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Exploration and Delineation of Potable and Prolific Aquifers in Bonny Kingdom

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Bonny Kingdom is an island in the Niger Delta region of Nigeria. It is composed of the mainland and creeked-villages, and surrounded by the Sea and Atlantic Ocean. In the Bonny Kingdom, there is water everywhere but there is little or no potable water for drinking and domestic uses. Upon this, the exploration and delineation of potable and prolific aquifers using the Vertical Electrical Sounding method is carried out. Of the many locations where the study is carried out, the reports of fourteen are considered herein, and the geologic data showing the apparent resistivity, depths, and

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thicknesses of the sub-surfaces are obtained, analyzed, and presented quantitatively and graphically. The results are analyzed using IPI2win iteration software, and they show that freshwater aquifers exist in the Bonny Kingdom at different degrees (some shallow and some deep) such that boreholes can be drilled to specified depths for domestic or industrial uses. The locations of the potable aquifers have been mapped out. The shallow aquifers are prone to surface influences such as contaminations and may likely dry up during the dry season; the deep aquifers have greater sustainability but require carefulness at the drilling stage to avoid encroaching into sub-surfaces with possible saline water. Furthermore, it is observed that there are more prolific freshwater aquifers on the mainland than in the villages.

Keywords: Bonny Kingdom; groundwater exploration; hydrogeology; Niger Delta; potable aquifers; prolific aquifers; Vertical Electrical Sounding (VES).

1. INTRODUCTION

The Niger Delta region of Nigeria is a vast and complex region created by the convergence of several major rivers, creeks, and creeklets. It occupies an area of about thirty thousand square kilometres (30,000 km^2). By the reason of its topology, characterized by difficult and inaccessible terrain is faced with physical development challenges. Due to accessibility challenges, and the nature of the soil the costs of executing projects are extremely high. However, the region is rich in hydrocarbon resources, which account for over 90% of Nigeria’s gross domestic product (GDP) (Wikipedia). Among the communities in the region is the Bonny Kingdom.

Bonny Kingdom is an island situated in the southern edge of Rivers State in the Niger Delta region of Nigeria. It is located at the edge of the Atlantic Ocean on the Bight of Bonny and lies between latitude 4°52' N to 5°02' N and longitudes 6°56' E to 7°04' E (Fig. 1). The Island has a relatively flat topography at an elevation of 3.05 mean sea levels [1].

The Bonny community is divided into two main segments: the mainland and the hinterland. The mainland comprises the Bonny metropolis and its segments: the Main Island (Township), Sandfill, Iwoama, Orosikiri, Aganya, Ayambo, Eagle Forest, Agaja, Oguede, Akiama, Abalamabie, NLNG Water Wells, Workers Camp, Finima and some outlying fishing settlements lying along the Bonny coastline. The hinterland includes the villages: Dema-Abbey, Banigo, George-Pepple, Dan-Jumbo, Burukiri, Sagama, Iseleogono-Beresiri, Greens, Jackmay, Christy-Wilcox, Halliday, William-Jumbo, Iyoba, Ebentubu, Ifokpo, Nunabie, Epelematubu, Oyorokutu, Egbelebie, Minima, Epelema, Oruperi, Owupiri, Peterside, Kuruama, Fibiri, Ayama, Kalaibiama, Oloma, etc. The major means of transport to and from the Island are speed boats, and air (using the NLNG aerodrome).

Bonny Kingdom is the home of Africa’s largest liquefied natural gas plant (NLNG), gas export terminals for Shell Petroleum Development Company (SPDC), and Exxon Mobil. This unique position spurred economic and infrastructural development in the area due to the continuous influx of people into the land for better opportunities.

1.1 Geological and Hydrogeological Characteristics of Bonny Kingdom

The geological characteristics of the Niger Delta have been extensively studied by various geoscientists [2-6]. These studies collectively affirm the presence of three principal formations beneath the Niger Delta region: Akata, Agbada, and Benin formations (Fig. 2). Notably, the Akata formation is predominantly shale and clay while the Agbada formation is characterized by fluviatile and fluviomarine deposits. The Akata and Agbada formations are crucial for hydrocarbon exploration. Importantly, the structural traps formed in the Agbada Formation during sedimentation, such as faults and roll-over anticlines, facilitate the accumulation of petroleum in the Niger Delta reservoirs. On the other, the Benin formation, occurring at shallower horizons, consists mainly of continental deposits of sand and gravel, unconsolidated and highly porous [7]. The Benin Formation holds the groundwater/freshwater and civil construction sectors [8,9].

