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Delineation of the Groundwater Potential Zones using Integrated Geospatial Techniques and Multi-criteria Decision Approach in the Cretaceous Lower Benue and Niger Delta Basins of Abia State, Southern Nigeria

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ABSTRACT

Delineation of the groundwater potential zones in the Cretaceous Lower Benue and Niger Delta basins of Abia state, Nigeria with geographic information system (GIS) / remote sensing (RS) multi-criteria decision approach (MCDA) considered the significant hydrogeomorphological factors affecting the availability of groundwater resources. The factors (geology, rainfall, slope, drainage density, lineament density, soil type, and land use land cover) were ranked using the analytical hierarchical process, a multi-criteria decision-making tool. The integration of the factors into a geographic information system (GIS) and weighted overlay analysis were then carried out using ArcGIS software. The result indicates 31.5% of zones of high to very high groundwater occurrence are in the southern section, and 41.6% of poor to very poor zones in the northern section. While the moderate zones make up the 26.8% of the study area. The study demonstrates that the groundwater occurrence in the study area is primarily controlled by the interactive impact of geology, rainfall, and slope factors, thus revealing the causes of the incessant random borehole failures in the moderate zones. Thus, the groundwater resources can be sustainably exploited, developed, and managed with the help of the map produced from the resulting demarcation of groundwater potential zones in the study.

Keywords:
Geographic Information System (GIS),
Remote Sensing (RS),
Analytical Hierarchy Process (AHP),
Weighted Overlay Analysis,
Groundwater Potential Zones Map

INTRODUCTION

Issues of scarcity in the midst of abundance as is the case with water resources must be addressed. Globally and annually, there is sufficient blue water to meet basic needs. The sufficiency is however strongly constrained by regional and seasonal variations causing water scarcity in some regions of the world during particular times. Approximately two thirds of the world's population suffers from severe water scarcity for at least a portion of the year (Mekonnen and Hoekstra, 2016). According to statistics, roughly 3.6 billion people suffers inadequate sanitation services, and about 55.6% of that lack access to clean and safe drinking water (UNWWDR, 2023). In Nigeria for instance, 60 million people lack home access to clean water despite several interventions from the government and River Basin Authorities (The World Bank, 2021).

Subterranean water has earned the status of the most significant natural resource for dependable and sustainable water supplies worldwide. It is thus evident that one of the challenging problems of this century and probably centuries to come is supplying freshwater to meet human demand while simultaneously safeguarding ecosystems within maximum sustainable limits per catchment. A contributing factor is the lack of data on water quantity, hydrology, hydrogeology (aquifer condition and withdrawal limits) which has led to unsustainable groundwater exploration and exploitation in several nations including Nigeria.

Location, Physiography and Geology of the Study Area

The study area is Abia state of Nigeria and spans approximately about 5,000 square kilometers between latitudes 4° 49' N and 6° 01' N and longitudes 7° 09' E and 8° 01E (Fig. 1).

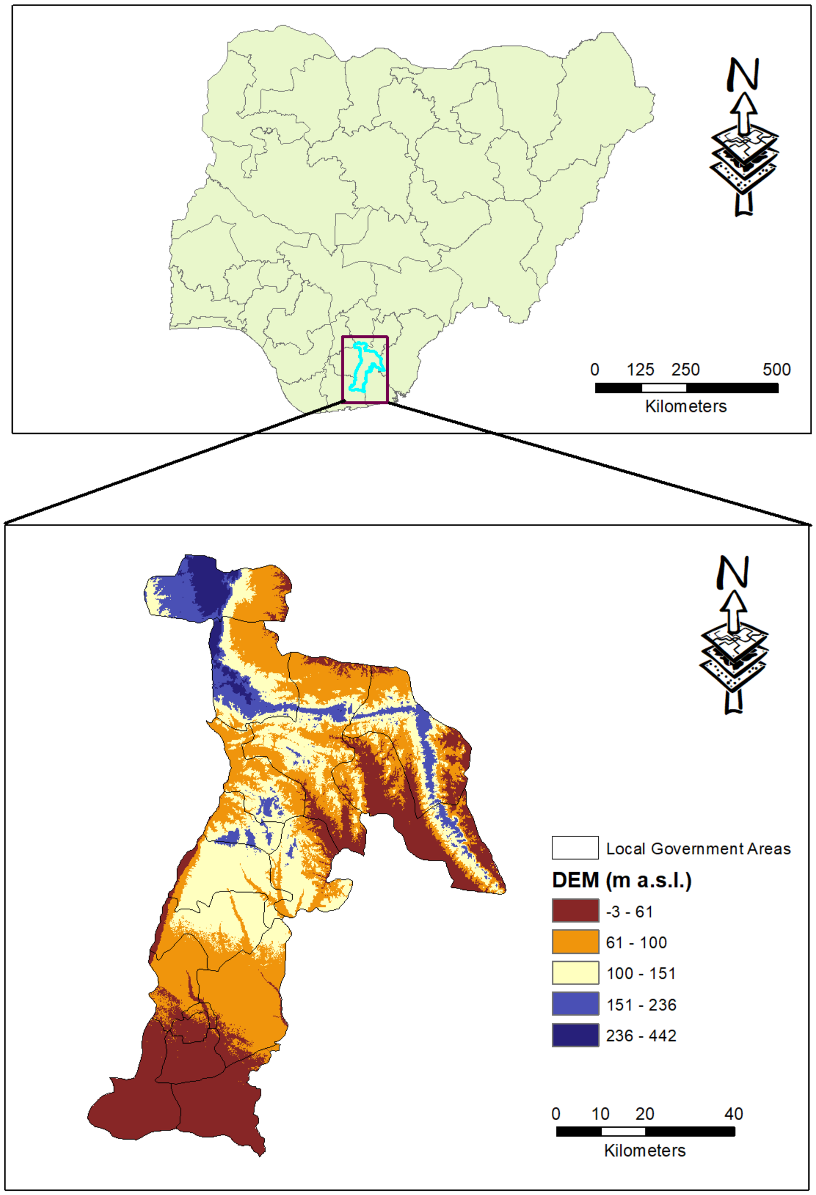

Figure 1: Map of the study area with its Digital Elevation Model (DEM)

The states of Anambra, Enugu, and Ebonyi border it to the north and northeast; Rivers and Imo border it to the south and southwest; and Akwa Ibom and Cross River border it to the east and southeast. The state is dominated by commercial, industrial, and agricultural activity; and has seen a sharp rise in population in recent years, which has consequently raised the demand for groundwater. Topographically, it is generally a low-lying to moderately high plain (-3 to 442m above sea level).

The study area, which is part of the sub-equatorial belt, receives between 2000 and 2400 mm of rainfall annually and 70% relative humidity. The rainfall peaks occur in July and September, with a little break in August. The aquifers found herein are replenished by a number of transient and recurrent streams. The average daily mean temperature varies from 23.5°C (between 23° and 24°C) in July to 30.5°C (between 29° and 31°C) in March over the course of the year's 3600 hours of sunshine. Forming an excellent dendritic drainage network, the two main rivers – Rivers Imo and Aba, along with all their tributaries greatly influence the region's watershed. While the former flows through the state and the boundary between the state and Imo state; the latter has its source from a valley in Ohuru Isimiri of Obingwa Local Government Area within the state flowing through many communities before joining the

Opobo River in Rivers State. Both rivers eventually empty into the Atlantic Ocean.

Geologically, the study area falls within the Cretaceous Lower Benue "CLBB' (Anambra basin), and the Cenozoic Niger Delta Basin (Tertiary Niger Delta Basin 'TNDB' and Tertiary-Quaternary Niger Delta 'T-QNDB' Basin).

The Cenozoic Niger Delta is situated at the intersection of the Benue Trough and the South Atlantic Ocean where a triple-R junction developed during the separation of the continents of South America and Africa in the Late Jurassic. Subsidence of the African continental margin and cooling of the newly created oceanic lithosphere followed this separation in Early Cretaceous times; and subsequently by Mid-Cretaceous onwards Marine sedimentation took place in the Benue Trough.

Benue Trough is arbitrarily divided into Lower, Middle and Upper Benue Trough; and by Santonian times Benue Trough underwent intense folding and compression whereby over 100 anticlines and synclines were formed.

