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Mapping Groundwater Potential Zones in Parts of Southwestern Nigeria: An Integrated Approach

Mumeen Adebayo Yusuf[1]*, Olajumoke Bukola Yusuf[2], Joseph Omeiza Alao[3], Tamiru Alemayehu Abiye[4], Tolulope Ayobi Oyeleke[5], Kehinde Ibrahim Olojoku[1], Oladele Ajiboro Omotoso[1], Ussein Taiwo Bakare[6], Ifeoluwa Mathilda Olaleye[7], Abdulmalik Olayinka Kola-Aderoju[1], Majeed Akogun[1]

[1] *Department of Geology and Mineral Sciences, University of Ilorin, Ilorin, NIGERIA*
[2] *Kwara State Ministry of Water Resources, NIGERIA*
[3] *Department of Physics, Air Force Institute of Technology, Kaduna, NIGERIA*
[4] *School of Geosciences, University of the Witwatersrand, Johannesburg, SOUTH AFRICA*
[5] *Geocardinal Engineering Service Ltd, Abuja, NIGERIA*
[6] *National Centre for Hydropower Research and Development (NACHRED), NIGERIA*
[7] *Domasi College Education, Faculty of Science, Department of Biology, Zomba, MALAWI*

*Corresponding Author: siribo.ma@unilorin.edu.ng
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Abstract

Groundwater is undoubtedly the most abundant source of freshwater on Earth. However, groundwater assessment and exploration are multi-tasking particularly in the basement complex terrain due to uneven distribution of this resource within the subsurface aided by variations in hydrogeological factors. To overcome these tasks, the integrated approach based on advanced applications of Geographic Information System (GIS), Remote Sensing (RS), Analytic Hierarchy Process (AHP), and Vertical Electrical Resistivity (VES) serves as a useful and efficient tool for studying the development and management of the water resources in southern parts of Akure. Akure south region, comprising a hard rock terrain, is situated in the water grappled zone of southwest, Nigeria. The groundwater potential was evaluated based on eight relevant and effective factors: slope, lineament density, drainage density, geology, aquifer thickness, resistivity, hydraulic conductivity, and transmissivity. The final GWPZ map is categorized into three potentiality zones following overlay analysis of the thematic layers in the ArcGIS 10.8 environment: the poor zone (which makes up the majority of the area with 57%), the intermediate zone (35%), and the good zone (8%). After CR was used to validate the final Groundwater Potential Zones (GWPZ) map created by combining all the theme layers, it was found that AHP was a useful method (CR accuracy = 0.08 or 8%) for identifying possible groundwater zones in the research area. The research demonstrated that a multi-technique approach is the most reliable and effective method for accurately assessing groundwater potential.

1. Introduction

For life to exist, water is an essential natural resource [1, 2]. The search for potable water has intensified in recent years due to the constant rise in population, urbanization, and agricultural activities, all of which have increased the demand for groundwater as surface water supplies become increasingly inadequate [2]. The growing reliance on groundwater has led to its unregulated exploitation, contributing to water stress conditions [3, 4]. This situation highlights the urgent need for cost-effective and efficient techniques to evaluate and manage groundwater resources. Unlike surface water, which is more susceptible to depletion and contamination in the natural environment, groundwater provides a relatively stable and secure source of water [5, 6]. Water covers over 71% of the Earth's surface; fresh water is found in underground reservoirs called aquifers. Groundwater is widely regarded as one of the purest forms of natural water resources, capable of meeting the demands of growing populations [7]. As the water demand continues to rise, how we locate and utilize this resource has become crucial to the future of urbanization. Therefore, adopting advanced geospatial techniques with significant capabilities for assessing, regulating, as well as protecting groundwater resource is essential.

The quest for groundwater, particularly in crystalline terrains, is fraught with numerous challenges. Several researchers have investigated the factors that influence water availability in such terrains. According to the findings of [8, 9, 10], aquifers found within weathered overburden or fractured crystalline rocks may be the primary source of groundwater development in basement complex locations. They identified factors such as faults, joints, and fractures as critical for groundwater development in basement complex terrains, emphasizing the importance of considering these factors during groundwater exploration [9]. The dependence of water resources on various geological factors has led researchers to adopt multi-method approaches in groundwater exploration.

Geomorphic and geological structure typically controls an area's hydrological conditions and groundwater occurrence [11, 12, 13]. The proper delineation and identification of these geologic factors would ensure a successful exploration story. Over the years, researchers have adopted an integrated method of groundwater exploration in contrast to a single method of operation [5, 9, 14, 15]. According to [16] research, boreholes with low yields or unproductive wells are frequently drilled when groundwater exploration is conducted without integrated geophysical investigation. The work of [17] revealed that integrated geophysical approaches are more accurate in identifying areas that contain water, particularly in basement complex terrain. Several researchers have adopted integrated methods of groundwater exploration. [18] employed integrated electrical and electromagnetic techniques to handle complex environmental, hydrological, and geological challenges. [4] adopted an integrated geophysical method (VES and borehole logging) for Groundwater Exploration in Lagos, Southwestern, Nigeria.

The application of Remote Sensing (RS) and Geographic Information System (GIS) techniques has opened up a new route to precisely map various natural resources, such as groundwater, and evaluate vast amounts of geospatial data. Several researchers have identified possible groundwater zones by combining an integrated GIS and RS method with Multi-Criteria Decision-Making analysis (MCDM) [11]. The detection of groundwater potential zone (GPZ), environmental management, agricultural suitability, etc. were accomplished with the use of GIS-based MCDM [19], Analytic hierarchy process [20], Fuzzy logic [21], WOA [22], Influencing factors [23, 24, 25], etc. The primary benefit of these methods is that, in comparison to conventional field methods, GIS-based methods yield findings that are extremely exact and need less calculation time to determine the GPZ [26]. AHP's capacity to handle complicated issues and reach appropriate conclusions is another benefit of including it in groundwater potential zone analysis [27, 28]. Thus, to ascertain the GWPZ in the current study, a statistical analysis approach like AHP was merged with the GIS.

The study area (Akure south) is known for a seasonal scarcity of water which was evident as several dried-up wells were observed. The information gathered confirmed that the crisis created by water scarcity drops drastically in the rainy season suggesting a seasonal or climatic change effect on the groundwater. However, study area lacks adequate knowledge about the groundwater potential zones, water resource planning, and sustainable groundwater exploitation. The absence of a systematic approach to identify and map groundwater potential zones (GPZ) hampers effective water management and thus, this research study sort to fill this gap by providing valuable information for sustainable groundwater resource planning and development. Thus, the objective of the present study is to locate and demarcate zones with unique groundwater potential (GPZ) by the use of integrated techniques that include geographic information system approach (GIS), vertical electrical sounding (VES), and remote sensing (RS). To support future efforts targeted at sustainable groundwater management and development in the study area, policymakers, economists, and government planners are expected to find great value in the research findings.

2. Description and Geology of the Study Area

There are distinct wet and dry seasons in Akure's climate. The first rainy season lasts from March to mid-July, while the second one lasts from late August to mid-November. The precipitation pattern is bimodal. Additionally, there are two dry seasons: one that lasts from late November to March and another one shorter, lasting from mid-July to early August [29]. The region experiences 21 to 29°C yearly temperatures and year-round moderately high humidity. The region is characterized by dense rainforest, with mangrove swamps along the nearby rivers, and is situated in the heart of Ondo State. The satellite map of Akure South Local Government is shown in Figure 1, capturing features such as vegetation areas (greenish regions), built-up areas, road networks, and towns.

