**Journal of Informatics and Mathematical Sciences**
Vol. 9, No. 2, pp. 285–296, 2017
ISSN 0975-5748 (online); 0974-875X (print)
Published by RGN Publications

http://www.rgnpublications.com

*Proceedings of*
**International Conference on Science and Sustainable Development (ICSSD)**
**"The Role of Science in Novel Research and Advances in Technology"**
**Center for Research, Innovation and Discovery, Covenant University, Nigeria**
**June 20-22, 2017**

Research Article

# Estimation of Hydraulic Parameters from Vertical Electrical Resistivity Sounding

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**Abstract.** This study presents the assessment of the groundwater potential in Iyesi, Ota, southwestern Nigeria. Thirty (30) vertical electrical soundings (VESs) were conducted using Schlumberger array with a maximum half-current electrode spacing ($AB/2$) of 420 m. The apparent resistivity data observed were interpreted first by partial curve matching and then by computer iteration technique using WinResist program. Eight eoelectric layers were denoted as top soil (sandy clay), lateritic clay, silty clay, silty sand, mudstone, medium grain sand, coarse sand and clay mud were delineated. The sixth (medium grain sand) and seventh (coarse sand) layers delineated form the aquifer unit with the overlying mudstone (fifth layer) serving as the confining bed. The geoelectrical and hydrogeological characteristics of the delineated aquifer in the study area was evaluated. The study shows that the aquifer is highly productive and consequently a good groundwater potential. The litho-facies of the aquifer units are well sorted and graded; this accounts for the observed decrease in the model resistivity with depth and thus, increasing porosity with depth in the aquifer unit.

**Keywords.** Estimation; Hydraulic parameters

**MSC.** 93E10

**Received:** May 23, 2017 **Revised:** June 19, 2017 **Accepted:** July 11, 2017



## 1. Introduction

In our rapidly changing world where there are many challenges regarding water such as depletion of stored groundwater and groundwater pollution, it is necessary to pay ample attention to groundwater and its role in securing water supplies and in coping with water-related risk and uncertainty. Research on accurate groundwater resource assessment and groundwater management has highly increased during the past few years, due to the limited availability of groundwater resources and the exposure of groundwater to contamination from harmful chemicals from industrial wastes and dissolved minerals. For effective assessment and management of groundwater resources, it is therefore essential to estimate various hydraulic parameters of aquifers which include hydraulic conductivity (K) and aquifer depth. The electrical resistivity method is the most commonly used method for geophysical survey. Electrical resistivity is extensively used in the search for groundwater as a result of good correlation between electrical properties, fluid content and geology.

The basis for the present day practical application of electrical prospecting was first introduced in 1914-1915 by both Conrad Schlumberger in France and Frank Wenner in the USA. This idea which was introduced by Wenner and Schlumberger is presently used till date in electrical survey. Wenner and Schlumberger proposed method involves the injection of electrical current into the ground and the distribution of resulting potential on the surface of the ground is measured. Obviously, the potential distribution in a real Earth would differ from the potential in a homogeneous half space as heterogenieties, such as are present in a real Earth, and would distort the potential field (Ginzburg [10]). Dobrin Conrad, during the period of 1912 to 1914, was able to establish from his studies the importance of using electrical resistivity method for subsurface studies and analysis (Compagnie Generale de Geophysique [7]). According to Breusse [4], electrical resistivity method for groundwater investigation was first applied during the World War II. The theory and practice of the direct-current electrical prospecting methods was first developed by French, Russian and German geophysicists. Electrical resistivity method involves the detection of surface effects or the response of subsurface materials to the flow of electric current.

## 2. Basic Theory

The basic theorems of electrical resistivity for an isotropic and homogenous medium are Ohm's law and divergence theorem. Ohm's law is one the most important and fundamental law of electricity which relates current $I$ (amperes), voltage $V$ (volts), and resistance $R$ (ohms). Ohm's law can be represented mathematically as:

$$V = IR. \tag{2.1}$$

Considering the flow of electric current through a medium with length $L$, cross sectional area $A$, and current $I$. The current density $\vec{J}$ can be given as:

$$\vec{J} = \frac{I}{A}, \tag{2.2}$$

$$R \alpha \frac{L}{A} = \frac{\rho L}{A}. \tag{2.3}$$

$\rho$ is the electrical resistivity (ohm-m) of the medium. Electrical current will flow in a medium as charged particles moving in an electric field ($\vec{E}$).

$$R = \frac{V}{I}, \tag{2.4}$$

$$\frac{\rho \Delta x}{A} = \frac{\Delta V}{I}. \tag{2.5}$$

Rearranging gives,

$$\frac{\Delta V}{\Delta x} = \frac{I\rho}{A}. \tag{2.6}$$

Taking limits,

$$\frac{dV}{dx} = \vec{E} = \frac{I\rho}{A} = \vec{J}\rho, \tag{2.7}$$

$$\vec{J} = \sigma\vec{E}, \tag{2.8}$$

where $\vec{E}$ is the electric field strength (Volts per m). Figure 1 shows the current flow distribution in a homogeneous soil. Ohm's law gives the relationship to be $-\delta V = -\delta RI$. From equation (**??**) and (2.2) where $R = \frac{\rho\Delta x}{A} = \frac{\Delta V}{I}$, we obtained

$$\frac{\delta V}{\delta x} = -\frac{\rho x}{\delta A} = -\rho\vec{J}, \tag{2.9}$$

where $\frac{\delta V}{\delta x}$ represent the potential gradient through the element in volt/m, and $\vec{J}$ is the current density in $Am^{-2}$. Current density is the total flow of charge per time over a cross section of area, where $2\pi r^2$ is the surface area of a hemispherical sphere with a radius $r$. The current density $\vec{J}$ and potential $V$ can be expressed as:

