

Delineation of Groundwater Potential Using GIS, Hydrogeological, Geophysical and Analytical Hierarchy Process (AHP) Technique in Olorunda-Abaa, Ibadan, Southwest Nigeria

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Abstract
Integration Geographic Information System (GIS), hydrogeological, geoelectrical method involving Vertical Electrical Sounding (VES) technique, coupled with the Multi-Criteria Decision Analysis (MCDA) data mining technique were utilized with the aim to delineate the groundwater potential zones of Olorunda-Abaa area, Ibadan, southwestern Nigeria. Fifty-three (53) Vertical Electrical Sounding (VES) measurements using Schlumberger electrode array, depth to Water Level (DWL) estimation and determination of depth to the bottom of Hand dug wells were carried out across the study area. Multi-criteria Decision Analysis (MCDA) using Analytical Hierarchy Process (AHP) technique was applied to the factors controlling groundwater accumulation in the area. Weights were assigned and subsequently integrated in the ArcGIS environment using Arc Map 10.1 to develop the groundwater potential map of the investigated area. The geoelectric sections developed delineated four subsurface geological units consisting of the topsoil, weathered layer, partly weathered/fractured basement and the fresh bedrock. The VES gave depths to basement bedrock which generally range from 5.6 - 59.4 m. The groundwater conceptual model developed delineated five groundwater potential zones classified as low, medium, high and very high and validated with the thickness of water column obtained from wells over the entire study area. The groundwater potential map generated for the study area show that the medium to very high groundwater potential zones indicates the favourable area where groundwater development is feasible in the study area. This study concludes that the characterization of the groundwater potential zones in the study area can be adopted for future allocation of social amenities, planning, location, development and management of groundwater resources.
Keywords: Hydrogeology, Geophysical, Multi-criteria Decision Analysis, Groundwater Potential, Basement Complex, Ibadan.
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1. Introduction

Water is an essential and a non-negotiable ingredient that supports life just like air. According to national water policy (1987), water is a prime natural resource, basic human need, and precious natural asset while in general term it is defined as a universal solvent. The regular and adequate supply of potable and good quality water in the twenty first century in Nigeria depends on ability of individuals and Government Agencies such as State Water Corporation to sink a well or drill a borehole for his/her household, the community and industries at large. However, the use of water extends to various purposes such as industrial, domestic, agricultural, construction and recreational. Boreholes may be appropriate for domestic and recreational purposes when the supply is in adequate quantity. Factors such as wide availability of groundwater, its low capital development, cost and normally excellent natural quality are leading to rapid development of groundwater resources (Foster and Chilton, 1993). Groundwater occurrence in the crystalline basement terrain can be very irregular due to abrupt discontinuity in lithology, thickness, and electrical properties of the weathered bedrock (Satpathy and Kanugo, 1976). The quest for adequate and potable groundwater in any environment involves a detailed geological, geophysical and hydrological knowledge of the environment. In hard rock terrain, aquifers are mainly made up of decomposed and fractured rocks. The existence of fracture zone in a geologic medium can assist in creating groundwater conduit medium which can aid groundwater accumulation, migration and extraction (Hazell e*t al.,* 1988).

Groundwater is a hidden natural resource and hence cannot be directly accessed. Several techniques had been used to explore for groundwater resources. Hydrogeology, photogeology, geology, test drilling or exploratory wells and wells drilled for stratigraphic analysis are the oldest most reliable and standard methods for determining the thickness of the aquifer units and the location of boreholes (Madan *et al*., 2010). However, these methods of groundwater investigation are not time and cost effective, not environmentally friendly and also often require skilled personnel (Roscoe, 1990; Fetter, 1994). In lieu of this, the demand for groundwater and its sustainability has increased over the years and this has led to water scarcity and high rate of failed boreholes in many parts of the world. The increased in location of industries and the consequent population explosion in Ibadan metropolis has led to demand for more social amenities, groundwater supply inclusive in the study area.

The investigated area presently has no functioning pipe borne water facility, and also, there had been recorded cases of abortive and low yield hand dug wells and boreholes drilled in the study area by individual, small scale industries and Government Agencies. Therefore, there is need to carry out a detailed hydro-geophysical investigation of the study area to assess the groundwater potential. Recently, the search for groundwater development has increased across the globe by adopting hydro-geophysical method. However, some of the surface geophysical methods often employed in groundwater investigation include the electrical resistivity, Very Low Frequency Electromagnetic (VLF), magnetic and seismic refraction. This study adopt the electrical resistivity method due to its capability to accurately delineate the subsurface geologic layers, identify the aquifer units, determine both the lateral and depth extent, delineate depth to bedrock and the subsurface geologic structures (faults, fractures, joints and shear zones). Also, derivable secondary geoelectric parameters including total transverse unit resistance, total longitudinal unit conductance and Coefficient of Anisotropy that can be used as an indirect groundwater potential assessment can be obtained from the interpretation of primary geoelectric parameters (layer resistivity and thickness). It is also non-invasive and more cost-effective over large areas.

Several conventional methods such as photogeological, geological, hydrogeological and geophysical methods have been employed to delineate groundwater potential zones. However, with the advent of powerful and high-speed computers, digital technique is used to integrate various conventional methods with satellite image/remote sensing (RS) techniques and geographical information system (GIS) technology (Pinto, *et al*., 2015). In groundwater assessment, it is possible to combine various different thematic layer maps from hydrogeology, geology and geophysics, such as saturation thickness of aquifer, lithology, overburden thickness, total transverse unit resistance, total longitudinal unit conductance and Coefficient of Anisotropy as different parameters to delineate groundwater potential zones. There is no previous study related to determination of groundwater potential zones in the study area. Therefore, this study is focused on assessment of the groundwater potential using more integrated variables from hydrogeological, geological as well as geophysical data sets by adopting statistical modelling tool involving the Multi Criteria Decision Analysis concept of Analytical Hierarchy Process (MCDA-AHP) technique. Some of the statistical models commonly applied in groundwater studies includes logistic regression (Ozdemir, 2011; Pourtaghi and Pourghasemi, 2014), frequency ratio (Oh *et al*., 2011; Davoodi, *et al*. 2013), Stepwise Weight Assessment Ratio Analysis (SWARA) (Zolfani, *et al*. 2018), Adaptive-Network-based Fuzzy Inference System (ANFIS) (R-Jang, 1993, Ali *et al.* (2020) and Khaled *et al.* (2020), FUZZY (Jiang and Eastman, (2000)) and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Sabaghi *et al*. (2015) and Sangchini *et al*. (2017). Among these aforementioned statistical models, the MCDA- AHP and GIS-based modelling study is the most applied in the field of groundwater hydrology (Zeinolabedini and Esmaeily, (2015), Akinlalu *et al.* (2017), Vidhya and Vinay, (2018), Arulbalaji *et al.* (2019)). This is probably due to the fact that the AHP technique has a robust capability for the conjunctive and integrated analysis of multidisciplinary data sets (Chowdhury *et al*., 2010) and it also have capability of giving a broader view of the groundwater potential distribution of an area (Pinto, *et al*., 2015).

The Analytic Hierarchy Process (AHP) technique was first developed by Professor Thomas L. Saaty (Saaty, 1977, 1980, 1986 and 1992). In order to have broader view of the groundwater potential distribution in the study area involving many variables, the multi-criteria decision analysis (MCDA) technique was adopted. The Analytical Hierarchy Process (AHP) is an MCDA technique that supports decision makers in solving and constructing complex decisions (Saaty and Sagir, 2009, Karagiannidis *et al.,* 2010). The (AHP) technique is used to consider both qualitative and quantitative information in real decision situations, and sophisticated techniques to accommodate data uncertainty (Yeh *et al.,* 1999). However, AHP is capable of quantifying intangible criteria and evaluating choices in a multi-level, hierarchical structure of objectives with respect to criteria, sub-criteria, and alternatives. Pairwise comparisons are used to obtain the weights of importance for the decision criteria, and the relative performance measures of the alternatives in terms of each decision criterion. If the comparisons are not perfectly consistent, then AHP will provide a system for improving consistency (Saaty and Sagir, 2009). Base on these, there is therefore, the need to carry out a detailed hydro-geophysical investigation of the study area to assess the groundwater aquifers and to evaluate the groundwater potential. Therefore, this study engaged the GIS, hydrogeology and geoelectric method involving the Vertical Electrical Sounding (VES) technique, and the data mining technique of the MCDA-AHP technique to develop a model groundwater potential map. The produced map will serve as guide for social infrastructural resources location within the investigated area.

2. Description of the Study Area

The study area, Olorunda-Abaa area, Ibadan, Southwestern Nigeria, is situated between longitudes 3° 58ꞌ 25.8ꞌꞌ E and 3° 59ꞌ 51.0ꞌꞌ E, and latitudes 7°28ꞌ 24.0ꞌꞌ N and 7° 29ꞌ 46.9ꞌꞌ N (Fig. 1). It covers an areal extent of about 4.0 km^2. It is characterized by relatively gentle undulating terrain with topographic elevations varying from 213 m to 259 m above mean sea level. The study area is accessible through tarred roads, untarred roads and footpaths.

The area is drained by two major rivers. One river drains the northern part while river Asaun drains the southern part of the study area (Fig. 1). The area experiences a tropical climate with a dry season between the months of November and March and a wet season between April and October. The vegetation in the area is the tropical rainforest type. The annual rainfall range between 1500 mm and 2000 mm. Annual mean temperature is between 22 °C and 33 °C with relatively high humidity (Akintola, 1986; NIMET, 2011).

3. Geology and Hydrogeology

The study area is underlain by undifferentiated schist and gneiss; and migmatite rocks of the Crystalline Basement Complex rocks of Southwestern Nigeria (Rahaman, 1976). Undifferentiated schist and gneiss is the predominant rock unit which underlies the study area (Fig. 2). The rocks underlying the study area is expected to have undergone weathering and probably suffered deformation from previous tectonic activities leading to secondary porosity and

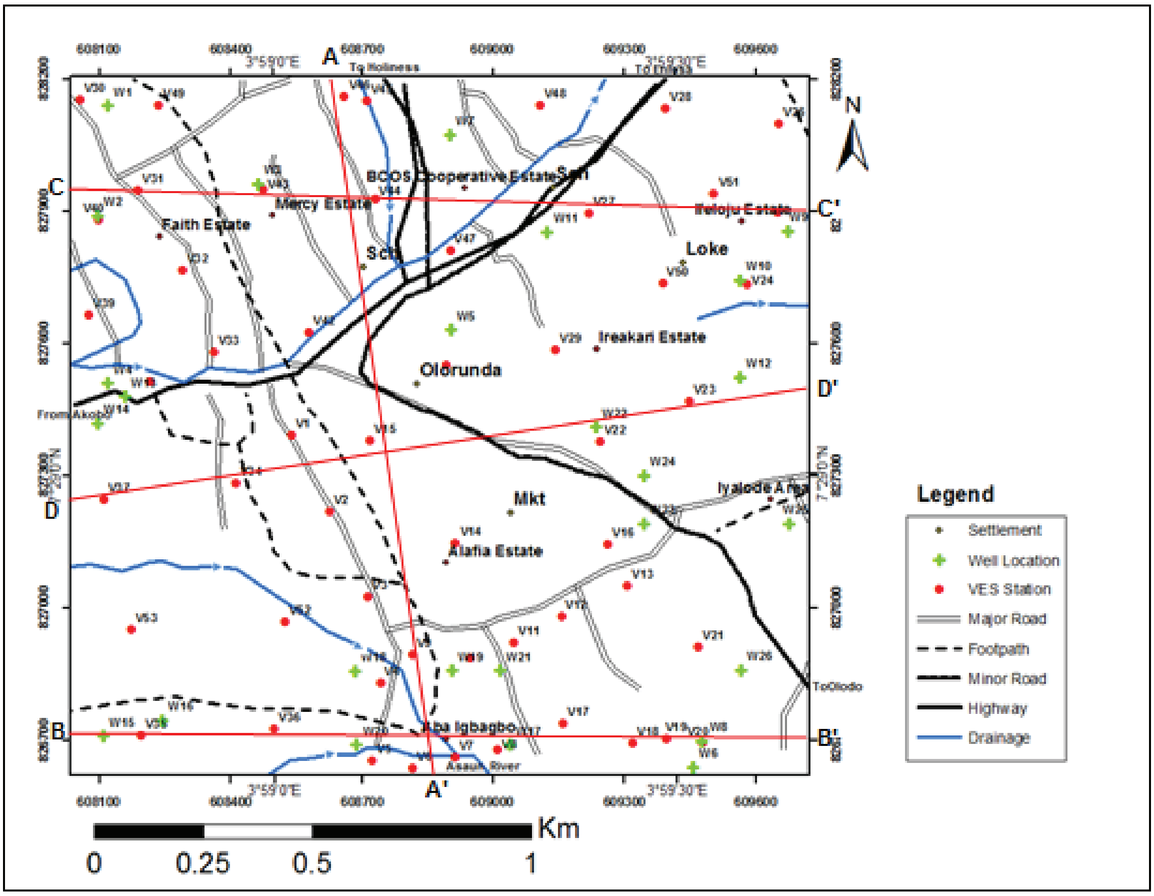

Fig. 1: Location and Data Acquisition Map of the Study Area.

increase permeability. In Crystalline Basement Complex area, groundwater is contained within the weathered and or fractured/jointed basement columns and shear zones. Therefore, the regolith of undifferentiated schist and gneiss; and migmatite rocks is expected to exhibit variable hydrogeological properties. Therefore, zones with thick and fully saturated weathered layer with relatively low resistivity values and structural features (shear zones, faults, fractures and joints) within the basement bedrock are possible targets for high groundwater potential in the investigated area.