After the Santonian-Campanian tectonism which formed the Abakiliki anticlinorium, the western margin of the Lower Benue Trough subsided, and the corresponding synclinorium became the Anambra basin where over 2500m of deltaic complexes accumulated. The Anambra Basin, which was created by the intense Middle-Santonian deformation and magmatism in the Benue Trough hosts the Cretaceous sediments of the Lower Benue Basin. With the series of tectonic events and the accompanied sea regressions and transgressions from Early Campanian to Palaeocene, the Nkporo, Mamu, Ajali, Nsukka and Imo Formation were deposited (Tattam 1944; Reyment, 1965, Obi, 2000; Obi et al.,, 2001). The Ajalli and Nsukka Formation are aquiferous units (Ukpai et al., 2017). The Ajalli Formation is a regional aquifer that provides a consistent supply of groundwater, while the Nsukka Formation is a perched aquifer. Other geological Formation are either non-aquiferous or poorly aquiferous due to their sedimentological characteristics.

However by Eocene, the inception of Tertiary Niger Delta basin commenced. Thus, the Late Cretaceous deltaic sedimentation in the Anambra basin was followed by the shift in deltaic deposition southward and consequently the construction or outbuilding of the Niger Delta took place.

The Niger-Delta started to evolve in Early Tertiary times when clastic river depositions increased leading to the delta progradation over the subsiding continental-oceanic lithospheric transition zone, and subsequently prograded on to oceanic crust of the Gulf of Guinea during the Oligocene. The source-sediments were through the weathering flanks of the continental basement outcrops of the Benue-Niger drainage basin. The delta has since Paleocene epoch prograded a distance of more than 250km from the Benin and Calabar flanks to the present delta front. The interplay between subsidence and deposition arising from a succession of sea transgressions and regressions (Hosper, 1965) gave rise to the deposition of three lithostratigraphic units in the Niger Delta (Short and Stauble, 1965).These units are Marine Akata Formation (Paleocene to Recent),, Paralic Agbada Formation(Eocene to Recent),, and the Continental Benin Formation (Miocene to Recent) in decreasing in decreasing age order (Short and Stauble, 1967; Avbobvo 1978; Doust and Omatola, 1990; Kulke, 1995).

Down dip towards the Niger Delta, the Akata Shale constitutes the Paleocene equivalent of the Anambra Basin (Imo Formation). Recent sediments deposited in coastal beaches, tidal channels and flats, lagoons, estuaries, mangrove and freshwater swamps, creeks, meander belts, and lakes with brackish water have been found to cap the Benin Formation. The overall thickness of these sediments is about 12,000 meters covering a total area of about 140,000km^2 (Obaje, 2009). The Benin Formation acts as the aquiferous unit at both shallow and deep depths, while the Akata and Agbada Formations are the basin's petroleum source and reservoir rocks, respectively (Murat, 1970; Amajor, 1991; Nwankwoala and Ngah, 2014).

The Aim, Justification/Significance of the Study and Choice of Methods

Globally in all the freshwater abstractions, one-third comes from groundwater (Das et al., 2018). It is a significant natural resource for any economic and social growth (Kordestani et al., 2019).

Abia State of Nigeria is one of the states in Nigeria where there are many reported cases of water boreholes' failure especially in the northern and central parts of the state while such cases are rarely reported in the southern part of the State.

Modern technologies that can factor in the peculiarities of each region must therefore be engaged to delineate the surface and groundwater resources.

For the fact that groundwater potential zones can be quickly and easily explored in a variety of geological contexts, sustainable development must be necessitated to alleviate the impact of water crisis on the teeming population (Scott and Rajabifard 2017). Consequently, novel, affordable, and effective tools are being sought in the exploration of groundwater. Groundwater potential zones have been delineated using many techniques (Igboekwe et.al, 2008; Afolayan et.al, 2004; Amos-Uhegbu and Ndubueze, 2022). Also, attempts in using remote sensing (RS) and geographic information system (GIS) techniques in determining groundwater potential zones have made it essential for long-term resource management. Central to this approach are multi-criteria decision-making techniques such as the analytical hierarchy process (AHP) which is due to its effectiveness and simplicity in allowing for the demarcation of potential zones (Achu et al., 2020; Aliabad et al., 2018). GIS and RS technologies are powerful tools that can manage vast amounts of geographical data which often involves natural resources evaluation and management; and their integration with AHP is quite popular in the subject of water resource engineering (Kaliraj et al., 2014; Chowdhury et al., 2010; Abel and Tijani 2011; and Ayele et al., 2014). Despite the use of many other techniques in search of groundwater in the study area, there are continuous reported cases of boreholes failure. Little or none of the earlier analyses of the groundwater potential of the study area have incorporated remote sensing, GIS methods, and AHP in a single investigation, nor were they carried out at a higher resolution than this study; hence the choice of this method. The aim of this study is to delineate the potential zones of groundwater resources in Abia State in an effort to fill a research gap by taking seven datasets into account - geology, rainfall, slope, drainage density, linear density, soil type, and land use land cover data. All the seven datasets play significant roles in the availability, distribution, and accessiblity to groundwater resources (Lentswe and Molwalefhe 2020, Amos-Uhegbu et. al., 2023). Furthermore, a detailed spatial groundwater potential map of Abia State is produced to help policymakers manage water resources more sustainably and, specifically, reduce the number of failed boreholes in the region.

MATERIALS AND METHODS

Multi-criteria decision making (MCDM) or multiple criteria decision analysis (MCDA), is a research area that involves the analysis of various available choices or factors in a situation or research area with the aim of determining the best alternative by considering more than one criterion in the selection process. This explicitly evaluates multiple conflicting criteria in decision making and is concerned with structuring and solving decisions involving multiple criteria.

In the delineation / evaluation of groundwater potential zones, there are many multi-criteria decision making methods such as Weights of Evidence (WOE), Index Models (IM). Fuzzy Logic (FL), Frequency Ratio (FR), Multi-Influencing Factor (MIF), Certainty Factor (CF), Ordinal Priority Approach (OPA), Analytic Network process (ANP), Analytical Hierarchy Process (AHP) etc. Amongst these methods, the most widely used is the AHP method because it one of the most efficient decisions making tools with reliable results (Murmu et al., 2019; Arulbalaji et. al., 2019).

Parameters of influence for the Evaluation of Groundwater Potential Zones

To choose acceptable criteria that have significant impact on groundwater occurrence, flow, storage and any other adequate proof indicative of groundwater availability is usually the initial necessary step to be taken in the evaluation of the groundwater potential of an area. Groundwater recharge is usually controlled by factors such as precipitation, land use land cover type, and rate of infiltration/percolation, whereas groundwater storage and movement are mainly controlled by the underlying lithology, soil characteristics, landforms, lineament and drainage/spring densities (Shao ET AL., 2020, Ifediegwu, 2021, Amos-Uhegbu et al., 2023). By taking into consideration the aim of the study, reconnaissance survey, literature review, the general characteristics of the study area, and the decisions of professionals in various fields related to groundwater; relevant hydrogeological, physiographical and biophysical information of the study area were outlined for the study; and the rankings of parameters in terms of their significance to groundwater potentiality were gotten. Seven (7) parameters: geology, rainfall, slope, drainage density, linear density, soil type, and land use land cover data were chosen in order of the significant roles they play in the availability, distribution, and accessibility of groundwater resources.

Geology

The lithological characteristics of the local rocks have a significant impact on both the infiltration and percolation of water into the ground (Mukherjee et al., 2012). Given that geology entirely controls the penetration and percolation of groundwater, it is an important factor to consider when evaluating groundwater potential (Aju et al.,2021).

Water infiltration and percolation into the subsurface can be strongly influenced by the lithological characteristics of the rocks existing in a region (Mukherjee et al., 2012). Since the lithology primarily controls both the porosity and fracture pattern, it has a significant impact on the storativity and permeability of the aquifers.

Rainfall

Period and intensity of rainfall also play a significant role in replenishing the groundwater. As has been pointed out that over an extended period of time, modest amounts of low-intensity rainfall will have a positive effect on the groundwater (Nasir et al., 2018).

Slope

Slope directly affects the surface runoff mechanism of an area and therefore affects groundwater recharge (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. Terrains of high steepness have poor groundwater potential due to faster water run-off and more erosion with less potential for recharge (Magesh et al., 2012a, b; Ganapuram et al., 2009; Nistor 2019; Igwe ET AL., 2020). Ordinarily, alluvial plains, flood plains, and plateaus are better suited for groundwater occurrence because such terrains favour greater infiltration capacity which in turn increases groundwater recharge. While, increased slope angles have negative effects on infiltration and groundwater recharge (Rukundo and Doan 2019, Conrad and Adams, 2007).