$$\vec{J} = \frac{I}{2\pi r}, \tag{2.10}$$

$$V = \frac{\rho I}{2\pi r}. \tag{2.11}$$

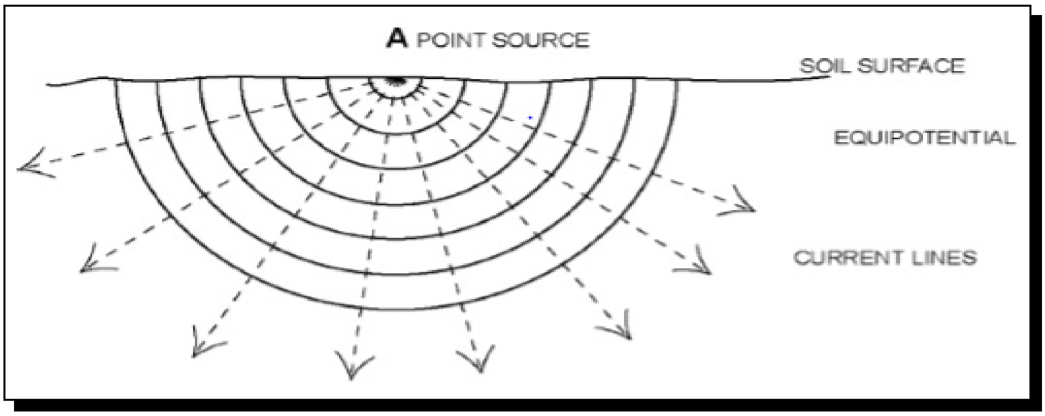


**Figure 1.** Current flow distribution in a homogeneous soil

In order to measure electrical resistivity of a formation, four electrodes are needed. Two electrodes usually referred to as the current electrodes C1 and C2 are used to inject current into the ground while the other two electrodes (potential electrodes) P1 and P2 are used to record the resulting potential difference ($\Delta V$). The equation is given as:

$$\Delta V = \Delta V_{P1} - V_{P2}, \tag{2.12}$$

$$\Delta V = \frac{\rho I}{2\pi}\left[\frac{1}{r_{c1p1}} - \frac{1}{r_{c2p1}} - \frac{1}{r_{c1p2}} + \frac{1}{r_{c2p2}}\right], \tag{2.13}$$

where $r_{c1p1}$, $r_{c1p2}$, $r_{c1p2}$ and $r_{c2p2}$ are the geometrical distance between the electrodes and the electrical resistivity can be calculated using:

$$\rho = \left[\frac{2\pi}{\frac{1}{r_{c1p1}} - \frac{1}{r_{c2p1}} - \frac{1}{r_{c1p2}} + \frac{1}{r_{c2p2}}}\right], \tag{2.14}$$

$$\rho = \frac{\Delta V}{IG}. \tag{2.15}$$

$G$ is a geometrical factor and it depends on the electrode configuration.

## 3. Materials and Methods

### 3.1 Electrode Configuration

The configuration used for the measurements of vertical electrical sounding (VES) data was the Schlumberger electrode configuration. The electrode configuration for Schlumberger array is shown in Figure 2.

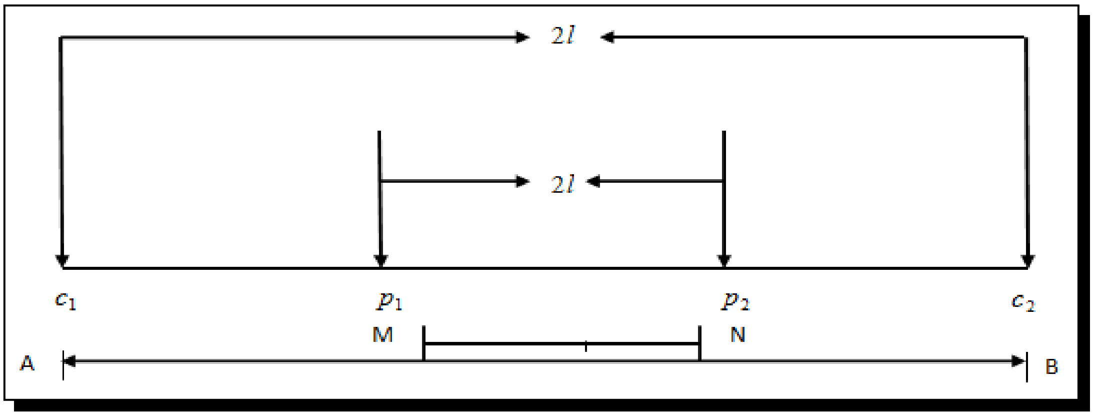


**Figure 2.** Schlumberger electrode configuration

In Figure 2, $2l$ is the spacing between the inner potential electrodes P1 and P2, while 2L is the spacing between the current electrodes C1 and C2. From the configuration above the apparent resistivity is given as:

$$\rho a = \pi \times \frac{V}{I}\left[\frac{(AB/2)^2 - (MN/2)^2}{MN}\right], \tag{3.1}$$

$$K = \frac{\pi l^2}{2l}, \tag{3.2}$$

$$\rho_a = K\frac{\Delta V}{I}, \tag{3.3}$$

where $\rho_a$ is the apparent resistivity and $K$ is the geometric factor, which depends on the geometry or arrangements of the four electrodes. The apparent resistivity obtained from the various VES points can be used to estimate the true resistivities of various layers (lithologies) delineated about the point investigated.

### 3.2 Data Collection and Processing

Vertical electrical sounding (VES) using the Schlumberger configuration was conducted at thirty locations in the study area. The equipment used to take the measurement in this survey was the ABEM Terrameter (it displays the apparent resistivity value). A 12V DC power source was used to power the Terrameter. The four electrodes were inserted into the ground following the Schlumberger configuration. The potential difference at each progressive point (AB/2) where measured and displayed on the ABEM Terrameter and then they were recorded and saved. The various apparent resistivities obtained from the vertical electrical sounding were plotted against the corresponding values for AB/2 using a log-log graph to give a sounding curve. The sounding curve obtained from the plot between the apparent resistivity values and then AB/2 was matched against the theoretical master curve to get an initial model for the interpretation. The model obtained from the curve matching was used as an initial input model for the computer iteration. The software used for the iteration is the WIN RESIST software.

