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Geospatial Assessment of Groundwater Availability in Asa and Oyun River Catchments, Northcentral Nigeria

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Abstract
Subsurfacewater development in localised crystalline aquifers poses significant challenges to the sustainable supply of potable water in developing countries. This study delineated groundwater potential zones in a basement area with two major rivers, Asa and Oyun, draining it using integrated geospatial techniques and Analytical Hierarchical Process (AHP) model. The processed images from landsat 8 OLI using the Maximum Likelihood Classifier infered 5 classes*: Settlement, Bare land, Vegetation, Riparian areas, and Water bodies. Lineaments serving as structural control for the drainage system underlying the area were extracted from Landsat 8 OLI (2015), Digital Elevation Model (DEM), and aeromagnetic data using inverse distance weighted interpolation. A GIS-based AHP model combined six thematic layers (lineament density, lithology, drainage density, rainfall, land use/land cover, and slope) to produce a groundwater potential map, which was validated against twenty two (22) borehole yield data through Receiver Operating Characteristic ROC analysis. The AHP model achieved a consistency ratio (0.077) indicating reliability. Five groundwater potential zones, ranging from very low to very high, were identified. Asa river catchment was dominated by low-potential zones, while Oyun catchment exhibited moderate to high groundwater potential. Borehole yields corresponded with the classified zones, varying from 0.3–1.5 l/s in low-potential areas to above 3.60 l/s in very high-potential areas. ROC validation produced an AUC of 0.777 (77.7%), confirming the robustness of the method.*

Keywords: Crystalline-aquifer; Geospatial; Groundwater-potential-zones; Landsat 8 OLI; River-catchment.

Introduction
Access to potable water remains a critical challenge in many developing countries, particularly in Africa, where rapid population growth and expanding urbanization intensify pressure on limited water resources (Kookana *et al.*, 2020 and Niasse and Varis, 2020). In regions underlain by Precambrian crystalline basement rocks, such Nigeria where over 50% of the land cover is underlain by these rocks, groundwater occurrence is typically locally confined to weathered and fractured zones. These aquifers are discontinuous and heterogeneous, making the prediction of water yield and quality complex and highly dependent on structural features, lithology, degree of weathering, geomorphology, and drainage characteristics (Hussain *et al*., 2022 and Bayowa *et al*., 2023).

Adabanija *et al.*, 2021 argued that groundwater mapping in crystalline basement terrains presents significant challenges because predicting both the yield and quality of subsurface water is inherently complex. In tropical regions, these rocks are often freshly to deeply weathered at depth, and this degree of weathering directly influences groundwater yield, storage, and quality. Kouamé *et al.*, 2021 showed that groundwater exploration generally focuses on fracture zones, as they may host varying amounts of water that control overall productivity. The weathered materials within these fractures further affect groundwater chemistry, which ultimately reflects the mineralogical composition of the underlying basement rocks. Factors such as lineament attitude of fracture and density, especially in freshly weathered horizons, together with the problem of groundwater over-abstraction, add further difficulties to groundwater potential mapping efforts.

Successful groundwater exploration therefore often targets highly fractured zones within the vadose zone to maximize yield potential.

The Analytical Hierarchical Process (AHP) is a structured decision-making tool that can be applied to groundwater mapping in crystalline rock regions, particularly in areas facing growing water insecurity. Incorporating AHP into groundwater exploration enhances the precision of identifying potential recharge and storage sites. The method evaluates factors such as rock type, fracture density, weathering profiles, and hydrological characteristics, assigning them weighted importance according to their order of importance. While machine learning algorithms such as Random Forest, Support Vector Machines (SVM), and Multivariate Adaptive Regression Splines (MARS) models have been successfully applied to groundwater assessment and exploration with strong predictive power (Pourghasemi *et al*., 2020 and Arabameri *et al*., 2021), the AHP provides decision-support insights for both technical experts and policymakers. The former are result-oriented and work on best fit and probability while the latter uses geostatistical techniques that are research-oriented that allows user-defined bias (Owolabi *et al.,* 2020). Integrating AHP in groundwater exploration will allow for flexibility in combining hydrogeological parameters in forecasting new aquifers with, probable, good yields. Overall, the integration of Geographical Information System (GIS) with AHP offers a simple, transparent, and reliable framework for groundwater exploration. By reducing complex decisions into structured pairwise comparisons of lithological, geomorphological, climatic, and hydrogeological parameters, this approach facilitates the delineation of reliable groundwater potential zones (Dar *et al*., 2020 and Pal and Das, 2020 and Masoud *et al*., 2022).

