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INTEGRATED GIS-AHP AND HYDROGEOPHYSICAL APPROACHES FOR GROUNDWATER POTENTIAL MAPPING IN AKURE METROPOLIS, ONDO STATE, NIGERIA

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INTEGRATED GIS-AHP AND HYDROGEOPHYSICAL APPROACHES FOR GROUNDWATER POTENTIAL MAPPING IN AKURE METROPOLIS, ONDO STATE, NIGERIA

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Abstract

Groundwater remains the principal source of potable water for domestic, agricultural, and industrial activities in many parts of Nigeria. However, increasing population growth, urban expansion, and climate variability have intensified pressure on groundwater resources, necessitating accurate assessment of groundwater potential zones for sustainable water resource management. This study integrated Remote Sensing (RS), Geographic Information Systems (GIS), the Analytical Hierarchy Process (AHP), and Vertical Electrical Sounding (VES) techniques to delineate groundwater potential zones in Akure Metropolis, Ondo State, southwestern Nigeria. Eight groundwater conditioning factors comprising geology, lineament density, land use/land cover, drainage density, soil, rainfall, slope, and elevation were selected and weighted using the AHP multi-criteria decision-making approach. The thematic layers were integrated through weighted overlay analysis to generate a groundwater potential map. Furthermore, forty-one (41) Vertical Electrical Sounding (VES) stations were conducted across the study area to characterize subsurface hydrogeological conditions using parameters such as overburden thickness, aquifer thickness, aquifer resistivity, bedrock relief, hydraulic conductivity, transmissivity, transverse resistance, and longitudinal conductance. The VES-derived groundwater potential map was subsequently integrated with the GIS-AHP model to improve prediction reliability and reduce uncertainty associated with surface-based analyses. The integration resulted in the classification of the study area into five groundwater potential zones: very low, low, moderate, high, and very high. Moderate potential zones covered the largest area—52.08%, high-26.36%, low-18.78%, very high-1.66% and the very low-1.12%. Areas with high to very high groundwater potential were predominantly concentrated in the northeastern and eastern parts of the study area, particularly around Ogbese and Ita-Ogbolu, where favourable geological formations, high lineament density, and enhanced aquifer characteristics occur. Conversely, low to very low groundwater potential zones were mainly located in the southwestern parts of the study area where unfavourable hydrogeological conditions prevail.The integration of GIS-AHP and hydrogeophysical data demonstrated strong spatial agreement between predicted groundwater potential zones and subsurface aquifer characteristics obtained from VES interpretation. The study highlights the effectiveness of integrating geospatial and hydrogeophysical techniques for groundwater exploration, borehole siting, and sustainable groundwater resource management in crystalline basement terrains.

Keywords: Groundwater Potential, GIS, Remote Sensing, Analytical Hierarchy Process, Vertical Electrical Sounding, Hydrogeophysics, Akure Metropolis.

1.0 Introduction

Water is an indispensable resource that is required to sustain human life and enable a variety of activities that are critical for improving socioeconomic circumstances [19]. However, issues related to water limited availability, toxicity, and usability continue to plague societies worldwide [28]. Around the world, as a region's population grows, so does the demand for groundwater (GW). In order to supply the growing population's water needs, an excessive amount of groundwater has recently been extracted [11]. Groundwater quality and quantity have been demonstrated to be greatly impacted by activities such as growing urbanization, manufacturing processes, and deforestation [10]. More than 50% of the farmland in densely populated nations, like those in Asia and Africa, is irrigated by groundwater [25]. Over half of Akure's population does not have access to potable water and is mostly dependent on untreated water from shallow wells and streams.

Ground surveys utilizing geophysical, geological, and hydrology instruments are a major component of conventional approaches for locating, characterizing, and charting groundwater reserves zones. These methods are typically laborious and costly [4]. On the other hand, groundwater studies have recently made extensive use of remote sensing (RS), geographic information systems (GIS), and multi-criteria decision analysis (MCDA) tools like analytical hierarchy process (AHP) [13]; [21]; [15]. It has been demonstrated that combining thematic variables, such as topographic features, land cover, and lithological characteristics, produces more reliable outcomes [15]; [22].