### 3.3 Hydraulic Parameters Estimation

Water samples were collected from different borehole points in Iyesi where thirty VES data were collected. The conductivity measurements for the water samples were conducted using a 4510 conductivity meter. From the conductivity values obtained for the water samples, the resistivity $\rho$ which is the inverse of conductivity $\sigma$ can be obtained from the water samples.

$$\rho = \frac{1}{\sigma} \tag{3.4}$$

From Archie's (1942, 1950) equation for electrical resistivity $\rho$,

$$\rho = a\rho_w\phi^{-m}, \tag{3.5}$$

$$F = \frac{\rho_f}{\rho_w}, \tag{3.6}$$

where $F$ is the formation factor, $\rho_f$ is the resistivity of formation, $\rho_w$ is the resistivity of water, $\rho_w$ is the tortuosity ($a \approx 1$, for unconsolidated sediments), $m$ is cementation exponent and $\phi$ is porosity. The cementation exponent ranges between 1.8 and 2.0, for consolidated sandstones, and 1.1 and 1.3 for unconsolidated clean sands.

$$F = a\phi^{-m}. \tag{3.7}$$

The porosity $\phi$ of the formation can be estimation using the value obtained from the formation factors. The water saturation $S_w$ can be accounted for in Archie's law as follows:

$$F_i = \frac{\rho}{\rho_w} = a\phi^{-m}S_w^{-n} \tag{3.8}$$

Equation (3.8) is known as the generalized Archie's second law, where exponent $n$ is the saturation index, usually equal to 2. Using the Kozeny-Carmen-Bear equation (Carmen [5]; Kozeny [11]), the hydraulic conductivity $K$ can be calculated given:

$$K = \left(\frac{\delta_w g}{\mu}\right)\left(\frac{d^2}{180}\right)\left[\frac{\phi^3}{(1-\phi)^2}\right] \tag{3.9}$$

where $\delta_w$ is the fluid density (1000 kg/m$^3$), $\mu$ is the dynamic viscosity of water (0.0014 kg/ms), $g$ is acceleration due to gravity (9.81 m/s$^2$) and $d$ is the grain size. The unit of $K$ is m/sec. The intrinsic permeability $k_f$ of the aquifer is given as:

$$k_f = \frac{d^2}{180}\frac{\phi^3}{(1-\phi)^2}. \tag{3.10}$$

Thus, the intrinsic permeability and hydraulic conductivity can be related using equation (Nutting, 1930) so that

$$K = \frac{\delta_w g}{\mu} k_f. \tag{3.11}$$

Using the relationship between the hydraulic conductivity $K$ and the thickness $b$ the transmissivity of the aquifer is given as

$$T = Kb. \tag{3.12}$$

Using the relationship between the hydraulic conductivity $K$ and electrical resistivity $\rho$ of an aquifer, the transmissivity of the aquifer is given

$$T = (K\rho)S, \tag{3.13}$$

where $\rho$ is the bulk resistivity and $S$ is the longitudinal unit conductance of the aquifer material with thickness $b$ given by $b/\rho$. For a lateral hydraulic flow and current flowing transversely, the transmissivity of the aquifer becomes

$$T = (K/\rho)R, \tag{3.14}$$

where $R$ is the transverse unit resistance of the aquifer material given by $b\rho$. If the aquifer is saturated with water with uniform resistivity, then the product $K\rho$ or $K/\rho$ would remain constant. The above equations may therefore be written as $T = \alpha S$; $\alpha = K\rho$ and $T = \beta R$, $\beta = K/\rho$ where $\alpha$ and $\beta$ are constants of proportionality.

## 4. Results

The geoelectric parameters obtained from the VES data interpretation for this work are presented in Tables 1 and 2. The results obtained from the water samples collected within the study area were used to obtain the hydraulic conductivity values. Table 3 shows the values obtained for the hydraulic conductivity, porosity, formation factor, transmissivity, permeability, longitudinal conductance and transverse resistance. The thickness and resistivity of the aquifer were obtained from the inverse model of the resistivity soundings while the formation factor and porosity were obtained using Archie's law.

**Table 1.** Table showing the VES correlation of the layer models obtained from the apparent resistivity and their lithologies

| Layer | 1 | | | 2 | | | 3 | | | 4 | | | 5 | | | 6 | | | 7 | | | 8 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lithology | Sandy clay | | | Lateritic clay | | | Silty clay | | | Silty sand | | | Mud stone | | | Medium grain sand (Aquifer unit 1) | | | Coarse Sand (Aquifer unit 2) | | | Clayey mud | | |
| Location | Resistivity (Ωm) | Thickness (m) | Bottom Depth (m) | Resistivity (Ωm) | Thickness (m) | Bottom Depth (m) | Resistivity (Ωm) | Thickness (m) | Bottom Depth (m) | Resistivity (Ωm) | Thickness (m) | Bottom Depth (m) | Resistivity (Ωm) | Thickness (m) | Bottom Depth (m) | Resistivity (Ωm) | Thickness (m) | Bottom Depth (m) | Resistivity (Ωm) | Thickness (m) | Bottom Depth (m) | Resistivity (Ωm) | Thickness (m) | Bottom Depth (m) |
| VES 1 | 89.3 | 1.3 | 1.3 | 152.9 | 2.7 | 4.1 | | | | 1277.8 | 4.8 | 8.8 | 3421.7 | 15.4 | 24.3 | 348.4 | 12.1 | 36.4 | 120.4 | 12.1 | 48.5 | 54.0 | | |
| VES 2 | 89.8 | 1.2 | 1.2 | 285.7 | 3.4 | 4.6 | | | | 1023.2 | 6.0 | 10.6 | 3403.9 | 31.7 | 42.3 | 382.7 | 12.1 | 54.4 | 120.3 | 12.0 | 66.4 | 45.5 | | |
| VES 3 | 128.3 | 1.2 | 1.2 | 225.0 | 2.7 | 3.9 | | | | 2408.3 | 4.1 | 8.0 | 9389.9 | 23.4 | 31.4 | 379.5 | 12.9 | 44.2 | 119.4 | 13.0 | 57.2 | 48.5 | | |
| VES 4 | 49.6 | 1.2 | 1.2 | | | | 981.8 | 8.6 | 9.8 | 1156.7 | 13.1 | 22.9 | 3680.1 | 27.9 | 50.8 | 545.7 | | | | | | | | |
| VES 5 | 24.6 | 0.9 | 0.9 | 979.0 | 3.9 | 4.8 | 174.1 | 8.2 | 13.0 | 1815.0 | 11.7 | 24.7 | 3255.5 | 20.7 | 45.4 | 354.3 | 20.7 | 57.3 | | | | 39.1 | | |
| VES 6 | 71.0 | 1.5 | 1.5 | 593.4 | 4.5 | 6.0 | 1478.5 | 10.8 | 16.9 | 2610.0 | 20.9 | 37.8 | 102591 | 45.7 | 83.5 | 781.0 | | | | | | | | |
| VES 7 | 203.3 | 1.0 | 1.0 | 54.7 | 1.9 | 2.9 | 678.6 | 2.8 | 5.7 | 2655.3 | 6.7 | 12.4 | 5117.9 | 21.7 | 34.1 | 364.6 | 12.2 | 46.3 | 120.9 | 12.0 | 58.3 | 43.7 | | |
| VES 8 | 84.5 | 1.4 | 1.4 | 279.1 | 4.7 | 6.1 | 731.3 | 16.6 | 22.7 | | | | 3084.0 | 30.3 | 53.0 | 484.0 | 12.8 | 65.8 | 170.9 | | | | | |
| VES 9 | 194.5 | 0.9 | 0.9 | 99.5 | 2.3 | 3.2 | 877.3 | 4.4 | 7.6 | 1831.4 | 7.1 | 14.6 | 3915.2 | 23.9 | 38.5 | 363.3 | 13.6 | 52.2 | 104.5 | 13.0 | 65.2 | 236.6 | | |
| VES 10 | 119.9 | 1.9 | 1.9 | | | | 501.4 | 8.2 | 10.1 | 1329.6 | 16.0 | 26.1 | 4063.1 | 31.8 | 57.9 | 379.2 | 13.7 | 71.6 | 122.9 | 13.2 | 84.9 | 68.4 | | |
| VES 11 | 321.9 | 1.6 | 1.6 | 165.2 | 2.1 | 3.7 | 545.7 | 5.8 | 9.6 | 1724.7 | 13.3 | 22.9 | 7027.6 | 41.7 | 64.6 | 442.2 | 14.2 | 78.8 | 124.4 | 13.2 | 92.0 | 89.5 | | |
| VES 12 | 107.7 | 1.9 | 1.9 | 276.6 | 2.1 | 4.0 | 1088.9 | 6.9 | 10.9 | 852.3 | 25.5 | 36.4 | 2335.8 | 20.5 | 56.9 | 407.1 | 13.5 | 70.4 | 123.1 | 13.1 | 83.5 | 116.9 | | |
| VES 13 | 63.0 | 1.0 | 1.0 | 338.0 | 1.9 | 2.9 | | | | 831.9 | 25.8 | 28.7 | 3354.3 | 27.9 | 56.6 | 403.3 | 14.1 | 70.7 | 120.3 | 13.0 | 83.7 | 70.4 | | |
| VES 14 | 47.4 | 1.4 | 1.4 | 187.5 | 2.0 | 3.4 | | | | 1072.1 | 33.3 | 36.7 | 1669.0 | 25.7 | 62.5 | 379.2 | 14.1 | 76.6 | 125.6 | 13.3 | 89.9 | 132.3 | | |
| VES 15 | 107.2 | 2.1 | 2.1 | 402.5 | 2.7 | 4.8 | | | | 1309.5 | 15.0 | 19.8 | 3070.1 | 30.8 | 50.6 | 376.0 | 16.1 | 66.6 | 123.8 | 14.3 | 80.9 | 95.1 | | |

