Asian Journal of Advanced Research and Reports

1(2): 1-11, 2018; Article no.AJARR.42166

Modeling of Groundwater Potential Using Vertical Electrical Sounding (VES) and Multi-caterial Analysis at Omitogun Housing Estate, Akure, Southwestern Nigeria

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Authors' contributions

This work was carried out in collaboration between all authors. Author ISO designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors AAB and OFE managed the analyses of the study. Author ISO managed the literature searches. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/AJARR/2018/v1i213043
Editor(s):
(1) Longan Shang, Professor, School of Biotechnology and Chemical Engineering, Ningbo Institute of Technology, Zhejiang University, Zhejiang, PR China.
Reviewers:
(1) Musa Garba Abdullahi, Yusuf Maitama Sule University, Nigeria.
(2) Yusuf Tanko Usman, Niger State College of Agriculture, Nigeria.
Complete Peer review History: http://www.sciencedomain.org/review-history/25036

Original Research Article

Received 23rd March 2018
Accepted 2nd June 2018
Published 7th June 2018

ABSTRACT

A geoelectric investigation of groundwater prospect at Omitogun Estate, along Benin/Ilesha express way Akure, within the basement complex of southwestern Nigeria was carried out with a view to providing information on the geoelectric characteristic of the subsurface sequence, bedrock topography, subsurface structural features and their hydrogeologic significance, in order to identify aquifer units and determine possible areas for groundwater potential zones. The study involved the use of Schlumberger vertical electrical sounding data at thirty (30) stations. The vertical electrical sounding data presented as field curves were interpreted quantitatively by partial curve matching method and computer iteration technique. Fracture resistivity map, aquifer resistivity map, aquifer thickness map and overburden thickness map were generated from the results. Groundwater potential map was also generated from the integration of these maps using multi-criteria decision

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analysis (MCDA). The study area has been classified into low, medium, high groundwater potential zones and the results from well data across the entire study area were used to validate the accuracy of the groundwater potential map. From the results obtained, it could be concluded that the study area is generalized to be of low groundwater potential.

Keywords: Aquifer resistivity; aquifer thickness; overburden thickness; MCDA and fractured resistivity.

1. INTRODUCTION

Communities located on Basement Complex terrains commonly have problems of potable groundwater supply due to the crystalline nature of the underlying rocks which lack primary porosity. Groundwater storage capacity in those areas is dependent on depth of weathering and intensity of fracturing of the underlying rocks [1]. For Basement Complex rocks to become good aquifers, they must be highly fractured and/or deeply weathered. Thickness of the weathered overburden and fracture zone determines the nature and intensity of hydrodynamic activities within the usually-discrete bodies of aquifers in the terrain. The discontinuous nature of the basement aquifer systems makes detailed knowledge and application of the geological, hydrogeological and geophysical investigations inevitable [2,1]. Hydrogeophysical has emerged over the years as one of the dominant sub-disciplines in near surface geophysics [3]. This worldwide geosciences discipline is ripe with research opportunities and abundance of potential applications. Maintaining and protecting current water supplies and developing new sources of clean water are essential as modern society expands and civilization continues to develop. Water is essential for life. It had been and will continue to be a hot topic in both the political and scientific arenas for years to come [3]. Development of new supplies of potable water will be essential for the prosperity of many communities as demand steadily increases and known supplies of water dwindle. Expansion of population densities requires greater volume of fresh water and at the same time emphasizes the need to protect and sustain known supplies and sources [1]. With advances in technology over the last decade has come an exponential increase in the potential number and diversity of viable geophysical applications in the water science. Both surface and borehole geophysical methods have been utilized with great success [3].

This research work focuses on the use of surface geophysical method involving electrical resistivity for hydrogeological studies. Electrical resistivity methods can give information at locations where neither gravity nor magnetic anomalies can exist for horizontal bedding. Further, the electrical resistivity methods can be used where structure is not complicated; apparent resistivity can be estimated with minimum error [1]. Although, the apparent resistivity is diagnostic to some extent of the actual resistivity of a zone in the vicinity of the electrode array, the apparent resistivity reflects the true resistivity only in a homogeneous ground. These resistivities are controlled among others by the bulk resistivity of the subsurface rocks (ρ_b) and the pore water resistivity (ρ_w) as obtained from [4] where Formation factor, F, is determined as:

