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# Assessment of Groundwater Potential Zones Using Multicriteria Decision Analysis: A Case Study of Umuahia Areas of Niger Delta Basin, Nigeria

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**ABSTRACT**

Affordable and effective measures must be employed in the search for groundwater resources given the exponential increase in the demand for water and the ensuing hunt for its availability. For ease of exploration and exploitation, these methods must take into consideration all the elements that affect groundwater occurrence, recharge, and transport, as was done in this analysis of the groundwater potential zones in Umuahia areas of Niger Delta Basin, Nigeria. Seven thematic layers such as rainfall, soil type, geology, drainage density, slope, lineament density, and land use / land cover were appropriately delineated using remote sensing data and the capabilities of the geographic information system (GIS). The analytical hierarchy process (AHP) enabled the prioritization of the layers which were then integrated into a single thematic layer using the weighted overlay tool of the ArcGIS software. The result of this study shows 3.3%, 93.8%, and 2.9% of the region to be of good, moderate, and poor groundwater potential zones respectively, indicating the amount to which each element under consideration had an impact. This emphasizes the widespread random borehole failures in some parts of Umuahia area. The precise map of groundwater potential zones created by this study can be adapted for optimal management of the current aquifers to sustainably meet the region's water demands.

**Keywords:**
Geographic Information Systems (GIS), Multi-criteria Decision Analysis, Analytical Hierarchy Process (AHP), Groundwater Potential Zones.

## INTRODUCTION

Groundwater is the source of almost a third of all freshwater abstractions worldwide (Das et. al., 2018). For any economic and social growth, it is a crucial natural resource (Kordestani et. al., 2019). Nations like Nigeria are experiencing a rise in groundwater demand as a result of the nation's fast urbanisation, population growth, and economic development which have serious implications for aquifer storage levels. In 2019, approximately 60 million Nigerians were living without access to basic drinking water services despite the government's declaration of a state of emergency in 2018 and the resulting national action plan (NAP) for the revitalization of her water supply, sanitation, and hygiene sector (The World Bank, 2021). In the existence of a generous endowment of both surface and underground water capable of meeting demand, Nigeria's economic water scarcity is an indication of the country's inability to protect and/or use water sources for socioeconomic development and environmental sustainability. Should the situation persists; satisfactorily meeting water demand becomes further out of reach.

Since groundwater potential zone can be quickly and easily explored in a variety of geological contexts (Igwe et. al., 2020; Ifediegwu et. al., 2019; Thapa et. al., 2017), sustainable development must be necessitated to alleviate the impact of water crisis on people's lives (Scott and Rajabifard 2017). As a result, novel, affordable, and effective tools are being sought in the exploration of groundwater. Groundwater potential zones have been delineated using remote sensing and GIS techniques since being able to determine these zones is essential for long-term resource management. Central to this approach are multi-criteria decision-making techniques such as the analytical hierarchy process (AHP) which due to its effectiveness and simplicity (Achu et. al., 2020; Aliabad et. al., 2018) allows for the demarcation of potential zones. As a result of the integration of GIS and AHP, data may be transformed into information that managers and policymakers can use (Guru et. al., 2017).

None of the earlier analyses of the groundwater potential of the study area incorporated remote sensing, GIS methods, and AHP in a single investigation, nor were they carried out at this high resolution. This study examines the potential zones of groundwater resources in some parts of Abia State in an effort to fill a research gap by taking seven datasets into account (rainfall, soil-type, geology, drainage-density, slope, linear density, and land use / land cover). All seven play significant roles in the availability, distribution, and access to groundwater resources (Hamdani and Baali, 2020; Lentswe and Molwalefhe, 2020). Furthermore, the study is aimed at the creation of a detailed spatial groundwater potential map of the study area which will help policymakers manage water resources more sustainably and, specifically reduce the number of failed boreholes in the region.

## Study Area

Ikuwano, Umuahia North, and Umuahia South Local Government Areas (LGAs) of Abia State, Nigeria, situated between longitude 7° 21' and 7° 38' E and latitude 5° 18' and 5° 41' N (Fig. 1), make up the researched location. Out of the 597 square kilometers region, Ikwuano, Umuahia North, and Umuahia South made up 39.6%, 38.5%, and 21.9% respectively. The study area is bordered to the south-east by Akwa Ibom State of Nigeria, to the south-west by Isiala Ngwa LGA of Abia State, and to the north by Obowo and Ihitte LGAs of Imo State, Isuikwuato, and Bende LGAs of Abia State (Fig. 1). The study area falls within the sub-equatorial belt, the location experiences annual rainfall between 2000 and 2200 mm and relative humidity levels around 70%. With rainfall maxima in July and September and a little break in August, the rivers Imo and Kwa Iboe, as well as all of its tributaries, form an excellent dendritic drainage network system in the region. The former and its tributaries, which run in a southwestern direction and empty into the Atlantic Ocean, drain the north of the study area (Umuahia North and South). The latter, which flows south, drains Ikwuano, which is located south of the study area and empties into the Atlantic Ocean as well. The area's dendritic drainage pattern denotes a homogeneous substructure with poor structural control. Numerous recurring and transient streams replenish the borehole aquifers where they are found. During the year's 3600 hours of sunshine, the average daily mean temperature ranges from 23.5°C (between 23° and 24°C) in July to 30.5°C (between 29° and 31°C) in March. Ikwuano/Umuahia's topographically unequal crustal mass distribution is typified by its 48 to 187 m elevation above mean sea level (Fig. 1).

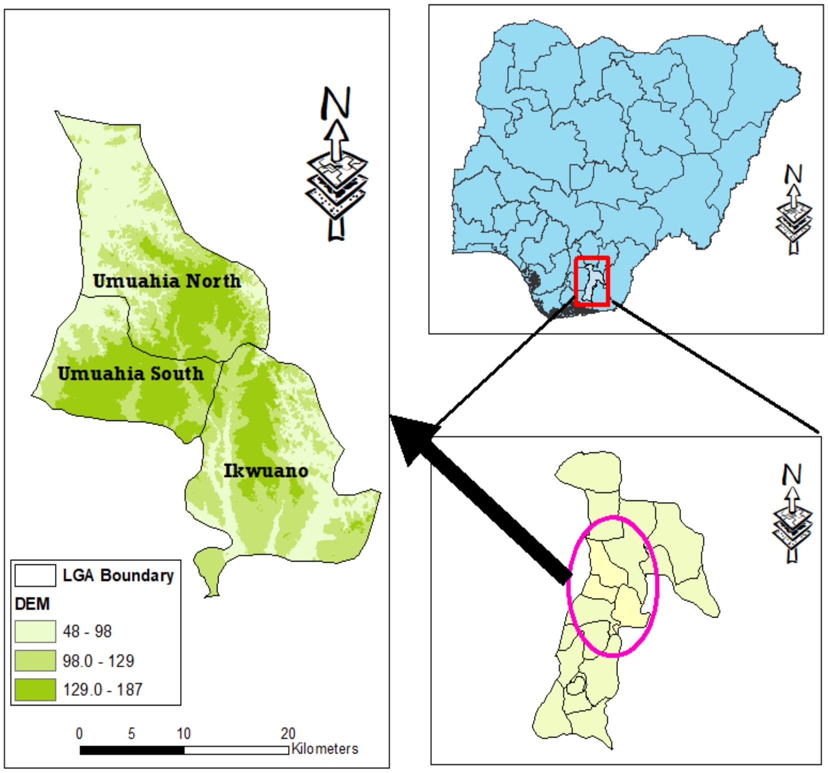


Figure 1: Map of the study area with its Digital Elevation Model

The Study area is situated in the sedimentary basin of the Eastern Niger Delta (Fig. 2). The basin was created during the Tertiary period as a result of the interaction between subsidence and accretion brought on by a series of sea transgressions and regressions (Hosper (1965). Three lithostratigraphic units were deposited in the Niger Delta as a result of this event namely Akata Formation, Agbada Formation, and Benin Formation in decreasing order of age (Short and Stauble, 1967). These Tertiary sediments are roughly 10,000 meters thick overall. In the Niger Delta, the Akata and Agbada Formations serve as the petroleum's source and reservoir rocks, respectively, while the Benin Formation serves as the aquiferous unit. Petrographic investigation reveals the rocks' composition as quartz grains (95–99%), Na+K-mica (1-2.5%), feldspar (0–1.0%), and dark-colored minerals (2.3%). The Benin Formation makes up about half of the different geologic Formation in Abia State. The sands are primarily medium to coarse-grained, pebbly, and moderately sorted; in addition to poorly cemented sands and clays that make up the Miocene to Recent Benin Formation. All of the boreholes in the research region draw their water from a multi-aquifer system, according to the sand-clay intercalations in the area.

