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(Research Article)

Structural geology and tectonic influence on lineament density and slope variation in Southern Ebonyi, Nigeria: An ArcGIS Approach

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Abstract

This study investigates the structural geology and tectonic influences on lineament density and slope variation in Southern Ebonyi, Nigeria, using ArcGIS. The research aims to analyze the spatial distribution and density of lineaments and their correlation with slope variations to understand the region's geomorphology. Slope data was categorized into five classes, revealing that the majority of the area exhibits gentle slopes, indicative of tectonic stability. Conversely, regions with steeper slopes suggest localized tectonic activity. The analysis of lineament density identified areas with varying tectonic influences, with most of the study area showing low-density lineaments, suggesting relative tectonic stability. High-density lineament zones correspond to regions of significant tectonic deformation, often aligning with steeper slopes. The study concludes that the geomorphology of Southern Ebonyi is predominantly shaped by long-term erosional processes and localized tectonic activities. The novelty of this research lies in its comprehensive spatial analysis of both slope variation and lineament density, providing new insights into the tectonic and structural dynamics of the region.

Keywords: Fault systems; Geomorphology; Lithological units; Structural deformation; Tectonic stability

1. Introduction

Geology and tectonics are fundamental factors shaping the Earth's surface, exerting significant influence over various geomorphological features, including lineament density and slope variation (Sajadi et al., 2019). Lineaments, typically defined as linear or curvilinear features visible on the Earth's surface, represent zones of structural weakness or discontinuities, such as faults, fractures, and joints (Mohammed et al., 2020). These features are often crucial indicators of underlying geological structures and tectonic forces that have acted upon a region over time (Reis et al., 2020). The study of lineament density and slope variation provides valuable insights into the tectonic history, geological processes, and structural integrity of a landscape, making it a critical area of research in fields such as geomorphology, structural geology, and environmental management (Ishola et al., 2020).

The relationship between geology, tectonics, and lineament density is complex and multifaceted. Lineaments are typically formed in response to tectonic stresses, which create fractures and faults in the Earth's crust. These tectonic stresses are influenced by various geological factors, including the type of rock, the presence of pre-existing structures, and the regional tectonic setting (Epuh et al., 2020). Regions with active tectonics, such as those located along plate boundaries, tend to exhibit higher lineament densities due to the intense fracturing and faulting associated with tectonic movements. Conversely, regions with stable tectonics may have lower lineament densities, reflecting the reduced tectonic activity and associated deformation (Olaseeni et al., 2020).

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Slope variation, another key geomorphological feature, is also significantly influenced by geological and tectonic factors. The slope of a landscape is determined by a combination of factors, including the underlying rock type, the degree of weathering and erosion, and the tectonic forces that have shaped the terrain (Derakhshan-Babaei et al., 2020). In tectonically active regions, steep slopes are often a result of recent faulting and uplift, which create sharp changes in elevation. In contrast, more subdued slopes may indicate regions where tectonic activity has diminished, allowing for the gradual processes of weathering and erosion to dominate (García-Delgado & Velandia, 2020). Understanding the interplay between geology, tectonics, and slope variation is crucial for comprehensively understanding the landscape evolution and the potential risks associated with natural hazards such as landslides and earthquakes.

The study of lineament density and slope variation has numerous practical applications, particularly in the fields of natural resource exploration, environmental management, and hazard assessment. Lineament analysis is often used in the exploration of minerals, groundwater, and hydrocarbons, as lineaments can indicate the presence of fault zones and fractures that serve as conduits for fluid flow (Sikakwe, 2020). In environmental management, understanding slope variation is essential for assessing soil erosion, landslide susceptibility, and flood risk, which are critical for land use planning and infrastructure development. Furthermore, the relationship between geology, tectonics, and these geomorphological features is integral to understanding seismic hazards, as areas with high lineament densities and steep slopes are often more prone to earthquakes and associated ground failures (Nebeokike et al., 2020).

Geologically, the formation and distribution of lineaments are influenced by the type of rock present in an area. Different rock types exhibit varying degrees of resistance to tectonic forces, which in turn affects the formation of fractures and faults (Adebayo et al., 2021). Brittle rocks, such as granite and basalt, are more prone to fracturing under tectonic stress, leading to the formation of prominent lineaments. In contrast, more ductile rocks, such as shale and limestone, may deform plastically under similar conditions, resulting in fewer visible lineaments (O'Ghaffari et al., 2023). The lithological composition of an area thus plays a crucial role in determining lineament density, with certain rock types being more conducive to the formation of lineaments due to their physical and mechanical properties (Oguama et al., 2020).

Tectonically, the formation of lineaments is closely related to the stress regime in a region. Tectonic forces, such as compression, tension, and shear, create stress fields that influence the orientation, spacing, and density of fractures and faults (Wajid et al., 2021). In compressional settings, where tectonic plates are converging, lineaments are often aligned parallel to the direction of maximum compressive stress, reflecting the orientation of the principal stress axes (Salawu et al., 2021). In extensional settings, where tectonic plates are moving apart, lineaments tend to be perpendicular to the direction of extension, reflecting the orientation of the principal tensile stress. In strike-slip settings, where tectonic plates are sliding past each other, lineaments may form in various orientations depending on the direction of shear stress and the presence of pre-existing structures (Epuh et al., 2020).