4. Materials and Methods

The Vertical Electrical Sounding (VES) using the Schlumberger configuration was adopted for this survey. A total of fifty three (53) VES were conducted (Fig. 1). The resistivity measurements were made with the Ohmega Resistivity Meter. The electrode spacing (AB/2) m was varied from 1 – 150 m. Partial curve matching was carried out for the qualitative interpretation of the VES data to obtain the initial geoelectric parameters (layer resistivities and thickness). The initial geoelectric parameters were used as the starting model for1-D forwarding modeling using the Win RESIST version 1.0 software (Vander Velper, 2004). The geoelectric parameters obtained (layer resistivities (r) and thickness (h)) were used to developed geoelectric sections and to derive the secondary geoelectric parameters (Dar Zarrouk parameters) such as Total Transverse unit resistance (T) and Total longitudinal unit conductance (S) which was used to derive the Coefficient of Anisotropy (λ).

4.1 The Concept of Secondary Geoelectric (Dar Zarrouk) Parameters.

A geoelectric layer is described by fundamental parameters of its resistivity (ρ_i) and thickness (h_i). Where 'i' indicates the number of layers in the section. The resistivity (ρ_i) and thickness (h_i) can be use to define the Total transverse unit resistance (T), Total longitudinal unit resistance (S), the average transverse resistivity (ρ_T) the average longitudinal resistivity (ρ_L) and the Coefficient of Anisotropy (λ) parameters. The parameters T, S, ρ_t , ρ_L and (λ) are particularly important when they are used to describe a geoelectric section consisting of several layers defined by using a unit cube of rock with n-layers and total thickness (H). For n-layers and total thickness (H), Maillet, (1947) and Keller and Frischneeht, 1966) defined T, S, ρ_t , ρ_L and the Coefficient of Anisotropy (λ) parameters by Equations 1 – 5 as follows:
The total transverse unit resistance (T) is

$$S = \sum_{i=1}^{n} \frac{h_i}{\rho_1} = \frac{h_1}{\rho_1} + \frac{h_2}{\rho_2} + \ldots + \frac{h_n}{\rho_n} \quad (1)$$

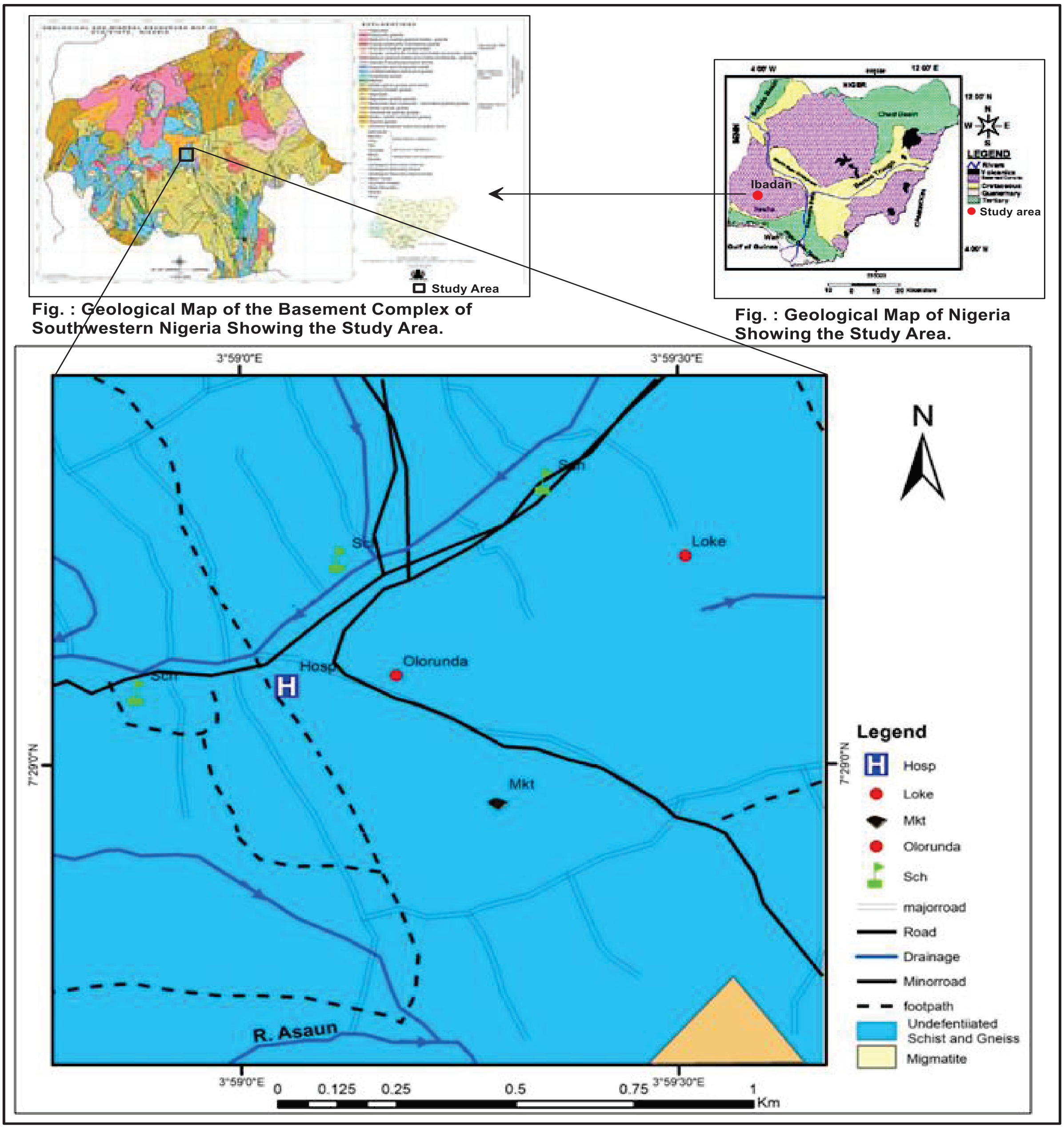

Fig. 2: Geological Map of the Study Area.

The total longitudinal unit conductance (S) is

$$T = \sum_{i=1}^{n} h_i \rho_i = h_1 \rho_1 + h_2 \rho_2 + ... + h_n \rho_n \quad (2)$$

The average transverse resistance (ρ_t) is

$$\rho_T = \frac{T}{H} = \frac{\sum_{i=1}^{n} \rho_i h_i}{\sum_{i}^{n} h_i} \quad (3)$$

The average longitudinal conductance (ρ_L) is

$$\rho_L = \frac{H}{S} = \frac{\sum_{i}^{n} h_i}{\sum_{i}^{n} \frac{h_i}{\rho_i}} \quad (4)$$

and the coefficient of anisotropy (λ) is

$$\lambda = \sqrt{\frac{\rho_t}{\rho_l}} = \frac{\sqrt{TS}}{H} \quad (5)$$

The units of (T) and (S) are respectively expressed in 1/ohm (mhos) and ohm-m^2. The secondary parameters described above could be very useful in describing a geoelectric section. A summary of the Dar Zarrouk parameters obtained in the study area is presented in Table 1. Henriet, (1976) and Modin *et al*., (1986), demonstrated that the combination of layer resistivity and thickness in the Dar Zarrouk parameters may be of direct use in aquifer studies. These parameters are regarded as powerful interpretation aids, which can be used to define aquifer geometry. Worthington (1976), demonstrated that through variations in one or other of the Dar Zarrouk parameters, the target areas for initial groundwater development can often be identified. The Coefficient of Anisotropy (λ) has been found to be related to groundwater yield (Olorunfemi *et al*., 1991, Ojo *et al*., 2015). The derived secondary geoelectric parameters include Total transverse unit resistance (T), Total longitudinal unit conductance (S) and Coefficient of Anisotropy (λ) (see Table 1) was incorporated with the overburden thickness and geology of the study area to develop a groundwater potential map for the study area.

4.2 Multi Criteria Decision Analysis (MCDA)

In this research, a GIS-based Multi Criteria Decision Analysis (MCDA) in the context of Analytical Hierarchy Process (AHP) technique was adopted with the aim of developing a conceptual model that will assist in evaluating the groundwater prospect in the study area. This involved integration of five thematic layer factors which have been selected to influence groundwater occurrence in the study area. The factors include lithology, overburden thickness, total transverse unit resistance (T), total longitudinal unit conductance (S) and coefficient of anisotropy (λ) maps produced were converted into the raster format using Arcmap 10.1 software. Weighted overlay analysis method using spatial overlay analysis tools in Arcmap 10.1 was used to obtain the groundwater potential index map. In weighted overlay analysis ranks was assigned to each individual parameter of each thematic layer map.

The weighted overlay analysis involved ranking of each individual parameter of each thematic layer map and weights were given base on the output of the MCDA (AHP) technique to a particular feature on the environment of groundwater occurrence in the investigated area (Pinto *et al*., 2015). The data used and their description are presented in Table 1.

4.3 Hydrologic Parameters

The hydrogeologic investigation of the study area involved measurement of the static water level and determination of depth to the bottom of Hand dug wells across the study area. The hydrogeological data were collected from the twenty six (26) available hand dug wells available in the investigated area during the field work. Depth to Water Level (DWL) below ground surface is measured using measuring tape. This depth value is subtracted from the height of the ground surface above mean sea level obtained from GPS using (Garmin GPSmap76Cx) altitude value at that point, to obtain the height (H) of the groundwater table above mean sea level in each hand dug well present in the investigated area.

4.4 Analytic Hierarchy Process (AHP)

The Saaty's Analytic Hierarchy Process (AHP) is a widely used MCDM technique in the field of water resource engineering and management (Aggarwal *et al*., 2009; Adiat *et al*., 2012, Bhatnagar and Goyal, 2012; Kaliraj *et al*., 2014). The method was first developed by Professor Thomas L. Saaty in the 1977s (Saaty, 1977). The Saaty's scale values of 1-9 to each map were assigned base on their relative importance (Saaty, 1980). The relationship between the five thematic layers was derived using the MCDA method to compute the relative importance of the theme. Following this, the approach adopted in computing the AHP includes: selection of factors which influence groundwater potentiality (occurrence)**,** constructing of hierarchical model, construction of pairwise comparison matrix, determination of weightage factors, and consistency examination of the pairwise comparison matrix, classifying and rating of parameters, using weighted overlay method. The data used and description of the hydrogeologic factors controlling groundwater occurrence in the investigated area is presented in Table 2.