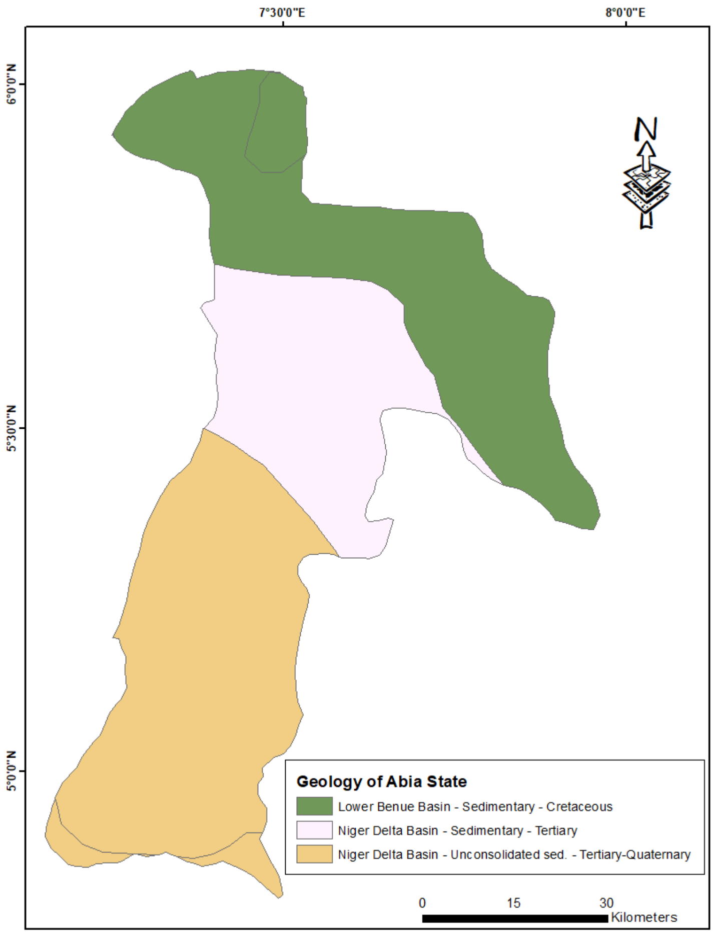


Figure 2: Map of the Sedimentary Basinsin Abia State

## MATERIALS AND METHODS

### The Parameters for Groundwater Potential Zones Assessment

The first stage in evaluating an area's groundwater potential is to choose acceptable criteria that either have a significant impact on water percolation and storage or offer sufficient proof of groundwater presence (Mahmoud and Alazba 2016; Oulidi ET. AL., 2009). While recharge is controlled by precipitation, land use / land cover, soil-type, and the rate of penetration; groundwater occurrence and movement are primarily governed by underlying lithology, landform, soil characteristics, lineament, and drainage densities (Shao ET AL., 2020). By examining the factors that control groundwater flow, storage, and occurrence, groundwater potentiality modeling can be completed (Yildirim 2021; Ifediegwu ET. AL., 2019). Therefore, seven criteria were chosen, (slope, drainage-density, land use / land cover, rainfall, soil properties (soil-type), geology (lithology), and lineament density) and their thematic layers were generated and combined to a create groundwater potential zone map using ArcGIS 10.3 software; while taking into account the goal and literature review, the data and available information, and also the characteristics of the study area. The full collection of map themes was rendered in the UTM Projection Zone 32N, Datum WGS84. The methods utilized to create the groundwater potential zones (GWPZs) map and GIS data layers are as shown (Fig. 3).

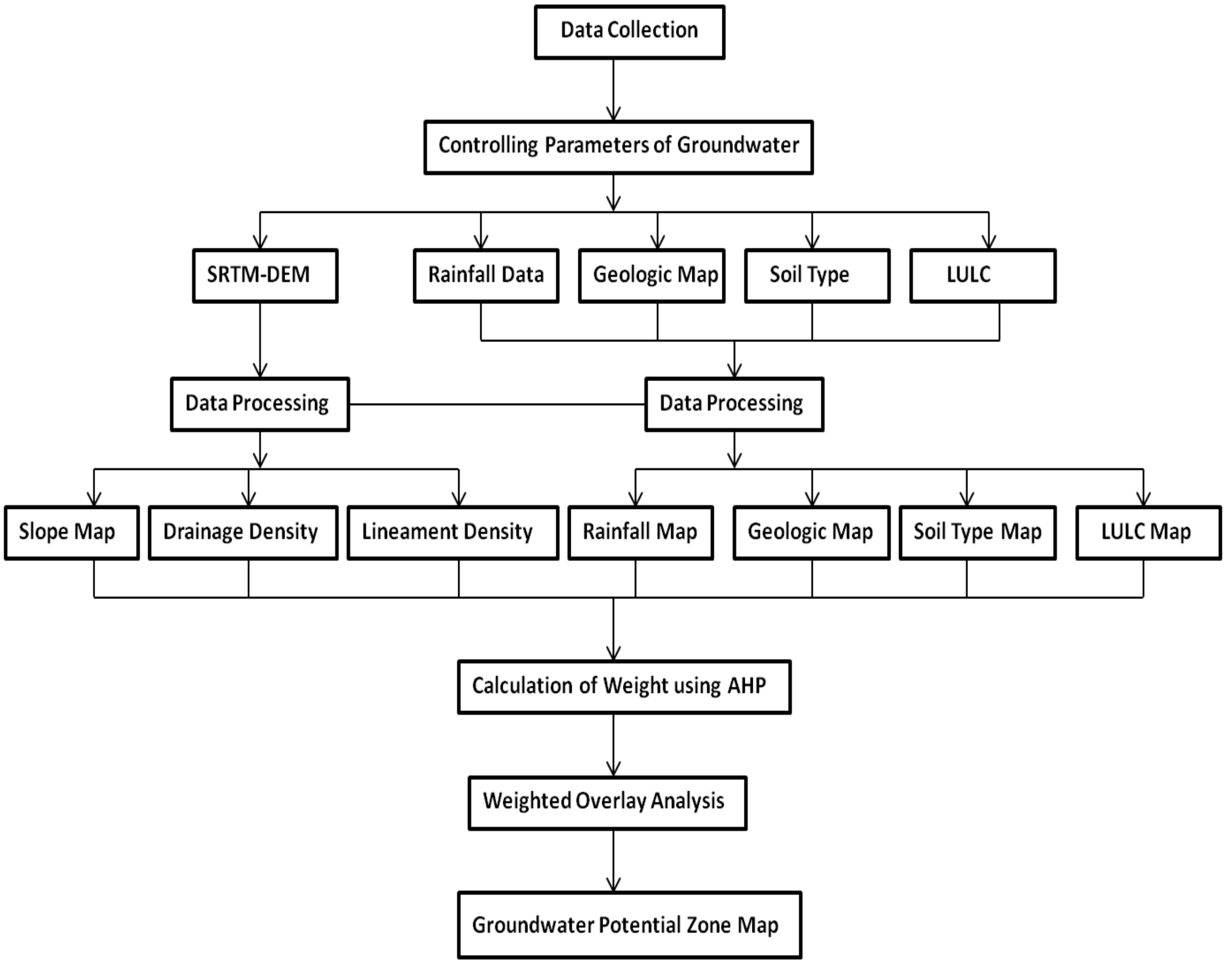


Figure 3: Methodological Workflow of the Investigation

**Data Collection and Integration into GIS Database**

The primary data sources used in this study were mostly remotely-sensed data, from which the seven thematic layers were created using appropriate processing techniques. The United States Geological Survey's data on world geologic maps (https://www.usgs.gov/media/images/world-geologic-maps-data-downloads) were used to create the study area's geology map, while the FAO/UNESCO soil map of the world was used to create the study area's soil map (https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/faounesco-soil-map-of-the-world/en/). Similar to how the land use land cover map comes from the ESRI land cover - living atlas (https://livingatlas.arcgis.com/landcover/ ), the rainfall data used is from the high-resolution gridded datasets of the climatic research unit (https://crudata.uea.ac.uk/cru/data/hrg/). The slope map, lineament density, and drainage density maps were produced using a digital elevation model that was accessible through the United States Geological Survey's Earth Explorer unit (https://earthexplorer.usgs.gov/). All the employed data were obtained in March 2023.