Limiting ourselves to the Benin formation, understanding the sedimentation pattern and stratification is crucial for identifying the aquifer type, quantity, and quality of water in the region. The Benin Formation can be differentiated into three zones: a northern bordering zone with shallow aquifers of continental deposits, a transition zone with intermixing marine and continental materials, and a coastal zone predominantly composed of marine deposits [10,11,12]. For these divisions, aquifer properties exhibit distinct spatial trends.

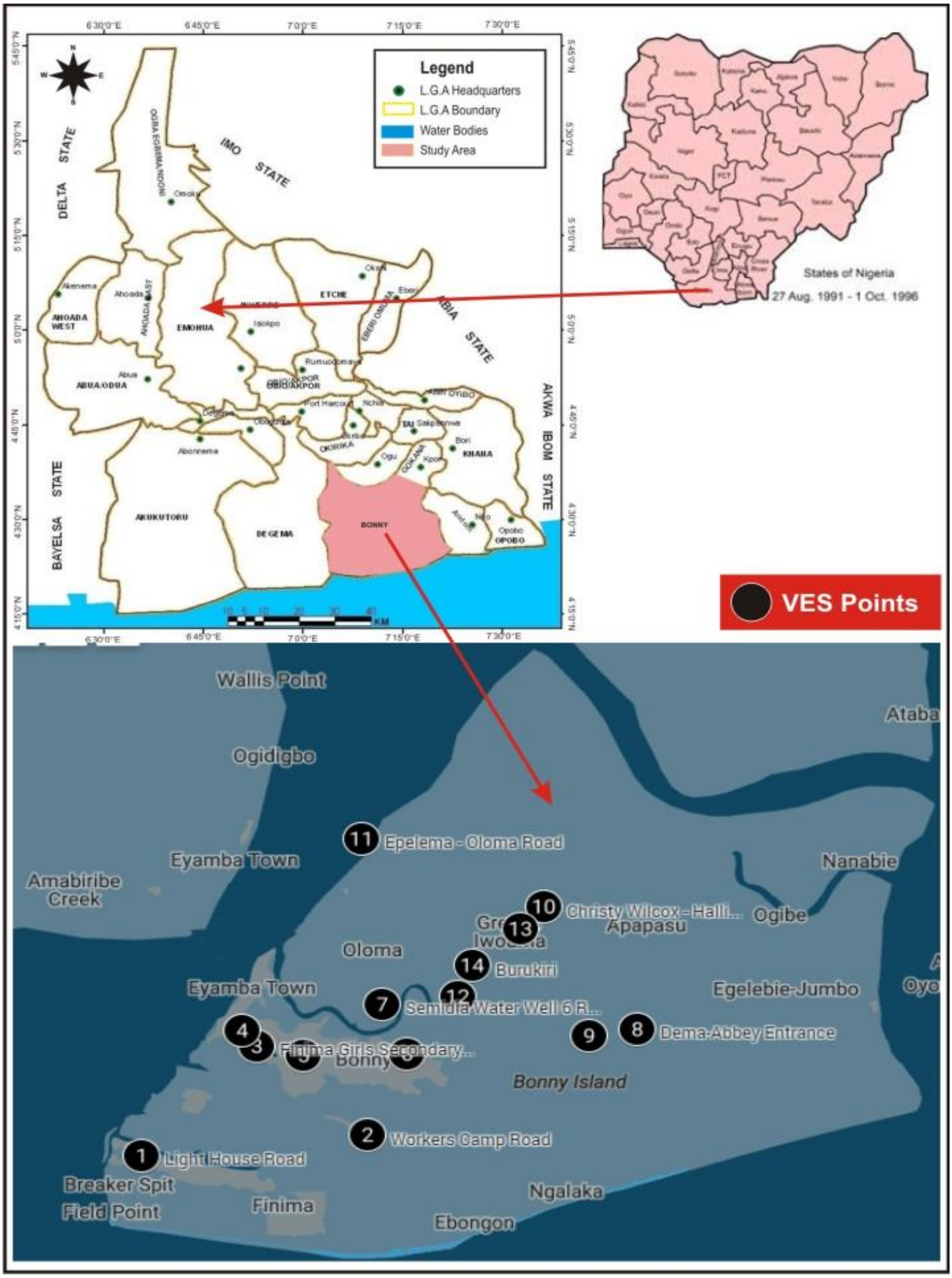

Fig. 1. Study area map

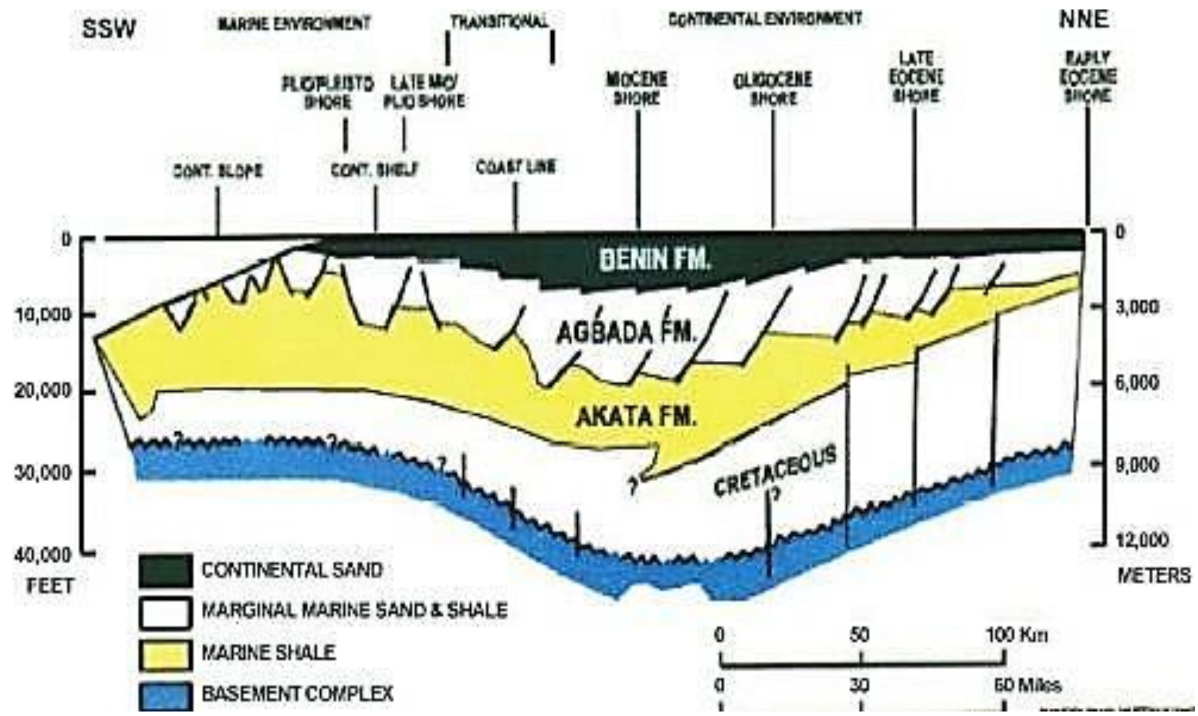

Fig. 2. Map of Akata, Agbada, and Benin Formations Short and Stauble, [3]

The coastal zone, which is adjacent to the Atlantic Ocean includes mangrove swamp areas and beach ridges. Borehole analysis shows the presence of thicker lenses of marine clay in this zone. This indicates the marine sedimentation conditions. Its proximity to the ocean makes this area more complex, and prone to compromising water quality.

Similarly, the hydraulic conductivities of the sand units in the Benin Formation suggest potentially productive aquifers; the transmissivity values and coefficient of storage indicate a good capacity to transmit groundwater [13] Offodile, 2002; Abam & Nwankwoala, [14].

Specifically, Bonny is situated in the coastal zone of the Benin Formation. It lies within the coastal alluvium and mangrove freshwater swamps hydrogeological province, where both confined and unconfined aquifers are present. The aquifers are highly salinized. More so, there is a hydraulic head differential between that of the groundwater level (higher) and the river water level (lower) [12] Ofodile, 2002; Ekine & Osobonye, [15] Ngah & Nwankwoala, [16] Abam & Nwankwoala, [14]. This induces the flow of river waters into the aquifers, with the attendant effect of partly recharging, and potentially polluting them through high iron content, saltwater intrusion, and tidal influence. Consequently, a lot of drilled boreholes have been abandoned [17].

The pH of surface water within the Bonny Kingdom is slightly alkaline, ranging from 7.2 to 7.9. This falls within permissible/allowable limits/levels for human consumption [18].

The climate of Bonny is tropical, with alternating wet and dry seasons. The wet season spans from April to October, while the dry season is from November to March. Bonny experiences a Tropical monsoon climate (Am classification) with an annual average temperature of 28.19ºC (82.74ºF), which is 1.27% lower than the national average for Nigeria. Throughout the year, Bonny receives approximately 350.75 millimeters (13.81 inches) of rainfall over 323.73 days (88.69% of the year), indicating a high likelihood of rainy days. The hottest month in Bonny is January, with an average temperature of 35.03ºC, while the coolest month is August, with temperatures averaging 22.87ºC (73.17ºF). The peak rainfall occurs in September, with 615.73 millimeters (24.24 inches), September is the wettest month making it significantly rainier compared to other times of the year. Meanwhile, December is the driest month, receiving only 114.79 millimeters (4.52 inches) of rain. There are around 41.27 days (11.31% of the year) with little to no rainfall, highlighting a predominantly moist environment throughout the year.