Advances in Geographic Information Systems (GIS) and Multi-Criteria Decision Analysis (MCDA) have enhanced groundwater exploration in basement terrains by enabling the integration of diverse hydrogeological datasets. The Analytical Hierarchical Process (AHP) provides a transparent and systematic framework for weighting controlling factors such as lithology, fracture density, slope, and drainage density, thereby supporting robust decision-making for resource management (Coulibaly *et al*., 2021).

Most studies are usually unilateral in their approach and do not use multilayer-decision-making process to inform on groundwater management and sustainability. This study employs a spectral solution to groundwater mapping in the crystalline basement of some tropical catchment areas in north central Nigeria, based on AHP as a Multi-Criteria Decision Analysis (MCDA) approach, to address water scarcity in densely populated urban metropolitan areas and the associated over-abstraction of groundwater. The Asa and Oyun catchment regions, which are densely inhabited, were chosen because of their perennial flow of surface water, which is directly related to vadose levels and well yields. The goals of this research are: a) to map regional structural trends using Landsat 8 OLI for groundwater exploration in the area; and b) to identify and evaluate groundwater potential zones in the area.

Location, geology and hydrogeology of the study area

The study area, a spatial extent that has two major rivers (Rivers Asa and Oyun), is bounded within latitudes $8^0$00’00” N and $8^0$35’15” N and longitudes $4^0$19’22” E and $4^0$55’00” E as presented in Figure 1. The study area is underlain by crystalline basement rocks, as shown in Figure 2, with shallow overburden with lineaments crucial for groundwater storage, recharge, and movement. The lithology of the area, mainly the migmatite gneiss quartzite Precambrian complex, was drawn from a 1:250,000 scale Geological Survey of Nigeria (GSN) 50 geological map. The migmatite gneiss complex is the dominant lithology in the area and is in line with the observations made by Oluyide *et al.* (1998); Afolabi *et al.* (2019) and Tijani (2023) where they differentiated the migmatite gneiss into banded, lit par lit and augen gneisses. Other rocks are quartzite, schists and igneous intrusions. These rocks have very poor porosity but better permeability due to fractures and freshly weathered overburden. These properties make the basement aquifers localised and rarely interconnected except for deep seated and regional fractures.

Groundwater occurrences in the western half of Nigeria are confined to the thin soil cover, mostly termed weathered layer aquifers (Raji and Abdulkadir, 2020; and Bayowa *et al.,* 2023), occurring between 3 m and

7 m, and fractured zone, occurring at 20-70 m. These aquifers are mostly localised and with the heterogenous basement rock compositions the nature of the water chemistry within these aquifers become complicated. The soil cover is comprised of layers of humus, sandy loam, and clayey or lateritic soil while the fractured zones are comprised of stratified fissured layer, vertical N-S fissure, and sub-vertical fissure sets (Adabanija *et al.,* 2021) resulting in a combined aquifer thickness ranging from 4.6 m to about 90m (Raji and Abdulkadir, 2020). Kolawole *et al*. (2017) earlier reported that the groundwater recharge, estimated from remote sensing for the Ilorin area, varied seasonally with recharge rates ranging from 15m^3/month to 40 m^3/month in the dry season and 63m^3/month to 110 m^3/month during wet seasoning.

