

Geophysical Techniques for Assessing Groundwater Potential in Basement Complex Terrains

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ABSTRACT

This paper presents the results of the interpretation of electrical resistivity survey using Schlumberger array at a test site (Ogodo Agbe, Akungba Akoko) in Akoko Southwest of Ondo state, in order to evaluate groundwater potential in the area.

The electrical resistivity method was used for detailed investigation in the study area. The results gotten from the investigation allow the study area to be classified into poor, intermediate and high groundwater potential zone. Zones with poor overburden thickness, poor weathered layer resistivity coupled with poor weathered layer thickness and high bedrock relief are considered to have poor groundwater potential, while zones with intermediate overburden thickness, intermediate weathered layer resistivity, intermediate weathered layer thickness and depressed bedrock relief are favorable to groundwater accumulation; hence are classified as zones with intermediate groundwater potential. While zones with high overburden thickness, good weathered layer resistivity, high weathered layer thickness and highly depressed bedrock relief are favorable to more groundwater accumulation; are therefore classified as zones with high groundwater potential. The results of the findings serve as a guide for citing productive boreholes and provide a reference for future geophysical development in the selected region.

Keywords: Electrical resistivity array, Groundwater, Potential zone, weathered layer, Bedrock relief.

INTRODUCTION

Groundwater is one of the most valuable natural resources for domestic, agricultural, and industrial development, particularly in regions where surface water is either inadequate, seasonal, or highly vulnerable to contamination. In many developing countries, especially within sub-Saharan Africa, groundwater serves as the major source of potable water supply for rural and urban communities because of its relatively stable quality and year-round availability [1], [2]. Increasing population growth, rapid urbanization, industrial expansion, climate variability, and prolonged drought conditions have intensified pressure on available freshwater resources, thereby increasing dependence on groundwater systems for sustainable water supply [3]. Consequently, the exploration, assessment, and management of groundwater resources have become critical scientific and socio-economic concerns worldwide.

In crystalline basement complex terrains, groundwater occurrence is often limited, localized, and highly heterogeneous due to the geological nature of the underlying rocks. Basement terrains are predominantly composed of crystalline igneous and metamorphic rocks such as granites, gneisses, schists, quartzites, migmatites, and charnockites [4]. These rocks generally possess negligible primary porosity and permeability because they lack interconnected pore spaces necessary for groundwater storage and movement. Unlike

sedimentary formations where groundwater occurs mainly within pore spaces between grains, groundwater occurrence in basement terrains is largely controlled by secondary porosity and permeability created through weathering, fracturing, jointing, and faulting processes [5].

The weathering of basement rocks produces a layer of decomposed materials known as regolith or saprolite, which may possess sufficient porosity and permeability to store groundwater [6]. Similarly, tectonic activities create fractures, joints, and faults that serve as conduits and reservoirs for groundwater movement and accumulation. Productive aquifers in basement terrains are therefore commonly associated with thick weathered overburden, fractured bedrock, lithological contacts, and fault intersections [7]. However, these aquifers are usually discontinuous and structurally controlled, making groundwater exploration in basement environments particularly difficult and uncertain.

In many basement complex regions, especially in countries such as Nigeria, Ghana, Ethiopia, Kenya, and Zimbabwe, groundwater constitutes the principal source of water supply for domestic and agricultural activities [8]. Unfortunately, borehole failure rates in these terrains remain high due to inadequate understanding of subsurface geological and hydrogeological conditions [9]. Random drilling without proper subsurface investigation often results in low-yield or completely dry wells, leading to significant economic losses and water supply challenges. This situation highlights the necessity for systematic groundwater potential assessment and reliable aquifer characterization prior to borehole development.

Traditional hydrogeological investigations alone are often insufficient for accurately delineating groundwater-bearing zones in crystalline basement environments because subsurface conditions cannot be fully understood from surface observations [10]. As a result, geophysical techniques have become indispensable tools for groundwater exploration and assessment in basement terrains. Geophysical methods provide rapid, cost-effective, non-invasive, and reliable means of investigating subsurface conditions over large areas without extensive drilling [11]. These techniques help identify weathered zones, fractured bedrock, lithological variations, aquifer thickness, and groundwater saturation conditions, thereby reducing the risks associated with failed boreholes.

Geophysical techniques involve the measurement of physical properties of subsurface materials such as electrical resistivity, conductivity, density, magnetic susceptibility, and seismic velocity [12]. Variations in these properties enable geophysicists to infer geological structures and hydrogeological conditions favorable for groundwater occurrence. The choice of geophysical method depends on factors such as geological setting, depth of investigation, accessibility, exploration objectives, and expected aquifer characteristics. In basement complex terrains, commonly applied geophysical methods include electrical resistivity, electromagnetic, seismic, magnetic, gravity, and self-potential techniques [13].

Among these methods, electrical resistivity techniques are regarded as the most widely applied and successful methods for groundwater exploration in basement terrains [14]. Electrical resistivity methods operate on the principle that different earth materials possess varying abilities to conduct electrical current depending on factors such as water content, porosity, clay content, permeability, dissolved salts, and degree of weathering [15]. Groundwater-bearing formations generally exhibit lower resistivity values than dry and compact basement rocks because groundwater enhances electrical conductivity within subsurface materials.

Electrical resistivity surveys are commonly carried out using techniques such as Vertical Electrical Sounding (VES), electrical profiling, and Electrical Resistivity Tomography (ERT). Vertical Electrical Sounding is widely used to determine resistivity variation with depth and to estimate aquifer thickness, depth to bedrock, and thickness of weathered overburden [16]. Electrical Resistivity Tomography provides two-dimensional and three-dimensional images of subsurface resistivity distribution, thereby enabling detailed mapping of fractures, weathered zones, and groundwater-bearing structures [17]. The effectiveness of resistivity methods in distinguishing topsoil, weathered layers, fractured basement, and fresh bedrock has made them highly valuable in groundwater investigations within basement complex environments.

Electromagnetic (EM) methods are also important in groundwater exploration because of their ability to rapidly detect conductive subsurface structures without direct contact with the ground [18]. Techniques such as

Very Low Frequency Electromagnetic (VLF-EM), Time Domain Electromagnetic (TDEM), and Frequency Domain Electromagnetic (FDEM) methods are commonly used to identify fractures, faults, and conductive weathered zones associated with groundwater occurrence [19]. VLF-EM methods are particularly effective in mapping conductive linear structures such as fractures and fault zones that may serve as groundwater conduits.

Seismic methods have also proven useful for groundwater assessment in basement terrains. These techniques utilize artificially generated seismic waves to investigate subsurface geological structures and layering [20]. Seismic refraction surveys are commonly employed to determine depth to bedrock, identify weathered zones, and characterize fractured basement structures. Variations in seismic wave velocities provide information about rock competence, degree of weathering, and groundwater saturation conditions [21]. Although seismic methods are relatively expensive and technically demanding, they provide valuable complementary information where resistivity interpretations are ambiguous.