Drainage Density

The length of the stream channel per drainage watershed area is known as the drainage density (Magesh et al., 2012a, b). The density of drainage systems can also affect how quickly water percolates into the ground, especially during precipitation when a dense network of drainage allows water molecules to exit the system more quickly. Climate, lithology, relief, infiltration capacity, vegetation covers, and runoff intensity index all affect how a drainage system develops. A high drainage density value, especially in alluvial sediments, indicates a low groundwater potential zone because it promotes runoff. Low-permeable lithology, sparse vegetation, high relief regions, and higher rainfall intensities favour a dense network (Bali et al., 2012).

Lineament Density

Lineaments are linear or curvilinear features with structural control that are identified by their relative linear alignments in satellite imagery. The underlying structural features, such as faults, fracture zones, and geological contacts between various lithologies enhances permeability and secondary porosity; such features give expression to surface topography being mapped as lineament (Bashe, 2017; Nair et al., 2017). Lineament features are significant parameters in hydrogeology because they provide pathways for groundwater flow and also determine permeability (Magesh *et al.*, 2012). This is indicative that water infiltration rate increases with increasing lineament density because areas of high lineament density will have greater water circulation, and subsequently greater groundwater potential.

Soil Type

The kind of soil, which is determined by the processes of pore saturation or desaturation, 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 because coarse-grained matrices have stronger groundwater potential, while fine-grained matrices have poorer groundwater potential.

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, thus the impacts of these land use land cover elements give rise to low permeability (Doerr ET AL., 2006; Masoumi ET AL., 2020). Therefore, it significantly affects groundwater recharge.

Data acquisition and the development of thematic layers

Already seven significant parameters (geology, rainfall, slope, drainage density, lineament density, soil properties, and land use land cover) have been chosen for the study. The parameters are to be generated and combined with their thematic layers to create a groundwater potential zones map using ArcGIS 10.3 software, while taking into consideration the aim, the literature review, the available information, the acquired data, and the characteristics of the study area. The full collection of map themes was rendered in the UTM Projection Zone 32N, Datum WGS84; and articulated steps were taken in generating the groundwater potential map for the study area (Fig. 2).

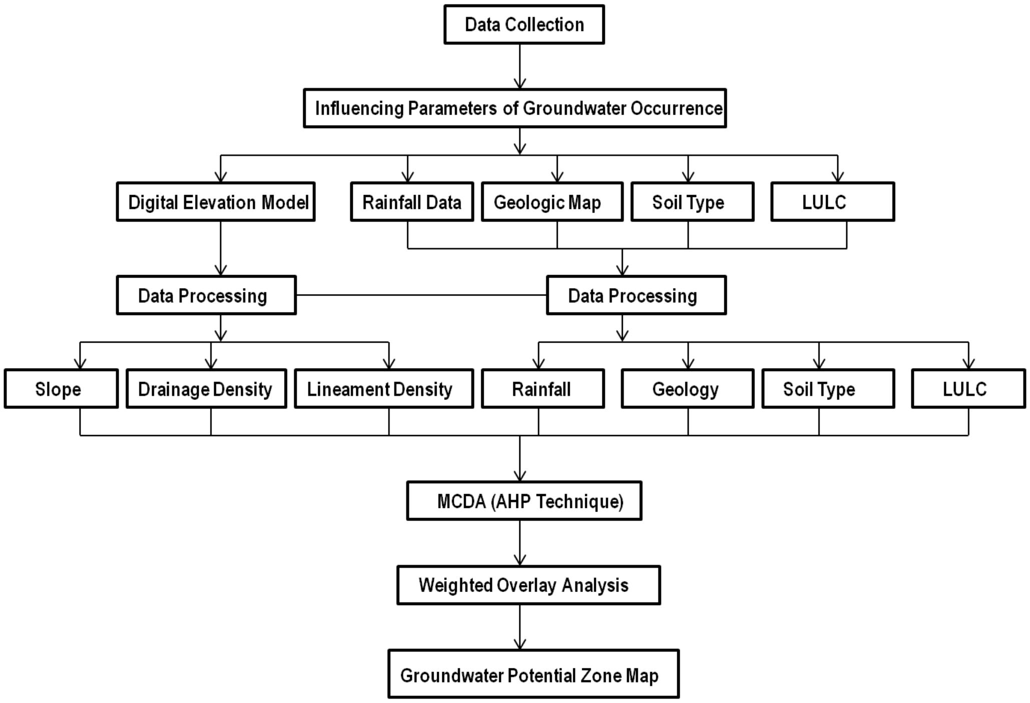

Figure 2: Methodological Workflow of the Research Investigation

The geology map of the study area was created from the United States Geological Survey's world geologic maps (https://www.usgs.gov/media/images/world-geologic-maps-data-downloads). While, the rainfall data was created from the high-resolution gridded datasets of the climatic research unit (https://crudata.uea.ac.uk/cru/data/hrg/).On the other hand, the FAO/UNESCO soil map of the world was used to create the soil map of study area (https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/faounesco-soil-map-of-the-world/en/). Similarly, the land use land cover map of the study area was created from the ESRI land cover - living atlas (https://livingatlas.arcgis.com/landcover/). 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 aforementioned data were obtained in December, 2023.

The Digital Elevation Model (DEM) of the study area was suitably processed within ArcMap to obtain fracture lines, from which the lineament density map of the study area was created in line with equation (1)

$$\mathrm{Ld} = \sum_{-1}^{n} \left(\frac{\mathrm{L_i}}{\mathrm{A}}\right) \qquad (1)$$

Where, Li is the length of the ith lineament, $\sum Li$ is the total length of the entire lineaments (km); and A is the area of the grid (km^2). The azimuth and altitude values were adjusted after reviewing literatures in order to produce a linear representation that accurately reflects the study area. When the detected lineaments were compared to slope face of the study area, a positive correlation was found thus indicating the reliability of the software's output.

The drainage density of the study area was produced from the stream networks in line with equation (2):

$$Drainage\ density = \frac{Total\ length\ of\ river\ network\ (km)}{Drainage\ area\ (km^2)}$$

$$\mathrm{Dd} = \sum_{-1}^{n} \left(\frac{\mathrm{D_i}}{\mathrm{A}}\right) \qquad (2)$$

Where, $\sum Di$ is the total length of all the streams in stream order i (km); and A is the area of the watershed (km^2).

The SRTM 1 Arc-Second Global DEM data with cell size resolution of 30 m, pixel depth of 16 bit, and datum WGS 1984 was used to create the slope map of the study area.

The rainfall distribution map was created from the high-resolution gridded rainfall datasets by spatially interpolating the data using the Inverse Distance Weighted (IDW) method after they were imported into ArcMap. This interpolation technique combines the ideas of trend surface gradual changes with proximity to follow Thiessen polygons deduced with equation (3):

$$\mathrm{P} = \frac{p1+P2+p3\ .....Pn}{n} \qquad (3)$$

Where, P is the annual average amount of rainfall data of the area for 35years, P_1, P_2, P_3 and P_n are the annual rainfall data at various observatory locations 1, 2, 3, for 35years and n is the total number of observatory locations within the catchment area.

Finally, the analytical hierarchy process (easyAHP tool) was used to apply the appropriate weights to the resulting geographical (thematic) layers in accordance with their evaluated hierarchy of groundwater potential modified after Saaty's 1–9 significance scale (Table 1). The weighted data layers were overlaid to produce the spatial map of the groundwater potential zones by using the weighted overlay tool of ArcGIS 10.3 software.

Table 1: AHP's Fundamental scale (Modified after Saaty, 1980)

Less influential	Extremely less important	1/9
	Very strongly less important	1/7
	Strong importance	1/5
	Moderately important	1/3
Equally influential	Equal importance	1
More influential	Moderately more important	3
	Strongly more important	5
	Very strongly more important	7
	Extremely more important	9
Intermediate values		2, 4, 6, and 8

Multi-Criteria Decision Making (MCDM) via Analytic Hierarchy Process (AHP)

The most popular Multi-Criteria Decision Making (MCDM) technique for evaluating groundwater potential is Analytic Hierarchy Process (AHP), which has been shown to have superior accuracy when it comes to mapping groundwater potential (Murmu et al., 2019; Arulbalaji et al., 2019; Singh et al., 2018). AHP is 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). Here, the pairwise comparison of the alternatives was carried out using the systematic and random assessments or decisions of various professionals (hydrologists, hydrogeologists, environmentalists, GIS experts, exploration engineers and geoscientists) pertaining to groundwater potential. 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 relevant values of the criteria are obtained (equation 4).

$$A = \begin{bmatrix} a_{11} & \cdots & a_{n1} \\ \vdots & \ddots & \vdots \\ a_{1n} & \cdots & a_{nm} \end{bmatrix} i, j = 1, 2, \ldots, n. \qquad (4)$$

Where, A is the pairwise comparison matrix; (a_{ij}) are the elements of the comparison matrix, and n shows the number of criteria.

