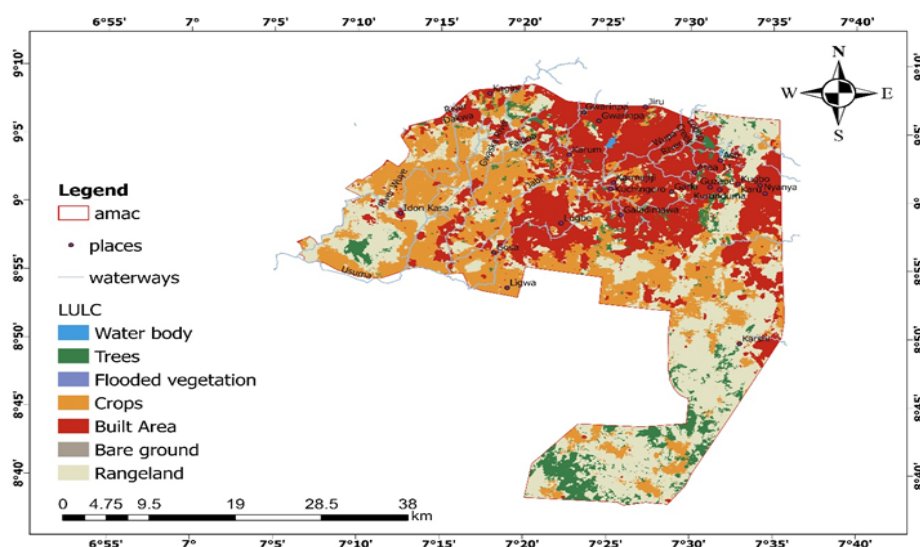


Figure 16: LULC Map of the Study Area

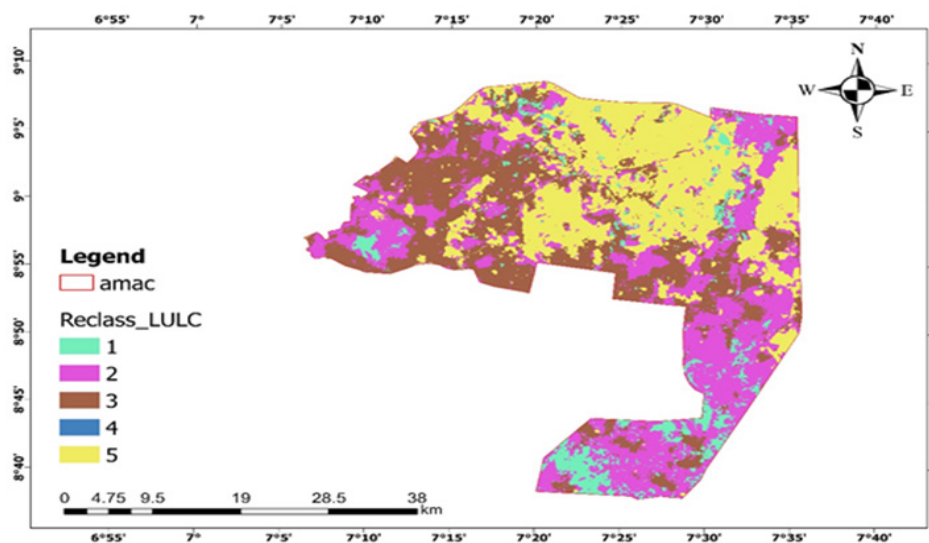


Figure 17: LULC Map of the Study Area (reclassified)

Weighted Linear Combination Method to generate Flood Vulnerability Map

The calculated weights obtained from the AHP pairwise

comparison matrix for each criterion was applied on the various raster criteria in WLC equation to obtain the flood risk map for the study area (Figure 10a).

Table 8: Priority Vector/Weight Vector

Criteria No.	Criteria	PV/WV	Percentage (%)
C1	TWI	0.17	17
C2	Elevation	0.14	14
C3	Slope	0.13	13
C4	Precipitation	0.16	16
C5	LULC	0.06	6
C6	NDVI	0.08	8
C7	Distance to Stream	0.14	14
C8	Drainage Density	0.12	12

The flood-risk map was categorized into three: low, moderate, and high flood-vulnerable zones. Areas with flood-risk index of 1 to 2 are classified as low, while 3 and

4 to 5 are classified as moderate and high, respectively. Table 9 shows the areal coverage of each zone and (Figure 10b) shows the flood vulnerability map.