Ground-truth validation is still essential for models trustworthiness, even with advances in geographic modeling. Geophysical methods, particularly Vertical Electrical Sounding (VES), are extremely useful in this situation [26]. Research has demonstrated that incorporating resistivity data to validate GIS-AHP results improves model reliability and aids in confirming aquifer boundaries found through thematic overlay [12]; [23]. Although there are studies that combine VES and GIS-AHP, as was previously indicated, there aren't many that combine hydrogeophysical validation with GIS-based groundwater modeling in Akure.

Although several groundwater studies have been conducted within southwestern Nigeria, relatively few have integrated GIS-based AHP modelling with extensive hydrogeophysical validation for groundwater potential assessment within Akure Metropolis. Existing studies in the area have largely focused on either geophysical investigations or GIS-based analyses independently, thereby limiting the ability to comprehensively evaluate groundwater occurrence using both surface and subsurface indicators. Furthermore, rapid urban expansion within Akure has increased groundwater demand, necessitating updated and spatially validated groundwater potential information for sustainable water resource planning and management.

This study therefore integrates Remote Sensing, Geographic Information Systems (GIS), the Analytical Hierarchy Process (AHP), and Vertical Electrical Sounding (VES) techniques to delineate groundwater potential zones within Akure Metropolis, Ondo State, Nigeria. Eight groundwater conditioning factors comprising geology, lineament density, land use/land cover, drainage density, soil, rainfall, slope, and elevation were evaluated using AHP, while hydrogeophysical parameters derived from forty-one (41) VES stations were utilized to characterize subsurface groundwater conditions. The resulting groundwater potential maps from both approaches were integrated to produce a more reliable groundwater potential zonation model.

The novelty of this study lies in the integration of GIS-based multi-criteria groundwater modelling with detailed hydrogeophysical validation using forty-one VES stations within a crystalline basement terrain environment. By combining surface-derived environmental indicators with subsurface aquifer characteristics, the study improves the reliability of groundwater potential prediction and provides a robust framework for groundwater exploration, borehole siting, aquifer management, and sustainable water resource planning in Akure Metropolis and similar basement complex regions.