Magnetic and gravity methods contribute significantly to regional groundwater investigations by mapping structural features such as faults, fractures, buried valleys, and basement depressions favorable for groundwater accumulation [22]. Magnetic surveys measure variations in the Earth's magnetic field caused by differences in magnetic susceptibility of subsurface rocks, while gravity surveys detect density contrasts within geological formations [23]. Though these methods do not directly detect groundwater, they provide critical structural information that complements electrical and seismic investigations.

Recent advances in remote sensing and Geographic Information Systems (GIS) have significantly enhanced groundwater potential assessment in basement terrains [24]. Remote sensing techniques utilize satellite imagery, aerial photographs, and digital elevation models to identify geomorphological and structural features associated with groundwater occurrence, including lineaments, drainage patterns, valleys, lithological boundaries, and weathered zones [25]. Lineament analysis is particularly important because fractures and faults identified from satellite imagery often correspond to groundwater-bearing zones in crystalline terrains. GIS technology facilitates the integration of geological, geophysical, hydrological, and remote sensing data for groundwater potential mapping and spatial analysis [26].

More recently, integrated approaches involving multi-criteria decision analysis (MCDA) techniques such as Analytic Hierarchy Process (AHP), fuzzy logic, and machine learning models have been adopted to improve groundwater potential mapping accuracy in basement environments [27]. These techniques allow for the integration of diverse datasets and objective weighting of groundwater-controlling factors such as lithology, lineament density, slope, drainage density, land use, and rainfall distribution. The integration of geophysical methods with GIS-based analytical models has significantly improved groundwater exploration success rates in heterogeneous basement terrains.

Despite the effectiveness of geophysical methods, interpretation ambiguity remains a major challenge because similar geophysical responses may arise from different geological conditions. For instance, clay-rich formations and water-saturated zones may both exhibit low resistivity values, potentially resulting in misinterpretation [28]. In addition, electromagnetic and magnetic surveys may be affected by cultural noise from power lines, fences, and buried metallic objects. Therefore, geophysical investigations should be integrated with hydrogeological information and validated through borehole drilling and pumping tests for improved reliability.

Sustainable groundwater development in basement complex terrains requires comprehensive understanding of subsurface geological conditions and aquifer characteristics. Geophysical techniques provide a scientific basis for groundwater assessment, borehole siting, aquifer delineation, and groundwater resource management, thereby reducing drilling failures and improving water supply sustainability [29]. Consequently, the application of geophysical methods in basement complex terrains remains an important area of hydrogeological research and water resource development worldwide.

This geophysical prospecting will also enable the researcher to know if the locations can be used for citing borehole, the depth of groundwater from the surface and as reference materials for future geophysical prospecting and development of borehole around the area.

Location and Geological Setting

The study area is located in Ogodu Agbe, Akungba Akoko in Akoko Southwest one of the eighteen Local governments that made up Ondo State in the South-Western Region of Nigeria. The location falls within latitudes and longitudes $7^{\circ} 29.000' \text{ N}$, $005^{\circ} 43.730' \text{ E}$ and $7^{\circ} 29' 0.4'' \text{ N}$, $5^{\circ} 43' .01'' \text{ E}$ respectively. Topographically, the area is characterized by elevation which ranges between 639m and 642m above sea level. The area of study is within the rainforest belt of Nigeria with a climate of long wet season (May to October) and a short dry season (November to March). The survey was carried out in dry season of March 3rd and 4th, 2025.

MATERIALS AND METHOD

Field Instrumentation and Acquisition

The instruments used for survey is a 12V DC powered 2 Hz low frequency pulsed square high variable voltage (50-300V) Dr AF 2kW resistivity meter. It is locally made and well correlating with other imported resistivity equipment. It can easily be troubleshooted and repaired with reliable components and IC. This instrument measures potential difference and current of subsurface materials which is later converted to resistance and apparent resistivity. The global positioning system (GPS) Garmin GPS 12 XL 12 channel was used to get the coordinates of the VES positions and their altitudes.

These geo-electric sounding lines are oriented along N-E direction, each covering a total length of 200 meters. It comprises VES points; 1, 2, 3 and 4 with different locations, in which the longitude and latitude are as follows: $7^{\circ} 29.000' \text{ N}$, $005^{\circ} 43.730' \text{ E}$, $7^{\circ} 28' 59.86'' \text{ N}$, $5^{\circ} 43' 43.99'' \text{ E}$, $7^{\circ} 28' 34.5'' \text{ N}$, $5^{\circ} 44' 1.95'' \text{ E}$, $7^{\circ} 29' 0.4'' \text{ N}$, $5^{\circ} 43' .01'' \text{ E}$ respectively. The area is underlain by granite gneiss and few pegmatite rocks are at the Centre of and traversed by the Schlumberger electrodes spread.

Data Processing, Software Inversion, and Model Fitting Criteria

Field apparent resistivity data were initially plotted on log-log graph sheets for manual curve matching using standard master curves and auxiliary charts. Quantitative 1D computer inversion was subsequently performed using IPI2win software. The software utilizes a non-linear least-squares optimization technique to minimize the Root Mean Square (RMS) error between the observed apparent resistivity and calculated model resistivity.

Iterative inversion convergence was defined by an RMS error tolerance threshold of $< 0.1\%$ between successive iterations, yielding final model fit errors between 10.1% and 10.5% across all stations.

Functional Description of the Circuit Components:

1. **Power Input (12V DC):** Usually powered by a deep-cycle lead-acid battery.
2. **DC-DC Step-Up Converter:** This is the core of the "2kW" capability. It uses a high-frequency transformer and a PWM (Pulse Width Modulation) controller to boost the 12V DC up to the required 50V–300V DC range.
3. **Timing & Control Unit (2 Hz Logic):** Using an IC like a 555 timer or a microcontroller, the circuit generates a 2 Hz frequency. This controls the polarity switching to prevent electrode polarization in the soil.
4. **H-Bridge Inverter:** A set of four high-power MOSFETs or IGBTs arranged in an "H" configuration. These take the high-voltage DC and "flip" the polarity at 2 Hz, sending a pulsed square wave into the ground through the Current Electrodes (C_1 , C_2).
5. **Current Sensing (I):** A low-resistance shunt resistor is placed in series with the output to measure the exact current being injected into the subsurface.

6. **Potential Measurement (V):** High-impedance differential amplifiers are connected to the Potential Electrodes (P_1 , P_2) to measure the voltage drop across the subsurface without drawing significant current from the ground.
7. **Processing & Display:** The measured V and I are processed (often by an Analog-to-Digital Converter) to calculate the resistance ($R=V/I$), which the operator then uses to determine apparent resistivity based on the Schlumberger array geometry.
8. **Integration with GPS:** While the GPS (Garmin GPS 12 XL) is a separate handheld unit, it is used concurrently with the circuit's operation to provide the spatial metadata (XY coordinates and Altitude) required to map the resistivity values into a 2D or 3D subsurface model.

