

Development of Hazard Atlas from Flood Inundation Patterns in Makurdi Local Government Area of Nigeria

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Abstract

Flooding is a recurrent environmental and socio-economic challenge in Makurdi, Nigeria, driven by a combination of climatic variability, topography, drainage constraints, land-use change, and urban expansion. This study presents a comprehensive assessment of flood risk in Makurdi over the period 1984 – 2024 using a GIS-based approach. The assessment integrates flood inundation to develop a hazard atlas for the region. High-resolution Digital Elevation Models and river discharge records were used to quantify spatial and temporal patterns of flood exposure. The Flood Hazard Atlas identified low-lying settlements along the Benue River, including Wadata, Wurukum, and North Bank, as highly vulnerable. High and very high susceptibility zones cover over 55 % of the Local Government Area. Flood hazard zoning and the Regional Flood Risk Atlas show that approximately 63 % of Makurdi falls under high to very high flood hazard categories, with critical infrastructure and over 75 % of roads located in vulnerable zones. The findings underscore the need for integrated flood management. Recommended measures include improved hydrologic design, Sustainable Urban Drainage Systems, enforcement of floodplain regulations, ecosystem restoration, and scenario-based urban planning. This study provides a robust evidence base to support climate-resilient urban planning, disaster preparedness, and sustainable flood risk management in Makurdi and similar riverine cities.

Key: Flood inundation, Flood Hazard Atlas, Makurdi, Rainfall, River discharge;

1 Introduction

Floods are among the most destructive natural disasters globally, causing significant loss of life and economic damage (UNISDR, 2012; Wallemacq *et al.*, 2018; Ali *et al.*, 2022; Ikyapa *et al.*, 2022; Jonkman *et al.*, 2024). Between 1998 and 2017, floods accounted for 43 % of all recorded natural disasters, resulting in 44 % of disaster-related deaths and 47 % of economic losses (Wallemacq *et al.*, 2018; CRED, 2019). The increasing frequency and intensity of floods, driven by climate change, have heightened the vulnerability of urban areas, especially where infrastructure is inadequate and urban planning is poor (Wing *et al.*, 2018).

Makurdi, located in the Benue River Basin, is particularly susceptible to flash, riverine, and urban flooding (Ocheri and Okele, 2012; Abah, 2013; Isma'il and Kersha, 2018). Its vulnerability is further exacerbated by inadequate drainage systems, deforestation, and rapid

urban growth, which strain existing infrastructure and increase flood risks (Abah, 2013; Hula and Udoh, 2015). Recurrent floods have caused considerable damage to lives, property, and infrastructure, underscoring the urgent need for effective flood risk assessment and mitigation (Lamond and Adelekan, 2016).

Traditional flood risk assessments often rely on historical records and basic hydrological observations, which may not capture the complexities of modern urban environments. Geographic Information Systems (GIS) offer a more comprehensive approach, integrating spatial data with hydrological models to predict flood inundation patterns and assess risks. Despite these advantages, GIS-based assessments remain underutilized in Makurdi, leaving gaps in flood risk management (Komolafe *et al.*, 2015). Existing literature highlights significant gaps in flood risk analysis in Makurdi, particularly in integrating advanced flood modeling with spatial analysis. Current methodologies often fail to combine critical factors such as hydrological data. The limited use of GIS in flood risk assessment, hampers understanding of multi-scenario flood risks. Furthermore, the absence of a comprehensive flood risk atlas and the limited consideration of environmental impacts, such as water quality degradation and habitat disruption, reduce the effectiveness of current flood resilience strategies. Addressing these gaps through holistic flood risk assessment frameworks is essential for sustainable flood resilience in Makurdi.

This study aims to leverage GIS technology to conduct a comprehensive flood risk assessment of Makurdi. Key objectives include determining flood inundation patterns and developing a flood hazard atlas over the period 1984–2024, developing a Hydrological Hazard Susceptibility Index (HHSI), and develop a regional flood risk atlas. This research offers a detailed assessment of flood risks, providing a clearer basis for informed urban planning and disaster management.

Study Area

Makurdi Local Government Area (LGA) is located in North-Central Nigeria, between latitudes 7°33'00"N and 7°44'00"N and longitudes 8°22'00"E and 8°40'00"E (Figure 6). The Local government area (LGA) occupies a land area of approximately 804 km², with its administrative boundary clearly delineated. Within this boundary, Makurdi is subdivided into 11 council wards, namely: Agan, Ankpa, Bar, Clerks Market, Central/South Mission, Fiidi, Mbalagh, Modern Market, North Bank 1, North Bank 2, and Wailomayo. These wards differ in settlement density and land use, with those along the River Benue corridor such as Fiidi, Wadata, and Wailomayo being particularly vulnerable to seasonal flooding, while peripheral wards such as Agan and Mbalagh exhibit more rural and agrarian landscapes.

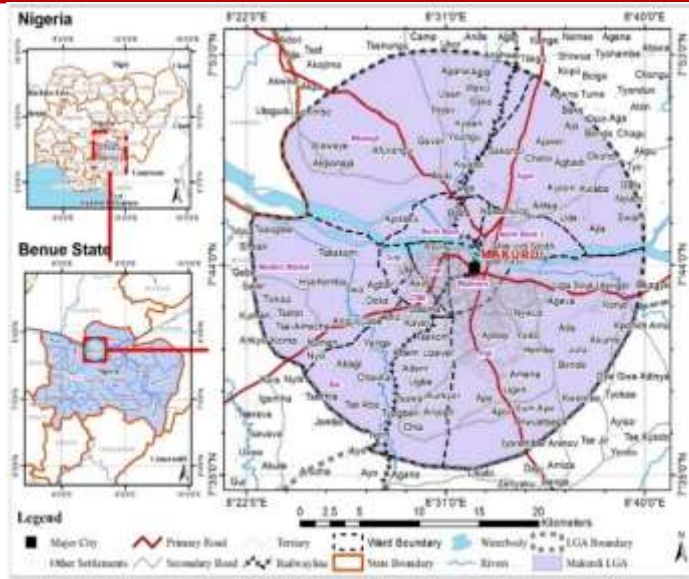


Figure 1: Location Map of Makurdi LGA Showing the 11 Wards.

