World Journal of Innovation and Modern Technology E-ISSN 2756-5491 P-ISSN 2682-5910
Vol 8. No. 4 2024 www.iiardjournals.org Online version

Comprehensive GIS-Based Flood Risk Assessment of Vulnerable Areas in Anambra State, Nigeria

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DOI: 10.56201/wjimt.v8.no4.2024.pg1.23

Abstract
Flood risk assessment is critical for effective flood management and mitigation strategies. Understanding spatial variability in flood susceptibility helps in designing targeted interventions. This study aims to evaluate flood risk in a specified area by integrating multiple hydrological and topographical parameters. The assessment incorporates drainage density, slope, land use and land cover (LULC), rainfall, elevation, and proximity to rivers and roads. Data were analyzed to categorize regions into five flood risk levels: very low, low, moderate, high, and very high. The study reveals significant spatial variability in flood risk. High-risk areas, constituting 37.28% of the study area, are primarily near drainage networks and steep slopes. Regions with low to moderate drainage density, covering 40.25%, are prone to waterlogging, while areas with high drainage density, accounting for 59.75%, manage local runoff but may exacerbate downstream flooding. The LULC analysis shows that forested areas (43.62%) mitigate flood risk, whereas built-up areas (35.20%) increase it. Higher rainfall in the southern part of the study area and varied elevation also influence flood risk distribution. High-risk regions need robust flood defenses and efficient drainage systems. Sustainable land management practices and advanced flood control measures are essential for mitigating flood risk, particularly in high rainfall and steep slope areas. This study uniquely combines multiple parameters to provide a comprehensive flood risk assessment, offering valuable insights for targeted flood mitigation strategies and enhancing regional flood resilience.

Keywords: *Drainage Density, Hydrological Studies, Slope Analysis, Spatial Variability, Topographical Parameters*

1.0 Introduction

Flooding is one of the most significant natural disasters affecting communities worldwide, causing substantial economic losses, environmental damage, and loss of human life (Dottori et al., 2018). The increasing frequency and intensity of flood events have become a major concern for policymakers, urban planners, and disaster management authorities (Da Silva et al., 2020; Ekeu-Wei et al., 2020 Buba et al., 2021). Effective flood risk assessment is essential for mitigating the adverse impacts of floods, particularly in regions prone to such events (Olorunfemi et al., 2020). Geographic Information System (GIS) techniques have emerged as powerful tools for flood risk assessment, offering the ability to integrate and analyze diverse datasets to produce detailed flood risk maps (Aja et al., 2019; Chukwuma et al., 2021 Zhou et al., 2021).

Anambra State, located in the southeastern part of Nigeria, is characterized by its complex terrain and diverse hydrological features. The state's topography includes low-lying floodplains, river systems, and varied LULC patterns, all of which contribute to its flood susceptibility (Souissi et al., 2019; Chukwuma et al., 2021). The state's geographical location within the lower Niger River Basin further exacerbates its vulnerability to flooding, particularly during the rainy season when river levels rise significantly. Given these challenges, there is a critical need for a comprehensive flood risk assessment framework that can guide effective flood management and mitigation strategies (Ezeokoli et al., 2015 Ugoyibo et al., 2017).

The success of flood risk assessment relies heavily on the availability and quality of diverse data sources (Komolafe et al., 2020; Malgwi et al., 2021). This study utilizes a wide range of data, including remote sensing data, GIS raster and vector data, meteorological data from weather stations, and other ancillary datasets. The integration of these data sources allows for a holistic understanding of the various factors influencing flood risk in the study area. Remote sensing data provides critical information on land cover changes, vegetation, and surface water bodies, which are essential for understanding the dynamics of flood events (Kandissounon et al., 2018 Refice et al., 2020). GIS raster data, such as digital elevation models (DEMs), are crucial for terrain analysis and identifying flood-prone areas based on topography (Okoli et al., 2024). Vector data, including river networks and infrastructure, help in mapping and analyzing the spatial distribution of flood risks (Sharifi, 2020). Meteorological data, such as rainfall intensity and duration, are vital for understanding the temporal patterns of flooding (Idowu & Zhou, 2019). Other ancillary datasets, like soil type and land use patterns, contribute to a comprehensive flood risk assessment by providing additional context on how different factors interplay to influence flood susceptibility.

A weighted linear combination (WLC) approach was utilized to generate the thematic map of flood risk. This approach is based on the concept of a weighted average of continuous data standardized on a common numeric range and then combined by means of a weighted average (Tang et al., 2021). Weights are assigned to each criterion by decision-makers based on their relative importance to each attribute considered for the analysis. These attribute criteria are then combined by applying the respective weights and summed to produce one composite overall flood risk map. The criteria considered in this study include elevation, slope, proximity to rivers, land use, soil type, and rainfall intensity. Each of these factors plays a significant role in determining the flood risk in Anambra State.

Elevation is a critical factor as low-lying areas are more susceptible to flooding. The analysis of DEMs helps in identifying such areas (Buba et al., 2021). Slope influences the speed and direction of water flow; steeper slopes tend to have faster runoff, reducing the likelihood of flooding, while flatter areas are more prone to water accumulation (Huang et al., 2018). Proximity to rivers is another crucial factor since areas closer to rivers are more likely to experience flooding during periods of high discharge (Ward et al., 2018; Owokotomo et al., 2020). Land use patterns also impact flood risk; for instance, urban areas with impervious surfaces can lead to higher runoff and reduced infiltration, increasing flood risk (Mahmoud et al., 2016). Rainfall intensity and duration directly impact the amount of water that can potentially cause flooding (Dike et al., 2020).

The WLC approach effectively integrates these diverse factors into a coherent flood risk map. This map provides valuable insights for decision-makers, enabling them to identify high-risk areas and prioritize them for intervention (Tang et al., 2017). Areas identified as high-risk can be targeted for flood defense infrastructure, such as levees and floodwalls, or for non-structural measures like improved drainage systems and floodplain zoning. The flood risk map can inform emergency response planning by identifying areas that may require evacuation or other emergency measures during flood events.

The aim of this study is to conduct a comprehensive GIS-based flood risk assessment of vulnerable areas in Anambra State, Nigeria. By integrating diverse datasets including remote sensing imagery, GIS raster and vector data, meteorological records, and geomorphological information, the study seeks to analyze and map key factors influencing flood susceptibility. This includes elevation, slope, proximity to rivers, land use and land cover patterns, soil type, and rainfall intensity. Utilizing a weighted linear combination (WLC) approach, the research aims to generate a detailed flood risk map that can effectively guide decision-makers in identifying high-risk areas and implementing targeted flood management and mitigation strategies. The study aims to contribute to the enhancement of disaster resilience and preparedness in Anambra State, thereby mitigating the adverse impacts of flooding on communities, infrastructure, and the environment.

2.0 Location and Geology of the study area

The study focuses on five Local Government Areas (LGAs) in Anambra State, Nigeria: Ekwusigo, Ihiala, Nnewi North, Nnewi South, and Ogbaru as shown in Figure 1. These regions are situated in the southeastern part of Nigeria, within the coordinates of approximately 5°45'N to 6°45'N latitude and 6°30'E to 7°30'E longitude. This geographical positioning places the study area within the lower Niger River Basin, making it particularly vulnerable to flooding.