In general, there is an interplay between geology, hydrogeology, and climate in the shaping of groundwater resources. For example, aquifers are recharged through rainwater, snowmelts, etc. in the wet season. In the dry season when there are no rainfall and snowfall the reverse is the case.

1.2 The Groundwater System

Groundwater is contained underneath the Earth. It is formed from freshwater (rain, melting ice, and snow), which sinks into the soil and is stored in between pore spaces, fractures, and joints in the rocks and geologic formations.

A geologic formation is a body of rocks having a consistent set of physical characteristics (lithology) that distinguish it from adjacent bodies of rocks, and which occupies a particular position in the layer of rock exposed in a geographical region (stratigraphic column).

There are different water-bearing structures in geologic formations. Some of these are the aquicludes, aquitards, and aquifers. Aquicludes are water-bearing layers in which both the horizontal and vertical flow components are negligibly small. Therefore, the flow of water in the aquicludes is zero. Similarly, aquitards are water-bearing layers in which the horizontal flow is negligibly small compared to the vertical components. Therefore, the water flow here is predominantly vertical.

Aquifers are geologic formations with sufficient yield of water to wells and springs. They are the main source of water for man obtained through wells and boreholes. Studies have shown that in aquifers, the vertical flow is negligibly small compared to the horizontal flow. Therefore, water flow in the aquifer is predominantly horizontal.

Aquifers have some characteristics: porosity and permeability. These characteristics depend on the textual arrangement of the rock matrix of the geologic formation. By these characteristics, the transmitting ability of the aquifers can be determined. Upon this, aquifers can be elementarily classified. For example, rock matrices with uniformly or tightly packed structures have high water-retaining ability but less transmitting ability, while those with high porosity and permeability give enough yield of water to wells and springs. Aquifers with high porosity and low permeability consist of granites and schists, and are called poor aquifers; those with high porosity and permeability contain a high percentage of fractured or volcanic rocks and are called excellent aquifers.

Furthermore, aquifers are classified into unconfined and confined aquifers, each with its unique characteristics. The unconfined aquifers are found near the soil surface. They are primarily composed of unconsolidated sediments such as sand and gravel. They do not have clayed or impermeable geologic materials above the water table (the upper layer of the water within the unconfined aquifers). They are often tapped for domestic water supply by local communities. They are more susceptible to surface influences or contamination such as saltwater intrusion and tidal influence.

There is a facet of unconfined aquifers, called the ‘perched aquifers’. They arise from situations where groundwater bodies are separated from their main body by a relatively impermeable rock layer above the main body. The water of the perched aquifers is not replenished. It is available for a short time.

The confined aquifers are composed of more consolidated geological formations such as sandstone or limestone. They are essential for industrial and agricultural water supply. The water therein is enclosed/sealed under impermeable rock layers and is under very high pressure. These aquifers lie below the unconfined aquifers. Their storabilities range from 0.0001- 0.01.

Additionally, there are different facets of confined aquifers: the artesian aquifers, the leaky, and the multi-layered aquifers. The artesian aquifers are found above the confined aquifers. The leaky aquifers are semi-confined aquifers, bounded above by an aquiclude. If the over-laying aquitard extends to the land surface, it may be partly saturated, and if it is over-lain by an unconfined aquifer that is bounded above the water table, it would be fully saturated. The multi-layered aquifers are a succession of leaky aquifers sandwiched between aquitards.

1.3 Methods of Groundwater Exploration: The Theoretical Foundation

There are several approaches to delineating aquifers: Geophysical and Esoteric approaches. In particular, Geophysical methods have emerged as highly effective tools in this endeavor, some invasive, and others non-invasive providing insights into subsurface geological structures and water-bearing formations. The geophysical methods include the Electromagnetic method (Time Domain, Frequency Domain, and Magneto-telluric); Ground-Penetrating Radar (GPR); Seismic methods (Reflection and Refraction); Gravity method; Magnetic method, Borehole method (Electrical Resistivity Log, and Gamma-Ray Log/Spectroscopy); Electrical method (Electrical Resistivity, Self-potential, and Induced Polarization). Each of these methods has its benefits and challenges and has been used by different explorers/researchers. Specifically, we consider the Vertical Electrical Sounding approach, an application of the Electrical Resistivity method.

