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Multi-Criteria Assessment of Groundwater Potential of Shallow Aquifers in the Vicinity of Osun State University, Ikire Campus and Environs, Southwestern Nigeria

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Abstract

In order to investigate the groundwater potentials of shallow water-bearing layers within the vicinity of the Osun State University Campus at Ikire, fifteen vertical electrical sounding (VES) resistivity data were acquired at random. The groundwater potential of the shallow water-bearing layers was inferred from the resistivity data based on three (3) existing criteria namely aquifer resistivity, transmissivity and reflective coefficient. At each VES station, the maximum electrode spreading employed for the resistivity data acquisition was between 200 m and 240 m, with the interpretation of the data carried out using partial curve-matching and computer iterative software. Geoelectric parameters obtained were used to compute the longitudinal conductance, transverse resistance, hydraulic conductivity, transmissivity and reflective coefficient using empirical relationships. The computed parameters were compared with existing classification tables to deduce the groundwater propensity in the shallow water-bearing layers of the study area. Four to five geoelectric layers corresponding to the HQ, HA and HKA geoelectric curve types were observed having lateritic materials as topsoil, sandy clay/clayey sand, weathered/fractured basement and fresh basement. In most cases, the water-bearing layer is mostly of clayey material with high porosity and low permeability and resistivity values that varies from 14.6 Ωm in VES 1 to 65.6 Ωm in VES 6. A few consist of sandy clay also with low resistivity values 76.9 Ωm in VES 7 to 107.1 Ωm in VES 4. The transmitivity values vary from 0.239 m^2/day in VES 2 to 2.522 m^2/day in VES 5. This same behavior was observed with reflective coefficient values which range from 0.690 in VES 6 to 0.994 in VES 1. The conclusions from the classification tables correlate in most of the VES stations. This study shows that the groundwater potential of the shallow water-bearing layers in the study area is generally poor within 0 to 80 m depth due to the low transmissivity of the clay materials at the shallow depths. Effective groundwater development in the study area must therefore integrate geophysical methods and remote sensing techniques to investigate depths beyond 100 m.

Nomenclature and units

m/day	*Meters per day*
m^2*/day*	*Meter squared per day*
mS	*Microsiemens*
Ω*m*	*Ohms meter*
Ω^{-1}	*Per Ohms*
Ωm^2	*Ohmmeter squared*

1.0 Introduction

Water which is a valuable natural resource is not only essential to human survival but also to the ecosystem's health (Oloyede-Kosoko 2015). The entire water bodies on earth are composed of coastal water bodies and freshwater bodies (lakes, rivers and groundwater) (Usali and Ismail, 2010). Groundwater resource is one of the most important resources available to humanity (Christophoridis *et al.*, 2000). The availability of water has played a key role in the development of all civilizations. Man's insatiable quest for fresh potable water has been on a constant increase, and with the advancing technology, various techniques have been developed to determine the potential of various geological formations for underground water exploitation. Agriculturally, water is used for growing food, domestically used for cooking, washing, and sanitation, industrially used in the manufacturing sector, medically used in medical and paramedical establishments in manufacturing drugs and economically used for tourism and in the sustainability of the earth's ecosystem (Burnett *et al.*, 2014). The water that accumulates as groundwater is mostly derived from rainfall or atmospheric precipitation which percolates into the soil or bedrock directly or from surface lakes and streams (Ojo *et al.*, 2014) and it generally flows downward under the force of gravity until it reaches a potential aquiferous unit at depth.

Shallow groundwater has been the most available source of groundwater, especially for dwellers in the rural settlements of Sub-Saharan areas of Africa where about 70% of the people live below the global poverty level. This is not unconnected with the fact that assessing deeper aquifers is usually expensive, thus and very few people can afford to sink deep boreholes. However, groundwater from shallow wells is becoming more and more unavailable for people to harness due to several factors, some of which include geologic factors, hydraulic factors, physiographic factors and hydrogeologic factors. The truth is that not all geologic terrain has good groundwater prospects. Hence, accessing good and portable groundwater from shallow aquifers has become more and more challenging over the years. A thorough appraisal of the hydrogeologic condition of the subsurface of any particular place would go a long way towards finding lasting solutions to these hydra-headed challenges. Fortunately, these hydrogeological parameters are hidden in the field test data and their identification is possible using the available physically plausible methods suitable for the prevailing field circumstances (Chachadi and Pradip 2012). The works of Kelly (1977) and Kelly and Reiter (1981) and Yadav and Abolfasi (1998) have shown that the hydraulic conductivity of any aquifer can be revealed from the geoelectric information of such subsurface interval. So also the works of Kosinski and Kelly (1981), Mazac *et al*, (1985) and Utom et al., (2012) which confirms that transmitivity can be derived from geoelectric parameters.

Also, the works of Niwas and Singhal (1981), Niwas and Singhal (1983) and Niwas and Singhal (1985) have stressed that detailed information about an aquifer's transmitivity is hidden within the longitudinal conductance and the transverse resistance of the aquifer (popularly referred to as the Dar Zarook parameters) which are both derived from the geoelectric parameters of the aquifer. Geophysical techniques are useful tools that could unravel these geoelectric parameters.

The key aquifer metrics are those that forecast an aquifer's total hydraulic performance, or its capacity to hold or release groundwater. Pumping tests conducted in wells are frequently used to estimate some of these parameters. On the other hand, wells may not always be available at convenient locations. Furthermore, it could be expensive and time-consuming to drill new wells and perform circulating tests at each location. In addition, pumping test results are not always accessible. The only information that is widely accessible is only accessible via geophysical methods.

As a result, a large number of empirical and semi-empirical equations have been proposed and have been used by several workers in the past to correlate geo-electrical results and hydraulic parameters of aquifers under different geological conditions. A hydrogeological model of the link between geoelectric and hydraulic characteristics of an anisotropic watershed in the Ganga-Yamuna interfluves aquifer in North India is one of them, according to the works of Sinha and Singhal et al. (2009). In Tericol Village, North of Goa, India, Chachadi and Prasip (2012) have made an effort to correlate geoelectric and groundwater parameters in West Coast laterites..

In Nigeria, other several authors have carried out geophysical surveys using electrical resistivity techniques not only within the basement environment but also within the sedimentary areas of the country. For instance, Asokhia *et al*., (2000) used a simple computer iteration technique for the interpretation of vertical electrical sounding. Others include Ako and Olorunfemi (1989) who worked on geophysical investigation for groundwater within the basalts of Vom, Plateau State of Nigeria, Alile and Amadasun (2008) who employed direct current to probe the subsurface earth for water bearing layers in Oredo local government area of Edo State, Nigeria. Emenike (2001) and Oyedele (2001) on the other hand have investigated for the potential of groundwater within the sedimentary deposit of the Niger Delta basin and the Dahomey basin of Nigeria respectively.