Source: Author's GIS analysis (2025).

The River Benue bisects the LGA into northern and southern sections and supports domestic, agricultural, and commercial activities. The river also shaped both the ecology and the flood dynamics of the region. As an administrative hub, Makurdi also exposes critical infrastructure to the impacts of flooding. strategic location, riverine setting, and settlement patterns underscores its dual role as a socio-economic hub and a flood-prone environment.

Following the methodology outlined by the United Nations (2024), the projected population for the year 2024 was 526,713. Makurdi is characterized by a fast-growing population density of 655 persons per square kilometer, with its residents constituting about 7.9 % of Benue State's total population. The town's demographic profile includes a Tiv-speaking majority, followed by significant

Makurdi's climate is classified as tropical wet and dry season (Köppen Aw), The wet season typically extends from April to October, while the dry season runs from November to March. The tropical maritime (mT) air mass, which originates from the Atlantic Ocean and brings moist southwest winds, and the tropical continental (cT) air mass from the Sahara, associated with dry, cool, and dusty northeast winds known as the Harmattan dominates the climate. The boundary between these air masses, referred to as the Inter-tropical Discontinuity (ITD), shifts northward in August, marking the peak of the rainy season (averaging 221 mm) (Abah, 2012), and southward by January or February, indicating the height of the dry season (Odekunle, 2010; Abaje *et al.*, 2018). Temperatures range from 21°C to 35°C in dry season, and 23°C to 30°C in the wet season. Humidity levels fluctuate significantly from 80 % during the wet season to 30 % in the dry season (Oyatayo *et al.*, 2021). Wind speeds are generally light to moderate, though gusts can reach up to 66 km/h during squall events (Oyatayo *et al.*, 2021). These climatic variations are influenced by the movements of the Inter-tropical Convergence Zone (ITCZ) and local topography, which affects rainfall distribution across the region (Abah, 2012).

The geology of Makurdi is predominantly sedimentary formations, mainly sandstones, with low-lying areas such as Wadata being overlain by shale (Oyatayo *et al.*, 2021). The sandstone is classified into micaceous and feldspathic some of which are exposed in parts of the town. The soils reflect the local geology, with two major types present: hydromorphic soils, which develop on alluvial sediments along the River Benue, and red ferrasols, found on sedimentary rocks away from the river (Oyatayo *et al.*, 2021). The sandy topsoil facilitates infiltration, supporting shallow wells for water extraction.

Makurdi experiences a gentle slope on either side of the Benue River, elevations in the region vary, rising to approximately 154 meters above sea level at Daudu in the north and about 216 meters above sea level at Ikpayongo in the south (Oyatayo *et al.*, 2021). The Benue River serves as the primary drainage channel for the region, supplemented by several first-order streams and tributaries, including the Genebe, Kereke, Adaka, Asese, Ake, Idye, Demekpe, Abum, Aso, Baa, Kpege, Mu, and Uwurudu rivers (Abah, 2013; Hemba *et al.*, 2020; Oyatayo *et al.*, 2021). The southern part of Makurdi is particularly prone to waterlogging due to its low-lying relief (Oyatayo *et al.*, 2018). The combination of low-lying topography and proximity to the Benue River contributes to a high risk of flooding in many areas of the local government area.

2 Methodology

2.1 Materials and Instrumentation

This study employed a range of materials, instruments, and datasets that supported data collection and spatial analysis. Handheld GPS devices were used for field data collection, remote sensing datasets such as SRTM, ESA CCI Land Cover data, Sentinel-2 imagery, rainfall and river-discharge records, and population-density data downloaded from recognized open-source repositories and institutional databases. Each dataset was examined for completeness and spatial resolution before integration into the GIS environment and Sentinel imagery, and GIS software for data processing and map production. Their integration ensured that both field observations and remotely sensed data were harmonized, thereby improving the overall accuracy of flood risk mapping and GIS-based characterization of Makurdi.

Handheld GPS receiver was used to capture the coordinates of flood-prone locations and other relevant ground-truthing points. These coordinates were used to validate spatial datasets and verify flood-risk zones generated from the analysis. All spatial datasets were re-projected to a common coordinate system (WGS 84, UTM Zone 32N) to maintain spatial consistency across layers. The SRTM DEM was clipped to the Makurdi Local Government boundary and processed to derive topographic parameters including slope, flow direction, and flow accumulation using ArcGIS 10.8 and QGIS software. Rainfall and river-discharge data obtained from NiMet (Makurdi Station) and NIHSA were organized in Microsoft Excel and processed to determine long-term annual and seasonal trends. All processed datasets were stored in a structured geodatabase for subsequent spatial modeling. The combination of these pre-processing steps ensured that the input data were spatially consistent, free of projection errors, and suitable for flood-risk modeling and GIS-based characterization of Makurdi.

2.2 Data Analysis

The dataset acquired were analyzed using geospatial datasets derived from remote sensing and field observations, including the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM), rainfall and river discharge data, the primary objective was to integrate these datasets within a GIS framework to delineate flood hazard, vulnerability, and composite flood risk zones across the study area.

3.0 Results

The presented results are structured according to the hydro meteorological trends and spatial analyses that explain the drivers of flood inundations culminating in the generation of a flood hazard atlas for Makurdi; links Makurdi's rainfall variability to runoff, river discharge, and flooding. This section presents the results of analyses conducted to achieve the specific objective of the study, which is to determine flood inundation patterns and develop a flood

hazard atlas for Makurdi. The outputs are organized into terrain analysis, river discharge analysis, rainfall analysis, and the synthesis of these components into a flood hazard atlas.

3.1 Terrain analysis of Makurdi LGA

Digital Elevation Model (DEM) data formed the basis for terrain analysis, with flow direction and flow accumulation derived to delineate drainage networks and identify depressions prone to runoff concentration. The DEM output is presented in Figure 22, while derived flow direction and accumulation maps are shown in Figure3 and Figure4, Slope categorization results are presented in

Table 1, with the corresponding slope distribution shown in Figure5. The drainage network configuration is mapped in Figure6. Aspect orientation outputs are displayed in Figure7, supported by aspect distribution charts (Figure8: Bar Chart; Figure9: Rose Diagram).