4.4.1 Step 1: Construction of Hierarchical Model:

Review of previous work done on similar research topic was carried out on the bases of which different models for mapping groundwater potential was identified. The construction of the model was done by first defining the problem and then decomposed it into the various thematic layers containing the different classes of the individual thematic map to form a net work of the model.

4.4.2 Step 2: Consistency examination of the Generated Pairwise Comparison Matrix:

Pairwise comparison is the most frequently used interactive technique in order to establish trade-off relationships between criteria judgments. Scale for weight assignment and its interpretation contain the pairwise comparison matrix and the factor weights. In determining the weight of each factor, the comparisons ratings was based on Saaty's 1 – 9 scales (Saaty, 1980) and their importance in groundwater
potential are practically considered. Where a score of 1 represents equal influence between the two thematic maps and a score of 9 indicates the extreme influence of one thematic map compared to the other Table 3 (Pinto *et al*., 2015). Consequently, all the groundwater relevant factors are compared against each other in a pairwise comparison matrix Table 4.

Apart from AHP being a useful mechanism for checking the consistency of the evaluation it also measures the alternatives suggested by experts or decision makers, thus reducing bias in decision-making (Ariff *et al.,* 2008) through

Table 1: Summary of the Overburden Thickness and Secondary Geoelectric (Dar Zarrouk) Parameters for the Study Area.

VES No	Easting	Northing	Total Traverse Unit Resistance (R)	Total Longitudinal Unit Conductance (S)	Overburden Thickness (T)	Coefficient of Anisotropy (Λ)
1	608054	828153	2715.82	0.28	24.9	0.93
2	608216	827513	1201.9	0.22	15.0	0.57
3	608361	827580	1267.74	0.16	13.7	0.82
4	608904	827811	988.8	0.16	26.7	0.37
5	609107	828140	2373.33	0.17	16.9	0.93
6	608902	828080	21399.23	0.09	41.3	0.88
7	608732	827928	6064.23	0.28	40.8	0.76
8	608660	828187	11438.9	0.21	49.0	0.93
9	608473	827949	882.0	0.21	13.2	0.96
10	608188	827948	874.74	0.23	12.7	0.74
11	608041	827872	3074.91	0.23	24.5	0.86
12	608075	827664	2781.12	0.21	44.5	0.46
13	608289	827765	1722.6	0.08	10.9	0.99
14	608579	827625	2970.35	0.80	48.6	0.98
15	608235	828141	8371.32	0.12	31.5	0.97
16	609394	828133	25656.3	0.14	59.4	0.86
17	609654	828097	488.43	0.10	6.2	0.96
18	609712	827889	7254.88	0.31	42.7	0.78
19	609505	827939	353.16	0.05	3.9	0.90
20	609219	827894	3904.55	0.42	38.0	0.82
21	609582	827734	5653.46	0.20	32.0	0.81
22	609390	827736	2988.34	0.22	25.4	0.96
23	609143	827586	1784.6	0.07	11.2	0.94
24	609448	827468	2756.62	0.12	17.4	0.83

25	609244	827378	544.96	0.07	6.3	0.87
26	608894	827551	430.56	0.07	5.6	0.86
27	608109	827245	3750.76	0.23	28.8	0.72
28	608411	827282	3514.76	0.19	25.2	0.81
29	608742	826830	4775.96	0.29	36.8	0.93
30	608724	826653	2792.18	0.23	24.5	0.67
31	608194	826709	2885.85	0.32	29.5	0.78
32	608499	826724	4118.51	0.46	42.6	0.72
33	608816	826637	6794.1	0.31	45.4	0.67
34	608913	826660	5806.79	0.23	35.6	0.82
35	609011	826679	5742.0	0.50	52.5	0.84
36	608539	827392	3870.51	0.47	40.6	0.73
37	608718	827379	3405.51	0.20	25.6	0.84
38	608626	827219	2929.24	0.35	31.0	0.73
39	608714	827026	13103.54	0.26	55.3	0.91
40	608914	827146	11132.03	0.23	47.4	0.82
41	609262	827143	4064.25	0.21	28.7	0.79
42	609307	827050	680.96	0.22	11.8	0.95
43	609158	826980	1877.38	0.35	25.2	0.84
44	609049	826921	4038.64	0.24	27.9	0.91
45	608948	826885	5242.74	0.55	51.7	0.94
46	608815	826893	979.41	0.48	17.9	1.01
47	609469	826912	1891.43	0.40	24.1	0.94
48	609396	826703	7682.43	0.55	59.2	1.10
49	609482	826623	9893.06	0.45	59.1	1.13
50	609310	826627	7280.12	0.19	48.8	0.77
51	609160	826738	6549.27	0.20	35.3	0.87
52	608172	826951	1519.51	0.14	14.2	0.94
53	608523	826968	2942.64	0.14	20.3	0.97

Table 2: Description of Hydrogeological Factors in Relation to Groundwater Potentiality.

Category	Hydrogeologic factor	Description	Data type	Source
Geology	Lithology (unit less)	The geology of the study area has been divided into two lithology classes. Class 1: Undifferentiated schist and gneiss, weathered product contain more sand fraction; Class 2: Migmatite rocks, the end product is clayey. The higher the sand fraction of an aquifer unit the higher the groundwater potential.	Polygon	ALGIS
Geophysics	Overburden thickness (m)	Primary geoelectric parameter (layer thickness) from interpretation of VES data. This is the summation of thickness of weathered layer(s) above the basement bedrock. The higher the Overburden thickness, the higher the groundwater potential.	Polygon	ALGIS
Geophysics	Total Transverse Unit Resistance (ohm-m^2)	Secondary geoelectric parameters (Dar Zarrouk parameters). (Product of aquifer thickness and hydraulic conductivity). It is related to aquifer saturation and transmisivity. The higher the Total Transverse Unit Resistance the higher the aquifer saturation and transmisivity, and the higher the groundwater yield.	Polygon	ALGIS
Geophysics	Total Longitudinal Unit Conductance (mhos)	Secondary geoelectric parameters (Dar Zarrouk parameters). (summation of the division of the thickness by the resistivity of the geoelectric layers). It is related to hydraulic conductance and permeability of aquifers. The higher the Longitudinal Unit Conductance the higher the permeability and the higher	Polygon	ALGIS

Category	Hydrogeologic factor	Description	Data type	Source
		the groundwater yield.		
Geophysics	Coefficient of Anisotropy (λ) (unit less)	Secondary geoelectric parameters (Dar Zarrouk parameters). It is a measure of the degree of inhomogeneity of a medium, and also related to groundwater yield. The higher the Coefficient of Anisotropy (λ) the higher the groundwater potential and yielding capacity.	Polygon	ALGIS

Table 3: Scale for Assignment of Weight (After Rao, 2013 Kardi, 2006 and Adiat *et. al*., 2013).

Less Important						Equally Important	More Important					
Extremly Favour	Very Strongly Favour	Strongly Favour		Slightly Favour				Slightly Favour		Strongly Favour	Very Strongly Favour	Extremly Favour
9	7	5	4	3	2	1	2	3	4	5	7	9

Table 4: Pairwise Comparison Matrix Table.

	G	OT	TTR	TLC	COA
G	1	1/2	1/3	1/4	1/5
OT	2	1	1/3	1/4	1/5
TTR	3	3	1	1/3	¼
TLC	4	4	3	1	1/3
COA	5	5	4	3	1
Column Total	15	13.5	8.66	4.83	1.98

the principal Eigen value and the consistency index (Saaty, 2004). According to Saaty, the Consistency Index (CI) is defined as a deviation or degree of consistency as captured in Equation. (4):

$$CI = \frac{\lambda \max - n}{n-1} \qquad (4)$$

Where λ_{max} is the largest Eigen value of the pairwise comparison matrix and can be easily determined from the matrix and n is the number of groundwater conditioning features/factors. To control the consistency analysis and scale judgment (Pinto *et al*., 2015), the normalized weights of the factors of the pairwise comparison matrix are determined and tested for consistency ratio (CR) Table 5. Equation 5 is used to compute the Consistency Ratio:

$$CR = \frac{CI}{RI} \qquad (5)$$

Where, RI is the random index whose value depends on the order of the matrix; the value of RI for different n vales is given in this research work as RI = 1.12 (n = 5).

4.5 Weightage Analysis and Normalization

MCDA is a technique that allows two layer maps (parameters) to be weighted in order to reflect their relative influence/importance to the groundwater occurrence than the other (Eastman, 1996 and Navalgund, 1997). The best set of weight for each index was produced by computing the Eigen vectors. The pairwise comparison matrix was carried out by assigning weights to the parameters using the MCDA (AHP) technique Tables 3 and 4. According to Saaty (1980) and Malczewski (1999), the consistency ratio (CR) determined must be less than 0.1. In this research, the CR calculated is 0.066 ≈ 0.07. 0.07 is < 0.1 hence the matrix A is considered to be consistent, and the estimated weights shown in Table 4 were considered suitable to be used in this study. A perfect consistent level is reached when the consistency measure (λ max) is equal to n (Saaty, 1994). Therefore, when the matrix is perfectly consistent, CI = 0, and hence CR = 0. If CR is less than 0.1 (10 %), then the comparison matrix value is still considered as consistent. If CR > 0.1, then the entry values are not consistent, and the step pairwise comparison matrix has to be reconstructed to rank the judgment value carefully with respect to the dominant factor which influences groundwater potential in the overall thematic layer map. Geology, overburden thickness, Total Transverse unit resistance (T), Total longitudinal unit conductance (S) and the Coefficient of Anisotropy (λ) maps were generated and assigned a suitable weight as shown in Table 5.

To calculate the cumulative weights of criteria, Rates (R) were assigned to each class according to the order of the influence of the class on groundwater storage potential., Ratings (R) of 1–5 were adopted where rates 1, 2, 3, 4 and 5 represent very low, low, medium, high and very high groundwater potential respectively (Table 6). It should however be pointed out that since only two rock types are present in the study area, it implies that the lithology thematic layer

Table 5: Calculation of Relative Criteria and Normalized Weights.

	G (j = 1)	OT (j = 2)	TTR (j = 3)	TLC (j = 4)	COA (j = 5)	Normalized weights (1/n∑ij)
G(i = 1)	0.07	0.04	0.04	0.05	0.10	0.06
OT (i = 2)	0.13	0.07	0.04	0.05	0.10	0.08
TTR (i = 3)	0.20	0.22	0.12	0.07	0.13	0.15
TLC (i = 4)	0.27	0.30	0.35	0.21	0.17	0.26
COA(i=5)	0.33	0.37	0.46	0.62	0.51	0.46
	1	1	1	1	1	1

G = Geology; OT = Overburden Thickness: TTR = Total Unit Transverse Resistance:
TLC = Total Longitudinal Unit Conductance; COA= Coefficient of Anisotropy.

Table 6: Relative Weight of various Thematic Layers and Their Corresponding Classes (Parameter Weight and the Rating of Parameters).

Parameter	Classes	Groundwater Potentiality	Rating	Normalizes Weight
Geology	Schist and undifferentiated gneiss	Low	2	0.06
	Migmatite	Medium	3	
Overburden thickness	3.9 - 14.8 m	Very low	1	0.08
	14.8 - 25.2 m	Low		
	25.2 – 36.1 m	Medium	3	
	36.1 -47.5 m	High	4	
	> 47.5 m	Very high	5	
	>0.65 mhos	Very high	5	
Total Traverse Unit Resistance	353 – 2287 Ohms-m^2	Very low	1	0.15
	2287 –2975 Ohms-m^2	Low	2	
	2975 – 4905 Ohms-m^2	Medium	3	
	4905 – 10349 Ohms-m^2	High	4	
	>10349 Ohms-m^2	Very high	5	
Total Longitudinal Unit Conductance	0.05 – 0.20 mhos	Very low	1	0.26
	0.20 - 0.33 mhos	Low	2	
	0.33 – 0.50 mhos	Medium	3	
	0.50 – 0.65 mhos	High	4	
	>0.65 mhos	Very high	5	
Coefficient of Anisotropy	0.74 – 0.92	Very low	1	0.46
	0.92 – 1.03	Low	2	
	1.03 – 1.10	Medium	3	
	1.10 – 1.15	High	4	
	>1	Very high	5	

Table 7: Index Rating and Groundwater Potential Class.