$$F = \rho_b/\rho_w \quad (1)$$

In hard rock environment, it is not sufficient to consider only the weathered layer. Deep saturated fractures in bedrock are also potential targets of groundwater exploration. The electrical resistivity methods like vertical electrical sounding (VES) and profiling are widely used for this purpose. Also, vertical or sub vertical localized fractures can be located at larger depths using the conventional electrical methods [5]. The direct current (DC) resistivity method for conducting a VES is effectively used for groundwater study due to the simplicity of the technique, easy interpretation and the rugged nature of the associated instrumentation. The technique is widely used in soft and hard rock areas and previous study using this technique includes [6,7,8,9,10,11,1]. Multi criteria decision analysis (MCDA) is the general field of study that includes decision making in the presence of two or more conflicting objectives and/or decision analysis processes, involving two or more attributes [12] cited in [13,1]. The pairwise comparison method was introduced by Fechner in 1860 [14] and developed by Thurstone [15]. Based on pairwise comparison, the analytic hierarchy process (AHP) was developed as a method for multi-criteria decision-making [16]. AHP is a powerful and flexible weighted scoring decision making process to help people set priorities and make the best decision [17]. In the pairwise comparison method, criteria and alternatives are presented in pairs of one or more referees (e.g. experts or decision makers). It is necessary to evaluate individual alternatives, deriving weights for the criteria, constructing the overall rating of the alternatives and identifying the best one. Generally, the implementation of AHP is based on experience and knowledge of the experts or users to determine the factors/criteria affecting the decision process [17]. Apart from its capability to capture both subjective and objective evaluation measures, AHP also provides a useful mechanism for checking the consistency of the evaluation measures and alternatives suggested by experts or decision makers, thus reducing bias in decision-making [17]. The advantages of using AHP include achieving higher quality product and shorter product development process. MCDA has been applied to various domains of researches which include but not limited to: tourism [18]; agriculture [19]; technology [20] and [17]; and groundwater resources exploration and management [13]. The present study is to determine the geoelectric parameters in evaluating the groundwater potential of the study area. The groundwater stored is referred to as an aquifer. An aquifer has ability to store and transit water.

1.1 Study Location and Geology

The area investigated lies within the Akure metropolis along Benin/Ilesha express way southwest Nigeria (Fig. 1), located on latitudes 7°14'27. 97''N to 7°14'50.64''N and longitudes 5°10'5.03"E and 5°10'27.95"E. that is, (805100 to 805900 northings and 740200 to 740600 eastings) using the Universal Traverse Marcartor (UTM). Major and minor road linkages characterize the study area. The area of investigation falls in hard rock terrain and it is underlain by the Precambrian crystalline rocks typical of the Nigeria basement complex. The crystalline rocks are porphyritic granite, migmatite gneiss, biotite granite, charnokites, granite gneiss, pelitic schist, and quartzites, which has been reviewed by workers like [12,15, 21]. The dominant rock type is migmatite gneiss (Fig. 2).

