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Geophysical Investigation of Groundwater Potential using Dar Zaroouk Parameters in Shallow Aquifers of Northeastern part of Osogbo. Nigeria

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Abstract

The groundwater potential and aquifer protective capacity in the Kasmo Area of Osogbo were investigated using the Dar Zaroouk approach via the Schlumberger technique of electrical resistivity method. Five vertical electrical soundings (VES) points were occupied and surveyed using the ABEM SAS 1000 terrameter. The field data were first interpreted using the partial curve matching and later iterated using the WinResist software. The resistivities and thicknesses of the geoelectric layers were used to compute the longitudinal conductance and transverse resistance. These were later used to compute the hydraulic conductivity and transmittivity of the aquifers. Three to five geo-electric layers aquifer layers show a confined to semi-confined configuration with the aquiferous layer occupying the second, third and fourth layers. The resistivities vary from 66.5 Ωm in VES 4 to 141.9 Ωm in VES 3. The longitudinal conductance also varies between 0.0366 Ω^{-1} in VES 3 to 0.0074 Ω^{-1} in VES 1 while the transverse resistance varies between 34.8 Ωm^2 in VES 3 to 1043.8 Ωm^2 in VES 5. The transmittivity values were observed to range from 20736.10 m^2/day in VES 3 to 287787.81 m^2/day in VES 4, the aquifers possess high groundwater potential with transmittivity values far above the Offodile classification of aquifer potential limit of 500 m^2/day. The investigation concluded that aquifer potential determination through the estimation of Dar Zarook parameters gives a better aquifer potential determination than the conventional resistivity method as the method compares the potential of all points at once.

Keywords: Aquifer, Kasmo, Longitudinal, Resistance, Resistivity, Transverse

Introduction

With the claim that water constitutes about 71% of the total composition of the earth, access to groundwater usage is becoming a herculean challenge day after day. According to Adagbaba *et al.* (2012), about ten per cent of the population of this world is affected by abject water scarcity. If needed action is not taken, the situation may likely be aggravated to rise to one-third come 2025. However, with the use of water in various sectors of human endeavours, coupled with the unprotected nature of surface water, especially streams, rivers, and run-offs, groundwater has become a necessity for all and sundry to access. With this ever-increasing demand for portable water, there is a need for thorough planning and optimal utilization of water resources.

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The quest for fresh, portable water by man has increased in recent years, especially when the latest technologies are being harnessed to access the underground potential of water. Groundwater is being accessed in Sub-Saharan Africa, where most households depend on hand-dug wells, streams, and rivers due to dilapidated public water facilities established to supply pipe-borne water to communities. Subsurface water within aquifers, especially confined aquifers, remains the safest form of groundwater in terms of quality and portability. However, groundwater potential changes from place to place within the earth's subsurface, primarily due to water distribution. Also, prospecting for groundwater in any geologic formation depends on many hydrogeological parameters hidden in the field data, the determination of which is possible using available geophysical methods suitable for prevailing field circumstances (Chachadi & Pradip, 2012). These parameters include hydraulic conductivity, transmittivity, longitudinal conductance, transverse resistance, and storativity. All these parameters are useful in the assessment of the ability of an aquifer to contain or yield groundwater in economic quantity. These parameters are commonly deduced from geophysical survey data and pumping tests. Transverse resistance and longitudinal conductance (called Dar Zaroouk parameters) are two major and most important parameters deduced from geophysical surveys in assessing the potential of any formation to produce groundwater in economics. Both parameters have found applications not only in groundwater prospecting but also in estimating how protective an aquifer is, towards pollution. The longitudinal conductance (Lc) can define target areas of groundwater potential. An elevated value of Lc indicates a relatively thick succession of geologic layers. It has been accorded the highest priority when considering groundwater potential, while the transverse resistance (Tr) is one of the parameters used to define target areas of good groundwater potential. This directly relates to the transmittivity of water-bearing layers within the subsurface. The higher the Tr, the higher the transmittivity T of aquifers or aquiferous zones. Using this technique in groundwater potential assessment is of great importance because it is instrumental in recognizing and differentiating areas where fresh groundwater aquifer is located at depth from that where salty groundwater is located at depth in a sedimentary environment where the issue of saline water intrusion into coaster aquifer is prevalent. Water can move through the soil in so many ways. It can move as saturated, unsaturated, or fluid (Chandra *et al.*, 2008; Ghassen *et al.,* 2017). Longitudinal conductance and transverse resistance depend on the resistivity and thickness of the aquiferous layer, and these are both derived from electrical resistivity geophysical surveys, especially surveys involving the use of the vertical electrical sounding technique.

Many researchers have employed several approaches in groundwater potential investigation via using the electrical resistivity survey and have been able to use the results from this method in predicting aquifer parameters under different geological conditions. For instance, Braga *et al.* (2006), in their work on the use of the resistivity method in predicting aquifer protectiveness, have been able to show that layered medium usually possesses good fundamental hydrologic qualities that are of paramount importance in the interpretation of geoelectric layers and that these hydrologic qualities are dependent on the resistivity and thickness of the geoelectric layers (Batte *et al.,* 2010; Singh *et al.,* 2005).

Another worker, Sinha and Singhal *et al.* (2009) have established the relationship between geoelectric and hydraulic parameters of an anisotropic aquifer in Ganga-Yamuna interfluves aquifer in North India. Chachadi & and Pradip (2012) also correlated geoelectrical and aquifer parameters in West Coast laterites in Tericol village, North of Goa, India. Youssef (2020) conducted a geoelectrical analysis to evaluate the characteristics of aquifer hydraulics in the Ain El-Soukhna area, West Gulf of Suez, Egypt. He carried out 20 VES surveys that subdivided the shallow section into layers with varying lithologies and water contents under the subsurface of the Ain El-Soukhna area. He also determined the geoelectric Dar-Zarrok parameters in the aquifer hydraulic characteristics evaluation in the same study area. Nemer *et al.* (2023) also carried out a hydro geophysical investigation of aquifer parameters and seawater intrusion in Eastern Mitidja Plain, Algeria, to assess the use of geophysical methods in the estimation of hydraulic conductivity and transmittivity, both of which constitute important hydrogeological parameters. The study also evaluates the marine intrusion in the coastal aquifer of one of the most important plains of Algeria. The results could indicate the aquifer parameters relevant to the siting of water wells, and it also allowed easy delineation of the seawater/freshwater boundary within the subsurface.

Several approaches have recently been employed in aquifer parameter estimation, especially in developed nations. For instance, Zhuang (2019) has used graphical methods to predict aquifer parameters in Wuxi City, Jiangsu Province, China. Ren & Santamarina (2018) also used the variation in pore size characteristics to predict hydraulic conductivity near the Huangshui River basin in Qinghai Province of China.