**Table 2.** Table showing the VES correlation of the layer models obtained from the apparent

| Layer | 1 | | | 2 | | | 3 | | | 4 | | | 5 | | | 6 | | | 7 | | | 8 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lithology | Sandy clay | | | Lateritic clay | | | Silty clay | | | Silty sand | | | Mud stone | | | Medium grain sand (Aquifer unit 1) | | | Coarse Sand (Aquifer unit 2) | | | Clayey mud | | |
| Location | Resistivity (Ωm) | Thickness (m) | Bottom Depth (m) | Resistivity (Ωm) | Thickness (m) | Bottom Depth (m) | Resistivity (Ωm) | Thickness (m) | Bottom Depth (m) | Resistivity (Ωm) | Thickness (m) | Bottom Depth (m) | Resistivity (Ωm) | Thickness (m) | Bottom Depth (m) | Resistivity (Ωm) | Thickness (m) | Bottom Depth (m) | Resistivity (Ωm) | Thickness (m) | Bottom Depth (m) | Resistivity (Ωm) | Thickness (m) | Bottom Depth (m)r |
| VES 16 | 51.8 | 0.9 | 0.9 | 39.2 | 1.6 | 2.5 | 187.4 | 3.0 | 5.5 | 1356.2 | 13.8 | 19.3 | 2182.9 | 22.4 | 41.6 | 366.0 | 14.2 | 55.8 | 120.5 | 13.0 | 68.9 | 47.1 | | |
| VES 17 | 68.9 | 1.5 | 1.5 | | | | 458.0 | 2.2 | 3.7 | 2431.8 | 9.1 | 12.8 | 3435.4 | 18.7 | 31.5 | 399.2 | 14.2 | 45.6 | 177.7 | 13.8 | 59.5 | 35.5 | | |
| VES 18 | 94.5 | 1.8 | 1.8 | | | | 328.9 | 4.0 | 5.8 | 1840.9 | 11.4 | 17.2 | 3509.9 | 21.4 | 38.6 | 363.7 | 14.7 | 53.3 | 118.6 | 13.9 | 67.1 | 52.0 | | |
| VES 19 | 141.5 | 1.3 | 1.3 | | | | 540.2 | 3.9 | 5.2 | 1216.7 | 17.5 | 22.7 | 3815.3 | 26.4 | 49.1 | 411.4 | 15.5 | 64.6 | 121.7 | 14.1 | 78.7 | 97.4 | | |
| VES 20 | 85.1 | 1.7 | 1.7 | 103.7 | 3.2 | 4.9 | 457.5 | 4.4 | 9.2 | 1359.8 | 8.5 | 17.7 | 3120.6 | 21.4 | 39.1 | 364.5 | 14.6 | 53.7 | 118.3 | 13.8 | 67.4 | 46.4 | | |
| VES 21 | 22.5 | 0.9 | 0.9 | 239.6 | 1.6 | 2.5 | 654.7 | 6.0 | 8.5 | 1842.6 | 11.7 | 20.2 | 4064.5 | 23.8 | 44.0 | 368.2 | 13.8 | 57.8 | 119.3 | 13.7 | 71.6 | 36.0 | | |
| VES 22 | 76.7 | 1.1 | 1.1 | | | | 410.7 | 14.0 | 15.1 | 1102.2 | 21.3 | 36.4 | 2887.6 | 24.9 | 61.3 | 370.0 | 15.0 | 76.4 | 120.2 | 14.0 | 90.4 | 73.6 | | |
| VES 23 | 222.5 | 1.3 | 1.3 | 174.4 | 1.9 | 3.1 | 1084.0 | 5.4 | 8.5 | 1696.4 | 15.6 | 24.1 | 4175.1 | 29.7 | 53.8 | 375.2 | 15.4 | 69.2 | 121.2 | 14.0 | 83.2 | 64.0 | | |
| VES 24 | 55.1 | 1.1 | 1.1 | | | | 662.2 | 4.6 | 5.7 | 1026.2 | 15.0 | 20.7 | 2966.4 | 22.0 | 42.7 | 362.4 | 14.9 | 57.5 | 119.3 | 13.8 | 71.3 | 47.5 | | |
| VES 25 | 159.2 | 1.7 | 1.7 | | | | 558.2 | 5.5 | 7.2 | 1488.9 | 16.4 | 23.6 | 3571.4 | 28.1 | 51.7 | 373.2 | 15.5 | 67.2 | 121.5 | 14.1 | 81.3 | 57.2 | | |
| VES 26 | 53.5 | 1.2 | 1.2 | 166.0 | 2.5 | 3.6 | 966.3 | 6.0 | 9.6 | 1953.1 | 14.1 | 23.7 | 3490.5 | 25.2 | 48.9 | 369.4 | 15.3 | 64.2 | 120.7 | 14.0 | 78.2 | 54.6 | | |
| VES 27 | 56.4 | 1.4 | 1.4 | 150.8 | 3.4 | 4.8 | 769.6 | 7.4 | 12.2 | 1365.9 | 14.9 | 27.1 | 2713.7 | 21.3 | 48.5 | 372.6 | 15.1 | 63.5 | 120.2 | 14.0 | 77.6 | 55.5 | | |
| VES 28 | 185.4 | 1.3 | 1.3 | 280.6 | 3.0 | 4.4 | 970.3 | 5.4 | 9.8 | 2179.0 | 13.5 | 23.2 | 2896.1 | 23.7 | 46.9 | 368.9 | 15.2 | 62.1 | 120.6 | 14.1 | 76.3 | 50.1 | | |
| VES 29 | 72.0 | 1.0 | 1.0 | 720.7 | 2.5 | 3.5 | 1289.8 | 6.5 | 10.0 | 1572.3 | 16.7 | 26.7 | 3572.3 | 30.8 | 57.5 | 371.3 | 15.4 | 72.9 | 121.3 | 14.1 | 87.0 | 63.3 | | |
| VES 30 | 89.8 | 1.3 | 1.3 | 316.5 | 2.7 | 4.0 | 1011.3 | 6.2 | 10.2 | 2012.7 | 13.9 | 24.1 | 3885.2 | 29.9 | 54.0 | 371.4 | 15.4 | 69.3 | 121.1 | 14.1 | 83.4 | 55.7 | | |