A properly calibrated subsurface image can be used to infer the aquifer configuration: depth, thickness, and the horizontal and vertical extent of the aquifers. Thus, using the subsurface information obtained from vertical sounding investigations, one may define the subsurface features and details (such as size, shape, resistivity and thickness) of an aquiferIn groundwater investigation, combining two or more geophysical techniques can significantly increase water prospectivity (Kalinski and Bogardi, 1993).

Generally speaking, the degree of weathering or fracture in rocks affects the amount of water present, which in turn affects the electrical resistivity values. Based on this, Wright and Burgess (1992) claimed that boreholes located by hydrogeological reconnaissance surveys can frequently and successfully create regolith aquifers in favorable regions. He was of the opinion that when optimum weathering occur, regolith resistivity is within the range of 70 Ωm to 120 Ωm (with little variations from one lithology to another). He therefore suggested that where success rates or average yields are lower, or higher yields than normal are required, geophysical survey methods may be employed. He observed that it is possible to correlate aquifer groundwater potential with the resistivity of the weathered regolith. The correlations may be relatively insensitive and inherent sources of error can include over-riding influences of narrow high permeability zones, both sub-vertical or sub-horizontal (basal saprolite) which are not detectable in the overall resistivity response. Hence, total dependence on the resistivity of the basement cannot always be solely relied upon in identifying areas of promising aquifer within the basement terrain. This is because previous research has shown that the resistivity of earth material in an aquifer does vary from place to place and from one lithology to another such that where a resistivity range is rated as low to moderate groundwater yield, it may be of higher yield when drilled. Hence, some other parameters that could be taken into consideration include the local geology, overburden thickness, basement resistivity, bedrock relief and the reflection coefficient, coefficient of anisotropy, resistivity contrast as well as transmitivity of the aquifer layer.

In this study, the groundwater prospectivity is concluded, not only from the resistivity value of the weathered units derived from the subsurface regolith but also from other aquifer parameters such as the longitudinal conductance, transverse resistance, transmitivity, reflective coefficient and resistivity contrast. We desire to integrate all these parameters to assess groundwater potential in shallow wells in the vicinity of the Ikire Campus of the Osun State University and compare the result with that of the resistivity values. The objective is to carry out a vertical electrical sounding investigation using the Schlumberger array, delineate geoelectric layers and identify the aquifer layers, compute aquifer layers parameters such as hydraulic conductivity, transmissivity, transverse resistance, longitudinal conductance and reflective coefficient, generate transmissivity, hydraulic conductivity and water flow direction map and predict groundwater potential using information acquired from the study area. Integration of the above parameters, deduced from geoelectric soundings shall be explored for assessment of the groundwater potential in the vicinity of Ikire Campus of the Osun State University.

2.0 Description of Study Environment

The study area is located in Ikire town, headquarter of Ikire Local Government Area in Osun State of Nigeria. The centre of the study was carried out within the Ikire Campus of Osun State University, a higher institution situated on the outskirt of the town. The institution is situated between the longitude of 07º 23' 777" and 07º24' 056" and latitudes 004º 10' 983" and 004º 11' 033". It covers a total area of 4.52 km^2. It is accessible through some road networks. Ikire environment is situated among a range of hills with an average elevation of about 228 metres above sea level, stretching from north to south and wrapping around the city in the southwesterly direction. It is located on a generally undulating topography with three major landforms: hills, plains and river valleys (UN-Habitat, 2014). The study area is underlain by the crystalline Precambrian Basement Complex rocks which belong to the migmatite-gneiss-quartzite complex lithologic unit of southwestern Nigeria (Rahman, 1976). The major lithology in the study area include granite, gneiss and quartzite rocks from which the soils in the area are derived. Over these lies a mantle of weathered paddlers rich in minerals and nutrients. In many places, there abound large deposits of lateritic and feralitic soils which form a source of gravel supply for the building construction industries. The study area is mainly drained by River Osun which flows in many smaller streams and is dry for many months, especially from November to May. Local streams like Agbora, Shasha, Oranran, Aworin, and Ope are among these streams. With numerous tributaries that run into the Osun River, the Mooro and Moosa rivers are the main rivers of Ikire. The architecture and local geology of the study region regulate the predominantly dendritic drainage pattern that is typical of the area. The study area's agricultural activities stand to benefit greatly from the presence of these rivers and streams. These regions are tropical in nature, with alternating seasons of rain and dry weather. The average annual temperature is high, ranging from 27 to 32 degrees Celsius, with April seeing the highest recorded temperature. (UN-Habitat, 2014). The research area is located in a tropical rainforest that is home to numerous species of hardwood timber, climbers, and heterogeneous hardwood trees as well as thickets of bamboo. Every year, the dry season begins in November and ends in February, whereas the wet season typically lasts from March to October. September marks the apex of the 1200–1500 mm annual rainfall range. The relative humidity is almost 80% on an annual average. The average annual temperature is high, ranging from 27 to 32 degrees Celsius, with April seeing the highest recorded temperature. (UN-Habitat, 2014).