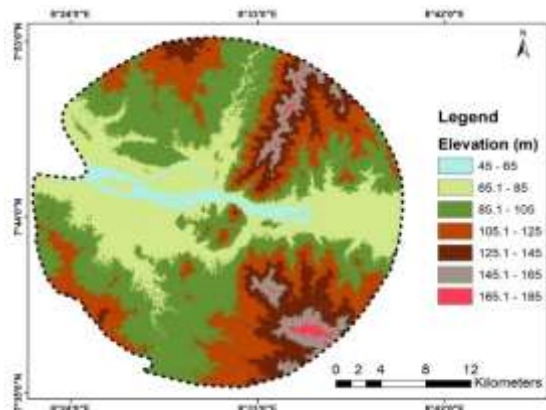


Figure 2: Digital Elevation Model (DEM) of Makurdi LGA

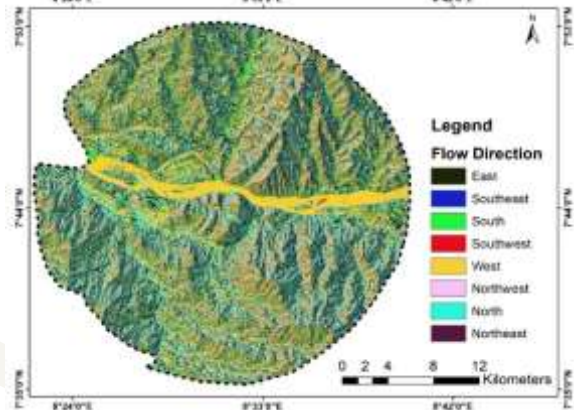


Figure 3: Flow Direction of Makurdi

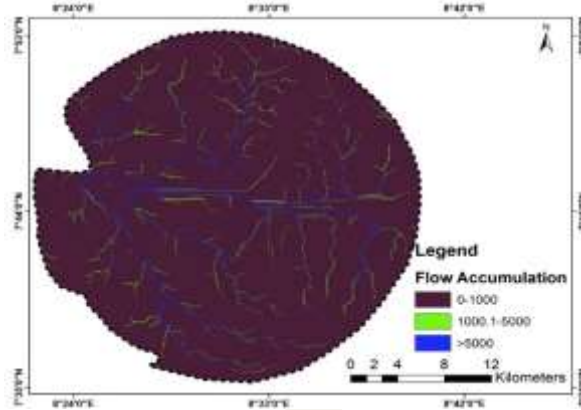


Figure 4: Flow Accumulation of Makurdi

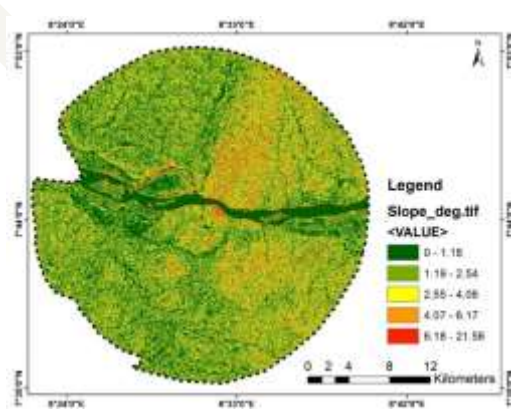


Figure 5: Slope Map of Makurdi

Table 1: Slope Categorization

Slope Range	Area Km ²	Area percentage
> 20°	0.00	0.00
10.1 - 2°	0.45	0.06
5.1 - 10°	33.75	4.17
2.1 - 5°	349.64	43.25
0 - 2°	424.65	52.52
	808.48	100.00

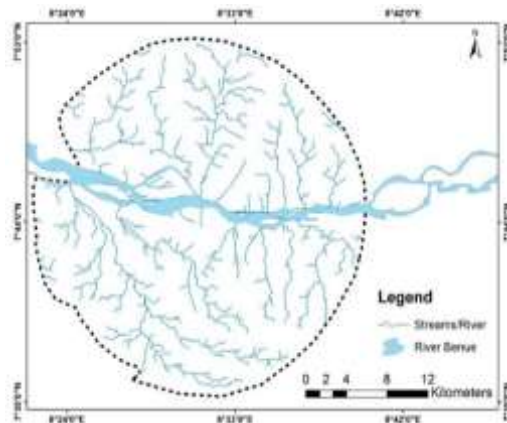


Figure 6: Drainage Network of Makurdi
length of Streams/ivers = 648km)

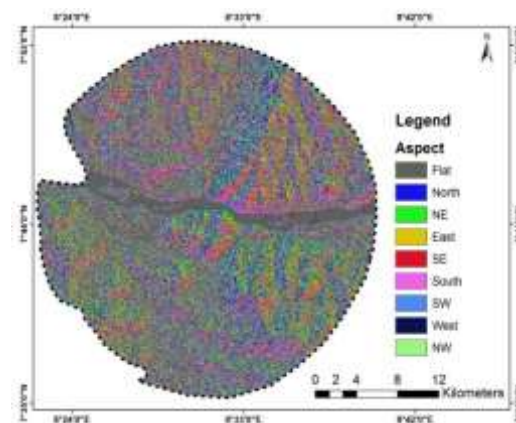


Figure 7: Aspect Orientation Map of Makurdi (Total

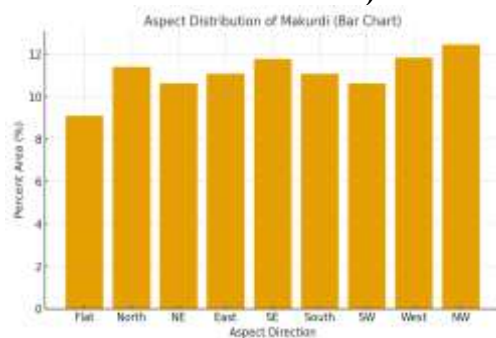


Figure 8: Aspect Distribution of Makurdi

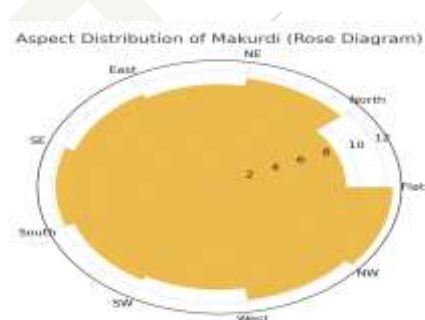


Figure 9: Aspect Distribution of Makurdi (Rose Diagram)

