GIS-Based Multi-Criteria Analysis of Groundwater Potential in Cross River North, Cross River State, Nigeria

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Abstract
Groundwater is an important water resource for domestic, agricultural, and economic activities, particularly in areas where access to reliable public water supplies is limited. This study examined groundwater potentials in Cross River North, Nigeria, using Geographic Information System (GIS)-based multi-criteria framework. Seven groundwater-conditioning factors; lineament density, drainage density, land use/land cover, slope, geology, rainfall, and soil, were integrated to characterize their combined influence on groundwater potential. The thematic layers were processed, reclassified into relative suitability classes, and combined through a weighted-overlay approach to produce an integrated groundwater-potential map. The results delineated four groundwater-potential classes: very low, low, moderate, and high. The very-low-potential zone covered 18,237 km² (34.12%), while the low-potential zone occupied 19,359 km² (36.22%). Moderate-potential areas accounted for 6,365 km² (11.91%), and high-potential areas covered 9,487 km² (17.75%), based on a total study-area extent of 53,448 km². Collectively, the very-low- and low-potential zones represented 70.34% of the mapped area, whereas moderate- and high-potential zones accounted for 29.66%. Preliminary field observations from five borehole locations indicated comparatively poor yields at Igoli, Okpoma, and Abuochiche, while substantial yields were reported at Obudu town and Sankwala. These observations provide local context for interpreting the spatial assessment but do not constitute a formal statistical validation of the groundwater-potential map. The findings provide a regional screening framework for prioritizing groundwater exploration and support the need for detailed geophysical investigations, hydrogeological assessments, and quantitative borehole-yield testing before drilling decisions are made.

Keywords: *Groundwater Potential, Geographic Information System, Multi-Criteria Analysis, Lineament Density, Weighted Overlay, Cross River North; Nigeria.*

1. Introduction

Groundwater is an important natural resource that supports domestic water supply, agricultural production, industrial activities, and socioeconomic development, particularly in regions where access to reliable surface-water resources is limited (MacDonald et al., 2012). Its importance is especially evident in many African communities where appropriately located and constructed boreholes provide essential sources of water for domestic use and other economic activities. However, groundwater resources are unevenly distributed, and the productivity of boreholes varies considerably with local geological and hydrogeological conditions (MacDonald et al., 2012). Groundwater occurrence and productivity are influenced by geological materials, structural features, topography, soil properties, rainfall, drainage characteristics, and land use and land cover (Arulbalaji et al., 2019; Thanh et al., 2022). Understanding the spatial distribution of these conditioning factors is therefore essential for identifying areas with favourable groundwater potential and supporting groundwater-resource planning.

Groundwater occurrence is governed by the interaction of surface and subsurface processes that influence infiltration, recharge, storage, and movement. Lineaments may represent fractures, faults, and other structural discontinuities that provide pathways for groundwater movement where they are sufficiently open and interconnected Thanh et al., 2022). Geological formations influence aquifer characteristics through variations in lithology, porosity, permeability, weathering, and fracturing. Slope affects surface runoff and infiltration, with relatively gentle terrain often favouring infiltration compared with steep terrain, although the relationship depends on local geological and soil conditions. Soil properties influence the infiltration and percolation of water, while drainage density provides information about surface drainage patterns and may indirectly indicate differences in runoff and infiltration. Rainfall supplies water for potential groundwater recharge, whereas land use and land cover influence infiltration, evapotranspiration, and surface runoff (Arulbalaji et al., 2019; Saidu et al., 2024; Thanh et al., 2022). These factors are consequently used in combination in groundwater-potential studies to account for the multiple controls on groundwater occurrence and distribution.

Conventional groundwater exploration commonly involves geological investigations, field surveys, and geophysical techniques. Although these approaches provide essential information for identifying aquifers and selecting drilling locations, conducting detailed investigations across extensive geographical areas can require considerable time and resources. Geographic Information Systems (GIS) and remote sensing offer complementary approaches for acquiring, processing, integrating, and analysing spatial datasets over large areas. GIS-based spatial analysis enables the combination of thematic layers representing different environmental and geological conditions, thereby supporting spatial modelling and resource assessment (Bonham-Carter, 1994). When integrated with multi-criteria decision-making methods, such as the Analytical Hierarchy Process (AHP), these techniques can be used to assign relative importance to groundwater-conditioning factors and combine them through weighted-overlay analysis to delineate groundwater-potential zones (Arulbalaji et al., 2019; Ejepu, 2020; Saaty, 2008). Nevertheless, groundwater-potential maps represent model-based assessments and should be evaluated against available field evidence to establish their practical reliability (Saidu et al., 2024).

Cross River North, Nigeria, provides a relevant setting for spatial groundwater assessment because groundwater prospects may vary with geological formations, terrain, soil characteristics, drainage systems, rainfall distribution, and land-cover conditions. Such spatial variability makes it necessary to examine the combined influence of multiple groundwater-conditioning factors rather than rely on a single environmental or geological indicator. A systematic spatial assessment can

help distinguish areas of relatively favourable groundwater potential from locations requiring more detailed investigation before drilling. Observations from drilled boreholes can provide additional field evidence for examining the relationship between mapped groundwater potential and actual groundwater development outcomes.

This study therefore characterizes seven groundwater-conditioning factors—lineament density, slope, geology, soil, drainage density, rainfall, and land use/land cover—and map groundwater-potential zones across Cross River North, Nigeria. Specifically, the study examines the spatial distribution of these factors, combines their influence through weighted-overlay analysis, delineates groundwater-potential classes, and considers the qualitative outcomes of five drilled boreholes in Ogoja, Yala, Bekwarra, Obudu, and Obanliku. By integrating spatial analysis with preliminary borehole observations, the study provides a basis for prioritising groundwater exploration and supporting groundwater-resource planning in the study area.