1.4 Vertical Electrical Sounding Approach

Vertical Electrical Sounding (VES) survey is an essential geophysical technique used to investigate subsurface properties and delineate groundwater resources. It employs specialized equipment and materials to measure the electrical resistivity of the subsurface, providing valuable information about the distribution and characteristics of aquifers. A Resistivity meter, which is capable of injecting electrical currents into the ground through two pairs of electrodes and measuring the resulting voltage differences is used.

The resistivity measurements are normally made by injecting current into the subsurface through two current electrodes (C_1 and C_2 in Fig. 3) and measuring the resulting voltage difference at two potential electrodes (P1 and P2).

The purpose of Electrical resistivity surveys is to determine the subsurface resistivity distribution by making measurements on the ground surface. From these measurements, the true resistivity of the subsurface can be estimated. Ground resistivity is related to various geological parameters such as porosity, fluid saturation, temperature, pressure, mineral, texture, pore geometry, salinity, organic content, and microbial activities. The fundamental physical law used in resistivity surveys is Ohm's Law which governs the flow of current

$$R = \frac{V}{I}$$

where V is the potential (V) and I is the current (A).

From the current (I) and voltage (V) values, an apparent resistivity (pa) value is calculated.

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

$$K = \frac{\left\{\frac{AB^2}{2} - \frac{MN^2}{2}\right\}}{MN}$$

where K is the geometric factor that depends on the arrangement of the four electrodes. Resistivity meters normally give a resistance value, R = V/I. In practice, the apparent resistivity value is calculated by ρ_a = KR.

Some research reports exist on the use of the Vertical Electrical Sounding method in groundwater exploration. For example, Ekine and Osobonye [19] examined possible sites for drilling boreholes in some parts of Bonny using Vertical Electric Sounding, and identified some prolific areas; George and Okwueze [20] investigated the groundwater potential in Oban Massif, south-eastern Nigeria with the aim of determining the depth to the water table, the thickness of the saturated overburden, and the depth to basement for purpose of groundwater development, and noticed that the study area has good potential aquifers for groundwater development; Okolie et al. (2005) used the Geo-electric method to estimate the groundwater in different parts of Niger Delta, and found out that aquifers in the area are unconfined; Akpoborie and Aweto (2012) used the Geo-electric method to delineate groundwater condition in the mangrove swamps of Ughoton area of western Niger Delta, and saw that the method is non-invasive and has high-resolution imaging capabilities; Alisiobi and Ako [21] investigated the groundwater potential in Ajebandele quarters, Ile-Ife, Osun State, Southwest Nigeria using the Vertical Electrical Sounding method with a view to determine the subsurface layer parameters (velocities, resistivity, and thicknesses) and also to categorize the groundwater potential of the area, and observed that both methods indicate viable aquifer at a fractured zone; Rolia and Sutjiningsih (2018) carried out a survey on the groundwater exploration from the surface using the Geoelectric method, and noticed that the geo-electric method is a fairly effective and reliable geophysical tool for detecting the presence of groundwater, lithology and rock stratigraphy in the earth; Iserhien-Emekeme (2020) used the Vertical Electrical Sounding method to ascertain the groundwater potential in the Omadigbo, and observed that southeast to southwest of the area is best suited for sitting boreholes, as the aquifers there are thicker, have higher transmissivity and protective capacity; Okoronkwo et al. (2022) investigated the subsurface lithology and groundwater transmissivity in Delta State University, Abraka, Nigeria using the Vertical Electrical Sounding and Deep Well Logs techniques, and observe that the most prolific and viable aquifers of in the area are at the depth of 28 to 40 m. Other scholars/explorers that used Vertical Electrical Sounding in the assessment of groundwater potential include Zhody et al., 1974; Kearey and Brooks 1991; Okwueze et al., 1994. Ugwu and Nwankwoala [22] Nwankwo et al. [23] Ushie and Eminue [24] Ilevbare and Ogundana [25] Ayanninuola [26] and Nyaberi [27].

In another development, studies have shown that integrating multiple techniques enhances the accuracy and reliability of groundwater exploration studies. For example, Omosuyi et al. (2007) used the Electromagnetic and Geoelectric Sounding approaches to locate fissured zones and associated groundwater-bearing media at Afunbiowo, near Akure, Nigeria, and found that sites with high electromagnetic anomaly are expected to be suitable for the development of groundwater resources; Adepelumi et al, (2013) used an integrated technique involving Electrical Resistivity and Magnetic methods to locate fissured zones and associated groundwater-bearing media at Baikin Area in Ondo State and noticed that the groundwater potential of the area is low [28,29].