The analytic hierarchy process (AHP) was then used to apply the proper weights to the resulting geographical layers according to their hierarchy in terms of groundwater potentiality. Using the weighted overlay tool of ArcGIS, weighted data layers were overlaid to produce the spatial map of the groundwater potential zones.

**Multi-criteria Decision Assessment Utilising AHP**

Saaty (1990) developed the AHP, a decision-assistance tool that is frequently used to make difficult decisions based mostly on pairwise comparisons. The identification of critical criteria for the target choice and the development of a pairwise comparison matrix based on expert assessments or decisions between the criteria constitute the first stage of the AHP technique (Saaty 1990, 2005). With the use of this pairwise comparison matrix, the convoluted decision-making process between the criteria is condensed into a single level, from which the relative relevance values of the criteria are obtained. Using Saaty's 1–9 significance scale (Table 1), the criteria are contrasted.

**Table 1: AHP Constant rating (Saaty, 1990)**

| | | |
|---|---|---|
| Less influential | Extreme importance | 1/9 |
| | Very strong importance | 1/7 |
| | Strong importance | 1/5 |
| | Moderate importance | 1/3 |
| Equally influential | Equal importance | 1 |
| More influential | Moderate importance | 3 |
| | Strong importance | 5 |
| | Very strong importance | 7 |
| | Extreme importance | 9 |
| Intermediate values | | 2, 4, 6, and 8 |

The normalised weights are computed using the geometric mean of the criteria in the second step of the AHP computations. Examining the consistency of the normalised criteria weights is the last step in the AHP technique. For the weights to be considered consistent, the consistency ratio (CR) value must be less than 0.10; otherwise, the pairwise comparisons must be re-examined. . The specified range ensures that the consistency of responses is maintained, thus ascertaining the reliability of the computation. The pairwise comparison matrix and the normalised weight values for the criteria used in this investigation are shown in Table 2. And the pairwise comparisons' consistency ratio (CR) is 0.05 which is within the recommended range.

**Table 2: The Pairwise Comparison Matrix and the normalised weights of the thematic layers**

| | Rainfall | Soil Type | Lithology | Drainage Density | Slope | Linear Density | Land Use / Land Cover | Normalised Weight |
|---|---|---|---|---|---|---|---|---|
| **Rainfall** | 1.00 | 2.00 | 3.00 | 4.00 | 4.00 | 6.00 | 7.00 | 0.338 |
| **Soil Type** | 0.50 | 1.00 | 2.00 | 2.00 | 4.00 | 5.00 | 6.00 | 0.223 |
| **Lithology** | 0.33 | 0.50 | 1.00 | 3.00 | 3.00 | 5.00 | 6.00 | 0.182 |
| **Drainage Density** | 0.25 | 0.50 | 0.33 | 1.00 | 2.00 | 3.00 | 4.00 | 0.106 |
| **Slope** | 0.25 | 0.25 | 0.33 | 0.50 | 1.00 | 3.00 | 3.00 | 0.077 |
| **Linear Density** | 0.17 | 0.20 | 0.20 | 0.33 | 0.33 | 1.00 | 2.00 | 0.043 |
| **Land Use / Land Cover** | 0.14 | 0.17 | 0.17 | 0.25 | 0.33 | 0.50 | 1.00 | 0.031 |

**Criteria Standardisation, Demarcation and Validation of Groundwater Potential Zones (GWPZ) Map**

The harmonization of all decision criteria to a single scale of measurement, data standardization, along with AHP, is widely used in GIS-based decision support research (Aykut 2021; Benjmel et. al., 2020; Panahi et. al., 2017). Each element of the raster GIS-based criteria map was ranked on a scale of 1-3 (poor, moderate, and good, respectively) in order to standardize the results (Table 3). Having obtained the normalized weight of each layer and ranked their various elements, thus making sure they were consistent, the groundwater potential zones (GWPZs) for the study area were generated using the weighted overlay approach.

Table 3: Allocated Ranks of the Layers' Elements and the Layers' NormalisedWeight

| Layer | Elements | Class | Rank | Normalised Weight (%) |
|---|---|---|---|---|
| | 2163.2 - 2198.1 | Good | 3 | |
| **Rainfall** | 2113.1 - 2163.2 | Moderate | 2 | 34 |
| | 206.2 - 2113.1 | Poor | 1 | |
| **Soil Type** | Nitosols | Moderate | 2 | 22 |
| | Nitosols | Moderate | 2 | |
| **Lithology** | Unconsolidated | Good | 3 | 18 |
| | Consolidated | Moderate | 2 | |
| | 0 - 87.0 | Good | 3 | |
| | 87.0 - 248.9 | Moderate | 2 | 11 |
| **Drainage Density** | 248.9 - 616.3 | Poor | 1 | |
| | 0 | Good | 3 | |
| | 0 - 89.6 | Moderate | 2 | 8 |
| **Slope** | 89.6 - 90.0 | Poor | 1 | |
| | 0.7 - 1.8 | Good | 3 | |
| **Lineament Density** | 0.3 - 0.7 | Moderate | 2 | 4 |
| | 0 - 0.3 | Poor | 1 | |
| | Deciduous conifer forest | Good | 3 | |
| | Irrigated Grassland | Good | 3 | |
| | Low Sparse Grassland | Moderate | 2 | |
| | Deciduous Broadleaf Forest | Moderate | 2 | |
| **Land Use Land Cover** | Tall Grasses and Shrub | Moderate | 2 | 3 |
| | Bare Desert | Poor | 1 | |
| | Semi Desert | Poor | 1 | |
| | Urban | Poor | 1 | |

## RESULTS AND DISCUSSION

### Rainfall

Among the variables taken into account in this study to build the groundwater potential zones (GWPZs), rainfall is the most significant element obtaining a normalized weight of 0.338 (Table 3). Under the same geomorphological conditions, theoretically, areas with higher rainfall rates have greater groundwater potential than those with lower rainfall rates, thus pointing out the favoured region is Ikwuano. The long-run average yearly rainfall values (1901–2021) data were retrieved and interpolated using the Inverse Distance Weighted (IDW) method in ArcGIS software for this study in order to create its spatial rainfall map. The study area receives on average 2065.18 to 2198.07 mm of rainfall (Fig. 4). Although the entire region received a good amount of precipitation, it increases southward. Inferring from the GWPZ map (Fig. 11) that the good GWPZs did not include the whole 28% of the study area that receive 2163.15 – 2198.07 mm, it is thus pertinent to note that factors other than rainfall totals play a significant role in replenishing the groundwater, including rainfall frequency and severity. Corroborating this situation, Nasir ET. AL., (2018) opined that over a long period, small amounts of low-intensity rainfall can have positive effects on the groundwater. However, the poorest GWPZs fall within 30% of the region that received the least amount of rainfall, thus indicating also the significant role of direct impact of rainfall.