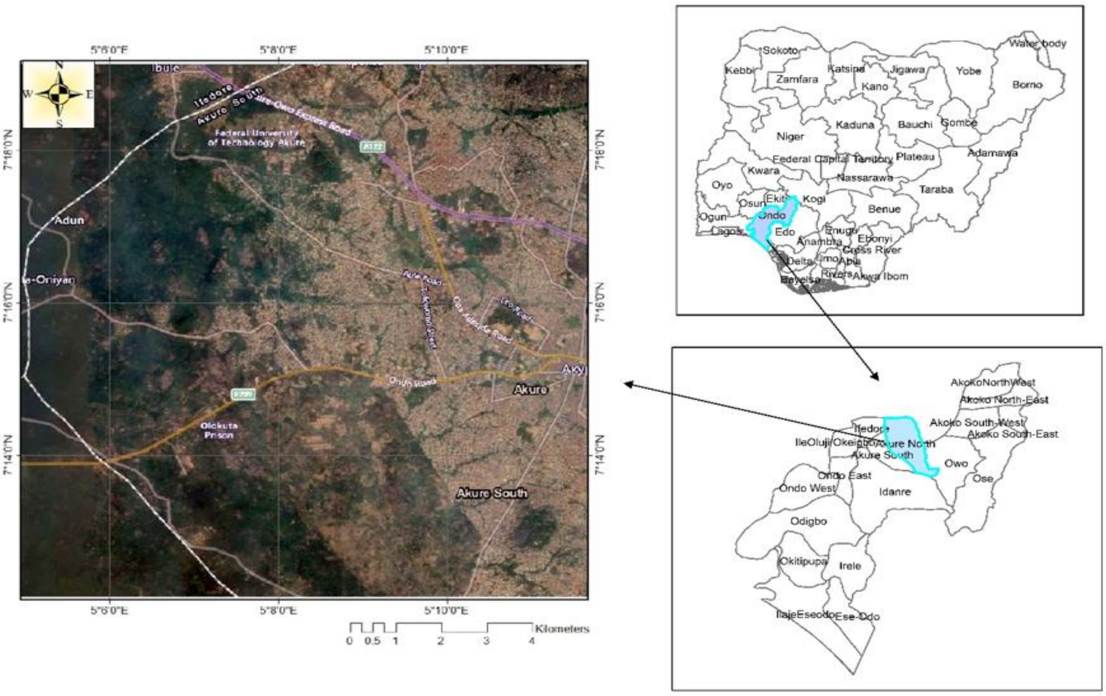

Fig. 1 *Location map of the study area*

Geologically, migmatite, banded gneiss, charnockite, and porphyritic granite underlie Akure (Figure 2). The largest locations for the porphyritic granite are along Owo Road in Akure and the Oba-Ile neighborhood. It consists of quartz and feldspar crystals embedded in a matrix of feldspar. The mafic minerals, which are sporadically scattered throughout the porphyritic granite, comprise biotite and other accessory minerals, whereas the felsic minerals are mostly quartz and feldspar. The migmatite is situated in Akure's center and consists of basic and leucocratic elements that alternate. Particularly in the vicinity of Shagari Estate, Akure, the leucocratic component is composed of medium-grained banded gneisses and fine-grained granitic gneisses [3] (Figure 2).

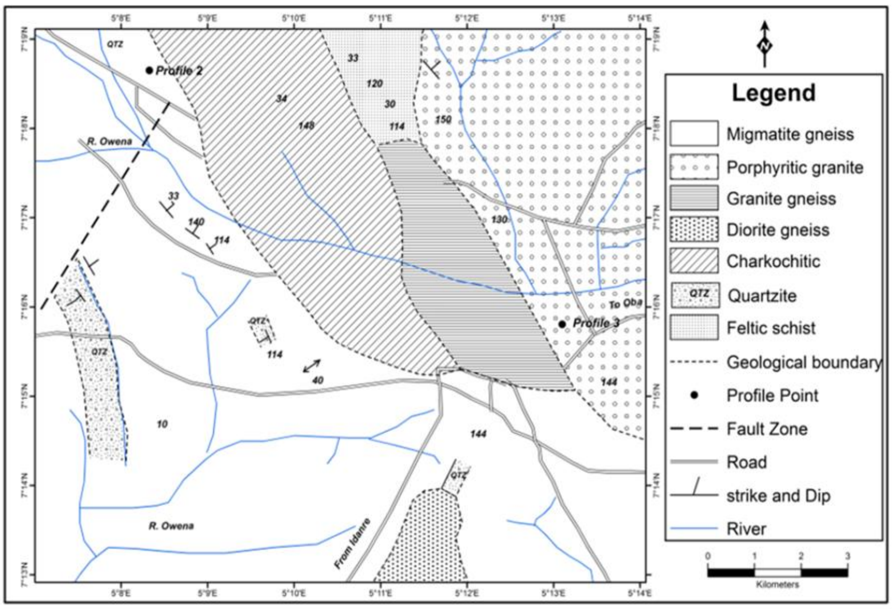

Fig. 2 *Lithology of the study area and the area covered by each lithology [3]*

3. Methodology

3.1 Preparation of Thematic Layers

Eight distinct thematic layers, including lithology, geomorphology, lineament density, slope, soil, rainfall, drainage density, and LULC, were created for assessing groundwater potential zones through the use of PCI Geomatica and ArcGIS 10.8 software in conjunction with remote sensing and conventional/existing data. Using Landsat 8 (30-m resolution) images that were downloaded from the U.S. Geological Survey's Earth Explorer website (http://www.earthexplorer.usgs.gov), the geomorphological features and lineaments were recognized. The false color composite (FCC) image was visually analyzed utilizing image interpretation keys such as shape, size, tone, texture, pattern, and association to determine the geomorphological landforms and lineaments. The LULC map was produced using Landsat 8 OLI data using the maximum likelihood classification algorithm and 490 ground control locations for ground verification.

This study made use of remote sensing data from the Shuttle Radar Topography Mission (SRTM), which had a resolution of 90 m, and the Landsat Operational Land Imaging (OLI), which had a resolution of 30 m. The explorer portal (http://www.earthexplorer.usgs.gov) provides access to the data, which are utilized to determine the research area's drainage pattern and slope. The ArcGIS line density tool was used to create maps of line density and drainage density, and the Hydrology Tools in ArcMap were utilized to extract the drainage pattern. The source of the soil map (in Vector format) was the World Soil Map Digital Site, accessible at https://worldmap.harvard.edu. The geological map that was acquired from the Nigeria Geological Agency (NGSA) was used to digitize and construct the lithology map. In order to build a rainfall distribution map in ArcGIS, the average total yearly rainfall was estimated using rainfall data from the Tropical Rainfall Measuring Mission (TRMM) based on 10-year (2010-2020) data of 18-point locations using the Inverse Distance Weighted (IDW) spatial interpolation approach. This method forecasts the values of variables at unobserved locations based on those of observed places by using the spatial correlation of variables [19]. When there are enough sample points at local scale levels with the right dispersion, this technique exhibits promise. Nonetheless, the value of the power parameter p is the main factor affecting the inverse distance interpolator's accuracy [30]. The neighborhood's size and population density are additional important variables that have an impact on how accurate the results are, after being ready, each theme layer was transformed into a raster format and projected with a spatial resolution of 30 meters onto the WGS 1984 coordinate system. Figure 3 depicts the overall methods used in this research.

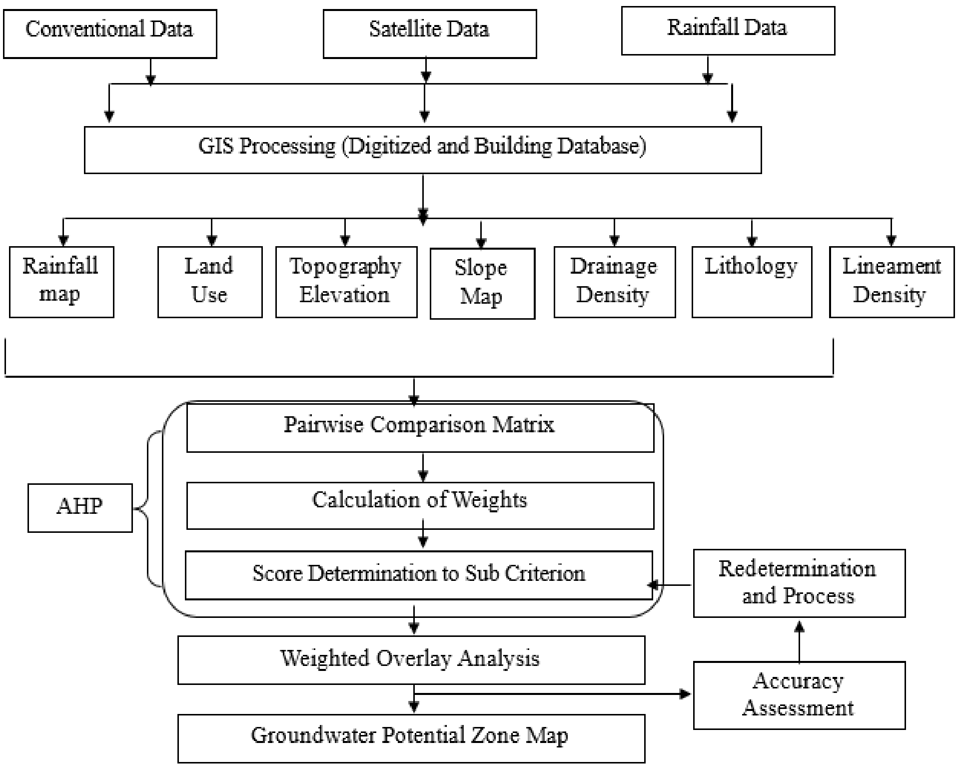

Fig. 3 *Flowchart showing the methodology adopted for the use of remote sensing in groundwater exploration [31]*

3.2 Assignments of Weight and Weight Normalization Using The Analytical Hierarchy Process (AHP)

In integrated analysis, the procedure of allocating proper weights to each class is critical since it significantly affects the output's accuracy [32]. Numerous methods, such as fuzzy logic, weights-of-evidence (WOE), frequency ratio (FR), certainty factor (CF), index models, and multi-influencing factor (MIF), have been used to compute weights for defining groundwater potential zones. Among them, the analytical hierarchy process (AHP), which provides quick, accurate, and affordable findings, has become a top method in groundwater prediction modeling. The geometric mean and normalized weight of each parameter are determined using the AHP approach, a pairwise matrix analytical method [31, 33, 34]. By using paired comparisons, it creates relative ratio scales [35].