The Bonny Kingdom is known for its saltwater encroachment and the presence of heavy metals in its aquifers. As a result, freshwater-prolific aquifers are not seen everywhere in the subsurface. Upon this, we are motivated to explore and locate the freshwater-prolific aquifers in the community using the Vertical Electrical Sounding method [30,31].

This work is presented in the following format: Section 2 is the Materials and Methodology, Section 3 is the Results and Discussion, and Section 4 is the Conclusion.

2. MATERIALS AND METHODS

2.1 Survey Materials

In this work, the Vertical Electrical Sounding (VES) method, an application of the Electrical Resistivity method is used. This survey employs specialized equipment and materials to measure the electrical resistivity of the subsurface, providing valuable information about the distribution and characteristics of aquifers. A Resistivity meter (Herojat-Rhomega Smart) which is capable of injecting electrical currents into the ground through two pairs of electrodes and measuring the resulting voltage differences is used. Other Supporting accessories used include hammers and measuring tape; field notebooks, which serve as logbooks for documenting survey details such as electrode locations and environmental conditions; pens; compasses; phones and whistles; and GPS for recording survey parameters, observations, and coordinates [32].

2.2 Survey Procedure

The field procedure adopted in the data acquisition involves survey planning to data interpretation. The survey locations were selected based on factors such as existing geological and hydrogeological information and accessibility. The survey was carried out by a five-man crew, the principal researcher at the centre controlling the instrument, adjusting the readings and recording the data displayed on the Terrameter, two (wide) men at the rear end of the traverse adjusting the current electrodes, while the last two (middle) men are handling the potential electrodes. Herojat-Rhomega Smart Terrameter equipment was set up, ensuring that the equipment was in good condition. In this survey, artificially generated direct current was introduced into the Earth through a pair of current electrodes, and the resulting potential difference measured by another pair of potential electrodes is read directly from the Terrameter. The fundamental purpose of the electrode is to send current into the subsurface and to measure the potential between two positions. There are four reels of cable which are connected to the resistivity meter at one end and the other ends are connected to the electrodes. Electrode spacing is measured using a tape-meter and two-thirds of the electrodes are driven into the Earth's surface using a hammer. Of the many locations covered using VES with Schlumberger configuration, fourteen are showcased herein, and they include Light House Road, Workers Camp, Finima Girls' School, Government School, Industrial Unit Field, Along Oguede Road, Semidia Water Well 6, Dema-Abbey Entrance, Dema-Abbey Old Settlement, Christy Wilcox-Halliday Road, Epelema-Oloma Road, Epelema-Minima Road, Greens-William Jumbo, and Burukiri.

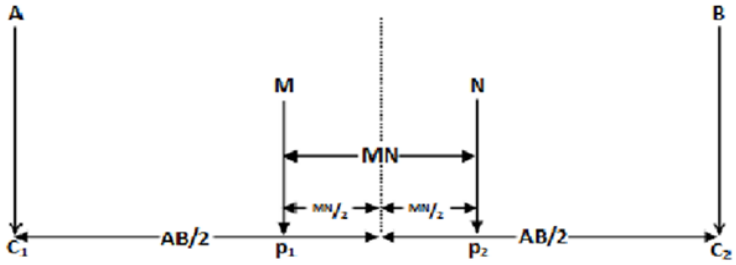

Fig. 3. A conventional four-electrode array to measure the subsurface resistivity

In the course of this survey, several precautions were taken to ensure accurate data collection and the safety of personnel. These include:

1. Site inspection, which was thoroughly conducted to identify any potential hazards.
2. The equipment was regularly checked and maintained to prevent malfunctions during the survey.
3. We ensured that all electrical connections were secure and insulated to prevent shocks or short circuits.
4. A clear communication protocol was adopted among team members through the use of whistles and cell phones to coordinate the surveying activities effectively.
5. We avoided areas with high-tension wires, since their high conductance may impede current into the ground

2.3 Data Analysis and Interpretation

The interpretation of the Vertical Electrical Sounding (VES) data involves a combination of visual inspection, curve matching, inversion modeling, and integration with geological data to characterize subsurface properties. The interpretation parameters obtained from the VES data include layer resistivities, thicknesses, depths to layer boundaries, and the number of layers. These parameters provide insights into lithological variations, aquifer characteristics, and geological structures. A quantitative interpretation approach is used in this study. This approach offers a more rigorous approach to data analysis and can provide quantitative estimates of subsurface parameters. The data obtained in this survey were first analyzed by calculating the apparent resistivity using

$$\rho_a = \text{K x } \frac{V}{I}$$

where K is a geometric factor, V is measured between the potential electrodes (M and N), and I is the current injected into the ground through the current electrodes (A and B). The obtained apparent resistivity values were subsequently inputted into a 1-D resistivity interpretation software IPI2WIN to obtain the resistivity curves shown below.