Circuit Breakdown and Logic

1. Power Supply and DC-DC Boost Stage

The 12V DC from the battery is first filtered to remove noise. Because 12V is insufficient to overcome the high resistance of dry subsurface earth, the instrument uses a Push-Pull DC-DC Converter.

- **Components:** A PWM controller IC (like the TL494 or SG3525) drives power MOSFETs.
- **Function:** These MOSFETs switch the 12V into a high-frequency transformer, boosting it to a high-voltage DC (adjustable between 50V and 300V via a potentiometer). This allows the 2kW power rating to be achieved for deep penetration.

2. The 2 Hz Commutator (H-Bridge)

To prevent "Electrode Polarization" (the buildup of charges around the electrodes that ruins readings), the DC must be converted into an AC-like pulsed square wave.

- **Components:** An H-Bridge consisting of four high-voltage IGBTs or MOSFETs.
- **Function:** A timing circuit (often a 555 timer or a CD4047 IC) set to 2 Hz triggers the bridge. It alternates the direction of the current through the ground electrodes (C_1 and C_2) every 0.5 seconds.

3. Current (I) Sensing Circuit

To calculate resistivity, the instrument is designed to know exactly how much current is entering or penetrating the ground.

- **Mechanism:** A precision "Shunt Resistor" is placed in the output path. The voltage drop across this resistor is measured by an Analog-to-Digital Converter (ADC) and displayed as Current (I) in Milliampères.

4. Potential (V) Measurement Circuit

This part of the circuit measures the response of the earth through electrodes P_1 and P_2 .

- **Components:** High-impedance Operational Amplifiers (Op-Amps) in a differential configuration.
- **Function:** The high impedance ensures the meter does not load the ground, allowing for an accurate reading of the small potential difference (ΔV) created by the injected current.

Summary of Instrument Operation

The geometric factor for the Schlumberger array depends on the spacing between the current and potential

electrodes. By progressively increasing the current electrode spacing during field measurements, the depth of current penetration increases, enabling investigation of deeper subsurface layers.

The DR 2KW resistivity meter is commonly integrated with a handheld Global Positioning System (GPS) device such as the Garmin GPS 12 XL during field operations. Although the GPS unit operates independently from the resistivity meter, it provides essential spatial information including coordinates (X and Y positions) and elevation data. These spatial datasets are combined with resistivity measurements during data processing to produce two-dimensional (2D) and three-dimensional (3D) subsurface resistivity models and groundwater potential maps.

During field operation, the operator adjusts the output voltage between 50V and 300V depending on ground resistance conditions until a stable current flow is achieved. The 2 Hz polarity reversal ensures that the subsurface remains electrically neutral, reducing electrode polarization effects and enhancing data reliability. The resulting voltage and current readings are then used with Schlumberger geometric factor (K) to calculate apparent resistivity (ρ_a) values, which are interpreted to identify geological layers, weathered zones, fractured basement structures, and groundwater-bearing formations.

The DR 2KW resistivity meter is particularly suitable for groundwater exploration in basement complex terrains because of its high-power capability, efficient current injection system, and ability to operate effectively in highly resistive environments. Its integration of power electronics, current sensing, signal amplification, and timing control systems makes it a reliable instrument for geoelectrical investigations and subsurface characterization.

For the Schlumberger array in electrical resistivity surveying, the apparent resistivity (ρ_a) is calculated using:

$$\rho_a = K \times R$$

where:

$$\rho_a = \text{Apparent resistivity } ((\Omega \cdot \text{m}))$$

$$K = \text{Geometric factor}$$

$$R = \text{Measured resistance} = \Delta V / I$$

$$\Delta V = \text{Potential difference (Voltage)}$$

$$I = \text{Current injected into the ground}$$

For Schlumberger Geometric Factor (K):

For the Schlumberger configuration:

$$K = \pi [(AB^2 - MN^2) / 4MN]$$

Where:

$$AB = \text{Distance between current electrodes A and B}$$

$$MN = \text{Distance between potential electrodes M and N}$$

Since usually $AB \gg MN$, the formula is often simplified to:

$$K \approx \pi AB^2 / 4MN$$

Apparent Resistivity Formula:

Substituting K into the resistivity equation:

$$\rho_a = \pi [(AB^2 - MN^2)/4MN] R$$

or approximately:

$$\rho_a \approx [\pi AB^2/4MN] R$$

Resistance Formula:

$$R = \Delta V / I$$

Where:

ΔV = Measured voltage

I = Current

Combined Equation:

$$\rho_a = K \frac{\Delta V}{I}$$

or

$$\rho_a = \pi [(AB^2 - MN^2)/4MN] \frac{\Delta V}{I}$$

These equations are standard for Vertical Electrical Sounding (VES) using the Schlumberger electrode arrangement.

Basis for Lithological Assignments and Equivalence Resolution

Because resistivity values are influenced by both groundwater saturation and matrix clay content, specific resistivity ranges were defined based on local hydrogeological calibration in Nigerian Basement terrains:

Table 3.1: Lithological Assignments and Equivalence Resolution

Resistivity Range ($\Omega \cdot m$)	Inferred Lithology / Formation	Hydrogeological Significance
< 100	Clay / Clayey Topsoil	Poor permeability; low yield/aquitard
100 – 500	Sandy Clay / Weathered Layer	Moderate-to-high yield potential (Aquifer)
500 – 1200	Weathered / Highly Fractured Basement	Conduit for groundwater storage and migration
1200	Fresh, Unfractured Basement Rock	Impermeable bedrock base

RESULTS AND DISCUSSION

Table 4.1: FIELD DATA INTERPRETED RESULT FOR VES 1

POTENTIAL (MN/2)	DISTANCE (AB/2)	VOLTAGE (mV)	CURRENT (mA)	RESISTANCE (ohm)	Electrode Constant	Apparent resistivity (Ohm m)
0.50	0.80	1.8100	0.00493	367.1400	2.01088	738.2744016