Table 9: Flood-Vulnerability Level with areal extent

Flood-risk level	Flood-risk index	Area (km2)	% Coverage
Low	1-2	134.91	9.19
Moderate	3	886.44	60.4
High	4-5	446.29	30.41

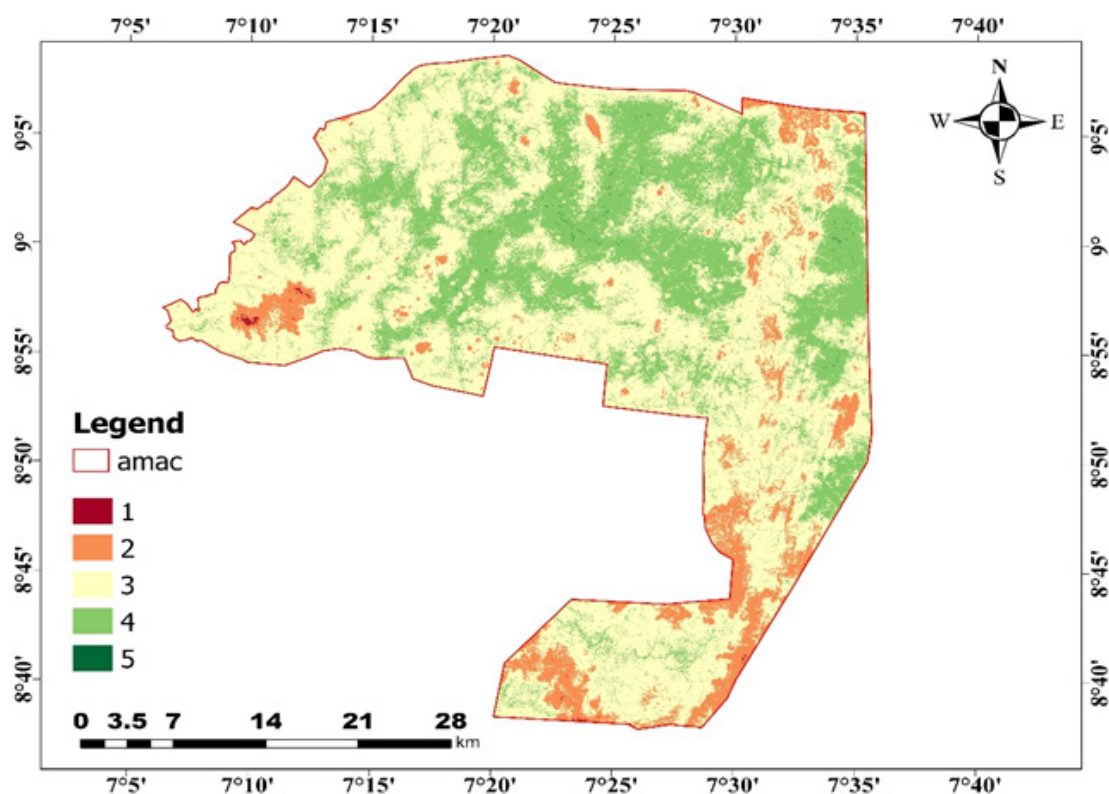


Figure 18: Flood Vulnerability Map (weighted overlay)