The latest advances in aquifer parameters prediction in recent times have been in the novel use of type curve analysis of pumping tests with piecewise-constant rates. Of significant note is the work of Li *et al.* (2023), which was carried out, also in Wuxi City, Jiangsu Province, China, to correct the variation of pumping test used for hydraulic parameter estimation, which was observed to vary with time due to some factors. This, they observed, has made the classical constant-rate model unsuitable for accurate parameter estimation. To address this issue, they developed a novel dimensionless-form analytical solution for variable-rate pumping tests involving piecewise constant approximations for variable pumping rates. The analysis and interpretation of the time-drawdown curves generated from the work revealed that the first-step type curve was consistent with the Theis curve. In contrast, subsequent steps performed deviated from the Theis curve. They were associated with the first inflexion time (It, D), which depended on the hydraulic conductivity (K) and specific storage (Ss) of the confined aquifers. This has been receiving worldwide attention in recent times.

In Nigeria, several authors have employed electrical geophysical methods and techniques in subsurface groundwater investigation {Emenike 2001, Asokhia *et al.,* 2000, Alile & Amadasun. 2008, Oyedele, 2001} but a few have discussed the relationship between the Dar Zaroouk parameters and the groundwater potential of an aquifer. For instance, Bayewu *et al.* (2018) carried out an electrical resistivity survey to investigate the subsurface rocks of the main campus of the Olabisi Onabanjo University, Ago-Iwoye, studying the aquifer protective capacity using the Schlumberger array technique. Nwachukwu *et al.* (2019) also evaluated the groundwater potentials of Orogun, South-South around Orogun Town, Ughelli North in Delta State, Nigeria, by geoelectric estimation of the Dar Zaroouk parameters. They combined this with the traditional resistivity approach. Their results revealed that the area has good groundwater potential but might have been highly contaminated, especially from hydrocarbon sources and other man-made pollutants. Adeniji *et al.* (2022) applied the Dar-Zaroouk approach to groundwater protective capability within the crystalline basement formation in southwestern Nigeria. The result revealed about 70% evidence of poor/weak groundwater protection potential – meaning that the availability of potable groundwater quality may not be feasible but may soon constitute a tragic event due to contaminating activities that could occur when contaminant plume percolate from the topsoil to the subsurface soil in the nearest future.

In a bid to delineate groundwater potential zones of the alluvial formations using Dar Zarrouk parameters and groundwater flow direction on the floodplain in Geriyo irrigation floodplain of River Benue, Adamawa State, Northeastern Nigeria. Ankidawa & Seli (2018) employed the Dar Zaroouk parameters from geoelectric data. Three groundwater potential zones were delineated on the floodplain based on the longitudinal conductance, transverse resistance, and transmittivity values obtained from their study area; the results of the hydraulic head reveal that the water levels in the floodplain is higher than the river and recharge the river. Other workers have also done extensive work in and around the Basement complex located in different parts of Nigeria (Chinwuko *et al.*, 2016; Anizoba *et al.,* 2015a, Anizoba *et al.,* 2015b, Ekenta 2015; George *et al.,* 2015, Obiora *et al.,* 2016, Olusegun *et al.,* 2016, Obiajulu & Okpoko, 2015, Badmus & Olatinsu, 2012).

The Kasmo area of Osogbo is a zone with difficult geologic terrain within the Osogbo metropolis whose groundwater potential has been a challenge, especially at shallow depths. Unlike in a typical quartzite terrain where groundwater prospect is enormous due to an extensive jointing system, the local geology of the Kasmo area is more of talc schist enclosed within a banded gneiss environment with few visible outcrops. However, the prospect of groundwater in such an area would be a challenge. Conventional geoelectric surveys used by workers have failed several times due to the intricacies associated with the area's geology. Therefore, this study desires to go further from the traditional geoelectric method in investigating the groundwater potential. The Dar-Zaroouk parameters were used in the assessment of the groundwater prospectivity around the Kasmo area, Ibokun Road, Osogbo, which is located at the Northeastern part of Osogbo by carrying out vertical electrical sounding using Schlumberger array, delineating geo-electric layers, determining the resistivities and thicknesses of the geo-electric layers, computing the hydraulic conductivity, longitudinal conductance, the transverse resistance and access the groundwater potential. The Kasmo community is of great concern because of its rapid urbanization in the Kasmo Area and the establishment of the Kasmo Soap factory, an industry that has been linked with the use of large volumes of water.

Location and Accessibility

The Kasmo area of Osogbo (very close to the "Kasmo Industry") is located around the Shasha area, along Ibokun road, northeast of Osogbo, South-West Nigeria. This area falls within latitude 004° 34.913' to latitude 004° 34.601', and longitude 07° 46.276 to longitude 07° 46.319 (with an elevation of 350 m above sea level). It is a large rural settlement located at the northeast extremity of Osogbo. Lots of buildings dominate the community with some residential apartments still under construction both for residential as well as for small-scale enterprises just springing up. Untarred roads mainly access the area. The Ibokun road runs from west to east and to the outskirts of Osogbo (Ibokun town). The study area is an undulating lowland area with an average elevation of 350 m. The Kasmo area is void of hills, mountains, huge outcrops, or rocks that may influence the relief. Erosional channels caused by run-off on undulating features characterise the area. Being a developing area, drainages are yet to be constructed, resulting in an undefined movement of water that has disrupted the untarred roads and surfaces.

Geologic Setting

Regional Geology of the Study Area

The geology of Nigeria can be divided into two major parts. First is the Basement Complex of Nigeria and the sedimentary basins of Nigeria. Three basement complexes exist in Nigeria: the Basement Complex of Southwestern Nigeria, the Basement Complex of Northern Nigeria and the Basement Complex of Southeastern Nigeria. The sedimentary basins of Nigeria are divided into nine basins. The basement complex of Southwestern Nigeria has been affected by the Pan African Orogeny, which occurred about 600 Mya and is formed due to the collision of the active Pharusian continental plate and the passive continental margin of the West African craton (Dada, 2006). Extensive migmatization, metamorphism, gneissification and granitization accompany the Pan-African deformation, especially at the regional level, thus, forming syn-tectonic granites coupled with homogeneous gneisses. Olayinka (1992) opined that the end of the orogeny was marked by extensive fracturing and faulting episodes. Rahaman (1988), stated that four major distinguishable petro-lithological units can be found in the Basement complex of Nigeria. These include the migmatite-gneiss and unmigmatite gneiss, quartzite, schist, metasedimentary and metavolcanic rocks.

The area covered by this work is located within the Southwestern Nigeria basement complex having its main lithologies comprising amphibolite, migmatite, gneisses, granites and pegmatite. Other important rock units are the schists, made up of biotite schist, quartzite schist talc-tremolite schist, and muscovite schists.