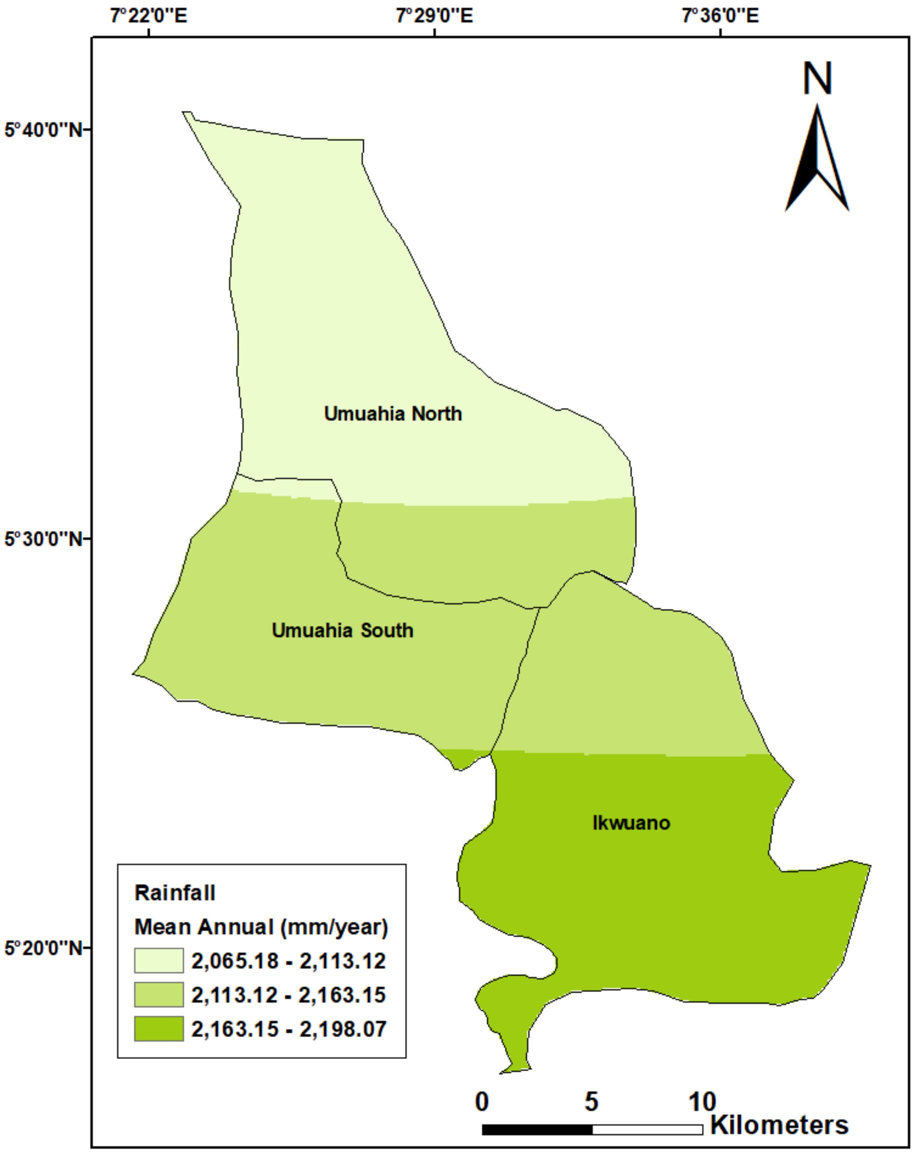


Figure 4: Rainfall Map of the study area

**Soil Type**

Soil-type or the kind of soil which is determined by the processes of pore saturation or de-saturation, has an impact on the increase in water entry into the soil (Ghosh ET. AL., 2020). The porosity of the different types of soil determines how much water is transported into the ground which aligns with propositions that soil-types with coarse-grained matrices have stronger groundwater potential, while soil types with fine-grained matrices have poorer groundwater potential (Ifediegwu ET .AL., 2019). Based on a normalised weight of 0.223, soil type placed second among the important factors used to define the GWPZs (Table 3). The only soil category in the area of investigation is nitosol (Fig. 5) which is one of the most productive soils in the humid tropics. This kind has a robust soil structure, which also makes it remarkably erosion-resistant. In addition, it is complemented by good workability, good internal drainage, and fair water-holding properties. As such, it was assigned a rank of 2.

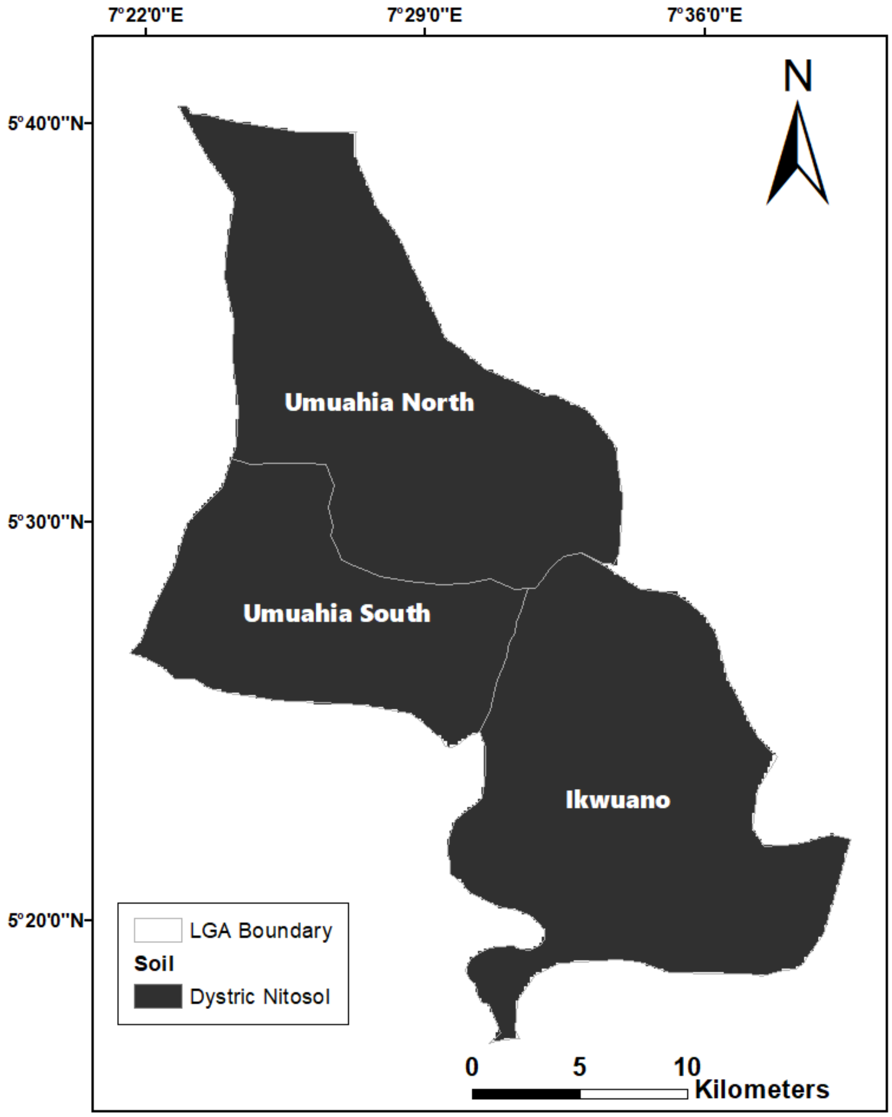

Figure 5: Soil Type Map of the Study Area

**Geology**

According to Mukherjee *et. al.,* (2012), the lithological characteristics of the local rocks have a significant impact on both the infiltration and percolation of water into the ground. Given that geology entirely controls the penetration and percolation of groundwater, it is an important factor of consideration when evaluating groundwater potential (Aju et. al.,2021).In addition, Yıldırım(2021) in his study stated that high porosity and permeability of a geologic unit increase the groundwater production and storage. In this study, the geology thematic layer is the third crucial factor used to determine the region's GWPZs with a normalised weight of 0.182. The area's lithology corresponded to the Sedimentary Tertiary and Unconsolidated Sedimentary Tertiary Formation in the Niger Delta Basin. The unit that underlies81% of the area is ranked 2. The unconsolidated units underlying the rest of the area (19%) being ranked 3 (Fig.6, Table 3), implies its higher potential for groundwater yield and storage.

