INTEGRATED GEOSPATIAL CHARACTERIZATION OF GEOMORPHOLOGICAL AND STRUCTURAL FEATURES IN PARTS OF ENUGU, SOUTHEASTERN NIGERIA: IMPLICATIONS FOR REGIONAL GEOLOGY AND LAND USE

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ABSTRACT

This study explores the spatial distribution of land cover and geomorphological features in Enugu East, North, and South LGAs, using Land Use/Land Cover (LULC) classification, slope analysis, drainage density, and lineament density. To analyze the current land use patterns, slope characteristics, drainage density, and lineament density in Enugu, and assess their implications for regional urbanisation and environmental management. LULC classification was performed using remote sensing data to categorize land cover into built-up areas, rangelands, water bodies, trees, crops, and other types. Slope analysis categorized terrain into five slope classes. Drainage density was assessed to determine the density of drainage networks. Lineament density analysis identified structural features affecting ground stability. Built-up areas and rangelands dominate the land cover, while agricultural areas are minimal. Slope analysis reveals a predominance of gentle slopes suitable for urbanisation, with smaller areas of steep slopes posing erosion risks. Drainage density varies, with moderate density areas showing suitable conditions for agriculture and urbanisation, and high-density areas prone to erosion and flooding. Lineament density indicates mostly stable ground with high potential for groundwater exploration in fractured regions. The dominance of built-up areas reflects significant urban expansion, while rangelands highlight non-intensive land uses. Steep slopes and high drainage densities present challenges for sustainable urbanisation and require targeted management strategies. Areas with high lineament densities offer potential for groundwater resources but demand careful consideration for construction. The study provides essential insights into land use and geomorphological factors, underscoring the need for integrated planning to balance urban growth with environmental sustainability. Proper management of slope, drainage, and lineament factors is vital for minimizing risks and optimizing land use. This comprehensive analysis integrates multiple geospatial and geomorphological features to offer a holistic understanding of land use dynamics and development constraints in Enugu Local Government Areas (LGAs), providing a basis for informed decision-making in regional planning.

Keywords: Drainage Density, Geomorphological Features, Lineament Density, Slope Analysis

INTRODUCTION

The integrated geospatial characterization of geomorphological and structural features is an essential approach in understanding the interplay between landform processes, land use patterns, structural lineaments, slope dynamics, and drainage systems (Teofilo *et al*., 2019). Geospatial tools, such as Geographic Information Systems (GIS) and Remote Sensing (RS), provide comprehensive frameworks for analyzing and visualizing these interrelationships over vast landscapes. These tools are particularly valuable in interpreting the spatial distribution of Land Use and Land Cover (LULC), lineament density, drainage patterns, and slope variations, which together shape the environmental and developmental landscape of any region (Sikakwe, 2020).

Geomorphological and structural features significantly influence the ecological and physical dynamics of the earth's surface. These features directly affect land use patterns, agricultural productivity, urban planning, flood risk assessment, and natural resource management (Keller *et al*., 2020). Understanding the geomorphological framework, such as slope characteristics and drainage networks, provides insights into terrain stability, erosion potential, and flood vulnerability (Arabameri *et al*., 2020). Meanwhile, structural features such as lineaments (faults, fractures, and joints) are crucial indicators of subsurface geological structures, which play a key role in groundwater movement, mineral exploration, and seismic risk assessment. In this context, geospatial characterization emerges as an invaluable method for mapping and analyzing the interconnected aspects of the natural and built environment (Epuh *et al*., 2020).

LULC is a crucial component of landscape analysis, representing the interaction between human activities and the natural environment (Akaolisa *et al*., 2023). Land use refers to the human utilization of land for agriculture, urbanization, forestry, and other activities, while land cover describes the physical material on the earth's surface, such as forests, water bodies, urban infrastructure, and agricultural lands (Abdu, 2018). Monitoring LULC patterns is vital for managing natural resources, planning urban development, and understanding environmental changes. Geospatial analysis of LULC changes over time provides critical insights into the impact of human activities on ecosystems, biodiversity, and climate (Akbar *et al*., 2019).

The characterization of LULC is often the first step in integrated geospatial analysis, as it provides a baseline for understanding how human-induced changes shape the landscape. In regions undergoing rapid urbanization, deforestation, or agricultural expansion, LULC studies help identify areas of environmental degradation, potential flood zones, and regions vulnerable to soil erosion (Camargo *et al*., 2019). A change from forest cover to agricultural land may lead to reduced infiltration rates, increasing surface runoff and altering drainage patterns. The conversion of rural landscapes into urban areas also has implications for flood management, groundwater recharge, and biodiversity conservation (Khalil *et al*., 2021). Therefore, integrating LULC data with slope, drainage, and lineament analysis offers a more holistic understanding of the environmental implications of land use changes.

Slope is a fundamental geomorphological features that influences various natural processes, including surface runoff, soil erosion, landslide susceptibility, and vegetation patterns. The slope of the terrain, expressed as the degree or percentage of inclination, affects water movement, sediment transport, and land stability (Deng *et al*., 2020). Steeper slopes are often associated with higher runoff rates, reduced infiltration, and increased erosion potential, making them more vulnerable to landslides and soil degradation. Conversely, gentle slopes are typically more conducive to agricultural activities, as they allow for better soil retention and reduced erosion risks (Prancevic *et al*., 2020). In geospatial studies, slope analysis is critical for assessing terrain stability and land use suitability. It plays a key role in urban planning, agriculture, and environmental conservation. Steep slopes are unsuitable for construction due to their instability, while moderate slopes might be ideal for terraced agriculture or managed forestry. Slope also influences drainage patterns, as water tends to flow more rapidly down steeper inclines, potentially leading to the formation of gullies and other erosion features (Berčič & Ažman-Momirski, 2020).