Slope variation is similarly influenced by the interaction between geological and tectonic processes. The steepness and orientation of slopes are often controlled by the underlying rock structure and the tectonic forces that have acted upon the landscape (Carlini et al., 2017). For instance, in areas with active faulting, slopes may be abruptly steepened due to the vertical displacement along fault planes, creating escarpments and cliffs. In regions where folding has occurred, slopes may vary depending on the orientation of the fold axes, with steeper slopes typically found on the limbs of anticlines and synclines (Harel et al., 2019). Tectonic uplift can create regional variations in slope by raising entire blocks of the Earth's crust, leading to the development of high-relief terrain with significant differences in elevation over short distances (Bamisaiye, 2019).

The interaction between geology, tectonics, and slope variation also plays a critical role in landscape evolution. Over time, tectonic processes such as faulting, folding, and uplift interact with surface processes such as weathering, erosion, and sedimentation to shape the topography of a region. In tectonically active regions, the rate of tectonic uplift often exceeds the rate of erosion, leading to the development of rugged, high-relief landscapes with sharp slope gradients (Bawallah et al., 2019). In regions where tectonic activity has diminished or ceased, the landscape may become more subdued as erosion gradually reduces relief and smooths out slopes. The study of slope variation in relation to tectonics is thus essential for understanding the long-term evolution of landscapes and the processes that drive their development (Mohammed et al., 2019).

The aim of this study is to investigate the structural geology and tectonic influences on lineament density and slope variation in Southern Ebonyi, Nigeria, using ArcGIS. The research seeks to analyze the spatial distribution and density of lineaments in relation to slope variations, providing insights into the tectonic activities shaping the region's geomorphology. By examining these factors, the study aims to enhance the understanding of the structural controls on landscape evolution and potential geohazards in the area.

2. Research Area and Geology of the Study Area

The study area comprises Ezza North, Ezza South, Abakaliki, and Ikwo Local Government Areas (LGAs) in Ebonyi State, South Eastern Nigeria. Geographically, this region is situated between approximately 6.0° to 6.6° N latitude and 8.0° to 8.6° E longitude. The area is characterized by a diverse landscape that includes both urban and rural settings, with a variety of natural features such as rivers, forests, and agricultural land.

The accessibility of the study area is facilitated by a network of major roads and water bodies. Key roads such as the Abakaliki-Enugu Road and the Abakaliki-Ishielu Road provide essential connectivity between the LGAs and other parts of Ebonyi State and beyond. These roads are crucial for transportation, trade, and emergency services within the region. Several smaller local roads link the rural areas within the LGAs, though their quality and accessibility may vary depending on weather conditions and maintenance.

The study area also benefits from proximity to significant water bodies. Rivers such as the Ebonyi River and the Akeze River flow through the region, providing vital water resources for agriculture, domestic use, and supporting local biodiversity. These rivers are integral to the local economy, offering irrigation for crops and fishing opportunities. The presence of these rivers also impacts the landscape, contributing to soil erosion and sediment deposition, which influence the area's geomorphology and geology.