The AHP approach, which was created by Saaty in 1980 and 1990, was employed in this study as a means of decision-making to determine the weights given to the various thematic layers and their corresponding attributes. By establishing objectives and selecting criteria and sub-criteria according to their relative importance in groundwater occurrence, the first steps in the AHP methodologies are utilized to break down the problem into a hierarchy [32]. One benefit of hierarchy is that it enables us to concentrate our judgment on individual attributes, all of which are necessary for coming to a well-informed conclusion [35]. To assess all elements against one another in a matrix style that helps determine measurement, paired comparisons were done. The relative importance values for each theme and its corresponding feature were ascertained using a standard Saaty's 1–9 scale, as indicated in Table 1. A value of 1 indicates "equal importance" between the two themes, while a value of 9 indicates the "extreme importance" of one theme relative to the other [36].

Table 1 *AHP pairwise comparisons scale*

Scale/Importance Level	Density of Importance Definition
1	Equal importance
3	One criterion is of moderate importance to the other
5	One criterion is of higher importance to the other
7	One criterion is more important than the other
9	One criterion is extremely important over the other
2,4,6 and 8	Intermediate values used between previous weights in numerical comparison

3.3 Evaluation of Potential Groundwater Zones

An area's groundwater potential zones can be identified with the use of the dimensionless Groundwater Potential Index (GWPI) [37]. Zones with groundwater potential were identified using the weighted linear combination approach.

A groundwater potential map was produced by combining the criteria weights and theme maps applying the analysis of weighted overlays (WOA) technique. The Weighted Overlay Analysis (WOA) technique offers a solution for users grappling with complex spatial issues related to site suitability, utilizing standardized measurements from various inputs. As a result, the WOA technique was used to determine the Groundwater Potential Zone (GPZ). The Total Scores (TS) (Muralitharan and Palanivel, 2015) were calculated by multiplying the weights of the thematic layers by the weights of the features in each thematic layer, adding the products of all the attributes, and using Equation 1 below:

$$\boldsymbol{TS} = \sum \boldsymbol{W} \times \boldsymbol{R} \tag{1}$$

where W and R stand for the weights of the features in theme layers and the thematic layer weights, respectively, and TS = Total Score. Using the information on the criteria's ranking and the matrix of comparisons between the alternatives, AHP generates a ranking of the solutions overall.

3.4 Validation of The Prospective Groundwater Zone

The current study's groundwater potential map was developed and confirmed utilizing the study area's vertical electrical sounding (VES) data as well as the field's productive wells.

AHP ranks parameters using eigenvalues and assigns weights to parameters based on expert insights and major eigenvectors. Using AHP, a binary comparison matrix is built to allocate parameter weights. The significance levels decided upon during the construction of the pairwise comparison matrices are evaluated using the consistency index (CI) provided in Eq. 2.

$$CI = \frac{(\lambda_{\max} - n)}{(n-1)} \quad (2)$$

In this case, n denotes the number of criteria, and λ_{max} represents the matrix's greatest eigenvalue. The consistency ratio (CR) is computed (Eq. 3) to assess the consistency of the pairwise comparison matrix.

$$\boldsymbol{CR} = \frac{\boldsymbol{CI}}{\boldsymbol{RI}} \quad (3)$$

Where RI, or the random index, is selected based on the number of criteria from Table 2.

Table 2 *Random index for various n values [35]*

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.89	1.12	1.24	1.32	1.41	1.45	1.49

AHP takes CR values between 0% and 10%. The comparison matrix is totally consistent if CR equals 0%; if CR value is more than 10%, the comparisons need to be reviewed [38].

3.5 Ratio of Consistency (CR)

The consistency ratio (CR) was established to guarantee the accuracy and consistency of the AHP analysis. There's a chance that you will run into some inconsistency when applying the Analytic Hierarchy method (AHP) pairwise judgment method. As such, assessing the degree of logical coherence in the paired decisions becomes crucial.

Introduced by [35], the coefficient of consistency (CR) is used to quantify the degree of consistency of the parameter weights. The ratios of the random index (RI) and consistency index (CI) were compared. To demonstrate the accuracy of the weights obtained in the Normalized Pairwise Comparison Matrix (NPCM), the CR is computed. According to [36], judgments must be reconsidered when the CR exceeds 0.10; otherwise, it is deemed more exact when the CR falls below 0.10 (10%).

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

3.6 Score Determination

Each criterion was scored based on its relative importance once the criteria weights were established. The sub-criteria were rated on a scale from 1 to 10, which represented their importance and applicability in determining groundwater zones. The most appropriate sub-criteria received a score of 10, while the least appropriate ones received a score of 1. Sub-criteria that were somewhat appropriate for determining the Groundwater Potential Zone (GPZ) were then assigned intermediate scores. Several characteristics were given scores, including soil, rainfall, geology, slope, land use, drainage density, and lineament density. The flowchart of the process used to deduce groundwater potential zones by remote sensing is displayed in Figure 3.

3.7 Vertical Electrical Sounding

The VES serves as a follow-up to the preliminary remote sensing technique used in the region. Using remote sensing, the VES locations were chosen in high-potential areas that were already created. With a Schlumberger array, the vertical electrical sounding (VES) survey was conducted. Thirty (30) VES in all were conducted in the research area. After manually curve-matching the VES data, IP2WIN software was used to process it. The geoelectric parameters were refined by computer iteration until the RMS error percentage fell below 5%. To improve the visualization of the subsurface's geoelectric properties, resistivity pseudo sections and maps were generated from the collected geoelectric parameters.

4. Result and Discussion

In other to complement each other and to enhance a high level of confidence in the resulting output, two distinct methods were adopted for delineating the potential zones of groundwater for the region under investigation namely: the geospatial technique and the electrical resistivity method (VES). The GIS platform was utilized to generate the seven selected thematic layers, and the AHP was employed to rank every parameter. While 30 VES were processed using IP2WIN software and their resistivity pseudo-section maps were developed.

Based on the above adopted parameters and resistivity maps the hydrogeological setting of the study area was carefully identified and delineated as discussed below:

4.1 Geological Settings

The potential for groundwater accumulation in a given area is mostly determined by its geology. A number of factors influence the occurrence of groundwater, such as the kinds of rocks, their main and secondary porosity, the existence of appropriate structures, and the degree of their interconnection. The porosity and permeability of aquifer rocks are directly impacted by these geological features [39]. Rocks with high porosity and weak textures that easily permit water percolation are favorable for groundwater accumulation. For example, rock types such as schist and quartzite are generally more conducive to groundwater accumulation compared to granite, granite gneiss, and migmatite.

Within the research domain, migmatite predominates, covering 50.8% of the region, followed by porphyritic granite at 17%, and charnokite at 13%. Other rock types present include granite gneiss (8.4%), schist (4.3%), diorite gneiss (4%), and quartzite (2.5%) (Figure 2). Consequently, areas dominated by schist (4.3%) are more favorable for groundwater potential within the study area (Figure 2).

4.2 Rainfall

The depth of rainfall throughout time plays a critical role in groundwater storage and infiltration. Low infiltration and excessive runoff resulted from the brief, intense downpour. Conversely, long-duration, low-intensity rainfall has a relatively higher penetration rate than surface runoff. As to the report of the Ondo State Ministry of Agriculture in 2005, the annual rainfall total falls between the range of 1300 mm to 1650 mm. The rainfall has remained fluctuating in the study area for the period considered (2003-1012) with a trend line having an almost zero slope (Figures 4a and 4b). Therefore, it is difficult to use this rainfall to estimate the study area's groundwater potential, thus giving credence to consideration for other geologic factors.

