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Research Article

Assessing Spatial Correlations Between Groundwater Potential Zones and Borehole Productivity in Lokoja, Nigeria

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ABSTRACT

This study evaluates groundwater potential zones in Lokoja Metropolis, Kogi State, Nigeria, using remote sensing and geospatial techniques. We analyzed Landsat 8 OLI satellite imagery, the Digital Elevation Model (SRTM), rainfall data, soil and geological maps, and borehole-yield data. The Analytical Hierarchy Process (AHP) was used to assess factors influencing groundwater potential, including geology, rainfall, lineament density, drainage density, slope, elevation, soil, and land use/land cover. The results show that Very low potential zones 14.01% (46.65 km²), underlain by amphibole schist, Low potential zones 24.02% (79.97 km²), with granite and charnockite, Moderate potential zones 24.93% (82.96 km²), underlain by migmatite, High potential zones 23.75% (79.06 km²), associated with sandstone and siltstone and Very high potential zones 13.24% (44.06 km²), in areas of undifferentiated alluvium. Findings indicate that geology is the major factor influencing groundwater potential (37% weight), lineament density has a significant influence (18% weight), and land use/land cover has a moderate influence (5% weight). Strong positive correlation of 0.917 between borehole yields and groundwater potential map, with a prediction accuracy of 78%. The study findings can inform decision-making for sustainable groundwater management in Lokoja Metropolis. The study recommends that the government provide alternative water sources in areas identified as having very low or low potential to alleviate water scarcity. This study demonstrates the effectiveness of remote sensing and geospatial techniques in assessing groundwater potential zones. The results can be used to optimize groundwater exploration and management in the study area.

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1 Introduction

Groundwater originates from rainfall or snow that seeps into the earth's geologic materials, eventually feeding into underground water systems and resurfacing into water sources (Nelson, 2015). The presence of groundwater in an area is influenced by various factors, including geology, slope, physiography, hydrogeology, weathering depth, geomorphology, drainage patterns, fractures, and surface water bodies (Rusia, 2018). Groundwater distribution is uneven, particularly in hard rock terrains where its occurrence is restricted (Suryabhagavan, 2017), making its abundance location-dependent (Adelana et al., 2008).

Groundwater potential refers to the likelihood of finding commercially viable quantities of groundwater in an area (Rahmati et al., 2016), determining the viability of an area as a potential aquifer for development (Lee et al., 2019). Accurate estimation and prediction of groundwater potential are crucial for efficient exploitation and management of groundwater resources (Oikonomidis et al., 2015). Groundwater potential directly affects borehole productivity, with yield being a critical factor (Midlands, 2023). Research has consistently shown a strong relationship between borehole yield and groundwater potential (Taylor et al., 2019; Smith et al., 2020). Groundwater potential is influenced by various hydrogeological factors, including aquifer properties, recharge rates, and geological structure (Fetter, 2001). Borehole yield, in turn, is affected by the aquifer's ability to transmit water and sustain pumping rates (Kruseman & de Ridder, 2000). The relationship between borehole yield and groundwater potential has significant implications for sustainable water management. Over-pumping and saline intrusion can lead to borehole failure, water table depletion, and land subsidence (Konikow & Kendy, 2005). Therefore, it is essential to carefully manage groundwater resources, monitor borehole yield, and implement sustainable pumping practices to ensure the long-term viability of aquifer systems.

The integration of Geographic Information Systems (GIS) and Remote Sensing methods, particularly Multi-Criteria Analysis using raster-based GIS, has proven effective in analyzing groundwater dynamics and supporting decision-making with multiple criteria (Argaz et al., 2019). The Analytic Hierarchy Process (AHP) is a widely used Multi-Criteria Decision Making (MCDM) technique that helps decision-makers evaluate complex problems with conflicting criteria (Zeinolabedinia & Esmaeily, 2015). Remote Sensing and GIS have been extensively used in groundwater research due to their

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ability to access inaccessible areas, cover large areas quickly, and acquire data at a low cost, making them valuable tools for identifying groundwater occurrence. Kogi State, particularly Lokoja metropolis, faces unreliable potable water supply from the state water corporation, forcing residents to rely on alternative sources like boreholes (Aremu et al., 2014). Groundwater offers a promising solution, but uneven distribution and lack of proper surveys lead to frequent borehole failures in Lokoja (Omali, 2014). This study aims to identify groundwater potential zones and examine the spatial relationship between borehole yield and groundwater potential zones in Lokoja metropolis, Nigeria.

Interestingly, research by Amigun et al. (2012) utilized airborne magnetic data for mineral exploration in the Okene iron ore province, demonstrating the applicability of geospatial methods in understanding the subsurface geology of the area. This approach could potentially be extended to groundwater exploration.

2 Materials and Methods

2.1 Study Area

The study area is situated within the lower Niger-Benue trough, covering approximately 332.7 square kilometers. It lies between latitudes 7° 45′N and 7° 51′N of the Equator and longitudes 6° 41′E and 6° 45′E of the Greenwich Meridian (Figure 1), with a population of around 791,000 in 2022, projected to increase to 931,000 by 2025 (Macrotrends, 2022). The city shares boundaries with Kogi LGA to the north, Kabba-Bunu LGA to the west, Bassa LGA to the east, and Adavi and Ajaokuta LGA to the south (Omada et al., 2009). Lokoja experiences a warm continental climate, classified as Koppen-Aw, with temperatures rarely dropping below 30.7°C (Olatunde & Ukoje, 2016; Ifatimehin et al., 2010).