2. Materials and Methods

2.1 Study Area

The study covers Cross River North, Nigeria, which covers Ogoja, Yala, Bekwarra, Obudu, and Obanliku Local Government Areas. It lies between Latitudes 05°59'00"N and 06°42'00"N, and Longitudes 08°25'00"E and 09°33'00"E of the Greenwich Meridian (Akpan–Idiok, 2012). The study-area extent is 53,448 km². The spatial database comprised Landsat 8 OLI imagery, SRTM elevation data, rainfall information, geological and soil maps, and administrative boundaries (see Figure 1).

The study area encompasses varied terrain, including relatively low-lying landscapes and elevated, mountainous areas, particularly around Obudu and Obanliku. These topographic variations, together with differences in geological formations, soil characteristics, drainage networks, rainfall distribution, and land use and land cover, provide a basis for examining the spatial factors influencing groundwater potential. The region experiences seasonal rainfall, with climatic conditions varying locally in association with elevation and terrain. Such environmental variability makes an integrated spatial assessment appropriate for identifying areas that may be more favourable for groundwater exploration

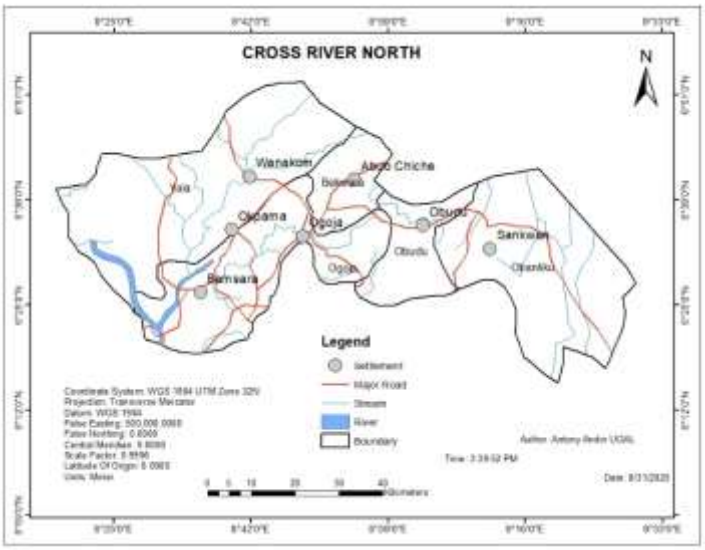


Figure 1: Location of Cross River North

Data Types and Sources

i. A 30m resolution Satellite image of the study area (Landsat 8 OLI) for the year 2023 was acquired and used to generate the land-use/ land cover map.

ii. Rainfall data from world climate data was downloaded from the http://worldclim.org/version2 and used to produce the rainfall map of the study area.

iii. Geology data was sourced from Nigeria Geological Survey Agency (NGSA) and used to produce the geology map of the study area.

iv. The Shuttle Radar Topography Mission (SRTM) with 90 meters resolution was downloaded from Global Land Cover Facility (www.ftp//glc£landsat) and used to generate DEM from which the slope, drainage density and lineament map of the study area was generated.

v. Soil map of the study area was generated from the soil map of Nigeria (Sonneveld, 1996).

vi. An administrative map which was obtained from Open Street Map was used to subset the study area.

GIS Preprocessing and Layer Generation

Landsat imagery was prepared and classified to generate a land-use/land-cover layer. DEM data were used to derive slope, drainage-related variables, and lineament density, was mapped from interpreted linear features; rainfall, geological, and soil datasets were prepared as thematic layers. The layers were clipped to the study area boundary, reclassified into suitability classes, and prepared for integration in ArcGIS 10.8.

Reclassification and Weighting

The seven thematic layers were integrated through a weighted-overlay framework. In general, the groundwater-potential index at each location can be expressed as:

$$GPI(x) = \Sigma (w_i \times r_i(x)), \text{ for } i = 1,\ldots,7$$

where GPI(x) is the groundwater-potential index at location x, w_i is the normalized criterion weight for criterion i, and $r_i(x)$ is the reclassified suitability score of that criterion at x. The class-level scores in the factor tables are not a substitute for criterion-level AHP weights.

AHP consistency was evaluated using the consistency index (CI) and consistency ratio (CR), where $CI = (\lambda max - n)/(n - 1)$ and $CR = CI/RI$. For seven criteria, the commonly used random index was 1.32, and a CR of 0.10 or less is often treated as an acceptable consistency level (Saaty, 1980).

Validation and Uncertainty Protocol

The borehole observations provide qualitative field evidence for comparison with the potential map. The study used comparative description rather than a statistical validation.

Borehole Drilling and Field Observations

One borehole was drilled in each of the five Local Government Areas; Ogoja, Yala, Bekwarra, Obudu, and Obanliku. During the field investigation, the locations were recorded by geographic coordinates and are listed with the observed qualitative outcomes in Table 9. Borehole performance was classified descriptively as substantial water yield or comparatively poor yield based on the field investigation notes.

3. Results and Discussion

3.1 Characterization of Groundwater-Conditioning Factors (Lineament, Slope, Geology, Soil, Drainage Density, Rainfall and Landuse/Landcover)

The spatial distributions of lineament density, drainage density, land use and land cover (LULC), slope, geology, rainfall, and soil were examined to characterize their relevance to groundwater occurrence in Cross River North, Nigeria. The reported class areas have been proportionally standardized to the agreed study-area total of 53,448 km², while the original class ranges, relative distributions, and weighting scores have been retained. The resulting tables provide a consistent basis for presenting the thematic-layer results. The standardized areas should be distinguished from independently recalculated GIS measurements.