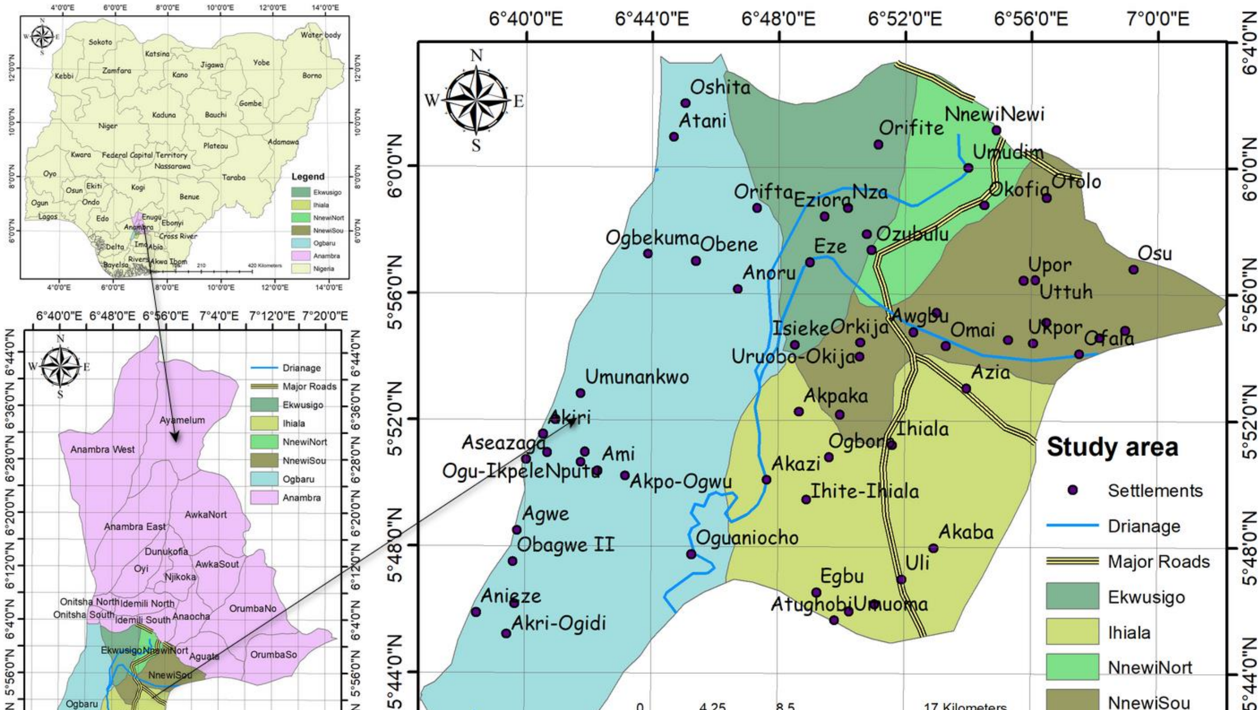

Figure 1: Map of Nigeria, Anambra and study area

Ekwusigo LGA is predominantly low-lying, with a mixture of flat and gently undulating terrain. The topography plays a crucial role in its susceptibility to flooding, especially during the rainy season. The soil composition in Ekwusigo is mainly alluvial, characterized by sandy loam and clay, which impacts drainage and water infiltration rates. Ihiala LGA lies to the south of Ekwusigo and shares similar topographical features. It is marked by a series of low-lying plains and minor undulations. The geology of Ihiala includes sedimentary formations predominantly composed of shale, sandstone, and siltstone. These geological features influence the area's hydrology, contributing to its flood risks. The region experiences significant seasonal variations in rainfall, which, combined with its geological structure, leads to periodic flooding. Nnewi North and Nnewi South LGAs are located adjacent to each other, forming a contiguous area in central Anambra State. Nnewi is renowned for its industrial activities, which have altered its natural landscape. The topography here is more varied compared to Ekwusigo and Ihiala, featuring a combination of flat plains and gently rolling hills. The underlying geology consists of sedimentary rocks, primarily sandstone and shale, interspersed with lateritic soils (Ifeanyichukwu et al., 2021). These geological formations affect water retention and surface runoff, making some parts of Nnewi prone to flash flooding. (Ifeanyichukwu et al., 2021) Ogbaru LGA is situated in the southern part of Anambra State, along the banks of the Niger River. This location makes Ogbaru highly susceptible to riverine flooding. The terrain in Ogbaru is predominantly flat and low-lying, with extensive floodplains. The geology of Ogbaru is characterized by alluvial deposits from the Niger River, consisting of sand, silt, and clay (Ezeokoli et al., 2015). These deposits create a highly fertile but flood-prone landscape. The proximity to the river means that even minor increases in water levels can lead to significant flooding in this area.

The geological setting of the study area is part of the larger Anambra Basin, a significant geological formation in southeastern Nigeria. The Anambra Basin is a Cretaceous sedimentary basin that plays a vital role in the region's hydrogeology. The basin's sedimentary sequences include the Nkporo Shale, Mamu Formation, Ajali Sandstone, and the Imo Shale (Dim et al., 2019). These formations have varying permeability and porosity, influencing groundwater movement and surface water dynamics.

The hydrology of these LGAs is primarily governed by the Niger River and its tributaries. The river systems in the area exhibit a dendritic drainage pattern, typical of regions with homogenous rock types and gentle slopes. This drainage pattern contributes to the widespread distribution of floodwaters during heavy rains. The alluvial soils in the floodplains have high water retention capacity, which can exacerbate flooding when the river overflows.

The climate in Anambra State is characterized by a tropical rainforest climate, with two distinct seasons: the rainy season (April to October) and the dry season (November to March). This climate pattern significantly impacts the hydrological cycle in the study area, with the rainy season bringing heavy rainfall that can overwhelm the drainage systems. The combination of high rainfall, flat topography, and alluvial soils makes these LGAs particularly vulnerable to flooding.

3.0 Methodology

3.1 Materials

The success of this research work relies heavily on diverse data sources to achieve the stated objectives. The data utilized includes remote sensing data, raster and vector data in GIS, meteorological data from meteorological stations, and other ancillary data. The following paragraphs outline the types and sources of data employed in this study.

3.1.1 Meteorological Data

For this research, 23 years of daily rainfall data (2023) were obtained for seven meteorological stations, with four located outside the basin and three within the study area in Anambra State, Nigeria. This extensive dataset was sourced from the Nigerian Meteorological Agency (NiMet). The data underwent rigorous quality control processes, including checking for missing values and applying statistical methods to ensure consistency. This consistency check is vital to maintaining the reliability of the data for subsequent analysis. In addition to rainfall data, streamflow data spanning from 2000 to 2023 were acquired from NiMet. These datasets are crucial for analyzing water resources and understanding the hydrological behavior of the basin, which directly influences flood occurrences and management strategies.

3.1.2 Remote Sensing Data

Satellite imagery, particularly from Landsat 8 Operational Land Imager (OLI), was obtained from the United States Geological Survey (USGS). This imagery provides detailed land use and land cover data, enabling the analysis of changes in the landscape over time. Additionally, Shuttle Radar Topography Mission (SRTM) elevation data from the USGS was used to derive slope and elevation models. These models are essential for understanding the topographic features of the basin, which influence flood dynamics and water flow patterns. Road network and river shapefiles were also sourced from USGS, contributing to the spatial analysis of infrastructure and hydrography within the study area.

3.1.3 Geomorphological Data

The geomorphological characteristics of the basin were examined using soil data from the Food and Agriculture Organization (FAO). The 2020 Digital World Soil Map from FAO provided detailed information on soil types and properties, which are critical for assessing flood risk and planning agricultural activities. Soil data helps in understanding the permeability and infiltration rates, which affect runoff and flood potential.

The comprehensive data collected for this study is summarized in Table 1 below:

Table 1: Data Type and Sources of Data

S/N	Data Category	Data Type	Data Source
1	Satellite imagery	Land use and Land cover data	United States Geological Survey (USGS)
2	GIS data	SRTM Elevation data	United States Geological Survey (USGS)
		Slope, Road Network shapefile, River shapefile	
3	Hydro-meteorological data	Rainfall data (2023)	Nigerian Meteorological Agency (NiMet)

The data utilized in this research encompasses a wide range of sources and types, each contributing uniquely to the comprehensive analysis of the study area. Remote sensing data provides critical insights into land use, land cover, and topographic features, while meteorological and hydro-meteorological data offer detailed information on rainfall and streamflow patterns. Demographic data elucidates population dynamics, and geomorphological data highlights soil characteristics. Ancillary data from stakeholder engagements enriches the analysis with qualitative perspectives. This multi-faceted approach ensures a robust and holistic understanding of the study area, facilitating effective GIS analysis and supporting the achievement of the research objectives.

3.2 Methods

The acquisition phase focused on gathering various types of data essential for flood risk assessment:

1. **Precipitation Data**: Obtained from the Nigerian Meteorological Agency (NiMet) to analyze rainfall patterns over 36 years, crucial for identifying trends and anomalies.
2. **River Data**: Collected to map the hydrological network and understand the flow dynamics within the study area.
3. **Road Data**: Acquired to assess the impact of infrastructure on flood dynamics and emergency response.

4. **Sentinel-2 Imagery**: Utilized for detailed land cover and land use analysis through multispectral imaging.
5. **Drainage Density**: Calculated to understand the concentration of drainage features in the area, which influences runoff and flood potential.
6. **Slope**: Derived from the SRTM DEM to assess the steepness of the terrain, which affects water flow velocity and accumulation.
7. **Elevation**: Obtained from the SRTM DEM to determine the relative height of land surfaces, which is critical for floodwater direction and depth.

Following the acquisition phase, a series of image pre-processing techniques were implemented. These pre-processing steps included radiometric correction, geometric correction, and atmospheric correction, which were crucial for enhancing the clarity and interpretability of the acquired imagery. This ensured that the subsequent analyses would be based on refined and accurate visual information.

After pre-processing, the study progressed to image classification using the maximum likelihood method for supervised classification. This involved creating signature samples for each identified class feature in the imagery, such as different types of land cover and land use categories. These samples were then utilized to categorize and delineate distinct patterns within the acquired imagery. The resulting classification output generated a detailed dataset, capturing the spatial distribution of various land cover and land use categories across the study area.

Subsequently, road and river data were converted to raster data formats. Euclidean distances were computed from these raster datasets to analyze proximity relationships and their potential impact on flood dynamics. This transformation was essential for integrating vector data into the raster-based analysis framework, ensuring compatibility across different data types.