The integration of slope data with other geospatial features, such as LULC and drainage density, allows for a comprehensive assessment of the landscape's vulnerability to natural hazards. Areas with steep slopes and high drainage density are more prone to flash flooding and landslides, especially when coupled with deforestation or urban development (Gbadebo *et al*., 2018). Geospatial characterization of slope dynamics, therefore, helps in identifying risk zones and developing mitigation strategies for land use planning and disaster management (Sur *et al*., 2022).

Lineaments are linear features on the earth's surface that often represent underlying geological structures, such as faults, fractures, and joints. These features are critical in structural geology, as they influence the distribution of natural resources, groundwater flow, and seismic activity (Joel *et al.*, 2020). Lineament density refers to the concentration of lineaments within a specific area and provides insights into the tectonic and structural framework of the region. The analysis of lineament density is essential in understanding the subsurface characteristics of a region, particularly in areas with significant geological activity (Liu *et al.*, 2021). Regions with high lineament density are often associated with increased groundwater availability, as fractures and faults can act as conduits for water movement. Similarly, lineaments can influence the distribution of mineral deposits, as ore-bearing fluids often migrate along fault lines. In seismic regions, lineament density analysis is crucial for identifying areas at risk of earthquakes, as faults and fractures can indicate zones of crustal weakness (Han *et al*., 2018).

Geospatial tools, such as satellite imagery and digital elevation models (DEMs), enable the detection and mapping of lineaments, providing a comprehensive view of the structural features of a region. Integrating lineament density data with other geospatial features, such as LULC and slope, enhances the understanding of the interaction between surface processes and subsurface structures (Abdelouhed *et al*., 2021). Areas with high lineament density and steep slopes are more prone to landslides, while regions with dense lineaments and high drainage density could indicate zones of significant groundwater flow. Drainage density is a measure of the total length of streams and rivers in a given area relative to the size of the area. It reflects the efficiency of the landscape in draining surface water and is influenced by factors such as slope, soil type, vegetation cover, and geological structure (Yan *et al*., 2020). High drainage density is often associated with steep slopes, impermeable soils, and limited vegetation cover, resulting in rapid surface runoff and increased erosion potential. Conversely, low drainage density indicates a well-vegetated landscape with permeable soils, allowing for higher infiltration rates and reduced surface runoff (Baartman *et al*., 2018).

The analysis of drainage density is critical in understanding the hydrological behavior of a landscape, particularly in terms of flood risk and water resource management. In areas with high drainage density, surface water is quickly funneled into streams and rivers, increasing the likelihood of flash floods during heavy rainfall events. Low drainage density, on the other hand, suggests regions with higher groundwater recharge potential, as more water is retained within the soil (Obeidat *et al*., 2021). Geospatial analysis of drainage density, when combined with slope and LULC data, provides valuable insights into the hydrological dynamics of a region. Areas with steep slopes, high drainage density, and urban land cover are particularly vulnerable to flash flooding, while regions with gentle slopes, low drainage density, and forest cover are more resilient to extreme rainfall events (Roy & Das, 2021). Understanding drainage patterns is also essential for managing water resources, as it helps identify areas suitable for groundwater recharge, irrigation, and flood mitigation measures.

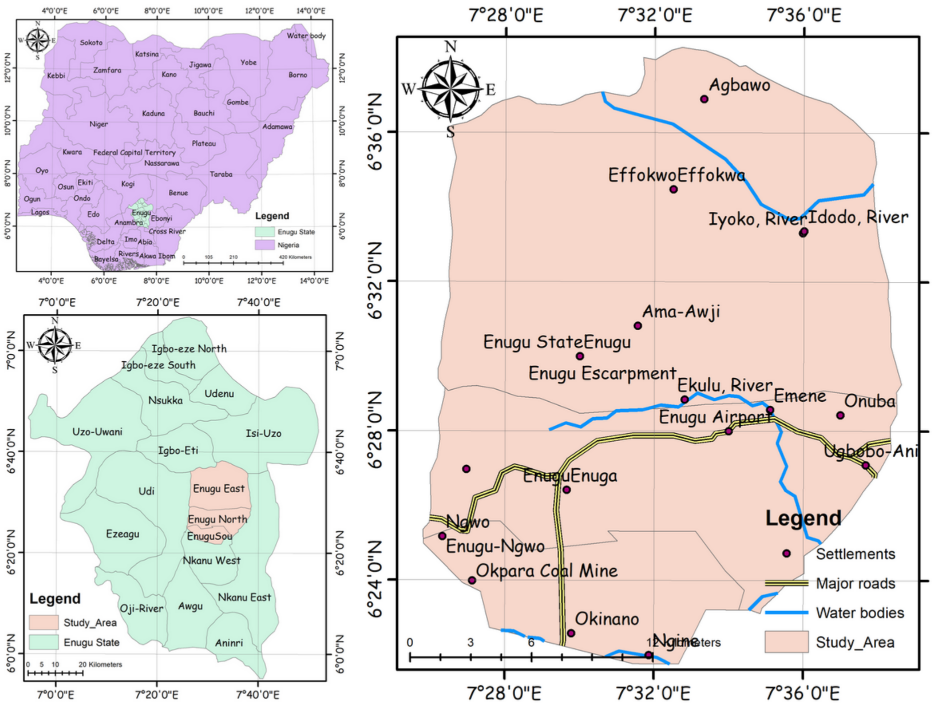
The integrated geospatial characterization of land use, slope, lineament density, and drainage density provide a comprehensive understanding of the interplay between geomorphological processes and structural features (Okoli *et al*., 2024). By analyzing these features together, geospatial tools offer a holistic approach to landscape management, helping identify areas at risk of natural hazards, optimizing land use planning, and enhancing resource management strategies. The features integration is essential for sustainable development, particularly in regions prone to environmental challenges such as flooding, erosion, and seismic activity. The aim of this study is to conduct an integrated geospatial characterization of geomorphological and structural features, specifically focusing on LULC, slope, lineament density, and drainage density. By leveraging GIS and RS technologies, the study seeks to analyze the spatial relationships between these features to better understand their influence on terrain stability, flood risk, groundwater movement, and land use planning.