The relationship between the seven thematic layers and the relative importance of each theme was determined and modified in accordance with Saaty's 1–9 significance scale. Each map was given a value based on the significance of its influence on the groundwater potential of the study area; and the values subsequently contrasted (Table 2). The normalized weights are computed using the geometric mean of the criteria in the second step of the AHP computations (equation 5).

$$\mathrm{Wn} = \frac{Gm}{\sum_{-1}^{n} \mathrm{Gm}} \qquad (5)$$

Where W denotes the Eigen vector weights and Gm denotes the geometric mean of the *ith* row of the judgment.

Table 2: The Pairwise Comparison Matrix and the normalised weights

Theme	Geology	Rainfall	Slope	Drainage Density	Lineament Density	Soil Type	Land Use Land Cover	Normalised Weight
Geology	1.00							0.432
Rainfall	0.33	1.00						0.221
Slope	0.20	0.50	1.00					0.115
Drainage Density	0.17	0.25	0.50	1.00				0.098
Lineament Density	0.14	0.25	0.50	0.50	1.00			0.068
Soil Type	0.13	0.17	0.33	0.25	0.33	1.00		0.038
Land Use Land Cover	0.11	0.14	0.25	0.20	0.33	0.50	1.00	0.028

MCDM -Overlay Analysis, Criteria Standardisation, Demarcation and Validation of Groundwater Potential Zones (GWPZs)

Examining the consistency of the normalised criteria weights is the last step in the AHP technique. In this stage, consistency of the decisions of various professionals were examined and finalized; while the accuracy of the matrix is determined by the Consistency Ratio (CR). It is a deviation or degree of consistency. The recommended CR values are as follows: < 0.05 for a 3 × 3 matrix, < 0.09 for a 4 × 4 matrix and 0.1 for larger matrices (Saaty, 1990).

Consistency ratio (CR) is a measure of consistency that the AHP provides by utilizing the principal eigen value and consistency index (Saaty 2004). It is determined as follows in equation (6):

$$CR = \frac{CI}{RI} \qquad (6)$$

Where CR denotes consistency ratio, RI denotes for random consistency index (Table 3); and CI denotes consistency index which is determined using equation (7).

$$CI = \frac{\lambda\max - n}{n-1} \qquad (7)$$

Where, λmax is the highest or principal eigen-value of the matrix calculated from the matrix; and n denotes the number of independent rows of the matrix.

The highest eigen-value of the matrix (λmax) is calculated by using equation (8).

$$\lambda_{\max} = \sum_{j=1}^{n} \frac{(A-\nu)j}{n\nu_j} \qquad (8)$$

Where n denotes the number of independent rows of the matrix, $\boldsymbol{A}$ denotes pair-wise comparison matrix, and v the matrix eigen-vector

Table 3: Random index (*RI*) corresponding to the number of evaluation criteria (*n*) (Saaty, 1990)

Evaluation criteria (n)	1	2	3	4	5	6	7	8	9	10
Random Index (RI)	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

For the weights to be considered consistent, the CR value must not be higher than 0.10 otherwise, the pairwise comparisons must be re-examined (Franek and Kresta 2014). The specified range ensures that the consistency of responses is maintained, thus ascertaining the reliability of the computation.

The pairwise comparison matrix and normalized weight values for the criteria used in this investigation shows that the consistency ratio (CR) is 0.06 which is well within the recommended standard (Table 2, Table 4).

Finally, the normalized weight values and pairwise comparison matrix for the evaluation's criteria show that the various thematic features have been relatively ordered according to strength of their significant influence in groundwater occurrence (Table 4).

For data standardization, all the decision criteria were reduced to a single scale of measurement whereby the distinct features of each thematic layer were also rated and recorded on a scale of 1–5, which ranges from very poor to very good (Table 4). Data standardization, along with AHP, is widely used in GIS-based decision support research (Aykut 2021; Benjmel et al., 2020; Panahi et al., 2017). A tripartite approach was followed in the rankings (thorough knowledge of the study area, literature review and consultations from various professionals). 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. The seven thematic layers were thereafter integrated in Arcmap and through weighted overlay function; the groundwater potential map for the study area was generated.

Table 4: Relative weight of various thematic layers and their corresponding classes

No	Theme	Various Classes					CR	Weight
1	**Geology**	CLBB	TNDB	T-QNDB			0.09	0.432
	Weight	1	3	5				
	Ranking	0.120	0.272	0.608				
	Class	Very Poor	Moderate	Very Good				
2	**Rainfall**	2019.34 – 2106.61	2106.61 – 2177.77	2177.77 – 2238.18	2238.18 – 2298.60	2298.60 - 2361.70	0.10	0.221
	Weight	0.047	0.085	0.150	0.259	0.459		
	Ranking	1	2	3	4	5		
	Class	Very Poor	Poor	Moderate	Good	Very Good		
3	**Slope**	0 - 2.43	2.43 – 4.85	4.85 – 8.32	8.32 – 13.69	13.69 – 44.20	0.07	0.115
	Weight	0.501	0.230	0.150	0.069	0.049		
	Ranking	5	4	3	2	1		

	Class	Very Good	Good	Moderate	Poor	Very Poor		
4	**Drainage Density**	0 – 0.35	0.35 – 0.63	0.63 – 0.93	0.93 – 1.29	1.29 – 2.21	0.05	0.098
	Weight	0.475	0.285	0.134	0.063	0.043		
	Ranking	5	4	3	2	1		
	Class	Very Good	Good	Moderate	Poor	Very Poor		
5	**Lineament Density**	0 – 0.000083	0.000083 – 0.000206	0.000206 – 0.000293	0.000293 – 0.000382	0.000382 – 0.000541	0.08	0.068
	Weight	0.035	0.068	0.134	0.260	0.503		
	Ranking	1	2	3	4	5		
	Class	Very Poor	Poor	Moderate	Good	Very Good		
6	**Soil Type**	Thionic Fluvisols	Dystric Nitosols	Xanthic Ferralsols	Dystric Gleysols	Dystric Fluvisols	0.09	0.038
	Weight	0.055	0.089	0.160	0.264	0.432		
	Ranking	1	2	3	4	5		
	Class	Very Poor	Poor	Moderate	Good	Very Good		
7	**Land use land cover**	Urban and Built-up Land	Mixed Dryland	Dryland Cropland	Shrubland	Savanna	0.10	0.028
	Weight	0.019	0.032	0.041	0.075	0.104		
	Ranking	1	1	2	2	3		
	Class	Very Poor	Very Poor	Poor	Poor	Moderate		
	Land use land cover	Grassland	Deciduous Broadleaf Forest	Cropland /Grassland Mossaic				
	Weight	0.148	0.191	0.390				
	Ranking	3	4	5				
	Class	Moderate	Good	Very Good				

RESULTS AND DISCUSSION

Lithology

The Cretaceous Lower Benue Basin and the Cenozoic Niger Delta Basin are the two basins within the study area (Fig. 3). The Cretaceous Lower Benue Basin (CLBB) accounts for 36.73% of the study area; while the Niger Delta Basin takes up the remaining 63.27% (T-QNDB: the Tertiary to Quaternary sediments account for 39.54%, and TNDB: the Tertiary sediments account for 23.73%). Geology has been found to be hydrogeologically responsible for the complex distribution, extractability, and quality of groundwater in these basins.

The central and southern regions of the study area are found to have more aquiferous units than its northern region. The lithology of such areas favouring groundwater occurrence is mainly sandstone. Since the study area is within sedimentary terrains, also influencing groundwater recharge is the structure and texture of soils. Fine-textured soils typically have lower infiltration rates and higher runoff rates than their coarse counterparts.