**Table 3.** Table showing aquifer geologic properties for VES data

| VES NO | THICKNESS $(m)$ | BULK RESISTIVITY $(\Omega m)$ | FORMATION WATER RESISTIVITY $(\Omega m)$ | FORMATION FACTOR | POROSITY | PERMEABILITY $(m^2)\times 10^{-4}$ | HYDRAULIC CONDUCTIVITY $(m/s)\times 10^2$ | TRANSMISSIVITY $(m^2/s)\times 10^3$ | LONDITUDINAL CONDUCTANCE $(\Omega^{-1})$ | TRANSVRSE RESISTANCE $(\Omega m^2)$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 12.1 | 120.4 | 19.3798 | 6.2127 | 0.2453 | 1.4397 | 10.0882 | 12.2067 | 0.10005 | 1456.84 |
| 2 | 12.0 | 120.3 | 19.3798 | 6.2075 | 0.2455 | 1.4440 | 10.1183 | 12.1420 | 0.09975 | 1443.60 |
| 3 | 13.0 | 119.4 | 19.3798 | 6.1611 | 0.2469 | 1.4743 | 10.3306 | 13.4220 | 0.10888 | 1552.20 |
| 4 | 12.7 | - | 19.3798 | - | - | - | - | - | - | - |
| 5 | 11.0 | - | 19.3798 | - | - | - | - | - | - | - |
| 6 | 16.7 | - | 19.3798 | - | - | - | - | - | - | - |
| 7 | 12.0 | 120.9 | 19.3798 | 6.2385 | 0.2446 | 1.4248 | 9.9838 | 11.9806 | 0.09926 | 1450.80 |
| 8 | 13.2 | 170.9 | 19.3798 | 8.8185 | 0.1874 | 0.5537 | 3.8799 | 5.1215 | 0.07723 | 2255.88 |
| 9 | 13.0 | 104.5 | 19.3798 | 5.3922 | 0.2736 | 2.1564 | 15.1102 | 19.6433 | 0.12440 | 1358.50 |
| 10 | 13.2 | 122.9 | 19.3798 | 6.3417 | 0.2415 | 1.3601 | 9.5304 | 12.5801 | 0.10740 | 1622.28 |
| 11 | 13.2 | 124.4 | 19.3798 | 6.4191 | 0.2393 | 1.3156 | 9.2186 | 12.1686 | 0.10611 | 1642.08 |
| 12 | 13.1 | 123.1 | 19.3798 | 6.3520 | 0.2412 | 1.3573 | 9.5108 | 12.4591 | 0.10642 | 1612.61 |
| 13 | 13.0 | 120.3 | 19.3798 | 6.2075 | 0.2455 | 1.4440 | 10.1183 | 13.1538 | 0.10806 | 1563.90 |
| 14 | 13.3 | 125.6 | 19.3798 | 6.4820 | 0.2375 | 1.2801 | 8.9698 | 11.9298 | 0.10589 | 1670.48 |
| 15 | 14.3 | 123.8 | 19.3798 | 6.3881 | 0.2402 | 1.3337 | 9.3454 | 13.3639 | 0.11551 | 1770.34 |
| 16 | 13.0 | 120.5 | 19.3798 | 6.2178 | 0.2452 | 1.4376 | 10.0734 | 13.0954 | 0.10788 | 1566.50 |
| 17 | 13.83 | 177.7 | 19.3798 | 9.1693 | 0.1819 | 0.4996 | 3.5007 | 4.8415 | 0.07766 | 2452.26 |
| 18 | 13.9 | 118.6 | 19.3798 | 6.1198 | 0.2482 | 1.5029 | 10.5310 | 14.6381 | 0.11720 | 1648.54 |
| 19 | 14.1 | 121.7 | 19.3798 | 6.2797 | 0.2433 | 1.3974 | 9.7918 | 13.8064 | 0.11586 | 1715.97 |
| 20 | 13.8 | 118.3 | 19.3798 | 6.1043 | 0.2487 | 1.5140 | 10.6088 | 14.6401 | 0.11665 | 1632.54 |
| 21 | 13.7 | 119.3 | 19.3798 | 6.1559 | 0.2471 | 1.4787 | 10.3615 | 14.1953 | 0.11484 | 1634.41 |
| 22 | 14.0 | 120.2 | 19.3798 | 6.2023 | 0.2457 | 1.4483 | 10.1484 | 14.2078 | 0.11647 | 1682.80 |
| 23 | 14.0 | 121.2 | 19.3798 | 6.2539 | 0.2441 | 1.4142 | 9.9095 | 13.8733 | 0.11550 | 1696.80 |
| 24 | 13.8 | 119.3 | 19.3798 | 6.1559 | 0.2471 | 1.4787 | 10.3615 | 14.2989 | 0.11567 | 1646.34 |
| 25 | 14.1 | 121.5 | 19.3798 | 6.2694 | 0.2436 | 1.4036 | 9.8352 | 13.8676 | 0.11605 | 1713.15 |
| 26 | 14.0 | 120.7 | 19.3798 | 6.2281 | 0.2449 | 1.4311 | 10.0279 | 14.0391 | 0.11599 | 1689.80 |
| 27 | 14.0 | 120.2 | 19.3798 | 6.2023 | 0.2457 | 1.4483 | 10.1484 | 14.2078 | 0.11647 | 1682.80 |
| 28 | 14.1 | 120.6 | 19.3798 | 6.2230 | 0.2450 | 1.4333 | 10.0433 | 14.1611 | 0.11692 | 1700.46 |
| 29 | 14.1 | 121.3 | 19.3798 | 6.2591 | 0.2439 | 1.4100 | 9.8801 | 13.9309 | 0.11624 | 1710.33 |
| 30 | 14.1 | 121.1 | 19.3798 | 6.2488 | 0.2443 | 1.4184 | 9.9309 | 14.0026 | 0.11633 | 1707.51 |