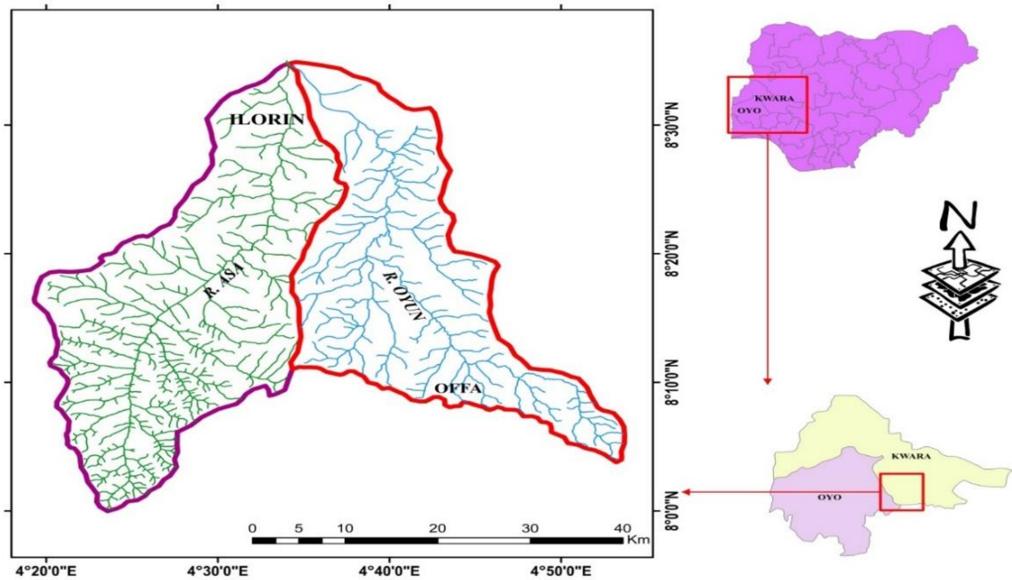

Figure 1: Drainage Pattern of the Study Area.

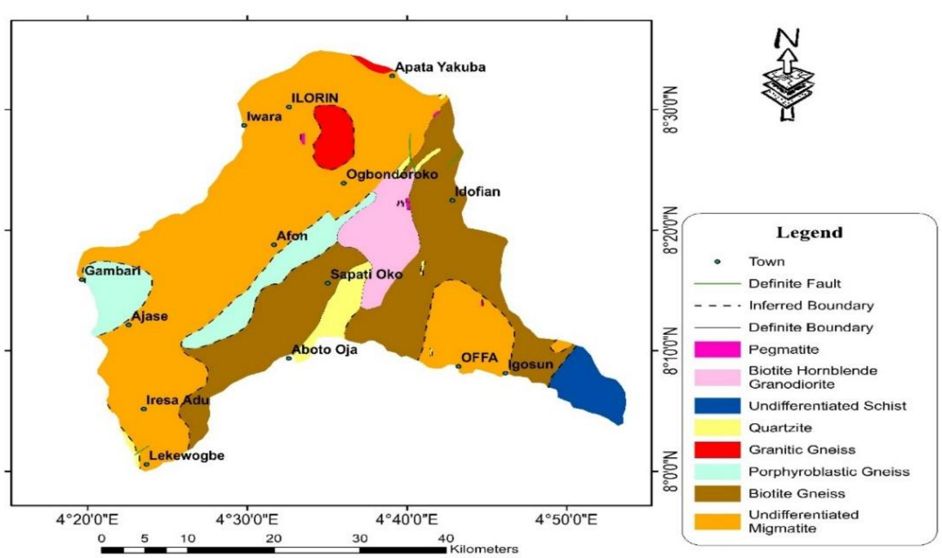

Figure 2: Lithological Distribution of the underlying Crystalline Basement modified after Oluyide *et al.* (1998) and Afolabi *et al.* (2019)

