**Communication in Physical Sciences, 2026, 13(5):800-825**

# A Multi-criteria Decision using the Analytical Hierarchy Process (AHP) for Delineation of Groundwater Potential Zones in Part of the Obudu-Massif, Nigeria

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**Received: 21 January 2026/Accepted: 05 May 2026/Published: 14 May 2026**

https://doi.org/10.4314/cps.v13i5.10

***Abstract:*** *Groundwater occurrence in crystalline basement terrains is strongly controlled by lithology, structural features, topography, and climatic conditions. This study evaluated groundwater potential zones (GWPZ) in parts of the Obudu Massif, Southeastern Nigeria, Using an integrated Geographic Information System (GIS) and Analytical Hierarchy Process (AHP) approach. Eight groundwater conditioning factors, namely lithology, lineament density, drainage density, precipitation, elevation, slope, aspect, and curvature, were analyzed and weighted through pairwise comparison with the AHP framework. The resulting consistency ratio (CR) of 0.071 indicated acceptable consistency in the weighting process. The analysis revealed that geology/lithology (42.6%) and lineament density (18.6%) exert the greatest influence on groundwater occurrence, followed by drainage density (12.5%) and slope (10.5%). The groundwater potential map produced, delineated the study area into three classes: low high and very high GWPZs. Raster pixel interpretation showed that high GWPZ cover approximately 119 km$^2$ (49.3%) of the study area, while very high GWPZ occupy about 30km$^2$ (12.3%). Low GWPZ account for 92 km$^2$ (38.4%). Areas with very high groundwater potential are mainly concentrated within the central-southern and southeastern portions of the study area, where favorable lithologic and structural conditions enhance groundwater recharge and storage. A strong positive agreement between intermediate-to-high transmissivity values obtained from pumping-test data and the mapped high-to-very-high groundwater potential zones confirmed the reliability of the model. The high to very high GWPZs were considered indicative of the model accuracy. The study demonstrates that the integration of GIS, remote sensing, and AHP provides a reliable and cost-effective approach for groundwater exploration, borehole siting, and sustainable groundwater resource management in crystalline basement terrains.*

***Keyword:*** *Groundwater, geographic information system, analytical hierarchy process, thematic, Obudu-Massif*

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## 1.0 Introduction

Groundwater is an essential natural resource that provides a reliable and sustainable source of drinking water in both urban and rural areas. The presence of sufficient quantity and quality of water resources, as well as their seasonal fluctuations for drinking, household, and agricultural purposes, influences the economic and social growth of any community (Ochelebe & Kudamnya, 2022; Kudamnya *et al.*, 2026c). However, rapid population growth, urbanization, and agricultural expansion have significantly increased the demand for available freshwater resources, thereby placing considerable pressure on existing groundwater reserves. Therefore, it is crucial to continually assess the occurrence of this resource, in order to guarantee its sustainability and proper management (Kudamnya *et al.*, 2019). In many communities, the scarcity of perennial streams and rivers, coupled with inadequate water infrastructure and poor sanitary conditions, has resulted in increased dependence on groundwater as the primary source of potable water. Groundwater resources are harnessed for use of hydraulic structures such as hand-dug well and borehole. However, in most communities, these hydraulic structures are not effectively managed and sustained and have not been able to adequately satisfy the purpose they were designed and constructed. Reasons attributed for this include limited knowledge and understanding of the structural, hydrogeological, hydrological and geomorphological conditions of the basement terrain; technical issues arising from the absence of, or sometimes poor field investigation; inadequate interpretation skills particularly of the modern field equipment and the use of sub-standard accessories, according to Kudamnya *et al.* (2017); Ige *et al.* (2021). These challenges frequently result in borehole failures, low-yielding wells, and inefficient utilization of available groundwater resources, particularly within crystalline basement terrains.

Globally, governments, non-governmental organizations (NGOs), and international development agencies invest substantial resources in groundwater development projects aimed at improving access to safe drinking water and enhancing water security (Njock *et al.*, 2025). In fact, cities in the United States of America (U. S. A.) such as New York, Las Vegas, California and Arizona in the USA are making major investments to channel water supplies from several kilometres away (Have *et al.*, 2026) through conduits and pipes. The amount of groundwater depends on the nature, condition of the aquifer and groundwater recharge (Megahed, *et al.*, 2023; Savelli *et al.*, 2023; Jasechko *et al.*, 2024). Factors such as soil sealing, vegetation removal, and drainage systems often limit groundwater recharge and infiltration capacity in urban areas (El-Farchouni *et al.*, 2025), whereas this is not the case in most rural communities and farmlands. In such areas, groundwater recharge is unhindered, since the impact of development is less compared to the urban areas.

Studies have shown that the presence of groundwater in a specific area is influenced by various factors, including the lithological variations beneath the surface, structural characteristics, landforms, slope, rainfall trends, vegetation cover, soil characteristics, land-use patterns, and climatic condition (Senthil-Kumar and Shankar, 2014; Kudamnya *et al.*, 2021; Have *et al.*, 2026). Therefore, it is essential to collect data about groundwater presence through scientifically proven method during its exploration. In Nigeria, for example, the scarcity of funding and resources has created significant barriers to carrying out site investigations prior to drilling water wells. Conventional geological, hydrogeological, and geophysical techniques have been utilized to explore and pinpoint groundwater locations, but these methods are often lengthy and expensive to execute efficiently (Kudamnya *et al.*, 2019).

Groundwater has been successfully mapped and delineated using conventional methods such as field-based geological and hydrogeological techniques (Huntoon, 1970; Edet *et al.*, 1994), geophysical techniques (Kudamnya and Osumeje, 2015; Osumeje *et al.*, 2023; Oyeyemi *et al.*, 2024) and remote sensing with GIS techniques (Kudamnya *et al.*, 2021; Li *et al.*, 2023; Have *et al.*, 2026). These techniques are often costly and time-consuming (Li *et al.*, 2023).

Several studies have demonstrated the effectiveness of integrating remote sensing, GIS, and multi-criteria decision-making techniques for groundwater potential mapping. For instance, Rahmati et al. (2014) and Pinto et al. (2017) successfully applied AHP-based models to delineate groundwater potential zones in hard-rock terrains. Similarly, Li et al. (2023) reported that GIS-AHP integration significantly improved groundwater prediction accuracy by combining hydrogeological and geomorphological parameters. Despite these successes, many studies have focused primarily on generating groundwater potential maps without validating the results using field-derived hydraulic parameters such as transmissivity and borehole yield. Although several groundwater investigations have been conducted within southeastern Nigeria using geological, hydrogeological, and geophysical approaches, comprehensive groundwater potential mapping studies integrating GIS, remote sensing, and AHP techniques remain limited in the Obudu Massif. Furthermore, available studies have not adequately incorporated pumping-test validation to assess the reliability of groundwater potential models in the area.

Remote sensing is an important source of data in the fields of geo-information mapping and is also timely and cost-effective manner (Swetha *et al.*, 2017). Therefore, research on groundwater potential zones is important, as it provides information about the geospatial distribution of groundwater (Naeem *et al.*, 2024). These insights are crucial to effective groundwater management, ensuring the sustainability of aquifers and ecosystem health, and the resilience of those communities that rely so heavily on these precious sources of water. Accurate mapping and modeling of groundwater potential recharge zones depend on understanding the factors that influence groundwater recharge.

The analytical hierarchy process (AHP) comprises both descriptive and quantitative phases based on a scale, ultimately producing a binary matrix as its final output (Saaty, 1980; Ardakani and Ekhesasi, 2016). Relative priorities or weightings for the criteria are derived through binary comparisons, which can be made verbally, numerically, or visually. AHP facilitates collective decision-making, allowing planners to deconstruct a problem into a hierarchical format for resolution (Razandi *et al.*, 2015). In the context of groundwater exploration, AHP assigns varying weightings to factors impacting groundwater, in conjunction with remote sensing and GIS technologies, to evaluate potential groundwater zones (Zeinolabedini and Esmaeily, 2015). AHP systematically identifies the key factors influencing groundwater (Rahmati *et al.*, 2014; Pinto *et al.*, 2017). Mahalingam *et al.* (2014) applied AHP to assign weights to groundwater control factors, which were then overlaid in ArcGIS to generate a map indicating groundwater potential. The results showed alignment with the analysis of collected sample data. AHP has been utilized in research related to natural disasters and construction for the purpose of rapidly comparing alternatives for decision-making (Ocul and Sisman 2023; Sari and Sari 2021; Ciftci and Kusak 2021). An advantage of AHP compared to other methodologies is that the consistency of the assigned weights can be statistically analyzed, and any mistakes can be rectified (Silwal and Pathak 2018). Using AHP enables the assessment of the relative importance of thematic layers for gauging groundwater potential. However, despite its benefits, AHP requires a complex data analysis process that demands expertise in quantifying the impact of various factors on groundwater potential compared to other methods (Sikakwe *et al.*, 2024).