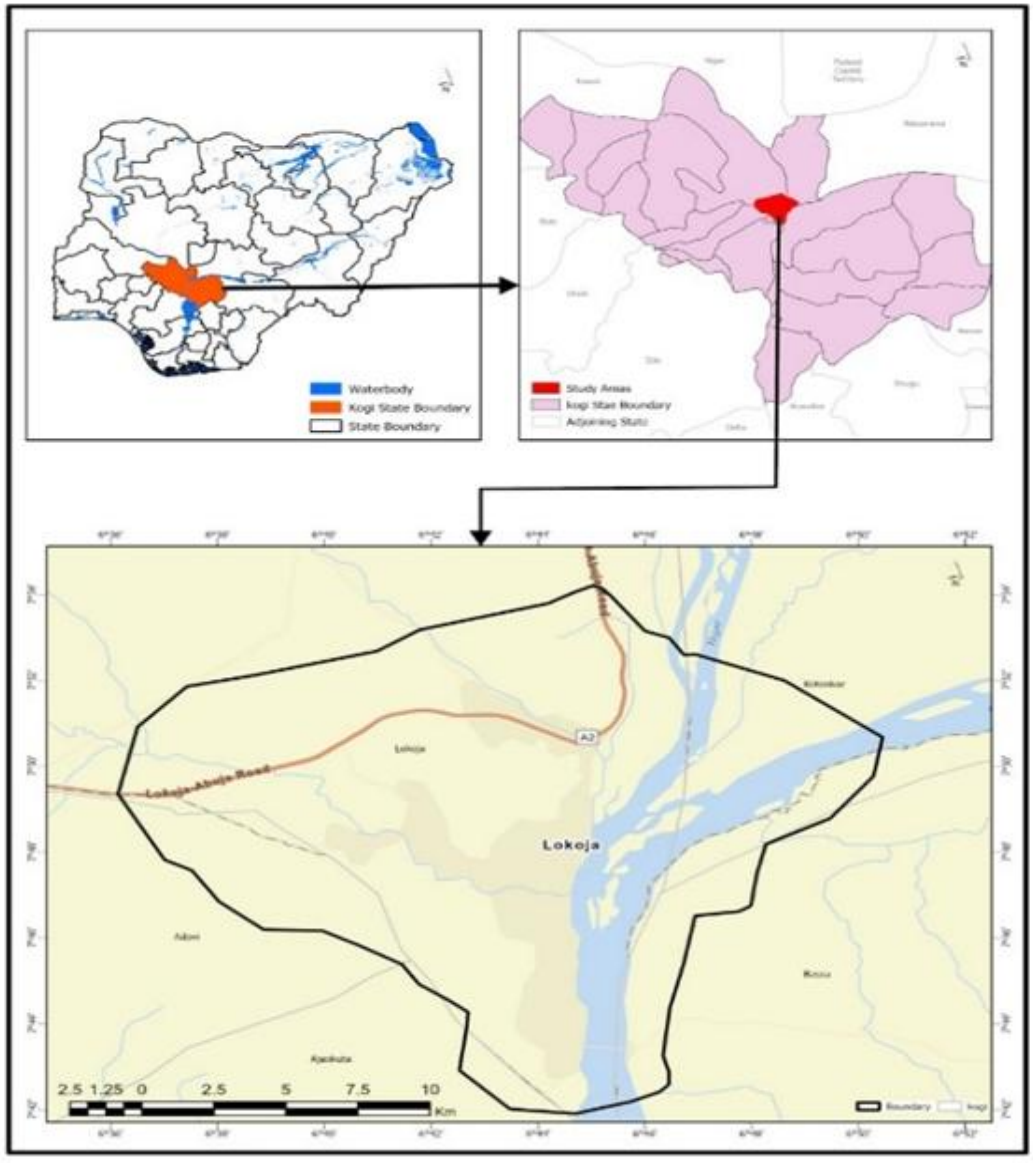


Figure 1: Study Area

The area features Guinea or parkland savanna vegetation, with long grasses and few trees, and soils characterized by sandy texture and weakly organized clay deposits (Luca, 2012; Atoyebi, 2013). Geologically, the Precambrian Basement Complex, consisting of Migmatite-Gneiss and Cretaceous deposits (Obaje, 2009), underlies it. The city's terrain is undulating, with high hills and river valleys, and its groundwater potential depends on weathering and fracturing of rocks (Areola, 2004; Omali, 2014). Historically, the Bassa-Nges and Oworos first inhabited Lokoja, with other Nupe groups settling in later (Lokoja Masterplan, 2009). The city is also home to diverse ethnic groups, including the Bassa Nge, Yoruba (primarily the Oworo subgroup), and Nupe.

2.2 Data Collection

This study on groundwater potential analysis emphasizes the importance of selecting the right criteria or factors, particularly in crystalline terrains. The factors considered include rainfall, lineament density, geology, drainage density, land use/land cover, soil, elevation, and slope, which are known to significantly influence groundwater potential (Benjmel et al., 2020).

Both the primary and secondary data were utilized in this research; the primary data were satellite imageries (Landsat 8 and Shuttle Radar Topographic Mission, (SRTM) and the secondary data comprises rainfall data and existing geological and soil maps of the study area, with the administrative map and geographical coordinates of dug wells/yields in the study area. Other literature was sourced from journals and textbooks for the literature review. The data used, their sources, and what they were used for are presented in Table 1.

Table 1: Types and Sources of Data

S/N	Data Types	Date of Acquisition	Resolution/Scale	Sources	Purpose
1	Landsat 8 OLI	2021	30m	USGS	LU/LC (Epuh, 2022).
2	STRM (DEM)	2020	30m	USGS	Elevation, slope, lineament, and drainage. (Ejepu, 2022).
3	Geology map	2014	1:10,000,000	NGSA.	Geology map (Fashae et al., 2014).
4	Soil data	1997	1:300,000	UNESCO	Soil map (Hyeman et al., 2020).
5	Rainfall Data	2022		NiMet	Rainfall map (Marcus et al., 2017).
6	Administrative map of Lokoja	2015	1:100,000	Min. of Lands Lokoja.	For the study area map.
7	Boreholes Data	2023		Volcano Minerals & Chemicals Limited.	Validation

2.3 Data Analysis

Each factor was analyzed individually in a GIS environment and weighted using the Analytic Hierarchy Process (AHP) based on its influence on groundwater occurrence. Table 2 shows the AHP pairwise comparison used a scale of 1 to 9, where 1 represents equal influence, and 9 represents extreme influence (Saaty, 1980).