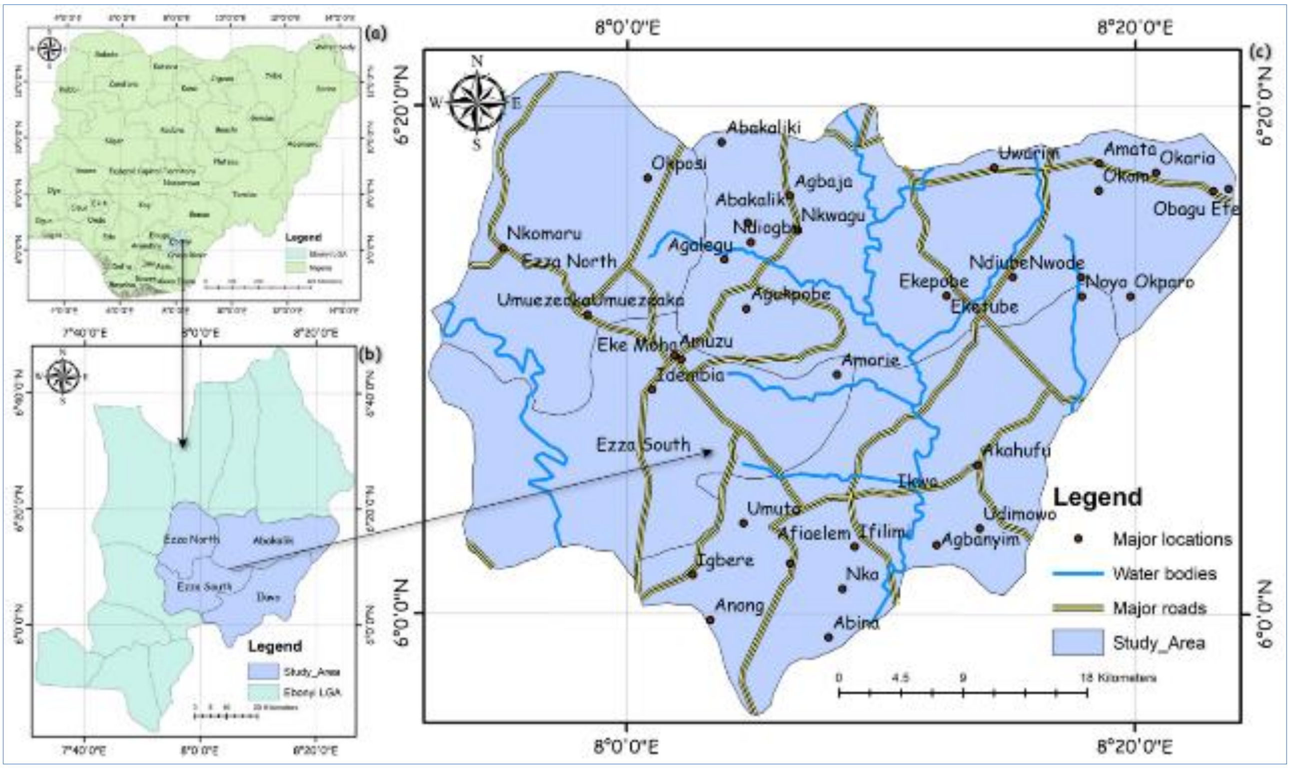

Figure 1 Geographic Maps of (a) Nigeria (b) Ebonyi State (c) Map of the Study Area with Water Bodies, Major Roads, and Major Settlements

The vegetation in the study area is predominantly tropical rainforest, which transitions into a more mixed forest and agricultural land as one moves towards the more developed urban areas. The dense forest cover in rural areas supports diverse flora and fauna, while also playing a role in soil conservation and water regulation (Oli et al., 2020). The urbanized zones, particularly in Abakaliki, exhibit a shift towards secondary vegetation and developed land, with significant residential, commercial, and industrial developments.

Urbanization has significantly impacted land use patterns in the study area. Abakaliki, the state capital, is the most developed urban center, characterized by densely packed residential areas, commercial zones, and infrastructure (Oli et al., 2020). The other LGAs, such as Ezza North, Ezza South, and Ikwo, remain more rural, with extensive agricultural activities and scattered settlements.