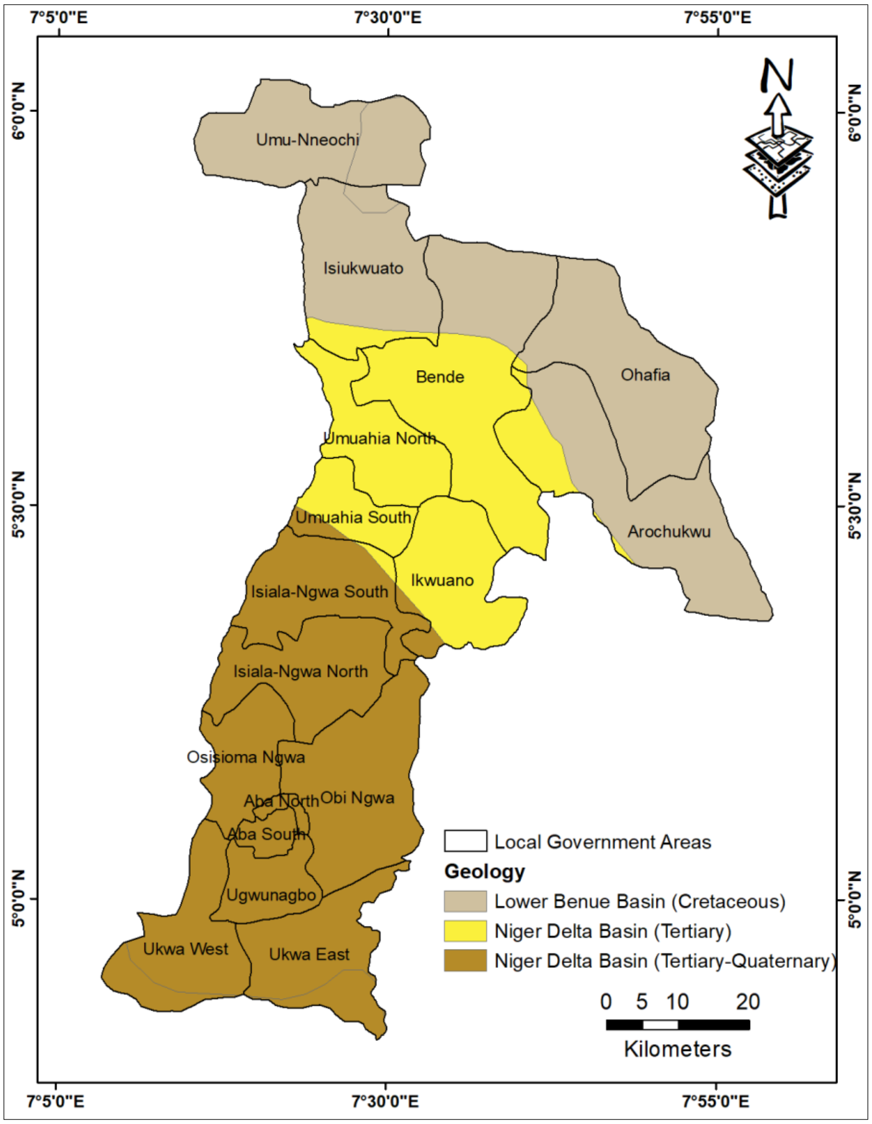

Figure 3: Geologic Map of the Study Area

Precipitation

The annual average rainfall amounts are higher in the southern parts of the area with a progressive decrease northerly (Fig. 4). The likelihood of a better groundwater potential in the southern part is favoured by the rainfall distribution and distinct rainfall pattern (2,019mm to 2,361mm per annum), as well as the slope gradient in the northern part. Under the same geomorphological conditions, it is theoretically possible for the groundwater potential in areas with higher rainfall rates to exceed that of areas with lower rainfall rates. Nevertheless, rainfall is not the only factor that matters in this context; period and intensity of rainfall also play a significant role in replenishing the groundwater. As has been pointed out that over an extended period of time, modest amounts of low-intensity rainfall will have a positive effect on the groundwater (Nasir et al., 2018). The rainfall thematic layer came in second place with a normalized weighting value of 0.221.

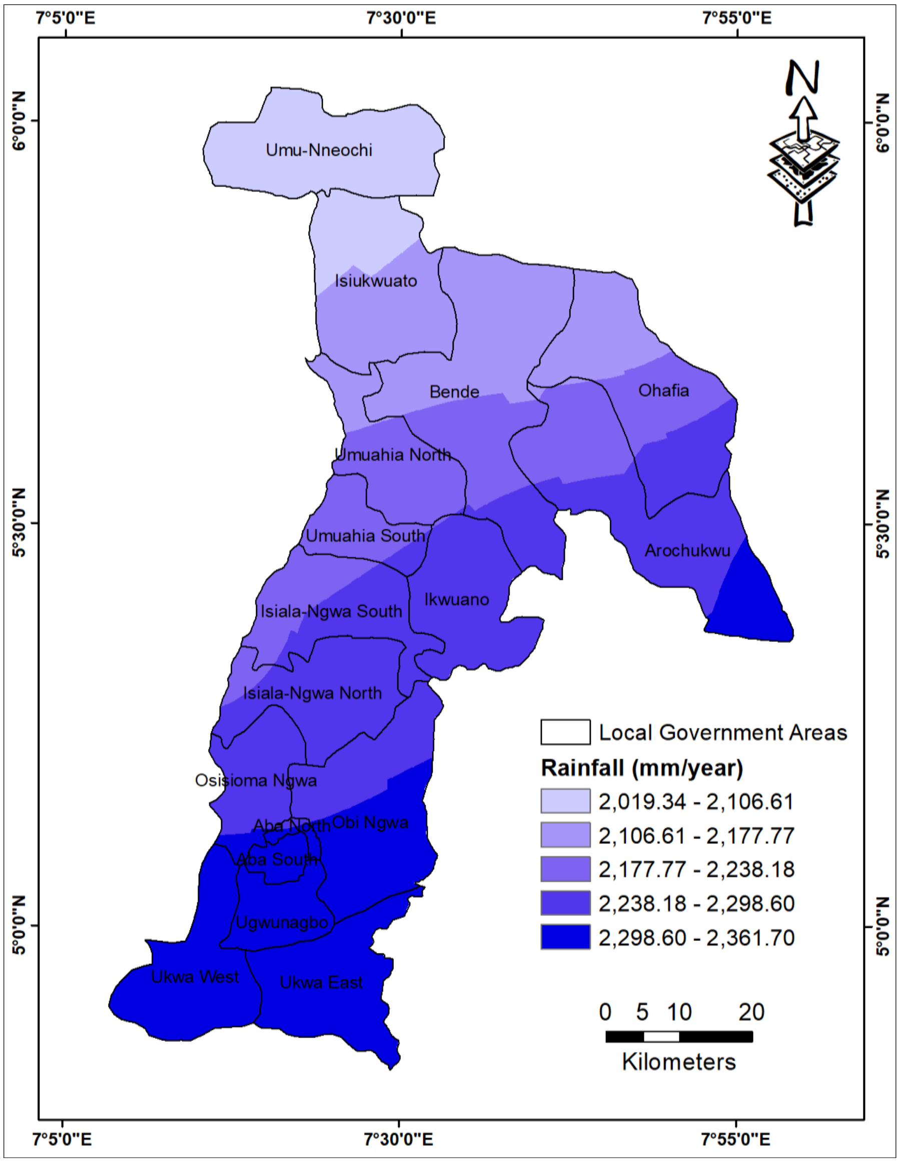

Figure 4: Rainfall Map of the study area

Slope

The slope of the study area, an expression of shape and relief of the ground surface is illustrated. The range of values of the slope was used to divide the study area into five classes (Fig. 5). Since surface slope primarily determines runoff and infiltration rates, areas with a slope of 0–2.43° (roughly 43.6% of the study area) are classified as "very good" in influencing recharge due to their nearly level terrain and relatively low runoff movement downstream (Manna et al., 2016; Zghibi et al., 2020). Having an opposite influence is 1.3% of the study area with higher slope (>13.79°) thus classified as extremely poor. The topography of the remaining 55.1% of the study area having 2.43–13.69° slope values is somewhat elevated. Third place went to the slope thematic layer as it had a normalized weighting value of 0.115.