0.50	1.30	0.6320	0.00927	68.1769	5.30998	362.0180539
0.50	3.30	0.2240	0.00836	26.7943	34.21638	916.8025263
1.30	3.30	1.5720	0.01533	102.5440	13.16014615	1349.494439
1.30	6.30	0.0430	0.00270	15.9259	47.96383846	763.8685385
1.30	8.25	0.0340	0.00303	11.2211	82.25091346	922.9475438
1.80	8.25	0.0420	0.00300	14.0000	59.4034375	831.648125
1.80	10.30	0.0420	0.00571	7.3555	92.59299444	681.0693112
1.80	15.30	0.0290	0.00991	2.9263	204.30855	597.8756761
2.30	15.30	0.0390	0.01370	2.8467	159.8936478	455.1716982
2.30	20.30	0.0320	0.01040	3.0769	281.475387	866.0781137
2.30	25.30	0.0200	0.01251	1.5987	437.2093	698.9756994
2.30	30.80	0.0100	0.01347	0.7424	647.9623652	481.0411026
3.30	30.80	0.0160	0.02137	0.7487	451.6101333	338.1264452
3.30	40.50	0.0200	0.01617	1.2369	780.8584091	965.8112667
3.30	46.50	0.0120	0.01834	0.6543	1029.362045	673.5193318
3.30	56.50	0.0120	0.02223	0.5398	1519.70447	820.35329
4.30	56.50	0.0140	0.02416	0.5795	1166.284826	675.8272996
4.30	61.50	0.0110	0.02351	0.4679	1381.84064	646.5438977
4.30	66.40	0.0230	0.03180	0.7233	1610.808409	1165.050107
5.30	66.40	0.0170	0.02879	0.5905	1306.882294	771.691525
5.30	76.40	0.0060	0.02590	0.2317	1730.163049	400.8099728
5.30	86.20	0.0070	0.03205	0.2184	2202.494574	481.0440566
6.30	86.20	0.0160	0.03494	0.4579	1852.89226	848.4910179
6.30	96.20	0.0040	0.01706	0.2345	2307.734165	541.0865569
7.30	96.20	0.0030	0.00699	0.4292	1991.606197	854.7666083
7.30	100.00	0.0060	0.01980	0.3030	2152.054795	652.1378165

Table 4.2: FIELD DATA INTERPRETED RESULT FOR VES 2

POTENTIAL (MN/2)	DISTANCE (AB/2)	VOLTAGE (mV)	CURRENT (mA)	RESISTANCE (ohm)	Electrode Constant	Apparent resistivity (Ohm m)
0.50	0.80	1.568	0.024	65.3333333	2.01088	131.3775
0.50	1.30	0.566	0.0156	36.2820513	5.30998	192.6570
0.50	3.30	0.548	0.0183	29.9453552	34.21638	1024.6217
1.30	3.30	0.539	0.009	59.8888889	13.16015	788.1465
1.30	6.30	0.112	0.0094	11.9148936	47.96384	571.4840
1.30	8.25	0.085	0.0123	6.9105691	82.25091	568.4006
1.80	8.25	0.183	0.0113	16.1946903	59.40344	962.0203
1.80	10.30	0.030	0.0051	5.8823529	92.59299	544.6647
1.80	15.30	0.019	0.004	4.7500000	204.30855	970.4656
2.30	15.30	0.030	0.0068	4.4117647	159.89365	705.4132
2.30	20.30	0.019	0.0075	2.5333333	281.47539	713.0710
2.30	25.30	0.011	0.0049	2.2448980	437.20930	981.4903
2.30	30.80	0.010	0.008	1.2500000	647.96237	809.9530
3.30	30.80	0.024	0.0158	1.5189873	451.61013	685.9901
3.30	40.50	0.015	0.0161	0.9316770	780.85841	727.5078
3.30	46.50	0.021	0.0199	1.0552764	1029.36205	1086.2615
3.30	56.50	0.008	0.0209	0.3827751	1519.70447	581.7051
4.30	56.50	0.012	0.01501	0.7994670	1166.28483	932.4063
4.30	61.50	0.005	0.0119	0.4201681	1381.84064	580.6053
4.30	66.40	0.014	0.02269	0.6170119	1610.80841	993.8880
5.30	66.40	0.005	0.0127	0.3937008	1306.88229	514.5206

5.30	76.40	0.005	0.0157	0.3184713	1730.16305	551.0073
5.30	86.20	0.009	0.01974	0.4559271	2202.49457	1004.1769
6.30	86.20	0.004	0.01748	0.2288330	1852.89226	424.0028
6.30	96.20	0.005	0.01835	0.2724796	2307.73417	628.8104
7.30	96.20	0.010	0.02112	0.4734848	1991.60620	942.9954
7.30	100.00	0.010	0.0253	0.3952569	2152.05479	850.6145

Table 4.3: FIELD DATA INTERPRETED RESULT FOR VES 3

POTENTIAL (MN/2)	DISTANCE (AB/2)	VOLTAGE	CURRENT(mA)	RESISTANCE (ohm)	Electrode Constant	Apparent resistivity (Ohm m)
0.50	0.80	1.3500	0.00395	341.7721519	2.01088	687.2628
0.50	1.30	0.1930	0.00158	122.1518987	5.30998	648.6241
0.50	3.30	0.0100	0.00257	3.891050584	34.21638	133.1377
1.30	3.30	0.3670	0.00492	74.59349593	13.16015	981.6613
1.30	6.30	0.0230	0.00105	21.9047619	47.96384	1050.6365
1.30	8.25	0.0220	0.00387	5.684754522	82.25091	467.5763
1.80	8.25	0.0400	0.00534	7.490636704	59.40344	444.9696
1.80	10.30	0.1180	0.01093	10.79597438	92.59299	999.6316
1.80	15.30	0.0080	0.0153	0.522875817	204.30855	106.8280
2.30	15.30	0.1190	0.01861	6.394411607	159.89365	1022.4258
2.30	20.30	0.0430	0.02016	2.132936508	281.47539	600.3691
2.30	25.30	0.0490	0.02153	2.275894101	437.20930	995.0421
2.30	30.80	0.0070	0.00648	1.080246914	647.96237	699.9593
3.30	30.80	0.0120	0.0089	1.348314607	451.61013	608.9125
3.30	40.50	0.0100	0.01529	0.654022237	780.85841	510.6988
3.30	46.50	0.0080	0.01455	0.549828179	1029.36205	565.9723
3.30	56.50	0.0060	0.01383	0.433839479	1519.70447	659.3078
4.30	56.50	0.0080	0.01209	0.661703888	1166.28483	771.7352
4.30	61.50	0.0060	0.01565	0.383386581	1381.84064	529.7792
4.30	66.40	0.0040	0.01723	0.232153221	1610.80841	373.9544
5.30	66.40	0.0160	0.01987	0.805234021	1306.88229	1052.3461
5.30	76.40	0.0120	0.02513	0.477516912	1730.16305	826.1821
5.30	86.20	0.0050	0.0217	0.230414747	2202.49457	507.4872
6.30	86.20	0.0070	0.02091	0.334768054	1852.89226	620.2891
6.30	96.20	0.0080	0.01763	0.45377198	2307.73417	1047.1851
7.30	96.20	0.0110	0.02332	0.471698113	1991.60620	939.4369
7.30	100.00	0.0110	0.02674	0.411368736	2152.05479	885.2881