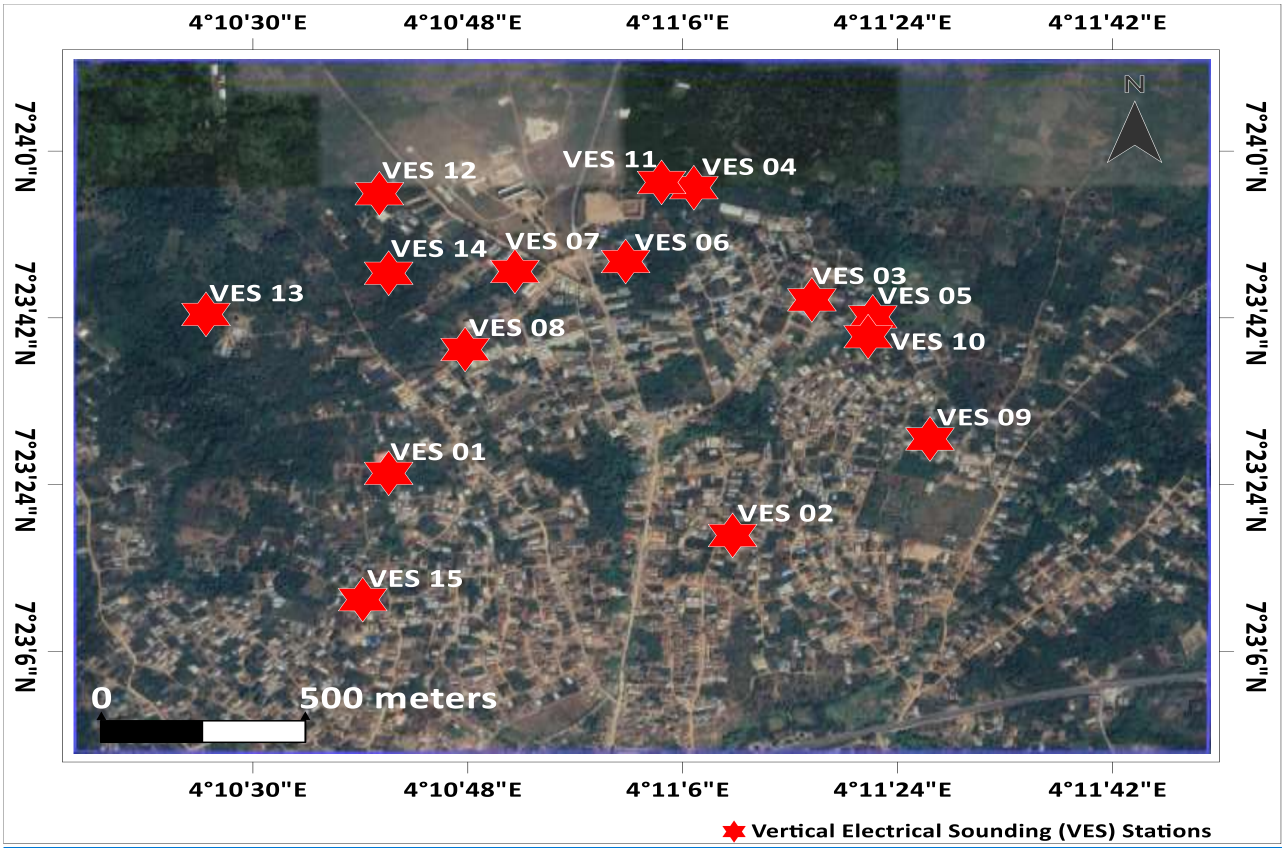

Figure 1: The Location Map of the study area in Ikire Campus and environs. At the top right is the map of Nigeria and bottom right is the map of Osun State showing the study area.

3.0 Materials and Methods

A reconnaissance survey involving study location geo-referencing, identification of access routes and field layout of data points was carried out. The data acquisition employed the electrical resistivity method, using the Schlumberger electrode configuration; fifteen vertical electrical soundings were carried out at selected points within the study location. Initial layer models (resistivities and thicknesses) derived from the interpretation of the raw field data through a partial curve matching technique were subjected to iterative modelling using WinResist software. The longitudinal permeability and transverse resistance, or Dar Zaroouk parameters, were calculated using the layer geo-electric characteristics that resulted. Using the Heidgold (1979) equation, the fluid conductivity of the aquiferous layers was determined. The hydraulic conductivities of each aquiferous stratum were used to calculate its transmissivity. For the study region, isopach maps of hydraulic conductivity, transmissivity, and depth were created. Three criteria and a categorization approach were used to access the groundwater potential of the study area: aquifer resistivity (Wright and Burgess, 1992; Table 1); transmissivity (Offodile, 1983; Table 2); and reflection coefficient (Olayinka, 1996; Table 3).

4.0 Presentation of Results and Discussion

Table 4 represents the summary of the geoelectric parameters obtained from the interpretation of the raw field data. Table 5 shows the longitudinal conductance and the transverse resistance as well as the aquifer protective capacity ratings. The weathered layer is a key component of the aquifer system and groundwater accumulation. Table 6 shows the classification of groundwater potential of the shallow aquifers based on parameters such as transmitivity values, as suggested by Offodile (1983), reflective coefficient as suggested by Olayinka (1996) and based on the resistivity of layered regolith, as suggested by Wright and Burgess (1992). Also, Figures 2, 3 and 4 are the transmitivity map of the study area, the hydraulic conductivity map, and the groundwater flow direction in the study area respectively.

About 46.6% of the total VES curves are in the H-curve category, an indication of a drop in the resistivity value which could give an idea of possible groundwater potential. However, there exists no presence of groundwater because the low resistivity intervals in these VES points are composed of clayey materials, which possess high porosity but do not release water.

Table 1: Aquifer potential Classification and resistivity (Ωm) of layered regolith (Wright and Burgess (1992)

Resistivity range	Classification
< 20	Clays with limited potential (or saline water)
20 – 100	Optimum weathering and groundwater potential
100 – 150	Medium conditions and medium potential
150 – 200	Little weathering and poor potential
>250	Negligible potential

Table 2: Classification of Groundwater Potential of Aquifer Based on Transmitivity Values (Offodile 1983)

Transmitivity (m^2/day)	Classification
>500	High potentials
50-500	Moderate potential
5-50	Low potential
0.5 – 5	Very Low potential
<0.5	Negligible potential

Table 3: Classification of Groundwater Potential of Aquifer Based on Reflective Coefficient (Olayinka, 1996)

Reflective Coefficient	Classification
>> 0.8	Very Poor Potential
> 0.8	Low Potential
< 0.8	High Potential
<< 0.8	Excellent Potential

Hence, interconnectivity between the pore spaces to transmit water is not guaranteed. Also, about 20% of the VES curves are HA-type curves; these occur at VES points 2, 7 and 15. In these cases, the drop in the resistivity value occurs at shallow depth, also within a clayey aquitard with no presence of groundwater of economic quantity. Other curve types observed in the study area include HKH (6%), Q curve (6%) and HAK (6%). All these show no trace of groundwater potential.

The idea of the resistivity interpretation is based on the knowledge of the physical property of the subsurface lithology, i.e. that is the conductivity (which is inversely proportional to the resistivity) of the subsurface layer. Areas with low resistivity indicate high conductivity: therefore in groundwater exploration, such zones are clues to water-bearing zones. Sandy or clayey sand zones are usually good aquifers because they possess high porosity and permeability while clayey layers have high porosity but low permeability. This enables it to hold water. Three to five geoelectric layers were delineated in all the VES stations with the following lithology; topsoil, sandy clay/clayey sand, concretional lateritic topsoil dominates the study area with a few consisting of lateritic sand topsoil. Classification table of Offodile (1983), Wright and Burgess (1992) and Olayinka (1996) were employed to determine the groundwater potential in the study area. Most of the water-bearing layers were observed to possess poor groundwater potential. They can best be described as aquitards. However, a breakdown of all the interpretations is discussed below in the following section.