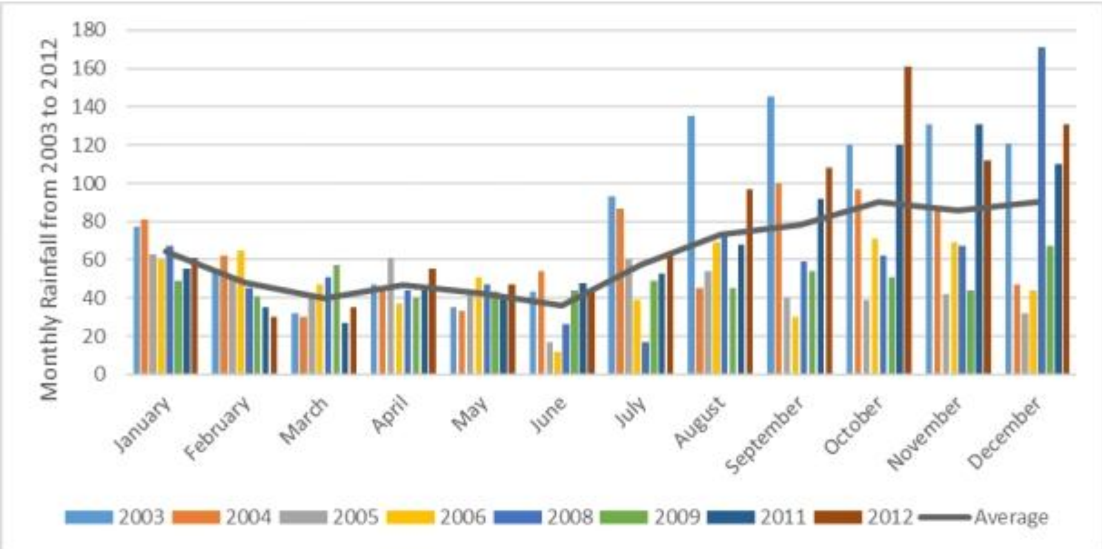

Fig. 4a *Rainfall trend in Akure from 2003 to 2012 from Ondo State Specialist Hospital, 2013*

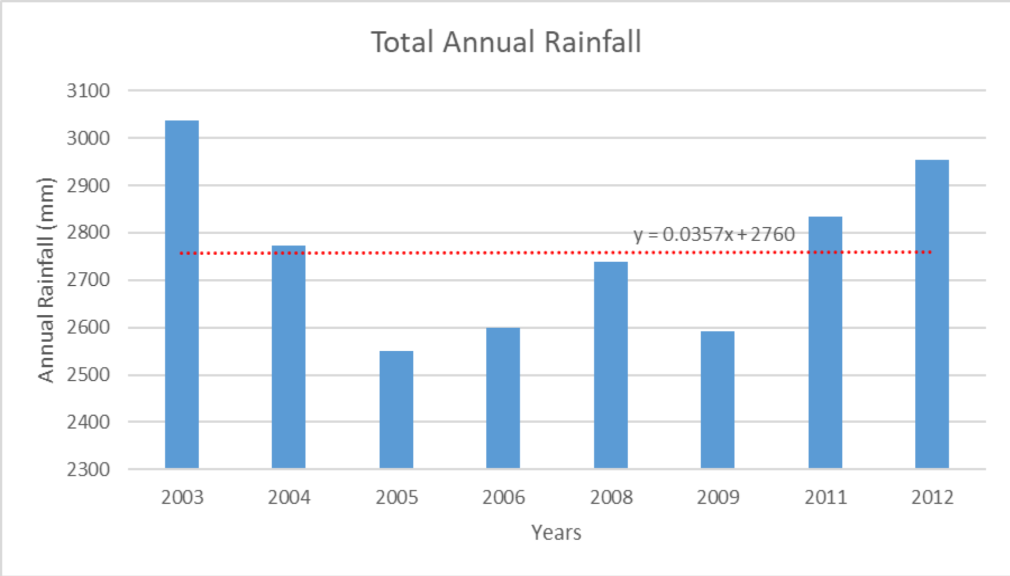

Fig. 4b *Map of the rainfall distribution in the study area*

4.3 Lineament Density (LD)

Hydrogeologically, lineament characteristics like joints, fractures, and faults are crucial because they facilitate groundwater movement, which increases porosity and acts as a groundwater prospect zone [40, 41]. Secondary porosity, or the existence of lineaments and fractures, is primarily responsible for controlling the occurrence and flow of groundwater in hard rock terrain [37, 42]. Because of the high rate of percolation, the areas surrounding the lineaments and the point of contact are thought to be good places for groundwater storage [40, 43].

The research area's lineament density was divided into five categories: very low, low, medium, high, and very high. The occupied zones by these classes are 156sqkm, 1329sqkm, 2232sqkm, 1086sqkm, and 59sqkm, respectively. The area with very low potential according to lineament density classification is 60%. This is followed by a region with an average potential of 20%. Others are characterized by Low (12%), high (2.4%), and Very High (5.6%) lineament density respectively (Figure 5). Hence, the region with high LD is considered favorable for groundwater potential and vice versa.

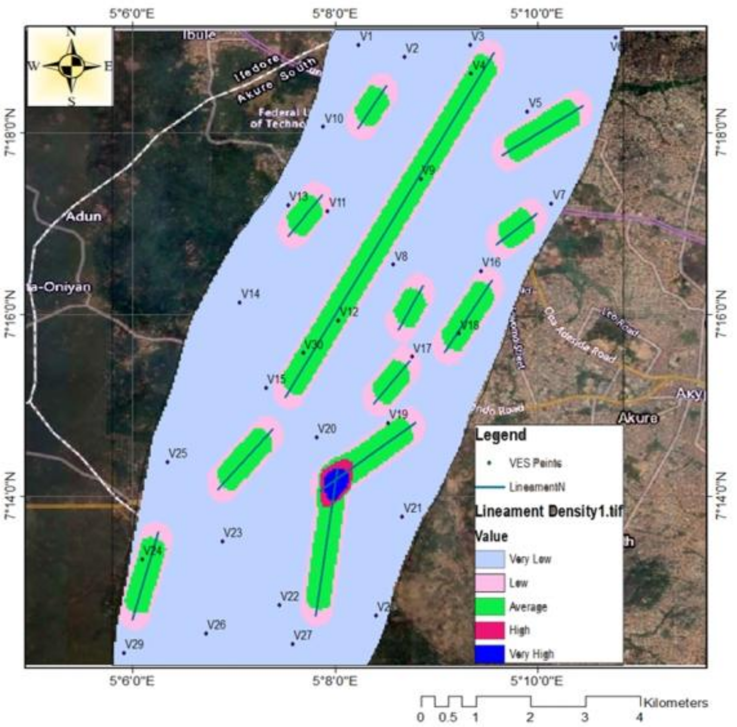

Fig. 5 *Lineament density map showing the classes of the lineament slope*

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4.4 Slope

Slope is one of the key factors influencing the occurrence and recharge of groundwater in a given location. [42]. As a direct result, slope gradient or steepness is a good indicator of groundwater potential because it influences rainfall infiltration. Steeper slopes tend to produce less groundwater recharge because of increased surface runoff, which reduces the amount of time that water can infiltrate and recharge the saturated zone [18, 25, 44, 45]. Gentler slopes, on the other hand, facilitate percolation and improve groundwater recharge. Essentially, an area's slope gradient is inversely correlated with its percolation or infiltration rate and directly correlated with its runoff rate [46]. Figure 6 displays the slope map generated for the research area.

In this investigation, the steepness of the slope was divided into five groups: very low (0–18°), low (19–36°), moderate (37–54°), high (55-72°), and very high (73–90°). Only 25% of the overall area has gentle slopes; the other 75% has moderate to extremely high slopes. Thus, the research area's preponderance of steep gradients is not conducive to water retention. On a scale of 1 to 9, the various slope classes were given ranks. Gentler slopes were given higher ranks because of their flat terrain, which provides a larger chance for groundwater recharging. While lower ranks were assigned to steeper slopes because of higher runoff and limited infiltration, these locations have good prospects for groundwater development due to minimal runoff [37, 47]. The final weights assigned to the slope features are shown in Table 3.