3.3 Generation of Thematic Maps for Flood Risk Assessment

Thematic maps are essential tools in flood risk assessment, as they visually represent various physical and environmental factors that influence flood hazards. The generation of thematic maps for drainage density, slope, LULC, rainfall, and soil in Anambra State, Nigeria. These maps were created using GIS techniques and various datasets, including SRTM DEM and Landsat-8 OLI satellite imagery. The systematic methodology employed in this study commenced with the acquisition of soil data, precipitation data, river data, road data, Sentinel-2 imagery, and SRTM DEM, covering the entirety of the designated study area in Anambra State, Nigeria. This initial step aimed to secure a comprehensive and high-resolution dataset that would serve as the foundational source for subsequent analyses.

3.3.1 Drainage Density

Drainage density (Dd) is a measure of the total length of streams per unit area in a watershed and is a critical factor in understanding flood potential (George et al., 2022). To prepare the drainage density map, drainage networks were generated from the SRTM DEM using hydrologic analysis in ArcGIS. The drainage networks were then used to calculate drainage density as shown in equation (Equation 1):

$$D_d = \frac{\sum_{i=1}^{n} L_i}{A} \quad 1$$

where $\sum_{i=1}^{n} L_i$ is the total length of streams (L) in the area, and A is the total area (L^2). The resulting drainage density map highlights areas with varying densities of drainage networks, indicating regions with different potentials for runoff and flooding.

3.3.2 Slope

Slope is a vital factor in flood risk assessment as it affects the velocity and direction of surface runoff (Adewumi et al., 2023). To prepare the slope map, the SRTM DEM data were preprocessed to remove depressions using sink and fill processes in ArcGIS. The slope map was then generated using the following equation (Eq. 2):

$$Slope = \frac{100 \times \sqrt{(DX)^2 + (DY)^2}}{Pixel\ size\ (DEM)}$$

2

where DXDX is the filtered DEM with an x-gradient filter, DYDY is the filtered DEM with a y-gradient filter, and Pixel Size (DEM) is the pixel size of the DEM. The slope map indicates areas with steep and gentle slopes, which are critical in understanding runoff and erosion processes.

3.3.3 Land Use and Land Cover (LULC)

The LULC map was prepared from Landsat-8 OLI imagery for the year 2020 using a supervised classification approach. The maximum likelihood supervised classification (MLSC) method was used due to its high accuracy in identifying land cover types (Akaolisa et al., 2023; Kanav et al., 2024). The resulting LULC map categorizes the study area into different land use types, such as urban areas, agricultural land, forests, and water bodies, which are important for understanding the interaction between land use and flood risk.

3.3.4 Rainfall

The rainfall map was prepared using annual average rainfall data of the years 2023, obtained from 76 rain gauge stations. The data were spatially interpolated using the Inverse Distance Weighted (IDW) technique in ArcGIS.

3.3.5 Elevation

Elevation is a fundamental factor in flood risk assessment as it determines the potential energy available for water flow and significantly influences the direction and speed of runoff. To prepare the elevation map, the SRTM-DEM data were utilized. The elevation values were extracted directly from the DEM, and areas were categorized into different elevation classes (Azizian & Brocca, 2019). This classification helps in identifying low-lying areas that are more prone to flooding compared to higher elevation regions. The elevation map provides a clear visualization of the terrain's topography, which is crucial for understanding flood dynamics and implementing effective flood mitigation strategies.

3.3.6 Distance to River

The proximity to rivers is a critical determinant of flood risk, as areas closer to rivers are generally more susceptible to flooding. To prepare the distance to river map, the river network data were obtained from hydrographic datasets and topographic maps (Idowu & Zhou, 2019). The Euclidean Distance tool in ArcGIS was used to calculate the shortest distance from each cell in the study area to the nearest river. The resulting map classifies areas based on their distance to rivers, with closer areas having higher flood risk values. This distance-to-river map is instrumental in assessing the vulnerability of different regions to riverine flooding and aids in prioritizing areas for flood prevention measures.

3.3.7 Distance to Road

Road networks can contribute to and mitigate flood risks depending on their design and location. Roads often act as barriers to natural water flow, potentially increasing flood risk in certain areas. Conversely, well-designed drainage systems along roads can reduce flood risk (Egbinola et al., 2015). To prepare the distance to road map, road network data were obtained from local government GIS databases. The Euclidean Distance tool in ArcGIS was used to compute the distance from each cell to the nearest road. This map categorizes areas based on their proximity to roads, with shorter distances indicating a higher potential impact from roadrelated flood risks. The distance-to-road map is essential for understanding how transportation infrastructure interacts with flood hazards and for planning flood mitigation interventions.

3.4 Flood Hazard Assessment Model

WLC approach was utilized to generate the thematic map of flood risk. This approach is based on the concept of a weighted average of continuous data standardized on a common numeric range and then combined by means of a weighted average. Weights are assigned to each criterion by decision makers based on their relative importance to each attribute considered for the analysis. These attribute criteria are then combined by applying the respective weights and summed to produce one composite overall flood risk map, as represented in Equation (3):

$$S = \sum(W_i \times X_i) \tag{3}$$

where is S the flood risk suitability, W_i is the weight assigned to factor i, and $X_i$is the criterion score of factor i.

The methodology involved reclassifying seven factors (LULC, Drainage Density, Distance to Road, Distance to River, Slope, Annual Rainfall, and Elevation) on a scale from 1 to 5, assigning weights based on expert consultation (LULC: 10%, Drainage Density: 15%, Distance to Road: 5%, Distance to River: 20%, Slope: 10%, Annual Rainfall: 25%, Elevation: 15%), creating a weighted overlay table in ArcGIS, and using the Weighted Overlay tool to combine the layers according to their weights, resulting in a composite flood risk map.

The generation of thematic maps using GIS techniques, combined with expert-driven weighting and modeling, provides a robust framework for flood risk assessment. This comprehensive approach ensures accurate identification of flood-prone areas and supports effective flood management and mitigation strategies in Anambra State, Nigeria (Udo et al., 2021). The integration of diverse datasets and the application of advanced analytical methods highlight the potential of GIS in enhancing disaster resilience and preparedness.

The systematic methodology employed in this study encompassed data acquisition, pre-processing, classification, environmental factor extraction, standardization, and modeling. These steps provided a robust framework for flood risk assessment using GIS. The integration of diverse datasets and expert evaluations ensures a comprehensive and accurate analysis, which is critical for effective flood management and mitigation in Anambra State, Nigeria.

4.0 Results and Discussion

4.1 Drainage Density map

Drainage density is a crucial parameter in hydrological studies and flood risk assessment as it quantifies the total length of streams and rivers per unit area of a region. This metric is indicative of the landscape's ability to convey water through its network of channels (Taofik, 2017). The drainage density values and their corresponding area percentages for the study area, as depicted in Figure 2, reveal significant variability across the region.

The data categorizes drainage density into five ranges: 0-55.89 km/km², 55.89-98.09 km/km², 98.09-140.29 km/km², 140.29-182.49 km/km², and 182.49-496.59 km/km². This range has the lowest drainage density, covering 11.94% of the area. Regions with such low drainage densities typically have less developed drainage networks and may experience slower surface runoff, potentially leading to waterlogging during heavy rains. This range covers 28.31% of the area, indicating moderately low drainage density. These regions may have more extensive but still relatively sparse drainage networks. They are somewhat more efficient in draining water compared to the lowest range but can still be susceptible to localized flooding, especially in low-lying areas. The largest portion of the area, 31.23%, falls within this range. This medium drainage density indicates a well-balanced network that efficiently channels water. These regions are likely to handle surface runoff more effectively, reducing the risk of flooding compared to areas with lower drainage densities. Covering 17.56% of the area, around the central part of the study area this higher drainage density range suggests a more intricate network of streams and rivers. Such areas can rapidly convey water away, reducing the likelihood of flooding. However, they can also contribute to higher peak discharges downstream, potentially increasing flood risks in lower-lying areas. The highest drainage density range covers 10.97% of the area. These regions have very dense drainage networks, often found in highly dissected or mountainous terrains. While these areas are less prone to local flooding due to efficient drainage, they can contribute significantly to downstream flooding during intense rainfall events.