The resistivity of the water-bearing interval varies from as low as 256.4 Ωm in VES 7 to 1736.0 Ωm in VES 12. These resistivity ranges generally are higher than the resistivity value of the regolith that has been subjected to optimum weathering. Hence, the possibility of having groundwater in economic quantity is not ascertained. The transmitivity values, on the other hand, are generally low; with transmitivity values varying from 0.239 m^2/day in VES 2 to 1.390 m^2/day in VES 11 except with VES 5, 6 and 7 where slightly higher values were observed to be 2.522, 2.500 and 2.071 m^2/day respectively. This same behavior was observed with reflective coefficient values which range from 0.798 in VES 8 to 0.994 in VES 1. All these values are shown in Table 5

Table 4: Summary Table of all Iterated and Interpreted Field Data

SN	Curve Type	Resistivity (Ωm)	Thickness (m)	Depth (m)	Lithology	Aquifer Depth (m)
VES 1		578.3	0.41	0.41	Lateritic Topsoil	
		14.6	1.09	1.50	**Clay aquitard**	1.50
	H	5383.5	-	-	Fresh Basement	
VES 2		1496.6	0.57	0.57	Lateritic Hard Pan	
	HA	86.0	1.11	1.68	**Sandy Clay**	1.68
		210.5	16.63	18.31	Clayey Sand Weathered layer	
		6737.0	-	-	Fresh Basement	
VES 3		845.1	0.70	0.70	Lateritic Topsoil	
	Q	241.0	2.37	3.07	**Clayey Sand**	3.07
		132.0	-	-	Sandy Clay	
VES 4		792.9	0.64	0.64	Lateritic Topsoil	
	HA	107.7	10.31	10.95	**Sandy Clay**	10.95
		1200.7	6.90	17.85	Partly-Weathered Basement	
		1427.0	-	-	Fresh Basement	
VES 5		286.3	1.28	1.28	Clayey Sand Topsoil	
	H	106.2	25.55	26.82	**Sandy Clay**	1.28
		2119.0	-	-	Fresh Basement	
VES 6		283.2	1.27	1.27	Clayey Sandy Topsoil	12.45
	H	46.6	11.18	12.45	**Clay aquitard**	
		254.3	-	-	Clayey Sand	
VES 7		256.4	0.95	0.95	Sandy Topsoil	
	HA	65.4	2.11	3.06	**Sandy Clay**	3.06
		742.1	38.84	41.91	Lateritic Soil	
		1340.0	20.80	62.70	Weathered Basement	
		4822.8	-	-	Fresh Basement	
VES 8	HAK	364.4	0.83	0.83	Sandy Topsoil	
		88.8	3.20	4.02	**Sandy Clay**	4.02
		790.7	4.21	8.23	Weathered Layer	
		1810.3	31.86	40.10	Fresh Basement	
		757.4	-	-	Fractured layer	
VES 9		704.8	0.56	0.56	Lateritic Topsoil	
	HKH	76.8	4.69	5.25	**Sandy Clay**	5.25
		998.0	8.47	13.72	Fresh Basement	
		491.1	44.15	57.87	Fractured layer	
		2190.3	-	-	Fresh Basement	
VES 10		755.4	1.21	1.21	Lateritic Topsoil	
	H	55.5	3.29	4.50	**Clay aquitard**	4.50
		1618.8	-	-	Fresh Basement	
VES 11		575.3	1.35	1.35	Lateritic Topsoil	
	H	60.9	3.92	5.27	**Sandy clay**	5.27
		1780.6	-	-	Fresh Basement	
VES 12		1736.0	0.92	0.92	Lateritic Hard Pan	
	H	32.0	1.41	2.33	**Clay aquitard**	2.33
		3268.6	-	-	Fresh Basement	
VES 13		454.9	1.02	1.02	Topsoil	
	H	45.5	3.88	4.89	Clay aquitard	4.89
		1641.8	-	-	Fresh Basement	
VES 14		352.6	0.74	0.74	Topsoil	
	HK	49.1	2.52	3.26	**Clay aquitard**	
		1622.7	13.20	16.47	Fresh Basement	3.26
		154.2	-	-	Fractured layer	
VES 15		332.6	0.68	0.68	Topsoil	
	HA	23.8	4.38	5.06	**Clay aquitard**	5.06
		432.5	6.27	11.33	Weathered layer	
		4235.7	-	-	Fresh Basement	

Table 5: Table showing the Aquifer Parameters in the Study Area.

VES	**Aquifer R (ρ)**	**Aquifer T (h)**	**Aquifer D (h)**	**Longitudinal Conductance** (Ω^{-1})	**Transverse Resistance** (Ωm^2)	**Hydraulic Conductivity** (m/day)	***Transmissivity T*** (m^2/day)	**Reflective Coefficient**
VES 1	578.3	1.09	1.50	0.00071	237.1	1.02	0.418	0.994
VES 2	1496.6	1.11	18.31	0.00038	853.1	0.42	0.239	0.939
VES 3	845.1	2.37	3.07	0.00083	591.6	0.72	0.504	0.292
VES 4	792.9	10.31	10.95	0.00081	507.4	0.76	0.486	0.835
VES 5	286.3	25.55	26.82	0.0045	366.5	1.97	2.522	0.904
VES 6	286.2	11.18	12.45	0.0044	363.5	1.97	2.502	0.690
VES 7	256.4	2.11	3.06	0.0037	243.5	2.18	2.071	0.839
VES 8	364.4	3.20	8.23	0.0023	302.4	1.57	1.303	0.798
VES 9	704.8	4.69	5.25	0.00079	394.6	0.85	0.476	0.857
VES 10	755.4	3.29	4.50	0.0016	914.0	0.79	0.955	0.933
VES 11	575.3	3.92	5.27	0.0023	776.6	1.03	1.390	0.933
VES 12	1736.0	1.41	2.33	0.00053	1597.1	0.36	0.331	0.980
VES 13	454.9	3.88	4.89	0.0022	463.9	1.28	1.305	0.946
VES 14	352.6	2.52	3.26	0.0021	260.9	1.63	1.206	0.941
VES 15	332.6	4.38	11.33	0.0020	226.2	1.72	1.169	0.895