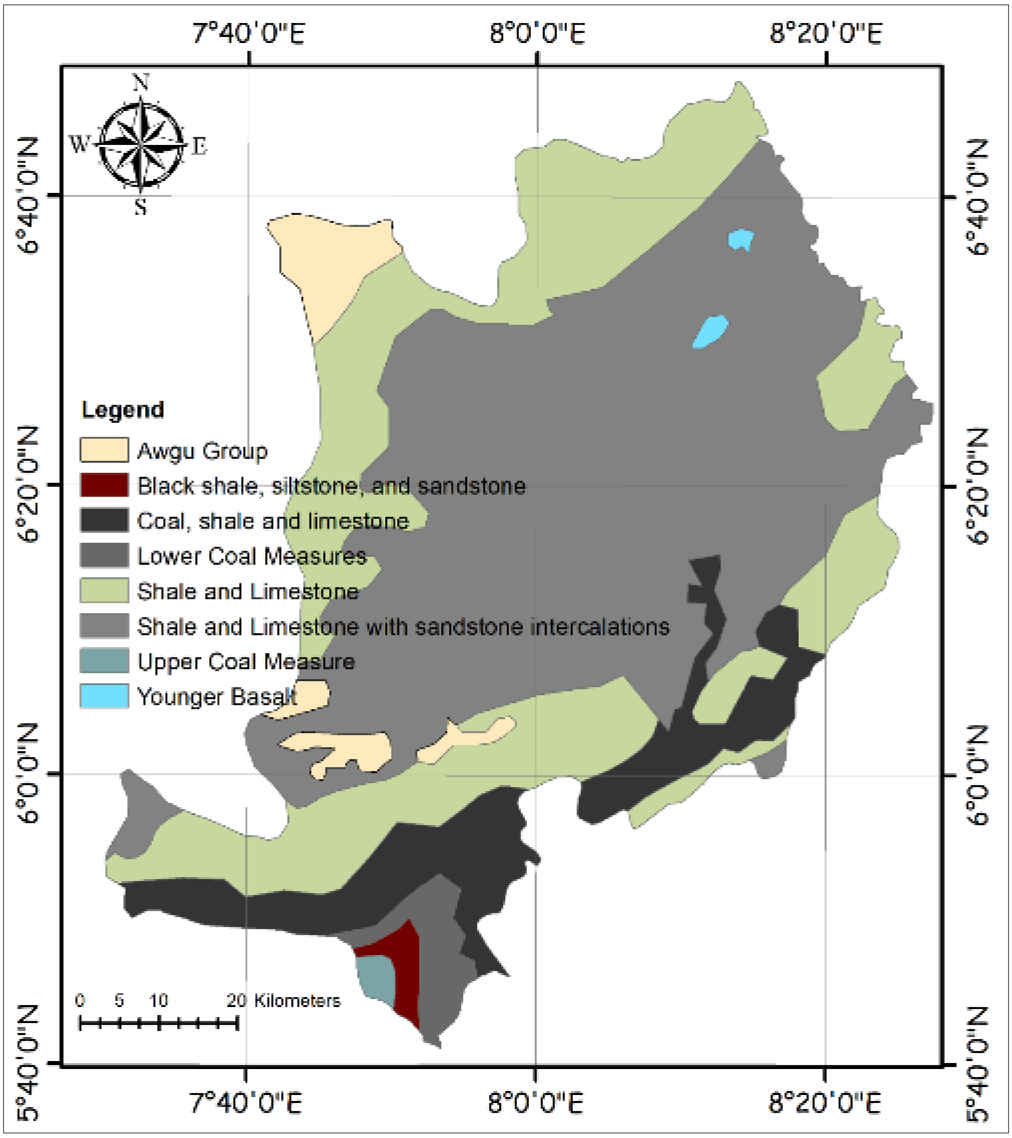

Figure 2 Geology of Ebonyi State

The geology of the study area is diverse, with notable influences from both the Basement Complex and sedimentary formations. According to the geological map of Ebonyi State (Figure 2), the region predominantly features Precambrian Basement Complex rocks, including granites, gneisses, and schists (Abraham et al., 2019). These rocks form the foundational geology of the area, characterized by their high degree of metamorphism and structural complexity. In addition, the area also includes outcrops of sedimentary formations, such as sandstone and shale, which contribute to the region's geological diversity and impact soil formation and erosion patterns.

3. Methodology

This study investigates the structural geology and tectonic influences on lineament density and slope variation in Southern Ebonyi, Nigeria, utilizing ArcGIS for spatial analysis. The objective is to analyze the relationship between lineament density and slope variations, providing insights into the tectonic processes shaping the region's geomorphology.

3.1. Data Collection

The primary data for this study includes topographic and geological information. The topographic data is sourced from the Shuttle Radar Topography Mission (SRTM) Elevation Data provided by the United States Geological Survey (USGS) (Okoli et al., 2024). This data provides a detailed digital elevation model (DEM) essential for analyzing slope variations. The SRTM data is accessed and processed in ArcGIS to generate slope maps and derive slope values.

Table 1 Data Source and Type

Data Type	Source	Provider
GIS Data	SRTM Elevation Data	USGS

By employing these methods, the study aims to elucidate the structural controls on landscape evolution and assess potential geohazards in Southern Ebonyi. The results will contribute to a deeper understanding of the tectonic processes influencing geomorphological features in the region.

3.2. Data Preparation

The SRTM elevation data is imported into ArcGIS and resampled if necessary to match the spatial resolution required for analysis. Using the DEM, the slope is calculated to determine the gradient of the terrain. Slope is expressed in degrees and calculated based on the change in elevation relative to the horizontal distance. In ArcGIS, the Slope tool is used to compute this information, resulting in a detailed slope map for the study area.

3.3. Lineament Extraction

Lineaments are extracted from high-resolution satellite imagery and existing geological maps using the ArcGIS Spatial Analyst extension. These linear features, which represent structural discontinuities in the landscape, are identified and mapped.

Lineament density is then calculated by counting the number of lineaments within specified grid cells and dividing this count by the area of each cell. This measurement provides an indication of the concentration of lineaments across the landscape.

3.4. Spatial Analysis

The relationship between lineament density and slope variation is analyzed through statistical methods. A correlation coefficient is calculated to quantify the strength and direction of the relationship between the variables—lineament density and slope. This coefficient helps in understanding how changes in lineament density might relate to variations in slope.

Maps showing lineament density and slope variation are created using ArcGIS. These visual representations highlight the spatial distribution and areas of significant tectonic influence, aiding in the interpretation of geological and geomorphological patterns.

4. Results and Discussion

4.1. Slope Variation Analysis

The analysis of slope variation in Southern Ebonyi, Nigeria, reveals significant insights into the geomorphological and tectonic processes shaping the region. The slope data, categorized into five classes, provides a comprehensive understanding of the terrain's topographical variation and its implications for structural geology and tectonic influences.

Table 2 Slope Classes and Corresponding Areas in Southern Ebonyi

Slope (Degrees)	Area (km^2)
0.00 - 1.29	8.39
1.29 - 1.75	553.82
1.75 - 3.04	633.16
3.04 - 6.66	297.14
6.66 - 16.87	131.75

Table 2 presents the distribution of slope degrees across the study area. The majority of the region falls within the slope class of 1.75° to 3.04°, covering an area of 633.16 km², followed by the slope class of 1.29° to 1.75°, which occupies 553.82 km². The steepest slopes, ranging from 6.66° to 16.87°, cover the smallest area, approximately 131.75 km².