Table 4.4: FIELD DATA FIELD DATA INTERPRETED RESULT FOR VES 4

POTENTIAL (MN/2)	DISTANCE (AB/2)	VOLTAGE	CURRENT(mA)	RESISTANCE (ohm)	Electrode Constant	Apparent resistivity (Ohm m)
0.50	0.80	10.4700	0.0406	257.8817734	2.01	518.5693
0.50	1.30	6.6700	0.0643	103.7325039	5.31	550.8175
0.50	3.30	2.2250	0.0696	31.9683908	34.22	1093.8426
1.30	3.30	6.5830	0.0744	88.4811828	13.16	1164.4253
1.30	6.30	0.6000	0.0403	14.88833747	47.96	714.1018
1.30	8.25	0.3900	0.0467	8.35117773	82.25	686.8920
1.80	8.25	0.7500	0.047	15.95744681	59.40	947.9272
1.80	10.30	0.4200	0.0459	9.150326797	92.59	847.2562

1.80	15.30	0.1300	0.0267	4.868913858	204.31	994.7607
2.30	15.30	0.0700	0.0229	3.056768559	159.89	488.7579
2.30	20.30	0.0800	0.0321	2.492211838	281.48	701.4963
2.30	25.30	0.0240	0.0314	0.76433121	437.21	334.1727
2.30	30.80	0.0030	0.0344	0.087209302	647.96	56.5083
3.30	30.80	0.0100	0.0372	0.268817204	451.61	121.4006
3.30	40.50	0.0290	0.0322	0.900621118	780.86	703.2576
3.30	46.50	0.0350	0.0389	0.899742931	1029.36	926.1612
3.30	56.50	0.0240	0.0375	0.64	1519.70	972.6109
4.30	56.50	0.0200	0.0291	0.687285223	1166.28	801.5703
4.30	61.50	0.0030	0.0353	0.084985836	1381.84	117.4369
4.30	66.40	0.0050	0.0389	0.128534704	1610.81	207.0448
5.30	66.40	0.0050	0.0387	0.129198966	1306.88	168.8478
5.30	76.40	0.0110	0.0308	0.357142857	1730.16	617.9154
5.30	86.20	0.0030	0.029	0.103448276	2202.49	227.8443
6.30	86.20	0.0150	0.029	0.517241379	1852.89	958.3925
6.30	96.20	0.0070	0.0355	0.197183099	2307.73	455.0462
7.30	96.20	0.0100	0.0456	0.219298246	1991.61	436.7557
7.30	100.00	0.0060	0.0247	0.24291498	2152.05	522.7663

Resist Graph

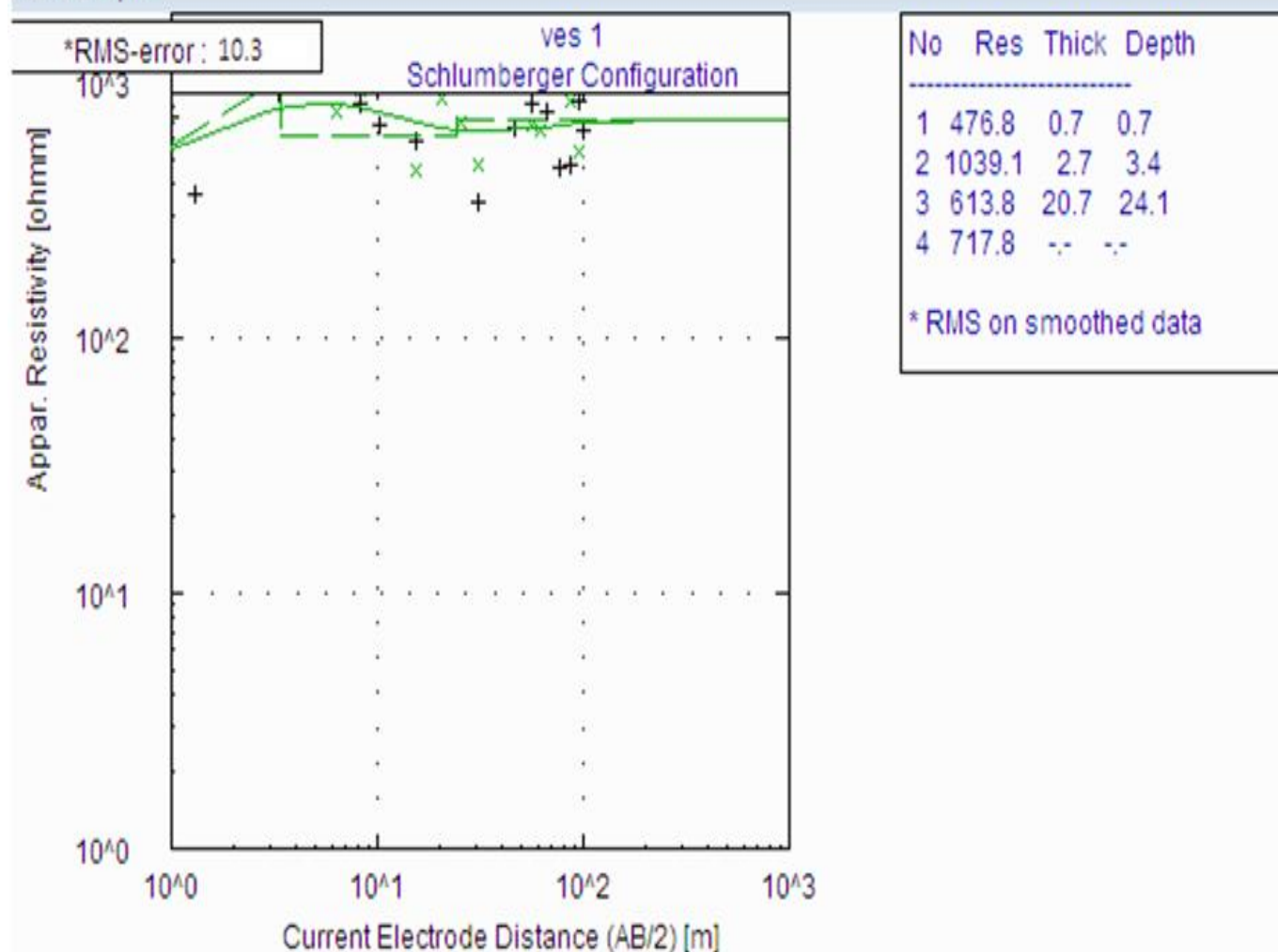


Figure 4.1 Schlumberger Vertical Electrical Sounding (VES) Resistivity Curve and Four-Layer Earth Model