Local Geology of the Kasmo Area

Figure 1 presents the local geology of the study area. At the local level, two major lithology units dominate this area: talc schist and banded gneisses, which are also constituents of the "gneiss-migmatite-quartzite complex" of the Basement Complex of Nigeria. Tijani & Omodera (2009) observed that ninety per cent of these rock protoliths are covered by lateritic topsoil since only a few rock exposures could help delineate the rocks. The gneiss occurs as banded granite gneiss or grey gneiss with coarse to medium-grained texture. The most common minerals in the lithology in the study area include quartz, feldspar and biotite, which have implications for groundwater accumulation and movement (Ayantunji, 2005). These minerals are weathered easily to form clay minerals. They also serve as water-bearing horizons of the regolith that produce the overburden. Major structural features exhibited by these rocks are foliation, faults, joints and micro folds, and sand-sized particles.

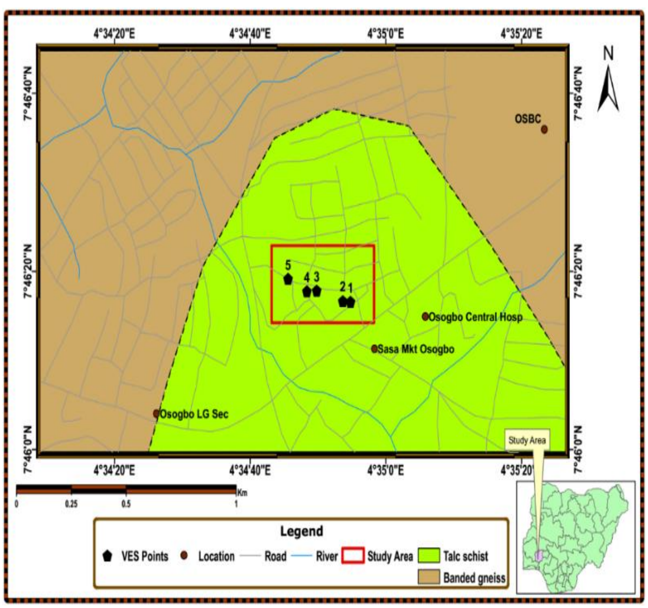

Figure 1: Local Geology of the Study Area showing the Position of the VES points.

1. Materials and Methods

The work was done in stages. A preliminary reconnaissance survey and visit were made to the site to access the location, topography and possible points to site the VES positions. The area under study was properly georeferenced. The second stage involved the proper geophysical investigation. ABEM SAS 1000 tetrameter was used to investigate vertical variation in electrical resistivity of the subsurface layers with depth. VES points were selected at random within the study area. The VES soundings were conducted over an electrode spread traverse that extend over 100 m from the centre reference to either side of the traverse. Schlumberger electrode configuration was employed. Five VES points were occupied in the course of the investigation. A partial curve matching technique was used to carry out the initial interpretation of the field data while the raw field data were later iterated and modelled using the WinResisit software using the apparent resistivity and thickness from partial curve matching as input into the software. Geo-electric parameters (resistivities and thicknesses) derived from the iterated data were extracted from the iterative curve. The geo-electric resistivities and thickness parameters were used to estimate the Dar Zarook parameters – longitudinal conductance and transverse resistance. The hydraulic conductivity of the aquiferous layers was derived using the Heigold *et al.* (1979) equation and using the resistivity of the groundwater (derived from the inverse of the conductivity) within the aquiferous layer as input into the equation. The transmittivity of each aquiferous layers was computed using the hydraulic conductivities. Isopach maps of depth to aquifers, transmittivity and resistivity maps were generated for the study area. Transmittivity values obtained were used to unravel the groundwater prospectivity of the Kasmo area using Offodile (1983) classification of transmittivity classification chart.

Theoretical Background

Hydraulic Conductivity (K)

Hydraulic conductivity is simply a measure of a material's capacity to transmit water. It is a constant of proportionality that relates the specific discharge of a previous medium under a unit gradient in Darcy's law:

$$V = -K * I \qquad (1)$$

where v is specific discharge, K is the hydraulic conductivity, and *i* is the hydraulic gradient.

Hydraulic conductivity can also be called the coefficient of permeability and has velocity units. e.g. m/sec or m/day. Theoretically, the hydraulic conductivity is computed using the Heigold *et. al.,* (1979) equation as shown below;

$$K = 386.40 * R_w^{-0:93283} \quad (2)$$

where K is the hydraulic conductivity and R_w is the resistivity of the water within the aquiferous layer. 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 values indicate that the materials are less permeable. Various earth materials possess different hydraulic conductivities.

Open gravels have hydraulic conductivity in the range of 10^{-2} m/sec, while un-fissured clays possess hydraulic conductivity in the range of 10^{-11} m/sec. This indicates that hydraulic conductivity values are higher in porous materials such as gravel and coarse sand and lower in less porous rocks like fine sand, silt and clay (Preene, 2014).

Transmittivity (T)

Transmittivity is the rate of flow of subsurface fluid (groundwater) under a unit hydraulic gradient in a unit breadth of the aquifer of a given saturated thickness. The volume of water that can be transmitted horizontally in an aquifer is dependent on the volume of water that is held in the aquifer and also dependent on the lithology of the aquiferous layer. Clay can retain water but it transmits the water slowly. Such a layer will have plenty of water but low transmittivity . One striking feature of a good aquifer is the ability to release much water when it is of a porous lithology such as sand, gravel, etc thereby possessing increased transmittivity . Fitts (2002) observed that if the hydraulic conductivity that is tangential to a particular layer *K can* be established over the thickness h of a layer, then, the transmittivity *T* of the layer could simply be related to its hydraulic conductivity as follows:

$$T = k * h \quad (3)$$

where *T* represents transmittivity, k is the hydraulic conductivity of the aquifer, and h represents the aquifer thickness. It is measured in m^2/day (or m^2/sec). However, if a hydrologic layer is made up of n number of strata with thickness *hi* and hydraulic conductivity (*Kt*)*i*, the total transmittivity of the layer can be expressed as the sum of all the transmittivity of each stratum that makes up the strata. That is,

$$T = \sum_{i=1}^{m} T_i \quad (4)$$

$$T = \sum_{i=1}^{m} (k_i) * h_i \quad (5)$$

Hence, using Darcy's law and the definition of transmittivity , it is possible to show that that the discharge of fluid in a particular direction x through a length of aquifer that extends a distance Δy in the *y* direction is

$$Q_x = -T \frac{\partial h}{\partial x} \Delta y \quad (6)$$

Longitudinal Unit Conductance and Transverse Unit Resistance

Two important parameters stand out amongst all the aquifer parameters and these two define the geoelectric characteristics of any subsurface earth layer. These are the longitudinal unit conductance (*Lc*) and transverse unit Resistance (*Tr*) both of which have been called the Dar Zaroouk (DZ) parameters. They were originally described by Maillet (1947). The other parameters include the coefficient of anisotropy, given by λ; which is a parameter that can derived easily from the distribution of the resistivity of the medium. The DZ parameters are significant in that they are often geo-electrically equivalent parameters and they both are the layer parameters that can be most easily and accurately defined from VES sounding, depending upon the arrangement of the geo-electric layers. They are both expressed as:

$$Lc = h/\rho \quad (7)$$

$$Tr = \rho * h \quad (8)$$

where *Tr* is the transverse unit resistance, *Lc* is the longitudinal unit conductance ρ, the aquifer resistivity and *h*, is the aquifer thickness. These two parameters represent the geo-electric properties of protective layers.