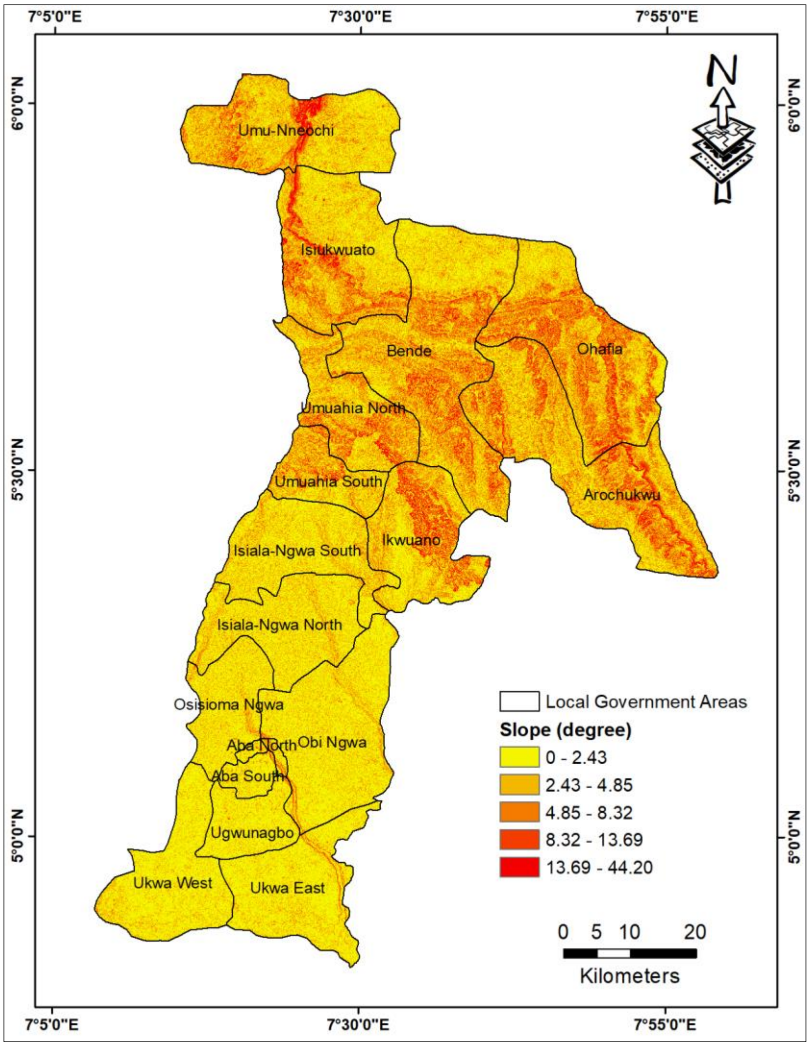

Figure 5: Slope Map of the Study Area

Drainage Density

In the groundwater system, drainage and lineament densities are essential because they serve as an aquifer's outlet and an improved natural recharge mechanism. It has been established that high lineament density raises groundwater potential (Rashid et al, 2012) which however has an inverse relationship with dense drainage system (Nair et al., 2017). There are five drainage density classes in the study area (Fig. 6). The classes could be grouped into two extremes of approximate halves as the low dense and the high dense areas. Among the other thematic layers, the drainage density ranked fourth after having a normalized weighting value of 0.098 in the pairwise comparison matrix. As was previously mentioned, drainage density's relationship to surface flow velocity and permeability indirectly relates to the suitability of groundwater potential zones. It is thus implied that there will be less water infiltration to the subsurface and a high surface flow velocity given the high drainage density of this area.

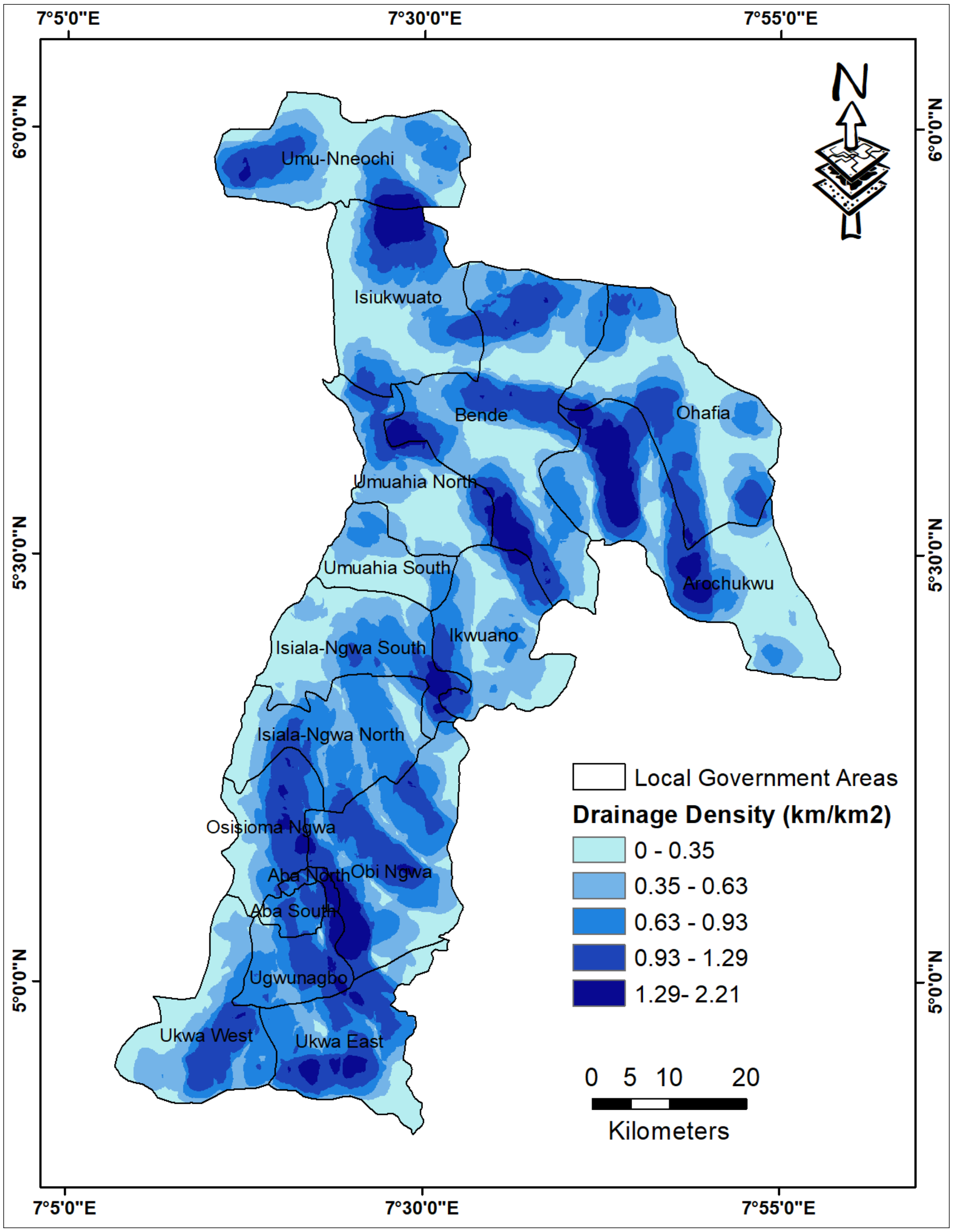

Figure 6: Drainage Density Map of the Study Area

Lineament Density

From the lineament density map of the study area, two observations are made (Fig. 7). First, the principal trends of the lineaments are NW–SE and NE–SW directions. Secondly, the central to the northern region is denser. Since the presence of lineaments typically indicates a permeable zone, groundwater potential zones are thought to be best in areas with dense lineament (Haridas et al., 1998; Lentswe and Molwalefhe, 2020). Such area will have more water circulation and thus more favourable for groundwater development. Among the parameters used to determine groundwater potential zones in the current study, lineament density is ranked fifth with a normalized weighting value of 0.068 (Table 2). The lineament density is generally low, with approximately 45% of the study area having a value < 0.000083 km/km^2.