Table 2: Procedure of Assigning Weightages in Analytical Hierarchy Process

Scale	Degree of preference	Explanation
1	Equal importance	Two elements contribute equally to the objective.
3	Moderate importance	Experience and judgment slightly favor one element over another.
5	Strong importance	Experience and judgment strongly favor one element over another.
7	Very strong importance	One element is favored very strongly over another.
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation.
2,4,6,8	Value for inverse comparison	Can be used to express intermediate values.

This was achieved by integrating the thematic maps of individual criteria. Weighted overlay analysis was carried out, where the weight of each thematic map was considered. The reclassified maps were overlaid using the weighted overlay in the spatial analyst tool in the ArcGIS environment to produce the Groundwater Potential Map

(GWPM). The thematic maps to be integrated were weighted. The Groundwater Potential Map (GWPM) produced was reclassified into 5 zones of very low, low, moderate, high, and very high groundwater potential zones.

$$GWPI = \Sigma ni = 1\, \Sigma mw = 1\, (Wi \times Xj) \quad (1)$$

Where;

Wi = normalized weight of the jth thematic layer;

Xj = rank value of each layer concerning the jth layer,

m = total number of thematic layers;

n = total no of classes in the thematic layer.

$$GWPI = RFwRFr + LDwLDr + DDwDDr + GLwGLr + SLwSLr + SOwSOr + ELwELr + LCwLCr \quad (2)$$

Where;

LC = landcover;

LD = lineament density;

SO = soil;

DD = drainage density;

SL= slope;

RF = rainfall

EL= elevation.

The subscripts "w" and "r "represent the weight of the feature and its subclass based on groundwater potentiality.

The consistency ratio was calculated (Mandal et al., 2016).

$$CI = \lambda max - n - n - 1 \quad (3)$$

Where;

CI = Consistency Index;

λmax = Principal eigenvalue;

n = number of factors

$$Consistency\ Ratio\ (CR) = \frac{CI}{RI} \quad (4)$$

Where;

RI denotes Ratio Index taken from Table 3. The Ratio Index varies based on the number of thematic layers considered.

Table 3: Ratio Index

N	3	4	5	6	7	8	9	10
RI	0.58	0.89	1.12	1.24	1.32	1.41	1.45	1.49

This methodological approach ensures a robust assessment of groundwater potential in the study area.

3 Results and Discussions

3.1 Elevation

The study area elevation was analyzed using SRTM-30m data, generating a DEM. The elevation ranges from 27m to 193m above sea level, with the highest point in the north-central part and the lowest point towards the east (Figure 2). The area was classified into five elevation classes: 27-58m (42.75%), 58-91m (27.32%), 91-122m (19.54%), 122-154m (6.44%), and 154-193m (3.93%).

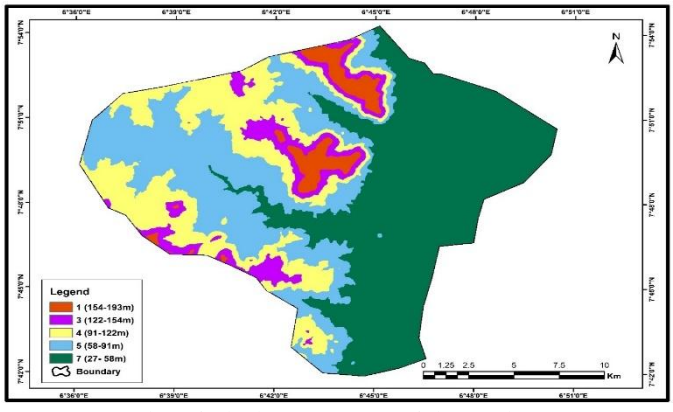


Figure 2: Reclassified Elevation map of the study area.

The way the various classes of elevation affect the occurrence of groundwater in the study area is shown in Table 4.

Table 4: Pairwise Comparison and Weighting of Elevation in the Study Area

Elevation (m)	27–58	58–91	91–122	122–154	154–193	Weightage	Potential
27–58	1	3	4	5	7	0.52	Very High
58–91	1/3	1	1	3	5	0.19	High
91–122	1/4	1	1	3	5	0.16	Moderate
122–154	1/5	1/3	1/3	1	3	0.08	Low
154–193	1/7	1/5	1/5	1/3	1	0.05	Very Low

Consistency Ratio=0.05

The study shows that areas with low elevation values have high groundwater potential, while high elevations have low potential, as lower elevations facilitate groundwater accumulation (Sener et al., 2005; Subba, 1992). Topographic data is crucial in determining water table elevations (Sener et al., 2005), and fracture convergence in low areas can create optimal aquifer horizons (Subba, 1992). In the study area, the lowest elevation range (27-58m) had the highest weight (48%) and best groundwater potential, while the highest elevation range (154-193m) had the lowest weight (4%), indicating reduced groundwater potential at higher elevations.

3.2 Rainfall

The mean rainfall for twelve years (2010 and 2022) was used to generate an average rainfall map of the study area (Figure 3). Rainfall is the major source of water used in recharging aquifers. The spread of rainfall in the study area was as follows: 1127-1137mm, 1137-1144, 1144-1152, 1152-1162, and 1162-1178mm covering 73.9 km² (22.2%), 90.4 km² (27.1%), 89.9 km² (26.9%), 53.1 km² (15.9%) and 26.1 km² (7.8%).

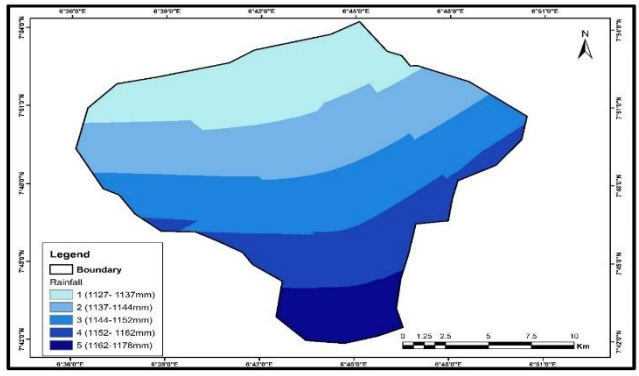


Figure 3: Reclassified Rainfall of the Study Area.