RESEARCH AREA

The study area for this research covers Enugu East, Enugu North, and Enugu South Local Government Areas (LGAs) of Enugu State, Nigeria. These LGAs are part of the larger Enugu metropolis, which serves as the capital of Enugu State, located in the southeastern part of Nigeria. Geographically, the study area is bounded by the coordinates 6°21' N to 6°30' N latitude and 7°26' E to 7°35' E longitude, covering a diverse landscape characterized by undulating terrain, hills, and valleys as shown in Figure 1. Enugu North is predominantly urban, hosting the state capital and central business districts, while Enugu East and Enugu South include a blend of urban areas and rural communities. Urban regions dominate in terms of infrastructure and population density, but rural areas in these LGAs maintain agricultural activities and less dense settlements, reflecting a balanced mix within the study area.

The inhabitant density across the study area varies significantly between urban and rural regions. Urban centers like Enugu North experience high population density due to increased economic activities, services, and residential housing. In contrast, rural areas in Enugu East and Enugu South have lower densities, characterized by more dispersed settlements and reliance on farming. On average, urban areas witness population densities exceeding 2,000 people per square kilometer, while rural regions are notably less dense, fostering diverse socio-economic dynamics.

Fig. 1: Map showing (a) Nigeria (b) Enugu state and (c) study area



The climate of the study area is tropical with two distinct seasons: the rainy season (April to October) and the dry season (November to March). The average annual rainfall ranges from 1,500 mm to 2,000 mm, with the heaviest precipitation occurring in the months of July and September. The temperatures in the region are generally warm throughout the year, with average daily temperatures ranging from 24°C to 32°C. During the rainy season, the area experiences heavy downpours, which often result in localized flooding, especially in low-lying areas. The dry season is characterized by the Harmattan, a dry and dusty trade wind that blows from the Sahara, reducing visibility and causing a drop in humidity. This climatic pattern has significant implications for land use, particularly in agriculture, infrastructure development, and water resource management (Nwankwo & Ene, 2020).

The study area is well-connected by a network of roads that facilitate access to various parts of Enugu State and neighboring states. Enugu-Nsukka Road, Enugu-Onitsha Expressway, and Enugu-Port Harcourt Expressway are major highways that traverse the region, providing access to key urban and rural areas. Within the metropolis, the road infrastructure is fairly developed, with major streets and avenues linking Enugu North, South, and East LGAs. However, certain parts of the study area, especially in the outskirts and rural areas, suffer from poor road conditions, particularly during the rainy season when unpaved roads become difficult to navigate due to erosion and waterlogging. The terrain, especially in hilly areas, presents challenges for road construction and maintenance, requiring careful consideration of slope stability and drainage during infrastructural development (Ezema *et al*., 2020).

Water resources in the study area are primarily derived from both surface and groundwater sources. Surface water is mainly obtained from rivers, streams, and ponds, with Ekulu River being one of the major rivers flowing through the Enugu metropolis. The river serves as an important source of water for domestic and agricultural purposes. However, its water quality has been affected by urban runoff and industrial effluents, making it unsuitable for direct consumption without treatment.

The study area lies within the Anambra Basin, a major geological formation in southeastern Nigeria, known for its sedimentary rock formations. The basin is primarily composed of sandstones, shales, and coal seams, with significant economic importance due to the presence of coal deposits. Enugu is historically known as the coal city due to its rich coal mines, which have played a pivotal role in the region's industrial development (Ezema *et al*., 2020). The geology of the study area is largely dominated by the Enugu Shale Formation, which consists of dark shales, sandstone intercalations, and siltstones. This formation is part of the Campanian-Maastrichtian age and is known for its potential in groundwater storage and mineral resources, particularly coal. The shale units are often fissile and laminated, contributing to their susceptibility to erosion and weathering, while the sandstone beds exhibit better resistance to weathering and serve as aquifers in the region (Igwe *et al*., 2020).

METHODOLOGY

The methodology for this study involves the integrated geospatial characterization of geomorphological and structural features, including LULC, slope, lineament density, and drainage density. The study area was analyzed using GIS and Remote Sensing techniques, with ArcGIS 10.8 as the primary tool for spatial data processing, analysis, and visualization. The following steps outline the procedures employed to generate and analyze the relevant geomorphological and structural features.

Data Acquisition

The study relies on multiple geospatial datasets, including satellite imagery, DEMs, geological maps, and hydrological data. The following datasets were used:

- *Landsat 8 OLI/TIRS* satellite images for LULC classification. The images were obtained from the United States Geological Survey (USGS) Earth Explorer platform.
- *SRTM (Shuttle Radar Topography Mission)* 30-meter resolution DEM for slope, elevation, and drainage density analysis.
- *Geological maps* to identify and digitize lineaments and fault lines in the study area.