## 4.1 Geoelectric Parameters

The subsurface comprises of different lithologies which are sandy clay, lateritic clay, silty clay, silty sand, mudstone (confining bed), fine-to-medium grain sand, coarse sand and clayey mud. From Tables 1 and 2, the resistivity of the top soil varies from 22.5 Ωm to 321.9 Ωm; the thickness ranges from 0.9 m to 2.1 m. The resistivity of the top soil depends on clay volume, moisture content and degree of compaction. The resistivity of the underlying geoelectric layer ranges from 39.2 Ωm to 979.0 Ωm with thickness ranging from 2.2 m to 16 m. The third layer is an intercalation of silt and clay and has its thickness and resistivity shown in Table 1 and Table 2. The fourth geoelectric layer, an intercalation of silt and sand, was delineated. The resistivity ranges from 831.9 Ωm to 2655.3 Ωm; the thickness ranges from 4.1 m to 33.3 m. Underlying this geoelectric layer is a very high resistive substratum with resistivity ranging from and thickness ranging between 1669.0 Ωm to 10259.1 Ωm and 15.4 m to 41.7 m.

The sixth layer (medium grain sand) which is also an aquifer unit is overlain by the confining bed (mudstone) which is characterized by its high resistive unit. The sixth layer has its resistivity ranging from 348.4 Ωm to 784.0 Ωm (Figure 4) and thickness ranging from 12.1 m to 16.1 m (Figure 5). Mudstone is a mix of silt and clay sized particles. It contains phosphate particle which is also responsible for its high resistivity value. The seventh geoelectric layer delineates the major aquifer which consists of unconsolidated coarse grain sands. Underlying the major aquifer is a low resistive layer ranging from 35.5 Ωm to 236.6 Ωm.