Considering a medium of subsurface rock having n layer, the total longitudinal unit conductance represented by T_{Lc} or S, is the summation of all the longitudinal unit conductance of all the geoelectric layers. This can be expressed by the equation given by

$$S = T_{Lc} = \sum_{i=0}^{n} \frac{h_i}{\rho_i} = \frac{h_1}{\rho_1} + \frac{h_2}{\rho_2} + \frac{h_3}{\rho_3} + \frac{h_4}{\rho_4} \dots\dots\dots\dots\dots\dots\dots\dots \frac{h_n}{\rho_n} \quad (9)$$

where i is the topmost layer and 1, 2, 3, 4 and n are the first, second, third, fourth and the nth layers. On the other hand, the total transverse unit resistance in several layers of the earth is expressed by the equation given by

$$P = T_{Tr} = \sum_{i=0}^{n} h_i\rho_i = h_1\rho_1 + h_2\rho_2 + h_3\rho_3 + h_4\rho_4 \dots\dots\dots h_n\rho_n \quad (10)$$

where "i" is the topmost layer and 1, 2, 3, 4 and n are the first, second, third, fourth and the nth layers. The Lc has been related to the protective capability of a layer (Oladapo & Akintorinwa, 2006). A protective layer in the subsurface is a layer that is highly resistive, e.g. clay, silty clay, fine sand etc. When *Lc* values are high for a protective layer, it is not a good aquifer with portable water. Values of *Lc* must be low, while that of *Tr* would be very high. In hydrogeological investigations, *Tr* has been demonstrated to be functionally analogous to hydraulic transmittivity. However, relatively little use has been made of parameters Lc. Herient (1976) used Lc to access the protective capacities of silty clay layers overlying a limestone aquifer. Table 4 is the table showing the range of values of Lc and their corresponding rating for the protective capability over an aquifer.

Results and Discussions

Geoelectric Parameters

This section presents the results of the interpretation and iteration of the field data. The field data were first interpreted using partial curve matching while iteration was carried out using the WinResisit software. Table 1 is the summary table of all the resistivity (ρ) values and the thickness (h) obtained from the iteration of the field data. Table 2 is the table that summarises the resistivities and thickness of the aquifers and the aquifer parameters viz - longitudinal conductance and transverse resistance, while Table 3 shows the summary of all the VES points, their coordinates, aquifer resistivities, Transmitivities, transverse resistance as well as the aquifer depth. Table 4 is the Dar-Zaroouk parameters classification of longitudinal conductance as proposed by Oladapo & Akintorinwa (2006), while Table 5 is the potential aquifer classification based on transmittivity values (as proposed by Offodile, 1983).

Figures 2 to 6 show the iterative curves obtained from the study area, while Figures 7, 8 and 9 show the resistivity map, the transverse resistance map and the transmittivity maps, respectively. Figure 10 is the aquifer depth map of the study area, while Figure 11 shows the geoelectric section of the study area and the geologic interpretation of the different layers. The idea of this interpretation is based on the knowledge of the physical properties of the subsurface lithology in terms of their resistivity (inverse of conductivity). Generally, low resistivity zones could indicate the presence of high conductive materials, conductive zones or the presence of clay–bearing layer. However, in this case study, low resistivity zones are indicative of a conductive water-bearing interval; this, therefore, aided in groundwater exploration.

The plot of VES data ranges from a typical "HA-curve" to KHA, HA and HKHA. The topmost geoelectric layer reveals a topsoil of about 334.0 Ωm of about 1.5 m thick in VES 1, 162.3 Ωm with a thickness of 1.1 m in VES 2. In VES 3, the resistivity of the topmost layer was observed to be 103.4 Ωm with a layer thickness of 0.8 m but it is 206.7 Ωm and 181.1 Ωm in VES 4 and 5 with thicknesses of 0.8 m in VES 4 and finally 1.0m in VES 5. The topmost layer is interpreted as clayey sand/sands.

The second layer has a thickness of 1.5 m and has its resistivity dropped to 202.4 Ωm in VES 1, the resistivity of 271.5 Ωm and thickness of 0.6m in VES 2 but of about 444.9 Ωm and thickness of 5.5m. in VES 3, 119.3 Ωm and thickness of 0.4 m in VES 4 and 437.8 Ωm and thickness of 3.4 m in VES 5. The second layer is interpreted to be sand bearing in VES 1, 2 and 4, while in VES 3 and 5; they were interpreted to be lateritic materials. In VES 1, the third layer has a resistivity value of 982.5 Ωm and lithologically, it represents a basement. The weathered interval overlying the basement is believed to be the unconfined aquifer (aquitard) because it has the lowest resistivity, indicating a fine sand layer. In VES 2, it is also the very low resistivity aquiferous zone of about 69.6 Ωm aquifer of thickness of 0.5m. In VES 3, a weathered layer of resistivity value 141.9 Ωm sits upon the basement layer, while the weathered zone represents the fourth layer in VES 4 and 5. These weathered zones sit conformably on the basement subsurface rock (Figure 2 to 6). Generally, it is evident from the depth of the aquifer within the study area that these aquifers constitute the shallow aquifer system.