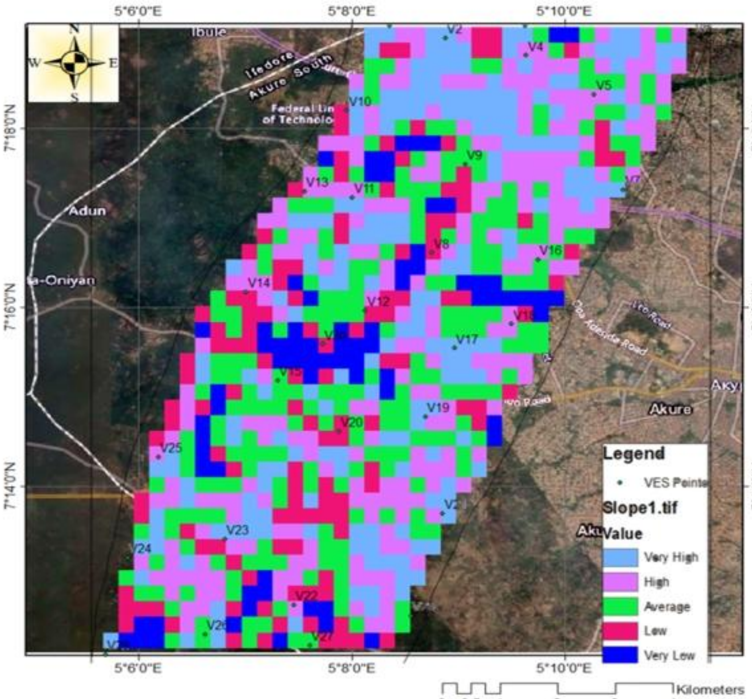

Fig. 6 *Slope map of the study area*

4.5 Drainage Density (DD)

Since drainage density regulates the underlying lithology, it is one of the most significant markers of hydrogeological features. According to [28] and [48], it is the closeness of the spacing between stream channels and is regarded as an inverse function of permeability. It is a measurement of the entire channel length of the stream per area. According to Prasad et al. (2008), the features of both surface and subsurface formation are reflected in the drainage pattern. Permeability and DD have an inverse relationship [25]. This suggests that a slower infiltration rate and more surface runoff are associated with higher DD values. Conversely, a lower DD denotes a higher percolation rate to replenish groundwater systems and less surface runoff. Five classes—very low, low, moderate, high, and very high—have been established for the area's drainage density (Figure 7). As a result, the groundwater potentiality map gave the lower DD class a higher score and vice versa.

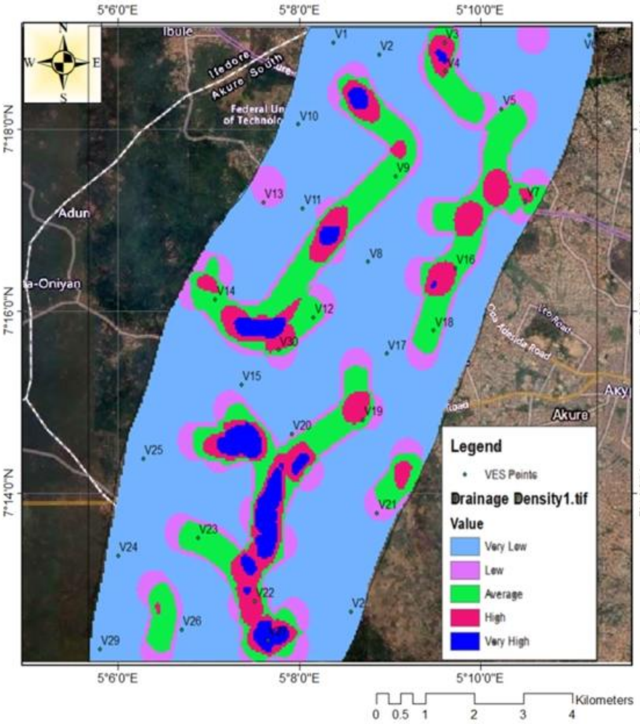

Fig. 7 *Drainage density of the study area*

4.6 Aquifer Resistivity

Groundwater potential regions could be delineated using weathered basement resistivity/aquifer resistivity. Using geoelectrical characteristics derived from correlated VES interpretation results, several publications have attempted to categorize and evaluate groundwater potential [49, 50]. A groundwater-prospect ranking was developed by [51] and included saprolite resistivity, fractured bedrock resistivity, and aquifer potential as a function of bedrock depth. Aquifer resistivity classification given by [51] which was modified after [10] was adopted to classify the aquifer resistivity in groundwater potential zones [10, 51]. Aquifer resistivity less than 20 Ohm-m is very low aquifer potential, 20 – 100 Ohm-m is optimum groundwater potential, 100 – 150 is good groundwater potential, while 150 – 300 Ohm-m is poor groundwater potential and greater than 300 Ohm-m is negligible groundwater potential [51].

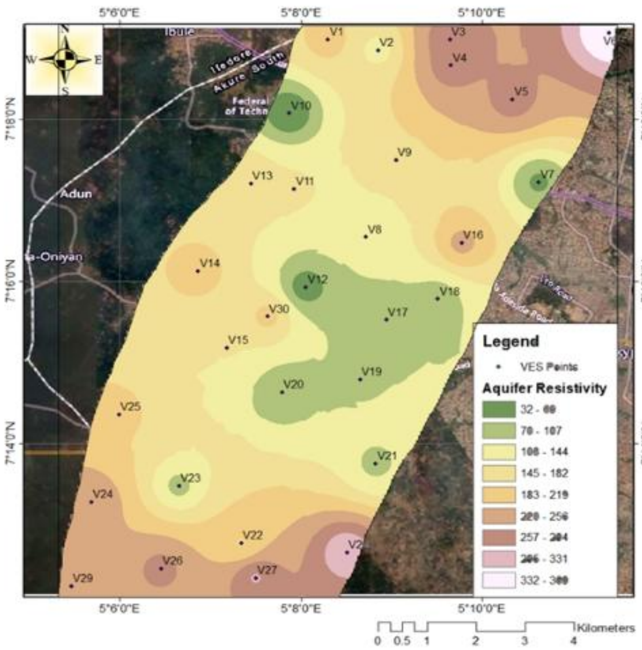

Fig. 8a *Aquifer resistivity spatial map of the study*

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Using the classification system of [51], the research domain is classified into Very Low, Low, Average, High, and Very High groundwater potential (Figures 8a and b).

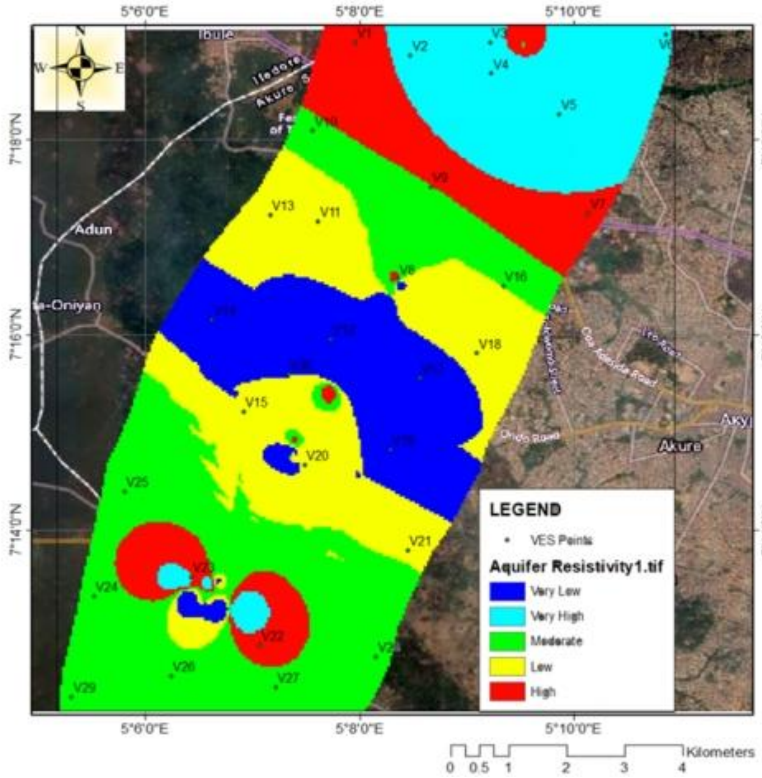

Fig. 8b *The study area's aquifer resistivity classification map*

4.7 Aquifer Thickness

The weathered basement thickness map as displayed in Figure 9a shows that the thickness aquifer ranges from 11 to 98 m. It depends on how much the bedrock has fractured and weathered. The weathered layer thicknesses recorded by [8] were often less than 20 m, yet in a relatively few locations in Akure, greater values of up to 64.6 m were obtained. In Abeokuta, regolith thickness varied from 2.1 to 35.9 meters, according to [52].