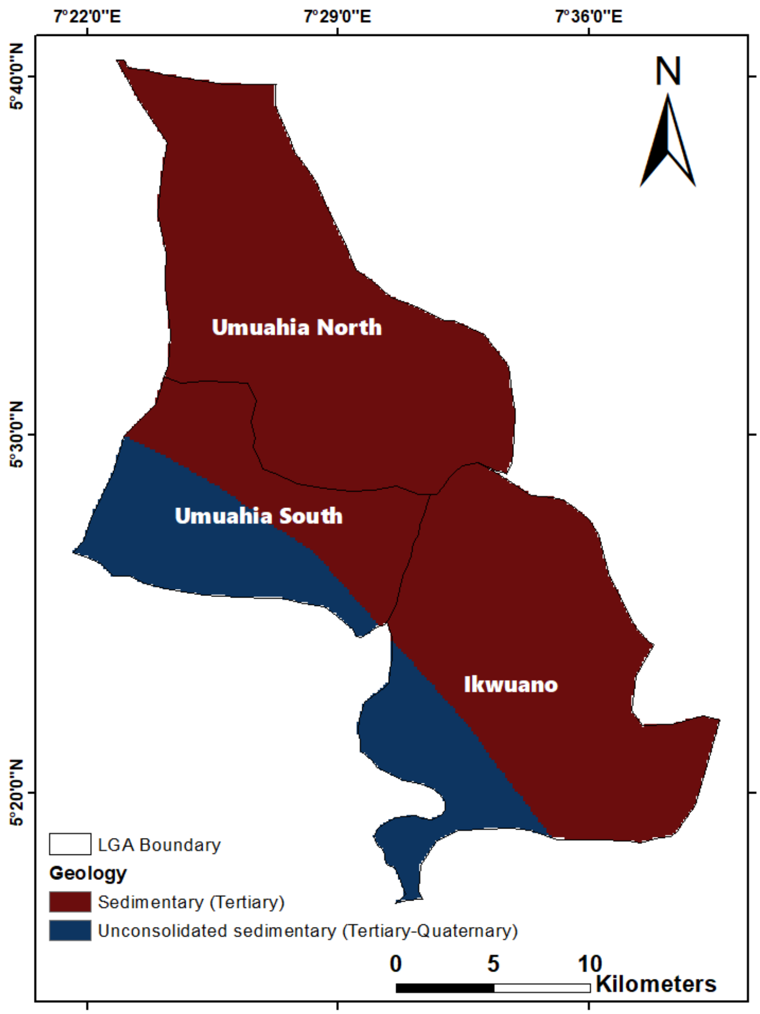


Figure 6: Geologic Map of the Study Area

**Drainage Density**

Drainage density affects the infiltration rate and water flow into the aquifer (Thapa ET. AL., 2017). Zones with low drainage density have better groundwater potential (Gnanachandrasamy ET. AL., 2018); since a system with a dense drainage network allows for faster run-offs. 60% of the study area is of low drainage density (Fig. 9), thus implying that the underlying rocks are of good permeability as reported by Shao ET AL., (2020) that high permeability of underlying rocks gives rise to low drainage density. According to Bali ET. AL., (2012), a denser drainage network is produced by low-permeable lithology, sparse vegetation, and high-relief regions with heavier rainfall. Therefore, it would seem that areas with a complex drainage system may also have a subpar aquifer as is the case with this study area. Drainage density values in this study ranged from 0 to 616.3 km/km2 (Fig. 7). Drainage density is ranked fourth among the parameters chosen in this study with a normalised weight of 0.106.

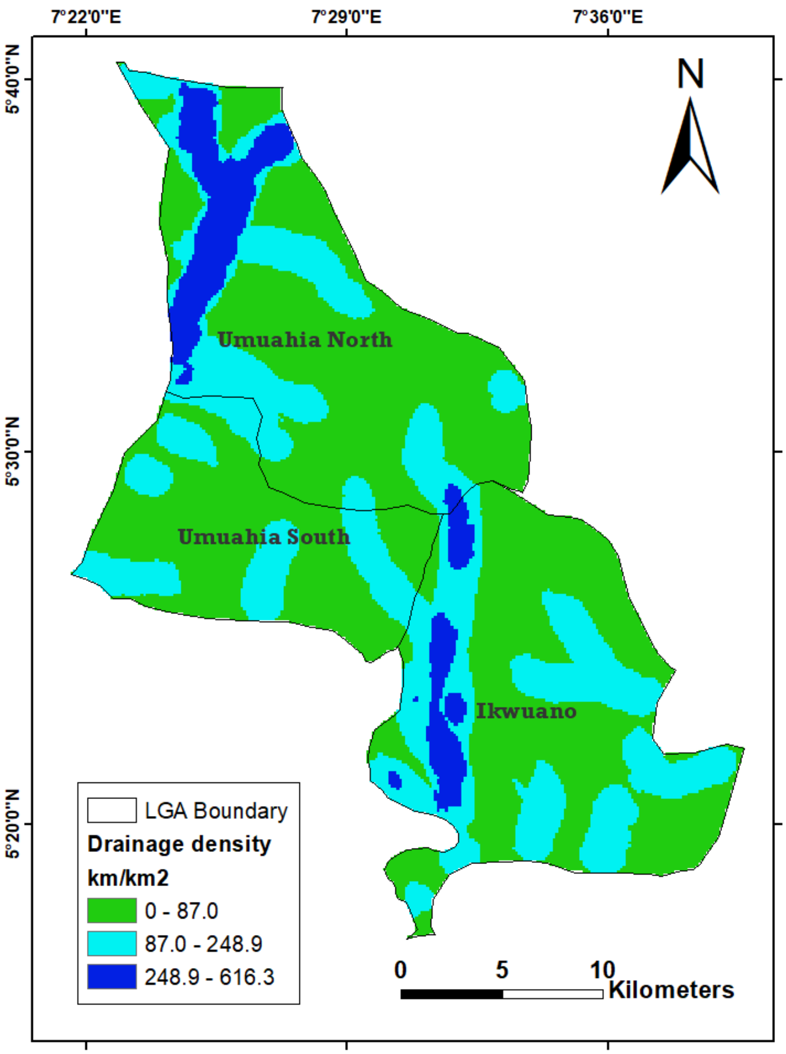

Figure 7: Drainage Density Map of the Study Area

**Slope**

The slope is important for groundwater recharge since it directly affects the surface runoff mechanism (Zghibi ET. AL., 2020). The increased residence time for rainwater to permeate the subsurface in low-slope areas has prompted preliminary analyses to conclude that such areas have a good potential for groundwater storage. About 99.6% of the study area has a slope angle of 89.6-90.0° implying high steepness. And according to Igwe ET. AL., (2020), such kinds of terrains have poor groundwater potential due to speedier water run-off. Based on proportional influence on the identification of groundwater potential zones among the factors used for this study, slope came in fifth place with a normalized weight of 0.077 (Table 3). The slope angle thematic map (Fig. 8) was re-classified: low slope angle favouring water residence was assigned a higher rank. This is supported by Rukundo and Doan (2019) and Conrad and Adams (2007) who similarly pointed out the negative effects of increased slope angles on infiltration and groundwater recharge.

