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The Assessment of Groundwater Availability in Sedimentary Environments Using the Electrical Resistivity Method: A Case of Ekpoma and Its Environs, Southern Nigeria

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Abstract: Groundwater resources are an ephemeral aspect of the ecosystem, especially in the university town of Ekpoma, where the issue of severe water shortages brought on by failed or unproductive boreholes has lingered over time. This study makes an effort to thoroughly define the groundwater-bearing zones and estimate their thicknesses and depths in order to identify the cause(s) of groundwater scarcity in Ekpoma and its peri-urban area. In order to accomplish the objectives of the work, fifteen (15) Vertical Electrical Soundings (VES) were conducted across the study location, leveraging Schlumberger electrode array, with current electrode spacing varying from 5.00 to 550.00 m. The results show there were five distinct geoelectrical strata identified: top soil, clayey sandstone, sand, consolidated sandstone, and unconsolidated sandstone. The unconsolidated sandstone layer constituted the aquifer units in the area, whose depth ranges between 103.00 m and 258.00 m. Besides, this study showed that there is strong indication/evidence of saturation of the aquifer identified in the Imo Shale Formation surrounding Irrua with highly porous and permeable materials atop it, justifying the region's highly productive wells and boreholes. The aquifers delineated in and around the Ekpoma community, on the other hand, have relatively high resistive values (3404.20–5303.00 Ωm), indicating less saturation, and are equally overlain by less porous and permeable materials, establishing why Ekpoma (located within the Bende-Ameki and Ogwashi Asaba Formations) has a perennial groundwater shortage. The shallow aquifer units in the area of study were discovered to be rather thin, with the majority having a thickness of less than 30 m, making them less sustainable for long-term groundwater abstraction and resulting in failed boreholes in most portions of Ekpoma town. The study indicates that the groundwater prospects of Ekpoma and its environs are poor, and deep boreholes reaching a minimum depth of 250.00 m should be drilled since it is sustainable due to its significant thickness to serve the Ekpoma community and its environs. The present investigation findings can aid in improving knowledge of underlying geological conditions, evaluating the feasibility of the researched area for predicted urban and economic development, and sustaining water supply for connected activities.

Keywords: Aquifer, Formations, Unconsolidated sandstone, Unproductive boreholes, VES

INTRODUCTION

Water is one of the most important ingredients that support human existence, just like air and land. Over the years, water from beneath the ground has been exploited for domestic use, livestock, and irrigation (Ozegin & Okolie, 2018). Two-thirds of the world's freshwater resources are found in the ground, making it the most crucial resource (Chapman, 1996; BGS, 2001). The majority of potable freshwater comes from groundwater, if glaciers and the polar ice caps are excluded. According to Ozegin & Okolie (2018), groundwater is characterized as water in the saturated zones that occupies the spaces that exist between mineral grains, fissures, and fractured rocks inside the rock mass. It is generally believed to mean that water fills every space inside a geologic layer. It begins as rain or snow, percolates through the soil into groundwater, and thereafter returns to the surface in rivers, lakes, or oceans.

In addition to serving as an essential source of life, groundwater aquifers play a significant role in sustaining numerous human growth and advancement endeavours. In order to develop groundwater resources over the long term and to plan water management procedures, it is crucial to recognize and understand the hydrogeological setting of these aquifers. An excessive lack of water can cause social and economic activities to become unsustainable. The availability of groundwater depends on the amount of recharge, porosity, and permeability of the rock layer. The search for groundwater has been on the increase across the globe because groundwater is considered all over the world to be the best source of potable and safe water for drinking, agricultural, and industrial purposes (Ikhifa et al., 2008; Hoque et al., 2011; Adiat et al., 2012 and 2013; Ozegin & Okolie, 2018).

The problem of acute water shortages in the study area, particularly in the University town of Ekpoma, has persisted over the years. Several boreholes and wells distributed across the area have always remained either nonfunctional or nonproductive. Attempts by private individuals and the government to permanently solve the problem of a lack of groundwater have remained futile. This has compelled the people of the area to rely on rain harvesting, streams, and rivers as sources of their water usage. It is, however, interesting and surprising to add that a nearby community, Irrua, despite not being far from Ekpoma, is not facing the problem of a lack of groundwater as many boreholes located in the area are not only functioning but also producing. It therefore becomes expedient to have a proper understanding of the subsurface geology available in the area with a view to holistically evaluating the groundwater potential of the area. This will further assist in establishing the reasons why Ekpoma is constantly and almost permanently experiencing groundwater problems, whereas groundwater occurrence is not too much of a problem in the nearby community of Irrua.

