International Journal of Science and Research Archive
eISSN: 2582-8185
Cross Ref DOI: 10.30574/ijsra
Journal homepage: https://ijsra.net/

(RESEARCH ARTICLE)

Stratigraphic Contributions to Hydrological Flow: A GIS-Based Analysis of Elevation and Flow Patterns in Udi, Ezeagu, and Ojir River Local Government Areas, Enugu

Charity Nkiru Nwokeabia [1,*], Benard Ifeanyi Odoh [1] and Chukwuneke Jude Chetanna [2]

[1] *Department of Geophysics, Faculty of Physical Sciences, Nnamdi Azikiwe University Awka, Nigeria.*
[2] *Department of Civil Engineering, Chukwuemeka Odumegwu Ojukwu University, Uli, Nigeria.*

International Journal of Science and Research Archive, 2024, 13(01), 614–626

Publication history: Received on 20 July 2024; revised on 05 September 2024; accepted on 07 September 2024

Article DOI: https://doi.org/10.30574/ijsra.2024.13.1.1656

Abstract

Understanding the elevation and flow dynamics of a region is critical for effective watershed management, especially in areas with diverse topographical features. The Udi, Ezeagu, and Ojir River Local Government Areas in Enugu, Nigeria, exhibit a complex elevation gradient, influencing both geological and hydrological processes. This study aims to analyze the elevation and flow direction within these regions to assess their impact on flood risk, erosion, and watershed management. We conducted a spatial analysis using Digital Elevation Models (DEMs) to map elevation, flow direction, and basin order. The data were processed using Geographic Information Systems (GIS) to visualize and interpret the topographical and hydrological characteristics of the study area. The analysis revealed significant variation in elevation, ranging from 15 to 597 meters above sea level. The flow direction analysis indicated diverse pathways influenced by the topography, with distinct patterns in Udi, Ezeagu, and Ojir River areas. Low elevation zones are prone to flooding due to flat terrain and slow water movement, whereas higher elevations in Udi Hills show rapid runoff, increasing erosion risks. The flow direction analysis highlights the influence of underlying geological structures on water movement. The study emphasizes the importance of elevation data in watershed management, highlighting areas vulnerable to flooding and erosion. This research provides a comprehensive spatial understanding of how elevation and flow direction influence hydrological processes, contributing to more effective watershed management strategies in Enugu.

Keywords: Basin order; Stream network; Surface runoff; Terrain analysis; Watershed management

1. Introduction

The study of hydrological systems and their interactions with geological features is fundamental to understanding the dynamics of water flow within a watershed. In this context, basin order, elevation, flow direction, and stream analysis are critical components that collectively shape the hydrological behavior of a region (Huang & Lee, 2021). These factors not only influence the distribution and movement of water but also play a significant role in the development of geomorphological features and the management of water resources. With the advent of GIS technology, tools like ArcGIS have revolutionized the way these hydrological parameters are analyzed, offering a powerful platform for spatial analysis and visualization (Choudhary et al., 2023). This introduction explores the significance of basin order, elevation, flow direction, and stream analysis in hydrology, and their applications in geological and environmental studies, particularly within the framework of ArcGIS.

Basin order, also known as stream order, is a fundamental concept in hydrology that refers to the hierarchical classification of streams within a watershed. First introduced by Strahler in 1952, stream order provides a systematic method for categorizing the relative position of a stream within the overall drainage network (Olla et al., 2020). A first-order stream is typically the smallest, originating from a source with no tributaries. When two first-order streams

---

[*] Corresponding author: Nwokeabia Charity Nkiru

converge, they form a second-order stream, and this pattern continues with higher orders representing larger and more complex networks (Yin et al., 2023). Understanding basin order is crucial because it directly correlates with various hydrological and geomorphological attributes such as stream length, discharge, sediment transport, and the energy available for erosion. Higher-order streams generally exhibit greater discharge and sediment-carrying capacity, influencing the morphology of river channels and floodplains. The classification of streams by order also aids in the prediction of hydrological responses within a watershed, such as the timing and magnitude of peak flows during storm events (Hooke, 2022).

Watershed management, basin order analysis helps in identifying key areas for conservation, flood control, and the sustainable management of water resources (Obeidat et al., 2021). For instance, lower-order streams, which are often more susceptible to pollution and habitat degradation, may require targeted protection efforts. Similarly, higher-order streams may be prioritized for flood mitigation measures due to their larger catchment areas and greater potential for flood hazards.

Elevation, or the height above a reference level (usually sea level), is another critical factor influencing hydrological processes within a watershed. The topography of a region, determined by its elevation, dictates the direction and velocity of water flow, the formation of streams and rivers, and the potential for erosion and sediment deposition (Rocha et al., 2020). Elevation gradients, particularly in mountainous or hilly regions, create variations in climate and vegetation, which in turn affect the hydrological cycle. In hydrological modeling and watershed analysis, elevation data is typically derived from DEMs, which provide a three-dimensional representation of the terrain. DEMs are used to generate elevation profiles, slope maps, and watershed boundaries, all of which are essential for understanding the movement of water within the landscape (Eludoyin & Adewole, 2019). In ArcGIS, elevation data is integral to the calculation of flow direction, flow accumulation, and other hydrological parameters that inform the analysis of drainage patterns and stream networks.

Elevation influences not only the flow of surface water but also the recharge of groundwater, the development of soil profiles, and the distribution of vegetation. In regions with significant elevation differences, such as mountainous areas, the variation in altitude can lead to diverse microclimates and distinct ecological zones (Egbueri & Igwe, 2020). These differences in elevation are also associated with varying rates of erosion and sediment transport, which contribute to the shaping of the landscape over geological timescales (Kudamnya et al., 2021). Understanding the role of elevation in watershed dynamics is essential for a wide range of applications, from predicting flood risks to designing infrastructure that can withstand the challenges posed by steep terrains. It also plays a crucial role in conservation efforts, as areas of high elevation may serve as important refuges for biodiversity and sources of freshwater (Lamine et al., 2021).