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2.0 Study Area

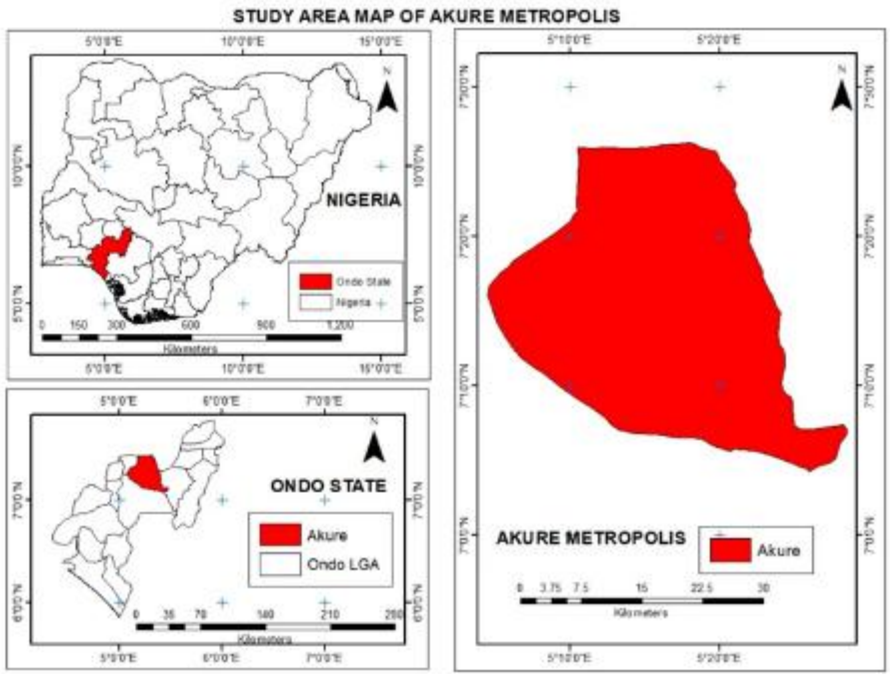

Figure 1: Map of the study area

The city of Akure is located in southwest Nigeria. It is Ondo State's capital and biggest city. It is located between latitudes 7° 09′ and 7° 19′ N and longitudes 5° 07' and 5° 17′ E, and roughly 15,500 km^2. Akure is roughly 311 kilometers northeast of Lagos, 186 kilometers west of Benin City, the capital of Edo State, and 204 kilometers east of Ibadan, the capital of Oyo State. With a population of 38,852 in 1952, 71,106 in 1963, 239,124 in 1991, and a projected 269,207 in 1996, Akure's current estimated population, at an annual growth rate of 3.18, is 474,848 [14]. According to Koppen's classification, Akure is in the humid tropical climate (Am) area. With a mean annual precipitation of 2378 mm, the wet season (April–October) is marked by sporadic floods, which has been connected to a lack of compliance with cadastral and standard planning requirements [8]. The dry season usually lasts from late November to March, as well as during the brief dry spell of the August break's "little dry season" [8]. According to [18] the mean temperature is roughly 22°C during harmattan (December to February) and 32°C in March. Situated on a level plain around 250 meters above sea level, Akure boasts tropical rainforest vegetation [3]. The geology of Akure belongs to Precambrian crystalline basement complex rocks of southwestern Nigeria [19].

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3.0 Materials and Methods

3.1 Data Acquisition and Preparation

This study employed both geospatial and hydrogeophysical datasets to delineate groundwater potential zones within Akure Metropolis, Ondo State, Nigeria. The datasets consisted of Landsat 8 Operational Land Imager (OLI) imagery, Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM), rainfall data, geological data, soil data, and Vertical Electrical Sounding (VES) measurements. Landsat 8 imagery with a spatial resolution of 30 m was obtained from the United States Geological Survey (USGS) Earth Explorer platform. SRTM DEM data with a spatial resolution of 30 m were used for the derivation of slope, drainage, and elevation thematic layers. Eight groundwater conditioning factors were selected based on their influence on groundwater occurrence and recharge processes. These factors include geology, lineament density, land use/land cover, drainage density, soil, rainfall, slope, and elevation. Below is the summary table of data collection and sources.

Table 1: Data characteristics and sources

S/N	Dataset	Scale/Resolution	Source	Purpose
1	Landsat 8 Imagery – Operational Land Imager (OLI)	30m x 30m	USGS https://earthexplorer.usgs.gov/	Land use land cover mapping
2	SRTM DEM (1 Arc Second Global)	30m x 30m	USGS	Elevation, slope and drainage extraction
3	Rainfall data	0.05° x 0.05°	CHIRPS	Rainfall map layer

4	Soil Map		Federal Department of Agricultural Land Resources-Nigeria	Soil classification
5	Geological Map	1:100,000	Nigerian Geological Survey Agency (NGSA)	Geological classification
6	VES Data	Field data	Primary data	Characterisation of acquifer

3.2 Generation of Thematic Layers

3.2.1 Land Use/Land Cover

Land use and land cover (LULC) were derived from Landsat 8 imagery using supervised classification based on the Support Vector Machine (SVM) algorithm. The classified image was grouped into built-up areas, vegetation, wetlands, bare land, and water bodies. These classes were ranked according to their relative influence on groundwater recharge.

3.2.2 Slope

Slope was extracted from the SRTM DEM using the slope function within the ArcGIS Spatial Analyst environment. Areas characterized by gentle slopes were assigned higher groundwater potential rankings due to enhanced infiltration capacity, while steep slopes received lower rankings owing to increased surface runoff.

3.2.3 Drainage Density

Drainage density was generated from the extracted drainage network using the line density tool in ArcGIS. Areas with low drainage density were assigned higher groundwater potential rankings because of increased infiltration opportunities.

3.2.4 Lineament Density

Lineaments were extracted from the SRTM DEM through digital image enhancement and structural interpretation techniques. The extracted lineaments were converted into a lineament density map using the line density function in ArcGIS. Areas characterized by high lineament density were assigned higher groundwater potential rankings due to the enhanced occurrence of fractures and secondary porosity, which facilitate groundwater storage and movement.

3.2.5 Geology

The geological map of the study area was obtained from the Nigerian Geological Survey Agency (NGSA), digitized, and converted into raster format. Geological formations were evaluated based on their hydrogeological significance and groundwater storage potential.

3.2.6 Soil

The soil map was extracted from the national soil database and classified according to soil texture and infiltration characteristics. Permeable soil types were assigned higher groundwater potential ratings.