Geotechnical and groundwater investigations frequently make use of geophysical methods like vertical electrical sounding (VES), electrical resistivity tomography (ERT), and ground-penetrating radar (GPR). They are commonly recognized as effective instruments for determining aquifer formation under diverse hydrogeological settings and mapping groundwater resources (Haque et al., 2020). They are widely utilized in subsurface investigations because they contrast different rock units' electrical properties with minimal to no environmental harm (Ozegin & Okolie, 2018). The geophysical method (vertical electrical sounding (VES)) of prospecting and delineation of anomalous zones extends its wide application to groundwater studies. The geophysical method is the basis for groundwater studies because of its reliability, relatively low cost, and time effectiveness. Almost every geophysical method is applicable to groundwater studies, and as such, it can be said that groundwater studies are the meeting point of all the geophysical methods. This gives room for composite interpretation; therefore, the best geophysical method should be selected for its best application (Akinlalu et al., 2017). Many geophysical approaches can be employed in groundwater studies, including the magnetic method, electrical resistivity, and electromagnetic method (Ikhifa et al., 2008; Ofomola et al., 2009; Adiat et al., 2009; Alile et al., 2011; Amigun et al., 2012; Ayuk et al., 2013; Okolie et al., 2013, 2014 and Akinlalu et al., 2017).

Groundwater is not an unlimited resource; therefore, evaluating and understanding the groundwater potential of an area is necessary for sustainable use. Groundwater studies cannot be limited only to the study of groundwater quantity but also to the aquifer characteristics that determine groundwater quantity (Ishola et al., 2013 & 2014; Bahrami et al., 2020). The electrical resistivity geophysical prospecting method via Vertical Electrical Sounding (VES) will be employed for the study. Vertical electrical soundings can be used to measure the resistivities, thicknesses, and depths of geoelectric heterogeneous subsurface units. As a result, structural and lithological variations can be identified. The objective of this study is to evaluate the groundwater potential in order to: determine the geoelectric parameters of the delineated subsurface layers; delineate aquifer zones; examine the hydrological significance of geologic materials overlaying the aquifer zones; and evaluate the groundwater potential of the area. In light of this, the study is geared to examine the hydrogeological system, assess groundwater incidents, and examine the vertical extends of the Ekpoma aquifer, which stands in for the area's primary aquifer.

STUDY AREA

The study area is located in the Anambra Basin. It is roughly located between Latitudes 6°41'N and 6°49'N and Longitudes 6°00'E and 6°14'E. It is approximately 78 kilometers from Benin City (Figure 1). The occurrence of groundwater and surface water in Ekpoma and its environs is generally controlled by the geology and geological structure (scarp fault and scarp fault line) in the area. For residential use, the area is primarily reliant on surface water from streams and wells. However, these bodies of water are very susceptible to contamination, exposing the populace to water-borne infections (Salufu & Ujuanbi, 2015; Ozegin et al., 2017). Also, the fast population growth of Ekpoma since the establishment of Ambrose Alli University in 1981 has made these sources of water inadequate for the dwellers, as has the need for quality and readily available potable groundwater in this area.

The study area falls within the Sedimentary terrain of the Benin Formation, Nigeria. The geologic Formations in the area are the Bende-Ameki, Ogwashi-Asaba, and Imo shale Formations (see Figure 2). The Bende-Ameki Formation is of middle Eocene age and consists of a series of highly fossiliferous grey-sandy clays with calcareous concretions and white clayey sandstones. Two lithological groups have been identified in parts: (a) the lower unit with fine to medium sandstones and intercalations of calcareous shale thin, shaly limestone; and (b) the upper unit with coarse to medium, cross-bedded sandstone, bands of fine, grey-green sandstone, and sandy clay (Salufu & Ujuanbi, 2015). The Ogwashi-Asaba Formation is the most recent Formation with an average thickness of about 232 m, overlying the Bende-Ameki Formation (Offodile, 2012). It is Oligocene to Miocene, formerly called the Lignite Group and Lignite Series. The rocks consist of fine- to coarse-grained, white and multi-colored sands, white, gray, pinkish, or dark gray clays, black carbonaceous clays, and lignite. The dominant rock is sand, which constitutes more than 55% of the bulk (Offodile, 2012). The Imo shale Formation, which is Paleocene in age, consists of thick blue-black clayey shale and shows lateral variations into sandstones in places. The Formation is essentially an aquiclude except for the small lenticular sands, which constitute good aquifers in some localities (Offodile, 2012).