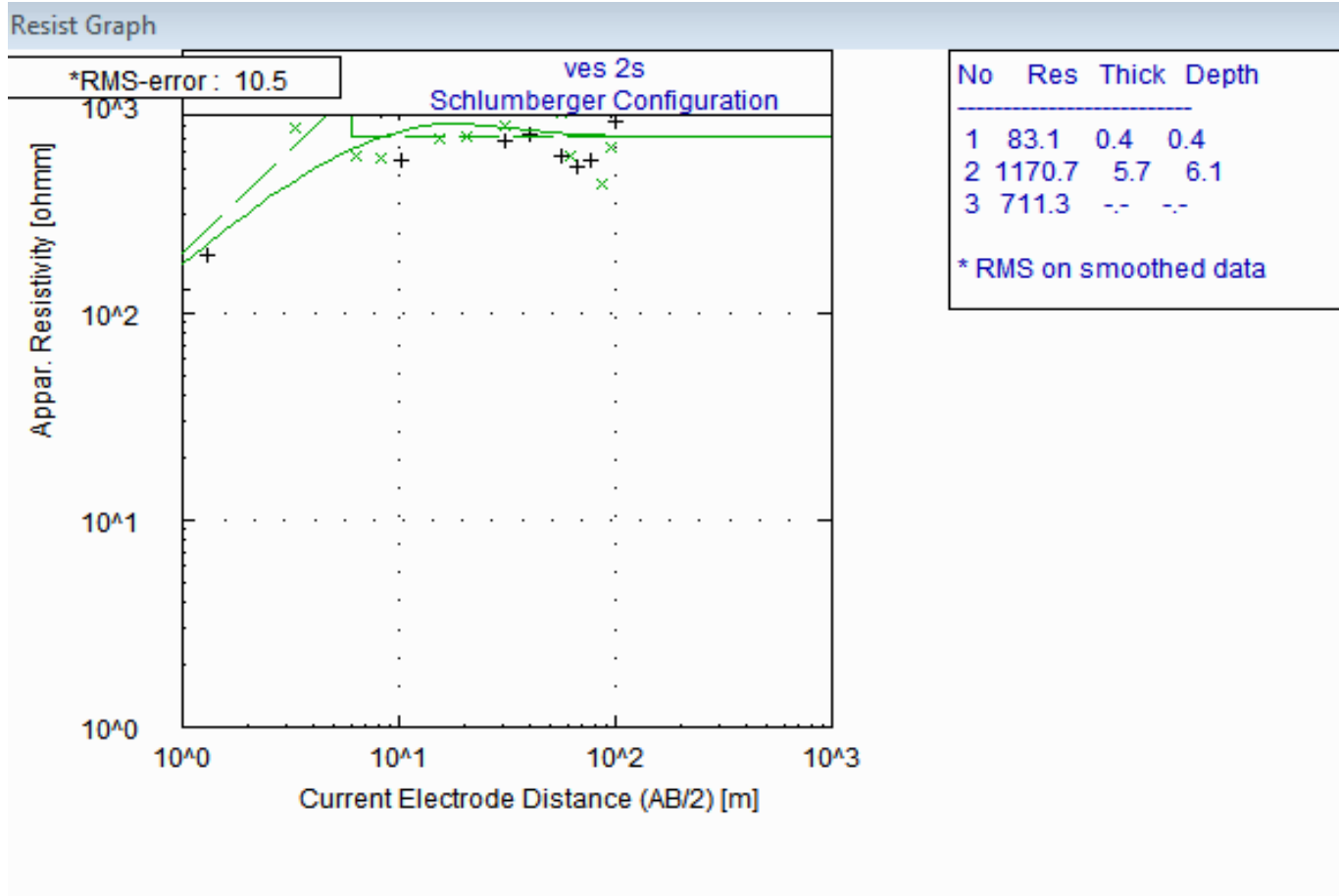


Figure 4.2 Schlumberger VES 2s Apparent Resistivity Curve and Three-Layer Geoelectric Model

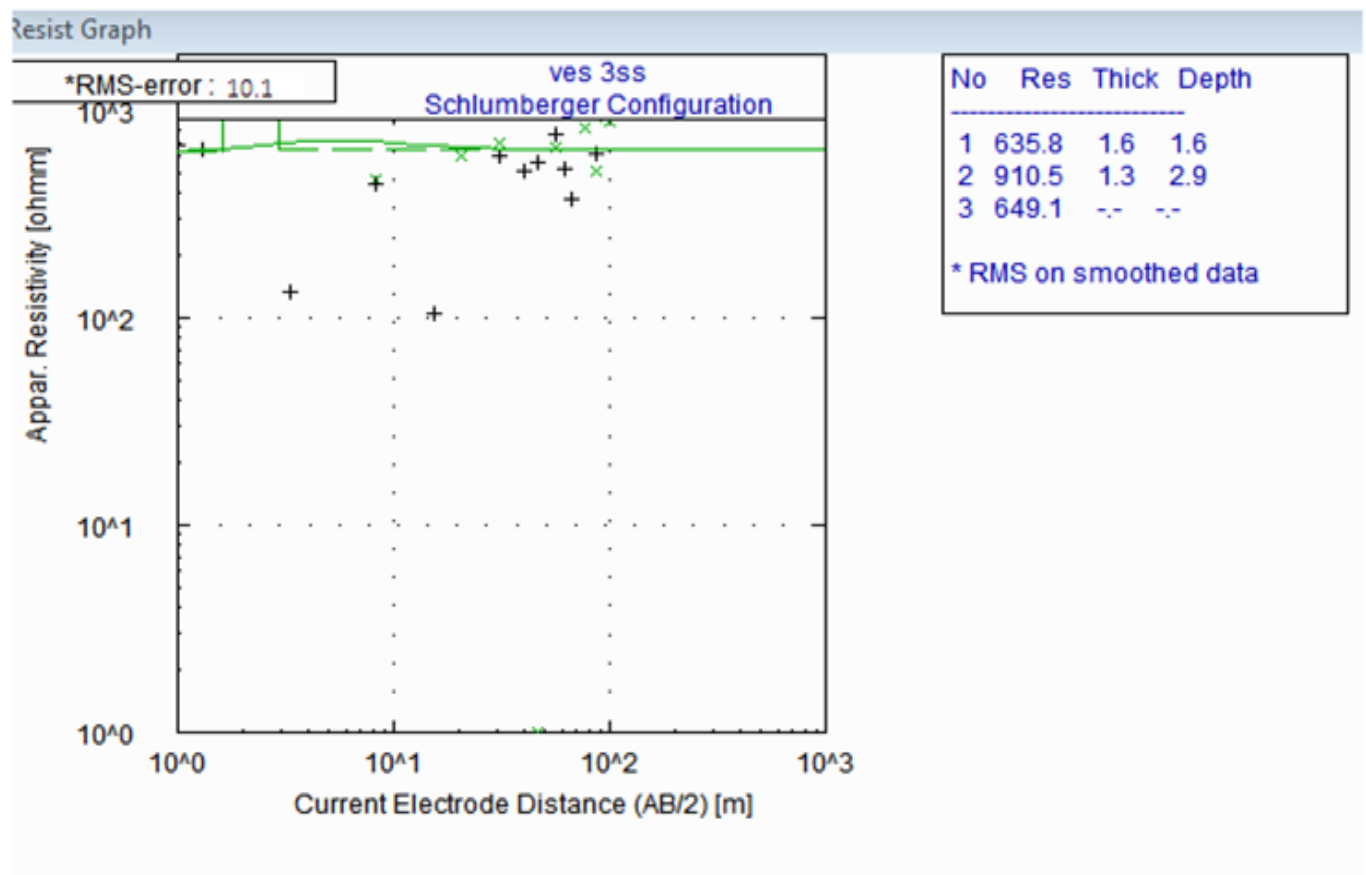


Figure 4.3 Schlumberger VES 3ss Apparent Resistivity Curve and Three-Layer Geoelectric Section