Groundwater exploration in Nigeria often suffers due to limited data, inadequate integration of influencing factors, and over-reliance on traditional methods. The Obudu Massif, is a region characterized by rugged terrain, variable rainfall, and complex geology, exemplifies these challenges. Despite the Massif's importance for communities and agriculture, its groundwater potential remains poorly mapped and under-utilized. Advanced spatial analysis methods such as the Analytical Hierarchy Process (AHP) allow studies to weigh multiple parameters like slope, land use, lineament density, and geology to generate reliable groundwater potential maps. Applying AHP in the Obudu Massif will provide a scientific basis for groundwater development, reduce drilling failures, and support rural water supply initiatives. The development of a reliable groundwater potential map is essential for reducing the cost and uncertainty associated with groundwater exploration. Such information can support sustainable groundwater development, improve borehole success rates, guide water-resource planning, and enhance access to potable water for rural communities within the Obudu Massif and similar crystalline basement environments. Therefore, this study aims to delineate groundwater potential zones within part of the Obudu Massif, Southeastern Nigeria, using an integrated GIS-based Analytical Hierarchy Process (AHP) approach and to validate the resulting groundwater potential map using pumping-test-derived transmissivity data. The integration of remote sensing, GIS, and multi-criteria decision-making techniques provides an efficient framework for groundwater assessment in data-scarce regions. By incorporating both environmental conditioning factors and field validation data, this study contributes to the growing body of knowledge on groundwater exploration within crystalline basement terrains and provides a decision-support tool for sustainable water-resource management in southeastern Nigeria**.**

## 1.1 The study area

### *1.1.1 Description of the study area*

The area under investigation is part of the Obudu Massif, located on the Oshie Ridge of the Sankwala Mountain range, in Cross River State, Southeast Nigeria. The study area lies approximately between latitudes 6°25′N to 6°41′N and longitudes 8°55′E to 9°11′E (Fig. 1). It is bordered by the Benue lowlands to the north and the Cross River plains to the south (Kudamnya ***et al.***, 2025). Major access routes to the study area include the Obudu–Obanliku road network, which connects the area to Ogoja and other nearby towns. The area is accessible by paved and unpaved roads, with several rural communities dispersed all around.

The area has a tropical climate with distinctive wet and dry seasons. The wet season is from the months of April to October with annual rainfall greater than 2000 mm (Kudamnya *et al.*, 2026a, b). The average annual temperature is approximately 26°C, while the average relative humidity exceeds 80%. (Sikakwe ***et al.***, 2024). The study lies within the forested zone with flourishing rainforest, also having less dense and more open vegetation reflecting the savannah type of vegetation. The relief is high and characterized by isolated highlands. The terrain is rugged, characterized by pronounced relief and elevations ranging from approximately 183 m in lowland areas to over 1,500 m above sea level within the highland sections. The dry season last from November to March when there is extreme harsh weather condition and the wet season is from April to October. Obudu highland is at an elevation ranging between 1500 and 2000 m above sea level (Sikakwe ***et al.***, 2024).

### *1.1.2 Geologic settings*

The area is underlain by Precambrian crystalline basement rocks. The Obudu Massif forms part of the Bamenda Massif in Cameroon, which consists of banded gneisses and schists, amphibolite, charnokite, dolerite, and dunite, with intrusions of basic, ultrabasic, and acidic rocks in the southern part of the Massif. The gneisses and schists are of magmatic origin and have reached the granulite facies indicating high-grade metamorphism (Ekwueme, 1990). There is evidence of tectono-thermal activity that has impacted the Nigerian basement rocks as a result of the Pan African Orogeny (Omang ***et al.***, 2025). This orogenic event resulted in the development of fractures, faults, and dykes oriented in North-South, NE-SW, and NW-SE directions (Ekwueme, 1994). Gneisses and schists are also prevalent in the Precambrian basement of Cameroon (Collingnon, 1968).

These gneisses and schists lie beneath Tertiary to recent alkaline volcanic formations, associated with significant regional uplift of the basement.


**Figure 1: Location map of the study**

### *1.1.3 Hydrogeology*

A study by Okereke ***et al.*** (1998), based on drilled boreholes and geophysical data, indicates a weathered basement layer interspersed with clay above it. Also, aquifers in Obudu are overlaid by a thin layer of overburden, contrasting with the thick overburden found in the basement complex of the Oban Massif in southeastern Nigeria (Edet *et al.* 1994). The occurrence of thin overburden materials suggests the presence of shallow aquifer systems that are highly vulnerable to contamination from anthropogenic activities, including indiscriminate waste disposal and agricultural practices. The hydraulic parameters reveal that borehole depths in parts of Obudu range from 6 to 36 m, while the static water levels fluctuate between 1.3 and 14.5 m. The estimated overburden thickness varies from 3.11 to 34.20 m (Okereke ***et al.***, 1998).

## 2.0 Methodology

### *2.1 Data sources, Image Acquisition and Processing*

The delineation of groundwater potential zones in parts of the Obudu Plateau was carried out using a multi-criteria decision analysis (MCDA) approach integrated with Geographic Information System (GIS) techniques. Eight groundwater conditioning factors, namely lithology, lineament density, drainage density, precipitation, elevation, slope, aspect, and curvature, were selected based on their recognized influence on groundwater occurrence, recharge, storage, and movement within crystalline basement terrains. A 30-m Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) obtained from the United States Geological Survey (USGS) was used to derive elevation, slope, aspect, curvature, drainage density, and lineament density maps.

The selected groundwater conditioning factors were converted into thematic raster layers using ArcGIS 10.7. Each factor was classified into groundwater suitability classes based on its relative influence on groundwater occurrence. The classes were assigned ranks ranging from 1 to 5, where higher values represented greater groundwater potential. The classification criteria were based on published hydrogeological studies and the local geological characteristics of the study area.

Thermal Emission and Reflection Radiometer (ASTER) at 30 m resolution, and gridded precipitation data. Lithological information of the study area was extracted from the geological map of Nigeria, while lineaments were mapped from enhanced satellite imagery using directional filtering and visual interpretation using ArcGIS 10.7. A Shuttle Radar Topography Mission (SRTM) DEM with appropriate spatial resolution was used to derive topographic parameters, including elevation, slope, aspect, curvature, drainage density, and lineament density. Long-term mean annual precipitation data were obtained from gridded climate datasets and interpolated to match the spatial resolution of other thematic layers. All datasets were projected to a common coordinate system and resampled to uniform grid resolution before analysis.

### *2.2 Analytical Hierarchy Process (AHP)*

ArcGIS 10.7 software was used to extract and assess thematic maps for the following variables: lithology, lineament density, drainage density, precipitation, elevation, slope, aspect, and curvature. Each of the thematic maps produced is classified into regions and weighted for each class obtained. The Analytical Hierarchy Process (AHP) was employed to determine the relative importance of the groundwater conditioning factors. A pairwise comparison matrix was constructed using Saaty's nine-point scale (as shown below), where each factor was compared against others based on their influence on groundwater occurrence in the study area. The normalized principal eigenvector of the matrix was used to derive factor weights.

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \quad (1)$$

where, $a_{ij}$ represents the relative importance of factor iii over factor j

Consistency of the pairwise judgments was evaluated using the Consistency Index (CI) and Consistency Ratio (CR). A CR value less than 0.1 was considered acceptable, indicating logical consistency in the comparisons. CR is assessed by the expression:

$$CI = \frac{\lambda_{max} - n}{n-1} \quad (2)$$

$$CR = \frac{CI}{RI} \quad (3)$$

where, n is the number of criteria, $\lambda_{max}$ is the maximum eigen value, RI is the Random index. Finally, the groundwater potential map of the study area is created by overlay weighted analysis using the ranking values entered into the ArcGIS 10.7.