The mean yearly temperature in Ekpoma is 24.8°C. Rainfall is at its lowest from December to January, with an average of 19 mm. September has the most precipitation, with an average of 303 mm. March is the warmest month of the year, with an average temperature of 26.6°C. August is the coldest month of the year, with temperatures hovering around 23.0°C. Precipitation totals 292 mm between the driest and wettest months. Temperatures vary by 3.6°C all through the year. The elevation of the research region varies between 243.9 m (812 ft) and 426.6 m (1420 ft) above sea level (Ozegin et al., 2017; Arewele et al., 2020).

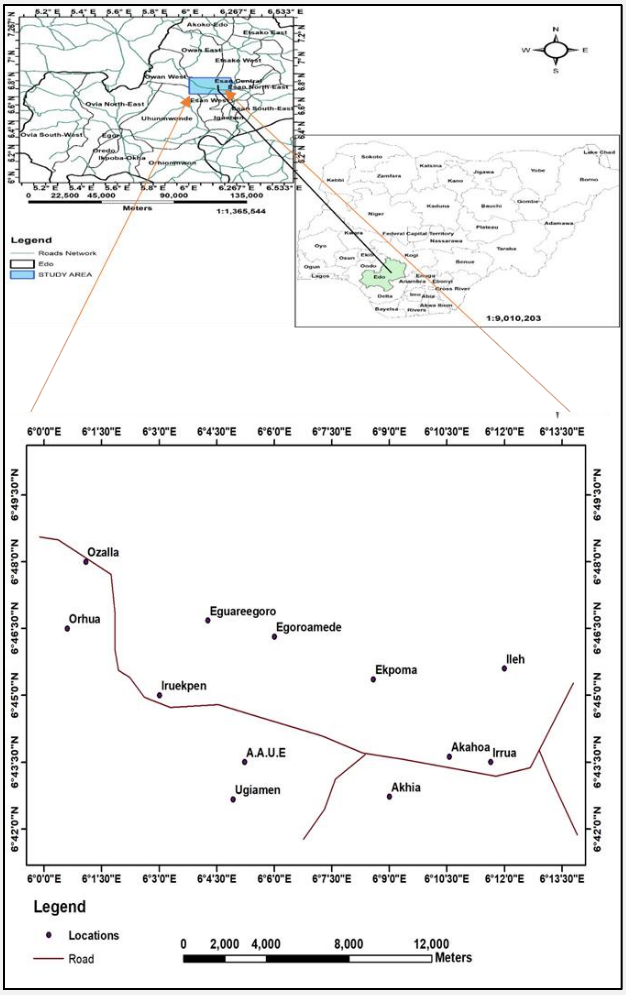

Figure 1. Location map of the study area.