3.2.7 Rainfall

Rainfall data were interpolated using the Inverse Distance Weighting (IDW) technique to generate a continuous rainfall surface. Areas receiving higher rainfall were assigned higher groundwater potential rankings due to increased recharge opportunities.

3.2.8 Elevation

Elevation data were derived from the SRTM DEM. Lower elevation zones were considered more favorable for groundwater accumulation and consequently assigned higher rankings.

Analytical Hierarchy Process (AHP)

The Analytical Hierarchy Process (AHP) developed by Saaty (1980) was adopted to determine the relative importance of groundwater conditioning factors. Pairwise comparisons were performed

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among the eight thematic layers using a nine-point preference scale. The resulting comparison matrix was normalized and used to derive the principal eigenvector representing the relative weights of each criterion. The final weights assigned to the thematic layers were Geology (26%), Lineament Density (22%), Land Use/Land Cover (16%), Drainage Density (11%), Soil (10%), Rainfall (6%), Slope (5%), and Elevation (4%). To evaluate the reliability of the pairwise comparison matrix, the Consistency Index (CI) and Consistency Ratio (CR) were computed according to Saaty (1980):

$$CI = (\lambda max - n)/(n - 1)$$

$$CR = CI/RI$$

where λmax represents the maximum eigenvalue, n is the number of criteria, and RI is the Random Index. A CR value less than 0.10 indicates acceptable consistency in expert judgment.

Table 1: Pairwise matrix and weights distribution using remote sensing data and AHP method

Matrix	Geology	Lineament Density	LULC	Drainage Density	Soil	Rainfall	Slope	Elevation	Normalized Principal Eigenvector
Geology	1	2	3	3	3	3	3	3	26%
Lineament Density	1/2	1	3	3	3	3	3	3	22%
LULC	1/3	1/3	1	3	3	3	3	3	16%
Drainage Density	1/3	1/3	1/3	1	2	3	3	3	11%
Soil	1/3	1/3	1/3	1/2	1	3	3	3	10%
Rainfall	1/3	1/3	1/3	1/3	1/3	1	2	3	6%
Slope	1/3	1/3	1/3	1/3	1/3	1/2	1	3	5%
Elevation	1/3	1/3	1/3	1/3	1/3	1/3	1/3	1	4%

3.4 Groundwater Potential Index (GWPI)

The Groundwater Potential Index (GWPI) was computed through weighted overlay analysis using:

$$GWPI = \Sigma(Wi \times Ri)$$

where Wi represents the normalized weight of the thematic layer and Ri represents the rank assigned to each thematic class. The weighted thematic layers were integrated within the ArcGIS environment using raster algebra to generate the groundwater potential zonation map.

3.5 Hydrogeophysical Investigation

A total of forty-one (41) Vertical Electrical Sounding (VES) stations were occupied across the study area using the Schlumberger electrode configuration. The VES data were interpreted to derive aquifer thickness, overburden thickness, aquifer resistivity, bedrock resistivity, bedrock relief, transmissivity, hydraulic conductivity, transverse resistance, and longitudinal conductance. The derived hydrogeophysical parameters were interpolated using spatial interpolation techniques to generate continuous thematic layers representing subsurface groundwater conditions.

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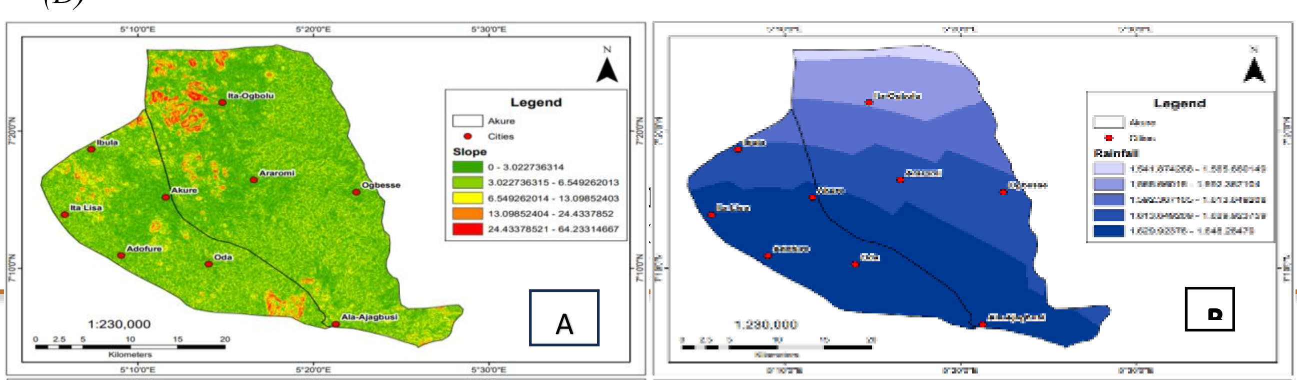
The derived hydrogeophysical parameters were interpolated using spatial interpolation techniques to generate continuous thematic layers representing subsurface groundwater conditions.