3.2 Results of Rainfall Variability and Hydrological Implications (1984–2024)

Rainfall data for 1984–2024 were analyzed to identify inter-annual variability, seasonal trends, and extreme event characteristics. Mean annual rainfall totals are presented in **Error! Reference source not found.**10, and the spatial variations across Makurdi are mapped in **Error! Reference source not found.**11. Extreme rainfall patterns were characterized using depth–duration–frequency (DDF). Return period rainfall magnitudes are visualized through spatial maps for 5-, 10-, 20-, 30-, 40-, and 50-year events. These outputs collectively define the rainfall regime and its role in flood generation within the study area.

3.3 River discharge analysis

River discharge dataset for the Benue River was analyzed to establish seasonal flow dynamics and long-term variability. Inter-annual discharge variations and mean annual flows is presented in Figure 12. Long-term variability and extreme events are illustrated in Figure 23.

Page 179

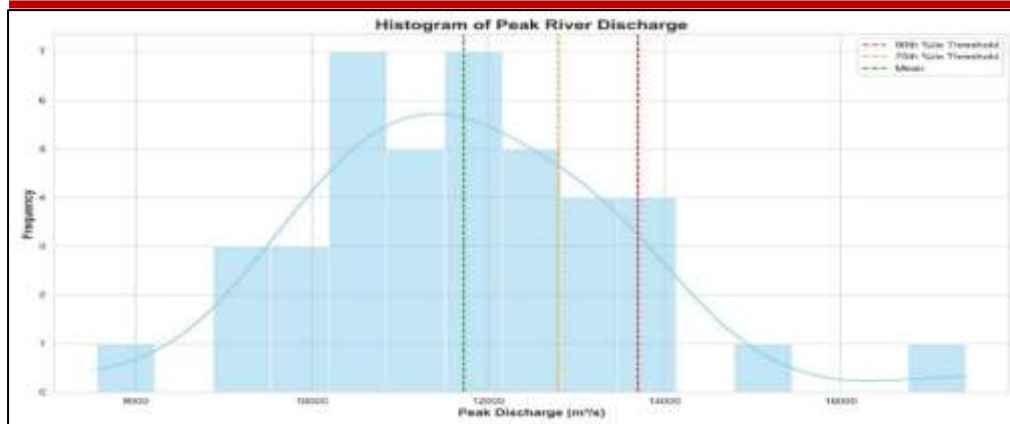


Figure 23: Hydrograph of Historical River Discharge

3.4 Flood hazard atlas Synthesis

A Flood Hazard Atlas for Makurdi was developed by integrating terrain, hydrological, rainfall, and land use datasets. Thematic layers were reclassified into hazard categories, with outputs presented for DEM (Figure 34), aspect orientation (Figure 15), flow accumulation (Figure 16), road networks (Figure 17), land cover (Figure 18), stream buffers (Figure 19), and slope (Figure 20). The weighted overlay of these inputs produced the composite Flood Vulnerability Atlas (Figure 21), which classifies the LGA into low, moderate, and high flood risk zones.

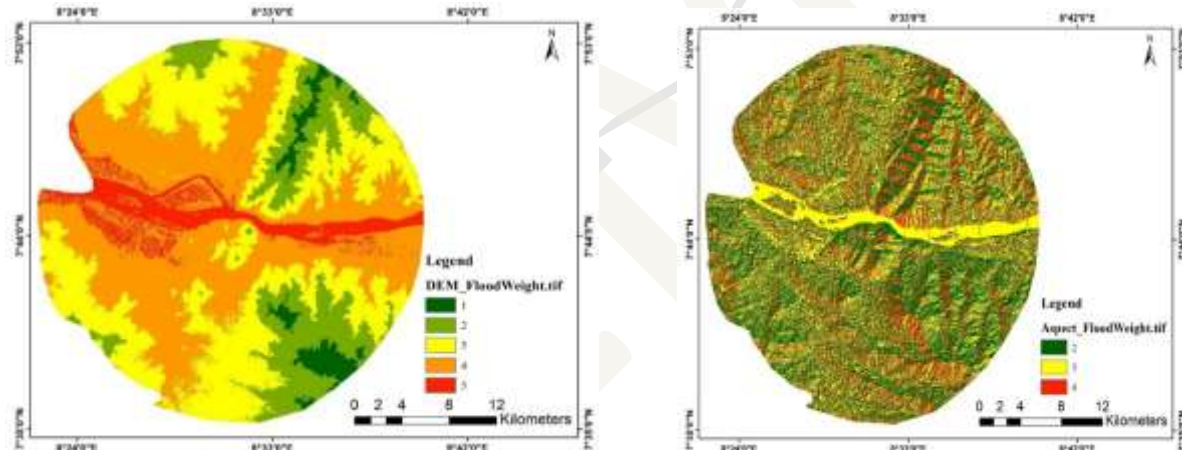
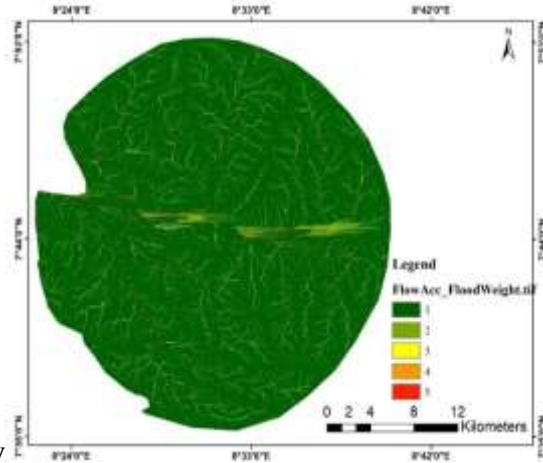