Flow direction is a key hydrological parameter that describes the direction in which water flows across the surface of the earth. It is determined by the slope of the terrain and is typically represented as a grid or raster dataset, where each cell indicates the direction of flow based on the steepest descent from that point (Amah et al., 2021). In ArcGIS, the flow direction is calculated using algorithms that analyze elevation data from DEMs to determine the path of water movement across the landscape. The analysis of flow direction is fundamental to understanding the movement of water within a watershed. It helps in delineating watershed boundaries, identifying drainage divides, and mapping the course of streams and rivers (Angelina et al., 2015). Flow direction data is also used to calculate flow accumulation, which represents the total amount of water flowing into each cell in the grid, and is crucial for identifying areas of potential flooding or high erosion risk (Abdramane et al., 2018).

In addition to its applications in flood risk assessment and erosion control, flow direction analysis is important for understanding the transport of pollutants within a watershed. By modeling the flow paths of water, it is possible to predict how contaminants may spread through the environment and identify critical areas for intervention (Marlim & Kang, 2020). This is particularly important in regions with complex drainage networks or where human activities, such as agriculture or urban development, may contribute to water pollution.

Stream analysis involves the examination of various characteristics of stream networks, including their length, order, gradient, and density (Varado et al., 2006). It is a critical component of hydrological studies as it provides insights into the development and behavior of drainage systems. Stream analysis is used to assess the connectivity and complexity of a watershed's drainage network, which has implications for water flow, sediment transport, and the overall stability of the landscape (Sajadi et al., 2021). One of the key metrics in stream analysis is stream density, which refers to the total length of streams per unit area of the watershed. High stream density often indicates a well-developed drainage network with efficient water removal, while low stream density may suggest a poorly drained area with potential for waterlogging or flooding (Gabriel et al., 2020). Stream gradient, or the slope of the stream channel, is another important parameter that influences the velocity of water flow, the potential for erosion, and the transport of sediment. In geological studies, stream analysis can reveal information about the underlying rock types and structures, as streams often follow lines of weakness in the bedrock, such as faults or fractures. The pattern and orientation of streams can also indicate the tectonic history of an area, providing insights into past geological events that have shaped the landscape (Olusola et al., 2020).

To analyze the geological and hydrological characteristics of a watershed by examining basin order, elevation, flow direction, and stream networks use ArcGIS, with the goal of understanding the relationship between these factors and their implications for effective watershed management and sustainable land use planning.

2. Research and Geology of the study area

The Udi, Ezeagu, and Ojir River Local Government Areas (LGAs) are located in Enugu State, Nigeria, encompassing a diverse and complex geological and topographical landscape. Situated between coordinates 6.3544° N latitude and 7.5077° E longitude, this region exhibits a range of geological formations and hydrological features that significantly influence its environmental and urban characteristics. Figure 1a provides an overview of Enugu State, while Figure 1b zooms into the study area, highlighting its location within the larger region. The road network in Udi, Ezeagu, and Ojir River LGAs is well-developed, with key roads such as the Enugu-Abakaliki Road and the Enugu-Onitsha Expressway facilitating transportation and connectivity. This network supports both urban and rural areas, impacting local development and access to resources.

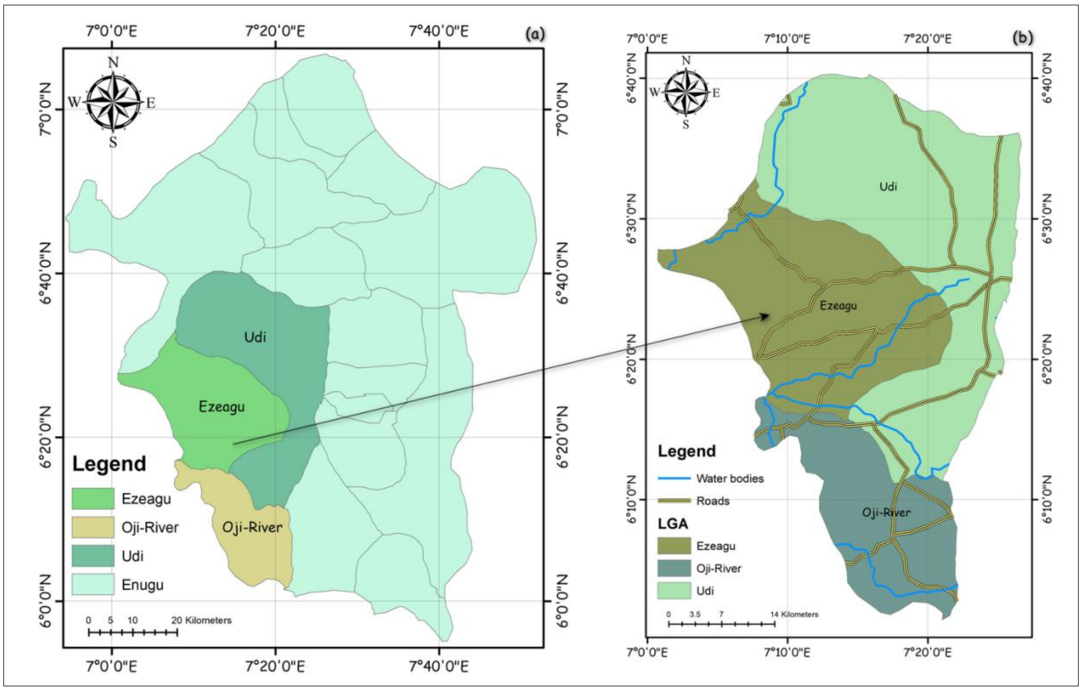

Figure 1 (a) Map of Enugu (b) Map of the study area

The water network in this region includes several rivers and streams, such as the Ojir River and its tributaries. These water bodies play a significant role in the region's hydrology, influencing water availability, erosion patterns, and flood risks (Umegbolu, 2018). The flow direction and water movement are shaped by the underlying geology and topography, with higher elevation areas in Udi contributing to rapid runoff and increased erosion, while the lower-lying zones in Ezeagu are more prone to water accumulation and potential flooding. The weather in the study area is characterized by a humid subtropical climate with distinct wet and dry seasons. The rainy season typically spans from March to October, bringing substantial rainfall that affects the region's hydrological dynamics. This rainfall is crucial for replenishing water resources but can also exacerbate flooding, particularly in lower elevation zones. The dry season, from November to February, is marked by reduced rainfall and higher temperatures, impacting soil moisture and vegetation (Umegbolu, 2018). Urbanization in the Udi, Ezeagu, and Ojir River LGAs is growing, with increased development in towns and rural areas. This urban expansion affects land use patterns, water management, and environmental sustainability. The interaction between urbanization and natural processes requires careful management to mitigate impacts such as increased runoff, erosion, and habitat disruption (Nebeokike et al., 2020).