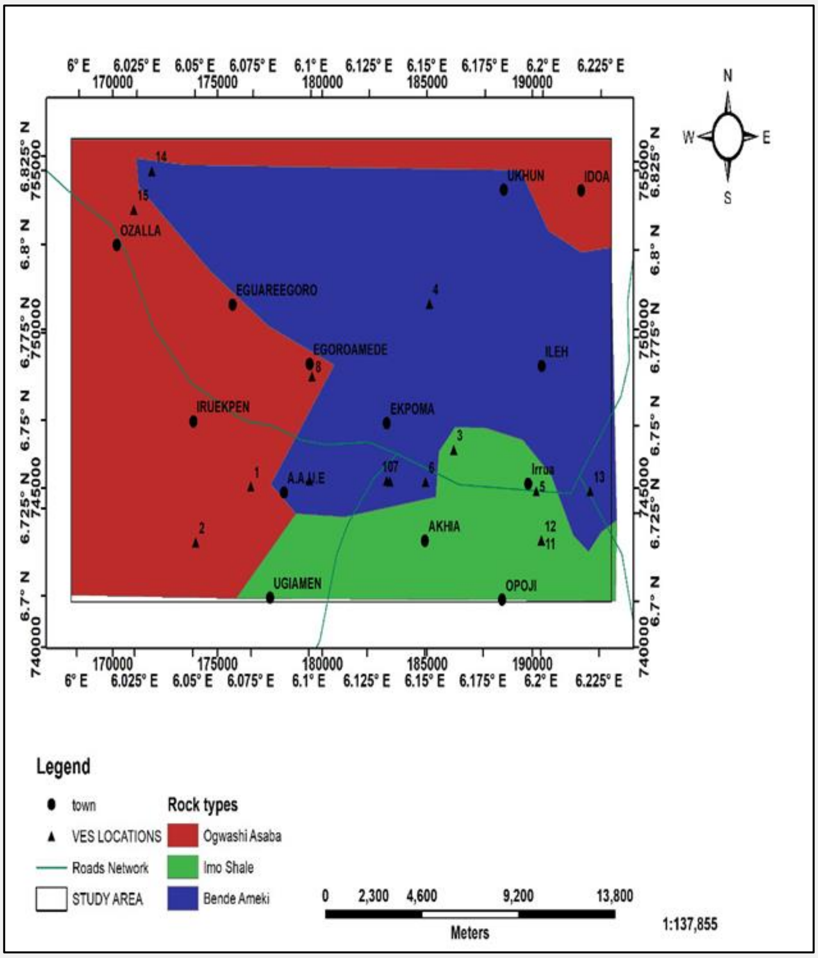

Figure 2. Geology map of the study area showing VES locations.

METHOD

The geoelectrical resistivity approach constitutes a variety of geophysical approaches used to study the functioning of electrical current in the earth. It is based on electrical resistivity (the inverse of conductivity), and it is the basic property of all earth's materials (Ozegin et al., 2017). Subsurface investigation using the electrical resistivity technique was done using the Vertical Electrical Sounding (VES) technique. Fifteen (15) VES stations were occupied in the study area using the ABEM Resistivity Meter SAS 1000 for electrical resistivity measurements. The Terrameter SAS1000 is a very capable resistivity system that may be used for a wide range of applications. It saves money on field time by determining resistivity, and it is extendable with a number of attachments.

The Schlumberger array was adopted with electrode spacing ranging from 5–550.00 m. These soundings were distributed across the study area. In this arrangement (Figure 3), the potential electrodes are positioned in the electrode array's centre at a distance that is typically less than one-fifth the spacing between the current electrodes (C_1 and C_2). Throughout the survey, the potential electrodes (P_1 and P_2) stay unattended while the gap between the current electrodes gradually increases until the measured voltage is insufficient to be observed.

An apparent resistivity (ρ_a) value is computed from the current (I) and voltage (V) data. ρ_a is equal to:

$$^{KV}/_{I} \qquad (1)$$

where K is the geometric parameter that depends on how the four electrodes are arranged. For the Schlumberger array, $K = \pi \sigma n(n+1)a$. In application, the apparent resistivity value is determined using the formula:

$$\rho_a = K\,R \tag{2}$$

since resistivity meters typically provide a resistance value, R = V/I.

When compared to Wenner configurations, Schlumberger soundings often have superior resolution, a deeper probing depth, and quicker field deployment. The necessity for longer current electrode cables and the need for a highly sensitive recording device are the two most notable drawbacks. Numerous articles (Loke & Barker, 1996; Ozegin et al., 2007; Loke et al., 2013) have provided considerably more information about field procedures for geoelectrical resistivity surveys.

The VES data were processed by plotting the apparent resistivity (ρa) measurement at each station against electrode spacing on a bi-logarithmic graph sheet. The curves were examined qualitatively to assess the variety and nature of the layers and quantitatively to generate preliminary estimations of the resistivity and thickness of the individual geoelectric layers at each VES location using partial curve matching. In an iterative forward modeling technique, the results of the curve matching were loaded into the computer as an initial model. The computer iteration technique compares the layer thickness and resistivity acquired by manual interpretation with those produced by computer-generated curves. When the inaccuracy in interpretation is less than 5%, the interpretation is regarded as acceptable. A geoelectrical model is constructed through qualitative and quantitative interpretation of the measured vertical electrical soundings. This geoelectrical model was developed using all the available information about the geology and hydrogeologic conditions. Seven geoelectric sections were built based on the results, which were interpreted to contain the layer resistivities and thicknesses.