Figure 34: DEM-Based Flood Vulnerability



Vulnerability

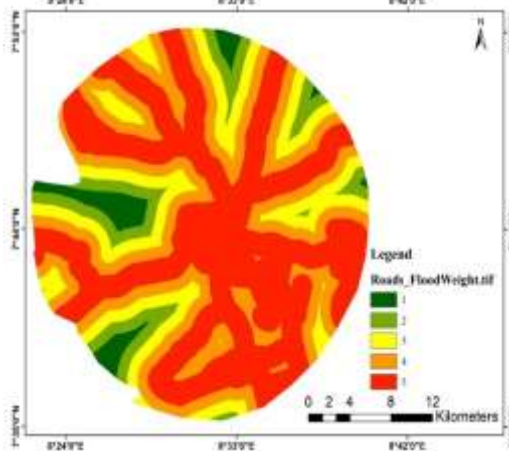


Figure16: Flow Accumulation-Based Flood Vulnerability

Figure15: Aspect-Based Flood

Figure17: Road-Based Flood Vulnerability

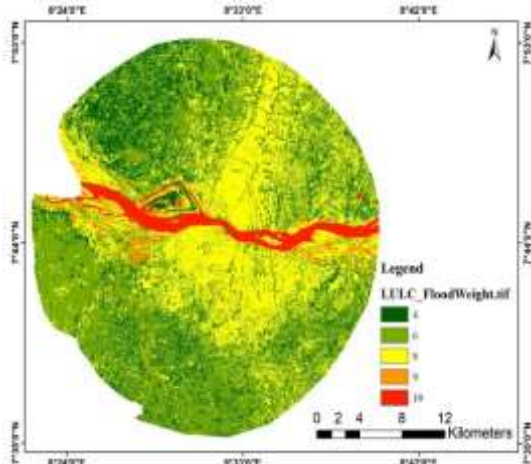


Figure18: LULC-Based Flood Vulnerability

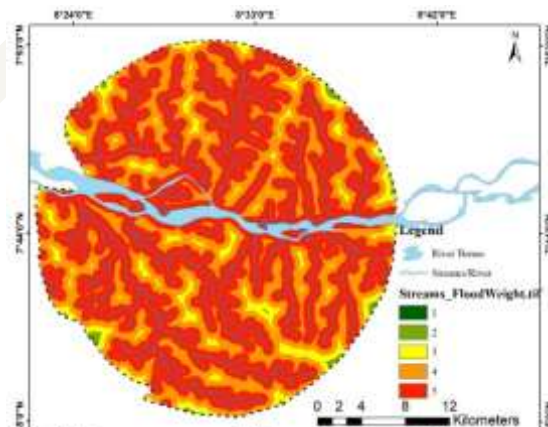


Figure19: Stream-Based Flood

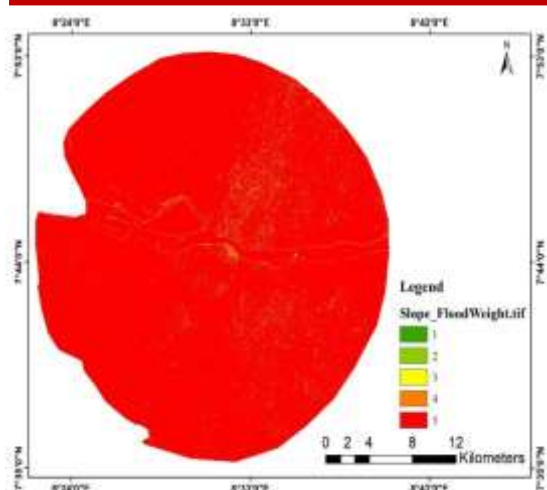


Figure 20: Slope-Based Flood Vulnerability

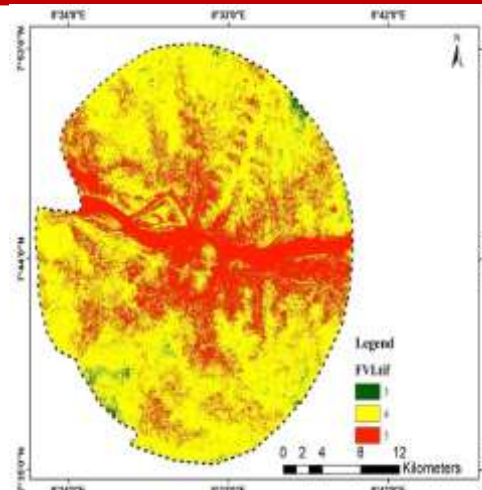


Figure 21: Flood Vulnerability/Atlas Map

3.5 Flood Inundation Patterns and Hazard Atlas Development

The analyzed flood inundation patterns in Makurdi LGA provides critical insights into the hydraulic response of the River Benue system during peak discharge events and the resulting spatial distribution of flooding across the floodplain. These patterns reflect the combined influence of discharge magnitude, catchment hydrology, and terrain morphology on flood frequency, depth, and severity. Geospatial analysis further reveals variability in flood exposure across land use and land cover types, with built-up areas, agricultural lands, and critical infrastructure exhibiting heightened vulnerability. Integrating these observations into a comprehensive flood hazard atlas produces a robust decision-support tool that quantifies risk and enhances spatial understanding of hazard distribution. This atlas can inform infrastructure design, guide urban development planning, and support disaster risk reduction strategies, directly contributing to the overarching research objective of understanding and mitigating flood risk in Makurdi.