The result of the pairwise comparison of the various classes of rainfall can be seen in Table 5.

Table 5: Pairwise Comparison and Weighting of Rainfall in the Study Area

Rainfall (mm)	1127–1137	1137–1144	1144–1152	1152–1162	1162–1178	Weightage	Potential
1127–1137	1	1/2	1/3	1/4	1/5	0.06	Very Low
1137–1144	2	1	1/2	1/3	1/4	0.10	Low
1144–1152	3	2	1	1/2	1/3	0.16	Moderate
1152–1162	4	3	2	1	1/2	0.26	High
1162–1178	5	4	3	2	1	0.42	Very High

Consistency Ratio=0.05

The southern part of the study area received the highest mean annual rainfall with an average range of 1162-1178 mm, while the lowest was seen in the north with an average of 1127-1137 mm, suggesting a humid tropical terrain with the entire study area receiving more than 1,000 mm of rainfall annually (Fashae et al., 2014). The higher the rainfall received in an area, the more the amount of water available to recharge the aquifers. The rainfall variations were classified from very low to very high according to their potential to affect the occurrence of groundwater, with the lowest average rainfall being very low and the highest being very high.

3.3 Slope

The slope of an area is a major factor controlling infiltration of precipitation. Hence, it is an important hydrological parameter in delineating groundwater potential zones (Graf & Przybyłek, 2014). The slope of the study area was classified in the following categories: 0-2° (Nearly Flat), 2- 6° (gentle slope), 6 –12° (Moderate slope), 12-20° (Steep Slope), > 20° (Strong Slope) with each covering 157.74 km² (47.22%), 114.45 km² (34.43%), 31.73 km² (9.53%), 20.77 km² (6.21%) and 8.69 km² (2.60%) respectively (Figure 4).

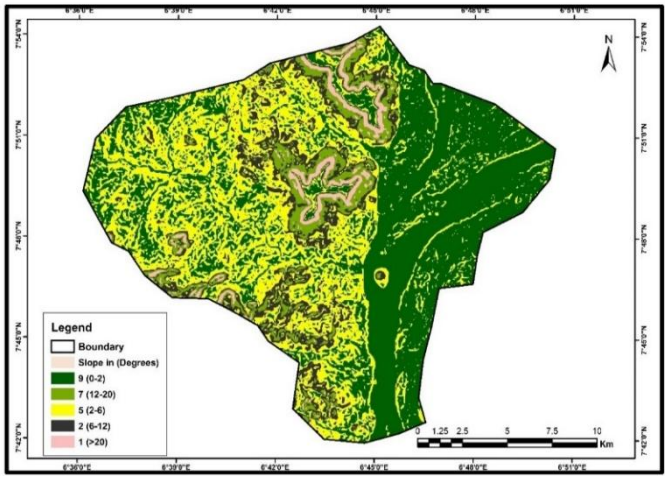


Figure 4: Reclassified Slope of the Study Area.

A pairwise comparison of the various classes of slope was done, and the result is presented in Table 6.

Table 6: Pairwise Comparison and Weighting of Slope

Slope (°)	0–2°	2–6°	6–12°	12–20°	>20°	Weightage	Potential
0–2°	1	2	5	7	9	0.46	Very High
2–6°	1/2	1	3	5	9	0.29	High
6–12°	1/5	1/3	1	3	7	0.14	Moderate
12–20°	1/7	1/5	1/3	1	5	0.08	Low
>20°	1/9	1/9	1/7	1/5	1	0.03	Very Low

Consistency Ratio=0.07

The analysis findings indicate that, at 46%, the research area's low-slope (0–2°) zones carry the largest weight. Rainwater infiltration is directly impacted by the slope gradient (Yeh et al., 2016). Because water runs quickly down a steep slope after rainfall, it does not have enough time to enter the surface and replenish the saturated zone, resulting in a reduced recharge when the slope degree (°) rises. As a result, groundwater will occur more readily in places with the lowest slope gradient and less readily in locations with a high slope gradient. For this reason, the slope classes were categorized based on their propensity to contribute to the occurrence of groundwater, ranging from extremely high to very low.

3.4 Drainage density

The drainage density in (km/km²) was computed from the drainage network, and it was seen that the highest drainage density (2.5 - 4.6) occurred in the northern, central, and southern parts of the study area. The different drainage density classes in the study area are as follows: 0-0.4, 0.4-1.0, 1.-1.7, 1.7-2.5 and 2.5-4.6 each covering 97.66 km² (29.29%), 99.02 km² (29.70%), 73.97 km² (22.18%), 46.82 km² (14.04%) and 15.90 km² (4.76%) (Figure 5).

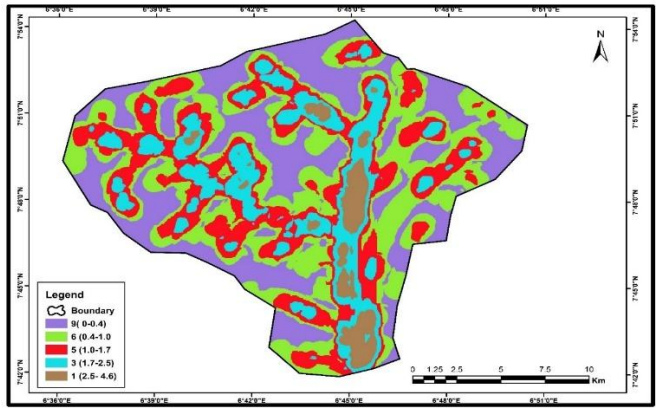


Figure 5: Reclassified Drainage Density of the Study Area.

The result of the pairwise comparison of the drainage density classes can be seen in Table 7.