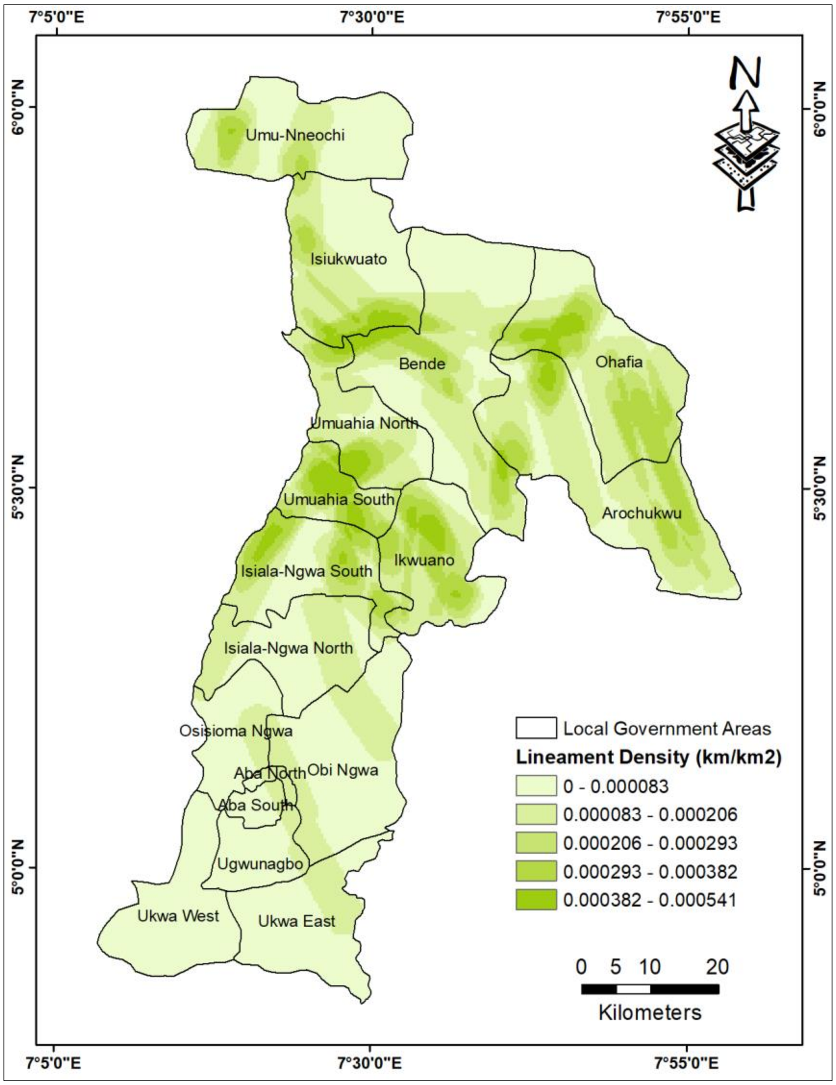

Figure 7: Lineament Density Map of the Study Area

Soil Type

Among the layers taken into consideration, the soil type's thematic layer came in sixth place with a normalized weighting value of 0.038. In increasing coverage area, Dystric gleysols (0.73%), dystric and thionic fluvisols (15.09%), xanthic ferralsols (25.91%), and dystric nitosols (58.27%) make up the soil type of the studied location (Fig. 8). The intense weathering of basic rocks found in level to undulating lands produces ferralsols and nitosols. While they are both permeable and free-draining soils, nitosols are less weathered. Gleysols are hydromorphic soils with basic to acidic mineralogy that are confined to low landscape positions and depression areas. Periodically flooded regions (unless they are embоldered) of alluvial plains, river fans, valleys, and (tidal) marshes are the parents of fluvisols. In addition to having a greater capacity to retain water than their counterparts, thionic fluvisols also contain acid sulfate which has a negative impact on water quality. To varied degrees, the soils are generally conducive to the occurrence of groundwater, though they can occasionally become dense as a result of frequent wetting and drying.

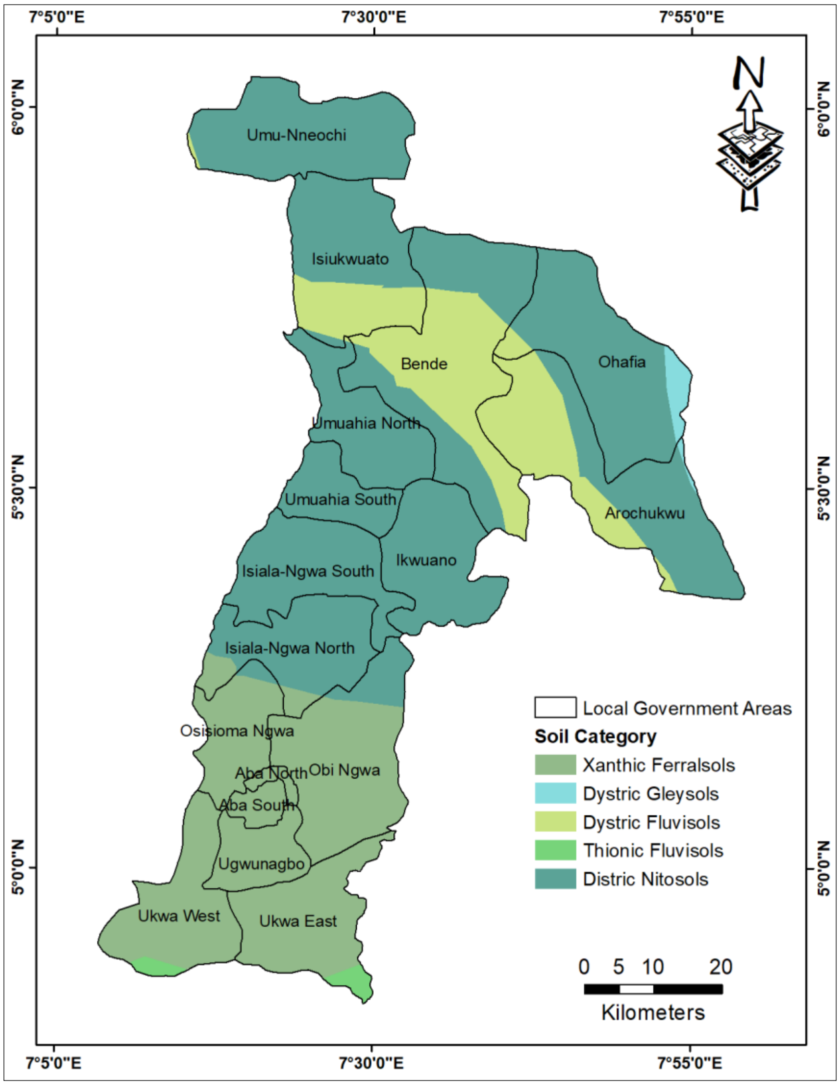

Figure 8: Soil Type Map of the Study Area

Land Use Land Cover

Because its effects are primarily manifested in changes in recharge, land use land cover has a significant impact on the occurrence and development of groundwater (Lerner and Harris, 2009). The land use type influences water percolation into the subsurface (Doer et al., 2006; Masoumi et al., 2020). Cropland/grassland mosaic, deciduous broadleaf forest, savanna, grassland, shrubland, dryland cropland and pasture, mixed dryland, and urban and built-up land are in descending order of infiltration of the land use land cover type found within the study area (Fig. 9). These categories were obtained based on the United States Geological Survey (USGS) land-use land cover classification system (Anderson 1976).

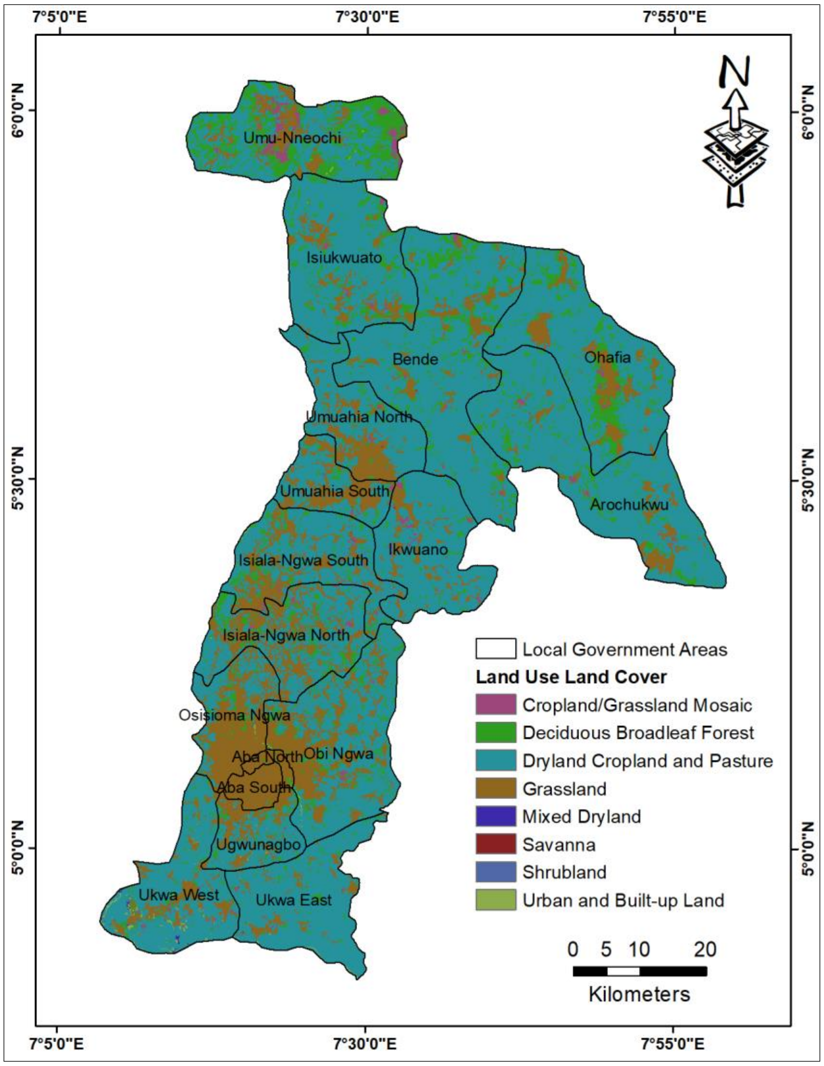

Figure 9: Land Use Land Cover Map of the Study Area

The land use of the study area is divided into eight classes with dryland cropland and pasture owning more than 70% of the total area (Fig. 9). This implies that the residents engage in extensive agricultural activity. It also implies that evapo-transpiration rate is relatively high; a region with a high rate of precipitation, like the study area, ought not to have large dryland coverage. Based on the type of land use, area coverage, infiltration capacity, and water retention capacity, the land use was classified for weighted analysis. With a normalized weighting value of 0.028, land use land cover ranked least of the seven thematic layers.