## 3.0 Results and Discussions

### *3.1 Results*

The results of the Analytical Hierarchy Process (AHP), including the pairwise comparison matrix, criterion weights, ranking of groundwater conditioning factors, and principal eigenvector solution, are presented in Tables 1–3. These results provide the basis for evaluating the relative influence of each thematic layer on groundwater occurrence within the study area.

The consistency ratio (CR) of 0.071 is less than the acceptable threshold value of 0.10 recommended by Saaty (1980), indicating that the pairwise comparisons are logically consistent and that the derived weights are reliable for groundwater potential modelling.

The AHP weighting results indicate that lithology exerts the strongest control on groundwater occurrence, accounting for 42.6% of the total influence. This reflects the importance of rock type, weathering characteristics, and fracture development in controlling groundwater storage within crystalline basement terrains. Lineament density ranked second (18.6%), highlighting the role of fractures and structural discontinuities in enhancing secondary porosity and groundwater movement. Drainage density (12.5%) and slope (10.5%) also exhibited considerable influence, whereas aspect (2.2%) and curvature (3.2%) contributed relatively little to groundwater occurrence.

**Table 1: Pairwise comparison decision**

| Prec. | Elev. | Slp. | D.D. | Geol. | Lin. | Asp. | Curv. |
|---|---|---|---|---|---|---|---|
| **1.00** | 0.33 | 0.25 | 0.20 | 0.14 | 0.17 | 4.00 | 1.00 |
| **3.00** | 1.00 | 0.50 | 0.25 | 0.14 | 0.20 | 4.00 | 4.00 |
| **4.00** | 2.00 | 1.00 | 1.00 | 0.17 | 0.50 | 5.00 | 4.00 |
| **5.00** | 4.00 | 1.00 | 1.00 | 0.17 | 0.50 | 5.00 | 4.00 |
| **7.00** | 7.00 | 6.00 | 6.00 | 1.00 | 4.00 | 9.00 | 7.00 |
| **6.00** | 5.00 | 2.00 | 2.00 | 0.25 | 1.00 | 5.00 | 6.00 |
| **0.25** | 0.25 | 0.20 | 0.20 | 0.11 | 0.20 | 1.00 | 0.50 |
| **1.00** | 0.25 | 0.25 | 0.25 | 0.14 | 0.17 | 2.00 | 1.00 |
| **0.04** | 0.07 | 0.11 | 0.12 | 0.43 | 0.19 | 0.02 | 0.03 |

**Key:** Prec. = Precipitation, Elev. = Elevation , Slp. = Slope , D.D. = Drainage Density , Geol. = Geology (Lithology) , Lin. = Lineament, Asp. = Aspect, Curv. = Curvature

**Table 2: Resulting weights in order of priorities for groundwater influencing factors based on pairwise comparison**

| Category | Influencing factors | Priority (%) | Rank | (+), % | (-), % |
|---|---|---|---|---|---|
| 1 | Precipitation | 3.70 | 6.00 | 2.10 | 2.10 |
| 2 | Elevation | 6.60 | 5.00 | 3.20 | 3.20 |
| 3 | Slope | 10.50 | 4.00 | 2.30 | 2.30 |
| 4 | Drainage density | 12.50 | 3.00 | 5.70 | 5.70 |
| 5 | Geology(lithology) | 42.60 | 1.00 | 20.70 | 20.70 |
| 6 | Lineament | 18.60 | 2.00 | 6.70 | 6.70 |
| 7 | Aspect | 2.20 | 8.00 | 1.10 | 1.10 |

| | | | | | |
|---|---|---|---|---|---|
| 8 | Curvature | 3.20 | 7.00 | 1.20 | 1.20 |

*** Number of comparison = 28; Consistency ratio (CR) = 7.1 % (0.0710)***

**Table 3: Resulting weight based on the principal eigenvector of the decision matrix**

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| **1** | 1.00 | 0.33 | 0.25 | 0.20 | 0.14 | 0.17 | 4.00 | 1.00 |
| **2** | 3.00 | 1.00 | 0.50 | 0.25 | 0.14 | 0.20 | 4.00 | 4.00 |
| **3** | 4.00 | 2.00 | 1.00 | 1.00 | 0.17 | 0.50 | 5.00 | 4.00 |
| **4** | 5.00 | 4.00 | 1.00 | 1.00 | 0.17 | 0.50 | 5.00 | 4.00 |
| **5** | 7.00 | 7.00 | 6.00 | 6.00 | 1.00 | 4.00 | 9.00 | 7.00 |
| **6** | 6.00 | 5.00 | 2.00 | 2.00 | 0.25 | 1.00 | 5.00 | 6.00 |
| **7** | 0.25 | 0.25 | 0.20 | 0.20 | 0.11 | 0.20 | 1.00 | 0.50 |
| **8** | 1.00 | 0.25 | 0.25 | 0.25 | 0.14 | 0.17 | 2.00 | 1.00 |

***Principal eigen value = 8.700; Eigenvector solution: 6 iterations, delta – 5.9E-8***

### *3.2 Discussions*

#### *3.2.1 Thematic maps*

*Lithology:*

The lithological map (Fig. 2) was reclassified based on rock types and their hydrogeological characteristics. Weathered and fractured lithologies with higher secondary porosity were assigned higher ranks because of their potential to store and transmit large volume of groundwater, while fresh, massive crystalline units were assigned lower ranks due to their low groundwater storage potential.

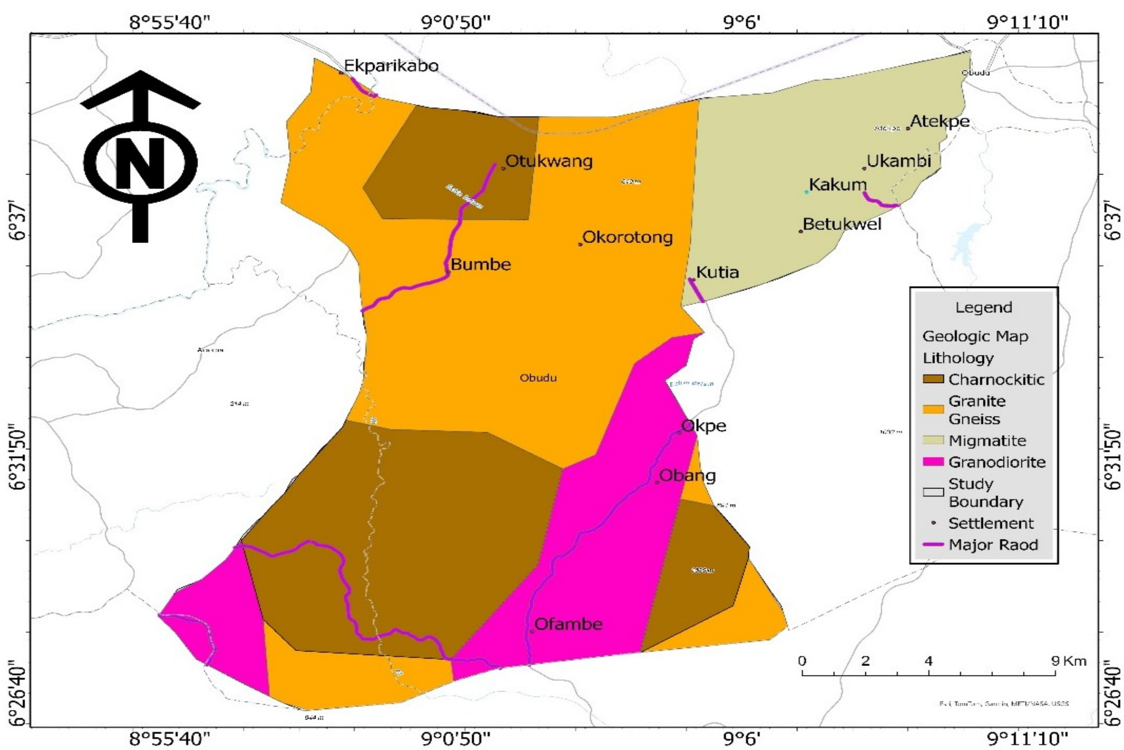


**Figure 2: Thematic map of lithology**

The rock units found within the study area together with their distributions have been presented (Fig. 2). The rock types present in terms of their relative abundance in the study area is in the order: ganite-gneiss, charnokite, granodiorite and migmatite. These rock types reflects the complex geological history and structural framework of the region. The central and western parts of the study area are dominated by Charnockitic rocks, which are typically hard and compact, exhibiting low primary porosity, although they may develop moderate secondary porosity in fractured zones.