Table 7: Pairwise Comparison and Weighting of Drainage Density

Drainage Density (km/km²)	0–0.4	0.4–1.0	1.0–1.7	1.7–2.5	2.5–4.6	Weightage	Potential
0–0.4	1	3	5	6	9	0.55	Very High
0.4–1.0	1/3	1	2	4	7	0.18	High
1.0–1.7	1/5	1/2	1	2	4	0.12	Moderate
1.7–2.5	1/6	1/4	1/2	1	2	0.09	Low
2.5–4.6	1/9	1/7	1/4	1/2	1	0.06	Very Low

Consistency Ratio= -0.05

Charon (1974) highlights the significance of drainage patterns as indicators of hydrogeological features controlled by underlying lithology. The stream pattern reflects the rainfall infiltration rate versus surface runoff, influenced by permeability linked to rock type and fracturing. Areas with high drainage density will not allow for adequate infiltration of water, as can be seen from the analysis, and had the lowest weight of 6%. On the contrary, areas with drainage density between 0 and 0.4 had the highest weight of 55% and, as a result, the highest potential for groundwater occurrence. Drainage density is an inverse function of permeability and is important in evaluating groundwater potential zones (Agarwal et al., 2009).

3.5 Lineament Density

The lineament density varies from less than 123.23 km/km², which covers 37% of the entire area, to 14.20 km/km², which covers 4.25 percent of the study area. According to Ndatuwong and Yadav (2014), this suggests that even in hilly locations that would ordinarily have no groundwater chances, areas with high lineament density may have significant groundwater prospects. A large portion of the study region consisted of areas with zero to 0.2 lineaments, which accounted for 36.06% of the total study area. The grouping of the lineament's density follows; 0-0.2, 0.2-0.4, 0.4-0.6, 0.6-0.9 and 0.9-1.8 covering an area extent of 123.23 km² (36.96 %), 65.19 km² (19.55%), 73.86 km² (22.15%), 56.89 km² (17.06%) and 14.20 km² (4.25%) (Figure 6).

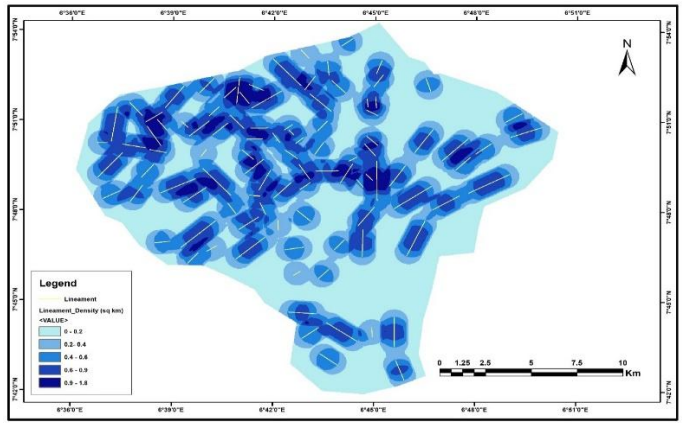


Figure 6: Reclassified Lineament Density of the Study Area.

The result of the pairwise comparison and weighting of the various lineament density classes was presented in Table 8.

Table 8: Pairwise Comparison and Weighting of Lineament Density

Lineament Density	0–0.2	0.2–0.4	0.4–0.6	0.6–0.9	0.9–1.8	Weightage	Potential
0–0.2	1	1/2	1/3	1/7	1/9	0.04	Very Low
0.2–0.4	2	1	1/2	1/4	1/7	0.10	Low
0.4–0.6	3	2	1	1/2	1/5	0.14	Moderate
0.6–0.9	7	4	2	1	1/4	0.32	High
0.9–1.8	9	7	5	4	1	0.40	Very High

Consistency Ration= 0.05

Lineaments, characterized by localized weathering and increased permeability, play a crucial role in groundwater flow and yield (Magowe & Carr, 1999). The areas with high lineament density were seen to have the highest weight 40% while those of low density had the lowest, with 4%. These areas with high lineament density will allow for the easy recharge of the underlying aquifers, which will make such areas favorable for groundwater occurrence.

3.6 Land use and land cover

Land use landcover are critical parameters influencing groundwater occurrence. The study area is mainly a scrub area, which makes up 39.5 % of the land use of the study area, while bare surface was the least with 1.4 %. The different land use/land cover of the study area are built-up areas, vegetation, water bodies, bare surface, and scrub, with each covering an aerial extent in percentage and kilometers (see Figure 7). The result of the percentage areal coverage of the land use land cover classes was presented in Table 9.

Table 9: Percentage Areal Coverage of LULC for Lokoja Metropolis

Land Use/Land Cover Class	Area (km^2)	Percentage (%)
Built-up Areas	77.5514	23.26
Vegetation	80.4477	24.12
Water Body	38.848	11.65
Bare Surface	4.873	1.46
Scrub	131.6752	39.49
Total	333.37	100.00

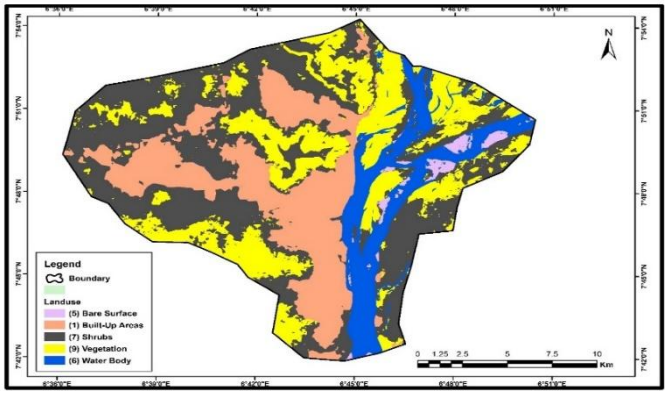


Figure 7: Reclassified Land use and Land cover of the Study Area.