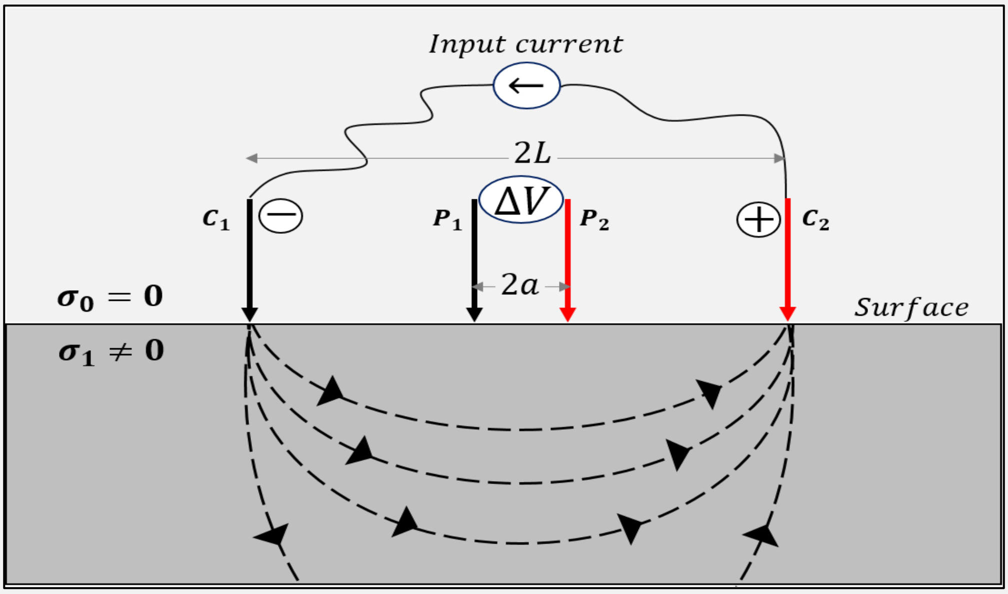

Figure 3. Schlumberger configuration: with the midpoint of both the current and potential electrodes converging, set the distance between the current electrodes at 2L and the distance between the potential electrodes at 2a.

RESULTS & DISCUSSION
Results

In order to comprehend the hydrogeological and geological features that are prevalent in the researched area, a direct current electrical resistivity sounding survey was acquired for investigations into the vertical variation of the soil electric characteristics. The resistivities, thicknesses, and depths of multilayered geoelectric subsurface units can be ascertained via vertical electrical soundings. It is possible to map structures and lithological changes as a result. Six curve types were obtained in the study area. The curve types are A, H, K, AK, KH, and HKH. The interpreted results are shown in Tables 1–3. Figures 4a–c shows the columnar section and groundwater potential evaluation of the Ogwashi Asaba Formation, Imo Shale Formation, and Bende-Ameki Formation, respectively. Geoelectric parameters were generated from the results of the VES interpretation (Tables 1–3) and utilized to generate the columnar configuration sections shown in Figures 4a–c.

Table 1. Summary of the VES data interpretation - Ogwashi-Asaba Formation.

VES No	Curve Type	No. of Layers	Resistivity Value (Ωm)	Thickness (m)	Depth (m)	Probable Lithologic Equivalence
1	KH	4	640.3	8.7	8.7	Top soil
			7909.1	84.3	93	Sandstone
			4326.6	25.8	118.8	Unconsolidated sandstone
			15465	-	-	Sandstone
2	KHK	5	1611.4	2.4	2.4	Top soil
			3083.5	7.8	10.2	Sandstone
			1237.9	4.9	15.1	Unconsolidated sandstone
			7677.4	86.2	101.3	Sandstone
			2299.5	-	-	Unconsolidated sandstone
8	H	3	576.6	11.3	11.3	Top soil
			157.5	85.9	97.2	Clay
			2242.3	-	-	Clayey sand
15	KH	4	177.8	11.1	11.1	Top soil
			435.8	24.2	35.3	Sandy clay
			119.6	131.6	166.9	Clay
			1486.8	-	-	Clayey sand

Table 2. Summary of the VES data interpretation-Imo Shale Formation.