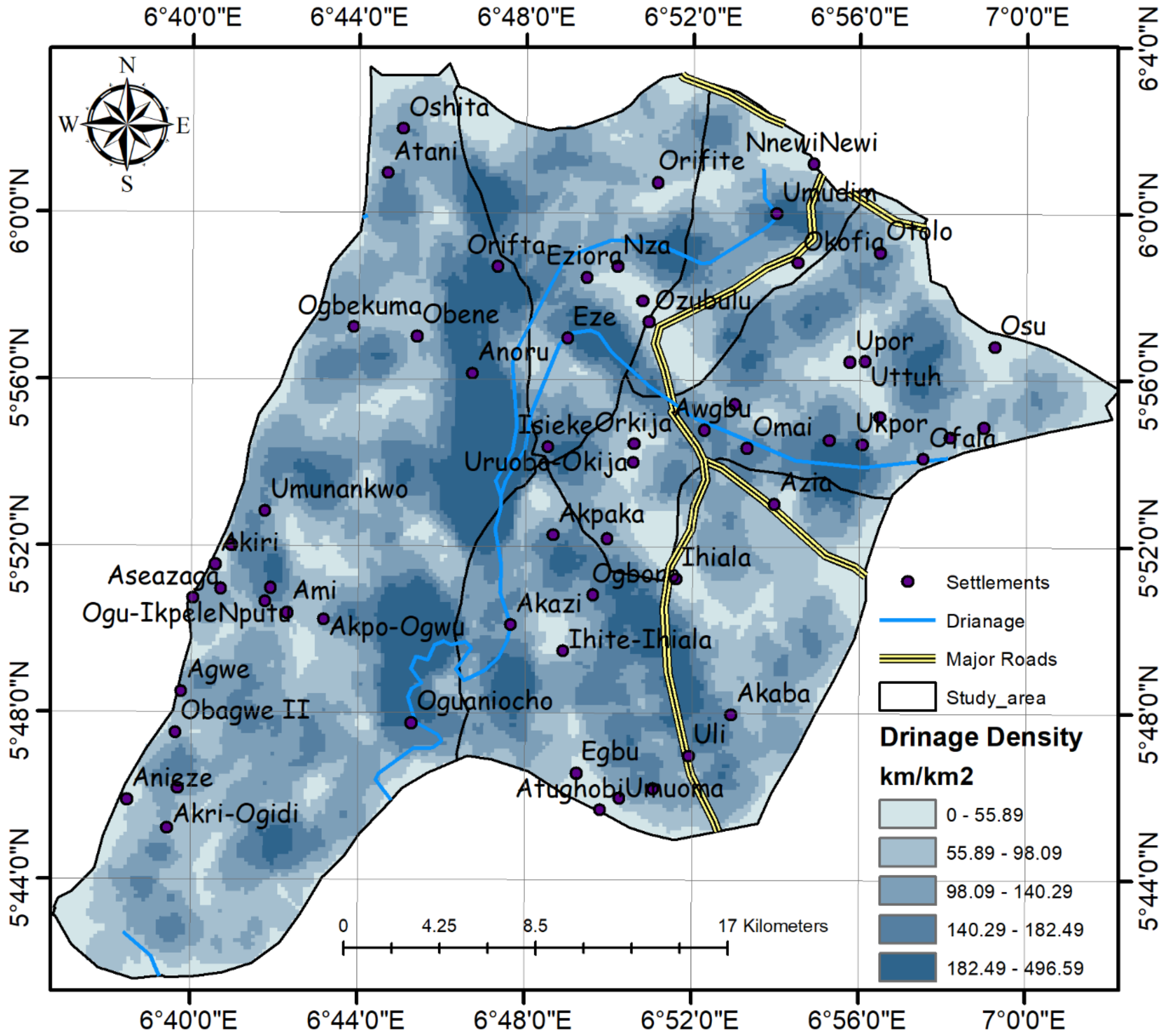

Figure 2: Map of drainage density of the study area

The variation in drainage density across the study area has important implications for flood risk management. Areas with low to medium drainage densities (0-98.09 km/km²) are more prone to local flooding and require targeted interventions such as improved drainage infrastructure and water retention systems. In contrast, regions with high drainage densities (98.09-496.59 km/km²) are effective in managing runoff locally but necessitate downstream flood control measures to mitigate the impacts of rapid water conveyance.

4.2 Slope map

Slope, expressed in degrees, is a critical topographical parameter influencing surface runoff, soil erosion, and flood potential. The slope distribution within the study area as shown in Figure 3, categorized into five ranges, reveals significant variation across the landscape, which has important implications for hydrological processes and flood risk management.

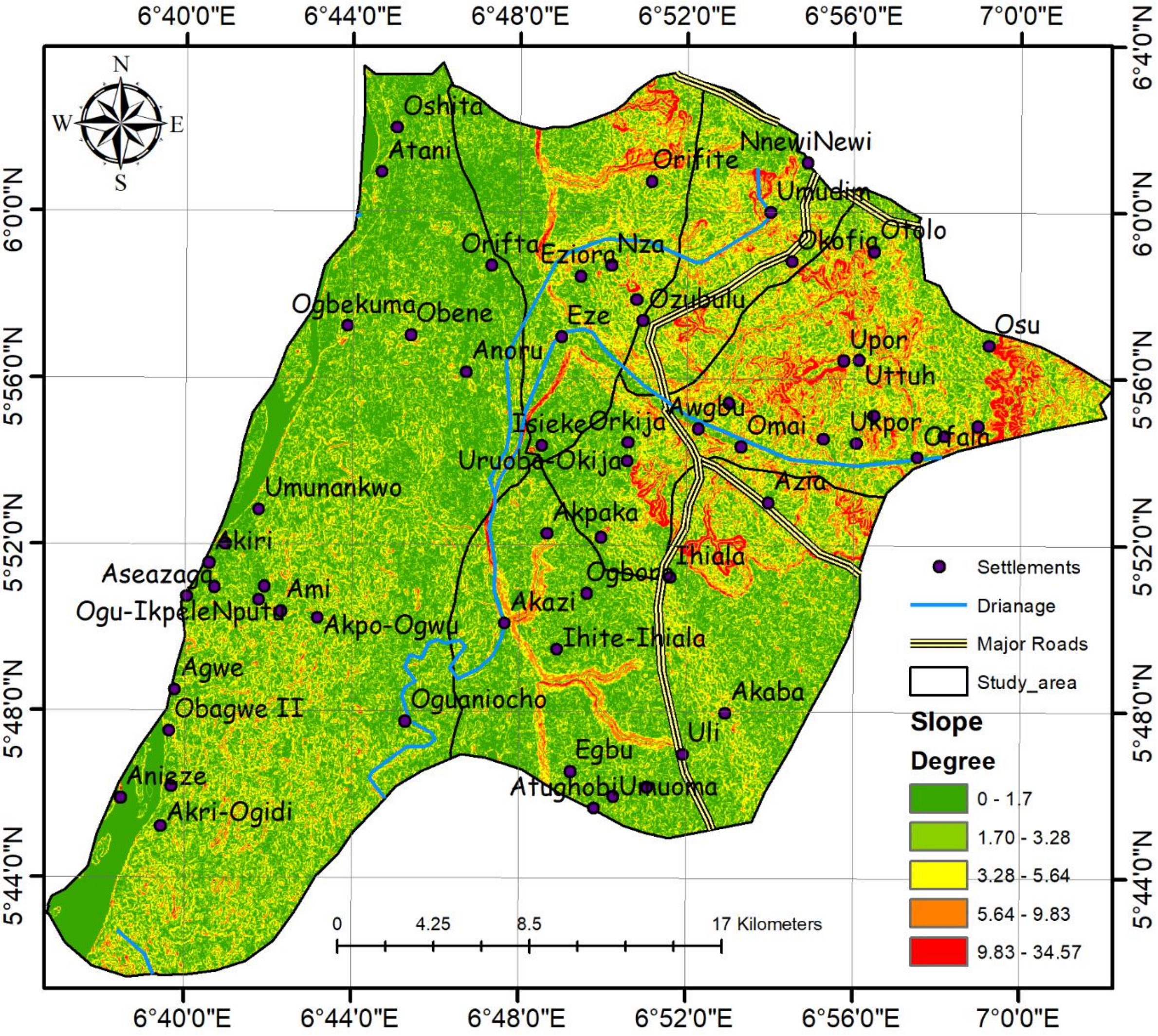

Figure 3: Slop map of the study area

Covering 2.02% (0 – 1.70^0) of the area around the western part of the study area, this range represents nearly flat terrains. These regions are typically low-lying floodplains or valleys where water accumulates easily, leading to a higher risk of waterlogging and flooding during heavy rainfall. This range (1.70 – 3.28^0) encompasses 7.39% of the area. Slightly sloped areas allow for marginally better drainage compared to flat terrains. However, they can still be prone to flooding, particularly if surface runoff is slow and accumulates over time. Making (3.28 – 5.64^0) up 21.08% of the area, this range represents moderately sloped terrain. These areas are better at channeling water and reducing surface water accumulation. While not as susceptible to flooding as flatter regions, they can experience erosion and sediment transport, affecting soil stability. The largest portion (5.64 – 9.83^0) of the area, 33.22%, falls within this range. These moderately steep slopes are efficient at directing runoff, which reduces the likelihood of local flooding but can increase the risk of erosion. The higher velocity of runoff water in these areas can lead to the rapid transport of sediments and potentially increase flood risks downstream. Covering (9.83 – 34.57^0) 36.29% of the area mostly in the southern part of the study area, these steep slopes are the most effective at directing surface runoff quickly. While these areas are less prone to local flooding, they can contribute to downstream flooding due to the rapid conveyance of water. Steep slopes are also highly susceptible to erosion, leading to significant sediment deposition in lower-lying areas.

The distribution of slopes across the study area has significant implications for flood risk and land management strategies. Areas with minimal slopes (0-3.288 degrees) require interventions to manage potential water accumulation and flooding. These could include the construction of drainage systems and water retention facilities to control and direct runoff effectively.