3.6 Integration of GIS-AHP and VES Results

The groundwater potential maps generated from GIS-AHP analysis and VES-derived hydrogeophysical parameters were integrated using weighted overlay techniques. Equal weights of 50% were assigned to each model to produce the final groundwater potential zonation map. The integration enhanced prediction reliability by combining surface and subsurface indicators of groundwater occurrence.

Result and Discussion

Figure 1: generated thematic layers—slope (A), rainfall (B), land use/land cover (C), and geology (D)



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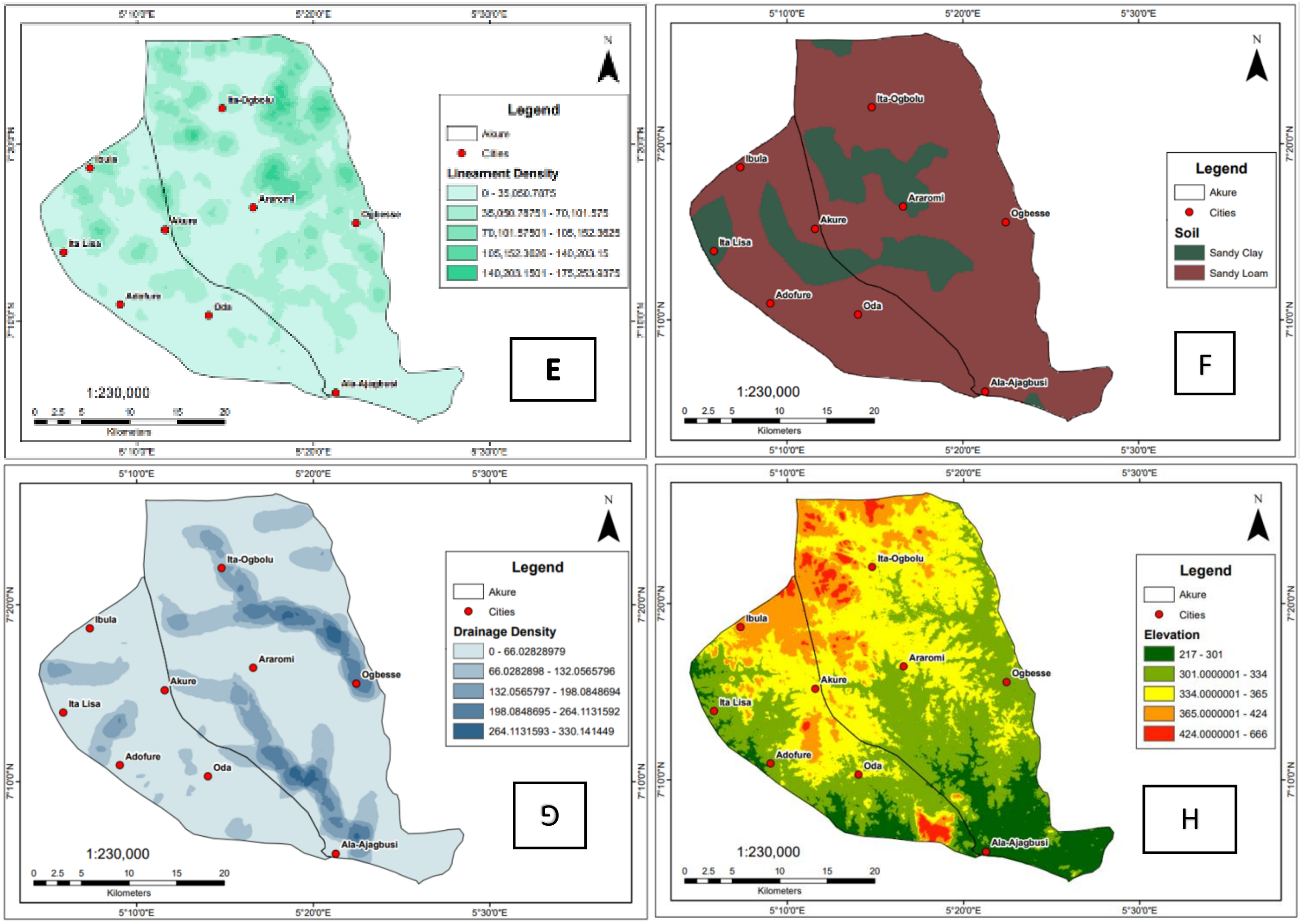