4.0 Discussion

4.1 Terrain and flow controls on flood inundation in Makurdi LGA

The susceptibility of Makurdi LGA to flooding is largely determined by the interaction of terrain morphology, drainage configuration, hydrological connectivity, and anthropogenic land-use pressures. Analyses using the Digital Elevation Model (DEM), slope classification, flow direction and accumulation, drainage network, and aspect orientation (

Table 1; Figure 22, Figure3, Figure4, Figure5, Figure6, Figure7, Figure8 and Figure9) highlight the geomorphological and hydrological controls on flood inundation across the Makurdi floodplain. Collectively, these terrain parameters explain how variations in elevation, slope, and surface orientation influence runoff patterns, water retention, and the spatial concentration of flood hazards within the study area.

i. Elevation and Terrain Morphology: DEM-derived elevations in Makurdi LGA range from 45 m to 185 m above sea level, delineating distinct hydrological zones (Figure 22). The lowest elevations (45 – 65 m) are concentrated along the Benue River floodplain, where flat relief, shallow groundwater, and proximity to the main river channel contribute to frequent inundation. Transitional zones (65 – 105 m) experience overbank flooding during extreme rainfall or high upstream discharge, while uplands above 125 m act as natural runoff sources and buffer zones, channeling water into central valleys. These altitudinal patterns align with

floodplain dynamics reported along the River Benue in Makurdi (Adeaga *et al.*, 2025; Ornguze *et al.*, 2023; Wuese and Usman, 2024). The coincidence of low-elevation zones with historical flood extents highlights high vulnerability in Wurukum, Wadata, and Low-Level districts, emphasizing the need to elevate critical infrastructure and regulate development in flood-prone areas.

ii. Slope Characteristics: Slope analysis indicates that over 95 % of Makurdi LGA lies within 0 – 5°, with 52.5 % (424.65 km²) classified as flat (0 – 2°) and 43.25 % (349.64 km²) as gently sloping (2.1 – 5°). Moderate slopes (5.1 – 10°) cover only 4.17 %, while steep slopes are negligible (<0.1 %) (

Table ; Figure5). Low-gradient terrain promotes infiltration but limits natural drainage, resulting in prolonged ponding during heavy rainfall. The flattest areas coincide with historically inundated zones, as highlighted by Iro (2025). Complementary evidence from Ighile *et al.* (2022) identifies low-lying, flood-prone areas, reinforcing the vulnerability of these zones, although slope gradients were not directly analyzed in that study. Engineering interventions such as micro-grading, pumping systems, and channel slope enhancement are therefore essential, while urban planning should avoid high density development without adequate stormwater infrastructure.

iii. Flow Direction and Flow Accumulation: DEM-based flow direction vectors indicate that runoff from eastern uplands drains westward, while western flows drain eastward, converging along the River Benue corridor, with secondary pathways extending northwest and southeast (Figure3). These convergence zones correspond with historical flood hotspots, where intersecting flows amplify localized inundation. Flow accumulation analysis further shows that most terrain falls in low accumulation zones (0 – 1000 cells), with moderate zones (1001 – 5000) tracing tributaries, and high accumulation zones (>5000) aligning with the main river channel and its tributaries (Figure4). High-accumulation areas correlate strongly with Wurukum, Low-Level, and North Bank districts, corroborating field observations of repeated flooding during peak discharge events. The integration of flow accumulation with slope and elevation underscores the critical role of topography in flood persistence.

iv. Drainage Network Structure: The drainage network in Makurdi LGA is predominantly dendritic to sub-dendritic, extending approximately 648 km and reflecting the uniform alluvial plains characteristic of the area (Figure6). Although this connectivity generally facilitates surface runoff, field observations in Wurukum and Low-Level districts indicate that channel constriction from informal settlements, agricultural expansion, and road construction has substantially reduced conveyance capacity, resulting in ponding and localized flooding. Similar reductions in drainage efficiency due to anthropogenic activities have been documented in Makurdi by (Nkwunonwo *et al.*, 2016; Bagenal *et al.*, 2025), reinforcing the relevance of these processes to the local context. Maintaining riparian buffers and integrating engineered interventions such as culverts, cross-drainage structures, and detention basins within natural flow paths are essential for sustainable flood management.

v. Aspect Orientation and Flood Dynamics: Aspect analysis indicates a predominance of southern, southeastern, and southwestern slopes (Figure7, Figure8 and Figure9), directing runoff toward the Benue floodplain. Northern and northwestern aspects, typical of upland areas, serve as efficient drainage sources. In Makurdi, these southern-facing slopes contribute to flood accumulation in Wurukum, Wadata, and Low-Level districts, corroborating field-

recorded inundation patterns. Slope aspect also influences soil moisture distribution and evapotranspiration rates, which in turn affect infiltration and prolong flood persistence in low-lying southern zones. These observations are consistent with findings from Ndabula and Oyatayo (2021), Abah (2013), and Ocheri and Okele (2012), highlighting the influence of slope orientation and terrain morphology on flood dynamics and vulnerability in Makurdi.

vi. Statistical and Spatial Quantification: Pearson correlation analysis indicates a strong inverse relationship between slope gradient and flood frequency ($r = -0.78$), demonstrating that low-gradient zones experience higher flood occurrence. Spatial overlay analysis reveals that 74 % of inundated areas are located below 100 m elevation and on slopes less than 3° . These quantitative findings corroborate DEM-based flow accumulation and aspect analyses, confirming that flood susceptibility in Makurdi is fundamentally terrain-controlled. Similar trends relating slope and elevation to flood occurrence have been documented in Makurdi-specific studies by (Ndabula and Oyatayo, 2021; Abah, 2013), reinforcing the relevance of these geomorphological controls in local flood hazard assessments.

vii. Implications for Engineering, Urban Planning, Environmental, and Geographical Management: The integrated analysis of terrain, flow dynamics, and spatial patterns highlights strategies for mitigating flood risk in Makurdi LGA. From an engineering perspective, it is essential to establish retention and detention basins at flow convergence points, augment drainage channels while aligning them with natural flow paths, deploy pumping systems and flap gates in flat floodplain areas, and apply micro-grading to improve local drainage efficiency. Urban planning measures should include enforcing low-density zoning in flood-prone areas, preserving riparian buffers and green corridors, locating critical infrastructure in upland zones, and integrating terrain-based parameters into predictive flood models and GIS-based monitoring systems. Environmental considerations such as maintaining natural floodplain vegetation, restoring wetlands, and promoting sustainable land use practices enhance infiltration, reduce runoff, and preserve ecosystem services. Geographically, interventions should consider the spatial distribution of elevation, slope, drainage connectivity, land use, and settlement patterns to ensure that mitigation strategies are context-specific and target areas of highest vulnerability. By synthesizing insights from the literature with Makurdi-specific DEM analysis, flood maps, and field observations, this study provides a robust, evidence-based framework for flood resilience planning, ensuring that engineering, planning, environmental, and geographical interventions work in harmony with natural terrain while effectively reducing recurrent flood risks.