Table 10: Pairwise comparison of the land use landcover classes of the study area

LULC Class	Vegetation	Scrub	Water Body	Bare Surface	Build-up Area	Weightage	Potential
Vegetation	1	5	6	7	9	0.61	Very High
Scrub	1/5	1	3	4	9	0.14	High
Water Body	1/6	1/3	1	2	7	0.11	Moderate
Bare Surface	1/7	1/4	1/2	1	4	0.08	Low
Build-up Area	1/9	1/5	1/6	1/4	1	0.06	Very Low

Consistency Ratio=0.04

The impact of land use and land cover is evident in its ability to either reduce runoff and facilitate groundwater recharge or trap water on vegetation leaves, contributing to groundwater replenishment. Land use and land cover can also have negative effects through processes like evapotranspiration. Vegetation had the highest weight of 61% while built-up areas had the lowest of 6%. Built-up areas are not suitable for groundwater occurrence because human activities such as the construction of concrete structures and the deposition of impermeable waste seal the soil surface, thereby preventing any form of infiltration. LULC plays a vital role in the development of groundwater resources because of its ability to influence hydrogeological processes such as infiltration, evapotranspiration, and surface runoff (Fashae et al., 2014).

3.7 Soil

Soil factors also play a crucial role in groundwater dynamics, affecting both recharge through infiltration and losses through run-off (Pandian & Kumanan, 2013). The specific type of soil and its permeability directly impact the water-holding and infiltrating capacity of that soil. Five major soil types were present in the study area; based on Food and Agriculture Organization (FAO) standards, identifies various soil types such as Fluvisols, leptosols, lixisol, luvisols, and nitisols, as depicted in Figure 8. The nitisols are the more dominant soil type covering an aerial extent of 133.34 Km^2 (40.03%), fluvisols 91.69km^2 (27.52%), leptosols 75.02 km^2 (22.52%), Lixisols 24.37 km^2 (7.31%), while the luvisols covered the remaining 8.67 km^2 (2.60 %) of the study area (Figure 8).

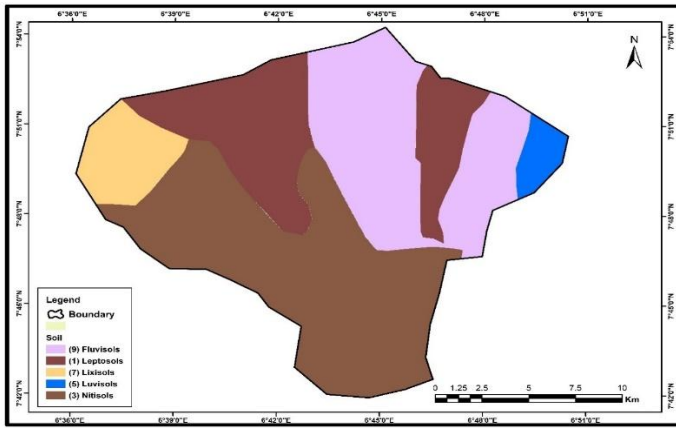


Figure 8: Reclassified Soil of the Study Area.

Table 11 shows the pairwise comparison between the five classes of soil present in the study area.

Table 11: Pairwise Comparison and Weighting of Soil

Soil Type	Fluvisols	Lixisols	Luvisols	Nitisols	Leptosols	Weightage	Potential
Fluvisols	1	3	5	7	9	0.56	Very High
Lixisols	1/3	1	3	5	9	0.18	High
Luvisols	1/5	1/3	1	3	7	0.12	Moderate
Nitisols	1/7	1/5	1/3	1	5	0.08	Low
Leptosols	1/9	1/9	1/7	1/5	1	0.06	Very Low

Consistency Ratio=0.06

In the analysis, it was observed that fluvisols have very high pore spacing and generally allow for easier infiltration of water due to their deep, well-drained nature and high permeability, with 56%. Lixisols rank high as they have moderate permeability and allow some groundwater infiltration. Luvisols are similar to the lixisols with smaller permeability for infiltration; nitisols are ranked as low, as they have low permeability and limit groundwater infiltration. Leptosols are ranked as very low, as they are shallow, poorly drained, and have low permeability, making them unfavorable for groundwater recharge, occupying the study area with 6%.

3.8 Geology

Lithologic composition of an area is an important factor in the occurrence and distribution of groundwater. This is because it controls infiltration rate and flow of precipitation (Adelana et al., 2008). The geology of the study area is made up of six major rock types which are the unconsolidated alluvium that allows extremely very high permeability and groundwater flow which forms the bedrock of the study area covering 89.53 km² (26.85%), sand and siltstone with high sedimentary rocks with high permeability, allowing significant groundwater flow covering 86.05 km² (25.81%), migmatite with moderate and partially melted rocks with variable permeability, allowing groundwater flow covering 102.56 km² (30.76%) granite and Charnock granite with low coarse grained granites with low permeability, limiting groundwater flow covering 1.89 km² (0.56%), granite migmatite and gneiss with low metamorphic rocks and low permeability, limiting groundwater flow covering 19.43 km² (5.82%) and Amphibole Schist which forms the remainder of the study area made of metamorphic rocks with extremely low permeability, unfavorable for groundwater flow covering 33.92km² (10.17%) (Figure 9).

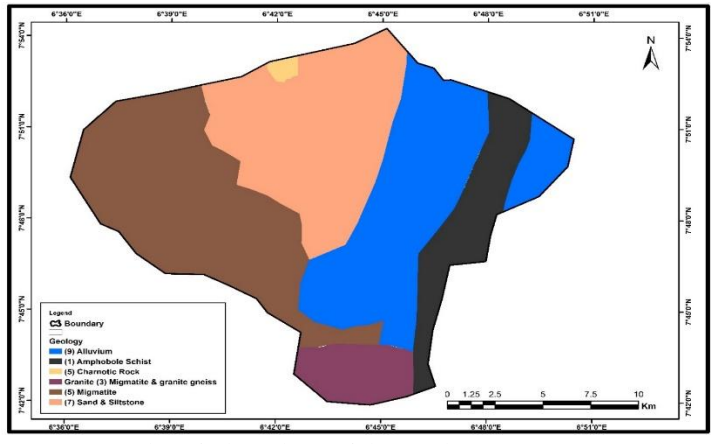


Figure 9: Reclassified Geology of the Study Area.