VES No	Curve Type	No. of Layers	Resistivity Value (Ωm)	Thickness (m)	Depth (m)	Probable Lithologic Equivalence
3	AK	4	500.9	9.6	9.6	Top soil
			4697	27.3	36.9	Sandstone
			11223.2	124.9	161.8	Sandstone
			2125.5	-	-	Unconsolidated sandstone
5	K	3	669.8	23.1	23.1	Top soil
			3781.8	139.1	162.2	Sandstone
			1539.7	4.9	167.1	Unconsolidated sandstone
11	K	3	671.9	18.4	18.4	Top soil
			3333.3	211.8	230.2	Sandstone
			1313.3	-	-	Unconsolidated sandstone
12	K	3	982.4	36.2	36.2	Top soil
			4338.1	221.3	257.5	Sandstone
			1471.3	-	-	Unconsolidated sandstone

Table 3. Summary of the VES data Interpretation-Bende- Ameki Formation.

VES No	Curve Type	No. of Layers	Resistivity Value (Ωm)	Thickness (m)	Depth (m)	Probable Lithologic Equivalence
4	KH	4	1173.2	2.5	2.5	Top soil
			2298.1	12.6	15.1	Sand
			1332.2	52.6	67.7	Clayey sand
			8227.3	-	-	Sandstone
6	AK	4	371.7	4.6	4.6	Top soil
			3169.4	20.1	24.7	Sand
			11644.8	211.5	236.1	Sandstone
			3404.2	-	-	Unconsolidated sandstone

VES No	Curve Type	No. of Layers	Resistivity Value (Ωm)	Thickness (m)	Depth (m)	Probable Lithologic Equivalence
7	KH	4	1156	19.4	19.4	Top soil
			12266.8	185.5	204.9	Sandstone
			5303	48.5	253.5	Unconsolidated sandstone
			11083.8	-	-	Sandstone
9	A	3	753	11.2	11.2	Top soil
			8386.9	85.9	97.1	Sandstone
			11425.7	-	-	Sandstone
10	K	3	710.3	11.6	11.6	Top soil
			13070	78.6	90.2	Sandstone
			10182.3	-	-	Sandstone
13	A	3	375.9	8.5	8.5	Top soil
			553	147.1	155.6	Sandy clay
			1261.8	-	-	Clayey sand
14	H	3	219.9	27.6	27.6	Top soil
			125.9	79.4	107	Clay
			781.4	-	-	Sandy clay

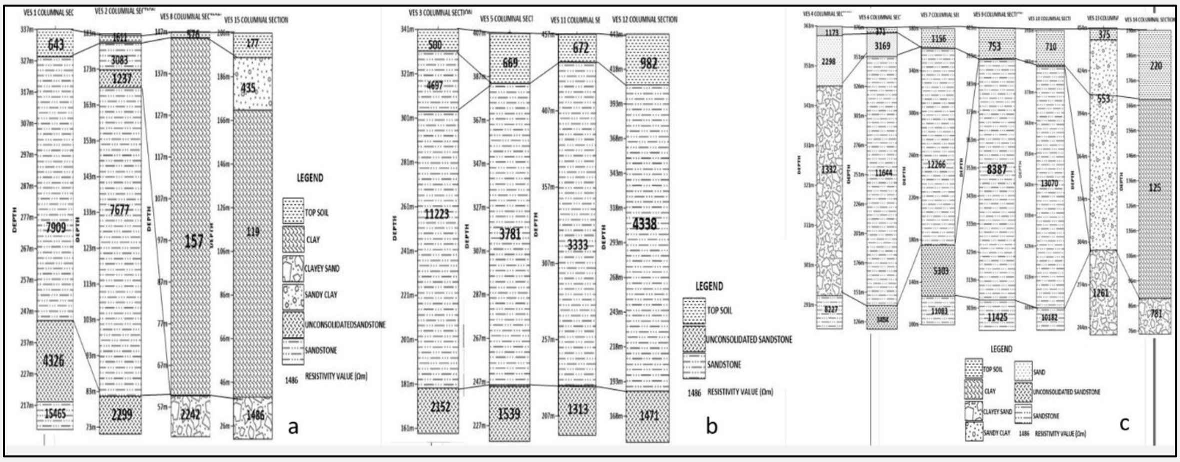

Figure 4. Correlation of the VES data in: (a) Ogwashi Asaba Formation; (b) Imo Shale Formation; (c) Bende-Ameki Formation.