S/N	Index Rating	Groundwater Potential Classification
1	0.0-1.0	Very low
2	1.0-2.0	Low
3	2.0-3.0	Medium
4	3.0-4.0	High
5	4.0-5.0	Very high

has only two classes which are also rated according to the influence of each rock type on the groundwater storage potentiality of the study area. The classes of the thematic layers for all parameters and their corresponding ratings (R) are shown in Table 6. Moreover, the cumulative weight was used to generate the Groundwater Potential Index Evaluation (GWPE) map for the study area, five different thematic analyzed maps comprising Geology, Overburden Thickness, Total Longitudinal unit Conductance (S), Total Transverse Unit Resistance (T) and Coefficient of Anisotropy (λ) were integrated in ArcGIS 10.1 software environment.

4.6 Estimation of the Groundwater Potential Index Map (GPIM) Using Weighted Overlay Method

Weighted linear average technique was used to estimate the GPIM (Eastman, 1996). This technique is usually specify in terms of normalized weightings for each factor as well as normalized scores for all options relative to each of the criteria. The final utility (U) for each option (Oi) is then calculated using Eq. 6 as follows:

$$U(O)_{I=1/5}U(O)i = \sum_{k=1}^{n-1} ZR(O)i + W(Cg) \quad (6)$$

where ZR (Oi) is the normalized score of option Oi under criterion CR and w(CR) is the normalized weighting for each criterion CR. Replacing the LHS of Eqn. 6 above with GPIM and the RHS to be replaced with the sum of the products of the normalized weights (w) and ratings (R) of each factor, the groundwater potential index (GPIM) for each VES point was computed using Eq. 7 after Prasad *et al*. (2008).

$$GPIM = (GwG_R + OTw\ OT_R + TTRw\ TTR_R + TLCw\ TLC_W + COAw\ COA_R) \quad (7)$$

where GPIM is groundwater potential index map, G is the geology, OT is Overburden Thickness, TTR is Total Traverse Unit Resistance, TLC is Total Longitudinal unit Conductance and COA is Coefficient of Anisotropy, The subscripts W and R indicate weights and ratings for each factor respectively.

The values at each of the VES locations are based on the rating of each criteria/factor. The GPIM obtained for all the locations are calculated as shown in table 6. It is noteworthy to state that since the minimum and maximum rating values (R) adopted in this study are 1 and 5 respectively, the minimum and maximum GPIM values obtainable are 1 and 5 respectively, it therefore follows that based on the computed values of GPIM shown in Table 6, the groundwater potential index for the area can be classified into five classes as presented in Table 7.

4.7 Validation

The water column obtained from hydrogeologic survey of twenty-six (26) wells located over the entire study area was used to validate the accuracy of the predicted groundwater potential map. The validation was carried out by superimposing the well locations on the prediction map of the study area. The thickness of the water column in each well was compared and correlated with the expected yield at each location on the groundwater prediction map of the investigated area.

5. Results and Discussion

5.1 Discussion of Factors Contributing to Groundwater Occurrence in the Study Area.

5.1.1 Geology Map

The geology of the study area is divided into two main rock types as earlier presented in Figure 2. These are undifferentiated schist and gneiss; and migmatite rocks that are of crystalline origin. The undifferentiated schist and gneiss cover the largest portion of the study area, constituting of about 99.25% of the entire study area. The migmatite rock unit occupies a small portion comprising of about 0.75% in the southeastern part of the study area. Undifferentiated schist and gneiss rocks weather into clay/clayey end product with limited hydrogeological significance and is assigned lower preference in determining its groundwater potential. The aquifer units in the area dominated by migmatite rock unit contain more sand fraction and hence, is considered to be a better aquifer unit with relatively good porosity and permeability with consequent higher groundwater storage potential. The pairwise comparison of the lithologic map was prepared based on the relative importance of the aquifer unit derived from each of the lithological units to groundwater potentiality (Fig. 2). In the investigated area, aquifer type was classified into two different lithologic units. The migmatite gneiss was considered to have greater storage capacity than the undifferentiated schist and gneiss and hence considered the least important weight.

5.1.2 Overburden Thickness (T) Map

Figure 3 present the overburden thickness map of the study area. The overburden thickness map was prepared by determining all the weathered materials overlying the fresh bedrock Table 6. The overburden thickness at each of the VES location was contoured and presented as map (Fig 3). Figure 3 shows that, the overburden thickness values in the study area generally range from 3.9 – 59.4 m having a mean value of 30.4 m. This was classified into five classes: very low (3.9 -14.8 m), low (14.8 -25.2 m), medium (25.2 – 36.1 m), high (36.1 – 47.5 m) and very high (47.5 -59.4 m) respectively. In general, the study area is mainly characterized by medium (25.2 – 36.1 m), high (36.1 – 47.5 m) and very high (47.5 – 59.4) overburden thickness values. These areas are classified to be prospective zones of medium to high groundwater potential zones within the investigated area (Fig. 3). The very low and low overburden thickness values of 3.9 – 14.8 m and 14.8 – 25.2 m classes respectively occupied a small portion and it is found across the

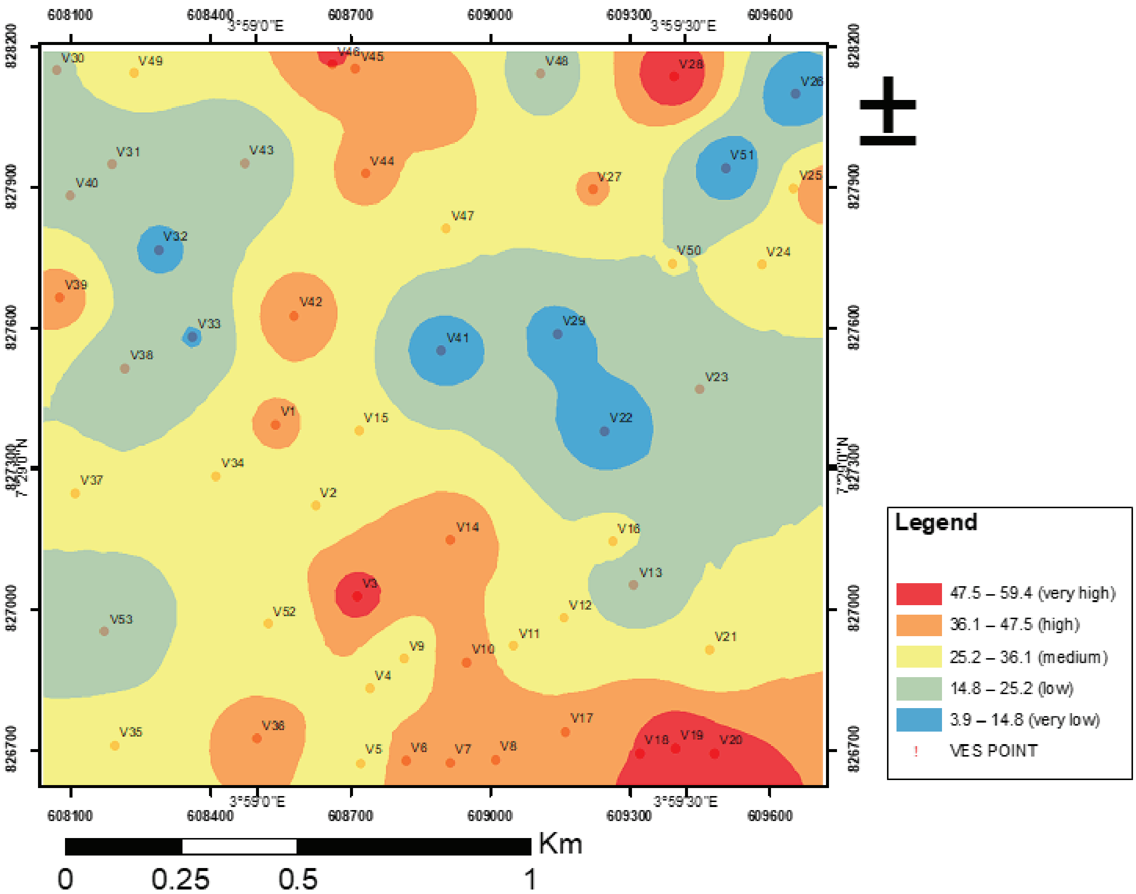

Fig. 3: Overburden Thickness Map of the Study Area.

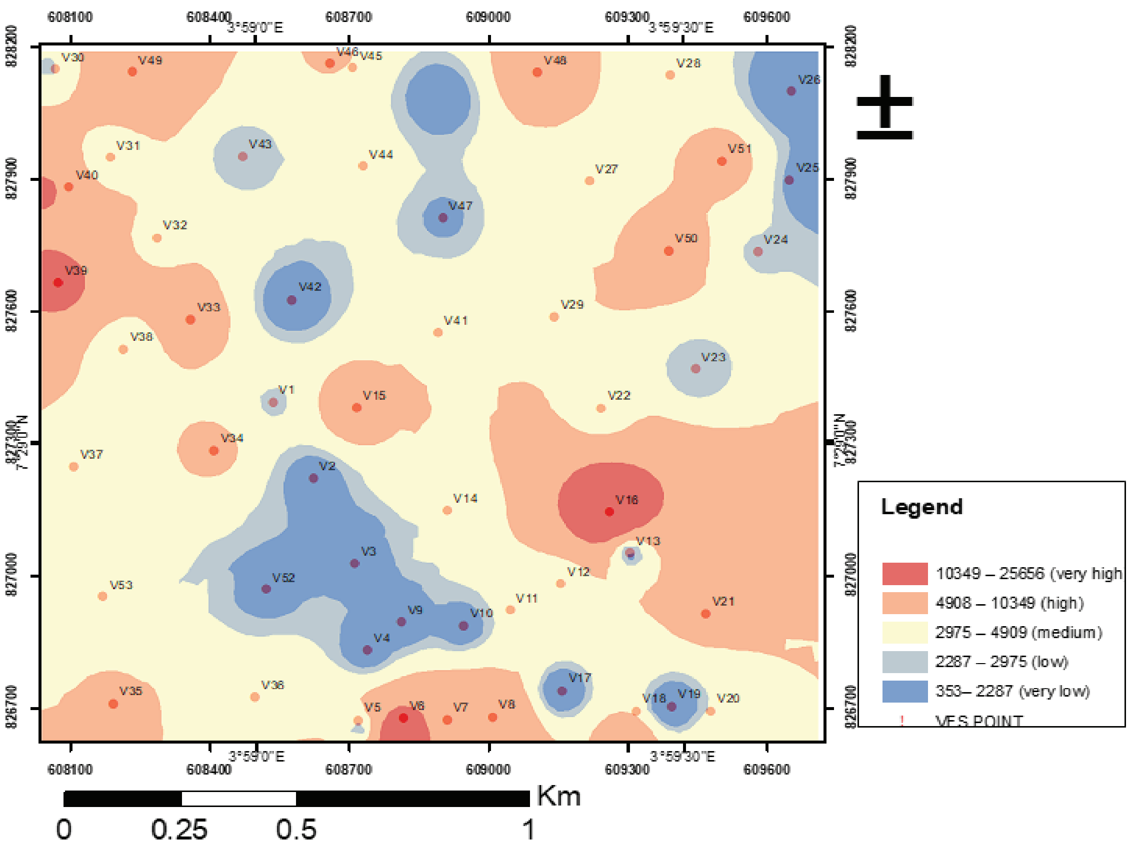

Fig. 4: Total Traverse Unit Resistance (T) Map of the Study Area.

investigated area. These areas are characterized by very low to low groundwater potential zones are found in the west, central – eastern and north eastern part the investigated area (Fig. 3).