3. RESULTS PRESENTATION

The VES data interpretation provides valuable insights into the subsurface resistivity distribution and its implications for groundwater potential. The results help to identify the different geo-electric layers and their resistivity values, which can be used to understand the subsurface composition concerning groundwater potential. The data obtained were analyzed using computer-assisted interpretation software (IPI2win). The summary of the VES data is given in Table 1, the curves in Figs 4 –10), and the geoelectric section in Figs 11 and 12 are shown below.

4. DISCUSSION

4.1 VES 1: Light House Road

In this station, five subsurface layers were delineated (Table 1 and Fig. 4, 11), and the geoelectric curve is HKQ-type. The topsoil which is the first layer has an apparent resistivity of 403 Ωm at a depth of 0.946 m and thickness of 0.946 m, indicating a relatively high resistivity, suggesting a layer composed of non-conductive or low-conductive materials like fine-medium sand formations. The second layer has an apparent resistivity of 48.1 Ωm at a depth of 1.95 m and thickness of 1.01 m, indicating the presence of more conductive materials, likely bedrock, metallic materials, and heavy metals. The presence of these metals could be due to the station proximity to a dump site. The third layer has an apparent resistivity of 273 Ωm at a depth of 4.46 m and thickness of 2.51 m, indicating the presence of less conductive materials, possibly a clay or shale formation. The fourth layer has an apparent resistivity of 34.8 Ωm at a depth of 22 m and thickness of 17.5 m, indicating the presence of clay or shale formation that acts as an aquitard, separating the upper aquifer from a deeper aquifer. The fifth layer has an apparent resistivity of 1.27 Ωm at an infinite depth, likely representing a saline or brackish water-bearing formation at an infinite or unknown depth. From the above data, the third layer indicates the presence of a freshwater aquifer. However, because of depth and thickness, it may be prone to contamination shortly, and dry up in the dry season. Upon the above findings, a borehole can be drilled in this station only for domestic uses to a depth range of 4 m to 20 m.

Table 1. Summary of VES survey

S/N	VES Location	Coordinate Long/Lat	Apparent resistivity (Ωm)	Thickness (m)	Depth (m)	Curve Type
1	Light House Road	7° 8′ 33.00″ 4° 24′ 15.557″	403.00 48.10 273.00 34.80 1.27	0.95 1.01 2.51 17.50 -	0.95 1.95 4.46 22.00 -	HKQ
2	Workers Camp Road	7° 11′ 45″ 4° 24′ 35″	164.00 12.50 149.00 3.59 8.76	0.47 0.45 4.54 3.31 -	0.47 0.92 5.46 8.77 -	HKH
3	Finima Girls School	7° 10′ 10″ 4° 25′ 59″	46.40 147.00 13.40 10.10 10773.00	0.71 3.27 12.80 17.80 -	0.71 3.98 16.80 34.30 -	KQH
4	Government School	7° 9′ 59″ 4° 26′ 12″	113.00 753.00 77.00 239.00 0.28	2.37 2.79 5.53 13.10 -	2.37 5.16 10.70 23.70 -	KHK
5	Industrial Unit Field	7°10′ 50.4354″ 4° 25′ 50.20356″	622.00 228.00 35.60 9665.00 27.10	0.81 4.15 4.63 5.04 -	0.81 4.96 9.59 14.60 -	QHK
6	Along Oguede Road	7° 12′ 17.4256″ 4° 25′ 51.18132″	1241.00 278.00 921.00 14.60 16010.00	0.64 15.00 9.21 20.20 -	0.64 15.70 24.90 45.10 -	HKH
7	Semidia Water Well 6	7° 11′ 57.1527″ 4° 25′ 38.619″	62.50 447.00 66.20 20.10 9355.00	1.38 3.22 44.70 23.80 -	1.38 4.61 49.30 73.10 -	KQH
8	Dema-Abey Entrance	7° 15′ 33.7464″ 4° 26′ 15.1224″	89.90 23.80 116.00 2.28 284.00	0.83 2.38 2.61 125.00 -	0.83 3.21 5.82 131.00 -	HKH
9	Dema-Abbey Old Settlement	7° 14′ 52.2528″ 4° 26′ 8.1852″	481.00 85.70 196.00 33.30 0.21	0.60 2.52 21.80 163.00 -	0.60 3.11 24.90 188.00 -	HKQ