The result of the pairwise comparison and weighting of the types of geology present in the study area is presented in Table 12.

Table 12: Pairwise comparison and weighting of Geology

Geology	Alluvium	Sand & Siltstone	Migmatite	Granite & Charnock	Granite Migmatite & Gneiss	Amphibole Schist	Weightage	Potential
Alluvium	1	3	5	5	7	9	0.51	Very High
Sand & Siltstone	1/3	1	3	5	5	9	0.17	High
Migmatite	1/5	1/3	1	1	3	7	0.10	Moderate
Granite & Charnock	1/5	1/3	1	1	3	7	0.10	Low
Granite Migmatite & Gneiss	1/7	1/5	1/3	1/3	1	5	0.07	Low
Amphibole Schist	1/9	1/9	1/7	1/7	1/5	1	0.05	Very Low

Consistency Ratio=0.06

It can be seen that alluvium has the highest weight of 51% and is more likely to be water-bearing when compared to the other rock types. Consequently, the rock types present were classified into very low, low, moderate, high, and very high based on their groundwater bearing potential.

As evident in Table 12, it can be observed that Alluvium exhibits a notably very high groundwater potential, while Sandstone and Siltstone display a high-water potential. Migmatite, Granite, and Charnock Rock present moderate groundwater potential; Granite Migmatite and Granite Gneiss present low groundwater potentials. In contrast, Amphibole Schist demonstrates very low groundwater potentials, respectively.

3.9 Groundwater Potential Zones of the Study Area

The result of the pairwise comparison carried out with the eight (8) factors considered in this research is presented in Table 13, and the groundwater potential zone map using the weightage index was generated (Figure 10). The table shows the contribution of each of the groundwater determinant factors in the study area.

Table 13: Pairwise comparison and weighting of groundwater controlling factors

Criteria	Geology	Lineament	Rainfall	Slope	Elevation	Soil	Drainage	LU/LC	Weightage	Weight (%)
Geology	1	8/7	8/6	8/5	8/4	8/3	8/2	8/1	0.37	37
Lineament	7/8	1	7/6	7/5	7/4	7/3	7/2	7/1	0.18	18
Rainfall	6/8	6/7	1	6/5	6/4	6/3	6/2	6/1	0.12	12
Slope	5/8	5/7	5/6	1	5/4	5/3	5/2	5/1	0.10	10
Elevation	4/8	4/7	4/6	4/5	1	4/3	4/2	4/1	0.07	7
Soil	3/8	3/7	3/6	3/5	3/4	1	3/2	3/1	0.06	6
Drainage	2/8	2/7	2/6	2/5	2/4	2/3	1	2/1	0.05	5
LU/LC	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	0.05	5

Consistency Ratio=0.04

Figure 10 shows the groundwater potential zones of the study area. It was reclassified into five zones, namely: very low potential, low potential, moderate potential, high potential, and very high potential zones. The researcher's findings indicate that geology is the primary factor influencing groundwater potential in the area, accounting for 37% of the total weight, followed by lineament density with 18%, while land use/land cover has the lowest weight at 5%. This underscores the significance of lithology, lineaments, and geomorphological factors in governing groundwater accumulation. The groundwater potential zone map reveals that areas underlain by undifferentiated alluvium, sand, and siltstone exhibit very high to moderate potential, whereas areas with granites and granite gneiss show poor groundwater potential due to low fracturing rates. Specifically, settlements like Adankolo and Banda are located in exceptionally high potential zones, while areas like Zango-Daji and Pati ridge have high potential, and Army Barrack and Ganaja Village have moderate potential. In contrast, communities such as Okume, Atakpa, and Emiwoziri fall within low and very low potential zones, with the western regions holding very high groundwater potential and the eastern part having

lower potential, correlating with dense lineaments and relatively flat or gently sloping terrain in the west and south. This aligns with the findings of Ejepu et al. (2022), which reveal that lineaments and slopes are key contributors to groundwater presence in the Federal Capital Territory, Abuja, and Central Nigeria. The finding is also similar to that of Fashae et al. (2014), which reveals that the geology of Kaduna metropolis was considered to be the most significant factor for groundwater accumulation because it takes into consideration the rock type, degree of fracturing, and grain size, reflecting the geologic history of the study area. It also takes into consideration the degree of different porosity and permeability levels caused by groundwater accumulation in the area. Ejepu (2022), which also reveals that the geology of Abuja, Central Nigeria, is strongly correlated to lithology, where it exhibits a higher level of primary porosity, and due mainly to the availability of sandstones in the region, low drainage densities have been shown to occupy the "Good" to "Moderate" classes. This reflects the importance of lithology, lineaments, and other geomorphological factors that govern groundwater accumulation in an area (Kumar et al., 2019).

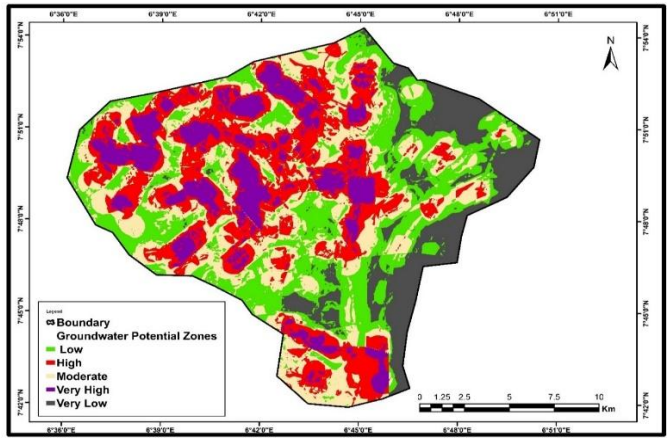


Figure 10: Groundwater Potentials Zone Map of the Study Area.