Moderately sloped regions (3.28-9.83 degrees) balance drainage efficiency with erosion risk. While these areas benefit from natural drainage, they require measures to prevent soil erosion and manage sediment transport. Techniques such as terracing, vegetation cover, and erosion control structures can help mitigate these risks. Steep slopes (9.83-34.57 degrees) necessitate comprehensive management strategies to address the dual challenges of rapid runoff and severe erosion. These areas are crucial for maintaining watershed health and preventing downstream flooding. Erosion control methods, reforestation, and the construction of check dams and retention basins are essential to manage the impacts of rapid water flow and soil loss.

The slope distribution in the study area highlights the diverse topographical challenges that influence hydrological dynamics and flood risks. A nuanced approach to flood risk management is essential, considering the specific needs of flat, moderately sloped, and steep regions (Jimme et al., 2016). By addressing the unique characteristics of each slope category, effective and sustainable flood mitigation strategies can be developed, enhancing resilience and reducing the adverse impacts of flooding in Anambra State, Nigeria.

4.3 LULC map

LULC is a critical component in understanding the spatial distribution of different land types and their implications for environmental and flood risk management (Siraj et al., 2018). The LULC distribution in the study area includes water bodies, trees, flooded vegetation, crops, built areas, bare ground, and rangeland as shown in Figure 4 and table 2. The analysis of each LULC type provides insights into the ecological and hydrological characteristics of the region, which are crucial for effective land management and flood mitigation strategies.

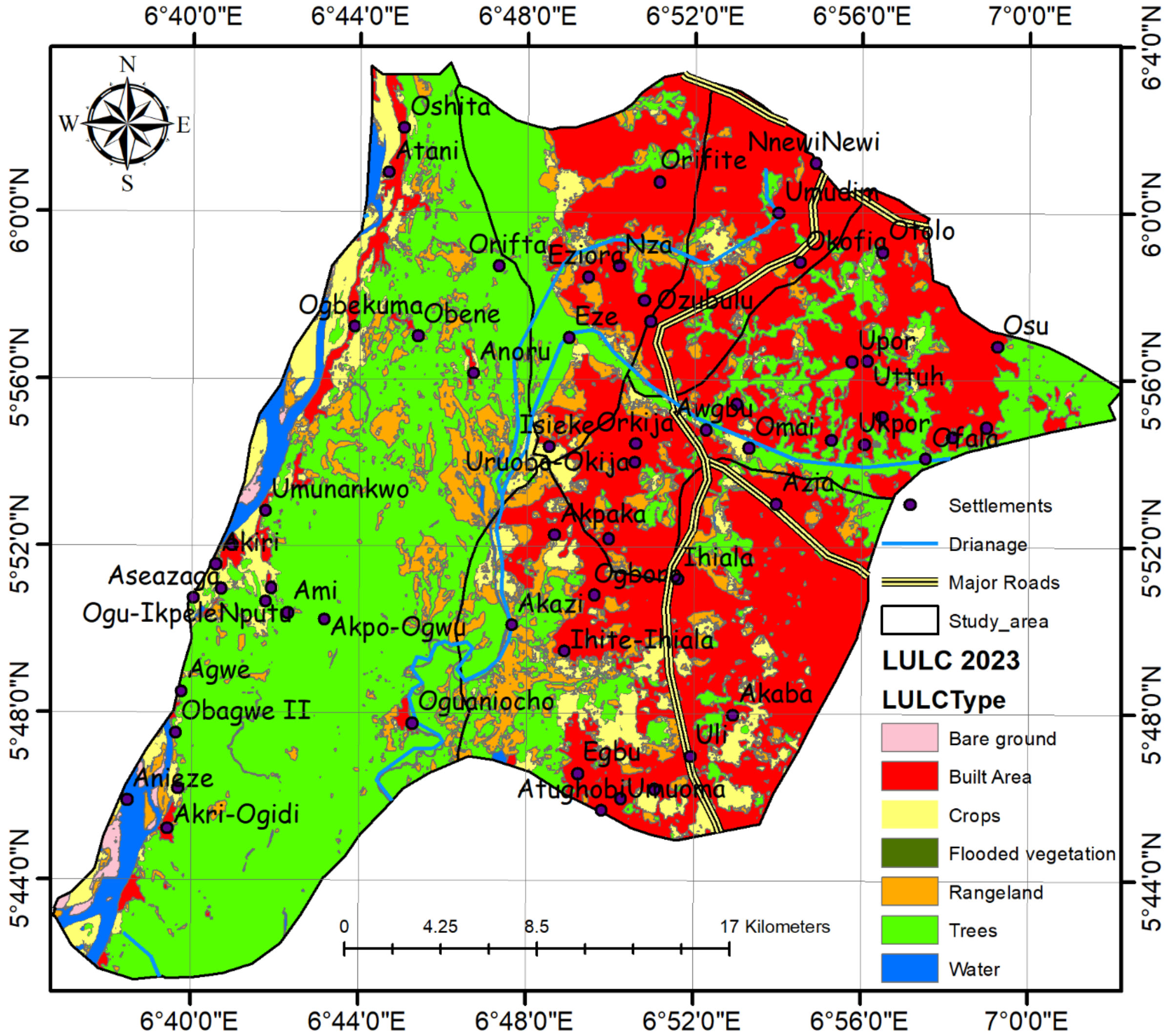

Figure 4: LULC map of 2023 in the study area

Water covering an area of 23.76 km², water bodies include rivers, lakes, and other surface water sources. These areas are significant for the hydrological cycle, serving as sources of water for various uses and playing a role in flood dynamics. Water bodies can act as both sources of floods during heavy rainfall and as flood mitigation areas by absorbing excess runoff. Trees (43.62%), with 418.14 km² of the area covered by forests and tree plantations, this category represents the largest LULC type. Trees play a vital role in maintaining ecological balance, reducing surface runoff, increasing infiltration, and preventing soil erosion. Forested areas are crucial for mitigating flood risks by acting as natural water retention systems. Flooded Vegetation (0.015%), although occupying a small area of 0.14 km², flooded vegetation indicates regions that are periodically inundated. These areas are important for biodiversity but can contribute to localized flooding if water management systems are inadequate. Crops (7.67%), agricultural lands cover 73.58 km². Crop areas are essential for food production but can be susceptible to flooding, affecting agricultural output and leading to economic losses. Effective water management and flood protection measures are necessary to safeguard these areas. Built Area (35.20%), urban and built-up areas span 337.42 km². These regions are characterized by impervious surfaces, such as roads and buildings, which increase surface runoff and reduce natural infiltration. Built areas are often at higher risk of flooding due to the reduced capacity for water absorption and drainage. Bare Ground (0.45%), covering 4.35 km², bare ground includes areas with minimal or no vegetation. These areas are highly susceptible to erosion and can contribute to increased runoff and sediment transport during rainfall events. Rangeland (10.56%), occupying 101.25 km², rangelands are used primarily for grazing and can be susceptible to overgrazing, leading to soil compaction and reduced infiltration rates. Proper management of these lands is necessary to maintain their ecological function and prevent degradation.

Table 2: LULC type in 2023 for the study area

LULC Type	Area (Km^2)	Area (%)
Water	23.76	2.48
Trees	418.14	43.62
Flooded vegetation	0.14	0.01
Crops	73.58	7.67
Built Area	337.42	35.20
Bare ground	4.35	0.45
Rangeland	101.25	10.56

The LULC distribution highlights the varying degrees of flood risk and land management needs across different land types. Areas dominated by water bodies and trees require preservation and management to maintain their natural flood mitigation functions. Urban areas and built-up regions need enhanced drainage systems and flood prevention infrastructure to manage increased runoff. Agricultural lands and rangelands require sustainable land management practices to reduce susceptibility to flooding and erosion.

4.4 Rainfall map

The annual rainfall data for 2023 in the study area reveals a significant gradient in precipitation, increasing from the northern to the southern parts as shown in Figure 5. The total annual rainfall ranges from 1992 mm to 2170 mm, indicating variability in rainfall distribution that has important implications for flood risk and water resource management.