Mohammed *et al.* (2012) observed that substantial overburden thickness zones in crystalline rock area are hydrogeological important. This is also regarded as a significant water-bearing layer in Basement complex terrains especially if considerably thick with relatively low resistivity values that suggest saturated condition. One of the cardinal focuses on groundwater assessment in the crystalline rock area is where the overburden and fractured basement aquifers are thick and are complementary or interconnected (Mogaji *et al.,* 2011 and Bayode, 2011*).* However, the weathered layer and the partly weathered/fractured basement constitute the major aquifer unit within the study area. The classification of overburden thickness for weighted analysis was decided based on the classified thickness values. The reclassified overburden thickness map is shown in (Fig. 3). Therefore, the zones that are characterized by medium to very high overburden thickness values can be considered to be of significant hydrogeological importance and are considered as prospective zones for possible location of borehole in the study area.

5.1.3 Total Transverse Unit Resistance (T) Map.

The total transverse unit resistance (T) values were calculated from Equ. (1) and presented in Table 6. The total transverse unit resistance values for the investigated area generally range from 353 - 25656 ohm-m^2 with an average value of 4702 ohm-m^2. The total traverse resistance values obtained in the study area was classified into five zones: very low (353– 2287 ohm- m^2), low (2287 - 2975 ohm-m^2), medium (2975 – 4909 ohm-m^2), high (4909 – 10349 ohm-m^2) and very high (>10349 ohm-m^2). The total traverse unit resistance map of the study area is shown in (Fig. 4). The very low (353– 2287 ohm- m^2) and low (2287 - 2975 ohm-m^2) values of total traverse unit resistance observed in the south, central, north central and northeastern flank of the study area are classified as low groundwater potential zones.

The remaining part of the study area is characterized by medium (2975 – 4909 ohm-m^2), high (4909 – 10349 ohm-m^2) and very high (>10349 ohm-m^2) values of total traverse unit resistance. Hence, this area can be classified as medium to very high groundwater potential zones in the study area. The total traverse unit resistance depicts aquifer productivity since higher borehole/well yield is obtainable in areas with higher saturated aquifer thickness and where resistivity values are moderately low in a typical Basement Complex area (Worthington, 1976).

The total traverse unit resistance is a function of aquifer transmissivity (product of aquifer thickness and hydraulic conductivity). Hence, the total transverse unit resistance (T) is one of the geoelectric parameters used to define target areas of good groundwater potential (Nafez *et al*. 2010). According to Braga *et al*., (2006), it has a direct relationship with transmissivity, where the highest (T) values reflect the most likely highest transmissivity values of the aquifers or aquiferous zone. Moreover, the total traverse unit resistance map show a good correlation with the overburden thickness and total longitudinal unit conductance maps (Fig. 3) generated for the study area.

5.1.4 Total Longitudinal Unit Conductance (S) Map

The total longitudinal unit conductance (S) values was evaluated from Eqn. 2 and presented in Table 6. The total longitudinal unit conductance values obtained for the investigated area generally range from 0.05 – 0.80 mhos with a mean value of 0.26 mhos. The total longitudinal unit conductance map of the study area is shown in (Fig. 5). The longitudinal unit conductance values was classified as very low (0.05 – 0.20 mhos), low (0.20 – 0.33 mhos), medium (0.33 - 0.50 mhos), high (0.5 – 0.65 mhos) and very high (> 0.65 mhos).

In the study area, the north central, northwestern, central and southwestern parts of the area are characterized by medium to very high total longitudinal unit conductance values (medium (0.33 - 0.50 mhos), high (0.5 – 0.65 mhos) and very high (> 0.65 mhos)) respectively while the northeastern, southeastern and a small portion of the southwestern parts are respectively characterized by very low (0.05 – 0.20 mhos) values. The remaining portion of the study area are characterized by low values of 0.20 – 0.33 mhos. The medium to high longitudinal unit conductance values of 0.33 - > 0.65 mhos could be attributed to the presence of linear features (such as fractures, fault and joints) at depth and thick weathered layer zones which are indicative of potential aquifer units in a Basement Complex terrain (Bayode *et al.*, 2006). The Longitudinal unit conductance is a function of hydraulic conductance and permeability i.e. S = KH (where K is the permeability, and H is the thickness of the aquifer unit). Hence, higher values of S correspond to higher permeability of the aquifer unit. Therefore, (S) can be a useful index of groundwater potential zonation because the higher the hydraulic conductance, the higher the porosity of the formation and the higher the permeability.

Therefore, the presence of these zones within the study area suggests moderate to high groundwater potential zones which are considered to be viable zones for groundwater abstraction in the investigated area. The observed regions that are characterized by high longitudinal unit conductance (S) values (> 0.5 mhos) correspond to the region where medium–high thickness values (43.4 m - >56.3 m) are observed in the study area this show a good correlation with the overburden thickness and total transverse resistance maps (Figs. 3 and 4). The total longitudinal unit conductance is a geoelectric parameter that can be used to define target areas for groundwater potential (Worthington, 1976). High values usually indicate relatively thick aquifer subsurface layer succession and should be accorded the highest priority in terms of groundwater potential evaluation (Austin and Gabriel, 2015).

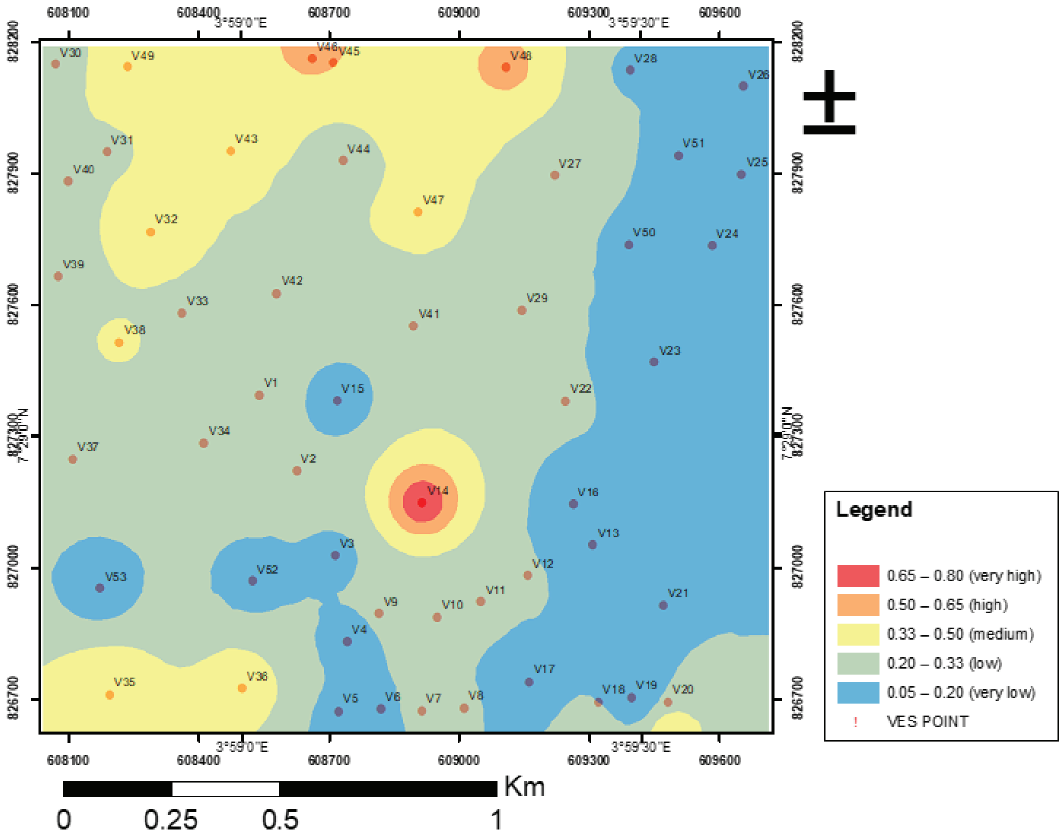

Fig. 5: Total Longitudinal Unit Conductance Map of the Study Area.

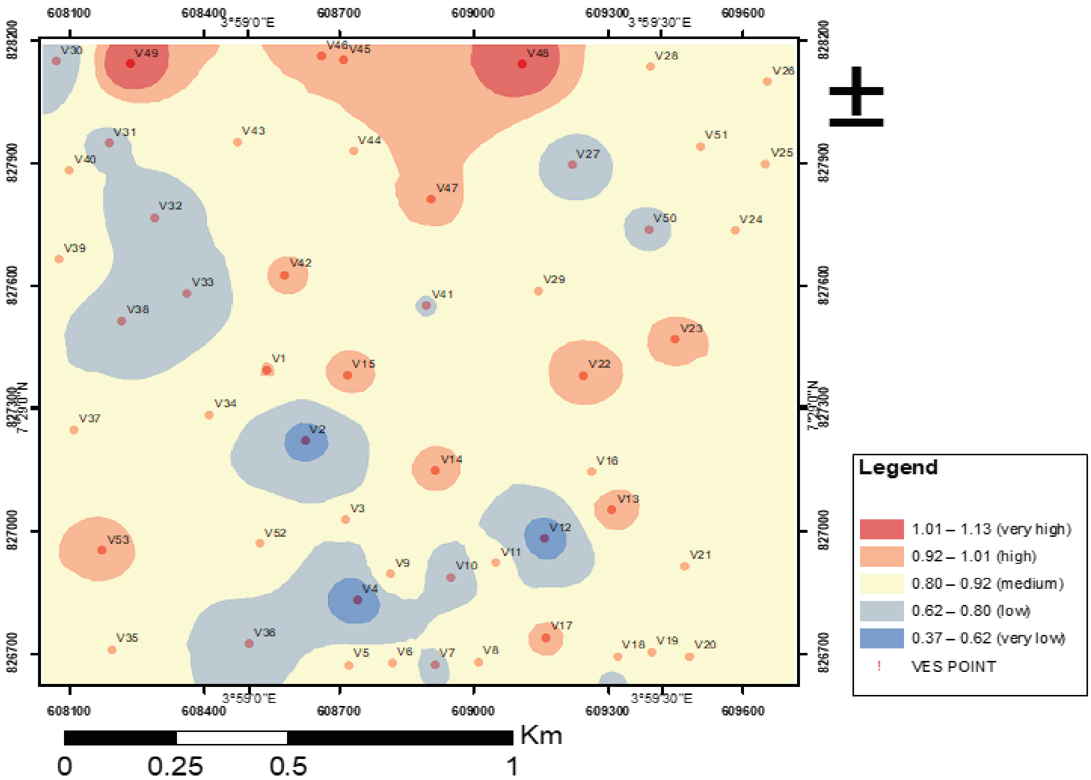

Fig. 6: Coefficient of Anisotropy (λ) Map of the Study Area.

5.1.5 Coefficient of Anisotropy (λ) Map.

The coefficient of anisotropy (λ) is a measure of the degree of inhomogeneity of a medium. Anisotropic values for the study area were calculated using Eqn. 3. The calculated values are presented in Table 6. The coefficient of anisotropy (λ) map is shown in Figure 6. The coefficient of anisotropy values obtained for the investigated area generally varies from (0.37 - 1.13) with a mean value of 0.84. The coefficient of anisotropy generated for the investigated area was classified into five classes: very low (0.37 - 0.62), low (0.62 - 0.80), medium (0.80 - 0.92), high (0.92 - 1.01) and very high (1.01 - 1.13). The areas that are characterized by very low (0.37 - 0.62) and low (0.62 - 0.80) values of λ are found in the south-central, western and northeastern part of the study area (Fig. 6). The medium (0.80 - 0.92) values mainly characterized the major part of the investigated area and are found to be distributed across the entire study area (Fig. 6). The high (0.92 - 1.01) values are also found to cover a small isolated area located in the southwest, southeast, central, northwest and north-central part of the study area (Fig. 6). The very high (1.01 - 1.13) values are found to cover a small area located in the northwest and north central part of the study area.