The slope variation in Southern Ebonyi suggests a predominantly gentle terrain, with slopes between 1.29° and 3.04° covering a large portion of the study area. This distribution indicates that the region is characterized by a relatively low gradient, which may be attributed to long-term erosion and weathering processes that have smoothed out the landscape. The minimal area covered by steeper slopes (6.66° to 16.87°) indicates that high-relief areas are limited, which could be associated with localized tectonic uplift or resistant rock formations that have withstood erosion.

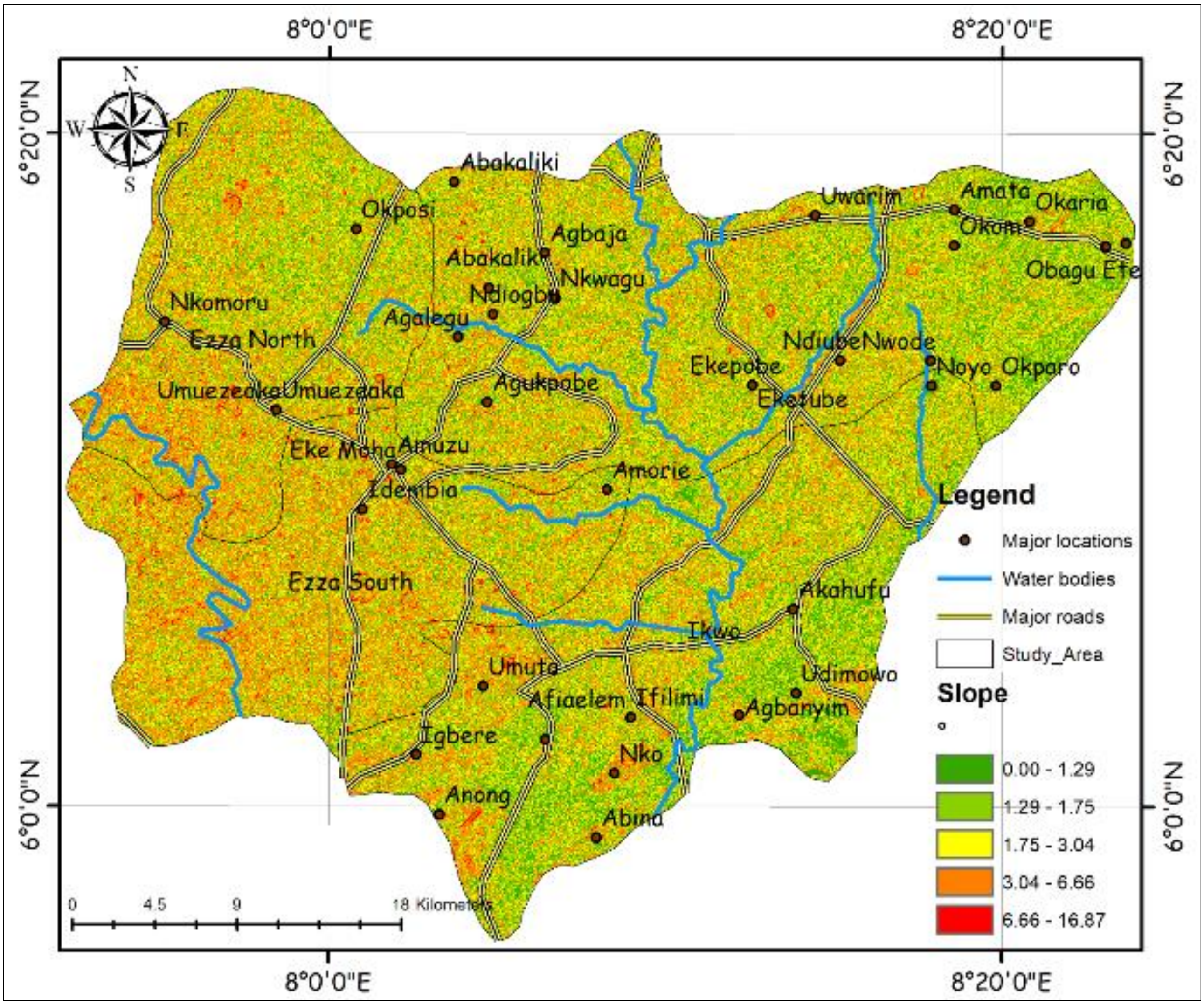

Figure 3 Spatial Distribution of Slope Classes in Southern Ebonyi, Nigeria

The slope analysis has significant implications for understanding the structural geology and tectonic influences in Southern Ebonyi. The dominance of gentle slopes (1.29° to 3.04°) suggests that the region has undergone extensive tectonic stability over time, allowing erosional processes to gradually reduce the topographic relief. This stability may also imply a lack of recent tectonic activity, as active tectonic regions typically exhibit more pronounced slope variations due to faulting and folding.

The areas with steeper slopes (3.04° to 16.87°) are likely indicative of tectonic influences, where faulting, folding, or other structural controls have resulted in more abrupt changes in elevation. These regions may correspond to areas of increased tectonic stress or the presence of resistant lithological units that have resisted erosion. The limited extent of these steep areas suggests that such tectonic influences are localized rather than widespread across the study area.