The study area's weathered basement layer is most prevalent in the southern and southwest regions, with scattered patches along the western and northwest regions (Figure 9b). These areas have a great deal of potential for groundwater development because it is thought that the main aquifer is the weathered basement layer.

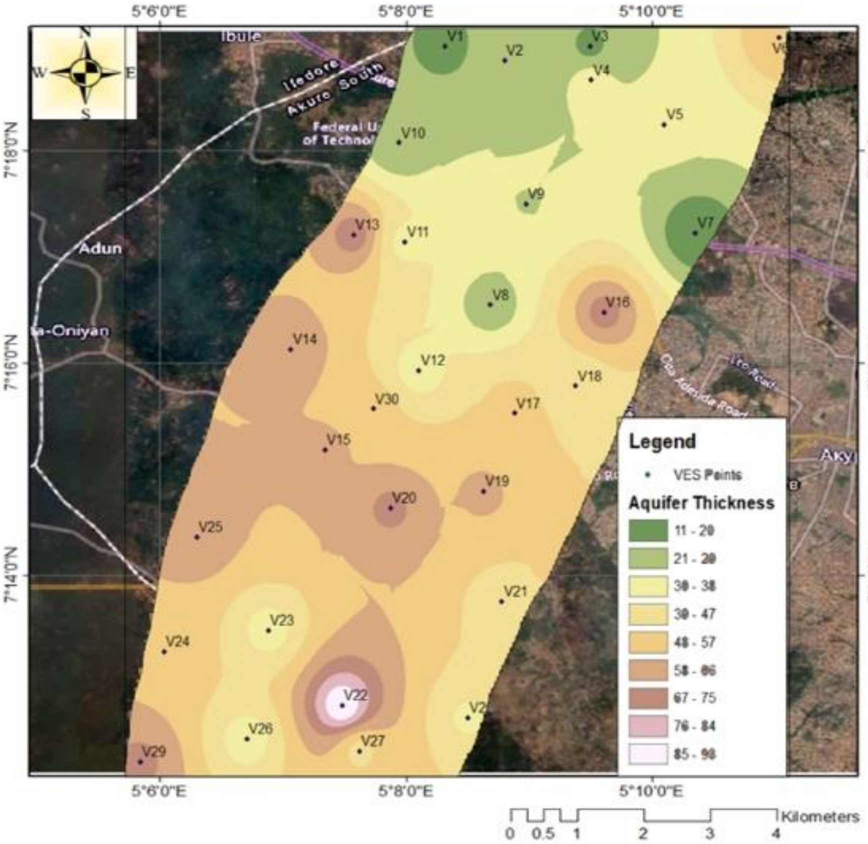

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Fig. 9a *Spatial map of aquifer thickness for the study area*

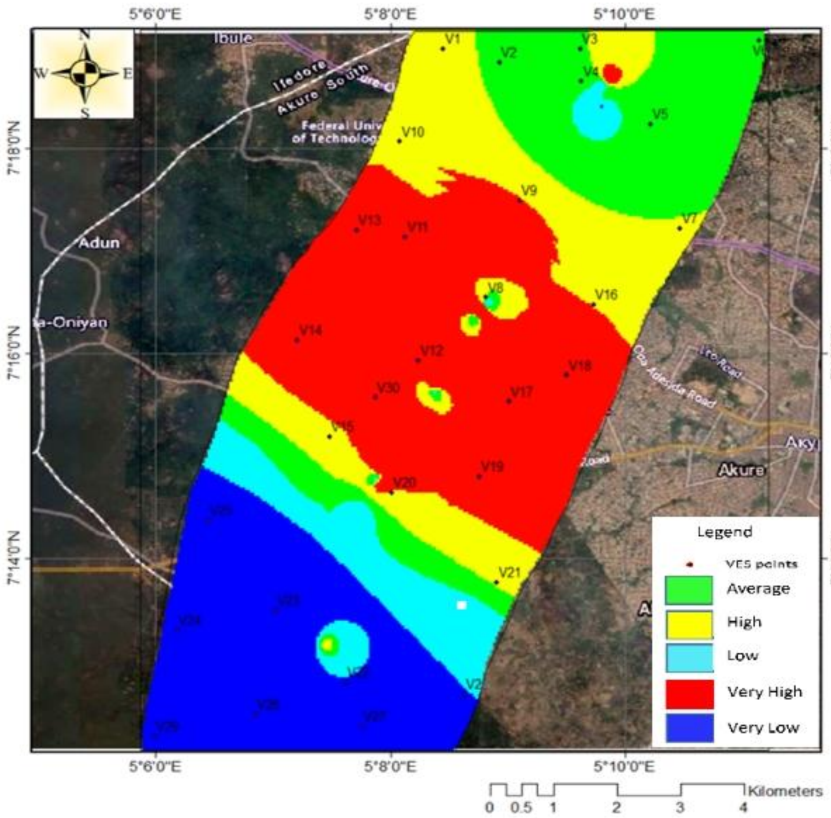

Fig. 9b *The study area's aquifer thickness classification map*

4.8 Hydraulic Conductivity

The values of hydraulic conductivity range from 2 to 15 m/day. With the exception of the northeastern edges of the study area, where hydraulic conductivity values are low, parts of the study region exhibit hydraulic conductivity values appropriate for guaranteeing moderate to high groundwater-yielding capacity (Figure 10). Therefore, groundwater withdrawal of local or smaller commercial importance is the only use for the central, southern, and western axes.

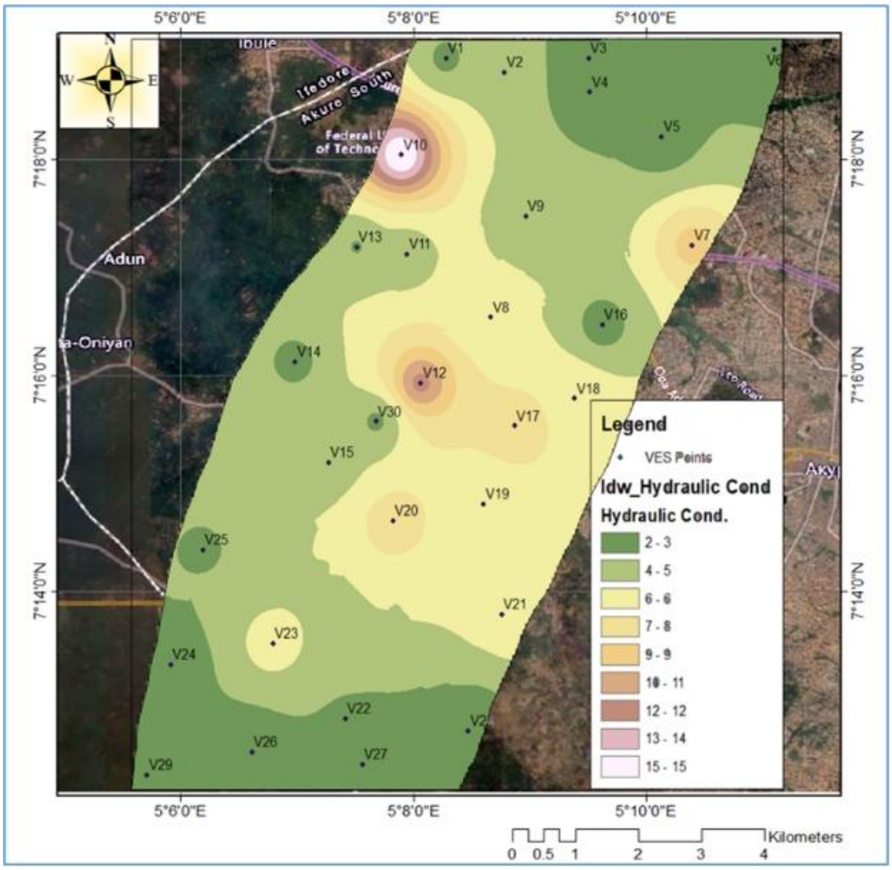

Fig. 10 *Spatial distribution map of aquifer hydraulic conductivity values within the study area*

4.9 Transmissivity

Figure 11a displays the distribution of aquifer transmissivity in the research area. Hydraulic conductivity and transmissivity distribution patterns are comparable. Hydraulic conductivity values range from 2 to 15 m/day, while aquifer transmissivity values range from 34.9 to 470.3 m2/day (Figure 11b). Concerning groundwater potential, the central region is the most favorable. The region's transmissivity values are adequate to guarantee a good groundwater-yielding capacity, except for the research area's southern and southeast boundaries, where the transmissivity is poor (less than 100 m2/day). The central region is the only one that is appropriate for groundwater withdrawal of local or smaller commercial value; the northern and northeastern axes are likewise questionable. Aquifer transmissivity values between 10 and 1000 m2/day are said to have groundwater-yielding capacity that can satisfy local demand and/or feed a relatively small community [53].