4.2 River discharge variability and flood hazard assessment in Makurdi.

The long-term analysis of River Benue discharge at Makurdi provides critical insights into the hydrological processes driving flood hazards, highlighting the influence of climatic variability, upstream inflows, and catchment-scale land-use changes. The 41-year record (1984 – 2024) shows alternating periods of moderate and extreme flow regimes, reflecting the dynamic response of the Benue Basin to both natural and anthropogenic factors. During the 1980s and early 1990s, mean discharges ranged between 10,000 and 12,000 m³/s, indicative of a relatively stable semi-humid tropical flow regime. Post 2010 data reveal increasing volatility, with extreme flows in 2012 (17,418.75 m³/s), 2015 (13,734.80 m³/s), 2017 (13,875 m³/s), 2018 (14,900 m³/s), and 2022 (13,698 m³/s), all surpassing the 90th percentile threshold (Figure 12). These high-magnitude events disproportionately affect low-lying districts such as Wurukum, Wadata, and Low-Level, where hydraulic convergence and limited drainage exacerbate flood exposure. Statistical analyses highlight positive skewness and increasing variance in peak flows, signaling an intensification of extreme events. Spatial overlays of peak discharge

recurrence with floodplain topography and land use reveal that built-up areas, agricultural lands, and critical infrastructure along the river corridor face the highest risk, emphasizing the need for location-specific mitigation strategies. Adaptive infrastructure planning, real-time hydrological monitoring, and flood-informed urban development, complemented by channel expansion, retention basins, and catchment management interventions, can reduce vulnerability and support sustainable flood resilience in Makurdi.

i. Temporal Variability and Forecasted Trends: The hydrograph of observed and projected discharge (1984–2074; Figure 112) shows recurrent high-flow episodes corresponding to major floods in Makurdi (Federal Republic of Nigeria [NEMA], 2013), with wetland loss and ecosystem degradation further elevating flood risk (Hemba *et al.*, 2020). Analysis of the 41-year record (mean = 12,710.29 m³/s; σ = 2,579.26 m³/s) indicates substantial inter-annual variability, while forecast projections reveal a gradual upward trend with widening 95 % confidence intervals, reflecting climate variability, land-use change, and upstream management interventions. These patterns align with observations from other African river basins, underscoring the role of climatic and catchment drivers in flood dynamics (Alsabhan *et al.*, 2003; Adeyeri *et al.*, 2025). The Hydrological Engineering Implications of the Projected discharges **may exceed 14,000 m³/s**, potentially placing significant pressure on bridges, culverts, levees, and urban stormwater systems. Based on established hydrological engineering principles, this study provides evidence-based guidance for updating hydraulic design standards to incorporate climate-resilient thresholds, adaptive safety factors, and scenario-based planning. By linking long-term discharge trends to infrastructure vulnerability, the analysis offers a context-specific framework for enhancing flood resilience and guiding sustainable infrastructure development in Makurdi.

ii. Hydrological Frequency and Extremes: The histogram of peak River Benue discharges (Figure 13) exhibits a positively skewed distribution, with most annual flows ranging from 10,000 to 13,000 m³/s, while extreme events above 15,000 m³/s remain infrequent but highly consequential. The 75th percentile marks the threshold for substantial flooding, whereas the 90th percentile corresponds to historically severe events. These percentile thresholds provide a quantitative basis for designing flood-resilient infrastructure. By integrating frequency analysis with return periods and accounting for climate variability, this study develops a context-specific framework for urban flood management, consistent with comparable hydrological and climate-risk approaches reported by Adeaga *et al.* (2025), Umaru and Adedokun (2020), and Adeyeri (2025) in other African river basins.

iii. Interdisciplinary Implications for Urban and Environmental Management: Hydrological fluctuations in the River Benue significantly influence urban expansion, land-use patterns, and ecosystem stability in Makurdi LGA. Periods of high discharge frequently coincide with settlement encroachment into low-lying floodplains, particularly in Wadata, Wurukum, and North Bank districts, where limited zoning and inadequate planning amplify flood exposure. By integrating long-term discharge records with GIS-based land-use data, this study enhances spatial flood prediction and informs risk-sensitive land-use policies, resilient infrastructure design, and greenbelt preservation. These results are consistent with local observations in Makurdi (Onuh *et al.*, 2025) and are also supported by evidence from other flood-prone urban areas (Ali *et al.*, 2021; Adeaga *et al.*, 2025).

Discharge variability additionally reflects catchment degradation, including deforestation, urban land sealing, and increased surface runoff, which reduce infiltration, destabilize riverbanks, and compromise natural flood retention. Adaptive watershed management and riparian buffer restoration are essential for moderating peak flows, maintaining ecosystem

services, and enhancing resilience, consistent with studies in Makurdi and other river basins (Nnam *et al.*, 2024; Ponsah Emmanuel *et al.*, 2025). By situating these findings within the local hydrological and urban context, this study provides an evidence-based framework for integrating flood risk considerations into sustainable urban and environmental management in Makurdi.

iv. Synthesis and Planning Implications: The four-decade record indicates a trend toward greater variability and intensity in the River Benue's hydrology, influenced by climate, geomorphology, and human activities. These findings highlight the need for an interdisciplinary flood management framework integrating engineering hydrology, environmental stewardship, and urban planning within a geospatial decision-support system. Aligning infrastructure design, land-use regulation, and ecological restoration with evolving discharge patterns strengthens flood resilience and reduces long-term exposure to hydrological hazards in Makurdi.