Generally, groundwater yield increases with increase in the value of the coefficient of anisotropy. This can also be attributed to increase porosity and permeability and hence, indexes of groundwater yield (Olorunfemi *et al*., 1991, Ojo *et al*., 2015). The medium to very high values of λ which range from 0.80 -1.13 are found to be distributed across the entire study area. Although the geology of the area is not mono-lithologic unit but predominantly schist, base on this, the inhomogeneity in the value of the coefficient of anisotropy could be attributed to variance in the parent rock composition and hence, the weathered layer material. The map is found to be in tandem with the overburden thickness map, total longitudinal unit conductance map and total traverse unit resistance map obtained in the study area. The areas classified as low values (0.37 - 0.80) correspond to the areas of low groundwater potential. In the study area, the medium to high (0.80 - 1.13) coefficient of anisotropy (λ) values can be inferred to be characterized by medium to high groundwater yielding capacity.

On the basis of the normalized weighting of the individual features of the thematic layers, the groundwater potential zones were estimated (Table 5). The groundwater potential zone was re-classified into very low (0-1), low (1.1-2.0), medium (2.1- 3.0), high (3.1 – 4.0) and very high (4.0-5.0) (Table 7). The groundwater potential index evaluation (GWPIE) map of the study area (Fig. 7) show that the very low (0 - 1) class index values are not found in any part of the study area. The low (1 - 2) index values are found to occupy a small portion in the southern part of the investigated area (Fig. 7). The medium (2 - 3) values of groundwater potential index evaluation were found to characterize the major part of the study area cutting across every segment of the investigated area (Fig. 7). The high (3 - 4) values of groundwater potential index is found to cover a smaller expanse of the study area located in the southwestern, northwest, and an isolated larger area coverage in the north central part of the investigated area (Fig. 7). The very high (4 - 5) values of groundwater potential index is found to occupy a small area in the northwest and north central part of the study area (Fig. 7).

The groundwater potential index evaluation percentage (%) distribution for the investigated area showed that 98% of the investigated area is characterized by medium to very high values (2 - 5) of groundwater potential index. This suggests that a larger portion of the study area have medium to high hydrogeologic significance. This implies that the study area will likely experience a high success rate of borehole drilled in the investigated area with characteristic medium - high groundwater yielding capacity. A detail observation of the groundwater potential index map shows that the availability of groundwater (high – Very high groundwater potential zones) in the study area is more or less a reflection of the thick overburden thickness of 32.0 – 59.2 m) and relatively high Coefficient of Anisotropy (λ) values.This can be attributed to the moderately thick vertical saturated thickness of the aquifer units with expected higher storage capacity of groundwater in the investigated area.

5.2 Groundwater Potential Zone (Groundwater Potential Index Evaluation (GWPIE) of the Study Area)

On the basis of the normalized weighting of the individual features of the thematic layers, the groundwater potential zones were estimated (Table 5). The groundwater potential zone was re-classified into very low (0-1), low (1.1-2.0), medium (2.1- 3.0), high (3.1 – 4.0) and very high (4.0-5.0) (Table 7). The groundwater potential index evaluation (GWPIE) map of the study area (Fig. 7) show that the very low (0 - 1) class index values are not found in any part of the study area. The low (1 - 2) index values are found to occupy a small portion in the southern part of the investigated area (Fig. 7). The medium (2 - 3) values of groundwater potential index evaluation were found to characterize the major part of the study area cutting across every segment of the investigated area (Fig. 7). The high (3 - 4) values of groundwater potential index is found to cover a smaller expanse of the study area located in the southwestern, northwest, and an isolated larger area coverage in the north central part of the investigated area (Fig. 7). The very high (4 - 5) values of groundwater potential index is found to occupy a small area in the northwest and north central part of the study area (Fig. 7).

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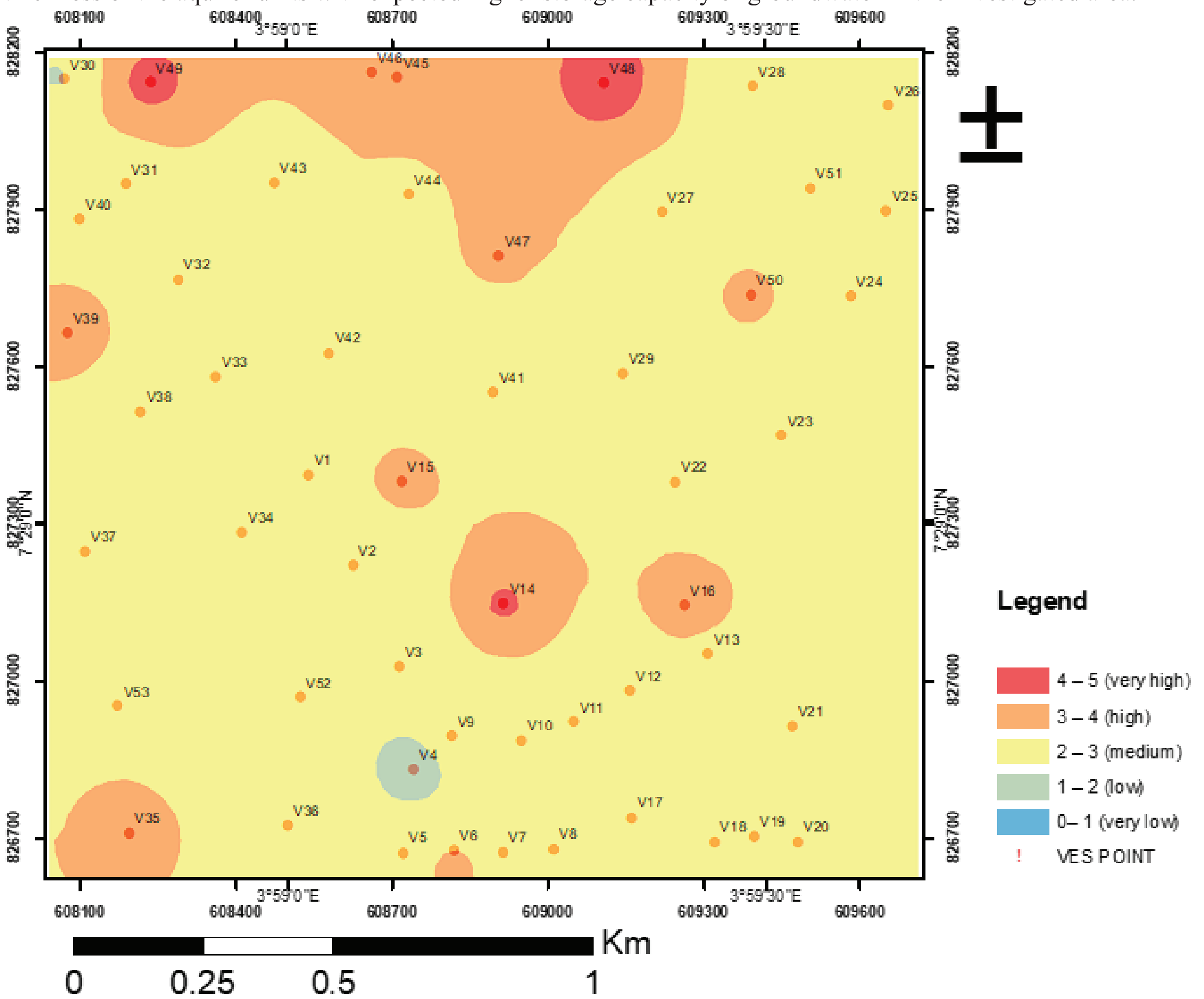


Fig. 7: Groundwater Potential Map of the Study Area.

5.3 Result validation

The predicted map of the groundwater potential zone of the study area is shown in Fig. 7. The accuracy of the predicted groundwater potential zones map thus obtained were validated with the thickness of water column in aquifer units with depth ranging from 5.5 – 14.6 m obtained from twenty-six hand dug wells located across the study area. The thickness of the water column obtained generally range from 0.6 – 1.9 m and it was classified as: low yield (0.5 – 1.0), medium yield (1.0 – 1.5 m) and high yield (1.5 – 2.0 m) (Table 8) while the very low and very high yields potentials (are not available). The validation was carried out by superimposing the expected wells yield data obtained from the thickness of the water column in wells on the prediction map of the study area (Fig. 8); the thickness of the water column in each well was compared with the expected yield at each location on the prediction map. It is observed that high potential zones are located in the north-central to the northwestern, and pockets of occurrence in the east, central, southwestern and southern part of the investigated area. A cross-validation study (Fig. 9) has been carried out to obtained values showing an agreement between the actual and the expected yields for a particular part of the investigated area is presented in Table 9. The cross-validation study is to ensure that the groundwater potential zones correlate with the thickness of water column in the aquifer units and the coefficient of anisotropy (λ) that are indices of expected well yields capacity in the investigated area. With respect to the data collected from the wells, the success rate of the prediction is estimated as follows:

Total number of accessible wells = 26
Number of wells with expected yield classifications = 21
Number of wells without expected yield classifications = 5

$$\text{Prediction Accuracy} = \frac{\text{Number of wells with expected yield classifications}}{\text{Total number of accessible wells}} \times 100\%$$

$$= \frac{21}{26} X\ 100\% = 81\%$$

The results obtained show that the accuracy of the prediction was 81%. This implies that the parameters used for this study have significant effect on the efficiency of Multi-criteria Decision Analysis (MCDA) and it determines the degree of accuracy of the prediction. In furtherance, it establishes the accuracy and the reliability of the set of criteria employed in this study. The well yield of 1.5 – 2.0 capacity is found in the very high potential zone while the medium yield of 1.0 – 1.5 is located in the medium potential zone (Fig. 7).

5.4 Geoelectric Section

Figure 10 show typical depth sounding curves obtained from the study area. Four geoelectric sections were developed across the investigated area. A maximum of five subsurface geologic layers were delineated. These are the top soil, weathered layer, partly weathered/ fractured basement and the fresh basement bedrock.

The first layer is the topsoil. The resistivity values range from 36 - 584 Ωm. The thickness values vary from 0.4 – 1.2 m (Figs. 11 (a-d)). The topsoil is made up of clay, sandy clay, clayey sand and laterite (Figs. 11 (a-d)).

The second layer is the weathered layer. The resistivity values range from 85 - 354 Ωm (Figs. 11 (a-d)). The thickness values vary from 1.4 – 50.9 m. The weathered layer is comprised of clay, sandy clay, clayey sand, sand and laterite.

The third layer is the partly weathered/fractured basement. The resistivity values range from 97 - 236 Ωm while the thickness values vary from 6.2 - 49.5 m (Figs. 11 (a-d)). The partly weathered/fractured basement is made up of partly weathered and fractured basement rock (Figs. 11 (a-d)).

The last layer is the fresh basement bedrock. The resistivity values range from 135 - 1120 Ωm. Depth to basement bedrock range from 5.6 - 59.4 m. The basement topography is gently undulating (Figs 11 (a-d)).

The weathered layer and the partly weathered/fractured basement have hydrogeological significance in the investigated area. The weathered layer generally has resistivity values which range from 33 - 354 ohm-m and thickness values which vary from 1.4 - 50.9 m while the partly weathered/fractured basement layer has resistivity values which range from 51 - 263 ohm-m and thickness which range from 6.2 - 49 m. The weathered and the partly weathered/fractured basement layer constitute the main target for groundwater development in the investigated area.