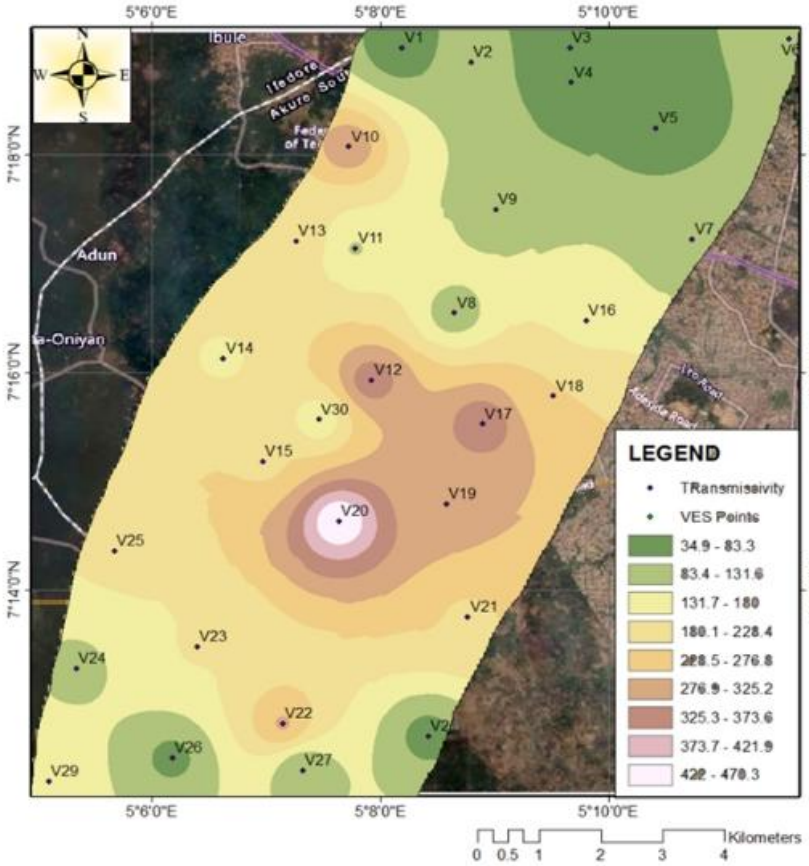

Fig. 11a *Spatial distribution map of transmissivity values within the study area*

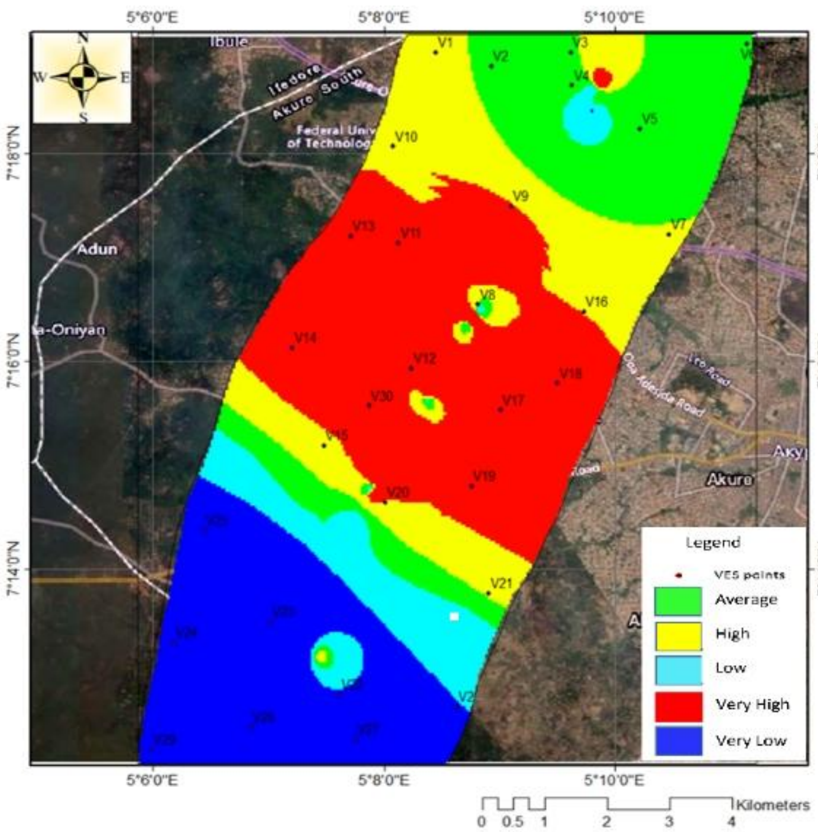

Fig. 11b *The study area's aquifer transmissivity classification map*

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4.10 Analytical Hierarchical Process (AHP)

First established by Thomas L. Saaty in the 1970s, the AHP model is one of the multi-criterion decision-making (MCDM) techniques used to find solutions for complex decision-making situations. The widely-accepted AHP model is used to standardize the weights assigned to each ground-water prospecting factor's thematic layer. The major Eigenvalue of the resulting matrix was used to determine the final weight for each theme layer (Table 3, Figure 12). The calculated consistency ratio (CR) and consistency index (CI) values indicated the output's dependability.

AHP Analytic Hierarchy Process n= 8 Input 1

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM	+/-
1	Transmissivity		29.8%	13.1%
2	Lineament Density		16.4%	7.3%
3	Drainage Density		10.3%	3.5%
4	Slope		12.5%	4.1%
5	Aquifer Thickness		5.0%	2.6%
6	Aquifer Resistivity		8.7%	3.5%
7	Geology		5.8%	2.5%
8	Hydraulic Conductivity		12.5%	1.2%
9		for 9&10 unprotect the input sheets and expand the		
10		question section ("+" in row 66)		

Fig. 12 *AHP with the percentage influence (weight) of each parameter*

The value of RCI was obtained from Saaty's 1–9 scale. The value of the Consistency Ratio (CR) should be less than 10% [36] for consistent weights; otherwise, the corresponding weights were re-evaluated to avoid inconsistency. The CR obtained for the study area is 8%.

The pairwise comparisons matrix was calculated

Maximum Eigenvalue (λ max) = 8.829

Number of factors (n) = 8

Consistency index, $CI = \frac{\lambda_{max} - n}{n - 1}$ = (8.829 – 8)/(8 – 1) = 0.829/7 = 0.1184

Random consistency index (RCI) = 1.9

Consistency ratio, $CR = \frac{CI}{RCI}$ = 0.08

In the context of the multi-criteria analysis, an inconsistency of less than or equal to 0.1 in the CR value is considered acceptable. The subjective assessment needs to be revised if the CR is higher than 10%. Given that 0.08 is smaller than 0.1, a high degree of consistency is indicated by the assigned weight.

Table 3 *Thematic map weightage and scores of criteria and sub-criteria*

Criteria	Map Rank	Map Weight (Wi) Rw	Influence (%)	Rank (Rr)	Overall, Weight
		Aquifer Thickness (R)			
Very low	7	0.05	39.3	1	39.3
Low				2	78.6
Average				3	117.9
High				4	157.2
Very high				5	196.5
		Geology (G)			
Quartz veins	6	0.058	21.1	1	21.1
Migmatite				2	42.2
Schist				4	84.4
		Slope (E)			
0 – 18	5	0.125	12.7	1	12.7
19 – 36				2	25.4
37 – 54				3	38.1
55 – 72				4	50.8
73 – 90				5	63.5
		Transmissivity (C)			
Very low	4	0.298	14.0	1	42.0
Low				2	56.0
Average				3	14.0
High				4	
Very high				5	70.0
		Lineament Density (L)			
Very low	1	0.164	11.1	1	11.1
Low				2	22.2
Medium				3	33.3
High				4	44.4
Very High				5	55.5
		Aquifer Resistivity (S)			
Very low	2	0.87	5.9	1	5.9
Low				3	17.7
Average				4	23.6
High					
Very high					
		Drainage Density (DD)			
Very low	3	0.103	5.0	1	5.0
Low				2	10.0
Medium				3	15.0
High				4	20.0
Very High				5	25.0
		Hydraulic conductivity			
Very low	3	0.125	12.5	1	12.5
Low				2	25.0
Average				3	37.5
High				4	50.0
Very high				5	62.5

4.11 Assessment of Groundwater Potential Zones

When all the themes and features in an integrated layer are taken into account, the groundwater potential index (GWPI) is computed as follows:

$$GWPI = RwRr + EwEr + SwSr + GwGr + LwLr + DDwDDr + CwCr + BwBr \quad (5)$$

Where: Rw=weight of transmissivity and Rr=rank of transmissivity, Ew=slope weight, Er=slope rank, Sw=aquifer resistivity weight, Sr=aquifer resistivity rank, Gw=geology weight, Gr=geology rank, Lw=lineament density weight, lineament density rank, DDw=Drainage density weight, DDr=Drainage density rank, Cw=hydraulic conductivity weight, Cr=hydraulic conductivity rank and Bw=aquifer thickness weight and Br=aquifer thickness rank.