4.3 Flood Hazard Synthesis and Spatial Risk Interpretation for Makurdi

The Flood Hazard Atlas of Makurdi (Figure19) provides a spatially integrated framework linking topography, hydrology, land use, infrastructure, and ecological characteristics to explain flood risk patterns across the Local Government Area. Developed using a multi-criteria GIS–AHP approach, the model incorporates elevation, slope, flow accumulation, drainage proximity, land-use/land-cover (LULC), and transport networks (Figure 34,

Figure15, Figure16, Figure17, Figure18, Figure19 and Figure20). This integration reveals how geomorphic form, hydrological processes, and human modifications converge to create localized vulnerability.

i. Terrain and Hydrological Control of Flood Risk: Low-lying terrain below 100 m and gentle slopes under 6° dominate approximately 42 % of the floodplain, particularly in Wurukum, Wadata, Fiidi, and Gyado Villa, coinciding with high flow accumulation zones ($>10^4$ cells; Figure15 and Figure16). These areas function as natural hydrological sinks during Benue River overflows. A strong negative correlation between elevation and vulnerability ($r = -0.81$, $p < 0.01$) confirms that flooding is largely terrain-controlled. Rapid urban expansion has further intensified this predisposition: built-up areas increased by ~ 240 % between 1984 and 2024, while vegetation cover declined by over 35 %, reducing infiltration and increasing peak runoff coefficients (Figure15 and Figure16).

Overlay analysis of LULC and flow-accumulation layers (Figure16 and Figure18) highlights the intersection of impervious surfaces with critical drainage paths, converting seasonal flows into perennial flood channels. Historical flood events in 2012, 2017, and 2022 correspond closely with these modeled hotspots, validating the atlas as both a diagnostic and predictive tool. Transport infrastructure contributes additional risk: approximately 55 km of primary and secondary roads traverse very-high-risk zones, with embankments acting as artificial levees that trap runoff and amplify local inundation. Engineering interventions including permeable pavements, raised carriageways, retention trenches, and culvert retrofits should therefore be prioritized along these corridors.

ii. Riparian and Ecological Contributions: The analysis indicates that riparian zones along the Benue River play a pivotal role in moderating flood impacts. Sections with reduced riparian vegetation exhibit higher vulnerability to runoff, increased sediment deposition, and elevated ecological stress. These observations are reinforced by evidence from similar urban–riparian environments, where wetland restoration and the establishment of 50 – 100 m riparian buffers

have been shown to mitigate flood peaks and enhance resilience (Zanetti *et al.*, 2016; Olokeogun *et al.*, 2020; Giovannini *et al.*, 2025).

iii. Spatial Orientation and Urban Exposure: Flood risk exhibits an east–west orientation along the Benue River, reflecting regional tilt, drainage asymmetry, and settlement concentration on low-lying alluvial plains. Peripheral uplands in Agan, Apir, and Bar, with elevations above 110 m and permeable soils, display low to moderate vulnerability and could serve as potential sites for planned expansion. Conversely, densely settled floodplain areas reveal gaps in planning and weak enforcement of the Benue Urban Master Plan, where natural flood-storage areas have been converted into urban land, embedding systemic risk into the city’s fabric (Figure20 and Figure21).

iv. Interdisciplinary Implications: The Hydrological Hazard Atlas developed in this study identifies critical areas for intervention across engineering, environmental, urban planning, and governance domains. From an engineering perspective, the atlas highlights locations requiring flood-resilient road and drainage designs, appropriately sized culverts, and retention structures to safeguard key infrastructure. Environmental management measures including riparian vegetation restoration, wetland rehabilitation, and infiltration-enhancing interventions are essential to reduce runoff, limit sedimentation and pollutant transport, and maintain ecological integrity within the floodplain. Urban planning strategies, such as sustainable urban drainage systems (SuDS), low-impact development (LID) practices, and adaptive zoning in high-risk corridors, can further reduce flood exposure while accommodating urban growth.

This finding underscores the need for proactive, climate-informed governance and policy frameworks to address emerging flood risks, consistent with regional and global projections reported in previous studies (IPCC, 2021; Okafor *et al.*, 2024). By integrating these interdisciplinary insights, the atlas provides a robust, evidence-based framework for reducing flood vulnerability, enhancing urban resilience, and guiding sustainable development in Makurdi LGA.

5.0 Conclusion

Makurdi is increasingly vulnerable to flooding due to climate change, inadequate drainage systems, and the escalating impacts. The current flood risk assessments in the region are fragmented and lack comprehensive data integration. This research has provided the evidence base needed for more effective flood risk management, helping to identify high-risk areas and vulnerable populations. By developing accurate flood hazard atlas, the study has support better preparedness, resource allocation, and disaster response, ultimately enhancing flood resilience in Makurdi. Additionally, the research has contribute to the literature on GIS-based flood risk assessment in developing countries, offering new insights into effective flood management strategies in urban environments. Effective flood management requires a unified strategy integrating engineering, ecological restoration, spatial planning, community adaptation, and climate-informed governance, transitioning the city from reactive response to anticipatory, data-driven resilience. The study concluded that sparse topographic and hydro meteorological data may limit local interpolation accuracy. It also concluded that the 30 m SRTM DEM may overlook micro-topographic variations affecting runoff routing. Historical flood patterns may underestimate future extremes; climate-informed adaptive planning is essential. Finally, the Land-use dynamics require continual updating to reflect urban expansion and ecological restoration.

Recommendations:

The study recommended;

- i) Integrating the flood hazard atlas with distributed hydrologic models for scenario-based planning (HEC-HMS, SWMM).
- ii) Prioritizing high-vulnerability sub-catchments for ecological restoration and engineered retention systems.
- iii) Implementing SuDS/LID measures and adaptive zoning along high-risk corridors.
- iv) Embed flood-resilient building codes and green-infrastructure corridors within urban planning policy.
- v) Updating drainage and infrastructure design standards based on projected rainfall extremes.

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CRedit authorship contribution statement

Seini Aboh Samuel: Writing – original draft, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Enokela Onum Shadrach:** Writing – review & editing, Supervision, Conceptualization. **Malum Flyin Japhet:** Methodology, Formal analysis, Data curation. **Udochukwu Okechukwu Martins:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

None.

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