Data Preprocessing

Before analysis, the datasets were preprocessed to ensure compatibility and accuracy. The following preprocessing steps were applied:

- *Image Correction*: The Landsat images were corrected for atmospheric effects using the Fast Line-of-sight Atmospheric Analysis of Hypercubes (FLAASH) tool in ArcGIS 10.8. Radiometric and geometric corrections were performed to enhance the image quality.
- *DEM Preprocessing*: The SRTM DEM was resampled to a consistent spatial resolution of 30 meters, and sinks were filled to remove anomalies that could interfere with hydrological analysis. The DEM was clipped to the study area boundary using the ArcGIS Spatial Analyst tool.

- *Georeferencing:* Geological maps were georeferenced and digitized to extract lineaments, which were then imported into the GIS environment for further analysis.

Land Use and Land Cover (LULC) Classification

LULC classification was performed using supervised classification in ArcGIS 10.8. The classification process involved the following steps:

- *Training Samples Collection:* Representative training samples were selected based on field surveys, Google Earth imagery, and expert knowledge. The classes included built-up areas, forests, agricultural land, water bodies, and bare land.
- *Classification Algorithm:* A Maximum Likelihood Classification (MLC) algorithm was applied to the Landsat 8 imagery to classify the different land use and land cover types.
- *Accuracy Assessment:* To validate the classification accuracy, an error matrix was generated using field data. The overall classification accuracy and Kappa coefficient were calculated to assess the performance of the classification.

Slope Analysis

Slope is a critical geomorphological feature that influences various natural processes. The slope was derived from the SRTM DEM using the following equation:

$$Slope = tan^{-1}\left(\frac{\Delta Z}{\Delta D}\right) \quad 1$$

Where: ΔZ is the difference in elevation between two points, and ΔD is the horizontal distance between those points.

In ArcGIS 10.8, the Slope Tool within the Spatial Analyst toolbox was used to generate the slope map, expressed in degrees. The resulting slope map was reclassified into five categories: flat (0-5°), gentle (5-10°), moderate (10-20°), steep (20-30°), and very steep (>30°). These categories helped identify areas prone to erosion, landslides, and other slope-related hazards.

Lineament Density Analysis

Lineament density was analyzed by digitizing the geological structures (faults, fractures, joints) from the georeferenced geological map. The lineaments were traced as polylines and stored in a vector format within the ArcGIS environment. The Line Density Tool in ArcGIS 10.8 was used to compute the density of lineaments within a defined neighborhood. The lineament density (LD) was calculated using the following equation:

$$Lineament\ Density = \frac{L_{total}}{A} \quad 2$$

Where: L_{total} is the total length of lineaments (in kilometers), and A is the area of the study region (in square kilometers).

The lineament density map was generated to visualize regions with high concentrations of geological structures, which suggests areas prone to groundwater accumulation or seismic activity.

Drainage Density Analysis

Drainage density is a measure of the total length of streams and rivers in a given area, providing insights into surface runoff and erosion potential. The drainage network was extracted from the DEM using the Flow Direction and Flow Accumulation tools in ArcGIS 10.8.

The Flow Direction tool was used to calculate the direction of water flow for each cell in the DEM, based on the steepest descent. The Flow Accumulation tool was applied to determine the number of cells that flow into each downslope cell, which helps in identifying stream channels. A threshold value was set to define the stream network by selecting cells with high flow accumulation values (Erdbrügger *et al*., 2021). This threshold was determined based on the local hydrological characteristics.

Once the stream network was delineated, the Drainage Density (DD) was calculated using the following equation:

$$Drainage\ Density = \frac{L_{stream}}{A} \quad 3$$

Where: L_{stream} is the total length of the drainage network (in kilometers), and A is the area of the study region (in square kilometers).

The resulting drainage density map was classified into low, medium, and high drainage density zones, indicating areas with varying runoff and erosion potentials.

RESULT AND DISCUSSION

Spatial Analysis of LULC

The LULC classification for the study area in 2023 reveals significant insights into the spatial distribution of land cover types. The analysis shows a predominance of built-up areas and rangelands, with smaller proportions dedicated to water bodies, trees, crops, and other land use categories. Table 1 summarizes the area coverage of each LULC type.