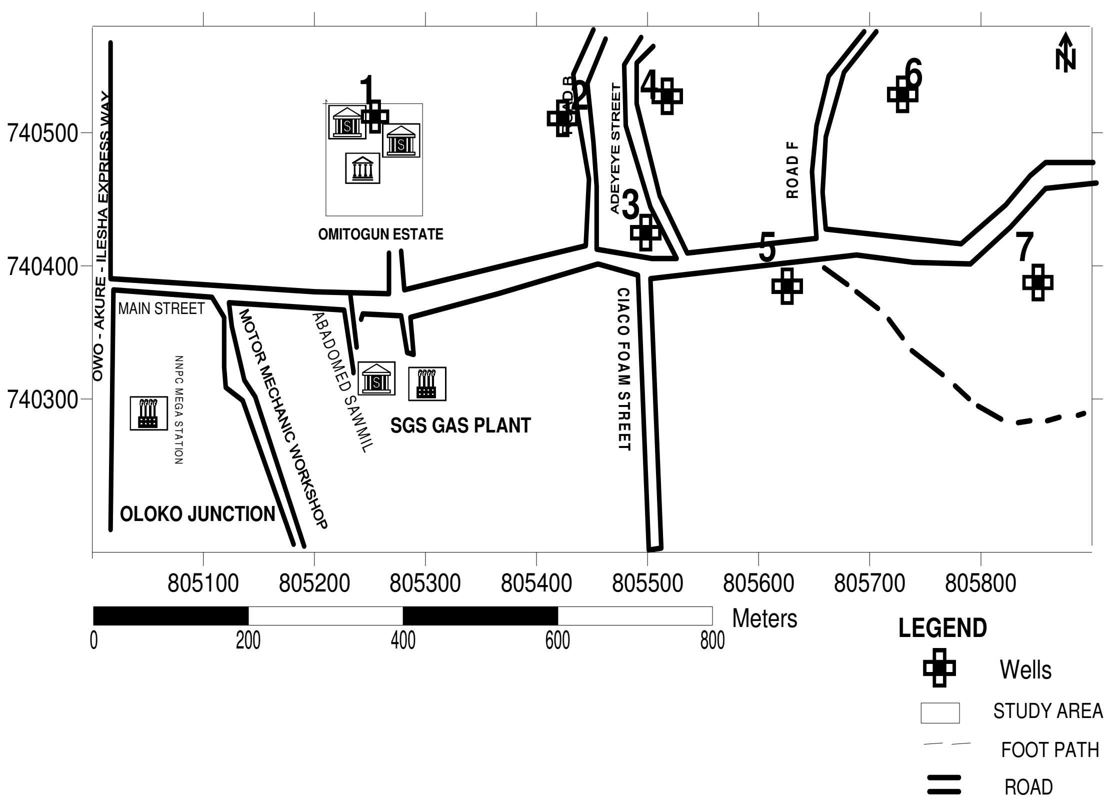

Fig. 1. Location map of the study area

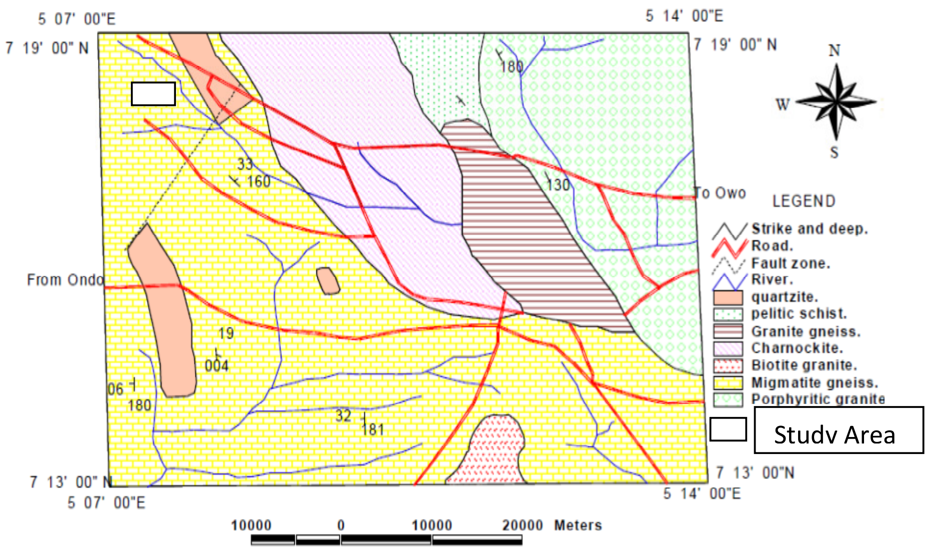

Fig. 2. Geological Map of Akure and Environ showing the Study Area [22]

2. METHODOLOGY

The field survey involves the generation of the base map and establishment of geophysical traverses in the study area, using the GPS and the "SURFER 10" software; electrical resistivity data collection using the Omega Resistivity meter and its accessories respectively. The vertical electrical sounding data were presented as geoelectric sounding curves and the sounding curves were interpreted qualitatively and quantitatively. The qualitative interpretation involved the visual inspection of the profiles and curves for anomalies typical of fractures and severe weathering zones, using two layer Schlumberger master curves and auxillary K, Q, A and H curves. The layer resistivities and thicknesses obtained were utilized for computer iterations using "RESIST^{TM} Software. The quantitatively interpreted sounding curves gave interpreted results as geoelectric parameters (that is, layer resistivity and layer thickness). The choice among a set of zones for evaluation of groundwater potentiality has been based upon multiple criteria such as aquifer resistivity map, aquifer thickness map, fractured resistivity map and overburden thickness map. The process is known as Multi-Criteria Evaluation (MCE). For a Multi-criterial Modelling, firstly a template has been created by identifying the quadtrees used in the analysis. The number of input quadtrees that can be selected is reduced to one less than the total number. A default weight is calculated by dividing 100 by the number of quadtrees used in the overlay and is assigned to each quadtree class. Each class is labeled with the short legend title taken from the input quadtree. Different categories of derived thematic maps have been assigned scores in a numerical scale of 1 to 3 depending upon their suitability to holding capacity of groundwater. A summation of these values led to the generation of final weight map.

Mathematically, this can be defined as:

$$GW = f(AR, AT, FR, OT \quad (2)$$

Where, GW is groundwater, AR is aquifer resistivity, AT is aquifer thickness FR is fractured resistivity and OT is the overburden thickness. The groundwater potential map value, thus derived is given by equation:

$$GWPI = \sum W_i CV_i \ ; \quad \text{with} \sum W_i = 1 \quad (3)$$

Where, $GWPI$ is the groundwater potential map value index. W_i is the probability value of each thematic map, and CV_i is the individual capability value to hold groundwater.