4.1 VES 1 to VES 5 Interpretation

Three to four geoelectric layers are encountered. In most cases, especially in VES 1 to VES 5, the topmost first layer is made up of a high resistive lateritic layer to a concretional lateritic hard pan with a resistivity that varies from 286.3 Ωm in VES 1, to 587.3 Ωm in VES 1, 792.9 Ωm in VES 4, 845.1 Ωm in VES 3 and 1496.6 Ωm in VES 2. The laterite layer a of relatively low thickness that ranges from less than 1 m thick to about 1.7 meters thick. This topsoil is underlain by the water-bearing layer that is predominantly made up of clay (in VES 1,2 and 3) and slightly sandy clay materials having thicknesses that range from a few meters (less than 2.0 meters) in VES 1,2 and 3 while the thickness increases to 10.27 and 23.3 meters in VES 4 and 5. These materials are believed to possess very high porosity but low permeability. This presupposes that even if they are water-bearing, the ease of release of the water from the matrix would be difficult. The aquitard layer is underlain by a fresh basement whose resistivity ranges from 1,200 Ωm in VES 4 to about 5,345 Ωm in VES 1. From all indications, the groundwater potential of the VES points 1 to 5 is not encouraging due to the clay materials that predominate the interval except in cases where clayey sand/sandy clay are encountered; and this only occurs in VES points 2,3 and 4. However, the groundwater potential of this sandy clay layer is not also encouraging. An estimation of the transmitivity and the reflective coefficient in the first five VES points showed that the hydraulic conductivity calculated in VES 1 is 1.02 mS while the transmitivity value was estimated to be 0.418 m^2/day. Also, the reflective coefficient was estimated to be 0.994. In VES 2, the hydraulic conductivity was calculated to be 0.42 mS, the transmitivity value was estimated to be 0.239 m^2/day and the reflective coefficient in 0.939. In VES point 3, the hydraulic conductivity was calculated to be 0.72 mS while the transmitivity value was estimated to be 0.504 m^2/day and the reflective coefficient was estimated to be 0.292. In VES point 4, the hydraulic conductivity was calculated to be 0.76 mS while the transmitivity value was estimated to be 0.486 m^2/day and the reflective coefficient was estimated to be 0.835. Finally, in VES point 5, the hydraulic conductivity was calculated to be 1.97mS while the transmitivity value was estimated to be 0.486 m^2/day and the reflective coefficient was estimated to be 0.904.

In all these cases, whereas the Wright and Burgess (1992) classification revealed that the water-bearing layer in the VES points has limited groundwater potential, the Offodile (1983) and Olayinka (1996) classifications of groundwater potential described this as poor groundwater potential. The geoelectric section of VES 1 to VES 5 is shown in Figure 2. Here, the water-bearing layer is seen and due to the materials at this depth, groundwater would be poor.

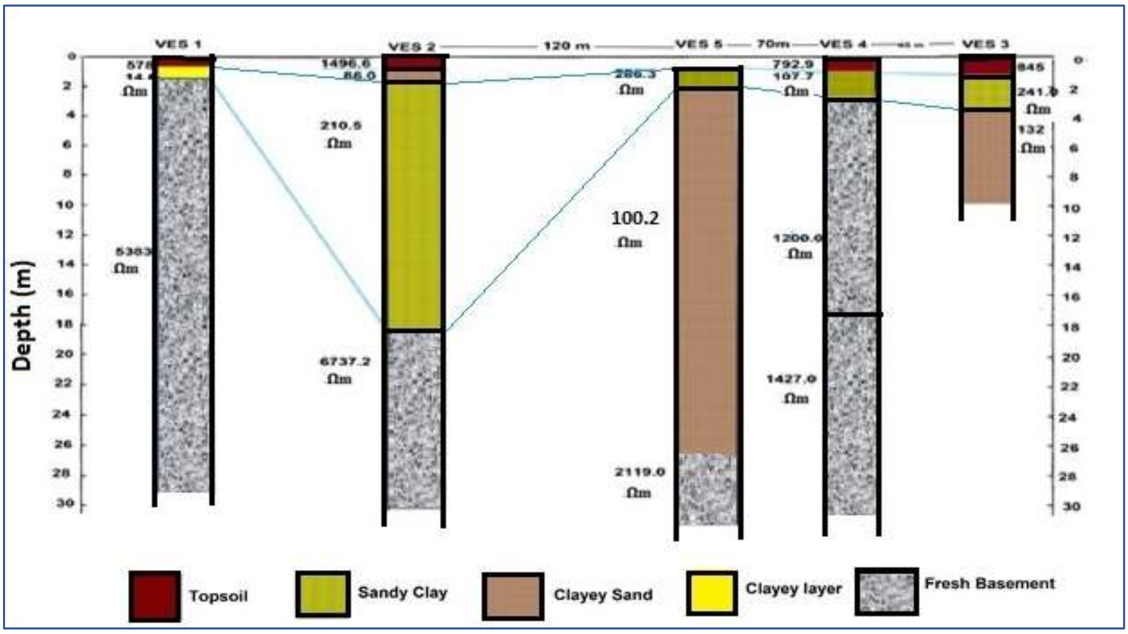

Figure 2: Geoelectric section of VES 1 to 5 showing the supposed aquifers and aquitards

4.2 VES 6 to VES 10 Interpretation

Interpreted field data in VES locations 6,7 and 8 as shown in the summary table revealed three to five geoelectric layers, the topsoil of which is made up of loose unconsolidated sandy topsoil with thickness and resistivity values of 1.27 m, 0.95 m, 0.83 m and 283.2 Ωm, 256.4 Ωm and 364.4 Ωm respectively. However, in VES points 9 and 10, there exists a thin lateritic topsoil of thicknesses and resistivity of 0.83 m and 0.56 m and 704.8 Ωm and 755.4 Ωm respectively. The topsoil is underlain by the clayey layer in VES 5 and 10 but with sandy clay in VESes 7, 8 and 9, all having thicknesses that range from as low as 2.11 m to 4.69 m except VES 6 where it is as deep as 11.18 m in VES. This interval is interpreted to be the shallow aquifer with resistivity values that vary from 46.6 Ωm and 55.5 Ωm (clayey) in VES 6 and VES 10 to 65.4 Ωm, 88.8 Ωm and 76.8 Ωm (sandy clay) in VES 7, 8 and 9. The shallow aquifer is further underlain by a high resistivity layer having a resistivity value of 742.1 Ωm in VES 7, 790.7 Ωm in VES 8, with a basement of resistivity value of 998.0 Ωm in VES 9. However, in VES 6, the aquifer layer is underlain by a clayey sand interval but in VES 9, it is a fractured interval that underlies the shallow aquifer. The depth to shallow groundwater aquifer varies from as low as 3.06 m in VES 7 to as high as 12.45 m in VES 1.