The dominance of lithology in the AHP weighting scheme (42.6%) confirms that groundwater occurrence in the Obudu Massif is principally controlled by lithological characteristics. Fractured granite-gneiss and weathered granodioritic units are expected to provide favorable groundwater storage due to enhanced secondary porosity. Similar observations have been reported in crystalline basement terrains of southwestern Nigeria and Ethiopia, where lithology was identified as the most significant groundwater conditioning factor. Weighting was assigned to the different lithologic unit was based on the degree of porosity and permeability for each. The porosity of a rock determines its ability to store groundwater, while permeability is the ease with which it transmits groundwater (Kudamnya *et al.*, 2019). The frequency and interconnectivity of these fractures control the ability of fresh rocks to become a water-bearing unit.

The high weighting assigned to lineament density (18.6%) further emphasizes the structural control on groundwater occurrence. Areas characterized by high lineament density are likely to possess interconnected fracture networks that facilitate groundwater recharge, storage, and movement. Consequently, these zones represent favorable targets for groundwater exploration and borehole development.

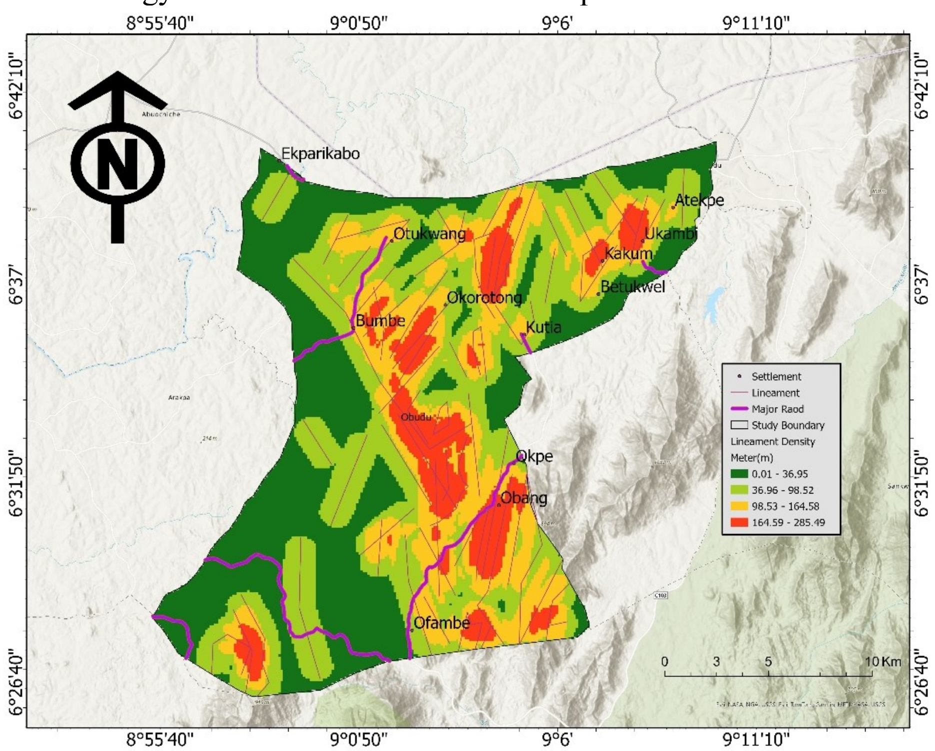


**Figure 3: Thematic map of lineament density**

### *3.2.2 Lineament:*

Lineament density is expressed as "*total lineament length per unit area*", and directly correlates with groundwater potential (Kanta *et al.*, 2018; Kudamnya *et al.*, 2019; Kassa *et al.*, 2025). Higher lineament density were considered more favorable for groundwater accumulation and recharge due to enhanced secondary permeability and fracture connectivity, creating favorable conditions for groundwater development.

Lineaments are linear structural features like fractures and faults visible on the land surface; they signify areas of weakness in the underlying rock. These features are crucial in groundwater studies because they act as groundwater storage and transport conduits, and play a pivotal role in groundwater occurrence (Hussein *et al.*, 2017). When interconnected, lineaments form zones of permeability, enabling the prediction of promising groundwater prospect and often leading to higher well yields. Therefore, the degree of connectivity among these lineament structures reflects the potential groundwater yield in a given area. For the study area, the lineament density map has been categorized into four classes (Fig. 3): 0.01 to 36.95 km/km$^2$, 36.96 to 98.52 km/km$^2$, 98.53 to 164.58 km/km$^2$, 164.59 to 284.49 km/km$^2$.

***3.2.3 Slope:***

Slope is an important terrain parameter influencing surface runoff, soil erosion, infiltration capacity, and groundwater recharge potential. In other words, it is critical to the occurrence of groundwater at any given place. The slope map of the study area (Fig. 4) revealed spatial variations in terrain steepness across the area. They are categorized into four slope classes: 1 – 6° (flat to gentle), 7 - 14° (Moderate to steep), 15 - 24° (steep), and 25 - 65° (very steep).

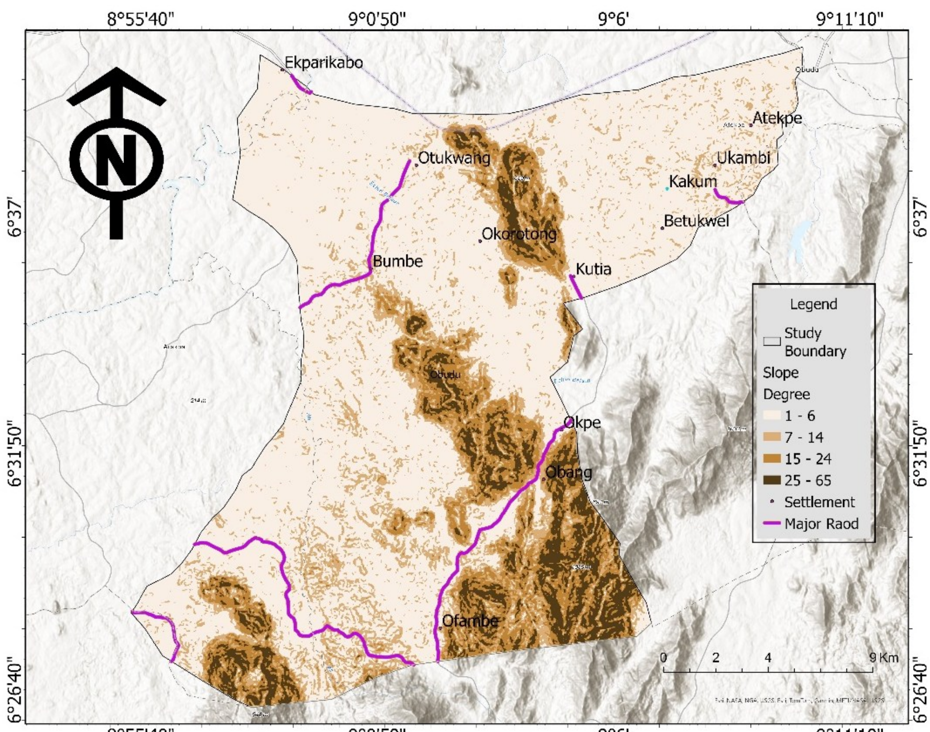


**Figure 4: Thematic map of slope**

They reflect flat to steep slopes and are useful in assessing geomorphological processes and land-use planning. Gentle slopes were assigned higher ranks due to enhanced infiltration potential, whereas steep slopes were ranked lower because of dominant runoff processes. The slope map produced for the study revealed that the area is dominated by gentle slopes ranging from 1° to 65°, suggesting relatively flat to very steep terrain. Flat to moderate terrains are typically more favorable for infiltration and less susceptible to surface erosion, making them potentially suitable for agriculture and groundwater recharge (Fentaw *et al.*, 2025). In contrast, the central and southern parts of the study area exhibit, steep to very steep slopes, indicating more rugged terrain with a higher risk of runoff and erosion thereby affecting recharge into the groundwater storage. In steeper areas, rapid runoff reduces infiltration time, leading to lower groundwater potential, while in flatter zones, prolonged water retention promotes recharge (Have *et al.*, 2026).The spatial distribution of slope in this region plays a significant role in controlling overland flow, sediment transport, and the potential for aquifer recharge.