Materials and Methods

Data collection and image processing

A range of geospatial datasets was integrated for groundwater potential mapping in the Asa and Oyun River catchments. The thematic layers included lithology (after Oluyide *et al*., 1998 and Afolabi *et al.*, 2019), lineament density, slope, land use/land cover, drainage density, and rainfall. Lineaments, slope, and land use/land cover were derived from Landsat imagery, while drainage networks were extracted from the ASTER Global Digital Elevation Model (GDEM). Rainfall data were sourced from the Nigerian Meteorological Agency and the Tropical Rainfall Measuring Mission (TRMM) Version 3B43RT dataset. The Rainfall data obtained from the Nigerian Meteorological Agency and the Tropical Rainfall Measuring Mission (TRMM) Version 3B43RT product were processed into a grid with a spatial resolution of 0.25° × 0.25°. The two datasets, covering the period from 1999 to 2024, were used for both validation and thematic mapping. Slope maps were generated using the slope function in ArcGIS. The land use and land cover were mapped using a Natural Colour Composite (NCC) image. The processed images from Landsat 8 OLI Bands 4, 3, and 2 will be used to generate landuse classification based on the data type presented in Table 1.

Image enhancement and lineament extraction

Landsat 8 OLI Bands 1–7 were pan-sharpened to 15 m resolution using the panchromatic Band 8 after radiometric correction. Principal Component Analysis (PCA) was then applied to reduced the dimensionality of the bands to Bands 2–8 using ENVI 5.3, excluding Band 1 (commonly used for aerosol analysis) with Factor 1 accounting for 94% of the total variance.

Directional filtering was applied to PC1 using four orientations (E-W, NE-SW, NW-SE, and N-S) with a 3×3 convolution kernel in ENVI 5.3. Additionally, Multi-Directional Oblique Weighted (MDOW) shaded relief maps were created from ASTER DEM using ArcGIS 10.4 with 0° and 180° illumination directions. Lineaments were extracted from the four directionally filtered Landsat images and two MDOW hillshade maps using PCI Geomatica (Version 17). Aeromagnetic data from the Nigeria Geological Survey Agency (NGSA) were interpreted using Oasis Montaj Version 7.5 to extract magnetic lineaments. All lineaments (from Landsat, ASTER GDEM, and aeromagnetic sources) were merged in ArcGIS 10.4 to generate a comprehensive total lineament map. TRMM data for 2022 were used to align with the 2022 Landsat imagery.

Statistical treatment and weight assignment

An Analytical Hierarchical Process (AHP) was employed to assign weights to six groundwater-influencing factors: lineament density, lithology, drainage density, rainfall, land use/land cover, and slope. Weight assignment, formulated using Equations 1 and 2, was based on:

i) Saaty's (1987) scale of relative importance as presented in Table 2,
ii) Previous studies in similar geologic terrains by Osinowo and Arowoogun, 2020; and Ejepu *et al.*, 2022,
iii) Historical reports within the study area by Oluyide *et al.*, 1998.

A pairwise comparison matrix and AHP computations (eigenvector, Consistency Ratio CR = 1, as presented in equation 1, and normalised weights) were performed using the AHP toolbox in ArcGIS 10.4.

$$CR = \frac{CI}{RI} \qquad 1$$

Where CR is the consistency ratio, RI is the Random index; CI is consistency index as shown in equation 2.

$$CI = \frac{\lambda_{max} - n}{n-1} \qquad 2$$

Where λ_{max} is the eigenvalue, n is the number of parameters.

Consistency ratio lesser than 0.1 or 10% is considered acceptable and the weightage is deemed adequate.

Groundwater potential mapping and validation

Weighted thematic layers were integrated in ArcGIS using a weighted overlay analysis to produce the final groundwater potential zones. The resulting map classified the study area into zones of varying groundwater potential. Model validation was performed using borehole yield data from selected locations across the study area. Receiver Operating Characteristic (ROC) analysis was applied to evaluate the accuracy of the groundwater potential model. The Area Under Curve (AUC) value was calculated and compared against standard accuracy thresholds to assess model performance as presented in Table 3.