A closer look at the resistivity value of the shallow aquifer layer in all these VES points revealed that they are composed of low resistivity of limited groundwater potential. This is confirmed by the computed transmitivity of the aquifers using the hydraulic conductivity and the aquifer thickness. The result shows that the transmitivity values were 2.502 m^2/day (in VES 6), 2.071 m^2/day (in VES 7), 1.303 m^2/day (in VES 8), 0.476 m^2/day (in VES 9) and 0.955 m^2/day (in VES 10). All these, according to Offodile (1983) classification of groundwater potential, can best be classified as very low groundwater potential. A similar conclusion was observed with the computed reflective coefficient of the aquiferous layer, all of which were observed to be high, even higher than the 0.80 threshold except in VES 6 where it can be classified into the moderate groundwater potential category. The observed values were 0.690 in VES 6, 0.839 in VES 7, 0.798 in VES 8, 0.857 in VES 9 and 0.933 in VES 10.

In all these cases, whereas the Wright and Burgess (1992) classification revealed that the aquifers in the VES points have limited groundwater potential, the Offodile (1983) and Olayinka (1996) classifications of groundwater potential described this as poor groundwater potential. Conclusions from this VES point does not seem to correlate due to contrasting groundwater prospectivity at the VES point based on the two opinions. The geoelectric section of VES 6 to VES 10 is shown in Figure 3. Here, it is clear that the shallow water-bearing interval layer in VES points 6 to 10 possesses very poor potential due to the resistivity values of the matrix material which is generally low (<50 Ωm).

4.3 VES 11 to VES 15 Interpretation

Interpreted field data in VES locations 11, 12, 13, 14 and 15 as shown in the summary table also revealed three to four geoelectric layers, the topsoil of which is made up of lateritic topsoil or concretional lateritic hardpan (especially in VES 12). The topsoils at all the VES points thin and range in thickness from as low as 0.68 meters in VES 15 to as high as 1.36 in VES 11.

The topsoils possess high resistivity values that range from 575.3 Ωm in VES 11 to 1736 Ωm in VES 12, 454.9 Ωm in VES 13, 352.6 Ωm in VES 14 and 332.6 Ωm in VES 15. In these stations, the shallow aquiferous layer is made up of a clayey layer except for station 11 where little sand is sandwiched between the clayey intervals. These all range in resistivity from as low as 23.8 Ωm in VES 15 to 49.1 Ωm in VES 14 except in VES 11 where it is about 60.9 Ωm. Just as in other previous aquiferous layers, the depth to the aquifers varies from as low as 2.33 meters in VES 12 to 5.27 meters in VES 11- an indication of very thin aquifers, possible with low permeability and transmitivity. The aquifer layers are further underlain in most cases by the fresh basement directly except in VES 14 and 15 where the fresh basement shows a trace of possible fracturing (VES 14) and weathered layer basement (VES 15). These basements are of varying resistivity that range from 1780.6 Ωm in VES 11 to 3268.6 Ωm in VES 12, 1641.8 Ωm in VES 13, 1622.7 Ωm in VES 14 and finally 4235.7 Ωm in VES 15.

From the Wright and Burgess Classification (1992) classification based on resistivity values, the aquiferous layers generally possess low groundwater values that fall below 60 Ωm – an indication that the interval possesses high porosity material with little or no permeability. However, the Offodile classification based on transmitivity values, the transmitivity value of the shallow aquifer layer in all these VES points showed that they possess transmitivity values and hydraulic conductivity that range from 1.390 m^2/day and 1.03 mS in VES 11 to 0.331 m^2/day and 0.36 mS in VES 12. Similar results were observed in VES 13, 14 and 15. These values, according to Offodile classification are indicative of low groundwater potentials. Using the reflective coefficient based on Olayinka (1996) suggestion, in the classification of the groundwater potential, the results obtained showed values that range from as low as 0.895 in VES 15 to as high as 0.980 in VES 11. These values show evidence of low groundwater potential and can best be described as aquitards.

In all these cases, all the classification parameters - Wright and Burgess (1992) classification, the Offodile (1983) and Olayinka (1996) classifications of groundwater potential seem to correlate in their conclusion of the groundwater prospectivity. The geoelectric section of VES 11 to VES 15 is shown in Figure 4. Here, it is clear that the shallow water-bearing layer in VES points 6 to 10 are very poor due to the resistivity values of the matrix material which are generally low (<50 Ωm).