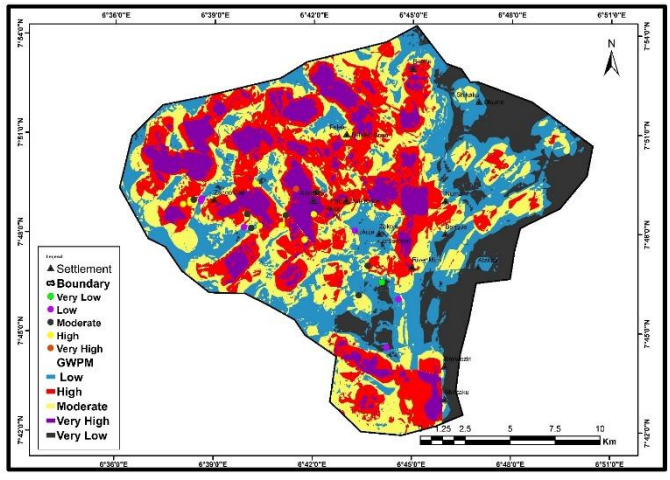


Figure 11: Borehole Location Superimposed on Groundwater Potential Zones of the Study Area

The area extent occupied by each groundwater potential zone is shown in Table 14.

Table 14: Area Extent of Groundwater Potential Zones in Lokoja Metropolis

Groundwater Potential Zones	Area (km^2)	Percentage (%)
Very High	44.06	13.24
High	79.06	23.75
Moderate	82.96	24.93
Low	79.97	24.02
Very Low	46.65	14.01
Total	332.7	100

The areal coverage of groundwater potential zones in Lokoja metropolis varies significantly, with the moderate zone covering the largest area at 25% (82.96 km^2), while the very high potential zone covers the smallest area at 13.24%. The low potential zone accounts for 24.02% of the area. The very high potential zones are characterized by undifferentiated alluvium, sand, and siltstone, as well as migmatite, which have a high potential for groundwater accumulation due to their secondary porosity, flat topography, high lineament density, and gentle slopes. These zones are predominantly found in the central to western, north, and southwestern parts of the study area.

3.10 Correlation between Existing Borehole Yield and the Groundwater Potential Zones

This research assesses the relationship between Groundwater Potential Map (GWPM) values and the yields of 36 existing boreholes in Lokoja metropolis using

Pearson moment correlation analysis. The borehole yields are categorized as follows: 2.8% very high, 36.1% high, 19.4% moderate, 16.7% low, and 2.8% very low, with 22.2% exhibiting different yields. The analysis reveals a significant correlation between the GWPM and borehole yields, with 78% of boreholes aligning with predicted yields, indicating moderate to high accuracy. However, 22.2% of boreholes show varying yields, suggesting local factors like geology, topography, or hydrological conditions influence groundwater potential. The research highlights the GWPM's utility in water resource management and infrastructure development, while emphasizing the need for refined mapping and site-specific assessments to enhance accuracy. Table 15 shows the classification of borehole yield and groundwater potential of the study area.

Table 15: Classification of Borehole Yield

Groundwater Potential	Discharge Rate (L/s)	No. of Actual Drilled Boreholes	No. of Drilled Boreholes Coinciding with the Expected Yield Map
Very High	2.87 – 3.90	2	1
High	2.45 – 2.87	18	13
Moderate	2.04 – 2.45	8	7
Low	1.59 – 2.04	7	6
Very Low	0.85 – 1.59	1	1

According to Fashae et al. (2014), utilizing existing borehole and well data is essential for validating groundwater potential zones. This study's results show a strong correlation between groundwater potential zones and borehole yields, with very low potential areas having extremely low yields (<1.5 l/s) and very high potential areas having substantial yields (>2.87 l/s). The yields are categorized into specific ranges for each potential zone: very low (0.85-1.59 l/s), low (1.59-2.04 l/s), moderate (2.04-2.45 l/s), high (2.45-2.87 l/s), and very high (2.87-3.90 l/s). The suitable groundwater areas are predominantly located in the southern, western, and central regions, while the northeastern to southeastern regions have a decreased chance of groundwater incidence. The validation accuracy suggests significantly accurate results, further supported by the Pearson correlation analysis, which reveals a strong and positive relationship (R = 0.917) between borehole yields and groundwater potential, indicating that as potential increases, borehole yield also increases correspondingly. The strength of this relationship is deemed very strong.

Table 16: Correlation Table

	GWPM	Borehole Yields
GWPM	1	0.917
Borehole Yields	0.917	1

The significance of the correlation result of 0.917 was tested using the Student's t-test.

Ho: There is no significant relationship between the existing borehole yield and groundwater potential in Lokoja metropolis, Kogi State.

$$\underline{t = R\sqrt{n-1}}$$

$$\sqrt{1-R2}$$

R = 0.917

n = 36

Therefore, calculated t =13.40. Tabulated value 0.05 level of significance at 34 degrees of freedom was found to be 2.042, while the calculated t-test value was 13.40. Decision rule: Since the tabulated Student's t-test (2.042) is lower than the calculated t-test value (2.042), we are rejecting the null hypothesis that states that there is no significant relationship between the existing borehole yield and groundwater potential in Lokoja metropolis, Kogi State.

The study findings on groundwater potential in the study area are consistent with prior research in similar geological settings, such as a Vertical Electrical Sounding (VES) study that revealed the presence of weathered and fractured aquifers indicative of potential groundwater zones (Aizebeokhai & Oyeyemi, 2014). The current study identified areas with high groundwater potential in the southern, western, and central regions of the study area, which may be attributed to the presence of such weathered and fractured aquifers. The study findings have important implications for groundwater management and development in the region, highlighting

the importance of integrating geospatial data and statistical analysis in groundwater potential mapping (Aizebeokhai & Oyedele, 2014).

4 Conclusion

This study analyzed and found that groundwater potential zones were very low potential (14.01%), low potential (24.02%), moderate potential (24.93%), high potential (23.75%), and very high potential zone (13. 24%) in Lokoja metropolis. The very high potential zone covering only 13.24% of the study area may be responsible for the borehole failure reported in the area. Given the correlation value of 0.917 between the existing borehole yield and groundwater potential in Lokoja metropolis, it can be concluded that there is a strong positive relationship between the existing borehole yields and the groundwater potential map produced from the analysis.

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