Lineament Density

The lineament-density distribution was dominated by the lowest density class (0–0.170), which accounted for 39,178 km² (73.31%) of the study area. The 0.170–0.340 class covered 6,839 km² (12.80%), while the 0.340–0.510 and 0.510–0.680 classes occupied 5,075 km² (9.49%) and 2,356 km² (4.41%), respectively. The distribution indicates that areas of low lineament density are more extensive than areas of high lineament density. In groundwater prospecting, lineaments may represent fractures or structural discontinuities that enhance secondary porosity and groundwater movement. Consequently, the higher scores assigned to the denser lineament classes reflect their presumed groundwater significance within the adopted suitability scheme (see Table 1 and Figure 2).

Table 1. Spatial Distribution of Lineament Density

Lineament-density class	Weight	Area (km²)	Area (%)
0–0.170	1	39,178	73.30
0.170–0.340	2	6,839	12.80
0.340–0.510	4	5,075	9.49
0.510–0.680	5	2,356	4.41
Total	**—**	**53,448**	**100.00**

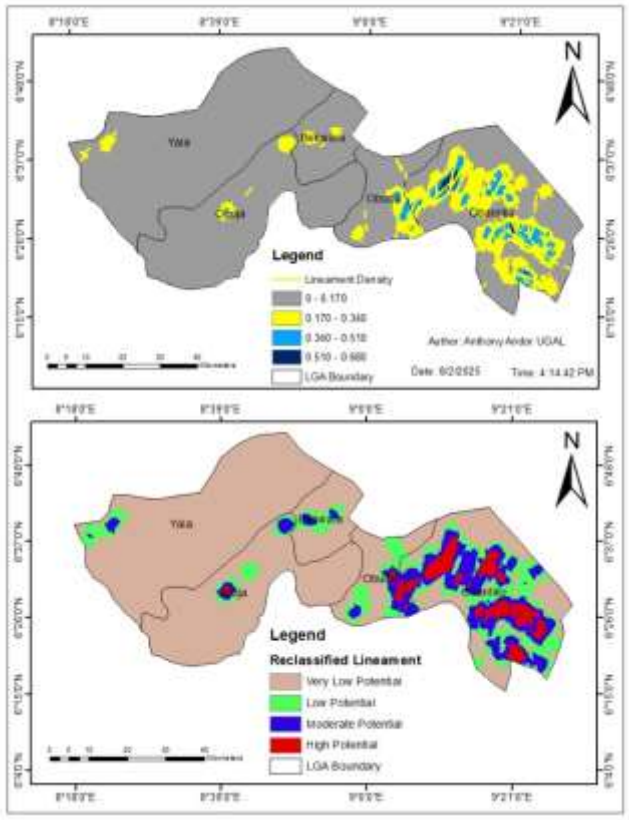


Figure 2: Spatial Distribution of Lineament Density

Drainage Density

The highest drainage-density class (172.305–247.854) accounted for 19,358 km² (36.22%), making it the most extensive class. This was followed by the 141.197–172.305 class, which covered 15,405 km² (28.82%). The 108.311–141.197 class occupied 12,270 km² (22.96%), while the lowest class (21.207–108.311) covered 6,415 km² (12.00%).

Drainage density is relevant to groundwater assessment because it reflects the relationship between surface runoff and infiltration. Low drainage density may indicate greater infiltration potential under suitable geological, soil, and topographic conditions, whereas high drainage density may be associated with rapid surface-water removal. However, this relationship is not universal and depends on local environmental conditions. The higher suitability weight assigned to the lowest drainage-density class reflects its presumed advantage for groundwater recharge (see Table 2 and Figure 3).

Table 2. Spatial Distribution of Drainage Density

Drainage-density class	Weight	Area (km²)	Area (%)
21.207–108.311	5	6,415	12.00
108.311–141.197	4	12,270	22.96
141.197–172.305	3	15,405	28.82
172.305–247.854	3	19,358	36.22
Total	—	**53,448**	**100.00**

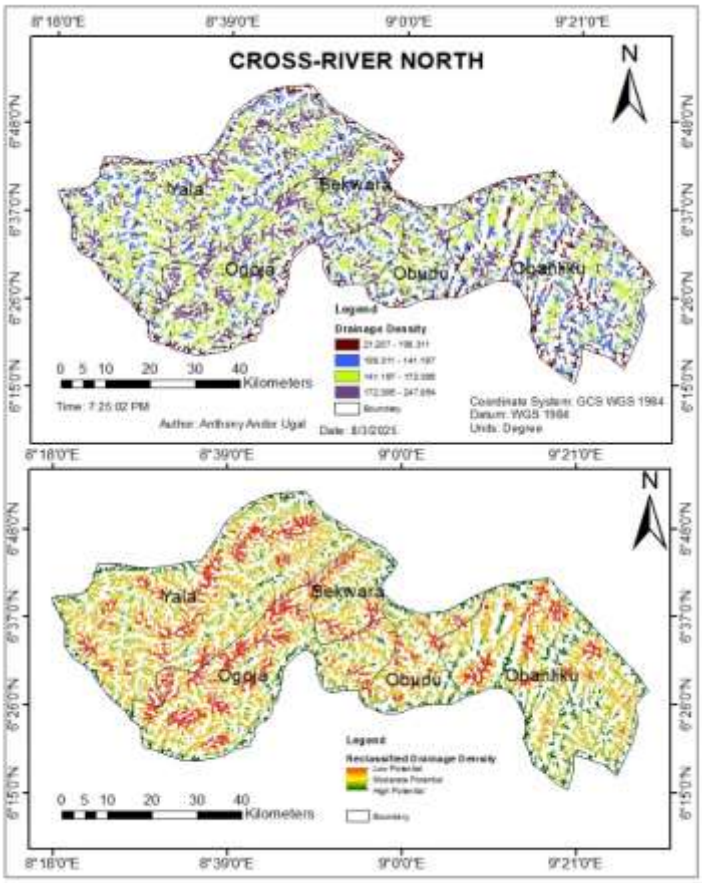


Figure 3: Spatial Distribution of Drainage Density

Land Use and Land Cover

Vegetation was the dominant land-cover class, occupying 28,441 km² (53.21%) of the study area. Bare land covered 12,109 km² (22.66%), while built-up areas accounted for 9,429 km² (17.64%). Rock outcrops occupied the smallest area, covering 3,469 km² (6.49%).