Table 8: Classification of Groundwater Potential Zones

Potential Yield Zone	Groundwater Column Thickness (m) Classification	Yield classification
Very high	NA	NA
High	1.5 – 2.0	1.5 – 2.0
Medium	1.0 – 1.5	1.0 – 1.5
Low	0.5 – 1.0	0.5 – 1.0
Very low	NA	NA

* NA = Not Available

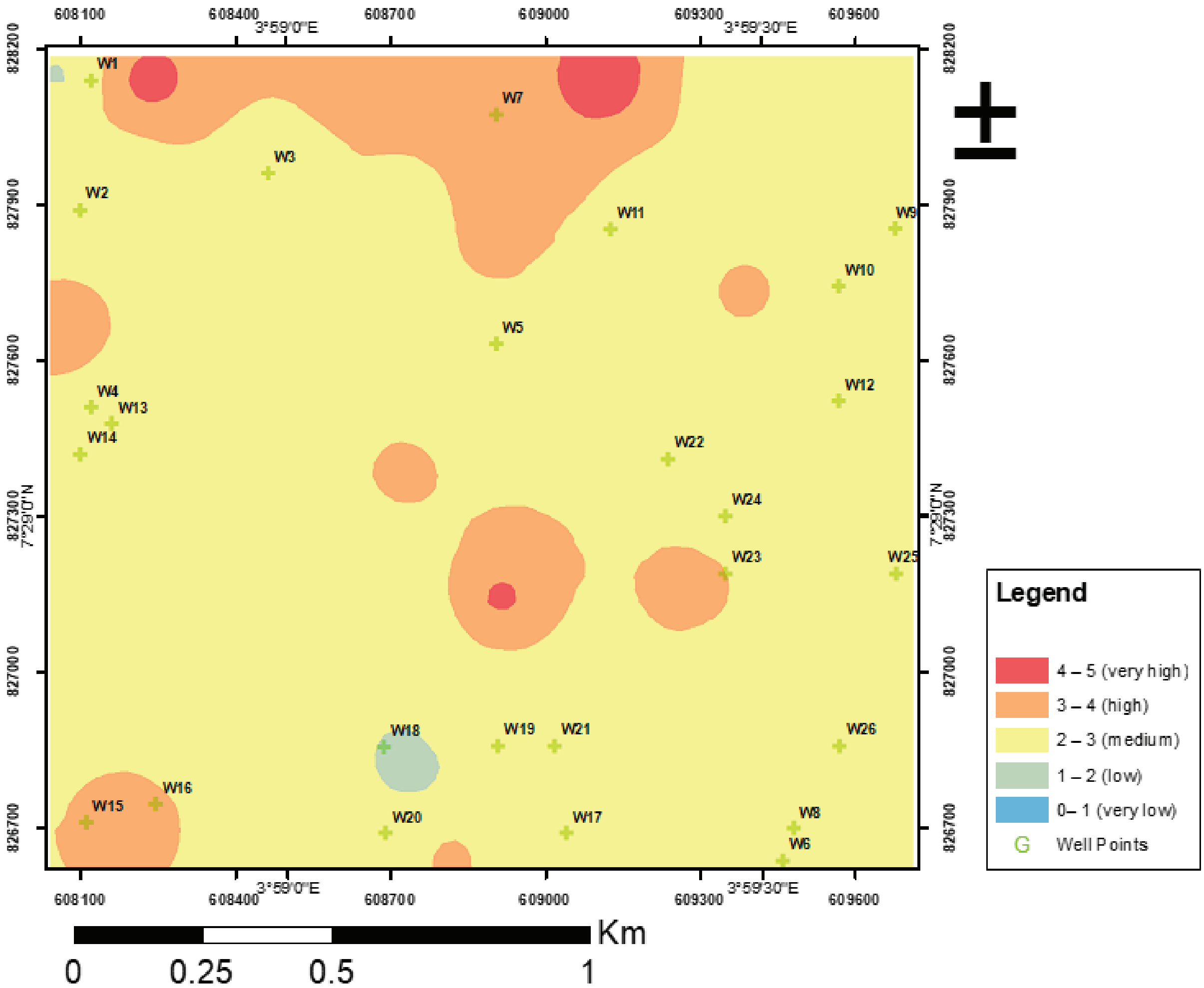


Fig. 8: Groundwater Prediction Validation Map using Thickness of Water Column in Aquifer Units in the Study Area.

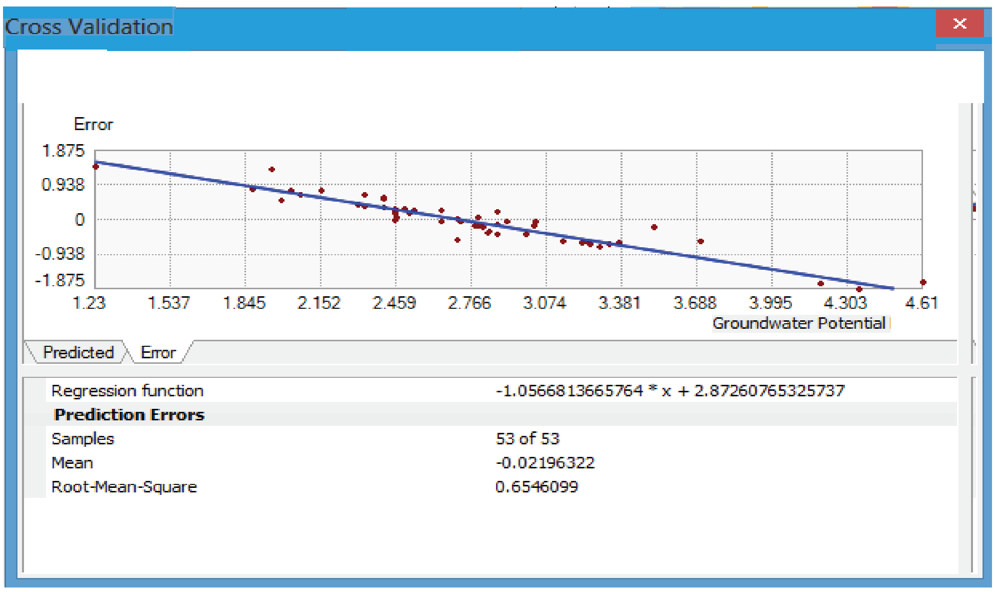
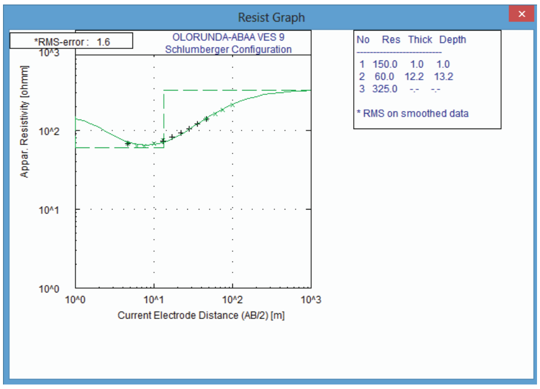


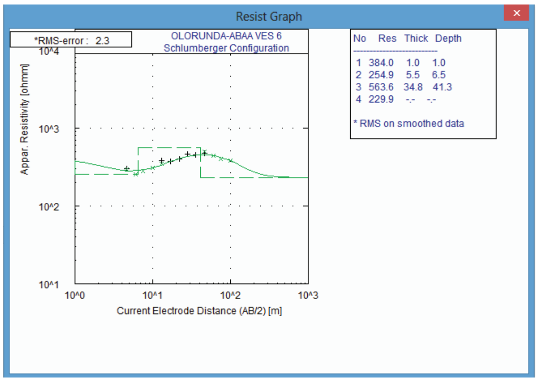
Fig. 9: Cross Validation Prediction Error for Groundwater Potential of the Study Area.

Table 9: Validation of Wells Data Used for the Development of Groundwater Potential Map.

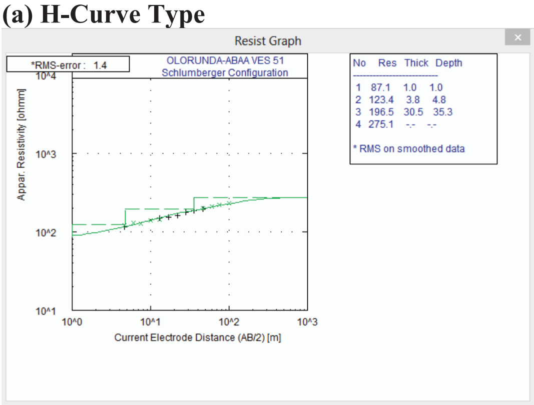
Well Numbers	Total Well Depth (m)	Static Water Level (m)	Groundwater Column Thickness (m)	Expected Yield from Groundwater Potential Map	Actual Yield from the wells	Remarks
1	12.3	10.9	1.4	Medium	Medium	Coincide
2	14.6	13.8	0.8	Medium	Low	Not Coincide
3	12.8	11.5	1.3	Medium	Medium	Coincide
4	10.3	8.9	1.4	Medium	Medium	Coincide
5	11.8	10.6	1.2	Medium	Medium	Coincide
6	9.6	8.3	1.3	Medium	Medium	Coincide
7	12.4	10.5	1.9	High	High	Coincide
8	6.7	5.9	0.8	Medium	Low	Not Coincide
9	9.0	7.9	1.1	Medium	Medium	Coincide
10	7.2	6	1.2	Medium	Medium	Coincide
11	8.7	7.3	1.4	Medium	Medium	Coincide
12	9.6	8.5	1.1	Medium	Medium	Coincide
13	12.5	11.2	1.3	Medium	Medium	Coincide
14	11.9	10	1.0	Medium	Medium	Coincide
15	5.5	4.9	0.6	Medium	Low	Not Coincide
16	6.1	5	1.1	Medium	Medium	Coincide
17	8.7	7.4	1.3	Medium	Medium	Coincide
18	6.6	5.3	1.3	Medium	Medium	Coincide
19	7.1	6.2	0.9	Medium	Low	Not Coincide
20	8.2	7.4	0.8	Medium	Low	Not Coincide
21	9.7	8.3	1.4	Medium	Medium	Coincide
22	10.5	9.3	1.2	Medium	Medium	Coincide
23	11.1	10	1.1	Medium	Medium	Coincide
24	10.5	9.1	1.4	Medium	Medium	Coincide
25	11.2	9.9	1.3	Medium	Medium	Coincide
26	10.9	9.8	1.1	Medium	Medium	Coincide



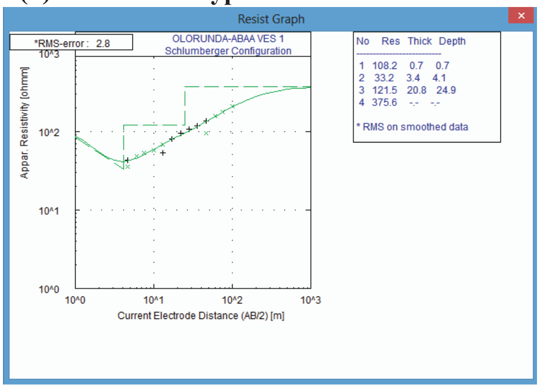
(a) H-Curve Type



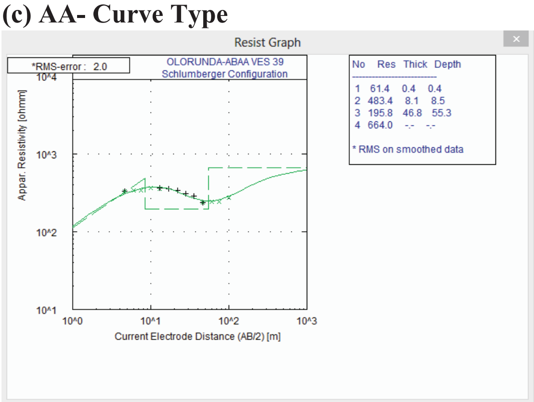
(b) HK- Curve Type



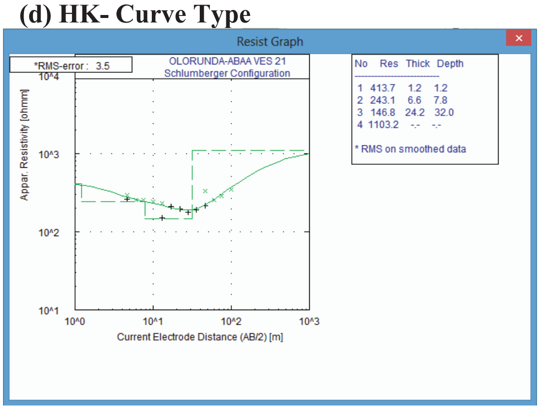
(c) AA- Curve Type



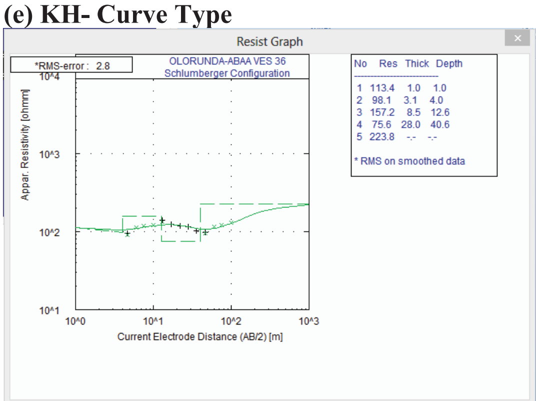
(d) HK- Curve Type



(e) KH- Curve Type



(g) QH- Curve Type



(h) HKH- Curve Type

Fig. 10: (a – h): Typical Depth Sounding Curves Obtained from the Study Area.