Discussion

Hydrogeological Characteristics of the Ogwashi Asaba Formation, Imo Shale Formation, and Bende-Ameki Formation

The Ogwashi Asaba Formation has four stations of vertical electrical sounding (1, 2, 8, and 15). Geoelectric parameters were generated from the results of the VES interpretation (Table 1) and used to generate the columnar configuration sections shown in Figure 4a. A maximum of six subsurface layers were delineated, and these are the top soil, clay, clayey sand, sandy clay, unconsolidated sandstone, and sandstone. The top soil varying with resistivity values of between 177 m and 1611 Ωm is suggestive of the heterogeneous nature of the materials constituting the layer. The thickness of the top soil varies between 2.4 m and 11.3 m. A pocket of sandy clay with resistivity and thickness values of 435 Ωm and 24 m, respectively, was delineated directly below the top soil in VES 15. The clay layer has resistivity and thickness values of 119 -157 Ωm and 86-132m respectively. The resistivity and thickness values of the sandstone layer are 7677-7909Ωm and 84–86 m, respectively. The unconsolidated sandstone has resistivity values ranging from 2299 to 4326Ωm and thickness varying from 26 m to infinity. The unconsolidated sandstone constitutes the aquifer in this Formation. It is, however, observed from the sections that the aquiferous layers in this Formation are overlaid by either a very thick column of highly resistive sandstone or a thick column of relatively low-resistive clay formation. Consequently, the recharge rate of the aquifer will be very low (Ozegin et al., 2023), making it less prolific. The implication of this, among other things, is that a borehole drilled in any part of this Formation is not expected to yield a good yield. In addition to this, the aquifer in the Formation is also observed to be very thin, occurring at depths of between 86m (276ft) and 132m (433ft). The implications of the occurrence of the aquifer at a very deep depth are that the abstraction of groundwater through hand-dug wells cannot even be contemplated within the Formation.

Four VES stations (VES 3, 5, 11, and 12) were occupied in the Imo Shale Formation. The VES interpretation results and the generated columnar sections are shown in Table 2 and Figure 4b, respectively. Three subsurface layers were delineated in this formation: the top soil, the unconsolidated sandstone, and the sandstone. These layers have varying resistivity values, suggesting the heterogeneous nature of the materials constituting the layers and their thickness. The unconsolidated sandstone layer constitutes the aquifer in the formation. The resistivity values of the aquifer vary between 1313Ωm and 2152Ωm. The relatively low resistivity values characterizing the aquifer layers might be an indication of a good level of saturation in the layer. Furthermore, the sandstone overlaying the aquifer in this Formation is of moderately high resistivity (except in VES 3), which implies that the rainwater percolates (recharges) the aquifer with moderately low resistance. Consequently, the aquifer in this formation is expected to be productive and prolific.

Seven VES (VES 4, 6, 7, 9, 10, 13, and 14) stations were occupied in this formation. The results of the interpretation of the VES yielded geoelectric parameters (Table 3) that were used in preparing columnar sections, as presented in Figure 3c. Seven subsurface layers were delineated from this Formation, and these are: top soil, clay, sandy clay, clayey sand, sand, unconsolidated sandstone, and sandstone. These delineated layers have varying resistivity and thickness values. The unconsolidated sandstone that constitutes the aquifer was only delineated as the last and second-to-last layers of VES 6 and 7, respectively. It is equally important to add that for the aquifer delineated at the two VES locations, there is no significant evidence of saturation, which accounts for the reason why the boreholes existing at VES 6 and 10 are not functioning as at the time of this data acquisition. It is generally observed that the subsurface in this Formation is either underlain by highly resistive sandstone (VES 6, 7, 9, and 10) or by relatively low resistive clay/sandy clay/clay sand layers (VES 4, 13, and 14), neither of which is favorable to groundwater accumulation, transmission, or abstraction. This, among other reasons, accounts for why many of the boreholes drilled in Ekpoma (largely located within the Bende-Ameki formation) are neither functioning nor producing, and this has resulted in the perennial acute water problem being faced by inhabitants of the area.