The predominance of vegetation suggests that substantial portions of the study area retain vegetated surfaces that may support infiltration where soil permeability and terrain conditions are favourable. Conversely, built-up areas may experience increased runoff where impervious surfaces restrict infiltration. Bare land and rock outcrops may have variable effects depending on surface characteristics, weathering, fractures, and soil development. Accordingly, land-cover classes provide useful indications of recharge conditions but cannot independently establish groundwater availability.

Table 3. Spatial Distribution of Land Use and Land Cover

Land-use/land-cover class	Weight	Area (km²)	Area (%)
Built-up	1	9,429	17.64
Vegetation	5	28,441	53.21
Bare land	3	12,109	22.66
Rock outcrop	2	3,469	6.49
Total	—	**53,448**	**100.00**

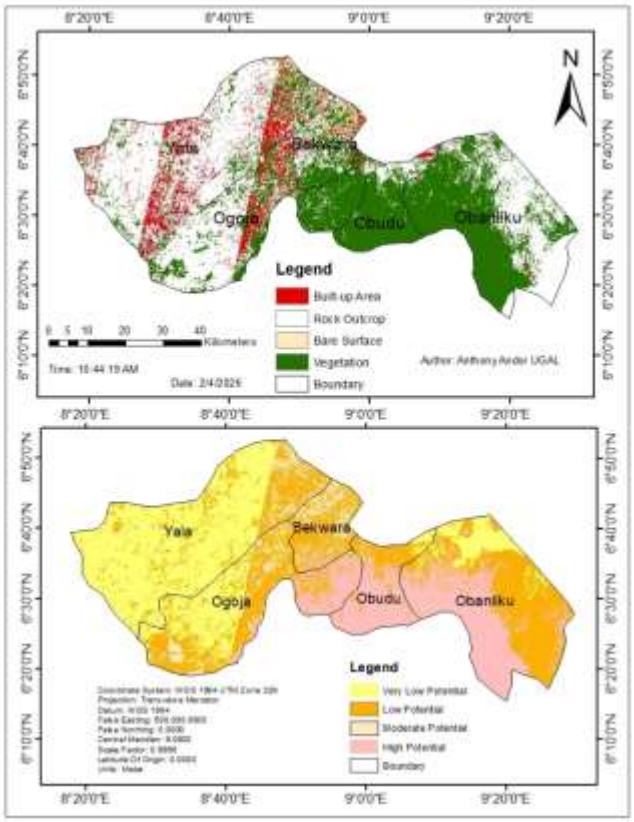


Figure 4: Land Use and Land Cover Distribution

Slope

The 37.8–66.2 slope class was the most extensive, covering 28,880 km² (54.03%). The 14.8–37.8 class occupied 11,265 km² (21.08%), while the 66.2–344.6 class accounted for 9,275 km² (17.35%). The lowest slope class (0–14.8) covered 4,028 km² (7.54%).

Slope influences the partitioning of precipitation between surface runoff and infiltration. Gentle terrain generally provides more opportunity for infiltration where soils and underlying geological materials are permeable, whereas steep terrain may encourage rapid runoff. The highest weight assigned to the lowest slope class reflects this relationship within the adopted suitability classification. Nevertheless, the dominance of the 37.8–66.2 class indicates that the mapped slope distribution is not dominated by the lowest-slope category.

Table 4. Spatial Distribution of Slope Classes

Slope class	Weight	Area (km²)	Area (%)
0–14.8	5	4,028	7.54
14.8–37.8	4	11,265	21.08
37.8–66.2	1	28,880	54.03
66.2–344.6	3	9,275	17.35
Total	**—**	**53,448**	**100.00**