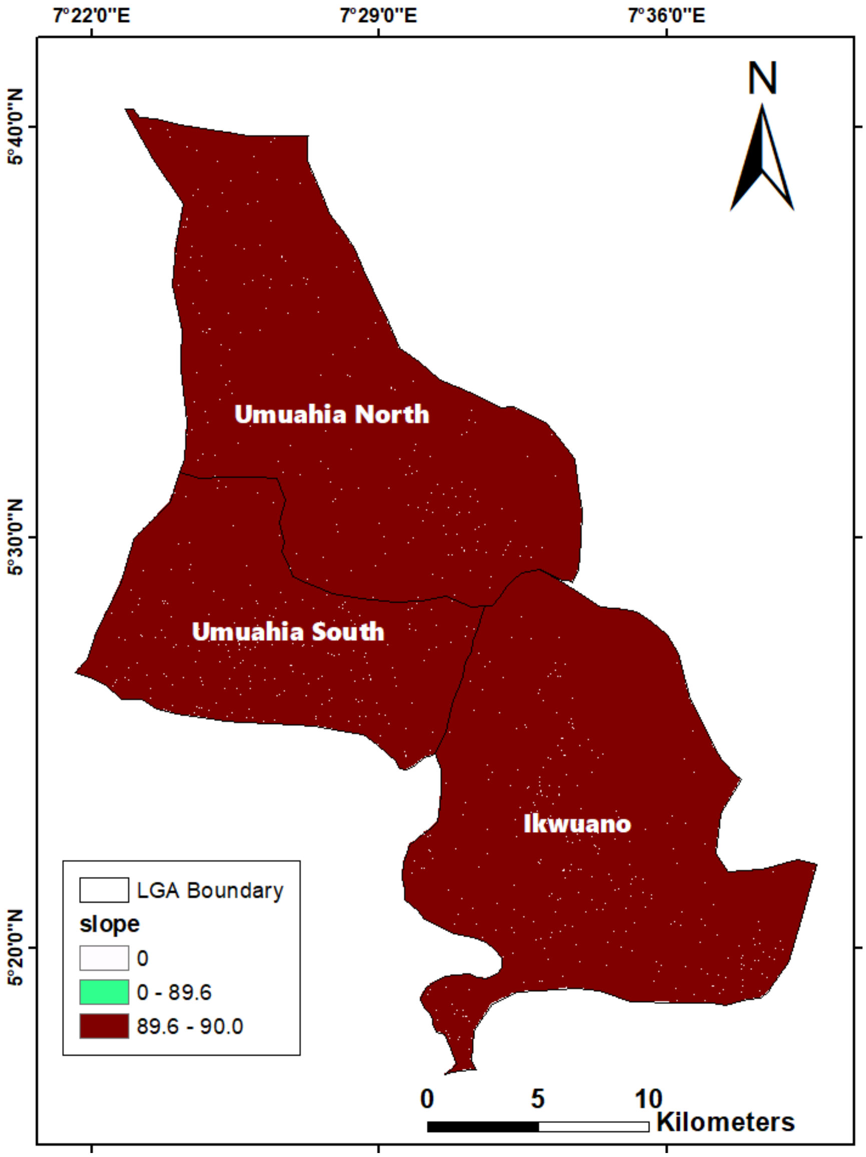


Figure 8: Slope Map of the Study Area

**Lineament Density**

Because they ultimately determine permeability and provide the pathways for groundwater movement, lineament features are crucial in terms of hydrogeology (Magesh *et al.*, 2012). Because areas with a high lineament density also have greater water circulation, these areas also have greater groundwater potential (Lentswe and Molwalefhe 2020). Since it is assumed that the water infiltration rate increases with increasing lineament density (Magesh *et al.*, 2012), the 79% (0.29-1.8 km/km2) moderate-to-good lineament density of the area (Fig. 9) indicates good groundwater recharge potential. However, considering that the GWPZs map did not follow this assertion, it could be that the linearments have been filled with soils. For this study, lineament density is the sixth important factor, with a normalised weight of 0.043. The main lineaments are found trending in theNE-SW and NW-SE (Fig. 9) directions.

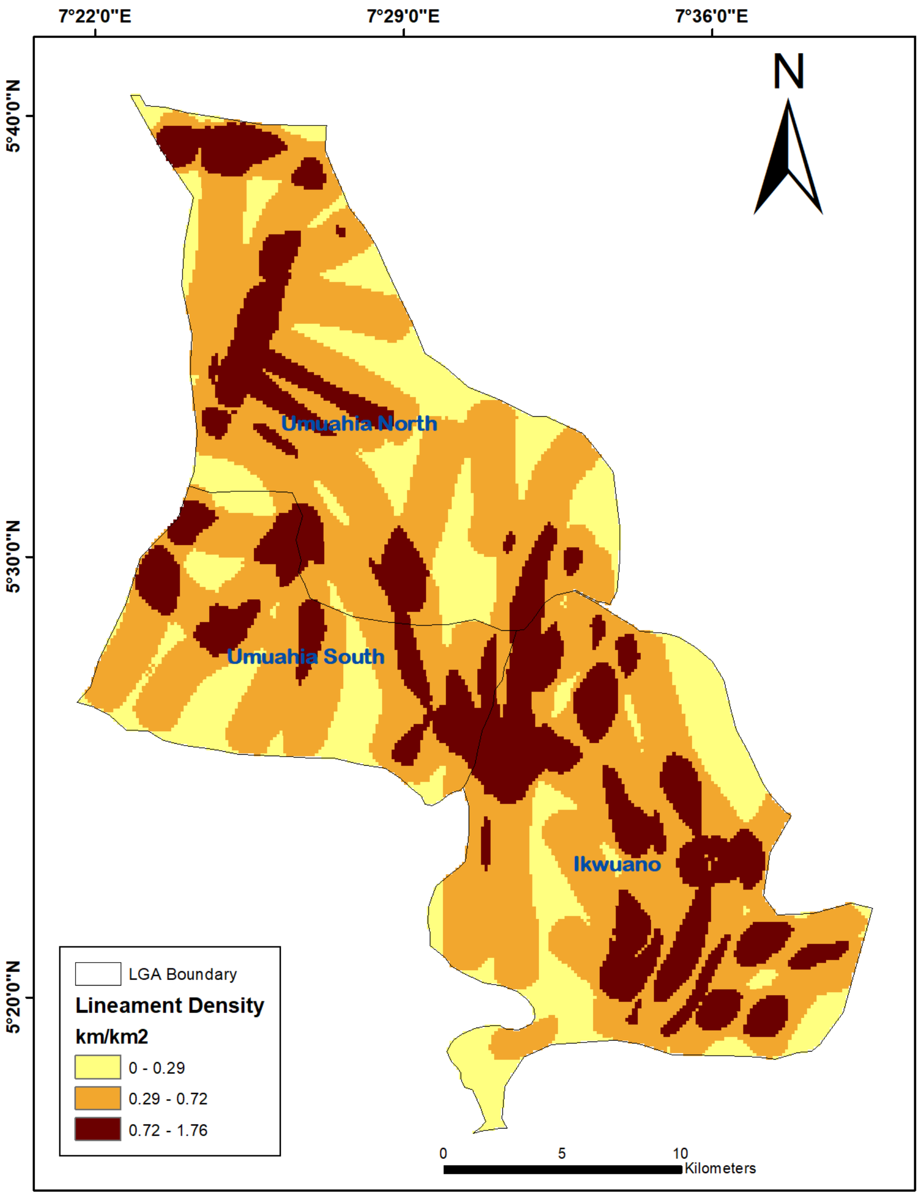


Figure 9: Lineament Density Map of the Study Area

**Land Use / Land Cover**

The distribution of a specific area's industrial, residential, and water body areas, as well as its vegetation cover, is included in land use land cover. Groundwater recharge, groundwater occurrence, and groundwater availability are all impacted by it (Kumar ET. AL., 2016; Pande ET. AL., 2017; Yeh ET. AL., 2016). This is because its operations greatly affect the permeability of the underlying soil as well as moisture content, particularly through evapotranspiration, penetration, and condensation. Given that the elephant share (68%) of the study area is covered by sparse grassland alone and a total of 74% is covered by urban, desert, semi-desert, and sparse grassland, the influence of these land use land cover elements which are of low permeability is likely to have contributed significantly to the overall poor GWPZs observed in the study area. This proposition is similar to the reports of Doer ET. AL., (2006), and Masoumi ET. AL., (2020). Therefore, it significantly affects groundwater recharge. The normalised weight for the land use land cover map is 0.031, placing it seventh overall among the factors used in this study to identify GWPZs (Table 3). The land use land cover features were ranked according to their interactive potentials ((Fig. 10, Table 3).