The inverse relationship between slope and groundwater potential observed in this study is consistent with established hydrological principles. Gentle slopes promote prolonged residence time of surface water, thereby enhancing infiltration and groundwater recharge, whereas steep slopes favor rapid runoff and reduced infiltration opportunities.

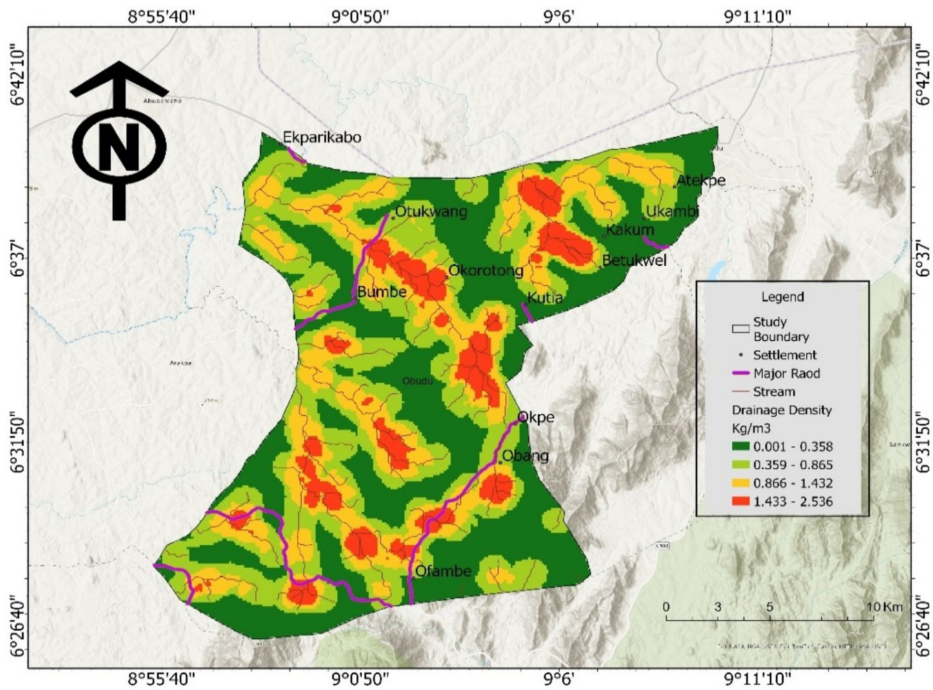


**Figure 5: Thematic map of drainage density**

***Drainage density:***

Drainage density is a fundamental hydrological indicator that reflects the closeness of spacing of streams and rivers within a watershed, derived as the ratio of total stream length to the basin area, and expressed in $km^{-1}$ (Kassa *et al.*, 2025; Ahmad *et al.*, 2020). It significantly influences surface runoff, infiltration rates, erosion potential, and groundwater recharge capacity (Fentaw *et al.*, 2025). The drainage density map of the study area was produced (Fig. 5). It categorized the region into four classes, ranging from very low (0.001–0.358 $km^{-1}$) to very high (1.364–2.536). These classes are color-coded from deep blue (low values) to light blue (high values), showing spatial variations in stream frequency across the terrain. High drainage density values are concentrated in the southern and central zones, which are characterized by steeper slopes and rugged terrain. This typically suggests impermeable or poorly permeable subsurface materials, reduced infiltration, and enhanced surface runoff (Shinde *et al.*, 2024). These areas are more prone to erosion and are less favorable for groundwater recharge. In contrast, area that exhibits low drainage density values are generally underlain by more permeable geological formations and possess gentler slopes, thus making them conducive to groundwater recharge and aquifer sustainability (Arya *et al.*, 2020; Chenini *et al.*, 2010).

The negative relationship between drainage density and groundwater occurrence reflects the reduced infiltration potential associated with highly dissected landscapes. Areas characterized by low drainage density are generally indicative of permeable subsurface materials and favorable recharge conditions.

***Precipitation***

Rainfall is a major climatic factor that directly influences the behavior of landscapes, affecting groundwater recharge, surface runoff, and erosion processes, thus directly influencing groundwater potential (Gedam & Dagalo, 2020; Ifediegwu, 2022). As a major hydrological parameter, rainfall not only serves as the primary source for groundwater recharge (Etikala ***et al.***, 2019), but also varies significantly based on environmental factors such as topography, vegetation, and surface geology. These factors ultimately affect the quantity of water that percolates into the ground. The spatial variability in rainfall distribution in the study area is low, only fairly observed from the north to south (Fig. 6). Four classes were categorized: red (161 – 213 mm), yellow (214 – 234 mm), Magenta (235 – 256 mm), and blue (265 – 288 mm).

The northern part receive the lowest range of rainfall depth and as such these areas are more prone to water scarcity, especially during dry periods, due to reduced infiltration and surface water availability. Areas receiving higher rainfall were assigned higher ranks due to increased groundwater recharge opportunities. High rainfall areas are prioritized for their positive impact on groundwater potential. Based on the mean annual rainfall and its contribution to groundwater recharge, relative ranks were assigned to each rainfall class. The southern part of the study area receives a higher amount of rainfall, indicating a greater potential for groundwater recharge and resulting in zones of high groundwater potential. In contrast, the lower rainfall levels in the southern region correspond to reduced groundwater recharge, which is associated with relatively lower groundwater potential (Melese & Belay, 2022).

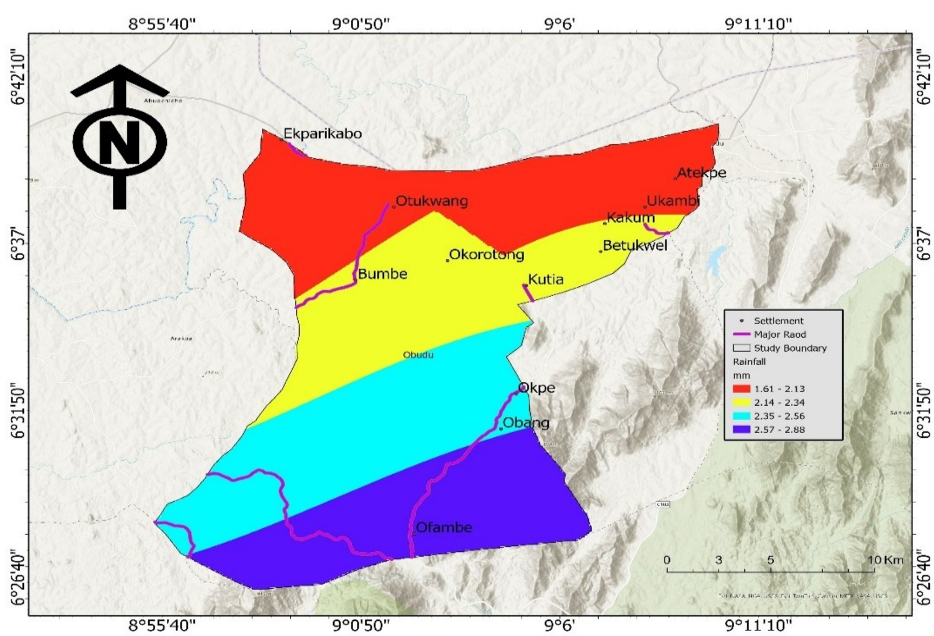

**Figure 6: Thematic map of precipitation (rainfall)**

***Elevation***

Elevation is the height above mean sea level of a terrain and an important factor in influencing groundwater occurrence and movement (Kudamnya *et al.*, 2019). It plays a crucial role in influencing the infiltration rate of rainfall, flow accumulation, transit, and dissipation zones, with areas of low relief closely associated with groundwater accumulation (Mallick *et al.*, 2015). Elevation in the study area ranges from approximately 101 to 1,094 meters above mean sea level (Fig. 7). Water inclines to accumulate more readily in low-lying areas compared to higher elevations; thus, higher elevations typically exhibit lower groundwater potential, and vice versa (Leyew *et al.*, 2022). Hence, lower elevation areas were ranked higher due to potential groundwater convergence, while higher elevations were ranked lower owing to increased runoff and reduced infiltration.