The spatial distribution of slope classes, as visualized in Figure 3, highlights the geomorphological diversity within the region. The gentle slopes are widespread, while the steeper slopes are clustered in specific areas, likely corresponding to tectonic features such as fault lines or folds. This pattern supports the hypothesis that structural geology plays a critical role in shaping the landscape of Southern Ebonyi.

4.2. Lineament Density Variation Analysis

The analysis of lineament density within Southern Ebonyi, Nigeria, revealed significant spatial variability, indicating distinct structural and tectonic influences across the region. The study area, covering approximately 1,630.08 km^2, was categorized into five distinct lineament density classes, ranging from 0.00 to 133.10 km/km^2. The majority of the area, 1,082.74 km^2, was characterized by the lowest lineament density (0.00 - 26.62 km/km^2), representing 66.41% of the total area. This indicates that most of Southern Ebonyi is less affected by tectonic fractures or other lineament-generating processes.

Conversely, the highest lineament density class (106.48 - 133.10 km/km^2) covered a mere 4.52 km^2, constituting only 0.28% of the study area. This suggests that intense tectonic activity or structural deformation is localized to specific, smaller regions. The intermediate density classes, ranging from 26.62 to 106.48 km/km^2, covered the remaining portions of the study area, with a notable concentration in areas with moderate to steep slopes. Specifically, the 26.62 - 53.24 km/km^2 class covered 439.62 km^2 (26.97% of the area), while the 53.24 - 79.86 km/km^2 and 79.86 - 106.48 km/km^2 classes covered 85.61 km^2 (5.25%) and 17.60 km^2 (1.08%), respectively (Table 3).

Table 3 Lineament Density Classes and Corresponding Area Coverage

Lineament Density (km/km^2)	Area (km^2)
0.00 - 26.62	1,082.74
26.62 - 53.24	439.62
53.24 - 79.86	85.61
79.86 - 106.48	17.60
106.48 - 133.10	4.52

These results were visually represented in a spatial map of lineament density (Figure 4), which clearly depicted the variation across Southern Ebonyi. The map highlighted areas with the highest lineament densities, corresponding with regions exhibiting complex structural geology and increased tectonic activity. The concentration of higher lineament densities in specific zones is indicative of underlying fault systems, fracture networks, or other tectonic features influencing the landscape.

The findings of this study have significant implications for understanding the structural and tectonic dynamics in Southern Ebonyi. The spatial distribution of lineament density, as illustrated by the quantitative results, provides valuable insights into the tectonic forces shaping the region. The dominance of low-density lineaments over a vast area suggests that much of Southern Ebonyi is relatively stable, with fewer tectonic disruptions. However, the presence of high-density lineament zones, though limited in area, points to regions of intense tectonic deformation or faulting.

The correlation between lineament density and slope variation is particularly noteworthy. Higher lineament densities were often found in areas with steeper slopes, suggesting a direct link between tectonic activity and topographical features. This relationship highlights the role of tectonic forces in shaping the geomorphology of the region, where faulting and fracturing have likely contributed to the development of steep terrain.

From a geological perspective, the concentrated high-density lineament areas could be associated with active fault zones or regions of significant structural deformation. These areas may be more prone to geological hazards such as landslides or ground subsidence, especially given the steep slopes identified in the study. The identification of these zones is crucial for future land use planning and hazard mitigation strategies in Southern Ebonyi.