The geology of the study area is predominantly characterized by the Precambrian Basement Complex, which includes various metamorphic and igneous rocks. The Udi Hills, a prominent geological feature, are composed of gneisses and schists, contributing to the area's high elevation and steep slopes (Nebeokike et al., 2020). The surrounding regions, including Ezeagu and parts of Ojir River, feature younger sedimentary formations that contrast with the more resistant rocks of the highlands (Nwankwo & Ene, 2020). These geological formations play a crucial role in shaping the local hydrology and land use. The diverse geological and hydrological characteristics of the Udi, Ezeagu, and Ojir River LGAs necessitate a comprehensive approach to watershed management and urban planning, considering the interplay between natural and human-induced factors.

3. Methodology

The morphometric analysis relies on high-precision DEM data provided by the Shuttle Radar Topography Mission (SRTM), which is part of the United States Geological Survey (USGS) dataset. The SRTM data was selected due to its superior accuracy and resolution, making it ideal for detailed morphometric investigations. This dataset supports a thorough examination of terrain features including elevation, slope, and aspect, which are essential for understanding the dynamics of watersheds and geomorphological processes within the basin.

Table 1 Data Source and Type

Data Type	Source	Provider
GIS Data	SRTM Elevation Data	USGS

Table 1 provides an overview of the GIS data used in the analysis. It specifies that the data type is GIS Data and that it consists of SRTM Elevation Data, with the USGS as the provider. This information is crucial for ensuring transparency and reproducibility in research by clearly documenting the data sources, which allows for accurate replication and comparison in future studies.

3.1. Data Acquisition and Preprocessing

The DEM data were systematically downloaded and preprocessed using ArcGIS software to meet the study's accuracy and compatibility requirements (Okoli et al., 2024). The preprocessing involved several essential steps to ensure the data's suitability for detailed analysis. Initially, the SRTM data were imported into ArcGIS and reprojected to the WGS 84/UTM Zone 32N coordinate system, which aligns with the study area's spatial framework. This reprojection is crucial for integrating the DEM with other geospatial datasets and maintaining spatial accuracy throughout the analysis.

A critical step in preprocessing was the correction of sinks within the DEM. Sinks are depressions in the terrain that can interfere with water flow and impact the accuracy of hydrological models. By filling these sinks, the DEM was adjusted to create continuous flow paths, which are essential for accurately simulating surface water flow in the basin (Okoli et al., 2024). Additionally, the DEM was clipped to the exact boundary of the study area, focusing the analysis on the relevant geographic region and improving the precision and applicability of the morphometric studies within this specific watershed.

The meticulous preprocessing of the DEM data was crucial to ensure both accuracy and relevance to the study's geographic and analytical needs (Akaolisa et al., 2024; Okoli et al., 2024). These preprocessing steps are foundational in geospatial analysis, providing a robust base for examining terrain characteristics, watershed dynamics, and geomorphological features.

3.2. Watershed Delineation

The process begins with calculating the flow direction from the preprocessed DEM. This calculation determines the path that water will follow across the terrain, which is crucial for understanding runoff patterns and identifying drainage pathways within the basin. Following the determination of flow direction, the next step involves creating a flow accumulation grid. This grid aggregates the number of cells contributing flow to each specific cell, effectively mapping the stream networks within the basin. This grid is vital for delineating primary channels and pinpointing areas susceptible to flooding or erosion.

After establishing the flow accumulation grid, the stream network is defined using a threshold value. This threshold helps differentiate between intermittent and perennial streams based on water flow accumulation, which is essential for identifying the main channels and tributaries that make up the basin's hydrological network. Subsequently, watershed boundaries are delineated based on the defined stream network. This step identifies the areas where all surface water drains towards a particular point, such as a river outlet or a confluence of streams. The watershed delineation process combines advanced geospatial techniques with hydrological principles, providing a comprehensive understanding of basin morphology and dynamics (Aziz et al., 2023).

3.3. Calculation of Morphometric Parameters

To thoroughly analyze the shape, size, drainage pattern, and network characteristics of the basin, several morphometric parameters were carefully calculated. These parameters are crucial for understanding the hydrological and geomorphological dynamics of the basin. Key parameters and their calculations include:

The basin area (A) was determined by aggregating the areas of all cells within the basin using the DEM. The perimeter (P) was calculated by summing the lengths of all boundary segments of the basin.

$$A = \sum(Cell\ area) \quad \text{………….}(1)$$

$$P = \sum(boundary\ length) \quad \text{………………..}(2)$$

The basin length (L_b) denotes the longest distance from the watershed outlet to the furthest point on the basin boundary, characterizing the basin's spatial extent. Stream order was determined using the Strahler method, which assigns an order of 1 to the smallest streams and increments the order at confluences of streams of the same order. For each stream order, the total stream length (L_u) was calculated by summing the lengths of all streams within that order. Drainage density (D_d) measures the total length of streams (L_u) per unit area (A) of the basin, offering insights into the density of the stream network within the basin.

$$D_d = \frac{L_u}{A} \text{………………..}(3)$$

These parameters are essential for comprehending water flow dynamics, sediment transport, flood risk assessment, and ecosystem management within the basin. Quantitative analysis of these parameters provides researchers with valuable insights into the basin's morphology, informing effective environmental and water resource management strategies.

4. Results and discussion

4.1. Elevation

The elevation analysis of the Udi, Ezeagu, and Ojir River Local Government Areas in Enugu revealed a diverse topographical landscape, with elevations ranging from 15 to 597 meters above sea level. This variation in elevation significantly influences the geological and hydrological characteristics of the watershed within the study area. The spatial distribution of elevation is illustrated in Figure 2, which provides a clear visual representation of the terrain.