It is also categorized into four classes: very low (101 - 240 m), low (241 – 417 m), high (418 – 644 m), and very high (645 - 1,094 m). The portions of the plateau that showed areas with the higher elevation values are depicted yellow to red in colour. These highland zones are characterized by resistant crystalline basement rocks that are with intrusive rocks as a result of tectonic activities, thus making them structurally and geo-morphologically distinct. In contrast, the regions that are characterized by lower elevations and relatively flat to gently undulating terrain are represented in green to lemon-green colour. Elevation plays a significant role in groundwater dynamics, as lower elevation areas with gentler slopes favor infiltration and recharge. However, steeper and elevated terrains enhance surface runoff and reduce groundwater accumulation (Gleeson *et al.*, 2012).

The observed inverse relationship between elevation and groundwater potential suggests that groundwater accumulation predominantly occurs within lower-lying topographic depressions that act as discharge and recharge convergence zones.

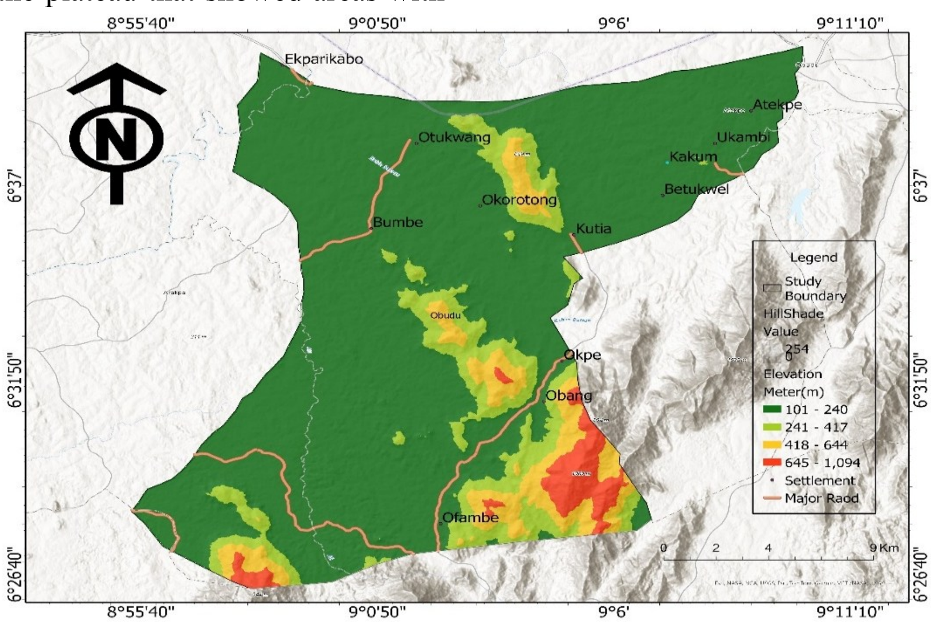


**Figure 7: Thematic map of elevation**

*Aspect*

Aspect reflects the orientation of slopes relative to solar radiation and prevailing moisture conditions. Sunshine is the parameter used here to evaluate the possibility of evapotranspiration, which plays an important role in assessing water infiltration (Have ***et al.***, 2026). Slopes facing directions associated with reduced evapotranspiration were ranked higher, while those prone to higher solar exposure were ranked lower. The sunniest areas were the least favorable to infiltration (Naeem ***et al.***, 2024). Nine (9) classes have been identified: flat, north, northeast, east, southeast, south, southwest, west, and northwest (Fig. 8).

Although aspect received the lowest weight (2.2%), it may exert localized influence on groundwater recharge by controlling solar radiation exposure, soil moisture retention, and evapotranspiration rates. However, its overall contribution to groundwater occurrence in the study area appears limited relative to lithological and structural controls.

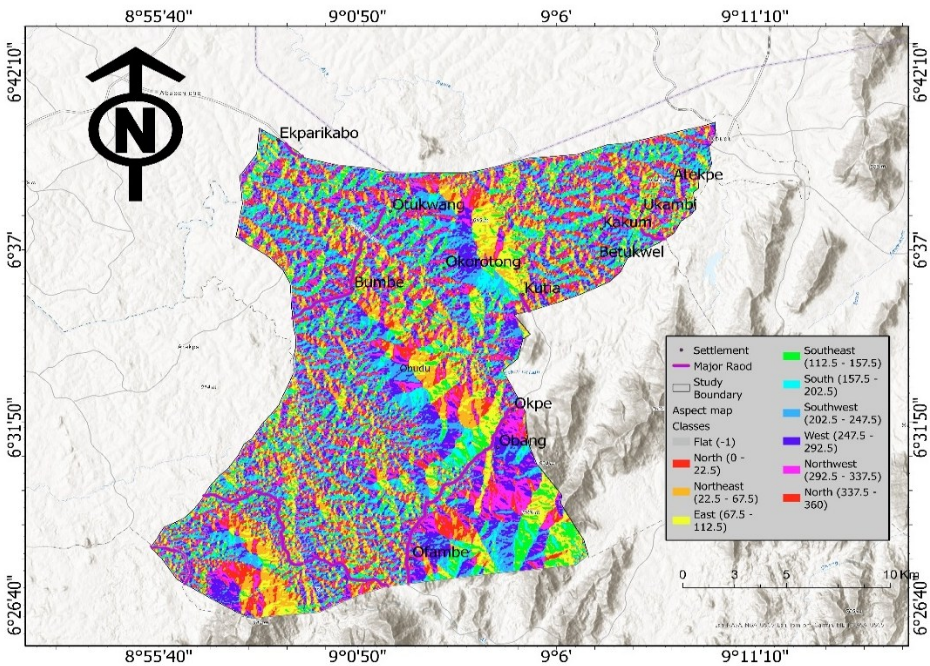


**Figure 8: Thematic map of aspect**

***Curvature***

Surface curvature is a significant topographic parameter for mapping the groundwater potential occurrence (Singh & Sharma, 2023), because it influences surface water and subsurface aquifer systems. Concave surfaces represent areas where water accumulation and infiltration are most favorable, whereas convex surfaces are less favorable. In this study, curvature was calculated from SRTM-DEM data as a second-order derivative of elevation. The curvature thematic map classifies the study area into two geo-morphometric surface forms: convex and concave curvatures (Fig. 9), according to the level of influence each has on groundwater recharge. The map reveals that the study area is overwhelmingly dominated by concave curvature surfaces (70%) represented as red regions. This indicates that much of the terrain consist of depressions or convergent land forms that are favorable for surface accumulation, increased infiltration, reduced run-off velocity and enhanced groundwater recharge potential. Conversely, the smaller proportion of convex surfaces (30%) represented by yellow region, corresponds to ridges and elevated terrains where run-off is rapidly dispersed, resulting in comparatively lower infiltration capacity and higher susceptibility to erosion. The predominance of concave morphology suggests that the area possesses geomorphic conditions supportive of groundwater development especially within valley fills, weathered zones and structurally controlled depression.