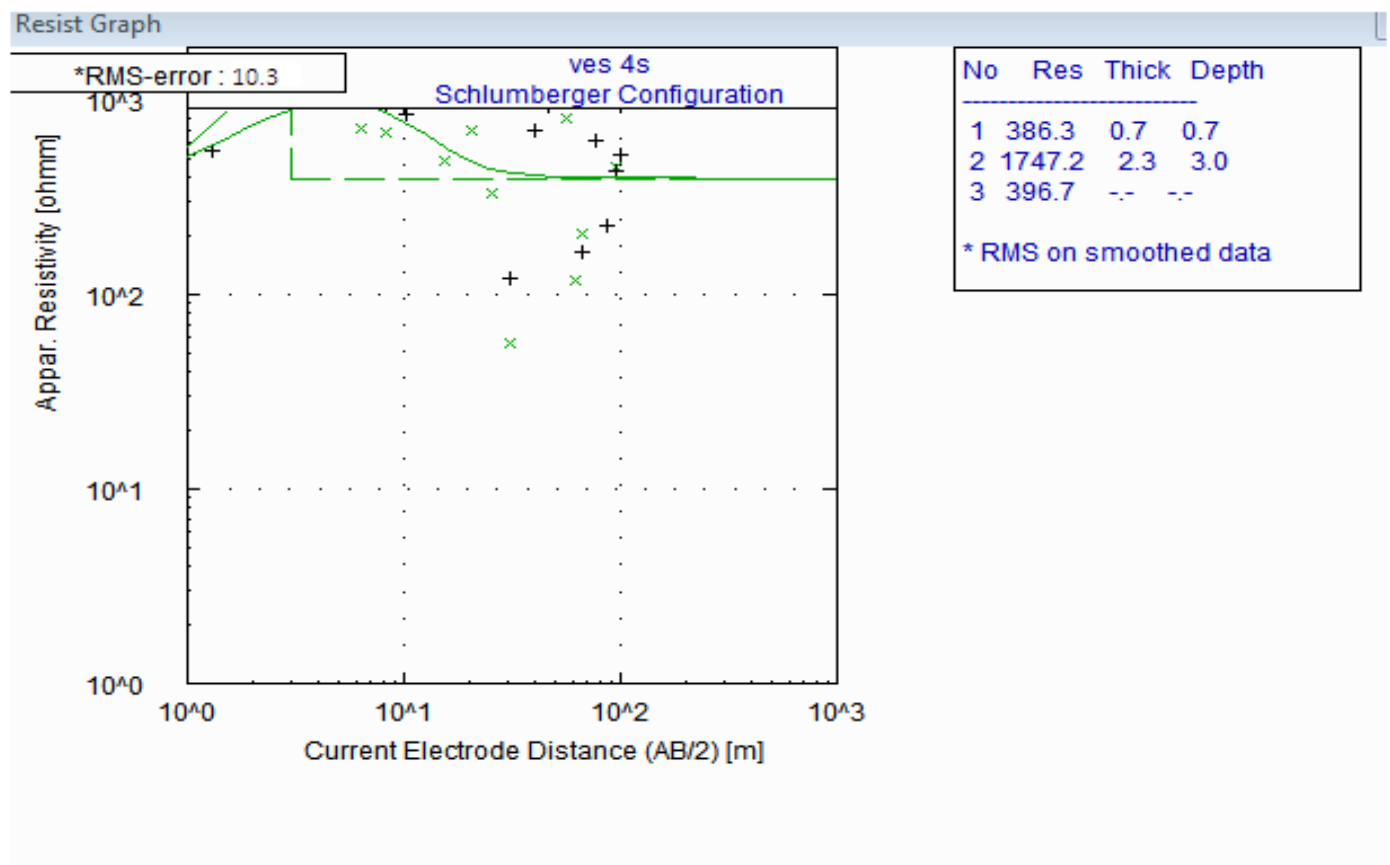


Figure 4.4 Schlumberger VES 4s Apparent Resistivity Curve and Three-Layer Goelectric Section

Table 4.5: Summaries of Goelectric Parameters of study Area

VES No	No of Layers	Layer Resistivity	Layer Thickness	Depth	Curve	Interpreted Lithology
1	3	476.8 1039.1 613.8 717.8	6.7 2.7 20.7 —	0.7 3.4 24.1 —	AK	Topsoil Lateritic Clay Fresh Basement
2	3	83.1 1170.7 711.3	0.4 0.7 —	0.4 6.1 —	HK	Topsoil Lateritic Clay Fresh Basement
3	3	635.8 910.5 649.1	1.6 1.3 —	1.6 2.9 —		Topsoil Lateritic Clay Fresh Basement
4	3	386.3 1747.2 396.7	0.7 0.7 —	0.7 3.0 —		Topsoil Lateritic, Sandy Clay, weather layer, Fresh Basement

DISCUSSION OF RESULTS

Goelectric Parameters and Model Reconciliation

The quantitative inversion results for the four Vertical Electrical Soundings (VES) are summarized below.

Reconciliation of VES 1: Previous discrepancies in layer counts for VES 1 have been reconciled. VES 1 is

confirmed as a **4-layer earth model** ($\rho_1 = 476.8 \Omega\text{m}$, $\rho_2 = 1039.1\Omega\text{m}$, $\rho_3 = 613.8\Omega\text{m}$, $\rho_4 = 717.8\Omega\text{m}$, corresponding to an **AK-type curve** ($\rho_1 < \rho_2 > \rho < \rho_4$).

Table 4.6: Summary of Reconciled Geoelectric Parameters

VES No.	No. of Layers	Curve Type	Layer Resistivity ($\Omega\cdot\text{m}$)	Layer Thickness (m)	Layer Depth (m)	Interpreted Lithology	RMS Error (%)
VES 1	4	AK	$\rho_1=476.8$	$h_1 = 0.7$	$d_1 = 0.7$	Topsoil	10.3
			$\rho_2=1039.1$	$h_2 = 2.7$	$d_2 = 3.4$	Lateritic Band	
			$\rho_3 = 613.8$	$h_3 = 20.7$	$d_3 = 24.1$	Weathered Basement	
			$\rho_4 = 717.8$	$h_4=\text{infinity}$	$d_4=\text{infinity}$	Fresh / Fractured Bedrock	
VES 2	3	HK	$\rho_1 = 83.1$	$h_1 = 0.4$	$d_1 = 0.4$	Topsoil	10.5
			$\rho_2=1170.7$	$h_2 = 5.7$	$d_2 = 6.1$	Lateritic Layer	
			$\rho = 711.3$	$h_3=\text{infinity}$	$d_3=\text{infinity}$	Fresh Basement	
VES 3	3	H	$\rho_1 = 635.8$	$h_1 = 1.6$	$d_1 = 1.6$	Topsoil	10.1
			$\rho_2=910.5$	$h_2 = 1.3$	$d_2 = 2.9$	Lateritic Clay	
			$\rho_3 = 649.1$	$h_3 = \text{infinity}$	$d_3 = \text{infinity}$	Fresh Basement	
VES 4	3	H	$\rho_1 = 386.3$	$h_1 = 0.7$	$d_1 = 0.7$	Topsoil	10.3
			$\rho_2=1747.2$	$h_2 = 2.3$	$d_2 = 3.0$	Lateritic / Sandy Clay	
			$\rho_3 = 396.7$	$h_3 = \text{infinity}$	$d_3 = \text{infinity}$	Fresh Basement	

The discussion integrates the geoelectric parameters to determine the viability of the site for water exploration.