The lower elevation zones, particularly those around 15 meters, are primarily located in the valleys and floodplains, where the terrain is relatively flat. These areas are likely to experience higher levels of water accumulation, making them susceptible to flooding, especially during the rainy season. The gentle slopes in these regions facilitate slow water movement, leading to increased infiltration rates, which can enhance groundwater recharge. However, this also poses challenges for flood management, as poor drainage in flat areas can exacerbate flood risks.

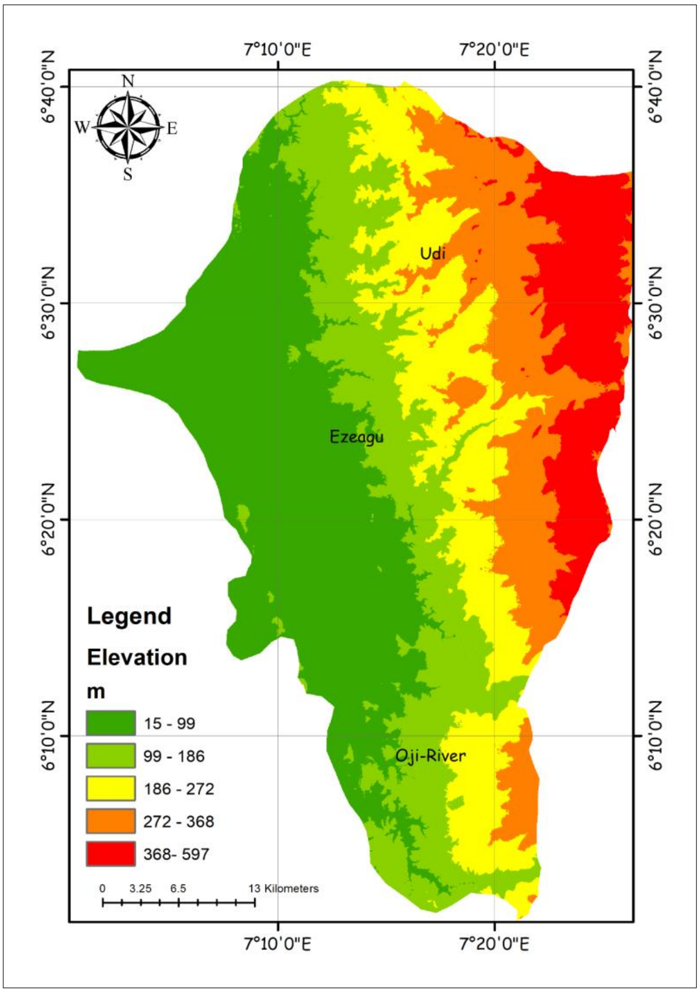

Figure 2 Spatial Distribution of Elevation in Udi, Ezeagu, and Ojir River Local Government Areas, Enugu

In contrast, the higher elevation areas, reaching up to 597 meters, are predominantly found in the Udi Hills and the surrounding highlands. These regions are characterized by steeper slopes, which promote rapid surface runoff and reduce the potential for water infiltration. The swift movement of water in these areas contributes to higher erosion rates, particularly during intense rainfall events. The erosion not only affects the stability of the landscape but also has implications for sediment transport, which can impact downstream water quality and reservoir siltation.

The elevation gradient across the study area creates a variety of microclimates, which influence vegetation patterns and soil development. The highlands, with their cooler temperatures and more significant rainfall, support dense vegetation that plays a crucial role in stabilizing the soil and reducing erosion. In contrast, the lower-lying areas, which may experience higher temperatures and more prolonged dry periods, support different vegetation types, potentially more sparse and less effective in erosion control.

From a watershed management perspective, the diverse elevation profile of Udi, Ezeagu, and Ojir River Local Government Areas requires tailored approaches to land use and water resource planning. In the lower elevation zones, efforts should focus on improving drainage infrastructure to mitigate flood risks and enhancing groundwater recharge through sustainable land management practices. In the higher elevation areas, erosion control measures, such as reforestation and the construction of terraces, are critical to preventing land degradation and maintaining soil fertility.

The findings from this elevation analysis also highlight the importance of integrating elevation data into the broader context of basin order, flow direction, and stream network analysis. The interplay between these factors can provide valuable insights into the movement of water within the watershed, the potential for erosion and sedimentation, and the overall sustainability of land use practices. Effective watershed management in this region will depend on a comprehensive understanding of these interactions and the implementation of strategies that address the unique challenges posed by the varying elevation.

4.2. Flow Direction

The flow direction analysis for the study area, covering Udi, Ezeogu, and Ojir River Local Government Areas in Enugu, reveals significant insights into the hydrological and geological characteristics of the watershed. The spatial distribution of flow direction, as depicted in Figure 3, illustrates the directional flow paths of surface water across the terrain. The flow direction categories (1, 2, 4, 8, 16, 32, 64, and 128) represent the eight possible flow directions, each corresponding to the steepest descent in elevation from a given cell within the watershed. These directions provide a clear understanding of how water navigates the landscape, from the headwaters to the downstream areas.

The flow direction map highlights the dominant pathways through which surface water travels, indicating the primary and secondary drainage channels within the watershed. The prevalence of certain flow direction categories suggests the presence of well-defined slopes and ridges that guide the water's movement. In Udi, the flow direction predominantly follows a southwest pattern, reflecting the area's topographical gradient. This directional flow contributes to the formation of stream networks that ultimately converge into larger rivers.

In Ezeogu, the flow direction is more varied, with significant portions of the watershed displaying a northeastward flow. This variation is indicative of a more complex terrain, with multiple ridges and valleys influencing the water's course. The diversity in flow direction in this area suggests potential challenges for water resource management, as the water's movement could lead to the formation of localized flood-prone areas, particularly during heavy rainfall events.