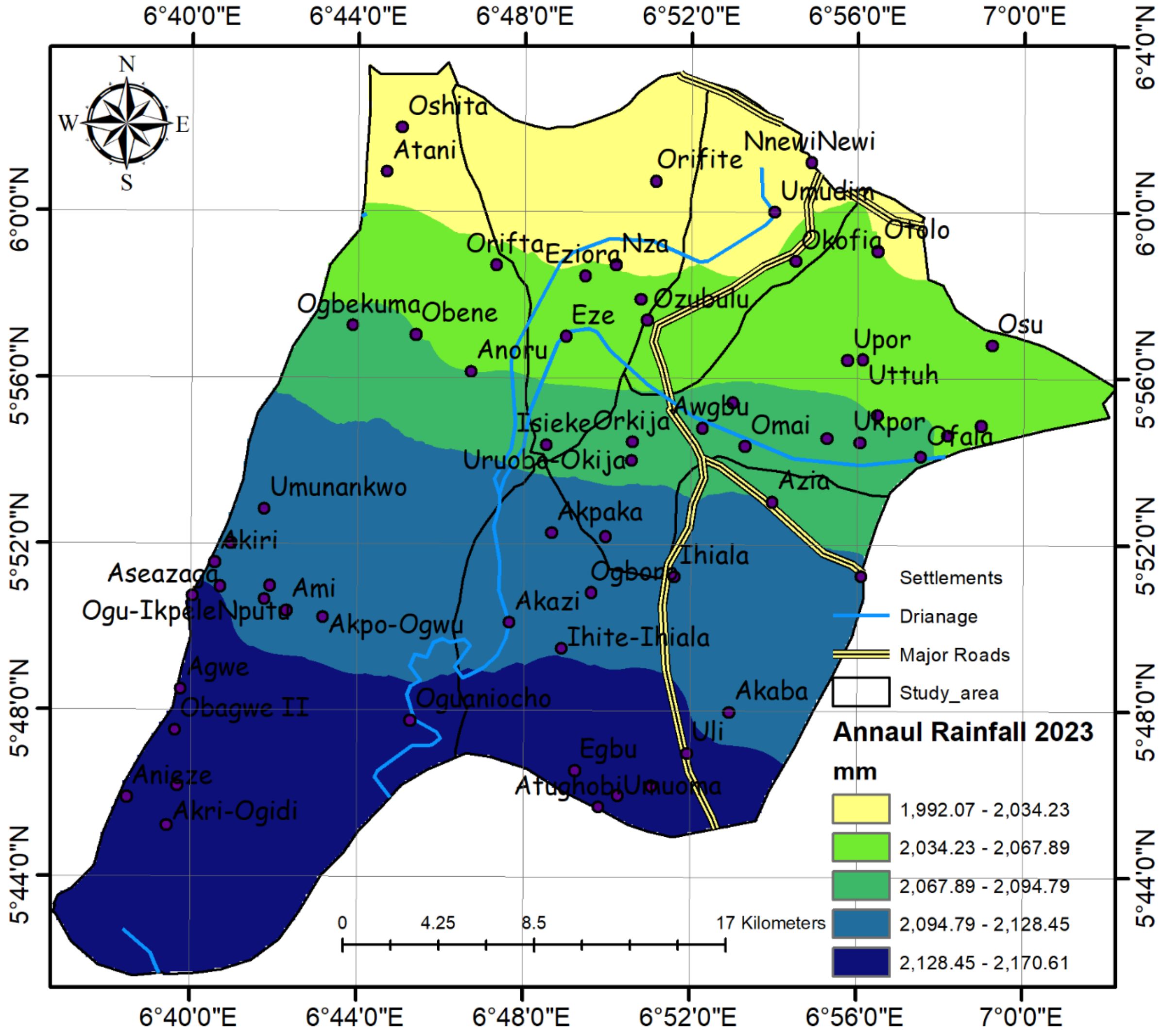

Figure 5: Annual rainfall in 2023 in the study area

The observed increase in rainfall from north to south suggests that the southern parts of the study area receive more precipitation annually compared to the northern parts. This gradient can be attributed to several factors, including geographical features, prevailing wind patterns, and proximity to water bodies. Southern areas, often closer to large water bodies or coastal regions, tend to receive more rainfall due to moisture-laden winds and orographic effects.

The variability in annual rainfall significantly affects flood risk across the study area. Regions with higher rainfall, particularly in the southern parts, are more susceptible to flooding due to the greater volume of water entering river systems and other water bodies (Ogunrinde et al., 2019). Increased precipitation leads to higher surface runoff, especially in areas with limited vegetation cover or impervious surfaces. This runoff can overwhelm drainage systems, leading to urban flooding. Higher rainfall contributes to the swelling of rivers and streams, increasing the likelihood of riverine flooding (Liu & Niyogi, 2019). Areas close to major rivers and streams in the southern part of the study area are particularly at risk. Persistent or heavy rainfall saturates the soil, reducing its ability to absorb additional water. This saturation can lead to flash floods, especially during intense rainfall events.

4.5 Map of Elevation

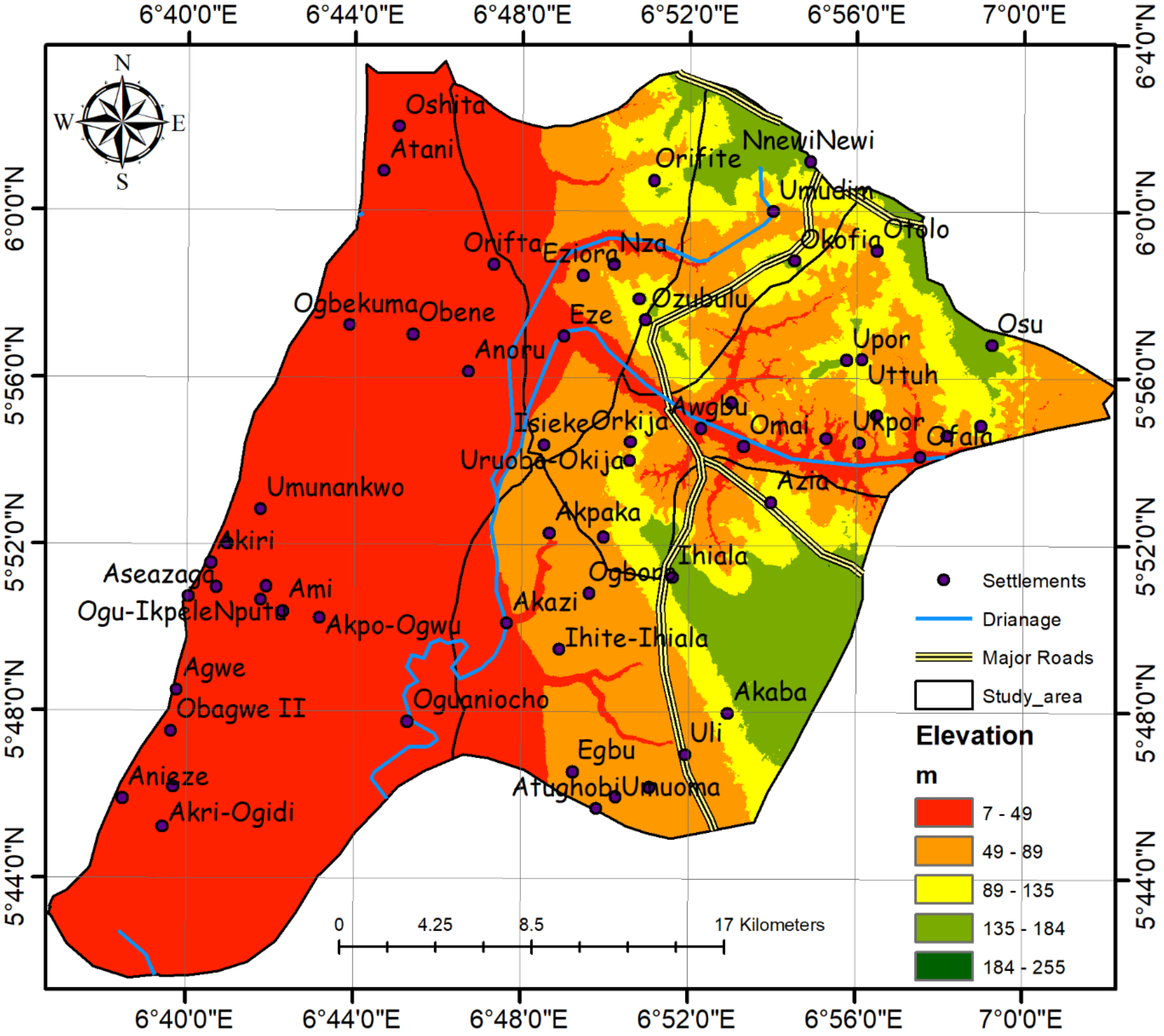

Figure 6: Elevation map of the study area

The elevation data for the study area, categorized into various ranges, reveals significant topographical diversity. The elevation ranges from 0 to 255 meters above sea level, with most of the area concentrated in the higher elevation ranges as shown in Figure 6.

Moderate Elevation (49 - 89 meters and 89 - 135 meters), these areas together constitute about 20.79% of the total area. Regions within these elevation ranges may experience moderate flood risks, particularly during heavy rainfall events. Proper drainage systems and flood management practices are essential in these zones to mitigate flood impacts. Higher Elevation (135 - 184 meters and 184 - 255 meters), these categories encompass the majority of the study area, with over 79.21% of the land falling within these elevation ranges. Higher elevation areas are less susceptible to flooding but can still be affected by heavy runoff during intense rainfall, leading to erosion and landslides.