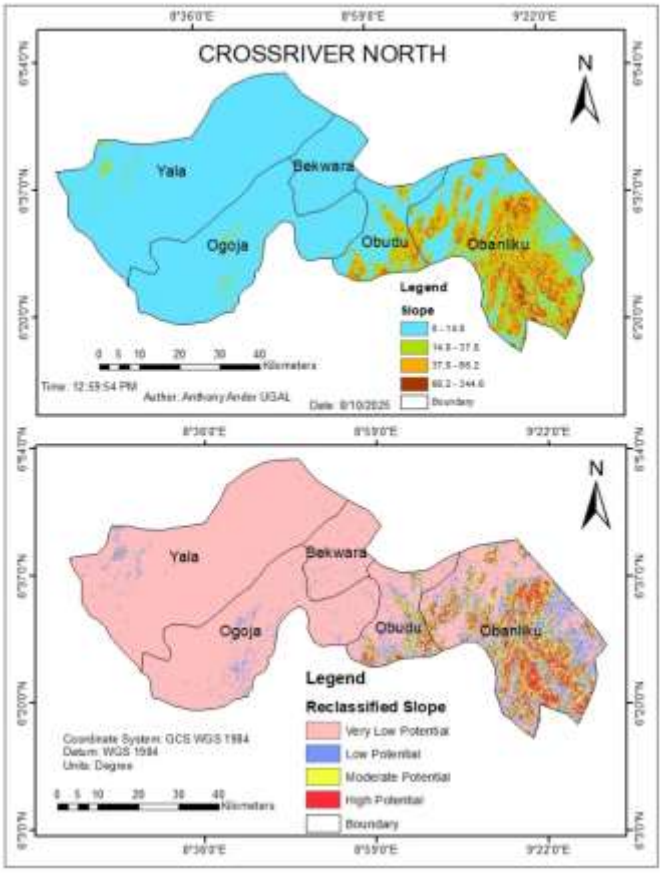


Figure 5: Slope Distribution

Geology

Precambrian metamorphic and igneous rocks (pCm) constituted the most extensive geological class, covering 25,398 km² (47.52%). Precambrian basement complex (K) occupied 20,005 km² (37.43%), followed by crystalline basement complex (KI), which covered 7,053 km² (13.20%). Mesozoic–Cenozoic intrusive rocks (Mi) accounted for 992 km² (1.86%).

The distribution demonstrates the predominance of Precambrian metamorphic and igneous rocks and basement-complex terrain. In crystalline geological environments, groundwater occurrence is commonly associated with weathered zones, fractures, joints, and other secondary openings rather than primary porosity. The suitability weights assigned to the geological classes reflect the assumptions adopted for the assessment; their relative groundwater productivity requires confirmation through field observations and borehole evidence.

Table 5. Spatial Distribution of Geological Units

Geological unit	Weight	Area (km²)	Area (%)
Mesozoic–Cenozoic intrusive rocks (Mi)	4	992	1.86
Crystalline basement complex (KI)	1	7,053	13.20
Precambrian basement complex (K)	1	20,005	37.43
Precambrian metamorphic and igneous rocks (pCm)	4	25,398	47.52
Total	—	**53,448**	**100.00**

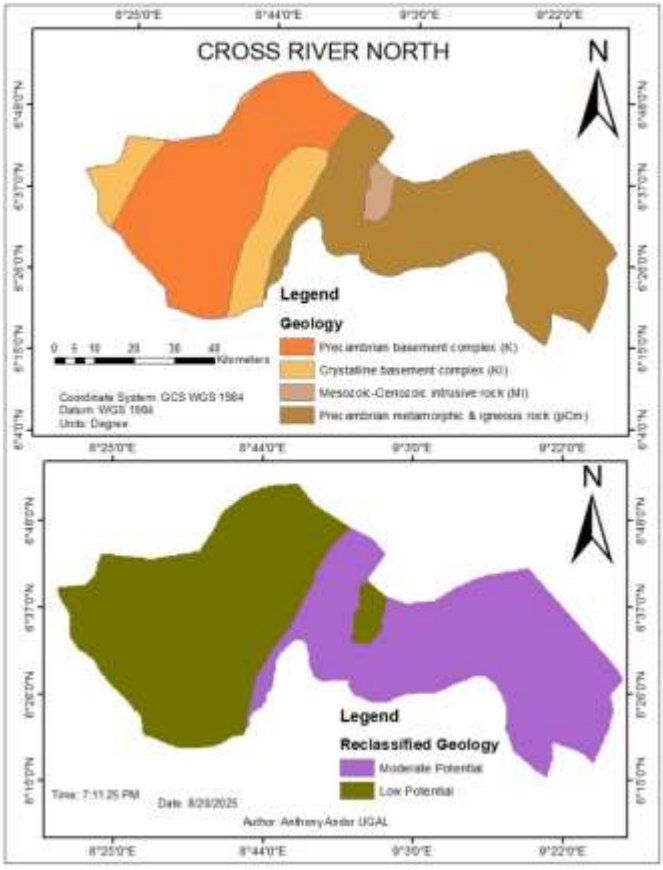


Figure 6: Geological Distribution

Rainfall

The lowest rainfall class (151.00–155.54) was the most extensive, covering 25,079 km² (46.92%). The 155.54–159.75 class occupied 12,953 km² (24.23%), while the 159.75–164.64 class covered 8,012 km² (14.99%). The highest rainfall class (164.64–170.98) accounted for 7,404 km² (13.85%). The distribution indicates that the lowest mapped rainfall class occupies the largest proportion of the study area, whereas the highest class is the least extensive. Rainfall is an important control on potential groundwater recharge because precipitation supplies water that may infiltrate and replenish aquifers. However, the amount of recharge also depends on evapotranspiration, runoff, soil permeability, topography, and geological conditions. Precipitation data were obtained from the WorldClim historical monthly weather dataset and expressed in millimetres (mm). The data covered the available period ending in 2024. The precipitation raster was classified into four ranges: 151–155.54 mm, 155.54–159.75 mm, 159.75–164.64 mm, and 164.64–170.98 mm. These ranges were used to represent the spatial variation in precipitation across the study area.