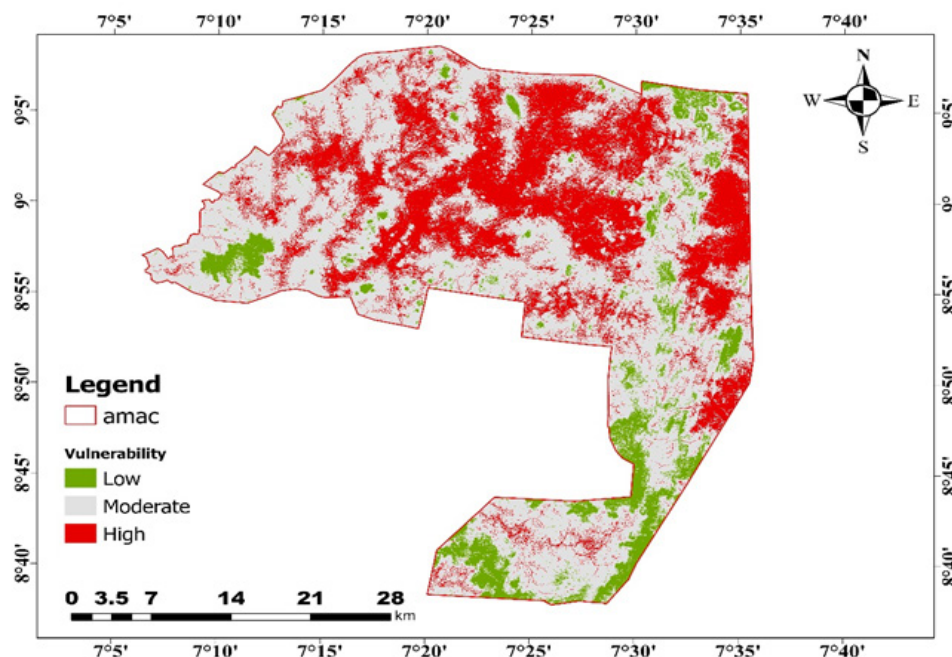


Figure 19: Flood Vulnerability Map (reclassified)

Discussion

The flood vulnerability assessment in Abuja Municipal Council, based on the weighted vector assigned to each criterion (TWI: 0.17, Elevation: 0.14, Slope: 0.13, Precipitation: 0.16, LULC: 0.06, NDVI: 0.08, Distance to Stream: 0.14, and Drainage Density: 0.12), provides several key insights into the factors contributing to flood risk in the area. In this section, the findings are compared with relevant literature to evaluate consistency and highlight any discrepancies.

The study found that Topographic Wetness Index (TWI) (0.17) and Precipitation (0.16) are the most significant factors contributing to flood vulnerability in the study area. These findings align with the work of Rahmati *et al.* (2019), who also emphasized the importance of TWI in predicting flood-prone areas in the Haraz River Basin, Iran. In their study, TWI was a critical determinant of flood risk, which mirrors our results indicating that areas with high TWI values are more susceptible to water accumulation and subsequent flooding. Similarly, Bera *et al.* (2018) demonstrated that precipitation is a crucial factor in flood risk assessments, especially in regions with high rainfall intensity like the Brahmaputra River Basin. Their study supports our findings that intense rainfall significantly contributes to flood risks in the study area, where heavy precipitation can quickly overwhelm the drainage systems, leading to flash floods and widespread inundation.

The findings from this study indicate that Elevation (0.14), Slope (0.13), and Distance to Stream (0.14) are also key factors influencing flood vulnerability in Abuja. These results are consistent with those reported by Jain *et al.* (2018), who found that elevation and distance to water bodies were significant predictors of flood risk in

the Yamuna River Basin, India, and Buba *et al.* (2021), who also found that elevation and distance to water channel were among the most significant factors of flood vulnerability in Lokoja, Kogi State of Nigeria. The study highlighted that lower elevations and proximity to rivers increased flood susceptibility, aligning with our observation that low-lying areas near streams in Abuja are more vulnerable to flooding.

Kazakis *et al.* (2015) also identified slope as an important factor in flood risk assessments in Greece, where steeper slopes contributed to rapid runoff and increased flood hazards. This supports our findings that areas with steep slopes in Abuja are more likely to experience rapid water flow and accumulation, exacerbating flood conditions downstream.

The lower weights assigned to Land Use and Land Cover (LULC) (0.06), NDVI (0.08), and Drainage Density (0.12) suggest that these factors are less influential in determining flood vulnerability in Abuja compared to hydrological and topographical factors. This finding contrasts with the results of Bera *et al.* (2018), who found that land use changes, particularly deforestation and urban expansion, significantly increased flood risks in the Brahmaputra River Basin. In their study, areas with reduced vegetation cover and increased impervious surfaces were more prone to flooding. However, this divergence can be explained by the different geographical and climatic contexts. While LULC changes are a major factor in flood risk in regions with extensive agricultural and forested areas, the urban environment of Abuja might reduce the relative impact of these factors. The built environment and infrastructure may already alter natural land cover significantly, which may explain why LULC and NDVI have lower weights in this study.