Comparative assessment of groundwater potential of the three geological Formations

Three geological formations are accessible in the study area. These formations are the Ogwashi Asaba formation, the Imo Shale formation, and the Bende-Ameki formation. From the results of the interpretation of the VES undertaken in the study, it has been established that the major aquifer delineated in the area is the unconsolidated sandstone. This aquifer has varying thickness values and is deeply seated. The depth of the aquifer ranges between 93m and 258m. The effectiveness of the aquifer is largely determined by the thickness of the layer, the resistivity value of the layer (a measure of its degree and saturation), the thickness of the overlying material, and its resistivity value, as these determine the ease and time with which the underlying aquifer will be recharged. It is, however, established from the study that there is a very good indication or evidence of saturation of the aquifer delineated in the Imo Shale Formation. In addition to this, the material overlying the aquifer in this Formation is suspected to be highly porous and permeable, owing to its moderately high resistivity values.

Consequent upon this, the rainwater will easily percolate into the aquifer layer, thereby enhancing or aiding the recharge rate of the aquifer in the Formation. The aquifer in this Formation is thus expected to be highly prolific and productive. This, among other things, accounts for the reason why Irrua, which is largely located within the Imo Shale Formation (Salufu & Ujuanbi, 2015), does not have a problem with groundwater because many of the boreholes located in the community are both functioning and highly productive. On the other hand, the aquifer delineated in the other two Formations is characterized by relatively high resistive values, suggesting less saturation of the aquifer in these Formations. Furthermore, it is also generally observed that the aquifers in these Formations are either overlain by highly resistive sandstone or relatively low-resistive clay, sandy clay, or clay sandy layers, neither of which is favorable for easy recharge of the aquifer system. Ikhifa et al. (2008) made a similar observation. Consequently, the aquifers in these Formations are not expected to be prolific, and this accounts for the reason why most of the boreholes in these Formations are not functioning. Therefore, from what has been established from the findings of this study, the chances of drilling a productive borehole in these Formations are very slim. This is the reason why most boreholes in Ekpoma are neither functioning nor productive.

CONCLUSION

In an effort to provide a lasting solution to the acute groundwater shortage in Ekpoma and its environs, the Electrical Resistivity Method (ERM) was successfully employed to understand the groundwater problem in the study area. Geoelectrical parameters (aquifer resistivity and overburden thickness) were determined from the VES measurements. The geoelectric characteristics of the layers, i.e., layer resistivities and thicknesses, were used to characterize the subsurface. The subsurface layers delineated in the area are: Top soil, Clay, Sandy clay, Clayey sand, Sand, Unconsolidated sandstone, and Sandstone. The curve types varied from three layers to five layers; these are: A, H, K, AK, KH, and HKH. The unconsolidated sandstone layer constituted the sole aquifer unit in the area. This aquifer unit has varying thickness values and is deeply seated. The depth of the aquifer ranges between 103 m and 258m. The study shows saturation in the Imo Shale Formation's aquifer with porous, permeable material. Rainwater easily percolates into the aquifer layer, enhancing recharge. This is the reason Irrua, located in the Imo Shale Formation, has abundant and productive boreholes, ensuring groundwater availability in the community due to its prolific aquifer. On the contrary, the aquifers in the Bende-Ameki and Ogwashi Asaba Formations have high resistive values, indicating less saturation. They are overlain by sandstone or relatively low-resistive clay, sandy clay, or clay-sand layers, making them unsuitable for easy recharge. This results in most boreholes not functioning. Therefore, from what has been established from the findings of this study, the chance of drilling a productive borehole in these Formations is very slim. This is the reason why most boreholes in Ekpoma are neither functioning nor productive. The study concludes that hand-dug wells shouldn't be contemplated, the groundwater prospects of Ekpoma and its environs are low, and alternative means of getting potable water should be put in place by the stakeholders. It is recommended that sustainable groundwater potential and output be achieved in order to provide a long-term solution to water scarcity, particularly in the Bende-Ameki and Ogwashi Asaba Formations.

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