The geophysical investigation identified three to four geoelectric layers across four Vertical Electrical Sounding (VES) points:

- **VES 1:** A four-layer earth model (AK curve type) consisting of topsoil, lateritic clay, a weathered layer, and fresh basement. It shows the highest overburden thickness at 24.1m.

- **VES 2:** A three-layer model (HK curve) with topsoil, lateritic clay, and fresh basement, reaching a depth of 6.1m.
- **VES 3:** A three-layer model with topsoil, lateritic clay, and fresh basement, reaching a depth of 2.9m.
- **VES 4:** A three-layer model consisting of topsoil, a combined lateritic/sandy clay weathered layer, and fresh basement, reaching a depth of 3.0m.
- **Lithology:** The subsurface generally comprises topsoil, lateritic clay, weathered layers, and a fresh basement rock.
- **Aquifer Potential and Overburden Thickness:** The primary aquifers in this basement complex terrain are the weathered layers and fractured zones. VES 1 stands out as the most promising location because it possesses the thickest overburden (24.1m) and a well-defined weathered layer. Thick overburden typically acts as a significant reservoir for groundwater storage.
- **Bedrock Relief:** The results suggest that "depressed bedrock relief" (as seen in VES 1) is more favorable for groundwater accumulation than "high bedrock relief". Locations like VES 3 and VES 4, with shallow depths to the fresh basement (2.9m and 3.0m respectively), are less likely to sustain high-yield boreholes.
- **Zoning Classification:** Based on the interpreted thicknesses and resistivities, the study area is heterogeneous. VES 1 is classified as a high potential zone due to its superior weathered layer thickness and deep basement. In contrast, VES 2, 3, and 4 represent poor to intermediate zones where the thin weathered layers and high bedrock relief limit groundwater storage capacity.

Apparent Resistivity Field Data Summary

Representative field measurements and calculated apparent resistivities across standard electrode spacings are formatted below:

Table 4.7 Apparent Resistivity Field Data Summary

AB/2 (m)	MN/2 (m)	Geometric Factor K (m)	App. ρ_a VES 1 ($\Omega \cdot m$)	App. ρ_a VES 2 ($\Omega \cdot m$)	App. ρ_a VES 3 ($\Omega \cdot m$)	App. ρ_a VES 4 ($\Omega \cdot m$)
0.80	0.50	2.01	738.3	131.4	687.3	518.6
3.30	0.50	34.22	916.8	1024.6	133.1	1093.8
15.30	1.80	204.31	597.9	970.5	106.8	994.8
30.80	2.30	647.96	481.0	810.0	699.9	56.5
56.50	3.30	1519.70	820.4	581.7	659.3	972.6
100.00	7.30	2152.05	652.1	850.6	885.3	522.8

Groundwater Potential Evaluation and Zoning

Combining geoelectric parameters, overburden thickness, and bedrock topography allows classification of groundwater potential:

- **High Potential Zones:** These are characterized by significant overburden thickness and highly depressed bedrock relief, which serve as natural reservoirs for water accumulation.
- **Intermediate Potential Zones:** These regions exhibit moderate weathering and favorable bedrock depressions, offering viable but less prolific water sources compared to high-potential zones.
- **Poor Potential Zones:** Characterized by thin overburden, high weathered layer resistivity, and high bedrock relief, these areas are generally unsuitable for productive borehole development.

The integration of specific geoelectric parameters, such as the AK curve type observed in VES 1, highlights the complexity of the subsurface and the necessity of high-resolution geophysical prospecting to avoid the high failure rates associated with random drilling in crystalline terrains. Furthermore, the study underscores that while electrical resistivity remains a primary tool due to its sensitivity to water saturation and clay content, its reliability is enhanced when integrated with hydrogeological data and other geophysical methods like seismic or electromagnetic surveys to resolve interpretation ambiguities.

Ultimately, this study provides a scientific framework for sustainable groundwater management in the selected area of Akungba Akoko region. By mapping the spatial distribution of aquifer-bearing weathered layers and fractured zones, the findings offer immediate practical guidance for citing productive boreholes. This approach not only optimizes economic investment by reducing the risk of dry wells but also contributes to the broader understanding of groundwater dynamics in sub-Saharan Africa's basement complexes, ensuring long-term water security for domestic and agricultural needs.

Explicit Interpretation Ambiguity and Hydrogeological Validation

Resistivity interpretations in basement terrains are inherently subject to equivalence and non-uniqueness. Low-to-moderate resistivity zones (100 - 500Ωm) can indicate water-bearing granular materials or impermeable, clay-rich weathered layers. To resolve this ambiguity and confirm aquifer transmissivity, independent borehole lithological logging, natural gamma logging, and pumping test validation are strongly recommended prior to full-scale drilling operations.

CONCLUSION

The geophysical investigation conducted at Akungba Akoko, Ondo State, successfully demonstrated the utility of electrical resistivity surveys, specifically the Schlumberger array, in delineating subsurface characteristics critical for groundwater accumulation in basement complex terrains. In such geological settings, where primary porosity is negligible, the occurrence of groundwater is fundamentally controlled by secondary features such as the thickness of the weathered overburden and the relief of the underlying bedrock.

This study successfully evaluated the groundwater potential at Ogodo Agbe, Akungba-Akoko using Vertical Electrical Sounding with the Schlumberger array. Software-assisted quantitative inversion using IPI2win yielded robust 3- to 4-layer geoelectric models with RMS fitting errors below 10.5%. Reconciled findings classify VES 1 as a high groundwater potential zone due to its thick overburden (24.1 m) and depressed bedrock topography. VES 2, 3, and 4 represent poor-to-intermediate potential zones due to shallow bedrock depths (less or equal to 6.1m). Integrating geophysical results with independent hydrogeological and borehole validation remains essential for minimizing drilling risks in crystalline basement environments.

Declarations

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Conflicts of interest: The authors declare that they have no conflict of interest

Availability of data: The datasets generated during and/or analyzed during the current study are not publicly available but are available from the corresponding author on reasonable request.

Ethical Approval: Not applicable

Code availability: Not applicable

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