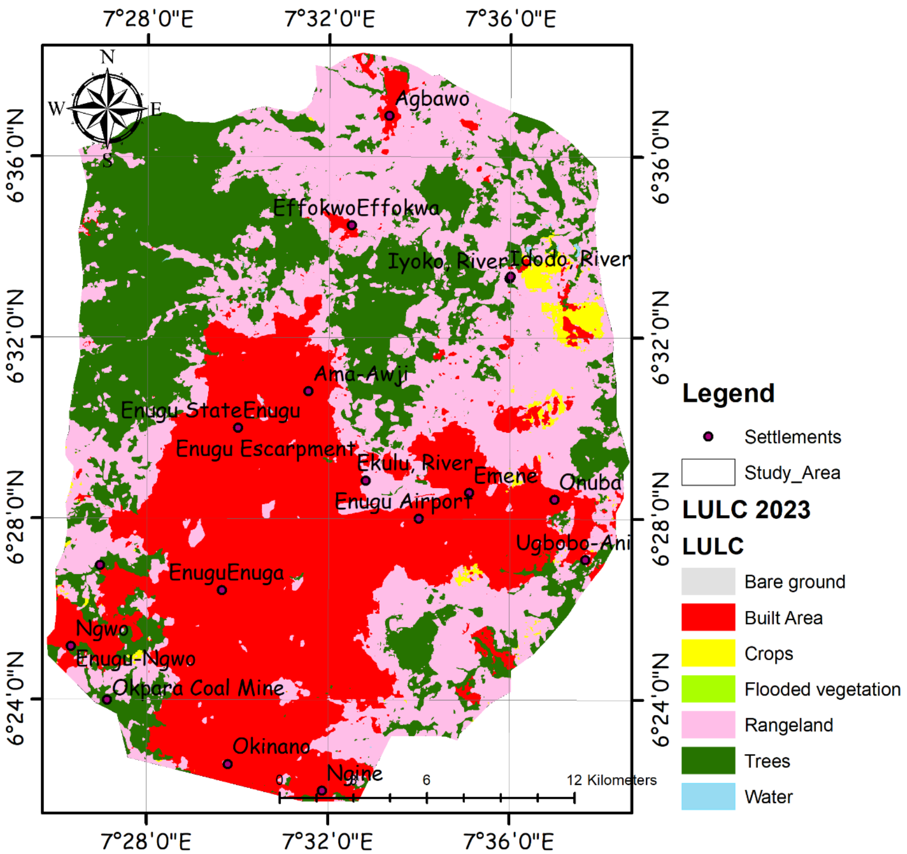
Table 1: LULC Types and Their Areas in 2023

LULC Type	Area (km²)
Water	0.450
Trees	164.329
Flooded vegetation	0.003
Crops	7.849
Built Area	200.048
Bare ground	0.011
Rangeland	184.897

The results show that built-up areas (200.05 km²) and rangelands (184.90 km²) dominate the land cover in Enugu East, North, and South LGAs, a finding consistent with Rowland & Ebuka (2024), who also reported extensive urbanization and human settlement in the region. These two categories constitute a large portion of the total land area, illustrating the ongoing urban expansion and infrastructure development, with built-up areas symbolizing this urban growth. In contrast, the rangelands, which cover nearly as much area, reflect open spaces used for grazing and non-intensive activities, further reinforcing Rowland & Ebuka's observations on land utilization patterns. The significant area covered by trees (164.33 km²) highlights the presence of vegetated zones, which play a crucial role in maintaining biodiversity and ecological stability, supporting previous findings on the importance of preserving green spaces within urban settings. However, agricultural land, comprising just 7.85 km² of crops, occupies a relatively small fraction of the total land area.

The presence of water bodies (0.45 km²) and flooded vegetation (0.003 km²), although minimal, indicates potential resources for water-based ecosystems and flood-prone zones. These areas could serve as indicators of flood risk, necessitating targeted environmental management to prevent future hazards. Bare ground, covering only 0.01 km², is the smallest LULC category, suggesting that most of the land in the study area is either vegetated or developed. Figure 2 provides a spatial map of these land cover types, showing the distribution and geographic extent of each category across the region.

Fig. 2: Spatial Distribution of LULC Types in the Study Area



The dominance of built-up areas and rangelands reflects ongoing urbanization and land use pressures in Enugu, aligning with Igwe *et al*. (2020), who also noted that expanding urban infrastructure poses challenges to regional land management. The presence of rangelands, though substantial, suggests that non-intensive land uses persist, but as Igwe *et al*. (2020) emphasized, these areas could be at risk due to the continued urban expansion. The relatively small portion of land dedicated to agriculture points to limited food production within the region, underscoring the need for further investigation into agricultural sustainability and land management practices, consistent with the observations made by Igwe *et al*. (2020). In addition, the small coverage of water bodies and flooded vegetation reflects the natural hydrological patterns of the landscape, as highlighted by Ozulu *et al*. (2021). This limited water coverage emphasizes the potential for flood risks in low-lying areas, reinforcing the importance of managing these zones to mitigate environmental hazards. These land use patterns provide crucial insights for regional planning, resource management, and sustainable development in Enugu, echoing the findings of both Igwe *et al*. (2020) and Ozulu *et al*. (2021) on the need for comprehensive land management strategies.

Spatial Analysis of Slope

The slope analysis of the study area provides important insights into the terrain and its implications for land use, erosion risk, and development potential. Slope values, expressed in degrees (°), are categorized into five classes, as summarized in Table 2 below.

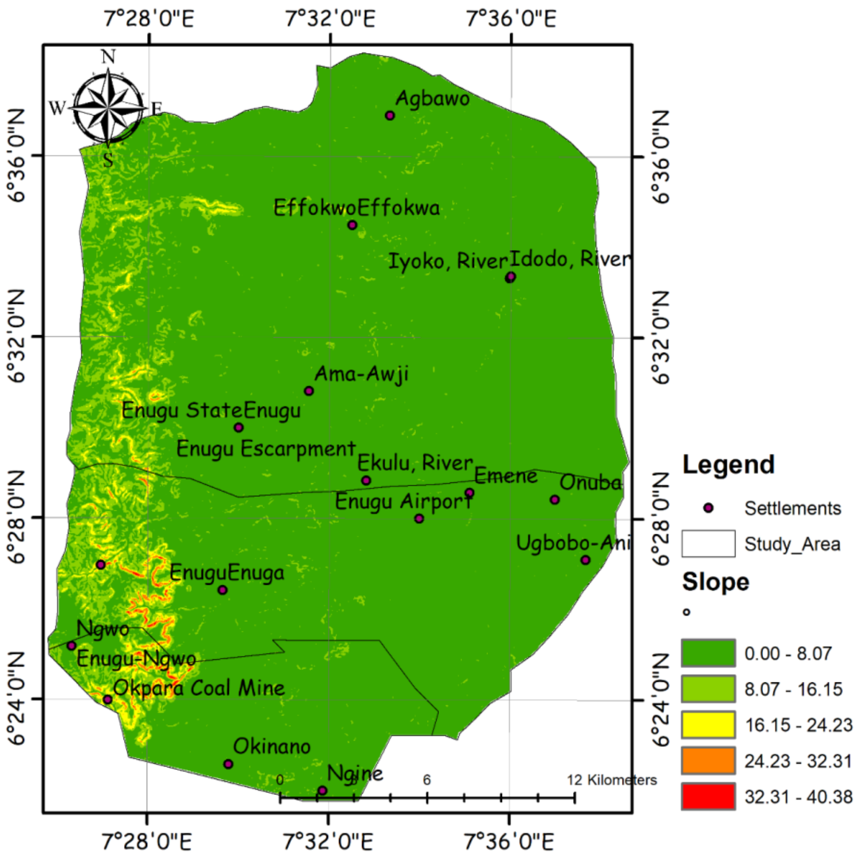
Table 2: Slope Classes and Their Area Coverage