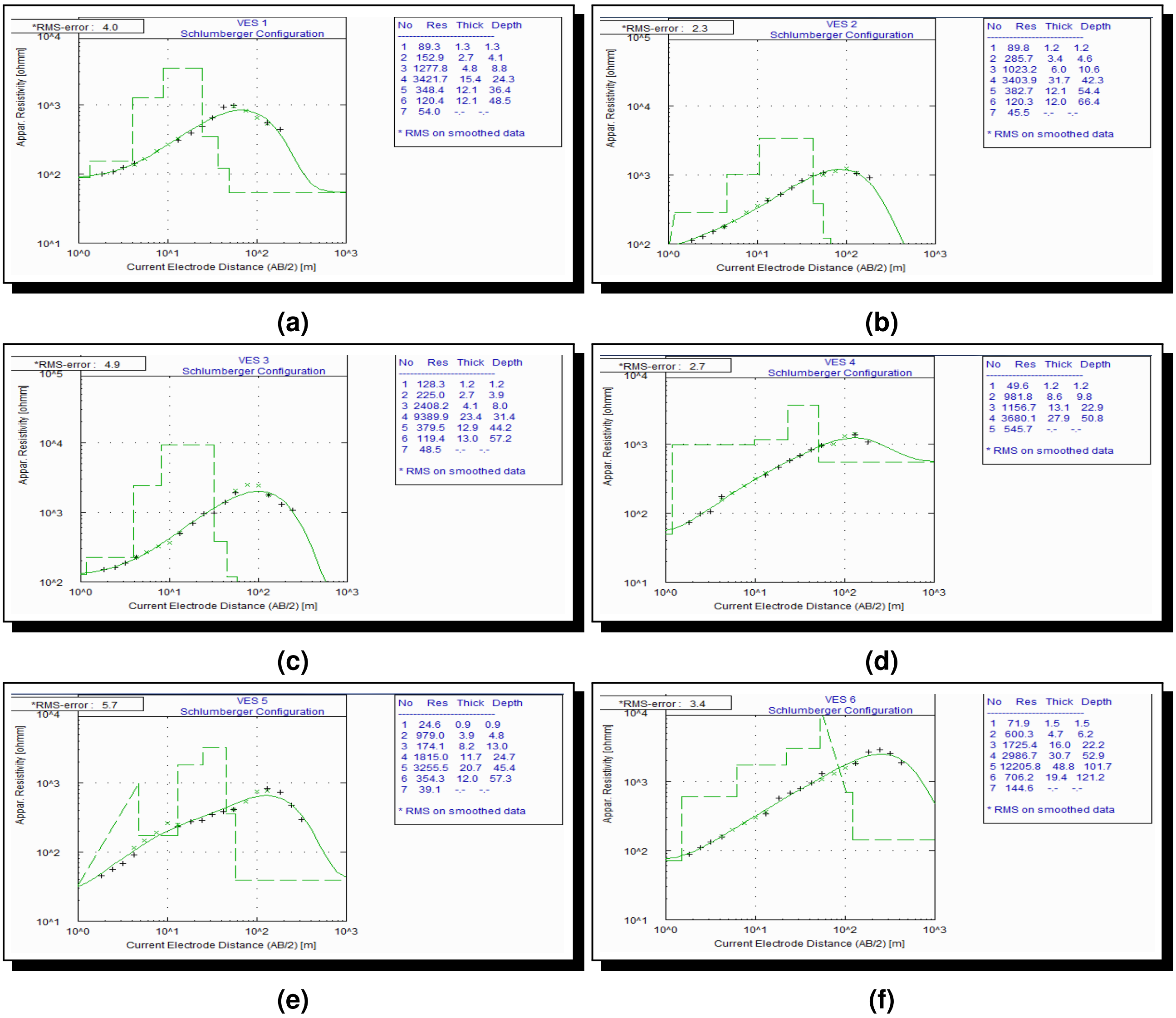


**Figure 3.** Representative of the iterated VES curves showing the inverse models of the geoelectrical parameters for (a) VES 1, (b) VES 2, (c) VES 3, (d) VES 4 (e) VES 5, (f) VES 6

## 4.2 Parameter Estimation

The hydraulic properties (hydraulic conductivity and transmissivity) and Dar'Zarrouk's parameters (longitudinal conductance and transverse resistance) are computed from the geoelectric parameters of the aquifer Table 3. Following the determination of the most appropriate values of the tortuosity parameter ($a$) and cementation factor ($m$) 1 and 1.3, respectively, the hydraulic parameters of the aquifer were calculated for all locations. These parameters i.e. ($m$) and ($a$) are essential to estimate an aquifer hydraulic parameters using geoelectrical resistivity. The longitudinal conductance of the major aquifer is generally low ranging from $0.07723\Omega^{-1}$ to $0.12440\Omega^{-1}$. The transmissivity in this area is generally high with a porosity range of 18 percent to 27 percent with an average of 22 percent and is spatially related to the hydraulic conductivity. This indicates a confined aquifer and is also characterized

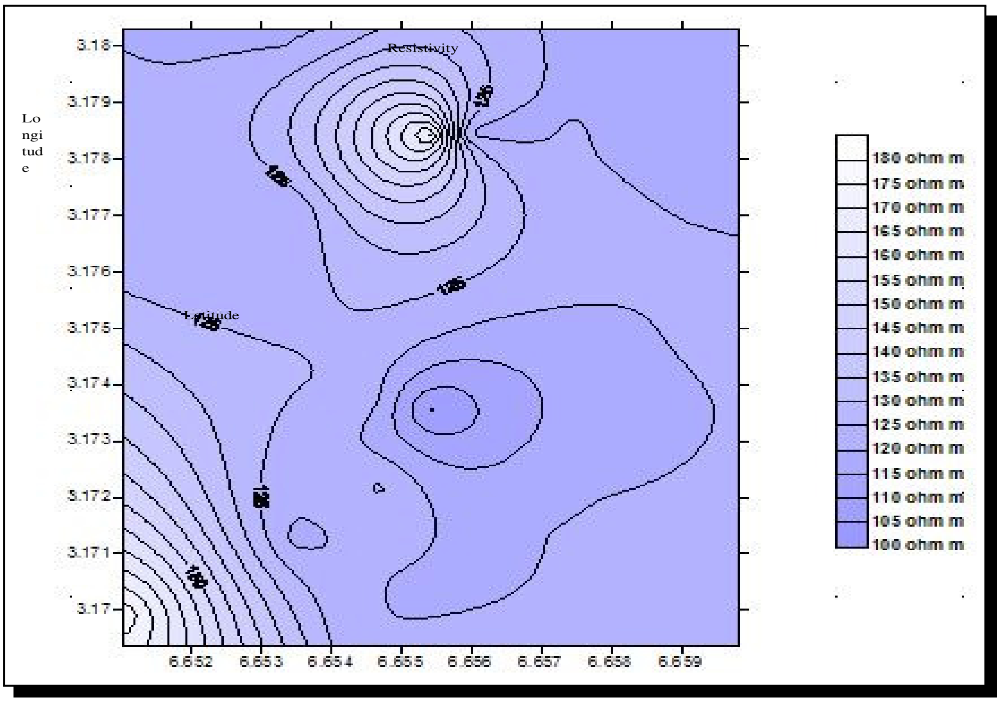


**Figure 4.** Iso-resistivity map of the aquifer.

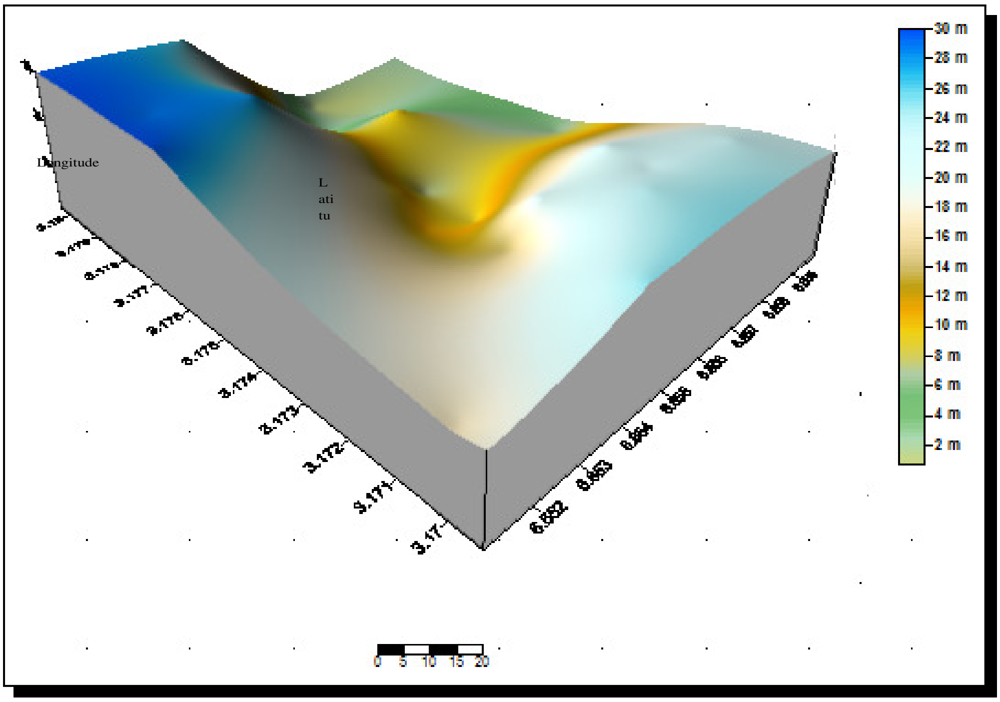


**Figure 5.** Representation of the aquifers thickness

with high hydraulic conductivity as indicated in the table above. The transverse resistance of an aquifer increases with increasing transmissivity and yield. The transverse resistance ranges from 1443.60$\Omega m^2$ to 2452$\Omega m^2$. This range indicates a high value of transmissivity and yield of the major aquifer in the study area.