Table 1: Geospatial Data Type and Description used for the study

Data	Bands	Spatial Resolution	Date of Acquisition	Institutional Source
Landsat 8 OLI	1-7 – VNIR and SWIR	30m	2022	Earth Explorer
	8 – Panchromatic	15m		
	9 – Cirrus	30m		
ASTER GDEM	ASTER Band 3 (Backswath)	15m	2002	Earth Explorer
Aeromagnetic Data		30m		NGSA
TRMM Data	3B43	0.25^{O}	1999-2013, 2022	Earthdata
Rainfall data (Ilorin)			1999-2013	NIMET
Lithology and structures			1998	

Table 2: Scale of Importance.

Scale	Definition	Explanation
1	Equal Importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgement strongly favour one activity over another
5	Essential or strong importance	Experience and judgement strongly favour one activity over another
7	Very strong importance	An activity is strongly favored and its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgements	When compromise is needed

Source: Saaty (1987).

Table 3: Area Under Curve (AUC) Value.

AUC Value	Test Quality
0.9 – 1.0	Excellent
0.8 – 0.9	Very Good
0.7 – 0.8	Good
0.6 – 0.7	Satisfactory
0.5 – 0.6	Unsatisfactory

Source: Trifonova *et al.,* 2013

Results and Discussion

Lithological description

The area is a crystalline basement with poor porosity and permeability except for instances where it is fractured. Fracturing of the basement complex may be linked to uplift and orogenic phases. The lithological composition has been discussed earlier.

Lineament analysis, drainage density and rainfall analysis

Structural lineament analysis for the catchment areas was carried out through integration of aeromagnetic data with enhanced Landsat 8 OLI and DEM datasets to delineate both surface and subsurface fractures influencing groundwater pathways. Recent hydrogeological studies in Nigeria confirm that mapping lineament and drainage density enhances understanding of fractured basement aquifers and groundwater potential in crystalline terrains (Ajadi *et al.*, 2025). Lineament density mapping, presented in Figure 3, in this study revealed a higher structural density in the Oyun catchment than in Asa, while both rivers display dendritic drainage patterns indicative of crystalline basement influence. Drainage density is generally high along valley floors, peaking above 112 km/km² in southern Asa and central Oyun catchments. Groundwater recharge in the study area primarily occurs through precipitation, recharging both shallow (in-situ soils) and deep (fractured basement) aquifers. Rainfall patterns indicated increasing rainfall from southwest to northeast, with the southern Asa catchment receiving the least (1200–1300 mm/year) and the northern Oyun catchment receiving the most (>1500 mm/year). Areas with higher rainfall are expected to have greater groundwater recharge potential thus favouring River Oyun's groundwater recharge potential.

Landcover and use classification

Land use plays an important role in the occurrence and distribution of groundwater. The land use class is given in Table 4. The study area is classified accordingly into waterbody (0.37 %), Riparian (7.83 %), Settlement (14.13 %), Barelend (31.02 %), and Vegetation (46.65 %).

Groundwater potential mapping

The weightage (equations 1 and 2) adopted after Burayu (2022) for this study favoured lineament density than lithology based on the premise that the productivity of boreholes/wells depended on the proximity to high lineament density area followed by drainage density, slope, rainfall, and landuse/landcover. The pairwise comparison gave a Consistency Index (CI) of 0.097 and a Consistency Ratio (CR) of 0.077. Both parameters (Consistency ratio and Consistency Index) and the weightage for the final groundwater potential map were estimated from the pairwise comparison and shown in Tables 2 and 5. The pairwise comparison matrix is normalised using weightage matrices and presented in Table 6. The class rating and overall weightage of the factors, presented in Table 7, employed in computing the Groundwater Potential (GWP) were obtained using Equation 3. It is from this that a groundwater potential map, shown in Figure 4, was generated.

$$GWP = 0.444LD + 0.252LTH + 0.145DD + 0.085SLP + 0.046RF + 0.026LULC \quad 3$$

Where LD is Lineament Density, LTH is Lithology, DD is Drainage Density, SLP is Slope, RF is Rainfall and LULC is Lauduse Classification.