3. RESULTS AND DISCUSSION

3.1 Fractured Resistivity Map

The fractured resistivity map (Fig. 3) shows resistivity distribution ranging from 250Ωm to 1000Ωm. the fracture shows a relatively high resistivity in the northeastern part. This fracture could be a good prospect for groundwater development if the supposed aquifer units are not clayey and the overburden thickness is sufficiently thick.

3.2 Aquifer Resistivity and Thickness Map

The aquifer resistivity map (Fig. 4) generated shows that aquifers with relatively low resistivity values are found around northeastern, southeastern, southwestern and central parts while moderate and high values are restricted to some part of central portion and northwestern portions of the study area. Fairly thick aquifer units are found at eastern, southwestern and northwestern portion of the study area (Fig. 5). These areas of moderate to high aquifer resistivity and moderate to high thickness aquifer are relatively good prospects for groundwater development.

3.3 Overburden Thickness Map

The overburden thickness in the study area is assumed to include the topsoil, the weathered layer and the fractured basement. Hence, the established depths to bedrock beneath all the VES stations were contoured to produce the overburden thickness map (Fig. 6). The overburden thickness varies from 3m to 23m. The map shows areas of relatively thick overburden (above 19m) in the northeastern part which correlate with area of high fractured resistivity. These areas correspond to basement depression which is groundwater convergent zones. Hence, they are relatively good prospects for groundwater development. The relatively thin overburden (less than 11m) corresponding to basement highs. Groundwater flow pattern is from the basement highs to the basement depression.

3.4 Well Data

3.4.1 <u>Well data and their depth in the study area</u>

The bar chart plot of well data of drilled groundwater holes and their respective depth carried out in some areas within the study area are presented in Fig. 7. It displays that the depth and static water level of these wells vary within the area considered; hence the same can be cited for other areas within the study area. Their values range from 4.8m m to 10.2m for the depth and 2.4m to 5.4m for static water level (Table 1). The well (1) have the higher groundwater level thickness and depth which implies that the area have high groundwater potential compared to other areas in the study area. This result also correlates well with the geophysical investigation.