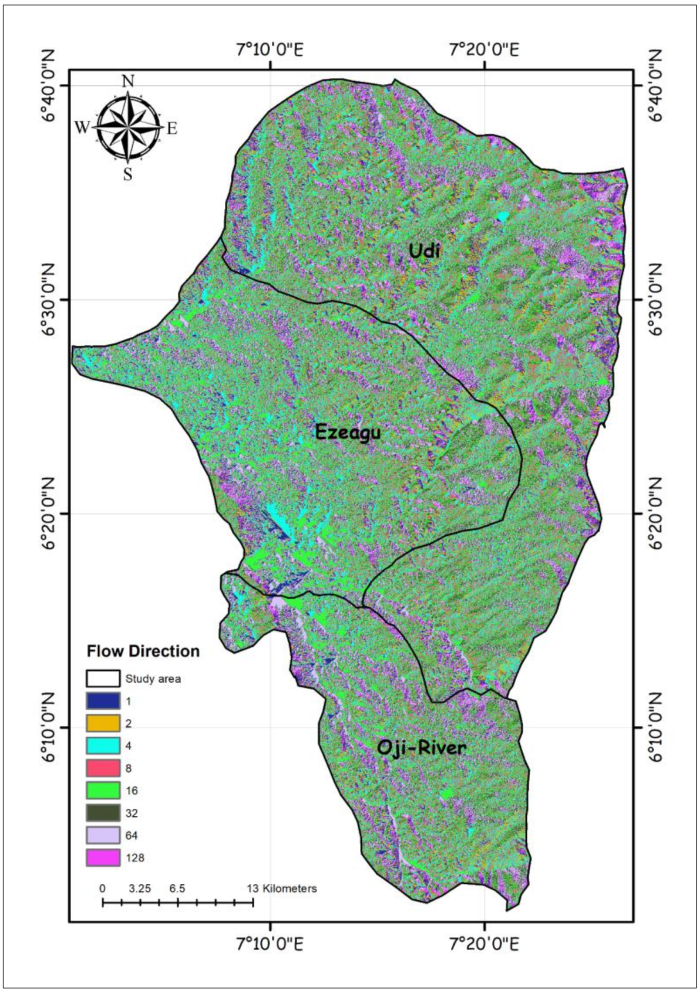

Figure 3 Spatial Distribution of Flow Direction in Udi, Ezeogu, and Ojir River Local Government Areas, Enugu

The Ojir River Local Government Area exhibits a strong eastward flow direction, which aligns with the natural slope of the land. This consistency in flow direction suggests a more straightforward drainage pattern, with fewer disruptions in the water's path. The uniformity of the flow direction in this region can facilitate more efficient water resource management, as the predictable flow paths allow for the effective planning of flood control measures and water conservation efforts.

The flow direction analysis also provides insights into the underlying geological features of the study area. The alignment of flow paths with specific directions often correlates with the geological structures, such as faults, fractures, or bedrock variations. In Udi, the southwest flow direction may be influenced by the presence of underlying geological formations that channel water along specific lines of weakness in the rock. This could indicate the presence of fault lines or fractures that guide the water's movement, contributing to the development of the region's drainage network.

In Ezeogu, the varied flow directions suggest a more heterogeneous geological landscape, where different rock types or structural features interact to create a complex drainage pattern. The northeastward flow in certain areas may be influenced by the orientation of bedrock layers or the presence of resistant rock formations that divert the water's course. Understanding these geological influences is crucial for predicting areas of erosion or sediment deposition, which can impact land use planning and infrastructure development.

4.3. Basin Analysis

The analysis of basin orders across the study area reveals significant insights into the hydrological and geomorphological characteristics of the region. The basin orders were grouped into five distinct categories based on the observed hierarchical progression as shown in Figure 4. The implications of these groupings provide a comprehensive understanding of the landscape's drainage pattern and potential environmental management strategies.

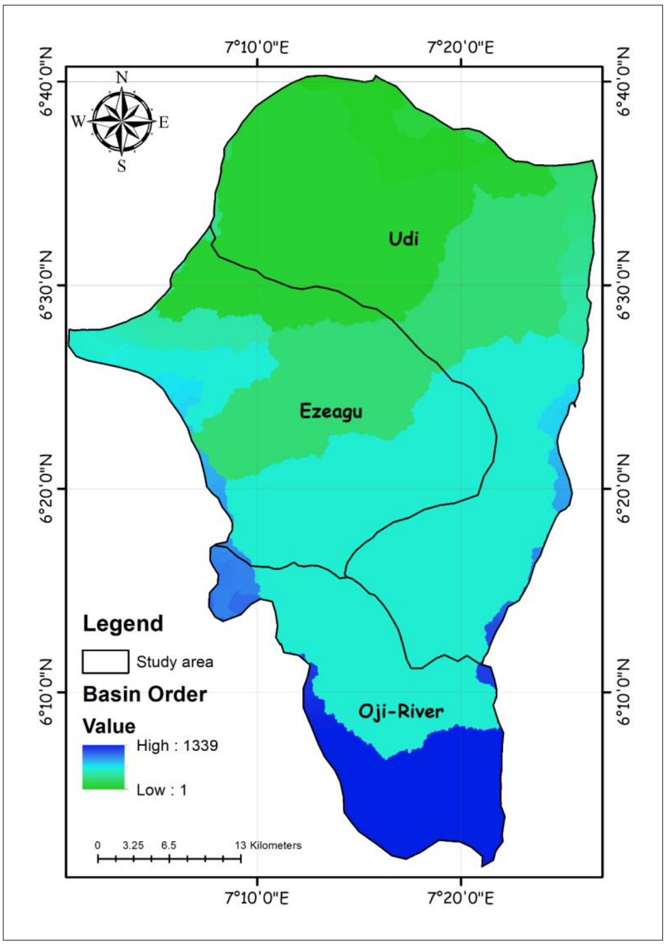

Figure 4 Spatial map of basin order distribution in the study area

Basin orders within this group represent the most fundamental and initial stages of stream development. These low-order basins are typically characterized by narrow and steep channels, often found in the headwaters or upland areas. The dominance of overland flow and limited channelization indicates a region with higher surface runoff potential and low infiltration rates. This group is crucial in understanding flood generation, as these basins contribute significantly to peak flows during storm events. Environmental management in these areas should focus on erosion control and maintaining vegetation cover to reduce surface runoff and soil loss.