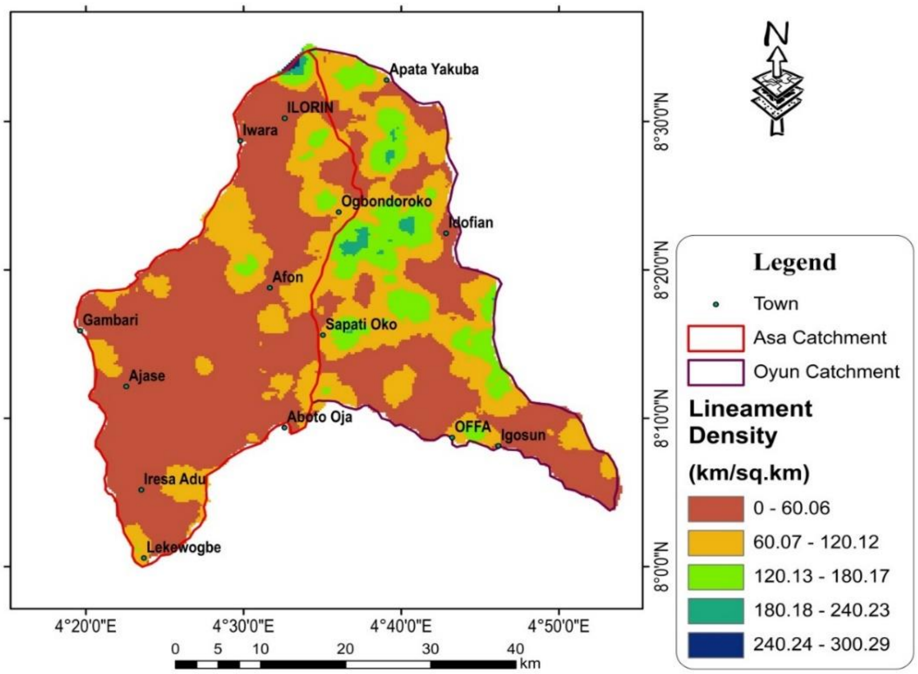

Figure 3: Lineament Density of the Study Area.