Table 6. Spatial Distribution of Rainfall Classes

Rainfall class	Weight	Area (km²)	Area (%)
151.00–155.54	2	25,079	46.92
155.54–159.75	4	12,953	24.23
159.75–164.64	6	8,012	14.99
164.64–170.98	8	7,404	13.85
Total	—	**53,448**	**100.00**

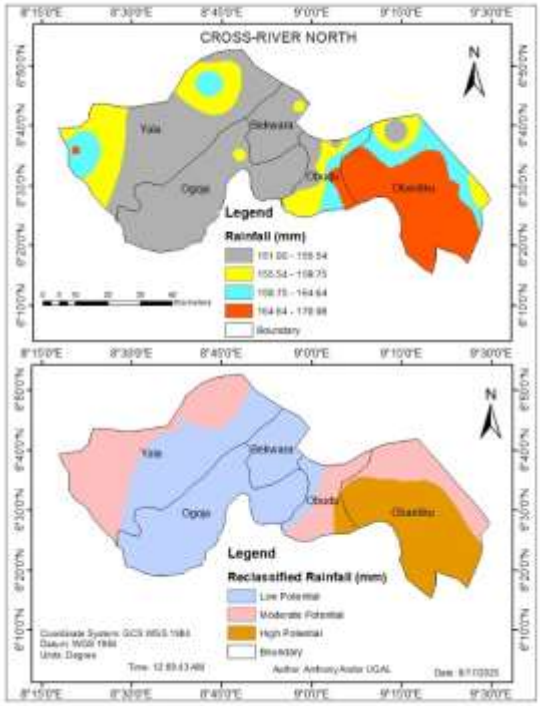


Figure 7: Spatial Distribution of Rainfall

Soil

Ferric Acrisols (Afl) were the most extensive soil class, covering 23,484 km² (43.94%). Alisols (Nd) occupied 13,781 km² (25.78%), while Acrisols (Fo) covered 9,323 km² (17.44%). Alisols/Acrisols (Ne) accounted for 4,331 km² (8.10%), and Cambisols (G) occupied 2,529 km² (4.73%). The dominance of Ferric Acrisols indicates that this soil class occupies a substantial proportion of the mapped area. Soil characteristics can influence infiltration, percolation, and the movement of water into underlying geological materials. However, the hydrological significance of each soil class depends on properties such as texture, structure, depth, compaction, and permeability. The weights assigned to the classes represent their relative suitability within the adopted assessment framework and should not be interpreted as direct measurements of infiltration or aquifer productivity.

Table 7. Spatial Distribution of Soil Classes

Soil class	Weight	Area (km²)	Area (%)
Ferric Acrisols (Af1)	3	23,484	43.94
Alisols (Nd)	3	13,781	25.78
Acrisols (Fo)	5	9,323	17.44
Alisols/Acrisols (Ne)	4	4,331	8.10
Cambisols (G)	3	2,529	4.73
Total	—	**53,448**	**100.00**

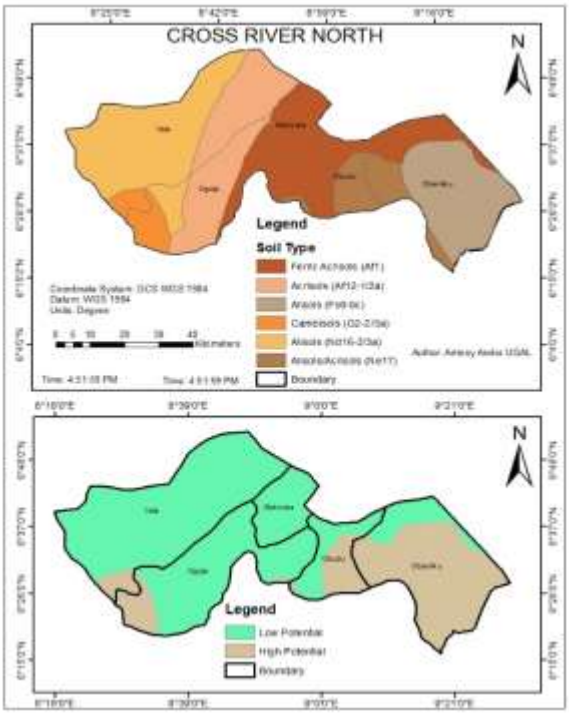


Figure 8: Spatial Distribution of Soil Types

The thematic-layer results demonstrate spatial variation in the factors relevant to groundwater occurrence across Cross River North. Vegetation and Ferric Acrisols are the dominant land-cover and soil classes, respectively, while Precambrian metamorphic and igneous rocks constitute the most extensive geological unit. The lowest lineament-density and rainfall classes also occupy the largest proportions of their respective standardized distributions, whereas the intermediate-to-higher slope classes dominate the mapped slope distribution.

These factors influence groundwater occurrence through different mechanisms and should therefore be interpreted collectively rather than independently. The assigned weights represent the adopted suitability assumptions and provide inputs for the integrated assessment. The resulting groundwater-potential classification is presented in the subsequent section.

3.2 Mapped Groundwater-Potential Zones in the Study Area

The weighted-overlay analysis delineated four groundwater-potential classes: very low, low, moderate, and high. Low-potential zones occupy the largest area, covering 19,359 km² (36.22%), followed by very-low-potential zones covering 18,237 km² (34.12%). High-potential zones account for 9,487 km² (17.75%), while moderate-potential zones cover 6,365 km² (11.91%). Collectively, the very-low- and low-potential classes occupy 37,596 km² (70.34%) of the study

area, whereas the moderate- and high-potential classes cover 15,852 km² (29.66%). This distribution indicates that a substantial proportion of the study area is classified as having relatively limited groundwater potential, although favourable groundwater prospects occur in specific locations.