*Figure 3: Generated thematic layers: Lineament density (E), soil (F), drainage density (G), and elevation (H)***.**

The created thematic layers—slope, rainfall, land use/land cover, geology, lineament density, soil, drainage density, and elevation—were proven to be important in regulating the availability and distribution of groundwater in the research area. This is consistent with earlier research [20];[27];[5];[16] that highlights the significance of incorporating a variety of environmental parameters in groundwater assessments.Due to decreased surface runoff, low-gradient areas (0-3.02 degrees) which are primarily found in the northeastern portion of the research area were found to favor infiltration and groundwater recharge, according to the slope map. High-slope (13.10 – 64.2 degrees) regions, on the other hand, encourage quick runoff, which reduces groundwater potential and infiltration. Due to the prolonged residence time for precipitation to infiltrate into the subsurface, low slope locations have a good potential for groundwater storage, according to previous research [9]. Additionally, it is consistent with research by [16], which found that steeper slopes had higher runoff rates, while gentler slopes (0–1.49 degrees) predominate and favor groundwater recharging. Groundwater recharge processes were further encouraged by the distribution of rainfall in the region, with zones of elevated groundwater potential correlating to areas of substantially greater precipitation (1.61mm–1.65mm). This result is consistent with previous research [5] that found rainfall directly influences groundwater formation through precipitation permeation and water percolation into the subsurface, with higher permeation being associated with prolonged and milder rainfall.

In addition, findings on the influence of Land use/land cover revealed that vegetated areas facilitate infiltration, while built-up areas restrict recharge due to impervious surfaces.. This result is in line with previous research [6]; [1], which discovered that because their surfaces are mostly impervious, built-up zones and outcrops/bareland areas have significantly less opportunities for groundwater accumulation. The results of this study are also in line with those of an earlier study [29], which discovered that groundwater recharge was most prevalent in forests (791.57 mm) and lower in urban areas (472.34 mm), while surface runoff grew by 5.7 percent in swamped forest areas. Also, geology and lineament density emerged as key controlling factors. Groundwater potential increased by high lineament density regions, which act as channels for groundwater collection and flow. The results of this study are consistent with those of [2], who established that a region's shortages of water is mostly caused by extremely low lineament density.

According to the AHP weighting, the two most important elements influencing groundwater potential in the research region are geology (26%) and lineament density (22%). This corroborates the results of [7], who discovered that the main factors affecting groundwater presence in the studied area are lineament density and geology. Similarly, [13], reported that high-potential zones for groundwater were mostly related with permeable lithologies, dense lineament networks, and gentle slopes. The two most important variables influencing groundwater distribution were found to be geology and lineament density according to the study.