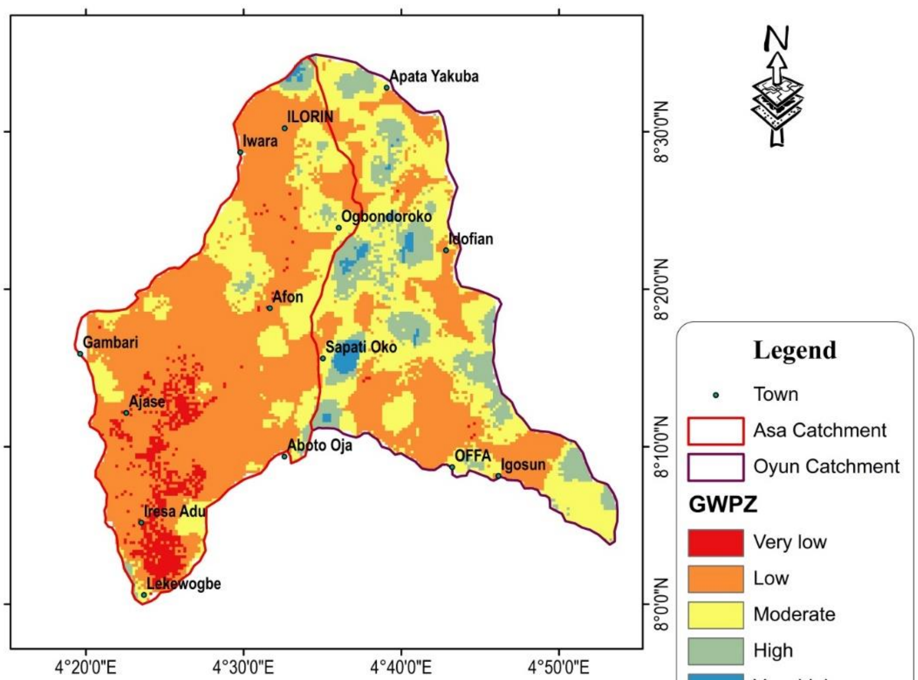

Figure 4: Spatial Distribution of Borehole yield on Groundwater Potential Map.

Table 4: Land Use Classification.

Land Class	Area (km^2)	% (%)
Unidentified	0	0
Waterbody	6.99	0.37
Vegetation	869.76	46.65
Riparian	146.92	7.83
Settlement	263.55	14.13
Bareland	578.35	31.02

Table 5: Pairwise Comparison Matrix of Factors.

	LD	LTH	DD	SLP	RF	LULC
LD	1	3	5	6	8	9
LTH	0.33	1	3	5	6	8
DD	0.2	0.33	1	3	5	6
SLP	0.17	0.2	0.33	1	3	5
RF	0.13	0.17	0.2	0.33	1	3
LULC	0.11	0.125	0.17	0.2	0.33	1

LD = Lineament Density, LTH = Lithology, DD = Drainage Density, SLP = Slope, RF = Rainfall and LULC = Lauduse Classification

Table 6: Normalised Weightage Matrix.

	LD	LTH	DD	SLP	RF	LULC	Normalised Weightage
LD	0.516	0.622	0.515	0.386	0.343	0.516	0.444
LTH	0.172	0.207	0.309	0.322	0.257	0.172	0.252
DD	0.103	0.069	0.103	0.193	0.214	0.103	0.145
SLP	0.086	0.041	0.034	0.064	0.128	0.086	0.085
RF	0.065	0.035	0.021	0.021	0.043	0.065	0.046
LULC	0.057	0.026	0.017	0.013	0.014	0.057	0.026

The groundwater potential map and the percentage coverage area, presented in Table 8, revealed 5 zones: ‘very low’ (4.37%), ‘low’ (52.91%), ‘moderate’ (31.93%), ‘high’ (9.57%) and ‘very high’ (1.21%). The River Asa catchment area has very low and low groundwater potential zones (GWPZs), while the River Oyun catchment area has moderate, high, and very high GWPZs. Dense lineament, shown in Figure 3, in the River Oyun catchment area may be linked to the high GWPZs observed.

Borehole yield data correlated well with these classifications. Quantification of this classification is as follows:

i) very low and low potential zones recorded yields between 0.3 and 0.9 l/s,
ii) moderate zones yielded 0.3–1.8 l/s,
iii) high potential zones yielded 1.5–3.6 l/s, and
iv) very high potential zones exceeded 3.6 l/s.

These findings suggest that the very low and low zones are only suitable for domestic use, the moderate zone can support domestic and limited municipal supply, while the high and very high zones are suitable for regional groundwater development and large-scale irrigation schemes.

Validation results demonstrate that the groundwater potential model performed satisfactorily when tested against 22 borehole yield data (l/s) compiled from previous studies. The comparison between observed borehole yields and the delineated groundwater potential zones, evaluated using Receiver Operating Characteristic (ROC) analysis, produced an Area Under Curve (AUC) value of 0.777 (≈0.8). This AUC value reflects a good predictive accuracy and confirms the reliability of the model for groundwater exploration within the study area.

Table 7: Weighted Factors influencing Groundwater Potential Zone.