Table 8. Extent of Integrated Groundwater-Potential Zones

Index/Class range	Potential category	Area (km²)	Area (%)
1; 100–192.75	Very low potential	18,237	34.12
3; 192.7500001–285.5	Low potential	19,359	36.22
4; 285.5000001–378.25	Moderate potential	6,365	11.91
5; 378.2500001–471	High potential	9,487	17.75
Total		**53,448**	**100.00**

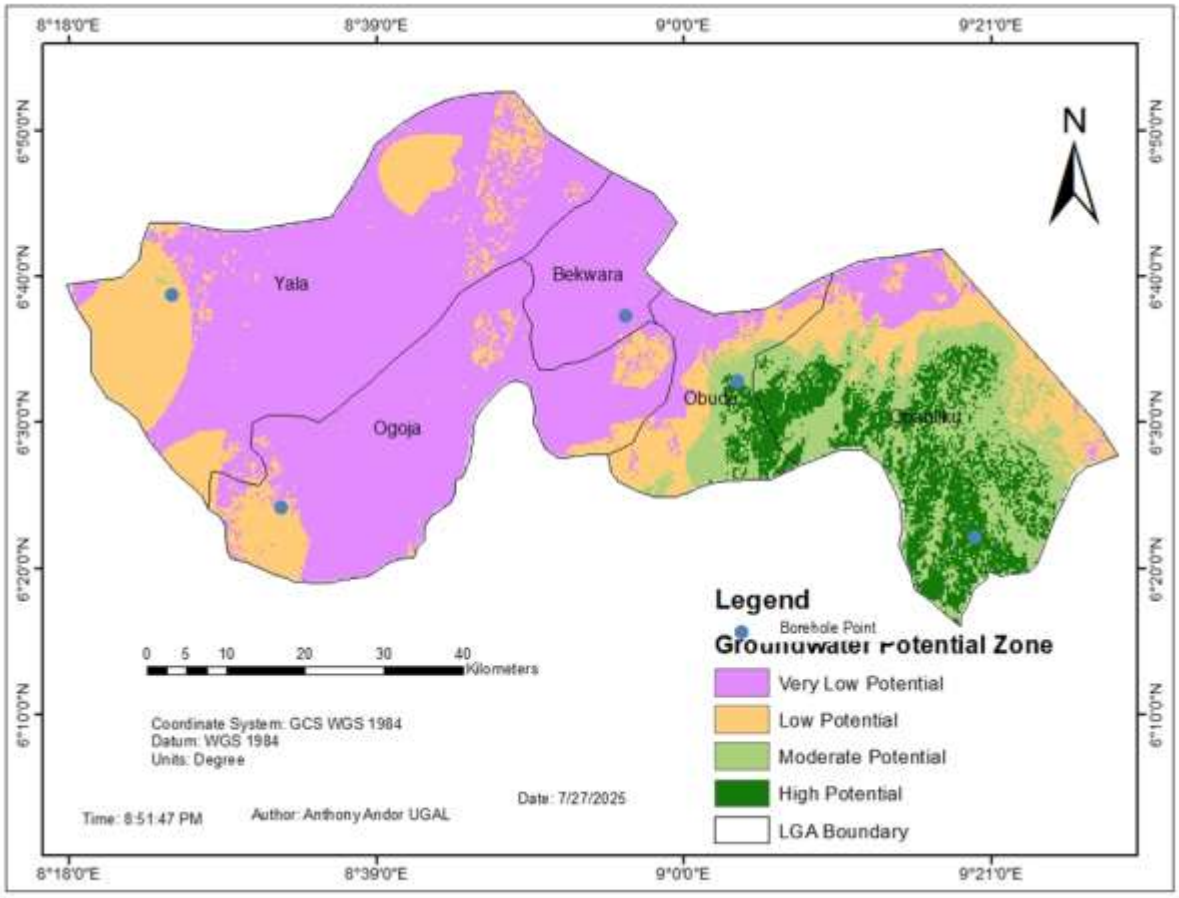


Figure 9: Spatial Distribution of Groundwater-Potential Zones

Borehole Drilling Outcomes

The qualitative outcomes of the five drilled boreholes indicate spatial variation in groundwater occurrence and yield across the study area. The boreholes at Igoli in Ogoja, Okpoma in Yala, and Abuochiche in Bekwarra recorded comparatively poor yields. In contrast, the boreholes at Obudu town in Obudu and Sankwala in Obanliku produced substantial water yields.

These observations suggest that the selected locations in Obudu and Obanliku were more favourable for groundwater abstraction than those investigated in Ogoja, Yala, and Bekwarra. The results provide preliminary field evidence for evaluating the groundwater-potential map. However, because the outcomes are qualitative, they do not establish numerical borehole yields or independently validate the mapped potential classes. Quantitative discharge measurements and information on borehole depth, water levels, and pumping-test results would be required for a more rigorous assessment.

Table 9. Coordinates and Qualitative Outcomes of the Five Boreholes Drilled

LGAs	Drilling locality	Latitude	Longitude	Qualitative outcome
Ogoja	Igoli	6°38′33.44″ N	8°47′28.26″ E	Comparatively poor yield
Yala	Okpoma	6°39′48.62″ N	8°36′18.26″ E	Comparatively poor yield
Bekwarra	Abuochiche	6°42′11.72″ N	8°53′58.89″ E	Comparatively poor yield
Obudu	Obudu town	6°40′09.65″ N	9°09′44.01″ E	Substantial water yield
Obanliku	Sankwala	6°36′25.19″ N	9°14′54.79″ E	Substantial water yield

The spatial pattern of the mapped zones can be further examined using the borehole observations presented in Table 10. The boreholes drilled at Igoli in Ogoja, Okpoma in Yala, and Abuochiche in Bekwarra recorded comparatively poor water yields, whereas those at Obudu town in Obudu and Sankwala in Obanliku produced substantial water yields. This contrast provides preliminary field evidence that groundwater occurrence and abstraction potential vary spatially across the study area. The comparatively poor yields recorded in Ogoja, Yala, and Bekwarra are consistent with the need for caution when interpreting areas classified as having low or very low groundwater potential. Conversely, the substantial yields recorded at Obudu town and Sankwala support the identification of these localities as promising areas for further groundwater investigation. These observations also highlight the practical importance of integrating thematic mapping with field-based evidence when identifying potential drilling locations.