The findings on drainage density also diverge from those of Maidment *et al.* (1993) in Bangkok, Thailand, where high drainage density was associated with increased flood risk due to rapid runoff concentration in urban streams. In Abuja, however, the weight of drainage density is moderate (0.12), indicating that while it is an important factor, it is not as critical as others like TWI and precipitation. This might suggest that while drainage infrastructure in Abuja plays a role in flood management, the overall impact of drainage density on flood risk might be mitigated by other more dominant factors, such as the topography and rainfall intensity.

The comparison of our findings with the existing literature highlights both consistencies and divergences that can provide deeper insights into flood vulnerability in the study area. The alignment of our findings with studies by Rahmati *et al.* (2019), Jain *et al.* (2018), and Kazakis *et al.* (2015), and Buba *et al.* (2021) underscores the universal importance of hydrological and topographical factors in flood risk assessments. These consistent findings reinforce the significance of using detailed topographic and hydrological data in flood risk mapping and management strategies.

On the other hand, the divergence in findings related to LULC, NDVI, and drainage density suggests that the impact of these factors may vary significantly based on local geographical and urban conditions. This discrepancy indicates that while LULC and vegetation cover are important, their influence on flood risk may be secondary to hydrological and topographical conditions in specific urban contexts like Abuja.

These findings suggest that flood risk management in the study area should prioritize interventions targeting hydrological and topographical characteristics. This includes enhancing drainage systems to manage high TWI and precipitation and preventing development in low-lying areas near streams. Additionally, while LULC and NDVI should not be overlooked, they may require different management strategies tailored to the urban environment.

CONCLUSION

Extreme weather events such as flooding will increase due to climate change dynamics. This study employed Multi-Criteria Analysis (MCA) and the Analytical Hierarchy Process (AHP) to model climate-induced flood risks, integrating Geographic Information Systems (GIS) and remote sensing data. Key climate-related factors analyzed include precipitation patterns, topography, land use/land cover (LULC) changes, among others. Findings reveal that increased rainfall intensity and urban expansion have amplified flood susceptibility, with low-lying and poorly drained areas at the highest risk.

This study provides a detailed flood vulnerability assessment for Abuja Municipal Council, utilizing a multi-criteria analysis (MCA) framework to evaluate the relative importance of various factors contributing to flood risk. The analysis revealed that Topographic Wetness

Index (TWI) and Precipitation are the most significant determinants of flood vulnerability, indicating that areas with high potential for water accumulation and intense rainfall are most susceptible to flooding. Elevation, Distance to Stream, and Slope also play crucial roles, underscoring the importance of topographical features in influencing flood risk.

Conversely, Land Use and Land Cover (LULC), Normalized Difference Vegetation Index (NDVI), and Drainage Density were found to have less impact on flood vulnerability in Abuja compared to hydrological and topographical factors. This suggests that while urban planning and vegetation management are important, they may not be as critical as hydrological and topographical conditions in this specific urban context.

Based on the findings of this study, Abuja Municipal Council should prioritize hydrological and topographical interventions, focusing on areas with high TWI and frequent heavy precipitation. This includes constructing retention basins, improving drainage systems, and implementing water management practices that enhance natural water retention in high-risk zones. Although LULC has a lower impact in this study, urban development should still avoid floodplains and low-lying areas near streams. Strategic land use planning should also consider the creation of green spaces and permeable surfaces to reduce surface runoff. There is a need to enhance drainage infrastructure by upgrading and maintaining drainage systems, particularly in areas identified as having significant flood risk due to poor drainage density. This can help mitigate the impact of intense rainfall events and reduce surface runoff. Periodic flood risk assessments should be conducted to monitor changes in flood vulnerability, especially in response to urban expansion and climate variability. This will help in updating flood risk maps and adjusting flood management strategies accordingly. AMAC can also engage local communities in flood preparedness programmes and disseminate information on flood risks and safety measures. This can help enhance community resilience and ensure a coordinated response during flood events.

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