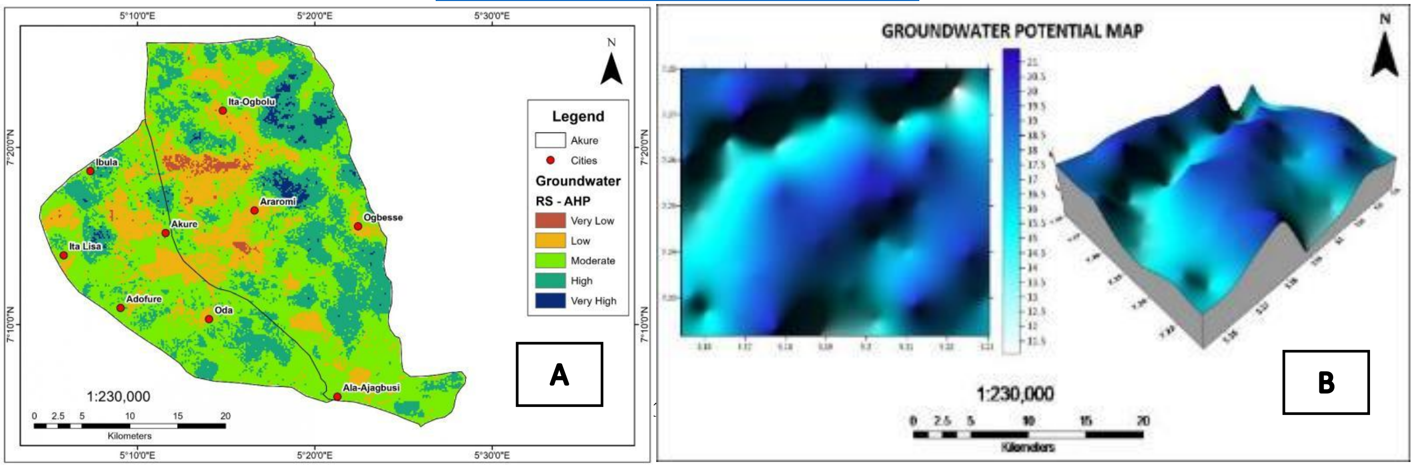

Figure 4: Groundwater potential map using remote sensing and AHP (A) and groundwater potential map using VES data (B)

The study area was divided into high, moderate, and low potential zones on the groundwater potential map produced by weighted overlay analysis. Groundwater studies have extensively employed and validated this methodology [24]; [5]. The northeastern and eastern regions of the research area were primarily home to high groundwater potential zones. These regions which include Araromi, Ita-Ogbolu, and Ita Lisa were distinguished by favorable geological formations, high lineament density, mild slopes, and permeable soils, all of which improve groundwater storage and recharge. While low potential zones are located in the southwestern region, where unfavorable factors like steep slopes and poor lineament density restrict groundwater occurrence, moderate potential zones in the study area represent transitional locations. Areas with favorable aquifer characteristics from VES results were found to be strongly correlated with high groundwater potential zones found by GIS analysis. The soundness of the integrated strategy is confirmed by this agreement. It has been demonstrated that such integrated methodologies improve groundwater study accuracy [2].

Table3*:* Area and percentage distribution of the groundwater potential zones

Class	Area (Km^2)	Percentage (%)
Very Low	11.28	1.12
Low	189.08	18.78
Moderate	524.34	52.08

High	265.39	26.36
Very High	16.71	1.66
Total	1006.8	100

Conclusion

This study successfully integrated Remote Sensing, Geographic Information Systems (GIS), the Analytical Hierarchy Process (AHP), and Vertical Electrical Sounding (VES) techniques for groundwater potential assessment within Akure Metropolis, Ondo State, Nigeria. Eight groundwater conditioning factors comprising geology, lineament density, land use/land cover, drainage density, soil, rainfall, slope, and elevation were evaluated using the AHP framework to generate a groundwater potential model. The AHP analysis revealed that geology and lineament density are the most influential factors controlling groundwater occurrence within the crystalline basement terrain of the study area. Groundwater potential mapping identified zones of varying groundwater occurrence potential, with high and very high potential zones predominantly located within the northeastern and eastern parts of the study area. These zones are characterized by favorable geological conditions, enhanced structural features, gentle slopes, and permeable soils. Hydrogeophysical investigation involving forty-one (41) Vertical Electrical Sounding stations provided detailed information on aquifer geometry and hydraulic characteristics. Parameters such as aquifer thickness, transmissivity, hydraulic conductivity, transverse resistance, and longitudinal conductance were used to characterize groundwater occurrence and aquifer protective capacity. The integration of GIS-AHP and VES results improved the reliability of groundwater potential prediction by combining spatially distributed surface indicators with detailed subsurface information. Strong agreement between groundwater potential zones and favorable aquifer characteristics demonstrates the effectiveness of the integrated methodology. The study therefore establishes that the combined application of geospatial technologies and hydrogeophysical techniques provides a robust framework for groundwater exploration, borehole siting, groundwater management, and sustainable water resource planning within Akure Metropolis and similar basement complex environments.

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