Table 1: Summary table of all VES interpretations showing the resistivities and inferred lithologies

SN	CURVE TYPES	VES POINTS	Resistivity (Ωm)	Thickness (m)	Depth (m)	Lithology Inferred	Aquifer Depth (m)
	HA	VES 1	334.0	1.5	1.5	Sandy Topsoil	
			202.4	1.5	3.0	Weathered layer	3.0
			982.5	--	--	Fresh Basement	
	KHA	VES 2	162.3	1.1	1.1	Clayey Sand Top soil	
			271.5	0.6	1.7	Sandy layer	2.2
			69.6	0.5	2.2	Weathered Basement	
			1569.0	--	--	Fresh Basement	
	KHA	VES 3	103.4	0.8	0.8	Clayey Sand Top soil	0.8
			444.9	5.5	6.3	Laterite layer	
			141.9	5.2	11.5	Weathered Basement	
			1953.0	-	-	Fresh Basement	
			206.7	0.8	0.8	Sandy topsoil	6.0
			119.3	0.4	1.2	Clayey Sand	
	HKHA	VES 4	898.0	2.4	3.6	Fresh Basement	
			66.5	2.4	6.0	Fracture layer	
			854.0	-	-	Fresh Basement	
	KHA	VES 5	181.1	1.0	1.0	Clayey Sand Top soil	13.9
			437.8	3.4	4.4	Laterite	
			122.8	9.5	13.9	Weathered Basement	
			2129.9	--	--	Fresh Basement	

Table 2: Table showing Dar Zaroouk Parameters in the aquifer in all VES Points

	Resistivity (Ωm)	Thickness (h)	Lc (Ω^{-1})	Tr (Ωm^2)
VES 1	202.4	1.5	0.0074	303.6
VES 2	69.6	0.5	0.0071	34.8
VES 3	141.9	5.2	0.0366	737.88
VES 4	66.5	2.4	0.0369	159.6
VES 5	122.8	8.5	0.0692	1043.8

Table 3: Summary Table of all the VES points, their Coordinates, aquifer resistivities, Transmitivities, transverse resistance as well as the aquifer depth.

	Coordinates	Aquifer Resistivities (Ωm)	Transmitivities (m^2/day)	Transverse Resistance (Ωm^2)	Aquifer Depth (m)
VES 1	N 07˚ 46.276’ E 004˚ 34.913’	202.4	71483.96774	303.6	3.0
VES 2	N 07˚ 46.278’ E 004˚34.894’	69.6	108620.9233	417.6	2.2
VES 3	N 07˚ 46.297’ E 004˚ 34.830’	103.4	20736.10217	82.72	11.5
VES 4	N 07˚ 46.296’ E 004˚ 34.806’	66.5	41689.98446	159.6	6.0
VES 5	N 07˚ 46.319’ E 004˚ 34.760’	122.8	287787.8128	1166.6	13.9

Table 4: Table showing the Dar Zaroouk Parameter Classification of Longitudinal Conductance (Oladapo & Akintorinwa, 2006)

LONGITUDINAL UNIT CONDUCTANCE (Ω^{-1})	RATING OF PROTECTIVE CAPACITY
> 10	Excellent
5-10	Very good
0.7-4.9	Good
0.2-0.69	Moderate
0.1-0.19 0.2	Weak
< 0.1	Poor