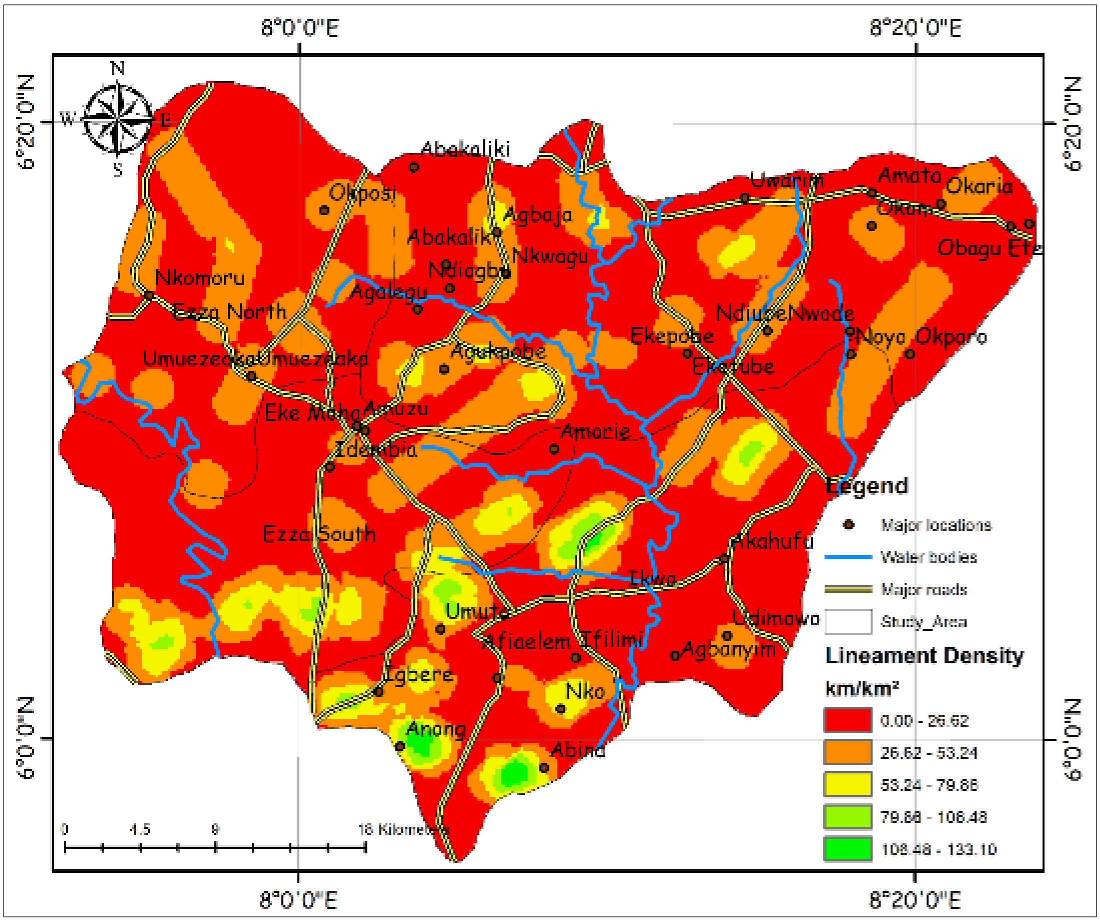

Figure 4 Spatial Distribution of Lineament Density

4.3. Drainage Density Variation Analysis

The analysis of drainage density within the study area of Southern Ebonyi, Nigeria, revealed significant variations across different regions, reflecting the influence of underlying structural geology and tectonic activities. The spatial distribution of drainage density values, as categorized into five distinct ranges, is presented in Table 4.

Table 4 Drainage Density Distribution in Southern Ebonyi, Nigeria

Drainage Density (km/km^2)	Area (km^2)
4.38 - 53.11	78.871
53.11 - 101.84	545.148
101.84 - 150.58	679.997
150.58 - 199.31	305.951
199.31 - 248.04	19.564

The lowest range of drainage density, between 4.38 and 53.11 km/km^2, covers an area of approximately 78.87 km^2. This suggests that these regions may be characterized by more permeable substrates, flatter slopes, or less intense tectonic activity, leading to a lower concentration of stream channels. Conversely, the highest drainage density range, between 199.31 and 248.04 km/km^2, is confined to a smaller area of about 19.56 km^2, indicating more intense structural control or reduced permeability of the underlying rock formations, which forces surface runoff to concentrate into well-defined channels.

The majority of the study area falls within the intermediate ranges of drainage density, specifically between 53.11 and 150.58 km/km^2. The largest area, covering approximately 680.00 km^2, is associated with drainage density values between 101.84 and 150.58 km/km². This suggests a balance between tectonic influence, slope steepness, and the lithological composition of the region, which moderately influences drainage pattern development.

The spatial distribution of these drainage densities is illustrated in Figure 5, providing a visual understanding of how structural and tectonic forces shape the hydrological network across Southern Ebonyi. The map highlights regions of higher drainage density corresponding with more tectonically active or structurally complex zones.