Slope (°)	Area (km²)
0.00 - 8.07	503.853
8.07 - 16.15	40.440
16.15 - 24.23	8.107
24.23 - 32.31	1.992
32.31 - 40.38	0.176

From the data, it is evident that the majority of the study area, 503.85 km², is characterized by gentle slopes in the range of 0.00° to 8.07°. This suggests that most of the terrain is relatively flat or gently undulating, which is favorable for urban development, agriculture, and infrastructure projects. Such low-slope areas are also less prone to erosion, making them ideal for sustainable land use practices. Areas with moderate slopes, between 8.07° and 16.15°, cover 40.44 km². These regions may pose moderate challenges for construction and agricultural activities due to increased susceptibility to soil erosion and runoff (Dorairaj & Osman, 2021). Nevertheless, these areas can still be utilized with appropriate soil conservation techniques and careful planning for infrastructure projects.

The steep slopes between 16.15° and 24.23°, covering 8.11 km², and the even steeper slopes of 24.23° to 32.31°, covering a smaller area of 1.99 km², indicate regions susceptible to high erosion rates, consistent with Pijl *et al*. (2020), who emphasized the unsuitability of such areas for large-scale agriculture or infrastructure development without significant engineering interventions like terracing or slope stabilization. The steepest slopes, ranging from 32.31° to 40.38° and accounting for only 0.18 km², are particularly vulnerable to erosion and landslides, especially during heavy rainfall events, supporting Mateso *et al*. (2023)'s findings regarding the risks posed by extreme slopes in terms of stability and development. In these high-risk regions, Mateso *et al*. (2023) recommended environmental management strategies aimed at preventing deforestation, which could further exacerbate erosion and destabilize the landscape. The spatial distribution of these slope classes, shown in Figure 3, illustrates how these varying degrees of slopes are geographically spread across the study area, highlighting areas that require careful land management and erosion control.

Fig. 3: Spatial Distribution of Slope Classes in the Study Area



The predominance of gentle slopes (0.00° to 8.07°) suggests that the study area is largely favorable for urban expansion, agriculture, and infrastructure development. The flat to gently sloping terrain reduces the costs and challenges associated with construction and makes these areas less prone to natural hazards like landslides and severe erosion (Simwanda *et al*., 2019). Areas with steeper slopes (16.15° to 40.38°) present significant challenges due to their higher susceptibility to erosion and potential landslide risks (Prancevic *et al*., 2020). These regions require careful land management practices to mitigate environmental degradation. Moreover, the presence of steep slopes may limit the expansion of urban areas and infrastructure, necessitating the adoption of innovative construction techniques or the use of these regions for conservation or low-intensity land uses such as forestry (Shi *et al*., 2023).

Spatial Analysis of Drainage Density

The drainage density analysis provides valuable insights into the spatial distribution of drainage networks in the study area. Drainage density, expressed in kilometers per square kilometer (km/km²), is an important geomorphological indicator that reflects the degree of terrain dissection and the hydrological characteristics of the landscape. Table 3 summarizes the drainage density classes and their corresponding area coverage.