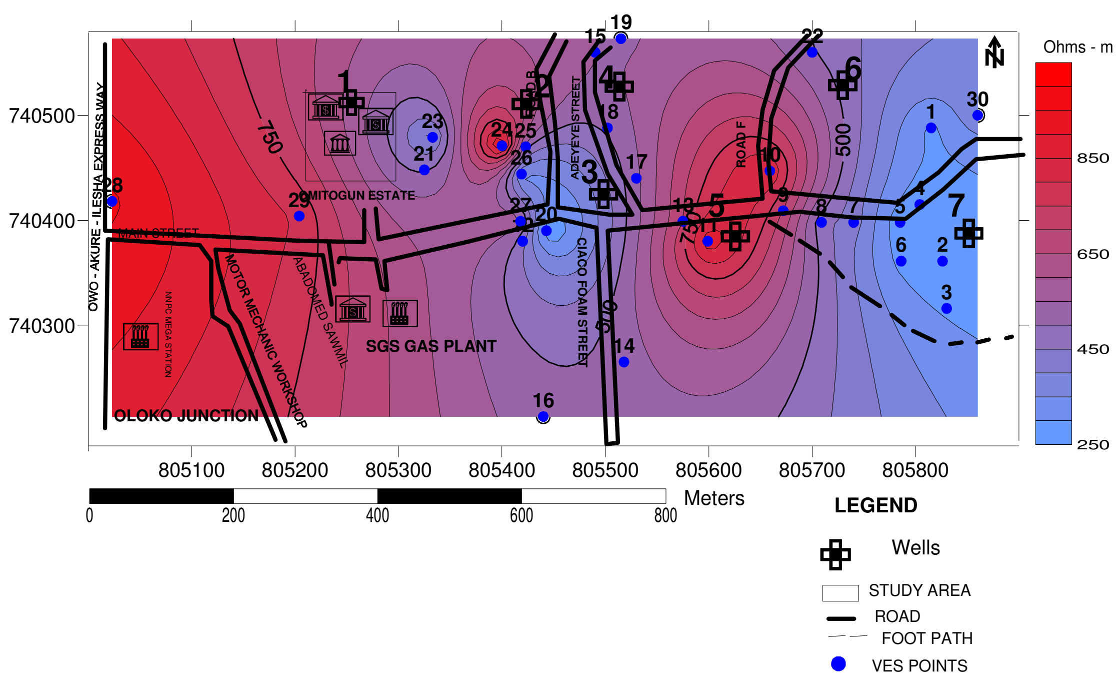

Fig. 3. Fractured resistivity map

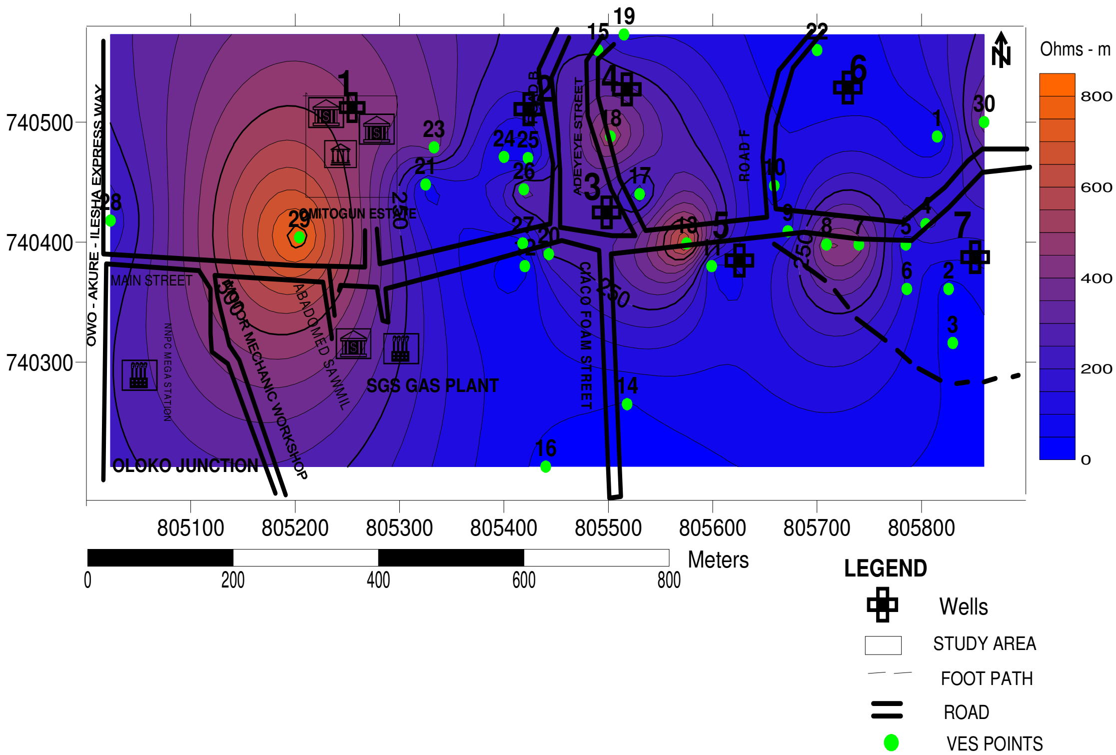

Fig. 4. Aquifer resistivity map of the study area

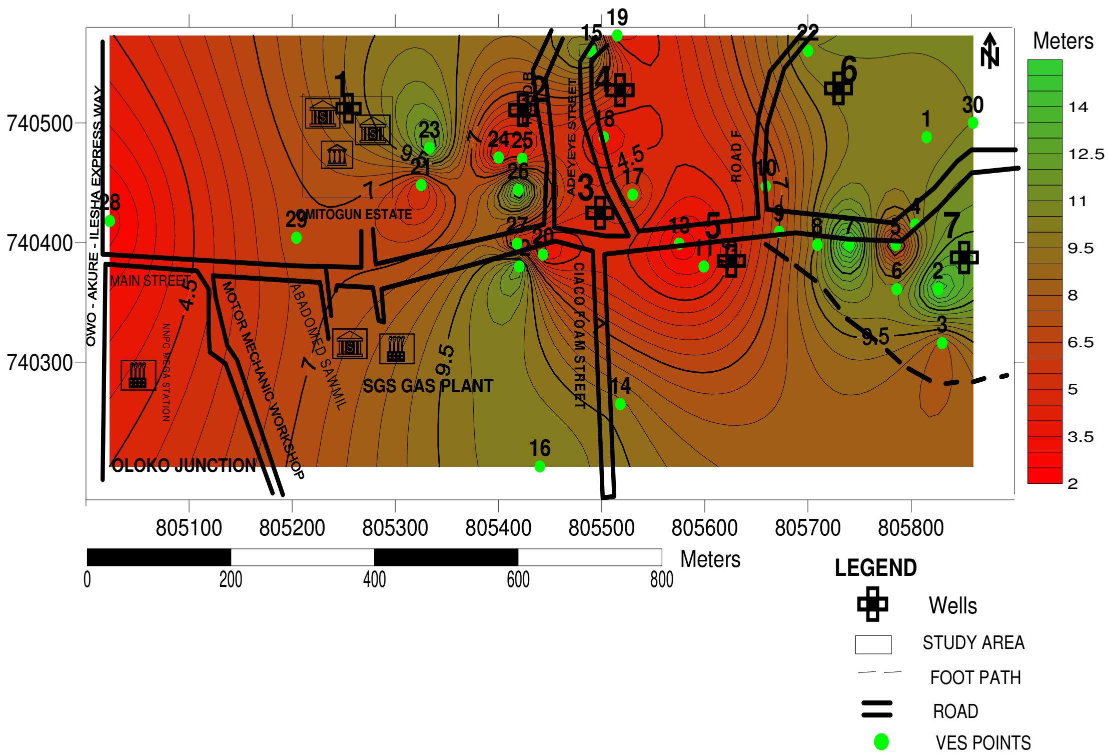

Fig. 5. Aquifer thickness map of the study area

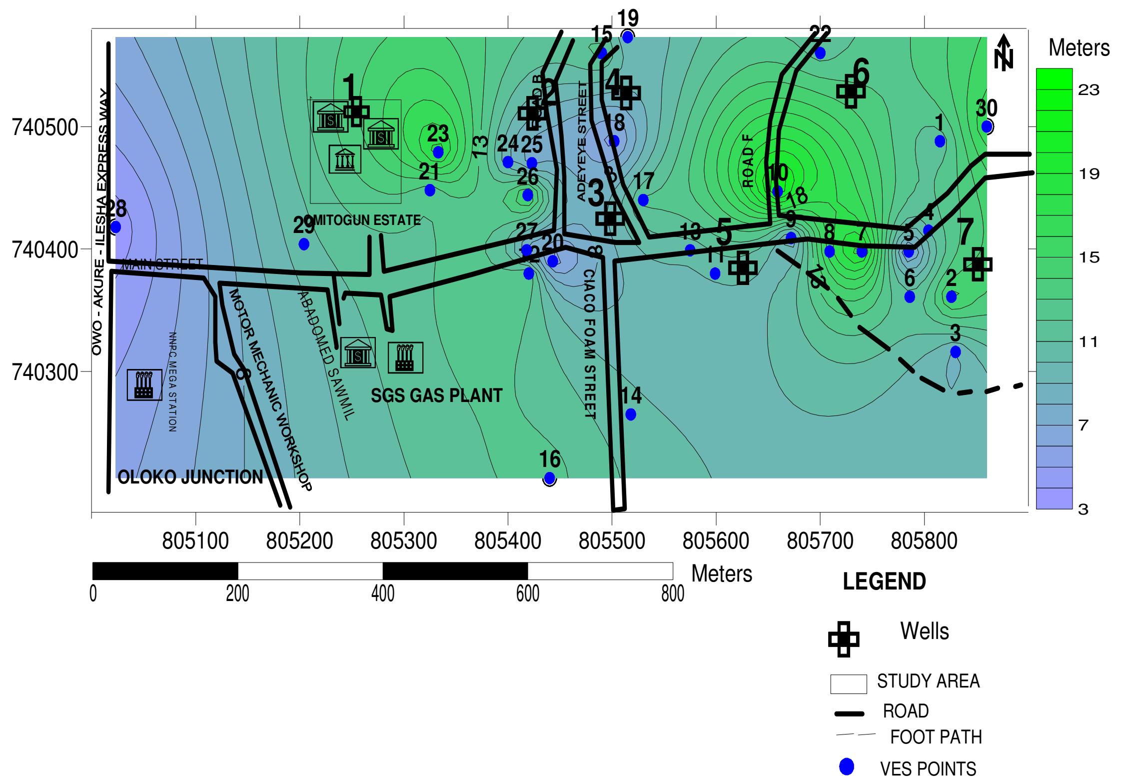

Fig. 6. Overburden thickness map of the study area

3.5 Modeling of Groundwater Potential Map

The groundwater potential map (Fig. 8) was generated by integration of the aquifer resistivity, aquifer thickness, fractured resistivity and overburden thickness using multi-criteria evaluation techniques. The groundwater potential rate (R) gives the ranges of groundwater storage potentiality within each parameter. Each parameter was classified and rated. However, since resistivity and thickness do not have the same units, a unified scaling technique was adopted in rating these parameters according to their degree of influence on groundwater occurrence. Different types of lithology with different resistivity and thickness ranges will have different groundwater prospect. Therefore, different range of values or features should have a different rating (R) in a scale according to its importance in accumulating groundwater. In this study, each parameter has been scored in the 1–3 scale in the ascending order of hydrogeologic significance. However, the resistivity range of any given rock type is wide and overlaps with other rock types. Therefore, different types of lithology may have same resistivity values. The integration of the aquifer resistivity, aquifer thickness, fractured resistivity and overburden thickness in the area were considered to obtain the classifications and ratings shown in Table 2.