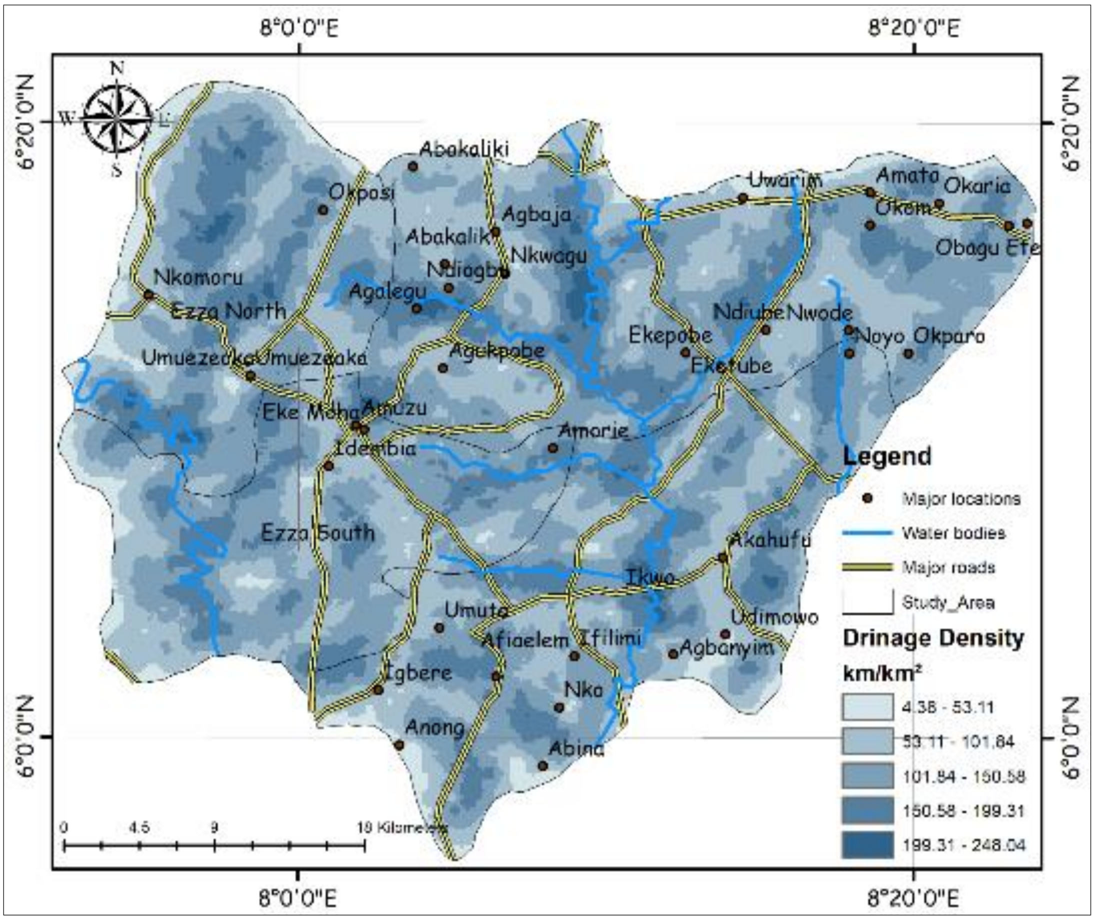

Figure 5 Spatial Distribution of Drainage Density

The results of this study have significant implications for understanding the structural controls on drainage development and landscape evolution in Southern Ebonyi. The observed variations in drainage density suggest that tectonic activities and structural geology play a crucial role in influencing the geomorphological characteristics of the region.

Regions with lower drainage density may indicate areas where tectonic uplift is less pronounced, or the rock formations are more permeable, allowing for greater infiltration and less surface runoff. This is often associated with flatter terrains or areas underlain by more permeable lithologies. Areas with higher drainage density are likely to be associated with more resistant rock types, steeper slopes, or regions where tectonic forces have uplifted the terrain, leading to more concentrated surface runoff and a denser network of streams.

The concentration of higher drainage densities in specific areas, as seen in Figure 5, suggests that these regions may be more prone to erosion and could be potential zones for geohazards such as landslides or flash flooding. Understanding these spatial patterns is critical for regional planning and hazard mitigation efforts, as it provides insights into the areas most susceptible to these processes.

Moreover, the variations in drainage density also reflect the impact of structural lineaments on drainage patterns. Lineaments, which are often expressions of faults or fractures, can significantly influence the direction and density of drainage networks by providing pathways for water flow or creating zones of weakness that channelize runoff. The alignment of higher drainage densities with known structural features further emphasizes the role of tectonic activity in shaping the region's hydrology.

5. Conclusion

The analysis of slope variation in Southern Ebonyi, Nigeria, has provided significant insights into the region's geomorphological and tectonic processes. The study revealed that the majority of the terrain is characterized by gentle slopes, particularly within the 1.29° to 3.04° range, covering approximately 633.16 km^2. This distribution indicates a region largely shaped by long-term erosion and weathering, suggesting tectonic stability over time. The limited area of steep slopes (6.66° to 16.87°), covering only 131.75 km^2, suggests localized tectonic uplift or resistant rock formations.

Lineament density analysis further highlighted the structural and tectonic influences across Southern Ebonyi. The majority of the study area exhibited low lineament density, with 66.41% of the region falling within the 0.00 - 26.62 km/km^2 class. This widespread low density suggests that much of Southern Ebonyi is tectonically stable, with fewer disruptions from fractures or faults. However, the presence of high lineament density zones, although covering a small area (0.28%), indicates localized intense tectonic activity, particularly in regions with steeper slopes.

The correlation between lineament density and slope variation underscores the influence of tectonic forces in shaping the region's topography. Higher lineament densities were often associated with steeper slopes, suggesting that tectonic processes such as faulting and folding have contributed to the development of more pronounced elevation changes. The drainage density analysis further supports these findings, with regions of higher drainage density corresponding to areas of structural complexity and tectonic uplift.

Overall, the study concludes that Southern Ebonyi's landscape is predominantly shaped by tectonic stability, with localized zones of tectonic activity influencing slope variation, lineament density, and drainage patterns. These findings provide valuable insights into the region's structural geology and highlight the critical role of tectonic forces in shaping its geomorphology.

Future studies should focus on detailed field investigations to validate the remote sensing and GIS findings. Integrating geophysical methods could provide deeper insights into subsurface structures, enhancing the understanding of tectonic influences in Southern Ebonyi.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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