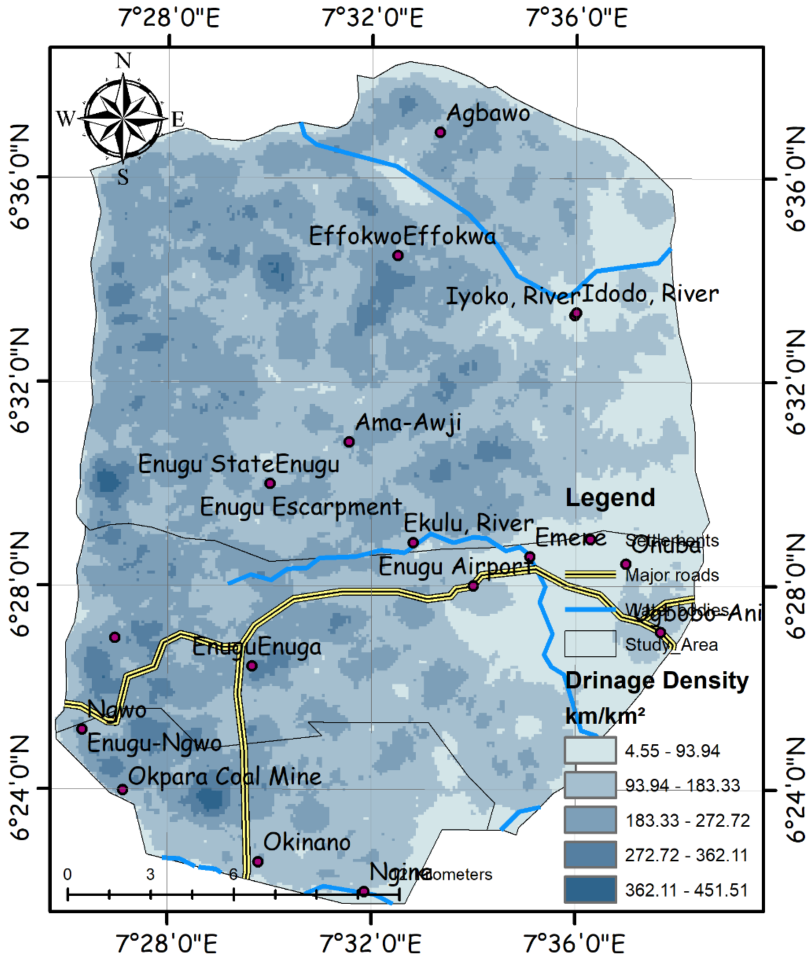
Table 3: Drainage Density Classes and Area Coverage

Drainage Density (km/km²)	Area (km²)
4.55 - 93.94	94.260
93.94 - 183.33	245.298
183.33 - 272.72	195.346
272.72 - 362.11	21.469
362.11 - 451.51	1.136

The drainage density classification reveals that most of the study area falls within the 93.94 to 183.33 km/km² range, covering 245.30 km². This moderate drainage density suggests a well-developed drainage network, indicative of moderate runoff and infiltration rates, consistent with the findings of Yang *et al*. (2022), who noted that such areas are prone to moderate erosion and flooding during heavy rainfall but generally offer suitable conditions for agriculture and other land uses. Areas with lower drainage density, ranging from 4.55 to 93.94 km/km² and covering 94.26 km², feature fewer drainage channels per unit area, reflecting lower terrain dissection and better conditions for groundwater recharge. This lower density also indicates reduced runoff and lower erosion potential, supporting Yang *et al*. (2022)'s assertion that these areas are favorable for sustainable agriculture, settlement, and other land uses. Conversely, regions with higher drainage density, particularly in the 183.33 to 272.72 km/km² range, cover 195.35 km² and are marked by a denser drainage network. This higher density, as noted by Idrees *et al*. (2022), corresponds to increased terrain dissection and faster surface runoff, heightening erosion and flood risks in these areas. These classifications highlight varying land use potentials and risks, aligning with both Yang *et al*. (2022) and Idrees *et al.* (2022)'s observations on the impacts of drainage density on erosion, flooding, and land suitability.

The highest drainage density classes, between 272.72 and 451.51 km/km², occupy a much smaller portion of the study area, with 21.47 km² and 1.14 km², respectively. These regions, with very high drainage densities, are prone to significant runoff and severe erosion during rainfall. Such areas should be prioritized for conservation or low-impact land uses to prevent environmental degradation and manage water flow effectively (Fu *et al*., 2022). Figure 4 illustrates the spatial distribution of drainage density across the study area, highlighting the concentration of high-density drainage networks.

Fig. 4: Spatial Distribution of Drainage Density Classes in the Study Area



The drainage density analysis has important implications for land use planning and environmental management in the study area. Regions with moderate drainage density are generally favorable for agricultural activities, urban development, and infrastructure projects, provided that proper water management strategies are in place. However, areas with higher drainage density require careful land use planning due to the increased risks of soil erosion and flooding (Fatoyinbo *et al.*, 2020). These regions should be targeted for erosion control measures, such as afforestation, terracing, and sustainable agricultural practices, to reduce the impact of surface runoff. In regions with very low drainage density, groundwater recharge potential is higher, which can be advantageous for water resource management and conservation efforts. Such areas may serve as key locations for aquifer recharge zones and should be managed to protect water resources and prevent excessive development that could hinder infiltration (Guerrón-Orejuela *et al.*, 2023).

Spatial Analysis of Lineament Density

The lineament density analysis provides insights into the structural features of the study area, with lineament density being an indicator of fracture and fault distribution within the terrain. Lineament density is measured in kilometers per square kilometer (km/km^2), and the classification and corresponding area coverage are presented in Table 4.