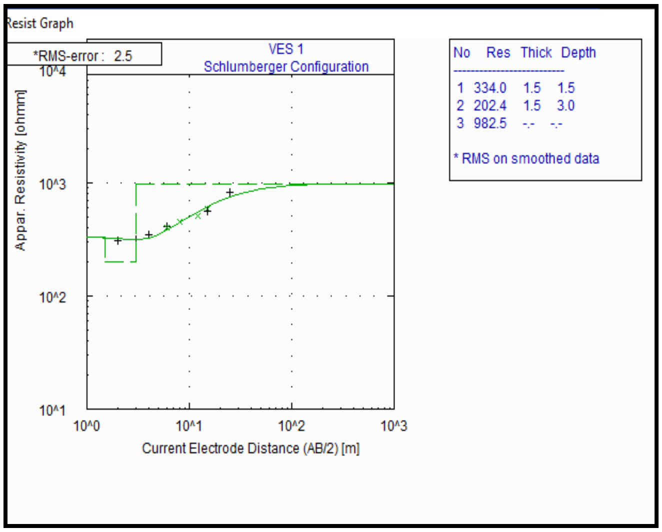

Figure 2: VES 1 Iterative Curves

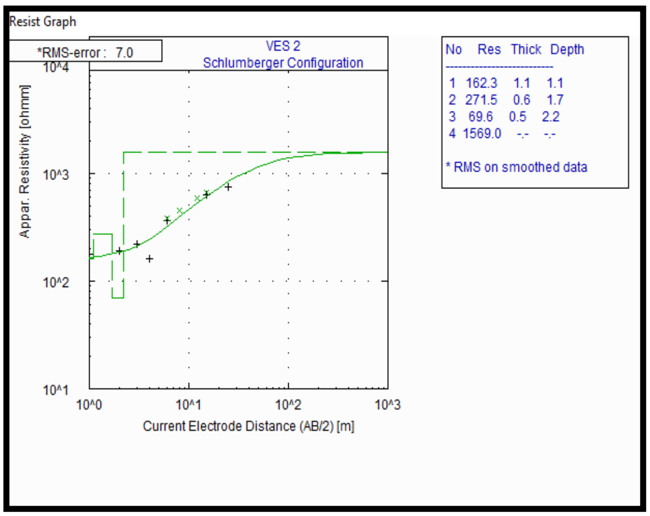

Figure 3: VES 2 Iterative Curves

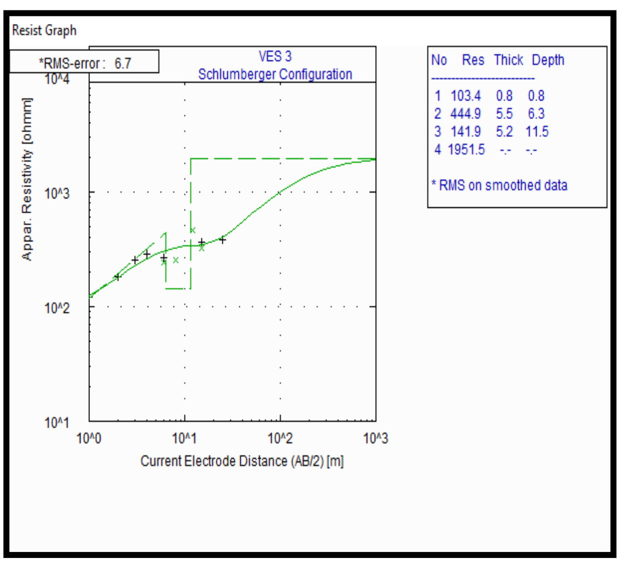

Figure 4: VES 3 Iterative Curves

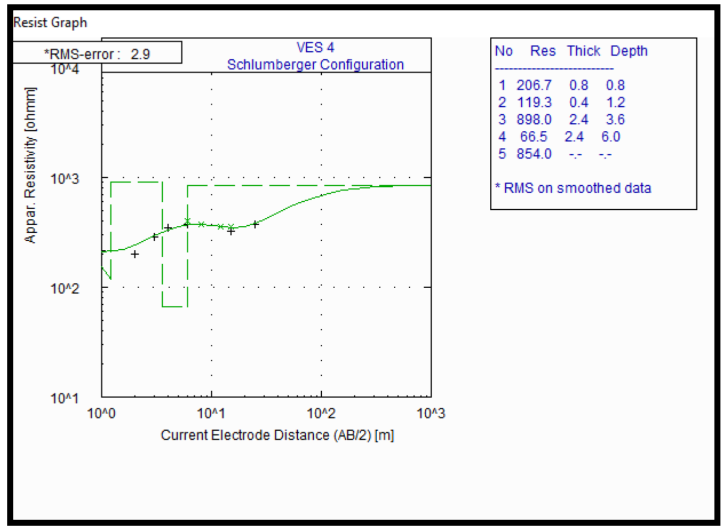

Figure 5: VES 4 Iterative Curves

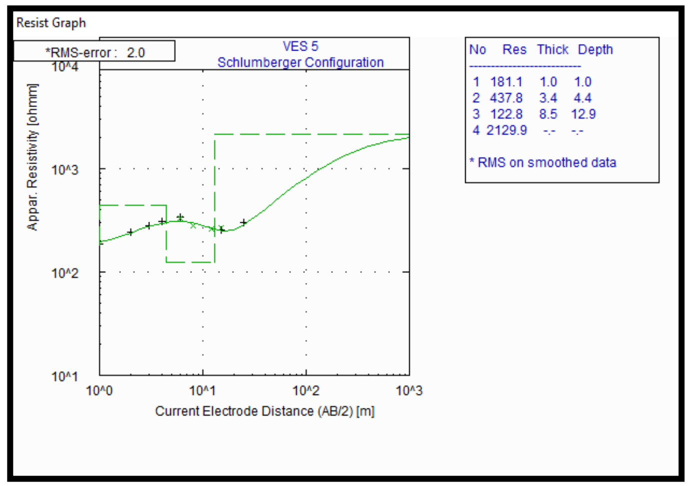

Figure 6: VES 5 Iterative Curves

Dar Zarouk Parameters

The result of the resistivities and the thicknesses of the aquifers from the iterative curve and the coordinates of the VES points are shown in Table 3. Here, the VES 1 aquifer is located at a depth of 3.0 meters while its resistivity is 202.4 Ωm. The Lc and the Tr of the aquifer in this VES point were calculated to be 0.0074 Ω^{-1} and 303.6 Ωm^2 respectively. In VES 2, the shallow aquifer is located at a depth of 2.2 meters while its resistivity is 69.6 Ωm. The aquifer's Lc and Tr in VES 2 were computed to be 0.0071 Ω^{-1} and 34.8 Ωm^2 respectively. However, in VES 3, the aquifer is located at a depth of 11.5 meters while its resistivity is 141.9 Ωm. The Lc and the Tr in VES 3 were calculated to be 0.0366 Ω^{-1} and 737.88 $\Omega m^{2,}$ respectively while the aquifer in VES 4 and VES 5 are both located at a depth of 6.0 m and 12.9 m respectively. The resistivity values in VES 4 and 5 were computed to be 66.5 Ωm and 122.8 Ωm respectively but their Lc and Tr were computed to be 0.0692 Ω^{-1} and 1043.8 Ωm^2 respectively.

Resistivity Distribution Map

Interpretation of the field data revealed that the highest resistivity values are found in VES 1, which is located towards the eastern part of Kasmo and in VES 5, which is located in the northern part of the area, while it is slightly low at the central part where VES 3 is located. However, lower values were found to concentrate in the middle portion of the study area where VES 2 and VES 4 are located (blue portion of Figure 7). Conversely, points where light blue colour bands were observed show that the area possesses resistivity values that are between 101.1 Ωm and 135.0 Ωm and this is observed in VES 3. Where blue colour bands exist are points where resistivity values are far lesser than 100.40 Ωm. The same is observed in VES 2 and VES 4. This shows that at VES point 5, the resistivity values are higher than that in VES 2, VES 3 and VES 4 but lower than in VES 1. The resistivity value in VES 5 is between 135.1 Ωm to 170 Ωm. However, in terms of transverse resistance, it is relatively proportional to the resistivity. This means that a high transverse resistance value is indicative of places with high resistivity materials and vice versa. However, this is not so in the transverse resistance map (Figure 7). On the contrary, the transverse resistance map shows that VES point 3 and VES point 4 have the lowest transverse resistance value; which is not only lesser than 354.0 Ωm^2 but also located on the green portion of the transverse resistance map. Also, the purple portion on the transverse resistance map has the highest transverse resistance value which is greater than 896.0 Ωm^2. However, the light green portion where the VES 1 point is located, has a transverse resistance value between 354.1 Ωm^2 and 625.0 Ωm^2, which is higher than what is obtained in VES 3 and VES 4 but lower than that of VES 5. This shows that at VES point 2, the transverse resistance value is higher than that in VES 1, VES 3, VES 4 and VES 4 but lower than in VES 5. The transverse value in VES 2 is between 625.1 Ωm^2 and 896.0 Ωm^2 (Figure 8).

Table 5: Potential Aquifer Classification Based on Transmittivity Values (Offodile 1983)

Transmittivity (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 6: Table showing the Transmittivity (T) and Transverse Resistances values.

	Resistivity of the Aquifers (Ωm)	Hydraulic Conductivity (mS)	Transverse Resistance	Transmittivity (m^2/day)
VES 1	202.4	235.4544	303.6	71483.96774
VES 2	69.6	260.1075749	417.6	108620.9233
VES 3	141.9	243.38498	737.88	179588.897
VES 4	66.5	261.2154415	159.6	41689.98446
VES 5	122.8	246.6893647	1166.6	287787.8128