The moderate-low basin orders reflect a transitional stage where tributaries begin to coalesce, forming more defined and interconnected drainage networks. The stream channels in these basins are more established, with increased channel length and moderate slopes. This group often represents the mid-sections of watersheds, where a balance between surface runoff and infiltration is observed. The implications of this group are particularly relevant for water resource management, as these basins play a significant role in groundwater recharge. Conservation efforts in these areas should aim at maintaining the natural flow regime and preventing excessive land-use changes that could alter the hydrological balance.

Moderate basin orders are indicative of more mature drainage systems, with well-developed channels and an extensive network of tributaries. These basins typically cover larger catchment areas and are associated with moderate relief. The streams within this group exhibit a more complex flow pattern, often showing signs of meandering and sediment transport. The hydrological implications include a greater capacity for flood attenuation, as the expanded network allows for more efficient water conveyance. However, these basins are also more susceptible to sediment deposition and channel modification, which can impact water quality and habitat integrity. Therefore, sediment management and stream restoration practices are critical in these areas to maintain ecological balance.

Basins within the moderate-high order group exhibit advanced drainage development, often encompassing broad valleys and lowland areas. These basins have extensive networks with multiple tributaries, resulting in a more distributed flow regime. The hydrological characteristics of these basins include increased base flow contribution, reflecting a higher degree of groundwater interaction. The management implications for these basins involve maintaining water quality and ensuring the sustainability of aquatic habitats. Since these areas are more prone to human activities due to their accessible location, integrated watershed management practices are essential to balance development and environmental preservation.

The high basin orders represent the most complex and mature drainage systems within the study area. These basins often include the mainstem rivers with extensive floodplains and are characterized by high stream order and large drainage areas. The flow dynamics in these basins are dominated by base flow, with a significant contribution from groundwater. These basins are crucial for regional water supply and flood regulation. The implications of findings in this group highlight the importance of large-scale river basin management, focusing on floodplain conservation, water resource allocation, and habitat protection. The high connectivity within these basins makes them vital for maintaining regional hydrological stability.

The grouping of basin orders into these five categories provides a nuanced understanding of the study area's drainage characteristics and their environmental implications. Each group exhibits distinct hydrological behaviors, necessitating tailored management strategies to address specific challenges such as flood control, water quality maintenance, and ecological preservation. By recognizing the varying characteristics across basin orders, more effective and sustainable watershed management practices can be developed to support the long-term environmental health of the region.

4.4. Stream Network

The stream network analysis for the Udi, Ezeogu, and Ojir River Local Government Areas in Enugu has revealed significant insights into the hydrological characteristics of the watershed. The stream segments were categorized into five groups based on their connectivity and flow patterns, each representing distinct hydrological behavior and implications for watershed management.

Headwater Streams, located primarily in the upper elevations of the study area, exhibit characteristics typical of first-order streams. They are the initial channels formed by surface runoff and are critical for groundwater recharge and sediment transport. The analysis of these headwater streams highlights their role in maintaining base flow during dry seasons. However, their sensitivity to land use changes and deforestation poses a risk to the watershed's hydrological balance. Conservation of these headwater regions is vital for sustaining the overall health of the watershed, as they contribute to the downstream flow and water quality.

Mid-Elevation Streams in this group are situated in the mid-elevation areas and serve as crucial connectors between the headwater streams and the larger river systems. These streams display a moderate gradient, which influences the flow velocity and sediment transport capacity. The mid-elevation streams are often subject to seasonal variations in flow, which can lead to erosion and sediment deposition in the downstream areas. The findings suggest that these streams play a significant role in buffering the impacts of heavy rainfall, but they also require careful management to prevent erosion and maintain water quality.

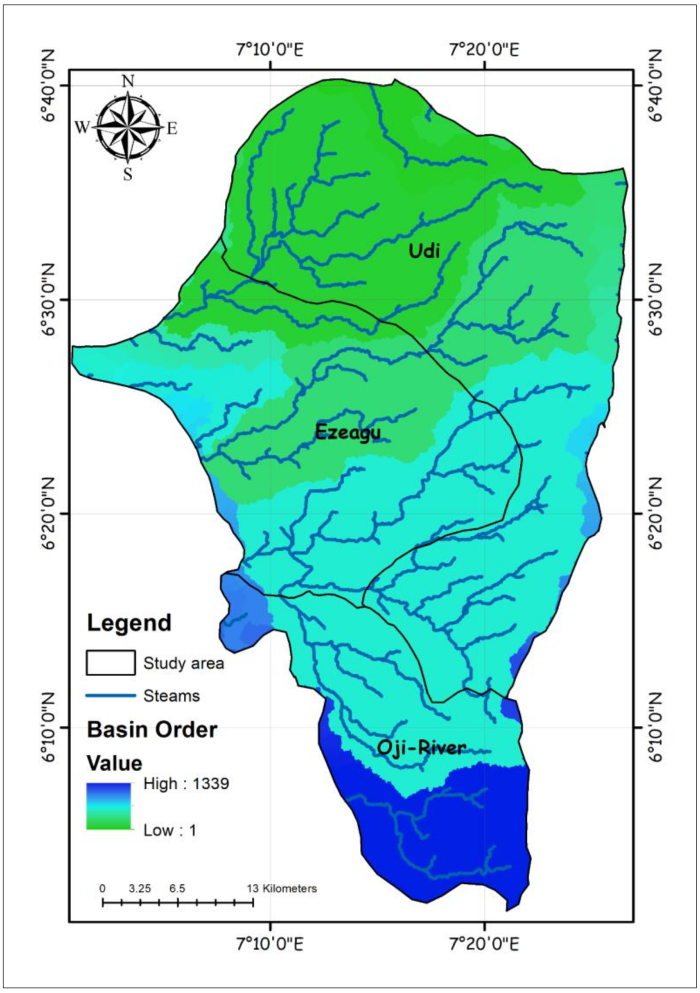

Figure 5 Spatial Distribution of Stream Networks in Udi, Ezeogu, and Ojir River Local Government Areas

Main River Channels in this group represent the primary river channels within the watershed, including the Ezeogu and Ojir rivers. These are higher-order streams that integrate flow from the upstream networks and have a significant influence on the overall hydrological dynamics of the region. The spatial analysis indicates that these rivers are prone to seasonal flooding, particularly during intense rainfall events. Effective flood management strategies, such as the development of riparian buffers and floodplain restoration, are essential to mitigate the impacts of flooding on surrounding communities and agricultural lands.