Given their high susceptibility to flooding, these regions should be prioritized for flood defenses such as levees, embankments, and floodwalls. Additionally, flood early warning systems and evacuation plans are crucial for protecting lives and property. Flood mitigation in these zones can be enhanced through improved drainage infrastructure, such as stormwater drains and retention basins. Land use planning should discourage development in flood-prone areas and promote green spaces that absorb excess water. While these regions are less prone to flooding, attention should be given to managing runoff and preventing erosion. Sustainable land use practices, such as afforestation and contour plowing, can help maintain soil stability and reduce the risk of landslides.

The elevation gradient affects water flow patterns within the study area. Water naturally flows from higher elevations to lower ones, meaning that runoff from the highlands can significantly impact lower-lying areas. Proper watershed management practices, including the maintenance of natural water channels and the construction of check dams, can help manage this runoff and reduce flood risks downstream.

4.6 Distance to River and Road maps

The study area exhibits a notable variation in the distance to rivers, with the central part of the region having shorter distances to rivers compared to the extreme western and eastern parts as shown in Figure 7.

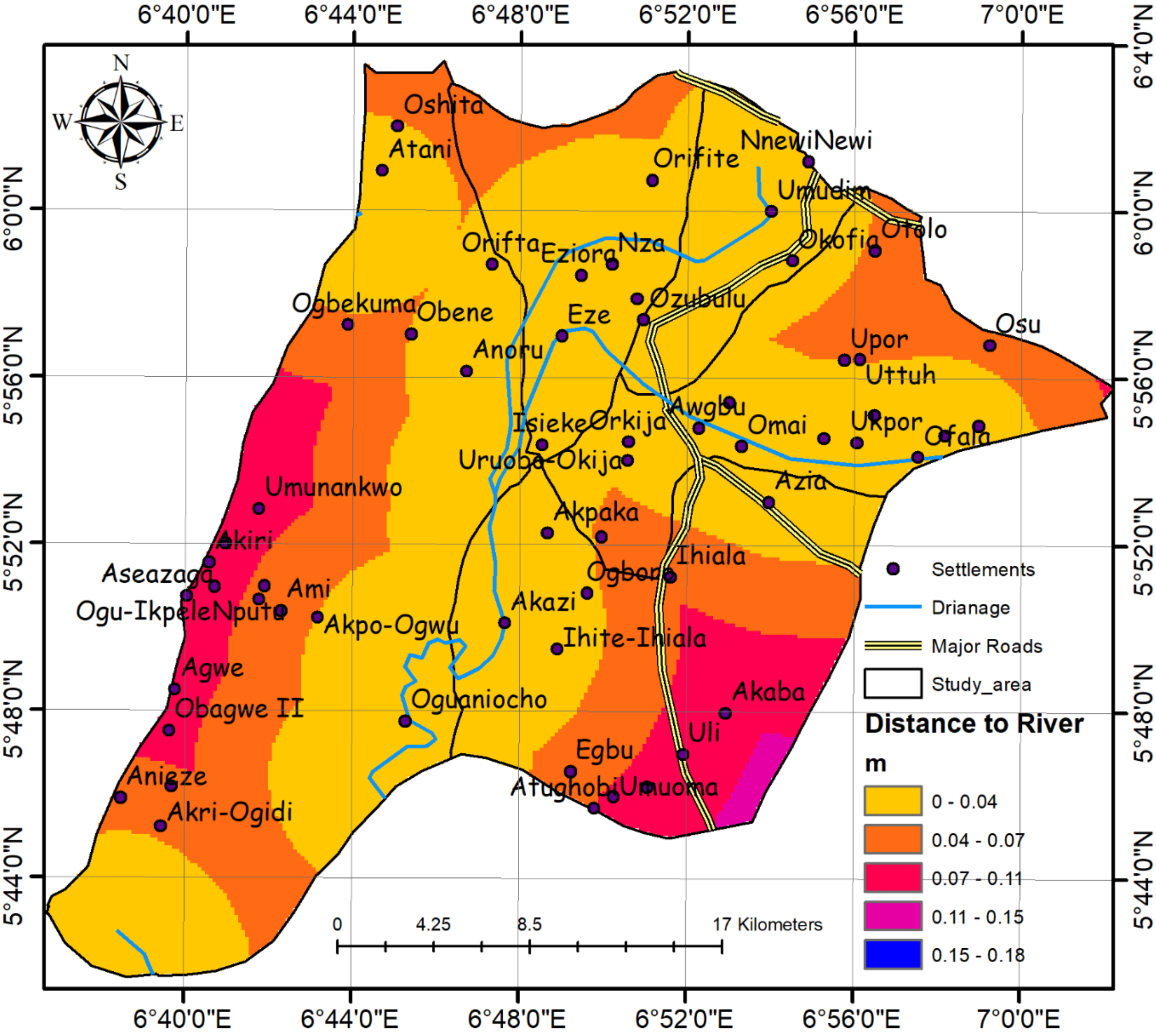

Figure 7: Map of distance to river in the study area

The distance to rivers is a crucial factor in flood risk assessment, as areas closer to rivers are generally more susceptible to flooding due to the higher likelihood of water overflow during heavy rainfall events. The central region of the study area is characterized by shorter distances to rivers. This proximity increases the area's vulnerability to riverine flooding, particularly during the rainy season when river levels rise significantly. The central part's closer proximity to rivers necessitates robust flood management strategies, including the construction of flood defenses such as levees and embankments, and the implementation of effective flood warning systems.

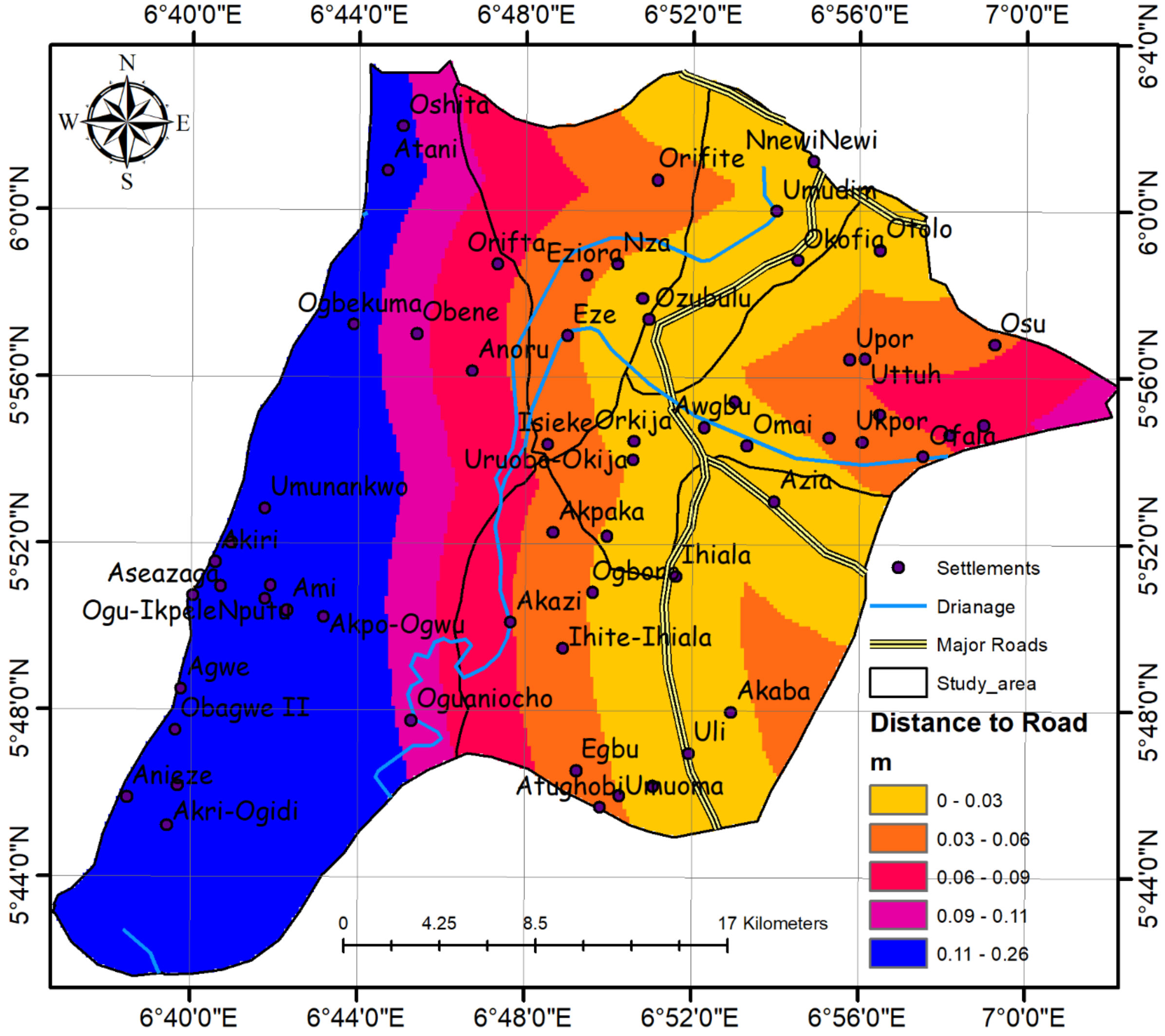

Figure 8: Map of distance to road of the study area

The analysis of the road network within the study area reveals significant variations in road density and proximity, with the eastern parts of the region having a higher concentration of roads and being closer to these roads compared to the western parts as shown in Figure 8.