In general, the integrated groundwater-potential map provides a regional framework for prioritising groundwater exploration, while the borehole results identify localities where groundwater development has yielded contrasting outcomes. Combining these two sources of evidence can improve the selection of future drilling sites and support more efficient groundwater-resource planning across Cross River North, Nigeria.

4. Discussion

The spatial characterization of groundwater-conditioning factors and the integration of the thematic layers through weighted-overlay analysis reveal considerable variation in groundwater potential across Cross River North, Nigeria. The delineation of very-low-, low-, moderate-, and high-potential zones demonstrates the importance of evaluating multiple environmental and geological factors when identifying areas favourable for groundwater occurrence and development. The results provide a regional framework for understanding groundwater prospectivity and prioritising locations for further investigation.

The distribution of the integrated groundwater-potential classes indicates that low-potential zones occupy the largest area, covering 19,359 km² (36.22%), followed by very-low-potential zones covering 18,237 km² (34.12%). Together, these two classes account for 37,596 km² (70.34%) of the study area. In comparison, moderate- and high-potential zones cover 15,852 km² (29.66%). This distribution suggests that relatively limited groundwater potential characterises a substantial

proportion of the mapped area, although more favourable conditions occur in specific locations. The relatively extensive low-potential classes highlight the need for careful site selection before borehole drilling, particularly in areas where surface characteristics and subsurface conditions may constrain groundwater occurrence or abstraction.

The borehole outcomes presented in Table 9 provide preliminary field-based evidence of spatial differences in groundwater yield. The boreholes at Igoli in Ogoja, Okpoma in Yala, and Abuochiche in Bekwarra recorded comparatively poor yields, whereas the boreholes at Obudu town in Obudu and Sankwala in Obanliku produced substantial water yields. This contrast indicates that groundwater development outcomes vary across the investigated locations and supports the importance of combining regional groundwater-potential mapping with site-specific hydrogeological investigations.

The substantial yields recorded at Obudu town and Sankwala identify these localities as promising sites for further groundwater-resource assessment. Their outcomes are also consistent with the reported concentration of more favourable groundwater-potential zones in parts of Obudu and Obanliku. The qualitative borehole outcomes therefore provide preliminary supporting evidence but do not, by themselves, constitute a quantitative validation of the integrated map.

Similarly, the comparatively poor yields recorded at Igoli, Okpoma, and Abuochiche demonstrate that successful groundwater development cannot be inferred from regional spatial patterns alone. Groundwater occurrence and borehole productivity depend on local subsurface conditions that may not be fully represented by regional thematic datasets. Consequently, even within areas assigned similar groundwater-potential classes, actual borehole performance may differ. This limitation reinforces the need for detailed investigations at proposed drilling sites rather than relying exclusively on the mapped suitability classes. The results have practical implications for groundwater exploration and water-resource planning. The integrated map can guide the preliminary identification of areas for further investigation, while the borehole observations provide useful information on the outcomes of drilling at the five sampled localities. Locations within moderate- and high-potential zones may be prioritised for additional geophysical surveys and exploratory drilling, subject to site-specific verification. In areas where boreholes have recorded comparatively poor yields, further assessment of subsurface geology, weathered materials, fractures, and groundwater conditions may help identify more suitable drilling locations.

However, the interpretation of the findings is subject to limitations. The borehole evidence comprises five locations and uses qualitative yield descriptions rather than measured discharge rates. The observations are therefore insufficient to establish the predictive accuracy of the groundwater-potential map or to generalise the outcomes to all five local government areas.

In summmary, the integration of groundwater-conditioning factors produced a regional classification of groundwater potential that, when considered alongside the five borehole outcomes, illustrates the spatial variability of groundwater development prospects across Cross River North. The substantial yields recorded at Obudu town and Sankwala and the comparatively poor yields at Igoli, Okpoma, and Abuochiche emphasise the importance of combining spatial modelling with field investigations. The resulting map is best regarded as a preliminary groundwater-exploration and decision-support tool, rather than a definitive prediction of borehole yield at individual locations.

5. Conclusion

The results demonstrate spatial variation in groundwater potential and highlight the importance of integrating multiple environmental and geological factors when identifying areas suitable for

groundwater exploration. The resulting map provides a regional framework for distinguishing areas of relatively favourable groundwater potential from those requiring more detailed investigation before drilling. The five borehole observations further revealed differences in groundwater yield among the investigated localities. The boreholes at Igoli in Ogoja, Okpoma in Yala, and Abuochiche in Bekwarra recorded comparatively poor yields, whereas those at Obudu town in Obudu and Sankwala in Obanliku produced substantial water yields. These observations provide preliminary field evidence of spatial differences in groundwater development prospects.
The study establishes a spatial basis for preliminary groundwater exploration and planning across Cross River North. The integrated groundwater-potential map can support the prioritisation of investigation sites, but successful groundwater development will depend on further geophysical surveys, hydrogeological assessments, and field verification at individual drilling locations.

6. Recommendations

Based on the findings of the study, the following recommendations were made:

i. **Groundwater exploration and site selection:** The groundwater-potential map developed from lineament density, slope, geology, soil, drainage density, rainfall, and land use/land cover should be used to guide preliminary groundwater exploration and prioritise potential drilling locations. Areas classified as having moderate and high groundwater potential should receive priority for further investigation, with geophysical surveys and site-specific hydrogeological assessments conducted before drilling.

ii. **Field validation and improvement of groundwater mapping:** Further studies should validate the mapped groundwater-potential zones using borehole yield measurements, pumping tests, and geophysical investigations across the study area. The results from the five boreholes, particularly the substantial yields recorded at Obudu and Sankwala, should be incorporated into subsequent assessments to improve the reliability of groundwater-potential mapping and support sustainable groundwater-resource development.

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