Confluence Zones includes streams located at the confluence points where smaller streams merge into larger channels. The confluence zones are identified as critical points for sediment accumulation and nutrient exchange. These areas often experience higher flow velocities, which can lead to scouring and bank erosion if not properly managed. The study suggests that these zones are crucial for maintaining the connectivity of the watershed and ensuring the continuous flow of water and nutrients downstream. Implementing erosion control measures and maintaining vegetation cover in these areas are recommended to reduce the risk of degradation.

The downstream tributaries are located near the lower elevations of the watershed, where the streams begin to flatten and widen as they approach the main river outlets. These streams are characterized by slower flow rates and increased sediment deposition. The analysis indicates that these areas are particularly vulnerable to pollution from agricultural runoff and urban development. The results emphasize the need for integrated land use planning and pollution control strategies to protect these tributaries from contamination and ensure the sustainability of water resources in the lower watershed.

The spatial distribution and characteristics of the stream groups in the study area provide valuable insights into the hydrological processes governing the watershed. The findings underscore the importance of preserving the natural flow regime and maintaining the ecological integrity of the stream network. By understanding the relationship between basin order, elevation, flow direction, and stream characteristics, watershed managers can develop targeted interventions to address specific challenges such as erosion, flooding, and water quality degradation.

The study highlights the need for comprehensive watershed management practices that take into account the unique hydrological characteristics of each stream group. For instance, protecting headwater streams from deforestation and land use changes will help sustain base flows and water quality in the downstream areas. Similarly, managing the confluence zones to reduce erosion and sediment accumulation will enhance the overall resilience of the watershed.

Furthermore, the results suggest that sustainable land use planning should prioritize the conservation of riparian zones and the implementation of best management practices to reduce the impact of agricultural and urban development on the stream network. This approach will not only protect the water resources but also support the long-term ecological health of the watershed.

5. Conclusion

The elevation analysis of Udi, Ezeagu, and Ojir River Local Government Areas in Enugu reveals a topographically diverse landscape, with elevations ranging from 15 to 597 meters above sea level. Lower elevation zones, found in valleys and floodplains, are prone to water accumulation and flooding, particularly during the rainy season. These areas experience slow water movement, enhancing groundwater recharge but posing flood management challenges. In contrast, the higher elevations, especially in the Udi Hills, are characterized by steep slopes that facilitate rapid runoff, leading to higher erosion rates and sediment transport. The variation in elevation across the study area creates distinct microclimates, influencing vegetation patterns and soil stability.

Flow direction analysis uncovers the primary and secondary drainage pathways, indicating how water navigates the terrain. In Udi, water predominantly flows southwest, forming well-defined stream networks, while Ezeagu exhibits more varied flow directions due to its complex terrain. Ojir River Local Government Area shows a strong eastward flow, reflecting a straightforward drainage pattern.

The basin order and stream network analyses further highlight the watershed's hydrological complexity. Lower-order basins, crucial for understanding flood generation, dominate the upland areas, while higher-order basins in lowland regions are vital for flood regulation and water resource management. The stream network analysis identifies the critical roles of headwater streams, mid-elevation connectors, and main river channels in maintaining the watershed's ecological integrity.

Effective watershed management in this region requires tailored strategies for different elevation zones. Enhancing drainage infrastructure in lowlands, implementing erosion control in highlands, and protecting headwater streams from deforestation are critical measures to ensure long-term environmental sustainability.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] Abdramane, D., Xiufen, Y., & Amadou, T. (2018). The Detection of Flow Directions of Surface Waters using ArcMap. https://doi.org/10.1109/icma.2018.8484708

[2] Akaolisa, C. C., Agbasi, O. E., Etuk, S. E., Adewumi, R., & Okoli, E. A. (2023). Evaluating the Effects of Real Estate Development in Owerri, Imo State, Nigeria: Emphasizing Changes in Land Use/Land Cover (LULC). Journal of Landscape Ecology, 16(2), 98–113. https://doi.org/10.2478/jlecol-2023-0012

[3] Amah, J. I., Aghamelu, O. P., Omonona, O. V., Onwe, I. M., & Agbi, I. O. (2021). Analysis of the impacts of hydrology, soil properties, and geotechnics on gully propagation on the Edda-Afikpo Mesas of the Lower Cross River watershed (southeastern Nigeria). Journal of African Earth Sciences, 174, 104074. https://doi.org/10.1016/j.jafrearsci.2020.104074

[4] Angelina, A., Djibo, A. G., Seidou, O., Sanda, I. S., & Sittichok, K. (2015). Changes to flow regime on the Niger River at Koulikoro under a changing climate. Hydrological Sciences Journal, 60(10), 1709–1723. https://doi.org/10.1080/02626667.2014.916407

[5] Aziz, N. A., Alwan, I. A., & Agbasi, O. E. (2023). Integrating remote sensing and GIS techniques for effective watershed management: a case study of Wadi Al-Naft Basins in Diyala Governorate, Iraq, using ALOS PALSAR digital elevation model. Applied Geomatics, 16(1), 67–76. https://doi.org/10.1007/s12518-023-00540-9

[6] Choudhary, S., Jangeed, D., Sharma, S., Chaudhary, M., Gupta, P., & Pandey, P. (2023). Assessment of Under Ground Water Resources through RS and GIS Techniques. IOP Conference Series Earth and Environmental Science, 1279(1), 012010. https://doi.org/10.1088/1755-1315/1279/1/012010