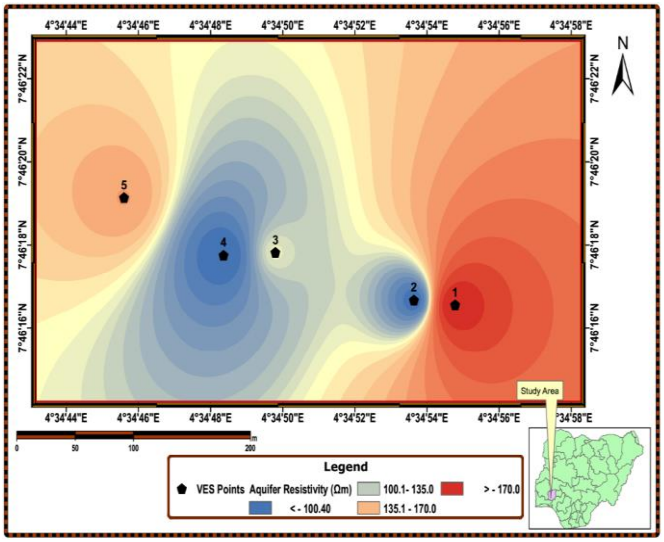

Figure 7: Aquifer Resistivity map of the study area

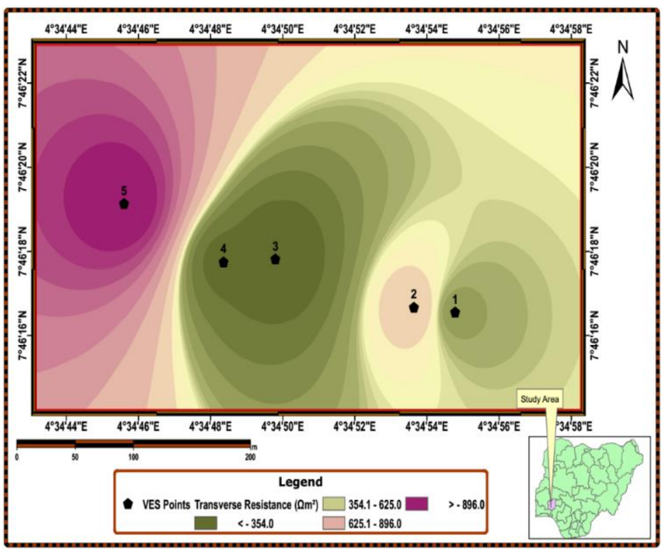

Figure 8: Transverse Resistance map of the study area

Transmittivity Estimation

Using the Heigold *et. al.* (1979) equation to obtain the transmittivity value in all the VES points, the result showed that the hydraulic conductivity in VES 1 was 235.45 m^2/day while that of VES 2 and VES 3 aquifers was computed to be 260.1076 m^2/day and 243.38498 m^2/day respectively. However, the hydraulic conductivities in VES 4 and VES 5 were also computed to be 261.22 mSeimens and 246.69 m^2/day respectively. From the study, it is observed that the hydraulic conductivity was observed to be low at VES point 1 and VES point 3 while it was highest in VES 2 and VES 4. However, in VES 5, it is averagely high. In all the VES points, the transmittivity is very high, and far above the Offodile (1983) aquifer potential classification table (Table 5) which states that any transmittivity value above 500 m^2/day is a high transmittivity value and such an aquifer has a very high groundwater potential. It went on to suggest that any transmittivity values between 50 m^2/day and 500 m^2/day will give a moderately high groundwater potential while transmittivity values between 5 to 50 m^2/day is a low groundwater potential. The result suggests that the area under investigation, the Kasmo area, has good groundwater potential. This is based on the transmittivity values computed for VES 1 to VES 5 as shown in Table 6.

The transmittivity values are higher towards the western part of the study area where VES 5 is located while it is slightly low at the middle of the study area. However, there seems to be a relatively high region of transmittivity towards the eastern part of the study area. (Figure 9). Within the study area, the transmittivity estimates were found to be very high and even higher than the 500 m^2/day as suggested by Offodile's (1983) classification. However, the transmittivity map showed that the area to the western part of the study area shows transmittivity values that are higher than all other areas on the map. This is depicted in the red portion of Figure 9. On the other hand, points where yellow colour bands are observed show that the area possesses transmittivity values that are between 154,000 and 221,000 m^2/day. Where deep blue colour bands exist are points where transmittivity values are the least. This shows that at VES point 5, the transmittivity values are higher than that in VES 2 while those in VES 3 and 4 possess lesser transmittivity. In terms of depth, VES point 3 and 5 have their aquifers at higher depths as they are both above 11 meters deep. This is as shown by the red portions on the aquifer depth map of Figure 10. On the other hand, VES points 1, 2 and 4 have their aquifers situated at shallow depths below 5.1 meters. This means that the groundwater aquifers in

VES 3 and VES 5 are at lower hydraulic potentials while those at VES 1, VES 2 and VES 4 are at fairly higher hydraulic potentials compared to VES 3 and VES 5.

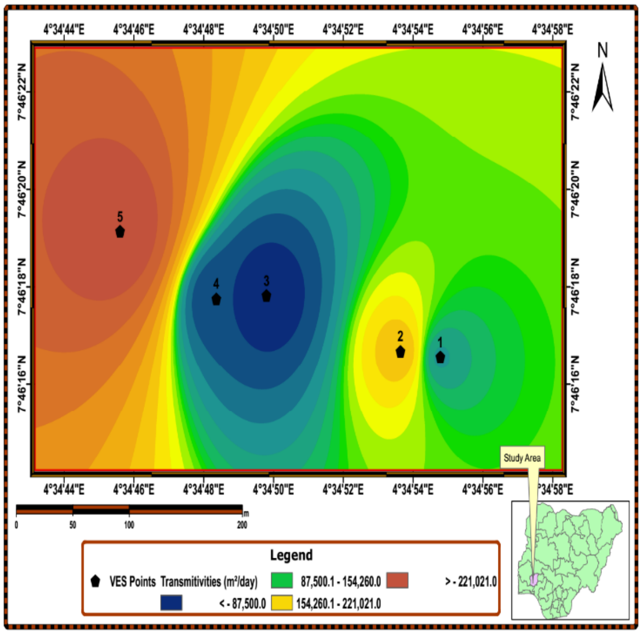

Figure 9: Figure Showing the Transmittivity Distribution in the Study Area

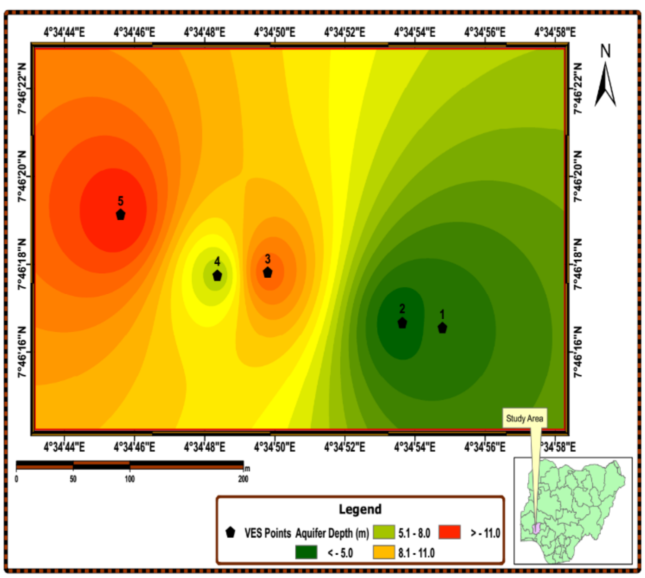

Figure 10: Aquifer Depth Map of the Study Area

Figure 11 represents the geoelectric section of the Kasmo area. The area under investigation is underlain by clayey sand /sandy topsoil having a resistivity that ranges from 103.4 to 181.9 Ωm within the clayey sand and from 206.7 Ωm^2 to 334.1 Ωm within the sand-bearing topsoil. This is followed at shallow depth by the aquiferous layers in VES 1 and 2 but at relatively deeper depth in VES 3, 4 and 5, first by laterite before encountering the water-bearing sandy clay interval. This aquiferous layer sits conformably on the basement rock from which the overlay is derived. Generally, VES 1 and 2 aquifers are relatively thin, having thicknesses of 1.5 m and 0.6 m respectively while in VES 3, 4 and 5 are relatively thicker than this. It is about 2.4 m, 5.5 m and 9.5 m in VES 4, 3 and 5 respectively. The resistivity of the shallow aquifers ranges from 66.2 Ωm in VES 4 to 122.8 Ωm in VES 5 and finally 141.9 Ωm in VES 3, an indication of optimum weathering, high to medium groundwater potential, hence the likelihood of possessing abundance groundwater potential (Wright & Burgess, 1992).