Criteria	Class Description	Rating	Weightage (%)	Subclass weightage
Lineament Density (km/km^2)	0.00 – 54.90	0.035	44.41	0.015
	54.91 – 109.80	0.068		0.030
	109.81 – 164.70	0.134		0.059
	164.71 – 219.61	0.260		0.116
	219.62 – 274.51	0.503		0.223
Lithology	Pegmatite	0.139	25.29	0.035
	Quartzite/Quartz Schist	0.333		0.084
	Biotite-Hornblende Granodiorite	0.045		0.012
	Granite Gneiss	0.045		0.012
	Biotite Gneiss	0.110		0.028
	Undifferentiated Schist	0.203		0.051
	Migmatite	0.066		0.017
	Porphyroblastic Gneiss	0.057		0.015
Drainage Density (km/km^2)	0.00 – 38.23	0.416	14.51	0.060
	38.24 – 76.46	0.262		0.038
	76.47 – 114.69	0.161		0.023
	114.70 – 152.92	0.099		0.014
	152.93 – 191.15	0.062		0.009
Slope (^{O})	0.00 – 1.95	0.416	8.51	0.035
	1.96 – 4.09	0.262		0.022
	4.10 – 6.62	0.161		0.014
	6.63 – 11.5	0.099		0.008
	11.51 – 49.68	0.062		0.005
Rainfall (mm)	1238.03 – 1312.41	0.062	4.63	0.003
	1312.42 – 1386.79	0.099		0.005
	1386.80 – 1461.17	0.161		0.007
	1461.18 – 1535.56	0.262		0.012
	1535.57 – 1609.94	0.416		0.019
Land use Classification	Waterbody	0.126	2.65	0.003
	Vegetation	0.264		0.007
	Riparian	0.161		0.004
	Settlement	0.068		0.002
	Bareland	0.380		0.010

Table 8: Groundwater Potentials zones and their coverage area.

		Asa Catchment		Oyun Catchment		Total Study Area	
		Area (km^2)	**% (%)**	**Area (km^2)**	**% (%)**	**Area (km^2)**	**% (%)**
Groundwater Potential Zone	**Very low**	78.73	7.74	0.87	0.11	79.61	4.37
	Low	702.73	69.12	264.41	32.87	963	52.91
	Moderate	210.94	20.75	368.19	45.78	581.09	31.93
	High	21.67	2.13	151.59	18.85	174.13	9.57
	Very High	2.61	0.26	19.28	2.39	22.1	1.21

a) to map regional structural trends using Landsat 8 OLI for groundwater exploration in the area; and b) to identify and evaluate groundwater potential zones in the area.

Conclusion

Lineament analysis derived from Landsat 8 OLI, ASTER, and aeromagnetic datasets revealed distinct structural patterns within the study area. The results indicate that the crystalline basement terrain drained by the River Oyun catchment exhibits a significantly higher lineament density compared to the River Asa catchment. Pairwise comparison and weighting using the Analytical Hierarchical Process (AHP) further confirm that the River Oyun catchment is characterized by more extensive fracture systems, which enhance groundwater storage and movement within the basement complex.The integrated GIS-AHP framework was used to map groundwater potential which identified five zones within the study. The River Asa watershed is dominated by very low to low groundwater potential zones, implying minimal aquifer production due to probable poor interconnectivty of the structural lineaments. In contrast, the River Oyun catchment is largely associated with moderate to very high groundwater potential zones due to its higher fracture density and favourable hydrogeological conditions, highlighting the importance of structural features and terrain characteristics in controlling groundwater occurrence in localised aquifer crystalline basement environments.

Overall, the integration of remote sensing, geophysical data, GIS, and AHP provided an effective framework for assessing groundwater potential in crystalline basement terrains with localised aquifers. The groundwater potential map produced in this study can guide groundwater exploration, sustainable water resource development, and borehole siting in the Asa and Oyun catchments and similar basement regions. Groundwater development should be prioritized in the moderate to very high potential zones, particularly within the River Oyun catchment, with detailed geophysical surveys and borehole validation conducted prior to large-scale abstraction.

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