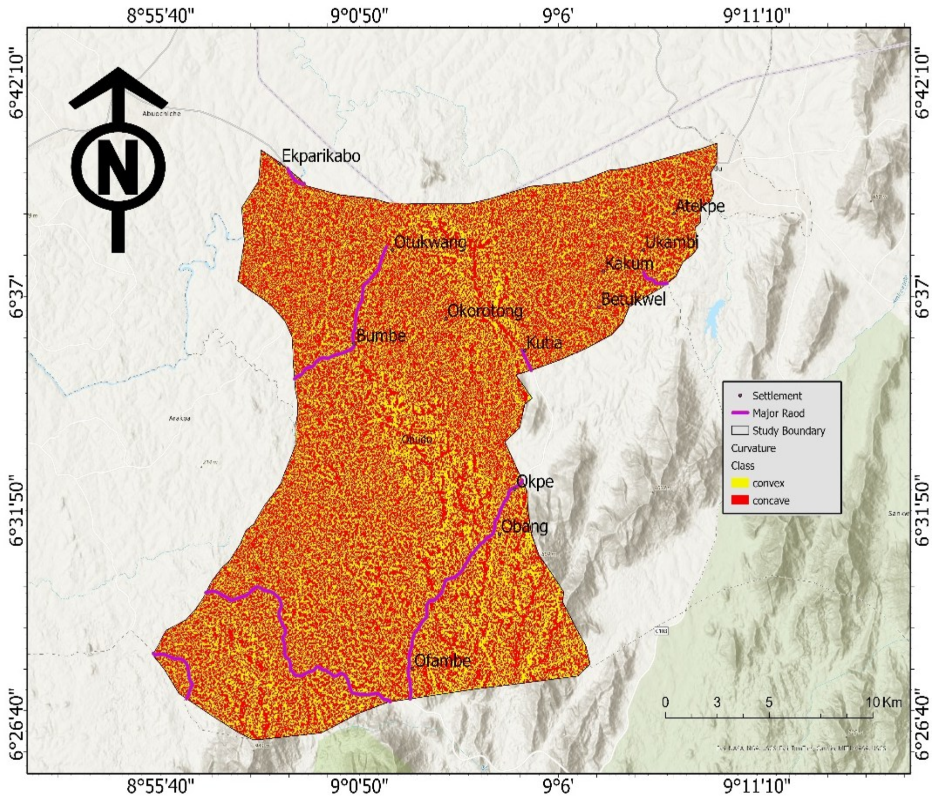


**Figure 10: Thematic map of curvature**

**Groundwater potential zones delineation**

Geographic information system (GIS) was used to evaluate the analytical hierarchy process (a multi-criteria decision analysis) to reveal the geospatial delineation of groundwater potential zones from this study. The information obtained from remotely sensed imagery, satellite data and existing maps was subjected to a statistical evaluation using the GIS. The groundwater influencing factors used include: precipitation (rainfall), elevation, slope, drainage density, geology (lithology), lineament, aspect and curvature. Based on the analytical hierarchy process (AHP) performed, the influencing factors on groundwater occurrence were prioritized according to their influence within the study area in the order of decreasing influence as geology (lithology) > lineament density > drainage density > slope > elevation > precipitation > curvature > aspect (Fig. 11). The ranking demonstrates that groundwater occurrence within the Obudu Massif is predominantly controlled by geological and structural factors rather than climatic or geomorphological variables. This observation is characteristic of crystalline basement terrains, where groundwater is primarily stored within weathered and fractured zones rather than within primary pore spaces.

Thematic maps of the various groundwater influencing factors such as precipitation (rainfall), elevation, slope, drainage density, geology (lithology), lineament, aspect and curvature, were integrated and further processed to produce predictive zones of groundwater occurrence (Fig. 12). In this study, the thematic map represents the spatial distribution of Groundwater potential zones (GWPZ) within the study area.

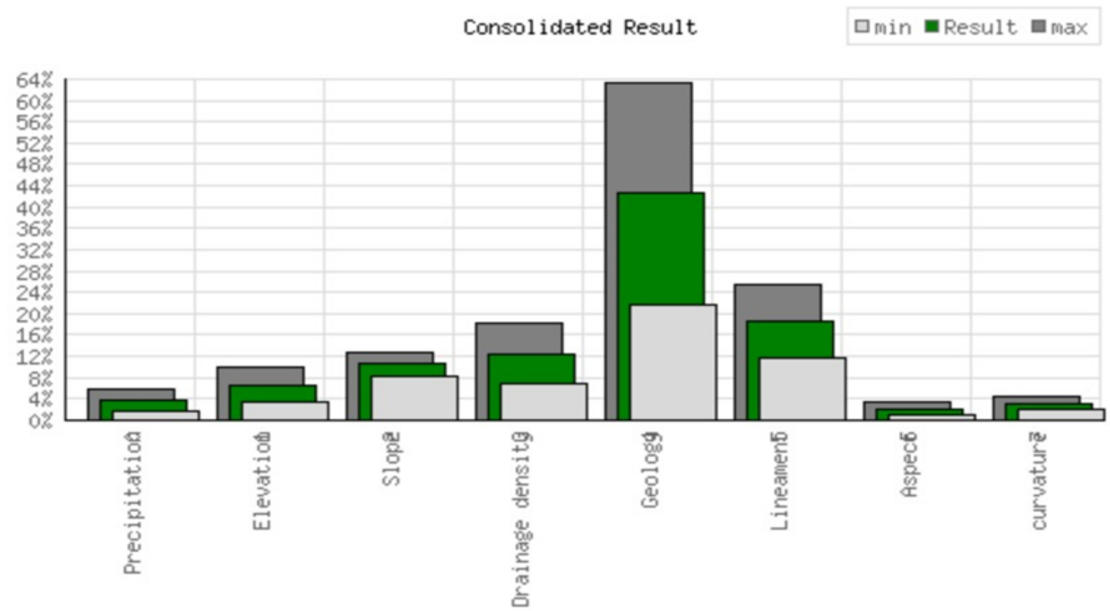


**Figure 11: The order of priority of groundwater influencing factors based on results of the AHP**

Three (3) classes were delineated: very high groundwater potential zones (red), high groundwater potential zones (greenish - teal), and low groundwater potential zones (cream/light yellow). From visual and pixel-based interpretation of the rasterized thematic map, the high GWPZ dominates the study area, and it suggests moderate to good aquifer characteristics, appreciable infiltration, favorable lithology/fracturing and sustainable groundwater occurrence. These are areas generally suitable for groundwater development and domestic water supply schemes (Fetters, 2001). Also, the very high GWPZ occurs mainly in the central – southern and southeastern regions around Obudu - Obang - Ofambe - Okpe axis. They represent zones of intense fracturing/weathering, high permeability, enhanced recharge, and high groundwater storage or yield potential, and most promising targets for productive borehole siting (Driscoll, 1986). The low GWPZ is more dispersed around the western and northern margins. It indicates areas with comparatively lower permeability, poor recharge conditions, thin weathered/fractured zones and less favorable hydrogeological characteristics. Borehole yield in these zones are expected to be relatively low (Freeze and Cherry, 1979; Todd and Mays, 2005). The proportions of each classes is such that the very high potential zones occupy 12.30 % of the total area of the study area, the high potential zones occupy 49.30 %, and the low potential zones occupy 38.40 % (Table 4).

The concentration of very high groundwater potential zones within the central-southern and southeastern parts of the study area reflects the combined influence of favorable lithology, high fracture density, moderate slopes, and enhanced recharge conditions. These areas therefore constitute priority zones for future groundwater development and borehole siting.

The groundwater potential map produced showed the effectiveness of integrating remote sensing and GIS to predict the occurrence of groundwater in a given place, as results from these method was validated using available transmissivity data (Table 5, Fig. 12) from borehole pump-test within the study area.