The weighted linear combination (WLC) was applied according to the following equation to estimate the groundwater potential index values (GWPI). This technique is usually specified in terms of normalized weightings (w) for each criterion as well as rating scores (R) for all classes relative to each of the criteria. The final utility GWPI for each option O_i is then calculated as follows:

$$GWPI = W_i R_i \tag{4}$$

where w_i is the weight (w) of parameter i and R_i is the rating score (R) of parameter i (Table 2).

Therefore, the groundwater potential index (GWPI) for each VES locations was computed using

$$GWPI = AR_W AR_R + AT_W AT_R + OT_W OT_R + FR_W FR_R \tag{5}$$

The subscripts w and R indicate weights and ratings for each parameter, respectively.

The groundwater potential index values obtained for each location was interpolated, using surfer 10 software to produce the groundwater potential map shown in Fig. 8 and the zones are summarized in the Table 3. It was observed in some part of northwestern and a small closure at the eastern parts are indicative of high

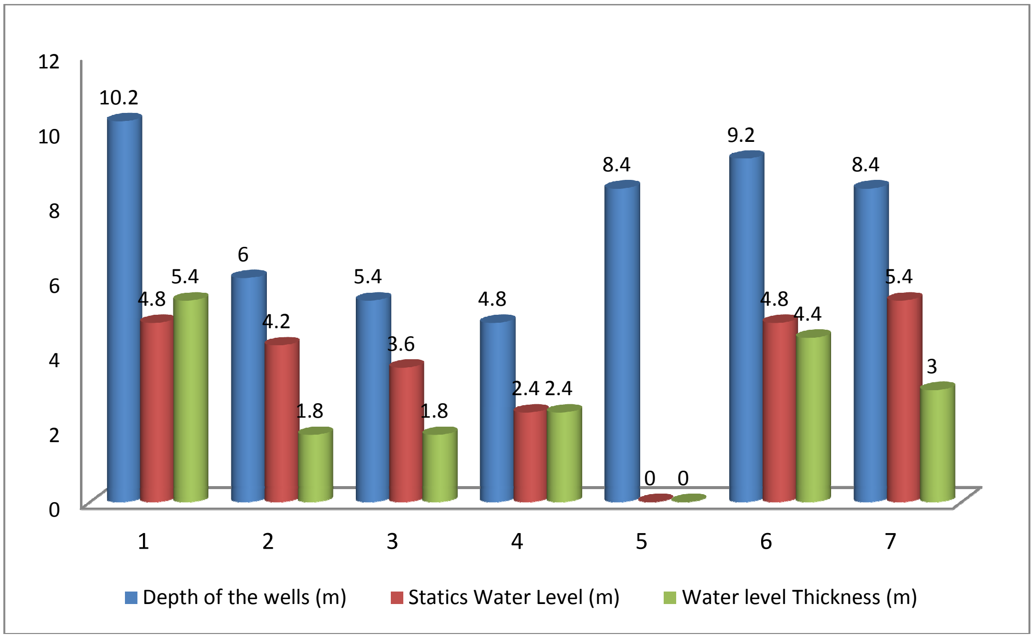

Fig. 7. Bar chart plot of well data and their depth of the study area

Table 1. The well data in the study area

No of Wells	Depth (m)	Static water level (m)	Groundwater column thicknesses (m)
1	10.2	4.8	5.4
2	6	4.2	1.8
3	5.4	3.6	1.8
4	4.8	2.4	2.4
5	8.4	Dry	-
6	9.2	4.8	4.4
7	8.4	5.5	3

Table 2. Probability rating (R) for classes of the parameters

Influencing Factors	Category (classes)	Potentiality for groundwater storage	Rating (R)	Normalised Weight (W)
Aquifer Resistivity (AR)	20 – 100	Low	1	0.22
	100 – 200	High	3	
	200 – 700	Moderate	2	
Aquifer Thickness (AT)	2 – 6	Low	1	0.21
	6 –10	Moderate	2	
	10 – 16	High	3	
Fractured Resistivity (FR)	250 – 450	High	3	0.33
	450 – 800	Moderate	2	
	800 – 1000	Low	1	
Overburden Thickness (OT)	3 – 11	Low	1	0.24
	11 – 19	Moderate	2	
	19 – 24	High	3	