Conclusion

In this research, the groundwater potential and protective capability of the subsurface soil in the Kasmo area in Osogbo in Osun State, Nigeria were investigated using the Dar Zarook approach. Five VES-sounding surveys were conducted with the ABEM SAS 1000 resistivity meter. The exercise was conducted using the Schlumberger electrode arrays that cover a total of 100 meters on each side of the central reference VES point (200 m in total) with the opportunity to view the shallow aquifers in the study area. Data obtained from the survey were first interpreted using partial curve matching and later iterated and modelled using the WinResisit software. Using the resistivities and the thicknesses of the aquiferous layer of each VES point, the Lc and Tr of the aquifers were calculated. In addition, the Heigold *et al.* (1979) equation was employed to compute the hydraulic conductivity of the aquifers in all the VES points using the resistivity derived for the aquiferous layers. Since the transmittivity of any aquiferous layer is a function of the prospectivity of the aquifer, the transmittivity in all the VES points was concluded using the hydraulic conductivity deduced from the Heigold *et. al.*(1979) equation.

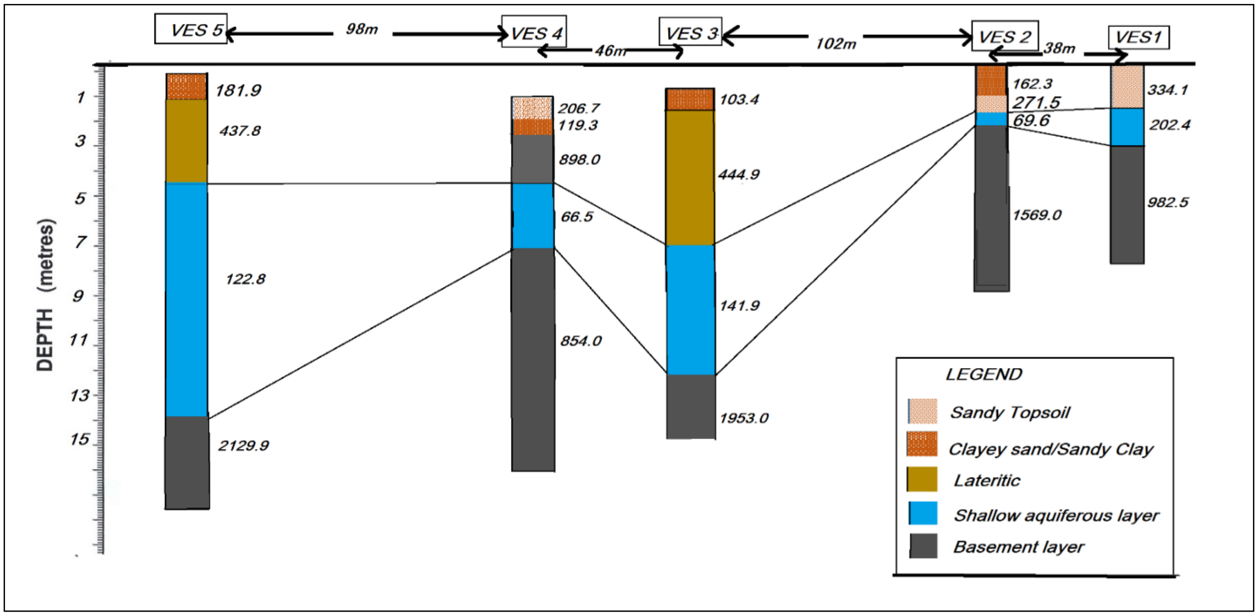

Figure 11: Geoelectric section showing the shallow aquifers of the Kasmo area

From the geophysical investigation, the resistivity-sounding results revealed five curve types in the study area. These are the HA curve (VES 1), and HKA curve (VES 2, 3, 4 and VES 5) with the geo-electric layers varying from three to five and varying resistivity and thicknesses across all VES points. The subsurface lithology comprises sandy or lateritic topsoil, a weathered basement and a fresh basement. Sandy materials in VES 1 and 2 but lateritic soils in VES 3, 4 and 5, underlie this. However, Offodile (1983) suggested that any well with transmittivity higher than 500 m^2/day would have high groundwater potential, the transmittivity values were high in all the VES and higher than 500 m^2/day ranging from 41689.98 m^2/day to 287787.81 m^2/day. From the analysis based on both the resistivity values and hydraulic parameters, all five VES points proved to harbour water (but may not be enormous) in weathered layers. However, the Dar Zaroouk parameters (i.e. longitudinal conductance unit and transverse resistance unit) and the transmittivity values for the aquiferous layer indicate that all VES points have high groundwater potential and proved to harbour groundwater.

Although the transmittivity values observed in this study area are generally high, the transmittivity map indicates that 60 % of the area falls under the category of very high to average to high transmittivity and hence, higher longitudinal conductance values in the northwestern-central part of the area, hence having a higher groundwater prospect than other. In addition, there exists a direct correlation between Tr and the transmittivity. This is shown in Figures 8 and 9 and Table 6. Lithologically, the area shows different layers in terms of the loose clayey sand/admixture of sand and clayey sand and little presence of lateritic material.

An improvement of this work is possible especially when geoelectric survey information is combined with aeromagnetic data or remote sensing data. The integration of the data from these three geophysical methods can go a long way towards improving the groundwater prospectivity determination in the study area, especially in such a terrain where there exists challenging geology by providing more information about the subsurface lineament, the possible orientation of the lineaments and the subsurface topography.

In this work, the result of the geophysical survey cum geoelectric section combined with the maps and aquifer parameters have been useful towards finding out the groundwater prospect of the shallow aquifer of the Kasmo area of Osogbo. This study is beneficial to the immediate community for the exploitation and exploration of the groundwater resource.

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Conflict of Interest

The authors of this paper admit that there exists no conflict of interest whatsoever as regards the writing and publication of this article.

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