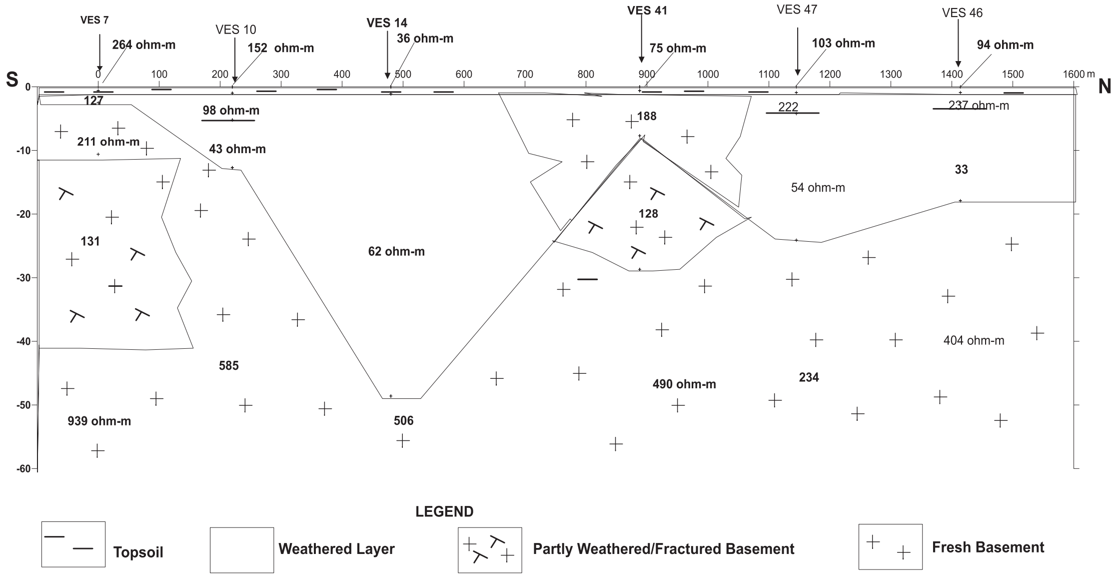


Fig. 11a: Geoelectric Section along Traverse One (TR 1).

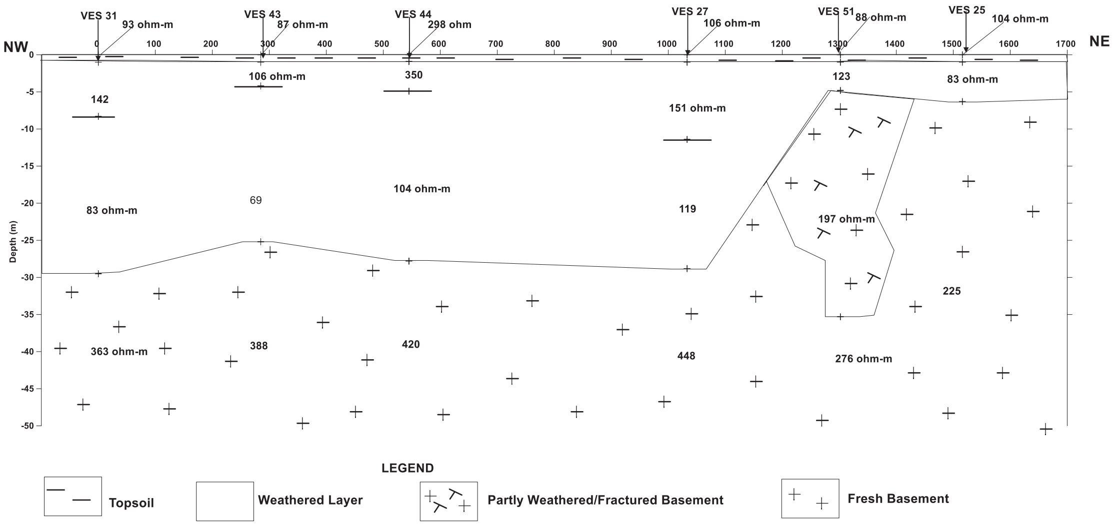


Fig. 11b: Geoelectric Section along Traverse Two (TR 2).

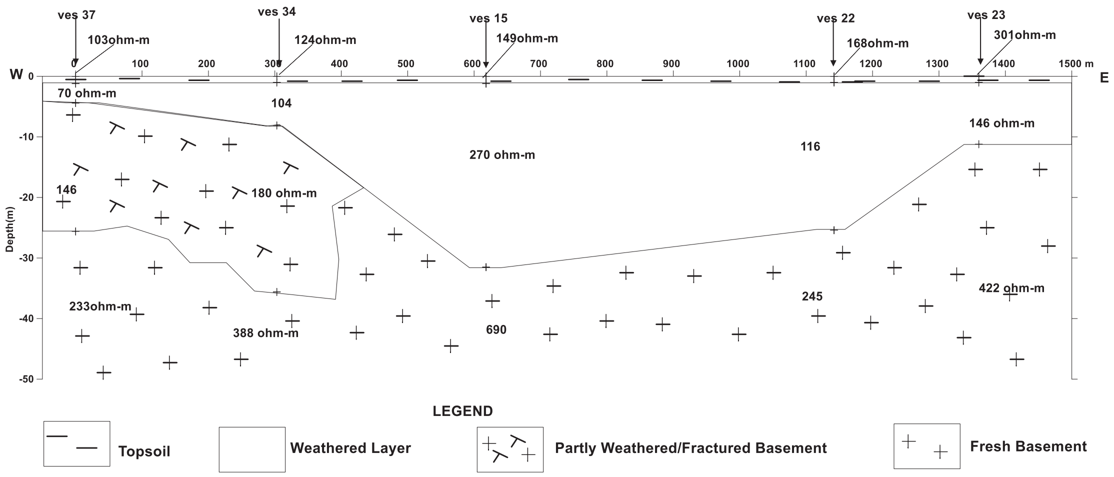


Fig. 11c: Geoelectric Section along Traverse Three (TR3).

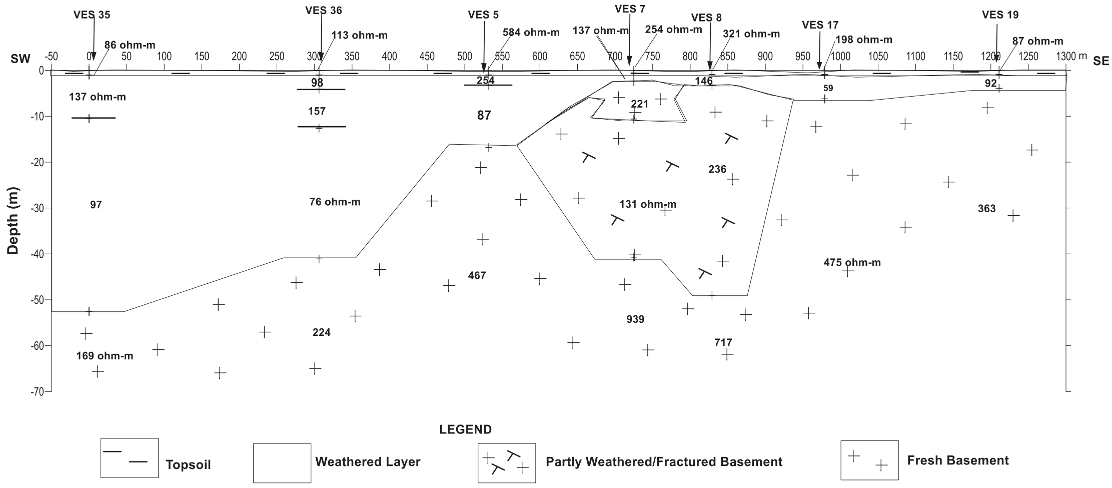


Fig. 11d: Geoelectric Section along Traverse Four (TR 4).

6. Conclusions

The application of GIS tool, geophysics, hydrogeology and Multi-Criteria Decision Analysis (MCDA) using Analytic Hierarchy (AHP) technique has been relied upon for delineation of groundwater potential zones in Olorunda-Abaa Area, Ibadan, Southwestern Nigeria. This study was used to determine the groundwater potential zones by analyzing five different hydrogeological factors influencing groundwater occurrence in the study area. The geological and geophysical factors such as Geology, Overburden Thickness, Total Traverse Unit Resistance, Total Longitudinal Unit Conductance and Coefficient of Anisotropy (λ) were identified as the major contributing factors to groundwater potentiality in the investigated area. The area occupied by migmatite gneiss rock unit was considered to have greater storage capacity due to higher sand fraction in the weathered product than the undifferentiated schist and gneiss that are characterized with higher clayey fraction. Areas with moderate to thick overburden thickness were considered to be characterized by high groundwater potential in a typical basement complex terrain like the investigated area. High Coefficient of Anisotropy (λ) which is a measure of groundwater yield also played a significant role in the location of high potential zones for groundwater occurrence in the study area. Areas with low groundwater potential zones are mainly characterized by very low – low Total Traverse unit Resistance, Total Longitudinal Unit Conductance and Coefficient of Anisotropy (λ). The geoelectric sections delineated four major subsurface geological units consisting of the topsoil, weathered layer, partly weathered/fractured basement and the fresh bedrock in the investigated area. The respective range of resistivity values are 36 - 584 Ωm, 85 - 354 Ωm, 97 - 236 Ωm and 135 - 1120 Ωm. while the thickness values vary from 0.4 – 1.2 m, 1.4 – 50.9 m and 6.2 - 49.5 m respectively. Depth to basement bedrock generally ranges from 5.6 - 59.4 m.

Geology, Overburden Thickness, Total Traverse Resistance, Total Longitudinal Unit Conductance and Coefficient of Anisotropy (λ) were observed to contribute 6%, 8%, 15%, 26% and 46% respectively to groundwater potential in the study area. These influencing factors were used to develop five thematic layer maps that were relied upon to classify the study area into very low (0 - 1), low (1 - 2), medium (2 - 3), high (3 - 4) and very high (4 - 5) groundwater potential zones.

The groundwater potential zones evaluation percentage (%) distribution for the investigated area reveals that 98% of the investigated area is characterized by medium to very high values (2 - 5) of groundwater potential zones. This suggests that a larger portion of the study area have medium to high potential hydrogeologic significance. The groundwater potential map generated for the study area show that the low groundwater potential zone is indicative of the least favorable region for groundwater development while the medium to very high groundwater potential zones indicates the favourable area where groundwater development is feasible in the study area. The developed potential map can serve as the basis of information to private, local authorities and other interested groundwater planners on suitable location and development of potable water in the investigated area.

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