Classification of Groundwater Potential Zones

The groundwater potential zones were estimated using the normalized weighting of the individual thematic layers (Table 2). Very poor, poor, moderate, good, and very good groundwater potential zones were consequently delineated (Fig. 10). The very good potential zone encompasses approximately 7.4% of the entire area. The good potential zone, found in the southern portion, makes up about 34.2% while the moderate zone is located in the center, covering 26.8% of the area. Poor and very poor zones, with respective areal extents of 30.8% and 0.7%, make up the remaining areas located in the far north of the study area.

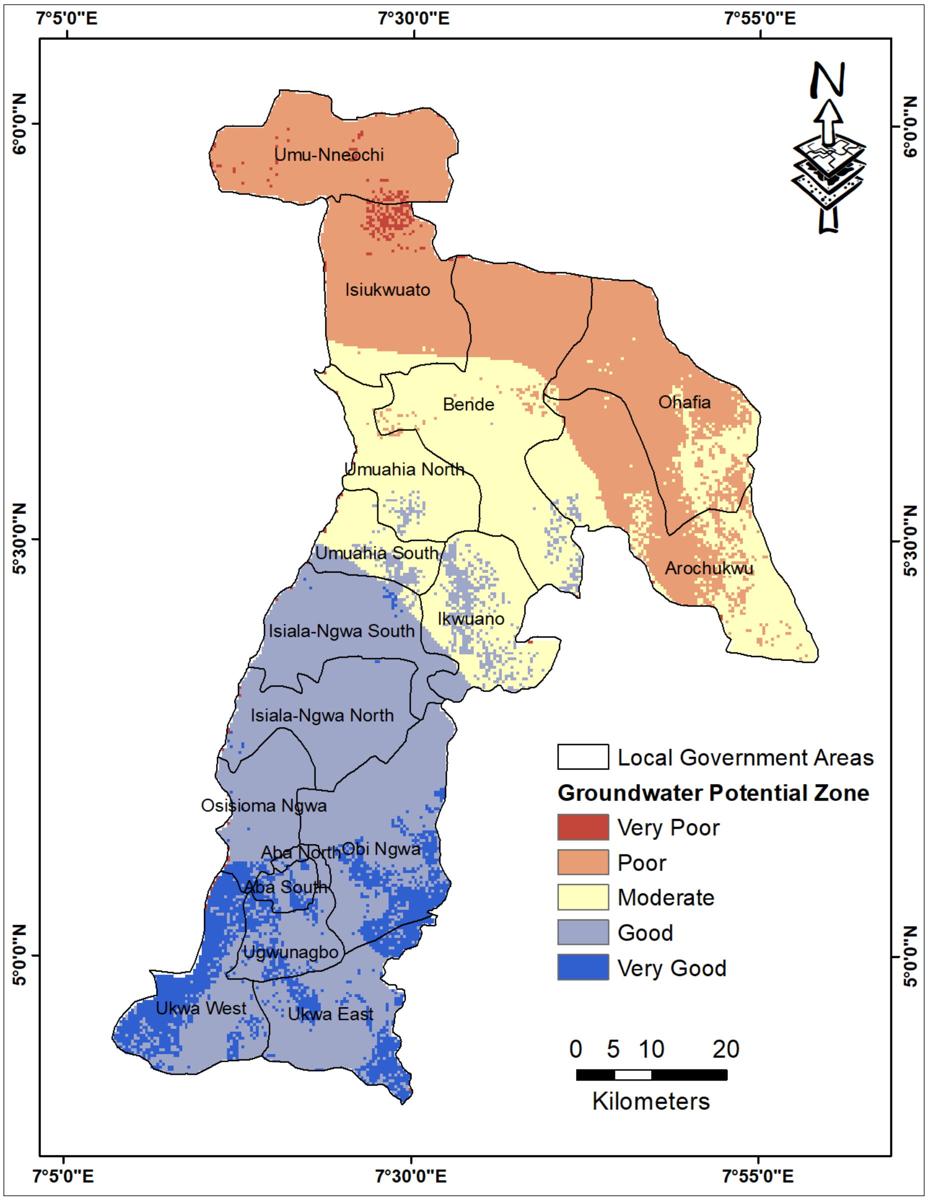

Figure 10: Groundwater Potential Zones Map of the Study Area

The local government areas in each zone class are outlined (Table 5). The most favourable zones align with regions of Benin Formation's Tertiary to Quaternary sediments, gentlest slopes and most rainfall recipient. The otherwise steep slope impeding recharge may have contributed to the occurrence of the poor zones in the northern area. A close examination of the groundwater potential zone map reveals that slope, rainfall patterns, and geological formations all essentially influence the amount of groundwater that would be available.

Table 5: Classification of Groundwater Potential Zones

Potential zone	Area (%)	Local Government Areas
Very Poor	0.71	Umu-Nneochi, Isiukwuato, Ohafia, Arochukwu
Poor	30.82	
Moderate	26.84	Bende, Umuahia North, Umuahia South, Ikwuano
Good	34.23	Isiala-Ngwa South, Isiala-Ngwa North, Osisioma Ngwa, Obi Ngwa, Aba North,
Very Good	7.40	Aba South, Ugwunagbo, Ukwa West, Ukwa East

CONCLUSION

The delineation of the groundwater potential zones in Abia state, Nigeria using GIS-RS data and multi-criteria decision approach was carried out in this study. The AHP technique used in multi-criteria decision approach gave rise to the use of seven significant parameters or criteria being ranked according to their influence on groundwater potentials. The thematic maps of the parameters (geology, rainfall, slope, drainage density, lineament density, soil type, and land-use land cover) were extracted and weighted accordingly by making pairwise comparisons and weighted overlay analysis; and were further integrated into Arcmap using ArcGIS 10.3 software to produce the groundwater potential zones map of the study area. A classification of the map was done into five classes: very poor potential, poor potential, moderate potential, good potential, and very good potential. The very good potential zone encompasses approximately 7.4% of the entire area. The good potential zone is in the southern part and it’s about 34.2%, while the moderate zone is located in the central part of the study area covering 26.8% of the area. Poor potential zone have cover about 30.8% of the study area and it is mainly in the Northern area, and very poor zone have 0.7% of the remaining areal extent located in the far north of the study area. It is observed that three significant factors (slope, geological formation, and rainfall patterns) out of the seven were more responsible in the determination of the groundwater potentiality of the study area; but the steep slope may have contributed more to the occurrence of the very poor zones and poor zones in the northern area.

Finally, the delineation of groundwater potential zones in the study area by the integrated use of GIS-RS data and AHP-multi-criteria decision has proved to be a reliable alternative and cost-effective method because a comparison of the findings with field experience and researches using other conventional methods corroborates the integrity / reliability of the generated groundwater potential zones map. Therefore, the implementation of the findings of the generated groundwater potential map, together with field experience shall give rise to the optimal management and sustainable use of groundwater in the study area. Furthermore, challenges and failure rates of groundwater exploration and exploitation can be reduced drastically in the study area. The method and research results can be considered for the development of regions with similar lithological, physiographical, geomorphological and climatic factors; and subsequently the basis for further researches have been created.

Subsequently, the outcome of this study will assist government agencies and relevant stakeholders (urban planners, environmental and natural resource managers etc) in developing efficient response strategies in tackling the environmental and economic challenges being faced with the exploration and exploitation of groundwater resources in the study area

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