## 5. Discussions

The direction of groundwater flow follows a curved path through an aquifer from areas of high water levels to areas of low water levels; that is from recharge areas to discharge points in valleys or seas. It is therefore necessary to know the direction of groundwater flow and take steps to ensure that land use activities in the recharge area will not pose a threat to the quality of the groundwater (Freeze and Cherry [9]). Hence, the direction of flow Figure 6 was generated using the surfer 8 software.

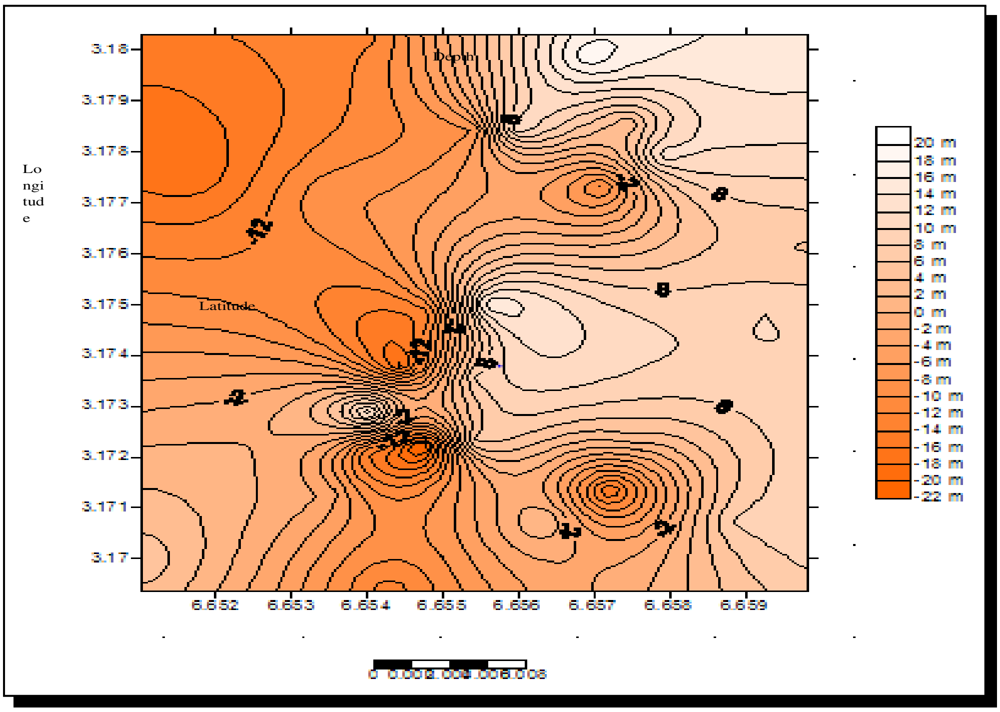


**Figure 6.** Map showing the groundwater flow in the subsurface

## 6. Conclusions

Geoelectrical resistivity survey was carried out in Iyesi, Ota, Ogun state, southwestern Nigeria. The aim of the survey was to assess the groundwater resource potential in the area. The information of groundwater resource potential is fundamental for groundwater resource improvement, administration and monitoring. The results of this study show that the depth to aquifer in the study area ranges from −23.6 m to 19.6 m. The aquifer unit show appreciable thickness that can support adequate drawdown for groundwater extraction. The porosity, hydraulic conductivity and transmissivity values indicate high productivity and high yield for the aquifer unit. It is recommended that boreholes within the study area should be drilled to a minimum depth of about 47 m (144 ft) to ensure adequate draw-down and perennial yield. Also, better planning, development and management of the groundwater resources.

## Acknowledgment

The authors appreciate Covenant University for partial sponsorship.

### Competing Interests

The authors declare that they have no competing interests.

### Authors' Contributions

All the authors contributed significantly in writing this article. The authors read and approved the final manuscript.

## References

[1] G. Archie, The electrical resistivity log as an aid in determining some reservoir characteristics, *Petroleum transactions of the American Institute of Mineralogical and Engineers* **146** (1942), 54 – 62.

[2] G. Archie, Introduction to petrophysics of reservoir rocks, *American Association of Petroleum Geologists Bulletin* **s** (1950), 943 – 961.

[3] J.J. Breusse, Modern geophysical methods for subsurface water exploration, *Geophysics* **28** (1963), 633 – 657.

[4] D.C. Carmen, Fluid flow through a granular bed, *Transaction Institute of Chemical Engineering* **15** (1937), 150 – 157.

[5] D.C. Carmen, *Flow of Gases through Porous Media*, Academic Press, New York (1956), 182 p.

[6] European Association of Exploration Geophysicists, Compagnie Generale de Geophysique, Master curves for electrical sounding, 2nd revised edition (1963), `https://books.google.co.in/books/about/Master_Curves_for_Electrical_Sounding.html?id=g1BmPAAACAAJ&redir_esc=y`.

[7] M.B. Dobrin, *Introduction to Geophysical Prospecting*, 2nd edition, McGrow-Hill, New York (1960), 446 p.

[8] R.A. Freeze and J.A. Cherry, *Groundwater*, Prentice Hall Inc., Englewood Cliffs, New Jersey (1979), 7 p.

[9] A. Ginzburg, Resistivity surveying, *Geophysical Surveys* **1** (1974), 325 – 355.

[10] J. Kozeny, Ueber kapillare leitung des wassers im boden, *Sitzungsberichte Akademie der Wissenschaften Wien* **136** (1927), 271 – 306.

[11] J. Kozeny, *Hydraulics*, Springer, Vienna (1953), 546 – 549.

[12] P.G. Nutting, Physical analysis of oil sands, *American Association of Petroleum Geologist Bulletin* **14** (1930), 1337 – 1349.