Using overlay analysis, the final groundwater potential map zones were produced. The groundwater potential zone was delineated by converting all of the thematic layers into raster format and adding them together using a raster calculator in ArcGIS software. This was done after determining the final normal weights of each thematic layer and its features. Based on the total weightage determined, the groundwater potential zone's score was divided into five zones: very high, high, moderate, low, and very low (Figure 13).

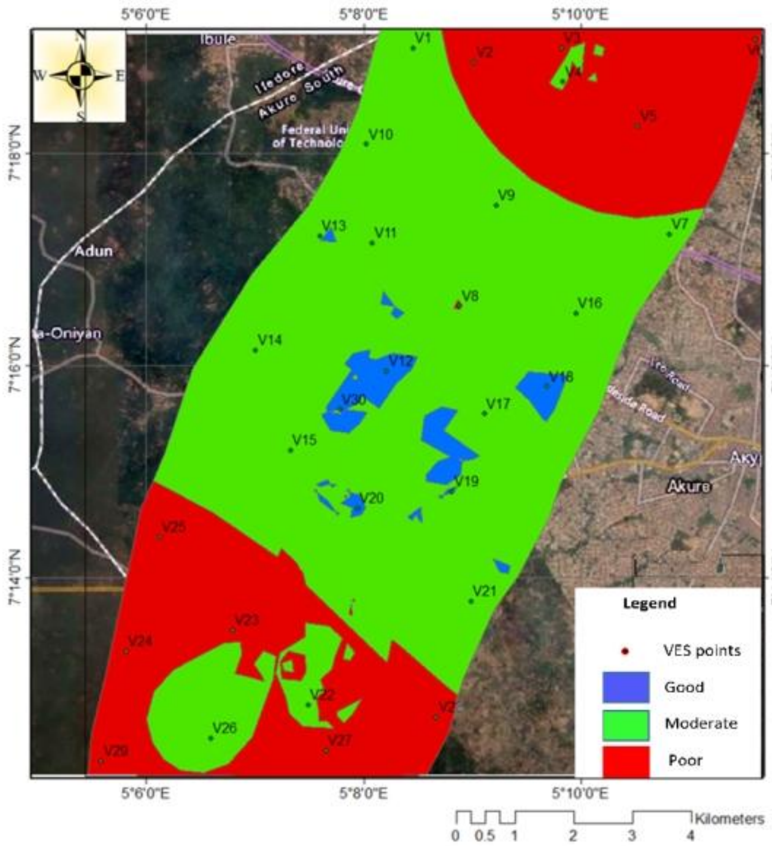

Fig. 13 *The groundwater potential zones map of the study area*

According to the groundwater potential map (Figure 13), the research area's southern and northern regions have poor groundwater potential zones, whereas the southern end has some intermediate potential zones. The good zones are clustered nearly entirely in the center of the study region, with the mediocre zones sandwiching them in part. Merely 8% of the examined region was deemed to have excellent groundwater potential, 57% moderate potential, and 35% poor groundwater potential. Thus, in the area under consideration, a total of 65% of the land can be categorized as a zone of moderate to high potential.

4.12 Groundwater Potential Zone Map Validation

Vertical Electrical Sounding (VES) data was used to validate the groundwater potential map that was created using GIS and the Analytic Hierarchy Process (AHP) technique. Subsurface resistivity is measured using the VES method, which is a trustworthy way to determine groundwater potential. We used thirty sites' worth of VES data points for this validation. We used the Receiver Operating Characteristic (ROC) analysis to numerically evaluate the groundwater potential map's forecasting accuracy. This required figuring out the False Positive Rate (FPR) and True Positive Rate (TPR) at different threshold values. An Area Under the Curve (AUC) value of 0.60 was obtained by plotting the ROC curve with FPR on the x-axis and TPR on the y-axis (Figure 14). This AUC value indicates that there is room for improvement in the model, especially in hard rock terrains where the presence of high-structure features like faults and fractures can affect groundwater distribution. It also suggests a moderate level of agreement between the predicted groundwater potential zones and the actual VES measurements.

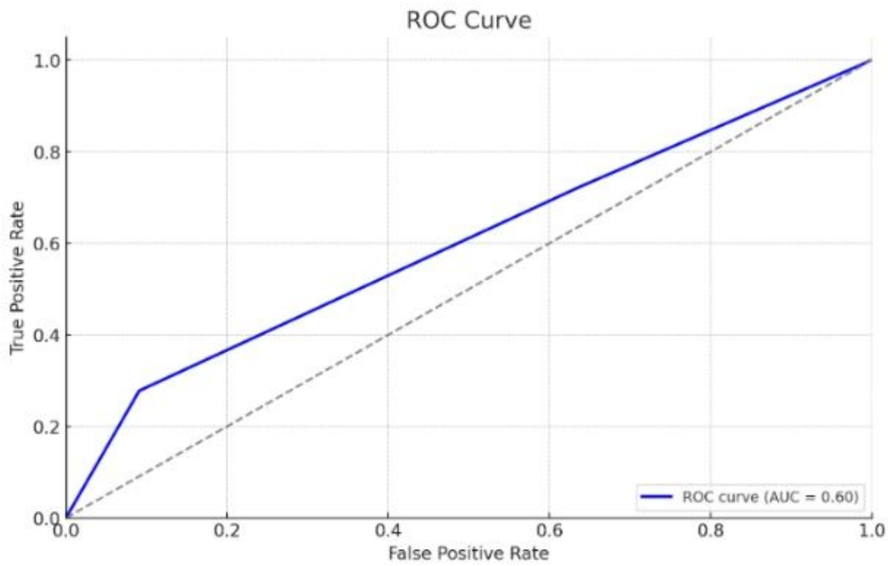

Fig. 14 *ROC curve of the GWP map*

5. Conclusion

In the search for groundwater potentiality, utilizing geographic information systems and remote sensing has drawn much attention globally. This geospatial method has shown to be a potent and economical way to identify groundwater potential zones in the Akure South of Ondo State, Nigeria when combined with multi-criteria-based AHP and VES. Eight major theme variables—lineament density, drainage density, slope, geology, aquifer resistivity, aquifer thickness, hydraulic conductivity, and transmissivity—that control groundwater in the region were considered for integration in the study. The groundwater potential zone maps provided residents, local government officials, and planners with up-to-date information about appropriate areas for groundwater exploration. Additionally, an effort was made to confirm the accuracy of the groundwater potential map zones by utilizing the Consistency Ratio (CR).

Using the AHP approach, the study region was divided into five GWPZs: very high (308 – 394), high (264 – 307), moderate (234 – 263), low (166 – 233), and very low (5 – 165). According to percentages, the research region has extremely high potential (20%), high potential (47%), moderate potential (30%), and low potential (3%). The research area's southern, southeast, and northern sections are classified as having poor to moderate groundwater potential. The study area's central regions are almost entirely composed of the good zones, with the very good zones sandwiching them in part. According to the adjudicated acceptable verification of the final GWPZ map acquired by CR result, AHP was a useful technique (CR accuracy = 0.08 or 8%) for identifying prospective groundwater zones. In summary, this research's results highlight the superiority of integrating geospatial techniques, MCDM, and geophysical methods for creating reliable Groundwater Potential Zones (GWPZ) and informing decision-making processes.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

*The authors confirm contribution to the paper as follows: **study conception and design:** Mumeen Adebayo Yusuf,; **data collection:** Olajumoke Bukola Yusuf, Joseph Omeiza Alao, Tamiru Alemayehu Abiye, Tolulope Ayobi Oyeleke, Kehinde Ibrahim Olojoku, Oladele Ajiboro Omotoso, Ussein Taiwo Bakare, Ifeoluwa Mathilda Olaleye, Abdulmalik Olayinka Kola-Aderoju, Majeed Akogun; **analysis and interpretation of results:** Mumeen Adebayo Yusuf; **draft manuscript preparation:** Mumeen Adebayo Yusuf. All authors reviewed the results and approved the final version of the manuscript.*

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