The eastern region of the study area is characterized by a higher density of roads. This increased road network connectivity facilitates better access and mobility for the residents. Due to the denser road network, the eastern part has shorter distances to the nearest roads, enhancing accessibility and potentially improving emergency response times during flood events. The concentration of roads in the eastern area can influence flood dynamics. Roads often act as barriers to natural water flow, potentially exacerbating flooding in adjacent areas if proper drainage systems are not in place.

4.7 Flood Risk Assessment map

The flood risk assessment for the study area has categorized the regions into five distinct levels of flood risk: very low, low, moderate, high, and very high as shown in Figure 9 and Table 3.

The distribution of these categories across the area provides valuable insights into the spatial variation of flood susceptibility.

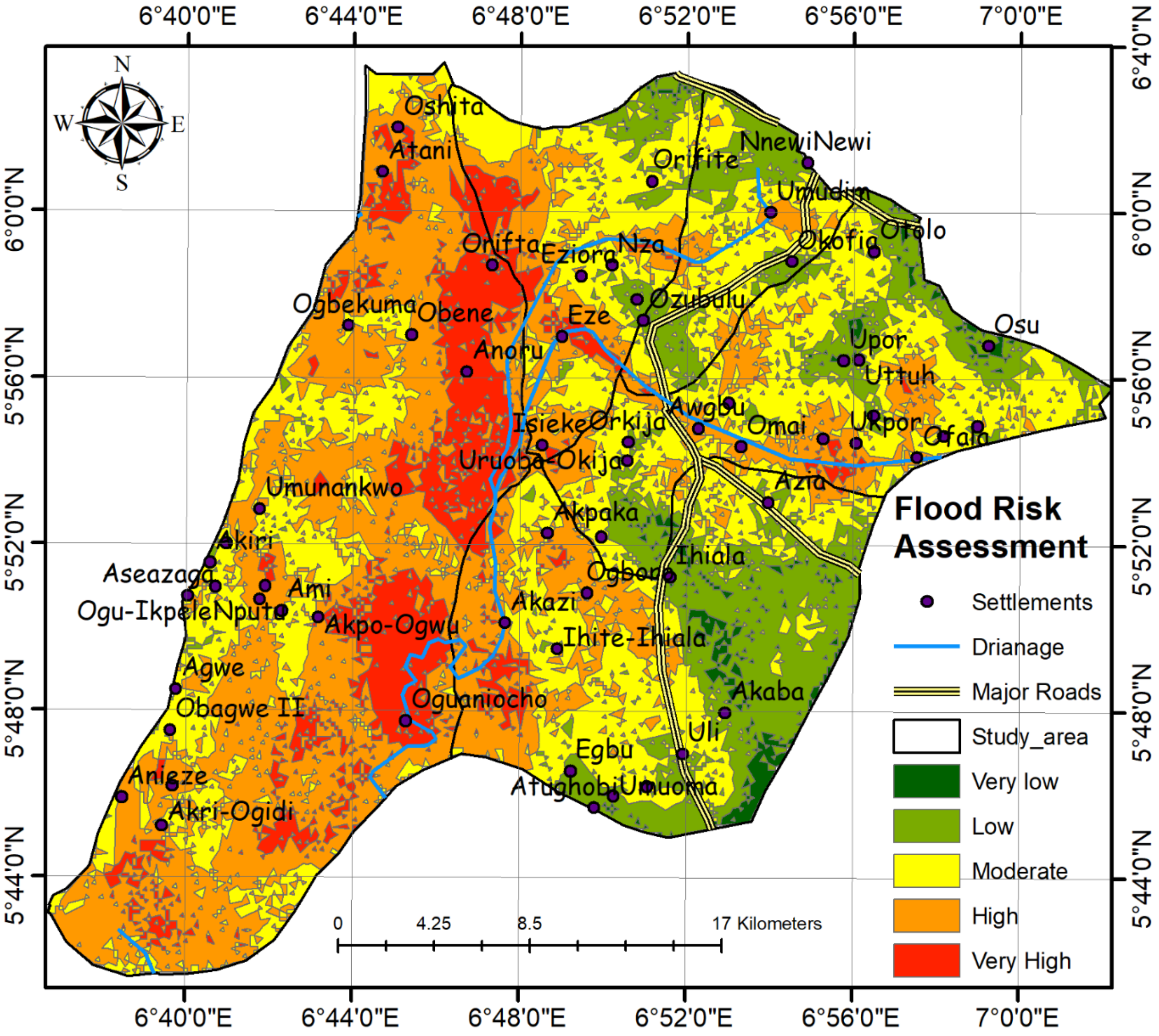

Figure 9: Flood risk assessment map of the study area

Table 3: Flood Risk Categories

Flood Risk Category	Area (Km²)	Area (%)
Very low	13.88	1.46
Low	150.70	15.82
Moderate	329.75	34.62
High	355.08	37.28
Very High	103.11	10.83

Regions surrounding drainage networks are predominantly classified under high to very high flood risk categories. This is expected as areas near rivers and drainage channels are more susceptible to flooding due to the potential overflow during heavy rainfall events. The eastern part of the study area generally falls between very low to moderate flood risk categories. This lower flood risk can be attributed to the better-developed drainage systems and higher road density, which facilitate efficient water runoff and accessibility during emergencies (Zhou et al., 2019). The western regions exhibit a range from moderate to very high flood risk. This increased susceptibility may be due to lower road density, inadequate drainage infrastructure, and possibly more natural features that contribute to slower water runoff and higher accumulation during rainfall events (Ahlmer et al., 2018; Dwarakish et al., 2024).

5.0 Conclusion

The flood risk assessment of the study area, incorporating various parameters such as drainage density, slope, LULC, rainfall, elevation, and proximity to rivers and roads, reveals significant spatial variability in flood susceptibility.

The distribution of flood risk categories indicates that the highest proportion of the area falls under high flood risk (37.28%), followed by moderate (34.62%), low (15.82%), very high (10.83%), and very low (1.46%). The study area shows considerable variation in drainage density, with values ranging from 0-496.59 km/km². Regions with low drainage density (0-98.09 km/km²) cover 40.25% of the area and are more prone to waterlogging. Areas with high drainage density (98.09-496.59 km/km²), accounting for 59.75%, are better at managing runoff locally but may contribute to downstream flooding. The slope analysis indicates that 36.29% of the area consists of steep slopes (9.83-34.57 degrees), which can rapidly convey runoff, increasing downstream flood risk. Moderately sloped areas (5.64-9.83 degrees) cover 33.22%, balancing runoff efficiency and erosion risk. The predominant land cover types are trees (43.62%) and built areas (35.20%). Forested regions mitigate flood risks through water retention, while urban areas with impervious surfaces increase runoff and flood susceptibility. The annual rainfall varies significantly, with higher amounts in the southern parts (up to 2170 mm) compared to the northern parts (1992 mm), influencing flood risk distribution. Most of the study area (79.21%) lies in higher elevation ranges (135-255 meters), reducing local flood risk but affecting downstream areas through rapid runoff. Central regions closer to rivers are more vulnerable to flooding. The eastern region, with a higher road density, has better accessibility and drainage, reducing flood risk compared to the western region.

High-risk areas, especially those near drainage networks, require robust flood defenses such as levees, embankments, and floodwalls. Efficient drainage systems and emergency response infrastructure are crucial in these regions. Areas with low drainage density need improved drainage infrastructure and water retention systems to manage waterlogging and reduce flood risk. High drainage density regions should focus on downstream flood control measures. Flat regions (0-3.28 degrees) are prone to water accumulation, necessitating interventions like drainage systems and water retention facilities. Moderately sloped regions need erosion control measures, while steep slopes require comprehensive management to address rapid runoff and severe erosion. Preserving water bodies and forested areas is essential for maintaining natural flood mitigation functions. Urban areas need enhanced drainage and flood prevention infrastructure to manage increased runoff. Agricultural lands require sustainable practices to reduce flood and erosion risks. Regions with higher rainfall, especially in the south, need advanced flood management strategies to handle increased surface runoff and riverine flooding. Higher elevation areas should focus on managing runoff to prevent downstream flooding and soil erosion. Proper watershed management practices are crucial to balance water flow and mitigate flood risks. Central areas near rivers should implement effective flood warning systems and defenses. The eastern region's denser road network helps in flood response but needs adequate drainage systems to prevent waterlogging.

The study area exhibits a complex interplay of factors influencing flood risk. High-risk regions, particularly those near drainage networks and with steep slopes, require immediate attention for flood mitigation. Enhancing drainage infrastructure, preserving natural landscapes, and implementing sustainable land management practices are essential strategies. By addressing the unique characteristics of each flood risk category and associated factors, effective and sustainable flood mitigation measures can be developed, enhancing the resilience of the study area against flood events.

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