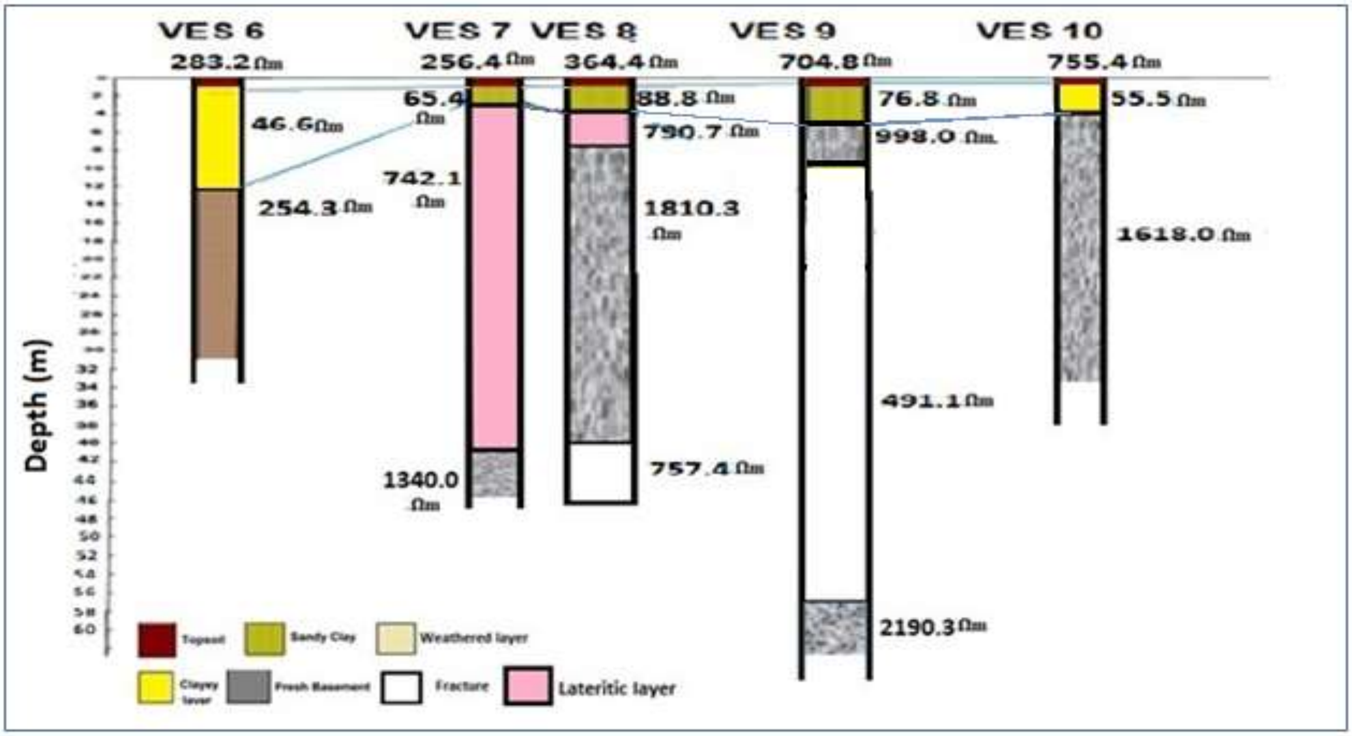

Figure 3: Geoelectric section of VES 6 to 10 showing the supposed aquifers and aquitards

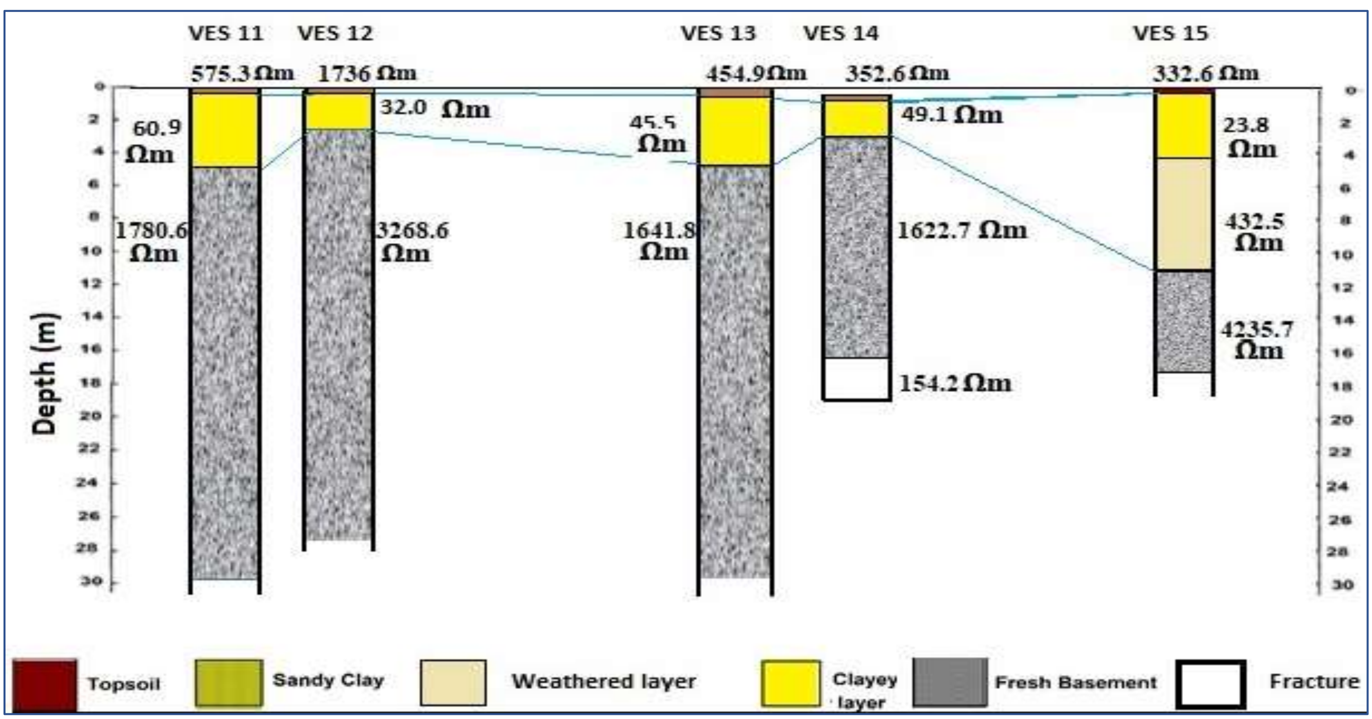

Figure 4: Geoelectric section of VES 11 to 15 with the supposed aquifers and aquitards

Table 6: Summary of Groundwater Potential defined by Offodile, Olayinka and Wright & Burgess Classifications Ikire.

	Aquifer Thick. (m)	Aquifer/Aquitard Resisitivity (Ωm) (Wright and Burgess 1992)		Aquifer/Aquitard Transmitivity (m^2/day) (Offodile, (1983)		Aquifer/Aquitard Reflection Coefficient (Olayinka, 1996)	
		Observed	Interpretation	Observed	Interpretation	Observed	Interpretation
VES 1	1.09	14.6	Clay with limited potential	0.418	Very low water potential	0.994	Very poor water potential
VES 2	1.11	86.0	Sandy Clayey sand with fair potential	0.239	Very low water potential	0.939	Very poor water potential
VES 3	2.37	241.0	Sand with moderate potential	0.504	Fair groundwater potential	0.292	Moderate water potential
VES 4	10.31	107.7	Sandy clay with fair potential	0.486	Very low water potential	0.835	Very poor water potential
VES 5	25.55	106.2	Sandy clay with fair potential	2.522	Very low water potential	0.904	Very poor water potential
VES 6	11.18	46.6	Clay with limited potential	2.502	Very low water potential	0.690	Moderate potential
VES 7	2.11	65.4	Clay with limited potential	2.071	Very low potential	0.839	Very poor potential
VES 8	3.20	88.8	Sandy clay with fair groundwater potential	1.303	Very low water potential	0.798	Very good water potential
VES 9	4.96	76.8	Sandy clay with fair groundwater potential	0.476	Very low water potential	0.857	Very poor water potential
VES 10	3.29	55.5	Clay with limited groundwater potential	0.955	Very low water potential	0.933	Very poor water potential
VES 11	3.92	60.9	Clay with limited groundwater potential	1.390	Very low water potential	0.933	Very poor water potential
VES 12	1.41	32.0	Clay with limited groundwater potential	0.331	Very low water potential	0.980	Very poor water potential
VES 13	3.88	45.5	Clay with limited groundwater potential	1.305	Very low water potential	0.946	Very poor water potential
VES 14	2.52	49.1	Clay with limited groundwater potential	1.206	Very low water potential	0.941	Very poor water potential
VES 15	4.38	23.8	Clay with limited groundwater potential	1.169	Very low water potential	0.895	Very poor water potential