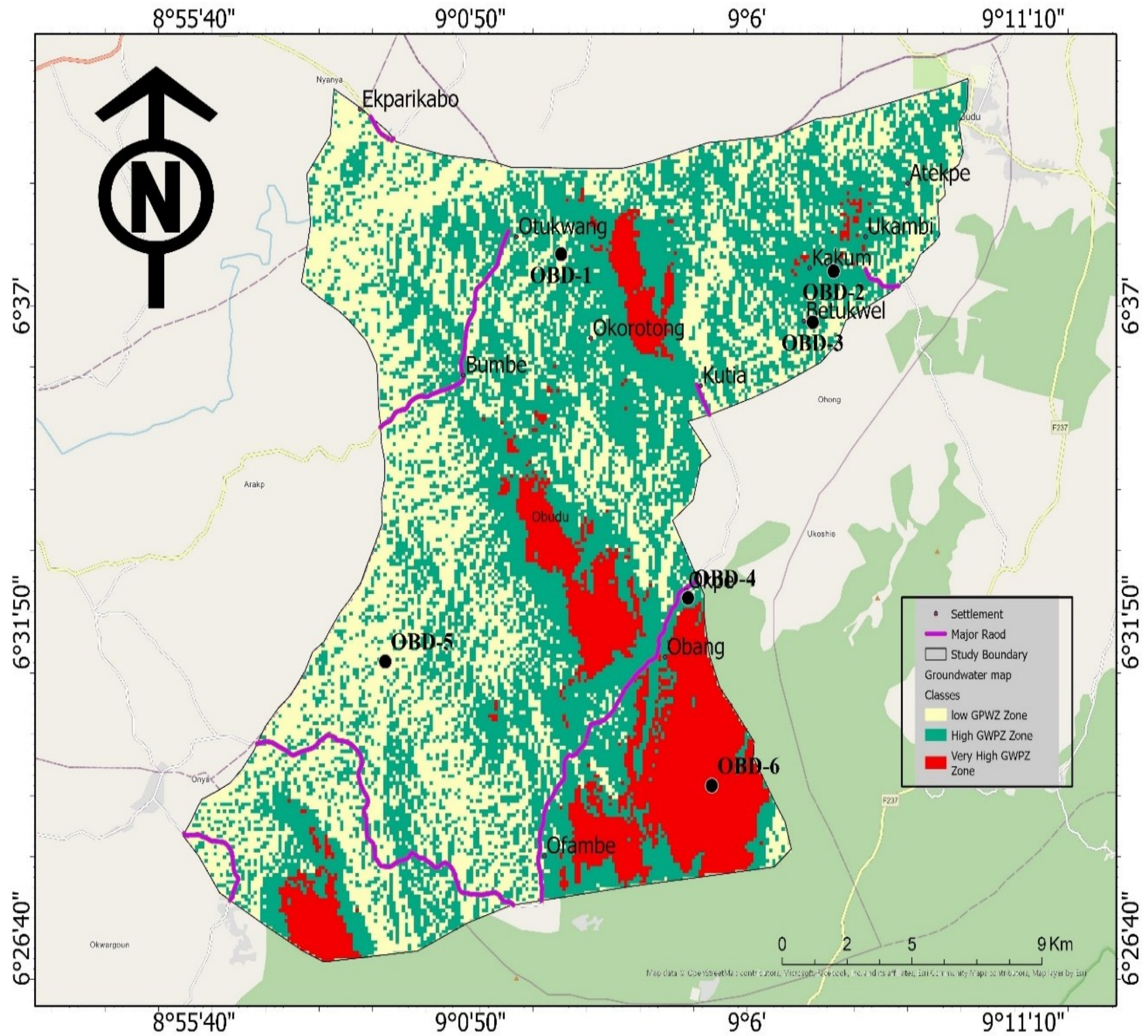


**Figure 12: Map of groundwater potential zones (GWPZs) produced**

**Table 4: Estimates obtained through raster pixel interpretation of the GWPZs**

| s/n | Groundwater potential Class | Approximate Pixel Count | Percentage Coverage (%) | Estimated Area (km2) |
|---|---|---|---|---|
| 1 | Low GWPZ | 89525.00 | 38.40 | 92.00 |
| 2 | High GWPZ | 114845.00 | 49.30 | 119.00 |
| 3 | Very High GWPZ | 29117.00 | 12.30 | 30.00 |
| | **Total** | **233487.00** | **100.00** | **241.00** |

It correlated positively with the field transmissivity data from pump-test, as region delineated as low GWPZ corresponds with field values of very low transmissivity class; high GWPZ corresponds with intermediate transmissivity class; while very high GWPZ corresponds with high transmissivity class. The spatial distribution of transmissivity values of productive wells was validated with the predicted groundwater potential zones to assess the reliability of the model. Higher correspondence between intermediate – high transmissivity wells and high - very high potential zones was considered indicative of model accuracy.

**Table 5: Field data used for validation of the AHP**

| Locality | Code | Latitude | Longitude | Field data | | Present study |
|---|---|---|---|---|---|---|
| | | | | Transmissivity ($m^2$/day) | Classes | |
| Utukwang | OBD-1 | 6° 38' 7" | 9° 2' 43" | 0.19 | Very low | Low GWPZ |
| Kakum | OBD-2 | 6° 37' 9" | 9° 7' 45" | 36.01 | Intermediate | High GWPZ |
| Betukwel | OBD-3 | 6° 36' 53" | 9° 7' 15" | 25.15 | Intermediate | High GWPZ |
| Okpe | OBD-4 | 6° 31' 55" | 9° 05' 32" | 23.31 | Intermediate | High GWPZ |
| Oraru Alege | OBD-5 | 6° 30' 15" | 8° 58' 24" | 0.31 | Very low | Low GWPZ |
| Bakom | OBD-6 | 6° 28' 45" | 9° 05' 26" | 103.21 | High | Very high GWPZ |

Validation of the groundwater potential model revealed a strong correspondence between transmissivity classes and predicted groundwater potential zones. Boreholes characterized by very low transmissivity values (<1 m²/day) occurred within low groundwater potential zones, whereas intermediate transmissivity values (20–40 m²/day) coincided with high groundwater potential zones. The highest transmissivity value (103.21 m²/day) occurred within a very high groundwater potential zone. This agreement demonstrates the reliability of the GIS-AHP model in predicting groundwater occurrence within the study area.

Overall, the integration of lithological, structural, hydrological, climatic, and geomorphological factors through the AHP-GIS framework successfully delineated groundwater potential zones within the Obudu Massif. The strong agreement between model predictions and field transmissivity data demonstrates that the approach is reliable for groundwater exploration, borehole siting, and sustainable groundwater resource management in crystalline basement environments.

## 4.0 Conclusion

This study successfully delineated groundwater potential zones within parts of the Obudu Massif, Southeastern Nigeria, using an integrated Geographic Information System (GIS) and Analytical Hierarchy Process (AHP) approach. The analysis demonstrated that geology (lithology), lineament density, drainage density, and slope are the most influential factors controlling groundwater occurrence within the crystalline basement terrain. The dominance of lithology and lineament density underscores the importance of rock characteristics, weathering processes, and structural discontinuities in governing groundwater storage and movement within the study area.

The groundwater potential map classified the area into low, high, and very high groundwater potential zones. High groundwater potential zones constitute the largest proportion of the study area (49.30%), while very high groundwater potential zones occupy approximately 12.30% and are predominantly concentrated within the central-southern and southeastern sectors of the Obudu Massif. These areas are characterized by favorable lithological and structural conditions that promote groundwater recharge, storage, and transmission.

The consistency ratio (CR = 0.071) obtained from the AHP analysis indicates acceptable consistency in the pairwise comparison process and confirms the reliability of the weighting scheme assigned to the groundwater conditioning factors. Furthermore, validation using borehole pumping-test-derived transmissivity data revealed strong agreement between observed aquifer productivity and the predicted groundwater potential zones, thereby confirming the accuracy of the GIS-AHP model.

Overall, the integration of remotely sensed data, GIS, and multi-criteria decision analysis proved to be an effective, reliable, and cost-efficient approach for groundwater exploration in complex crystalline basement terrains where conventional investigation methods are often expensive and time-consuming. The findings provide a scientific basis for groundwater development, borehole siting, and sustainable water-resource management within the Obudu Massif and other similar basement complex regions of Nigeria. The methodology developed in this study can also serve as a valuable framework for groundwater assessment in comparable data-scarce environments.

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**Declaration**

**Consent for publication**

Not applicable

**Availability of data**

Data shall be made available on demand.

**Competing interests**

The authors declared no conflict-of-interest

**Ethical Consideration**

Not applicable

**Funding**

The authors declared no source of funding

**Authors' contributions**

E.A.K. conceived and coordinated the study, supervised GIS and AHP modelling, and drafted the manuscript. V.E.N., I.K.A., E.E.O., A.A.O., and G.I.J. contributed to fieldwork, data acquisition, and GIS processing. H.I.A. assisted with the literature review and data organization. J.O.O. supported methodological design and validation. F.P.I. provided hydrogeological data and field verification. A.E., T.N.N., C.I.A., A.S.E., and G.T.K. contributed to interpretation, review, and manuscript revision. All authors approved the final manuscript.