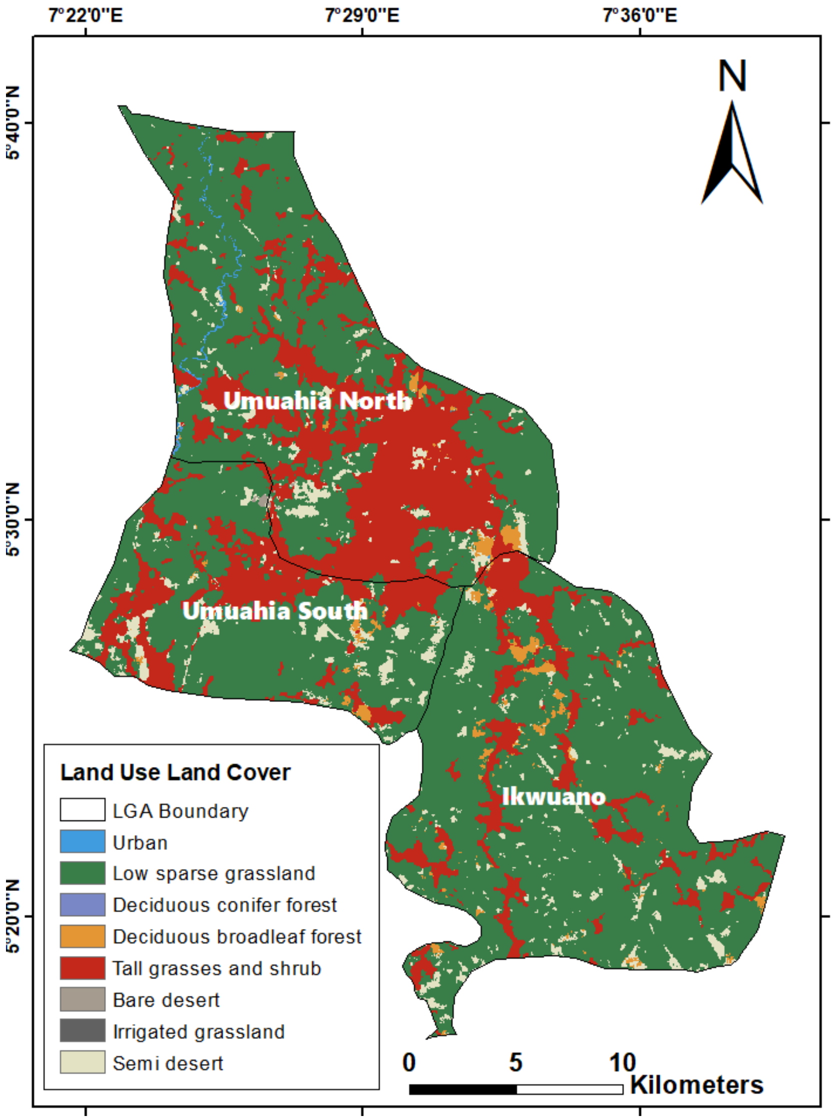


Figure 10: Land Use / Land Cover Map of the Study Area

**Determining the Possible Groundwater Potential Zones (GWPZs)**

The contributing influences of each thematic layer could be seen in the generated GWPZs map (Fig. 11). Quite profoundly, the entire area of good GWPZ are within the area receiving the heaviest amount of rainfall, implying a positive correlation between the rainfall pattern and the GWP of the area. Similarly, the area with the highest drainage density fittingly aligns with the poorest GWPZs revealing another positive correlation between drainage density and the GWPZs.

Finally, three categories considered as poor potential, moderate potential and good potential were delineated from the groundwater potential zones map of the study area (Fig. 11).

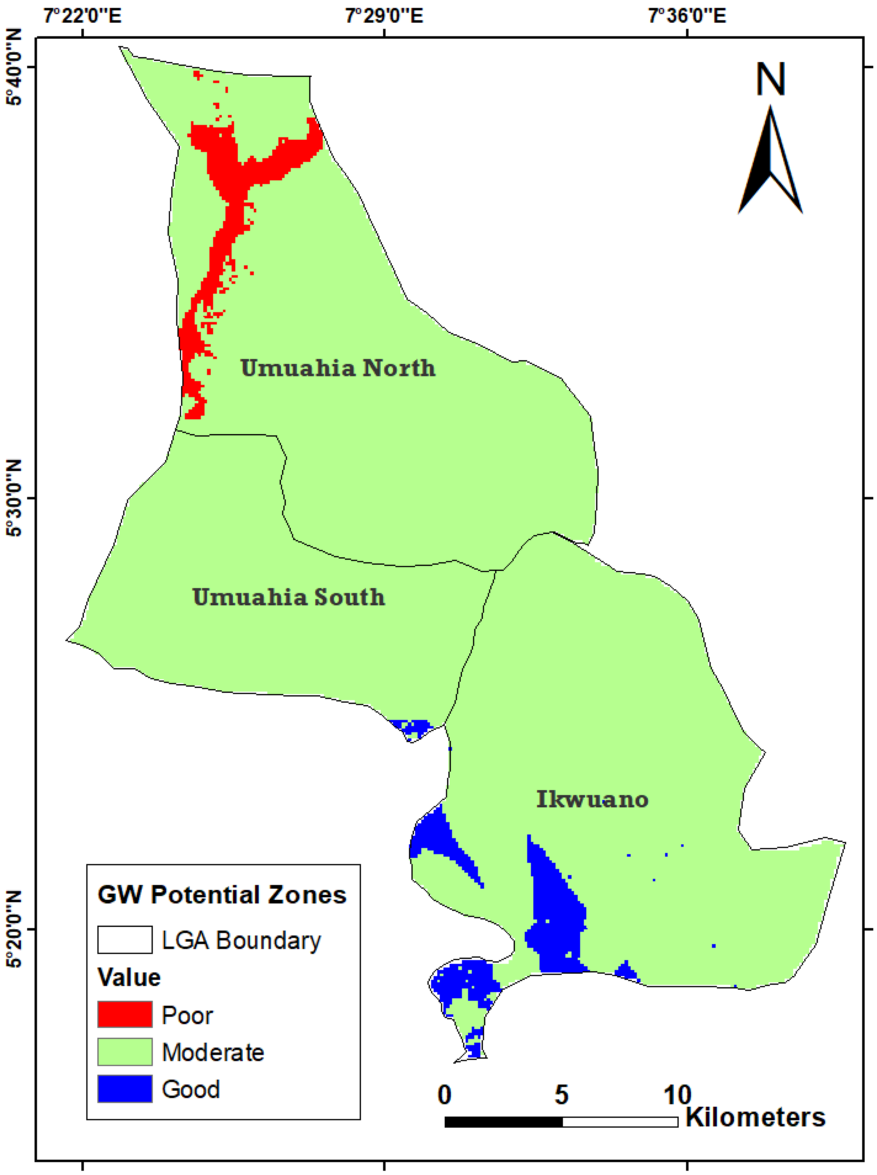


Figure 11: Groundwater Potential Zones Map of the Study Area

Around 2.9% of the total area (17.3 km2) is considered to have poor potential zones, while 93.8% of the study area (560.0 km2) is deemed to have moderate potential zones and 3.3% of the total area (19.7 km2) is deemed to have good potential zones (Table 4).

**Table 4: The Resulting GWPZs of the Study Area**

| **Potential zone** | **Area (km2)** | **Area (%)** |
|---|---|---|
| Poor | 17.3 | 2.9 |
| Moderate | 560.0 | 93.8 |
| Good | 19.7 | 3.3 |

## CONCLUSION

The integration of the seven different criteria used in this study shows the hydrogeological significance of different landform, lithological, and structure types, leading to the creation of a groundwater potential zones map of the Ikwunao, Umuahia-North and Umuahia-South Local Government Areas of Abia state, Nigeria. The results of this investigation revealing that about 2.9% of the studied area is of poor groundwater potential zone and that about 93.8% of the study area is of moderate groundwater potential. Hence, this outcome can be easily adapted for sustainable planning, development, and management of groundwater resources. Overall, this study has proven that despite limited data availability, the multi-criteria decision analysis technique together with analytical hierarchy process can be combined successfully with remote sensing and geographic information system techniques to provide a generally cost-effective and accurate assessment of groundwater potential. Therefore, to adequately meet up with the future water demand in the study area, sustainable development and optimal management of the current aquifers and others in similar regions is required.

**REFERENCES**

Achu, A. L., Reghunath, R., and Thomas J., (2020). Mapping of groundwater recharge potential zones and identification of suitable site-specific recharge mechanisms in a tropical river basin. *Earth Systems and Environment* 4 (1): 131–145. doi:10.1007/s41748-019-00138-5.

Aju, C. D., Achu, A. L., Raicy, M. C., and Reghunath, R., (2021). Identifcation of suitable sites and structures for artificial groundwater recharge for sustainable water resources management in vamanapuram river basin, south India. *HydroResearch* 4: 24–37. doi:10.1016/j.hydres.2021.04.001.

Aliabad, F. A., Shojaei, S., Zare, M., and Ekhtesasi, M. R., (2018). Assessment of the fuzzy ARTMAP neural network method performance in geological mapping using satellite images and Boolean logic. *Environmental Science and Technology*. https://doi.org/10.1007/s13762-018-1795-7

Aykut, T., (2021). Determination of groundwater potential zones using geographical information systems (GIS) and analytic hierarchy process (AHP) between Edirne-Kalkansogut (northwestern Turkey). Groundwater for Sustainable Development 12:100545

Bali, R., Agarwal, K. K., Ali S. N., Rastogi, S. K., and Krishna., (2012). Drainage morphometry of Himalayan Glacio-fluvial Basin, India: hydrologic and neotectonic implications. *Environmental Earth Sciences* 66 (4):1163–1174. doi:10.1007/s12665-011-1324-1

Benjmel, K., Amraoui, F., Boutaleb, S.,, Ouchchen, M., Tahiri, A., Touab, A., (2020). Mapping of groundwater potential zones in crystalline terrain using remote sensing, GIS techniques, and multicriteria data analysis (case of the Ighrem region, Western Anti-Atlas, morocco). *Water* 12:471

Conrad, J., and Adams, S., (2007). GIS based assessment of groundwater recharge in the fractured rocks of Namaqualand, South Africa. *Groundwater in Fractured Rocks*, 203-217. doi:10.1201/9780203945650.ch13.