4.4 Transmittivity Distribution in the Study Area

The map below (Figure 5) shows the transmissivity distribution of the study area where the NE and SE part of the map shows the VES points with the highest transmissivity (2.5 to 1.5) but still very low compared with Offodile (1983) classification of groundwater potential. VES 5, VES 6, VES 7 and a little part of VES 8 show the rate of high transmittivity as shown on the map below. The groundwater potential in these VES points is very poor. The NW and SW part of the map shows a very low transmissivity that may not be able to produce water due to its very low transmissivity units. The rate of low transmissivity as shown on the map below is between (1.3 to 0.2) which might not produce any water. The VES points are VES 1, VES 2, VES 3, VES 4, VES 8, VES 9, VES 10, VES 11, VES 12, VES 13, VES 14 and VES 15, due to very poor transmissivity in the study area, there might not be the availability of water in the VES points. The amount of water that is transmitted depends on the amount of water being held in the aquifer and also depends on the lithology.

4.5 Hydraulic Conductivity Distribution in the study area

Hydraulic conductivity is a measure of how easily water can pass through soil or rock: High values indicate permeable materials through which water can easily pass; Low value indicates that the material is less permeable. A key aspect of hydraulic conductivity is that a very wide range of values exist in natural soil and rocks, perhaps a value ranging from 10^{-2} m/sec (for open gravels) to 10^{-11} m/sec (for unfissured clays) Dominico and Schwartz (1990). The hydraulic conductivity of the map below (Figure 6) shows the hydraulic conductivity of the study area whereas the NE and SE part of the map shows the high hydraulic conductivity of the study area. The VES points with the highest hydraulic conductivity range from (2.1 to 1.3 m/sec) within VES 3, VES 5, VES 6, VES 7, and VES 8. The low hydraulic conductivity from the NW and SW of the map is between (1.1 to 0.3 m/sec) VES 1, VES 2, VES 4, VES 9, VES 10, VES 11, VES 12, VES 13, VES 14 and VES 15. Due to very poor hydraulic conductivity in the study area, there might not be good water potential in the VES points.

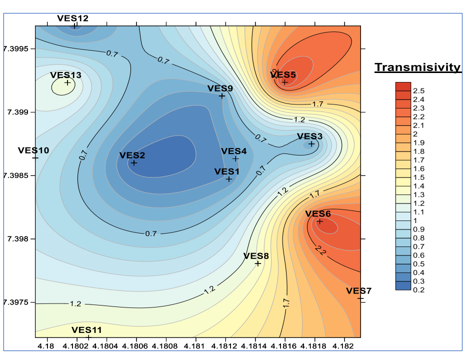

Figure 5: Transmittivity Distribution Map in the Study Area

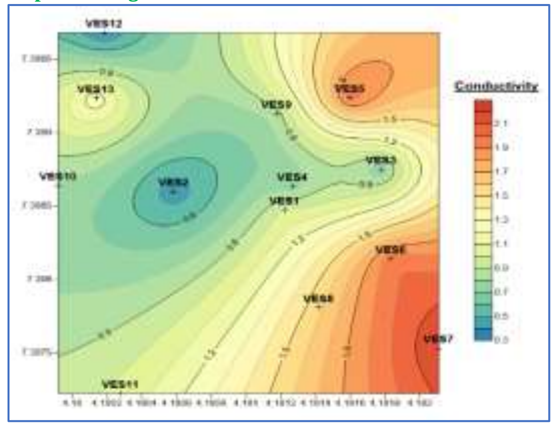

Figure 6: Hydraulic Conductivity Map in the study area

5.0 Conclusions and Recommendation

In this study, the project work is to employ the use of aquifer parameters prediction to unravel groundwater potential in shallow wells of Osun State University, Ikire Campus. Fifteen vertical electrical sounding surveys were conducted using the Schlumberger technique of electrical resistivity method. ABEM SAS 1000 resistivity meter was used for the study while traverses at each VES cover a total of between 100 m and 120 m on either side of the central reference point. Among the parameters estimated include transmissivity, longitudinal conductivity, transverse resistance, hydraulic conductivity and reflective coefficient.

The VES data interpretation involved quantitative partial curve matching and computer iteration using WinResisit. The resistivities and thicknesses of the geoelectric layers were obtained after the analysis and interpretation of the data. These were used to compute the longitudinal conductance and the transverse resistance while hydraulic conductivity and transmittivity were deduced using empirical equations. Classification tables of Olayinka (1996), Wright and Burgess (1992) and Offodile (1983) were used to deduce the groundwater prospectivity in shallow aquifers in the study area.

The result showed that all the curve types observed include H, Q, HA and HKA curves. Four to five geoelectric layers observed include lateritic topsoil, sandy clay/clayey sand, weathered/fractured basement and fresh basement. The predictions of aquifer parameters; resistance, transmissivity, hydraulic conductivity, longitudinal conductance, transverse resistance and reflective coefficient revealed that the aquifer in the study area at shallow depth possess poor to very poor in groundwater potential which is indicative of poor well water usage, hence can best be described as aquitard in most cases.

The results conclude from the use of more than one classification technique that groundwater potential at shallow depths at Ikire constitutes a major challenge, especially at depths less than 80 m deep. Groundwater potential concluded based on resistivity to be of moderate potential was found to be of very low groundwater potential based on the reflective coefficient and the transmitivity values. Therefore, for effective well water and groundwater development in the study area, it is recommended that depths higher than 100 m should be investigated. With the results of this study, there is a likelihood that the well water or groundwater potential in the area is very poor at shallow depths due to the inability to transmit water easily at the shallow aquifer. Therefore, a deeper geophysical investigation should be conducted. Future groundwater development in the study area should be concentrated towards greater depth into the subsurface with appreciably thick overburden which is determined through geophysical investigations.

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7.0 Declaration of conflict of interest

The authors have collectively contributed to the conceptualization, design, and execution of this journal. They have worked on drafting and critically revising the article to include significant intellectual content. We wish to state that this manuscript has not been previously submitted or reviewed by any other journal or publishing platform. Additionally, the authors do not have any affiliation with any organization that has a direct or indirect financial stake in the subject matter discussed in this manuscript.

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