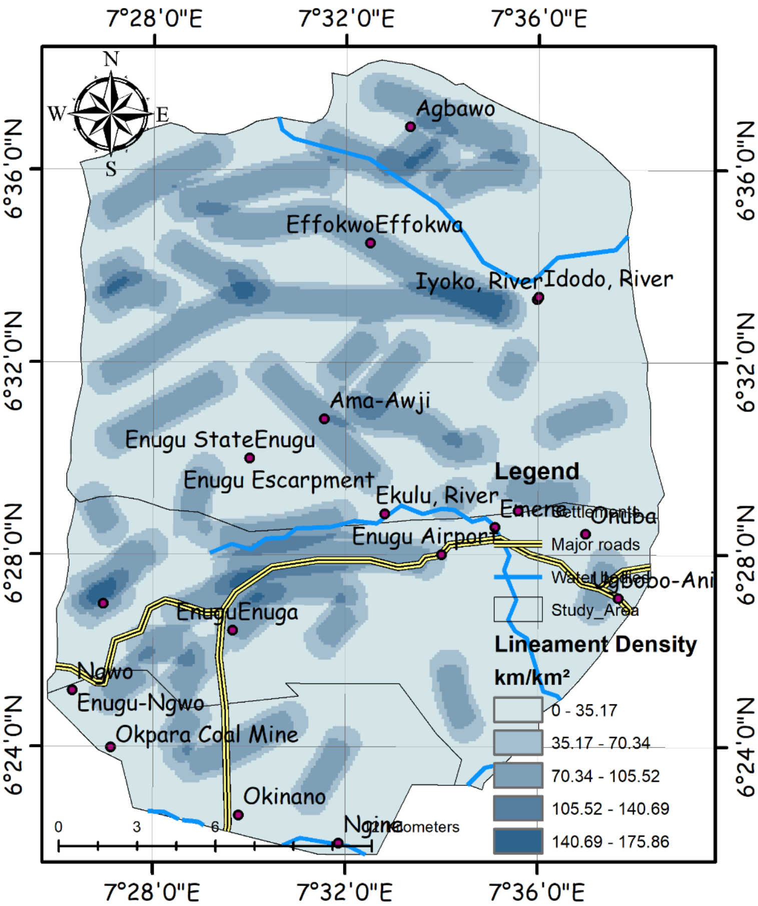
Table 4: Lineament Density Classes and Area Coverage

Lineament Density (km/km^2)	Area (km^2)
0.00 - 35.17	321.073
35.17 - 70.34	95.026
70.34 - 105.52	122.093
105.52 - 140.69	15.144
140.69 - 175.86	4.379

The data indicate that the majority of the study area, 321.07 km^2, falls within the lowest lineament density class of 0.00 to 35.17 km/km^2, suggesting relatively stable ground conditions with fewer fractures or faults. This observation aligns with Everest *et al*. (2020), who noted that areas with lower lineament densities are more suitable for development activities like construction and agriculture, as the reduced structural disruptions decrease the risk to buildings and infrastructure. Moderate lineament densities, ranging from 35.17 to 70.34 km/km^2 and covering 95.03 km^2, indicate an increased presence of fractures and faults that may influence terrain stability, though still within manageable levels. Pradhan *et al*. (2020) highlighted that such areas could offer potential for groundwater infiltration due to the fractures but may require additional engineering measures to address structural considerations during construction. Conversely, regions with higher lineament densities, particularly in the 70.34 to 105.52 km/km^2 range, cover 122.09 km^2 and exhibit a higher concentration of fractures and faults. This aligns with Fossi *et al*. (2021), who emphasized that while these areas may enhance groundwater infiltration and availability, the increased density of structural features poses risks for construction, as they are more susceptible to ground movement and potential instability during seismic activity or heavy rainfall. These findings illustrate the varying implications of lineament density on development and resource management, consistent with the conclusions of Everest *et al*. (2020), Pradhan *et al*. (2020), and Fossi *et al*. (2021).

The highest lineament densities, between 105.52 and 175.86 km/km^2, occupy a small portion of the study area, with 15.14 km^2 and 4.38 km^2 respectively. These regions are heavily fractured and could serve as key zones for groundwater exploration due to the high potential for water percolation through fractures. However, the high density of fractures also makes these areas less stable for construction and development, and they should be managed carefully to avoid environmental degradation and structural failures. Figure 5 shows the spatial distribution of lineament densities across the study area (Epuh *et al*., 2020).

Fig. 5: Spatial Distribution of Lineament Density Classes in the Study Area



The lineament density results are crucial for understanding the structural integrity of the study area and their implications for land use and water resource management. Areas with lower lineament densities (0.00 to 35.17 km/km²) are ideal for urban expansion and infrastructure development due to their stability. In contrast, regions with moderate to high lineament densities require more specialized engineering solutions to ensure structural safety (Epuh *et al.*, 2020). Moreover, the areas with higher lineament densities (105.52 to 175.86 km/km²) offer great potential for groundwater recharge and extraction due to the increased permeability associated with fractures and faults. These regions should be targeted for groundwater exploration and sustainable water resource management, but development in these areas must account for the potential risks associated with structural instability (Mpofu *et al.*, 2020).

CONCLUSION

The LULC classification of the study area for 2023 reveals that built-up areas (200.05 km²) and rangelands (184.90 km²) dominate the region, reflecting ongoing urbanization and extensive human activities. While trees cover a significant portion (164.33 km²), agricultural land is minimal (7.85 km²), indicating limited agricultural activities compared to other land uses. Water bodies and flooded vegetation occupy only small areas, which underscores the need for targeted environmental management, particularly in water-based ecosystems. Slope analysis further highlights that the majority of the terrain (503.85 km²) has gentle slopes, making it suitable for urban expansion, agriculture, and infrastructure projects. Steeper areas (ranging from 16.15° to 40.38°) are prone to erosion, requiring special land management practices to mitigate environmental risks. The drainage density analysis reveals moderate to high drainage densities in several regions, implying a balance between groundwater recharge potential and runoff. However, areas with very high drainage densities should be carefully managed to prevent environmental degradation and reduce flood risks. The lineament density findings indicate that the majority of the terrain has low to moderate fracture concentrations, making it stable for development. Areas with higher lineament densities, which cover smaller regions, offer excellent potential for groundwater exploration but present challenges for structural stability due to the increased risk of ground movement. To enhance sustainable development, it is essential to implement targeted land use planning in steep and highly drained areas. Groundwater exploration should focus on high lineament density zones, while managing urban expansion in low-density regions to ensure stability.

CONFLICT OF INTEREST

The authors declare that they have no competing interests.

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