[7] Egbueri, J. C., & Igwe, O. (2020). The impact of hydrogeomorphological characteristics on gullying processes in erosion-prone geological units in parts of southeast Nigeria. Geology Ecology and Landscapes, 5(3), 227–240. https://doi.org/10.1080/24749508.2020.1711637

[8] Eludoyin, A. O., & Adewole, A. O. (2019). A remote sensing-based evaluation of an ungauged drainage basin in Southwestern Nigeria. International Journal of River Basin Management, 18(3), 307–319. https://doi.org/10.1080/15715124.2019.1640226

[9] Gabriel, A. T., Yusuf, M. B., Bwadi, B. E., & Clement, Y. G. (2020). Morphometric Analysis and Flash Floods Assessment of River Taraba Basin in Taraba State, Nigeria. European Scientific Journal ESJ, 16(20). https://doi.org/10.19044/esj.2020.v16n20p158

[10] Hooke, J. M. (2022). Morphodynamics of a meandering channel over decadal timescales in response to hydrological variations. Earth Surface Processes and Landforms, 47(8), 1902–1920. https://doi.org/10.1002/esp.5354

[11] Huang, P. C., & Lee, K. T. (2021). Influence of topographic features and stream network structure on the spatial distribution of hydrological response. Journal of Hydrology, 603, 126856. https://doi.org/10.1016/j.jhydrol.2021.126856

[12] Kudamnya, E. A., Edet, A., & Ekwere, A. S. (2021). Analysing principal components of physiographic factors affecting groundwater occurrences within Keffi, North-Central Nigeria. The Egyptian Journal of Remote Sensing and Space Science, 24(3), 665–674. https://doi.org/10.1016/j.ejrs.2021.08.005

[13] Lamine, B., Ferreira, V., Yang, Y., Ndehedehe, C., & He, X. (2021). Estimation of the Niger River cross-section and discharge from remotely-sensed products. Journal of Hydrology Regional Studies, 36, 100862. https://doi.org/10.1016/j.ejrh.2021.100862

[14] Marlim, M. S., & Kang, D. (2020). Identifying Contaminant Intrusion in Water Distribution Networks under Water Flow and Sensor Report Time Uncertainties. Water, 12(11), 3179. https://doi.org/10.3390/w12113179

[15] Nebeokike, U. C., Igwe, O., Egbueri, J. C., & Ifediegwu, S. I. (2020). Erodibility characteristics and slope stability analysis of geological units prone to erosion in Udi area, southeast Nigeria. Modeling Earth Systems and Environment, 6(2), 1061–1074. https://doi.org/10.1007/s40808-020-00741-w

[16] Nwankwo, C. N., & Ene, E. C. (2020). Structural Investigation of Udi LGA of Enugu State, South Eastern Nigeria Using High Resolution Bouguer Gravity and Landsat Data. Asian Journal of Research and Reviews in Physics, 17–32. https://doi.org/10.9734/ajr2p/2020/v3i130112

[17] Obeidat, M., Awawdeh, M., & Al-Hantouli, F. (2021a). Morphometric analysis and prioritisation of watersheds for flood risk management in Wadi Easal Basin (WEB), Jordan, using geospatial technologies. Journal of Flood Risk Management, 14(2). https://doi.org/10.1111/jfr3.12711

[18] Obeidat, M., Awawdeh, M., & Al-Hantouli, F. (2021b). Morphometric analysis and prioritisation of watersheds for flood risk management in Wadi Easal Basin (WEB), Jordan, using geospatial technologies. Journal of Flood Risk Management, 14(2). https://doi.org/10.1111/jfr3.12711

[19] Okoli, E., Akaolisa, C. C. Z., Ubechu, B. O., Agbasi, O. E., & Szafarczyk, A. (2024). Using VES and GIS-Based DRASTIC Analysis to Evaluate Groundwater Aquifer Contamination Vulnerability in Owerri, Southeastern Nigeria. Ecological Questions, 35(3), 1–27. https://doi.org/10.12775/eq.2024.031

[20] Olla, O. O., Adeniran, K. A., Kasali, M. Y., & James, D. (2020). Determination of Physiographic Characteristics of an Ungauged Watershed in North Central Nigeria. IOP Conference Series Earth and Environmental Science, 445(1), 012026. https://doi.org/10.1088/1755-1315/445/1/012026

[21] Olusola, A., Fashae, O., Onafeso, O., & Adelabu, S. (2020). Morphologic and hydraulic variability of small bedrock and alluvial channels in relation to lithological controls, Upper Ogun River Basin, Southwestern Nigeria. Physical Geography, 41(6), 537–557. https://doi.org/10.1080/02723646.2020.1764168

[22] Rocha, J., Duarte, A., Silva, M., Fabres, S., Vasques, J., Revilla-Romero, B., & Quintela, A. (2020). The Importance of High Resolution Digital Elevation Models for Improved Hydrological Simulations of a Mediterranean Forested Catchment. Remote Sensing, 12(20), 3287. https://doi.org/10.3390/rs12203287

[23] Sajadi, P., Singh, A., Sang, Y. F., Mukherjee, S., & Chapi, K. (2021). "Assessing the key drivers of stream network configuration dynamics for tectonically active drainage basins using multitemporal satellite imagery and statistical analyses." Geocarto International, 37(14), 4108–4140. https://doi.org/10.1080/10106049.2021.1871668

[24] Umegbolu, E. I. (2018). Fate of e-waste in households in Enugu West Senatorial District of Enugu State, Southeast Nigeria. International Journal of Community Medicine and Public Health, 5(10), 4200. https://doi.org/10.18203/2394-6040.ijcmph20183954

[25] Varado, N., Braud, I., Galle, S., Lay, M. L., Séguis, L., Kamagate, B., & Depraetere, C. (2006). Multi-criteria assessment of the Representative Elementary Watershed approach on the Donga catchment (Benin) using a downward approach of model complexity. Hydrology and Earth System Sciences, 10(3), 427–442. https://doi.org/10.5194/hess-10-427-2006

[26] Yin, C., Chen, S., & Yin, Z. (2023). Clustering-based Active Learning Classification towards Data Stream. ACM Transactions on Intelligent Systems and Technology, 14(2), 1–18. https://doi.org/10.1145/3579830