Das, B., Pal, S., Malik, S., and Chakrabortty, R., (2018). Modeling groundwater potential zones of Puruliya district, West Bengal, India using remote sensing and GIS techniques. *Geology, Ecology and Landscape* 3:223–237

Doerr, S. H., Shakesby, R. A., Dekker, L. W., and Ritsema. C. J., (2006). Occurrence, prediction and hydrological effects of water repellency amongst major soil and land-use types in a humid temperate climate. *European Journal of Soil Science* 57 (5): 741–754. doi:10.1111/j.1365-2389.2006.00818.x.

Ghosh, D., Mandal, M., Karmakar, M., Banerjee, M., and Mandal, D., (2020) Application of geospatial technology for delineating groundwater potential zones in the Gandheswari watershed West Bengal. Sustainable Water Resources Management 6:14. https://doi.org/10.1007/ s40899-020-00372-0

Gnanachandrasamy, G., Zhou, Y., Bagyaraj M, Venkatramanan S, Ramkumar T, Wang S (2018). Remote sensing and GIS based groundwater potential zones mapping in Ariyalur district, Tamil Nadu. Geological Society of India 92:484–490. https://doi.org/10.1007/s12594-018-1046-z

Guru, B., Seshan, K., Bera, S., (2017). Frequency ratio model for groundwater potential mapping and its sustainable management in cold desert, India. King Saud University-Science 29:333–347. https://doi.org/10.1016/j.jksus.2016.08.003

Hamdani, N., and Baali, A., (2020). Characterization of groundwater potential zones using analytic hierarchy process and integrated geomatic techniques in Central Middle Atlas (Morocco). Applied Geomatics 12:323–335

Hospers, J. (1965). Gravity field and structure of the Niger delta, Nigeria, West Africa. *Geological Society of America Bulletin*, *76*(4), 407-422

Hussein, A.-A.; Govindu, V.; Nigusse, A.G.M. Evaluation of groundwater potential using geospatial techniques. Applied Water Science. 2016, 7, 2447–2461.

Ifediegwu, S. I., Nnebedum, D. O., and Nwatarali, A. N., (2019). Identifcation of groundwater potential zones in the hard and soft rock terrains of Kogi State, North Central Nigeria: an integrated GIS and remote sensing techniques. SN Applied Sciences 1:1151. https://doi.org/10.1007/s42452-019-1181-1

Igwe, O., Ifediegwu, S. I., Onwuka, O. S., (2020). Determining the occurrence of potential groundwater zones using integrated hydrogeomorphic parameters, GIS and remote sensing in Enugu State, Southeastern. Nigeria Sustainable Water Resources Management 6:39. https://doi.org/10.1007/s40899-020-00397-5

Kordestani, M. D., Naghibi, S. A., Hashemi, H., Ahmadi, K., Kalantar, B., and Pradhan, B., (2019). Groundwater potential mapping using a novel data-mining ensemble model. Hydrogeology 27:211–224. https://doi.org/10.1007/s10040-018-1848-5

Kumar, P., Herath, S., Avtar, R., and Takeuchi, K., (2016). Mapping of groundwater potential zones in Killinochi area, Sri Lanka, using GIS and remote sensing techniques. Sustainable Water Resources Management, 2(4), 419–430

Lentswe, G. B., and Molwalefhe, L., (2020). Delineation of potential groundwater recharge zones using analytic hierarchy process-guided GIS in the semi-arid Motloutse watershed, eastern Botswana. Hydrogeology: Regional Studies 28:100674

Magesh, N., Chandrasekar, N., and Soundranayagam, J. P., (2012). Delineation of groundwater potential zones in Theni district, Tamil Nadu, using remote sensing, GIS and MIF techniques. Geosience Frontiers. 3, 189–196.

Mahmoud, S. H., and Alazba, A. A., (2016). Integrated remote sensing and GIS-based Approach for deciphering groundwater potential zones in the central region of Saudi Arabia. *Environmental Earth Sciences* 75 (4): 344. doi:10.1007/s12665-015-5156-2

Masoumi, Z., Coello Coello, C. A., and Mansourian, A., (2020). Dynamic urban land-use change management using multi-objective evolutionary algorithms." *Soft Computing* 24 (6): 4165–4190. doi:10.1007/s00500-019-04182-1

Nasir, M., Khan, S., Zahid, H., and Khan, A., (2018). Delineation of groundwater potential zones using GIS and multi-influence factor (MIF) techniques: A study of district Swat, Khyber Pakhtunkhwa, Pakistan. *Environmental Earth Sciences* 77:367

Onyeagocha, A. C., (1980). Petrography and depositional environment of the Benin Formation, *Nig. Mining and Geology* 17 (2); p. 147-151

Oulidi, J., Löwner, H., Benaabidate, R., and Wächter, J., (2009). HydrIs: An open source GIS decision support system for groundwater management (Morocco)." *Geo-Spatial Information Science* 12 (3): 212–216. doi:10.1007/s11806-009-0048-9.

Panahi, M. R., Mousavi, S. M., and Rahimzadegan, M., (2017). Delineation of groundwater potential zones using remote sensing, GIS, and AHP technique in Tehran-Karaj plain Iran. *Environmental Earth Sciences* 76:792. https://doi.org/10.1007/s12665-017-7126-3

Pande, C. B., Khadri, S. F. R., Moharir, K. N., and Patode, R. S., (2017). Assessment of groundwater potential zonation of Mahesh River basin Akola and Buldhana districts, Maharashtra, India using remote sensing and GIS techniques. S*ustainable Water Resources Management*, 4 (4), 965–979

Rukundo, E., and Dogan, A., (2019). Dominant influencing factors of groundwater recharge spatial patterns in Ergene River catchment, Turkey. *Water* 2019, 11, 653.

Saaty, T. L., (1990). How to make a decision: The analytic hierarchy process. *European Journal of Operational Research* 1990, 48, 9–26. https://www.sciencedirect.com/science/article/pii/037722179090057I

Saaty, T. L., (2005). Theory and applications of the theory of the analytic network processes. Decision making with benefts, opportunities, costs, and risks. *RWS Publications*, Pittsburgh

Scott, G., and Rajabifard, A., (2017). Sustainable development and geospatial information: a strategic framework for integrating a global policy agenda into national geospatial capabilities. *Geo-spatial Information Science* 20 (2): 59–76. doi:10.1080/10095020.2017.1325594.

Shao, Z., Huq, M. E., Cai, B., Altan, O., and Li, Y., (2020). Integrated remote sensing and GIS approach using fuzzy-AHP to delineate and identify groundwater potential zones in semi-arid Shanxi Province. *Environmental Modelling and Software* 134:104868

Short, K. C., and Stauble, A. J., (1967). Outline of the Geology of the Niger Delta. *American Association of Petroleum Geologists Bulletin* 51: 761-769

Mukherjee, P., Singh, C. K., and Mukherjee, S., (2012). Delineation of groundwater potential zones in Arid Region of India—a Remote Sensing and GIS Approach." *Water Resources Management* 26 (9): 2643–2672. doi:10.1007/s11269-012-0038-9

Thapa, R., Gupta, S., Guin, S., Kaur, H., (2017) Assessment of groundwater potential zones using multi-infuencing factor (MIF) and GIS: a case study from Birbhum district, West Bengal. *Applied Water Science* 7:4117–4131. https://doi.org/10.1007/s13201-017-0571-z

The World Bank, (2021). Improving water supply, sanitation and hygiene services in nigeria. *Press Release*

Yeh, H. F., Cheng, Y. S., Lin, H. I., and Lee, C. H., (2016). Mapping groundwater recharge potential zone using a GIS approach in Hualian River, Taiwan. Sustainable Environmental Research. 2016, 26, 33–43.

Yıldırım, U., (2021). Identifcation of groundwater potential zones using GIS and multi-criteria decision-making techniques: a case study upper Coruh River basin (NE Turkey). ISPRS *International Journal of Geo-Information* 10(6):396. https://doi.org/10.3390/ijgi10060396

Zghibi, .A, Mirchi, A., Msaddek, M. H., Merzougui, A., Zouhri, L., Taupin, J. D., Chekirbane, A., Chenini, I., and Tarhouni, J., (2020). Using analytical hierarchy process and multi-influencing factors to map groundwater recharge zones in a semi-arid Mediterranean coastal aquifer. *Wat*er 12:2525