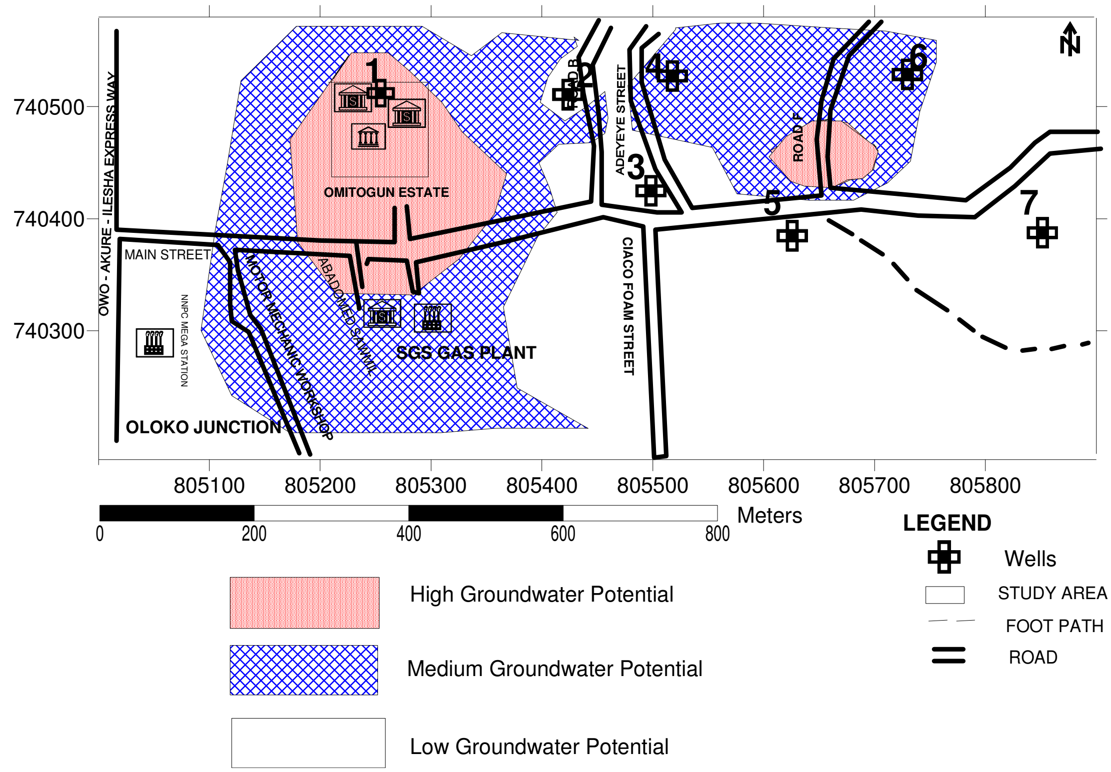

Fig. 8. Groundwater potential map of the study area

groundwater potential zone (red colour). Moderate groundwater potential zone was observed at the northern, southwestern, northwestern and northeastern parts of the study area (blue colour). Also the low groundwater potential zone was observed at the southern, southeastern, southwestern, central and small closure in the northeastern parts of the study area (white colour). Well data results across the entire study area, were used to validate the accuracy of the groundwater potential map and hence of the proposed methodology. The locations, names and the actual yield descriptions of these wells are displayed on the groundwater potential map and the validation was carried out by superimposing the wells on the groundwater potential map.

Table 3. Groundwater potential classifications

Groundwater potential values	Classifications
0.9 – 1.7 (White)	Low
1.7 – 2.0 (Blue)	Medium
2.0 – 2.4 (Red)	High

4. CONCLUSIONS

A geoelectric investigation of groundwater prospect at Omigun Estate, along Benin/Ilesha express way Akure, within the basement complex of southwestern Nigeria was carried out with a view to providing information on the geoelectric characteristic of the subsurface sequence, bedrock topography, subsurface structural features and their hydrogeologic significance, in order to identify aquifer units and determine possible areas for groundwater potential zones. We proposed an accurate way to integrate all the parameters that are significant to evaluate groundwater potential. The approach is based on the principle of MCDA in the context of the AHP. It allows the weighting and integrating of all the parameters in the order of their relative importance to groundwater occurrence. The method was used to prepare a prediction map for groundwater potentials in the area of our case study. The investigated area has been classified into low, medium, high groundwater potential zones and the results from well data across the entire study area were used to validate the accuracy of the groundwater potential map. From the results obtained, it could be concluded that the study area is an area of low groundwater potential.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Peer-review history:
The peer review history for this paper can be accessed here:
http://www.sciencedomain.org/review-history/25036