S/N	VES Location	Coordinate Long/Lat	Apparent resistivity (Ωm)	Thickness (m)	Depth (m)	Curve Type
10	Christy Wilcox – Halliday Road	7° 14′ 14.0208″ 4° 28′ 10.1604″	413.00 3699.00 107.00 4.17 17.68	0.29 0.73 4.16 5.72 -	0.29 1.01 5.17 10.90 -	KQH
11	Epelema - Oloma Road	7° 11′ 39.65712″ 4° 29′ 15.00792″	1671.00 7552.00 12.30 45195.00 119.00	0.34 0.94 0.37 9.35 -	0.34 1.28 1.65 11.00 -	KHK
12	Epelema - Minima Road	7° 13′ 0.9102″ 4° 26′ 45.8304″	32.20 34491.00 758.00 78000000 19082.00	0.003 0.24 0.99 19.20 -	0.003 0.24 1.23 20.40	KHK
13	Greens - William Jumbo Road	7° 13′ 54.0948″ 4° 27′ 50.0682″	4987.00 123.00 5666.00 292.00 2.01	2.73 2.66 6.38 91.00 -	2.73 5.39 11.80 103.00 -	HKQ
14	Burukiri	7° 13′ 13.0512″ 4° 27′ 14.6664″	1268.00 94.80 6.51 728.00 0.62	1.05 7.87 6.65 13.60 -	1.05 8.92 15.60 29.20 -	QHK

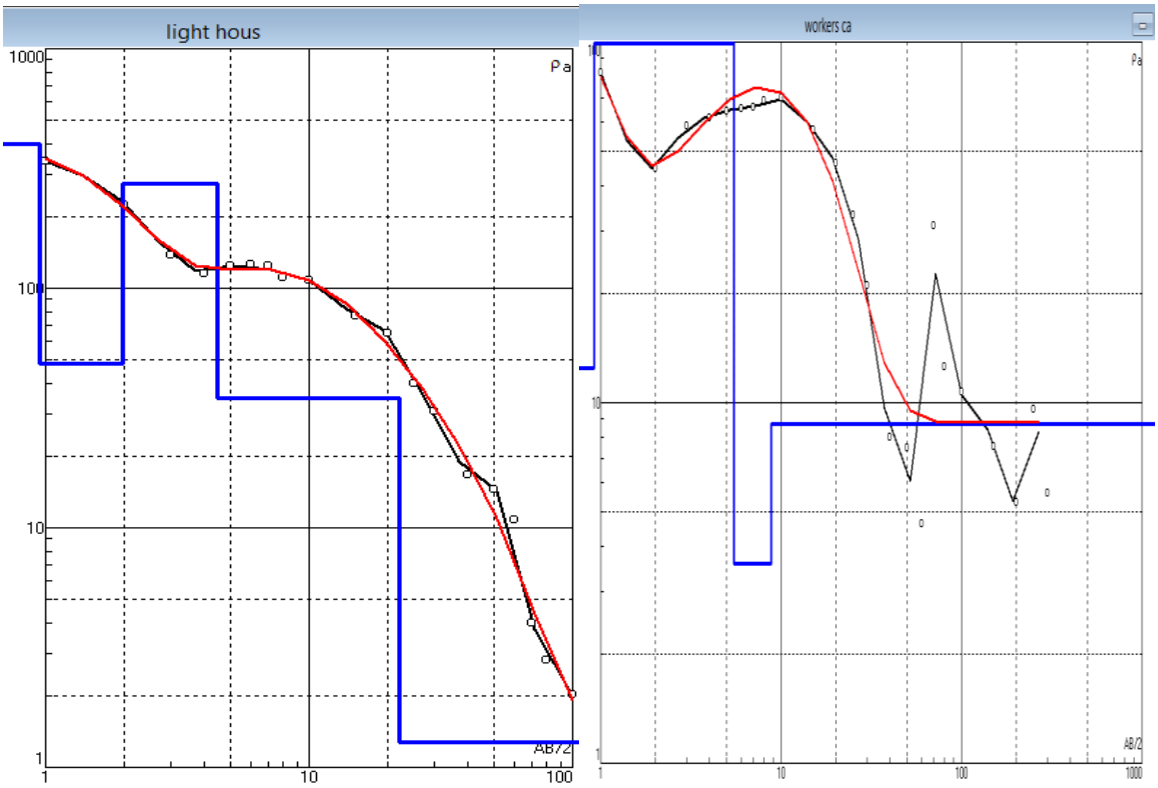

Fig. 4. VES 1 (Light House Road) VES 2 (Workers Camp)

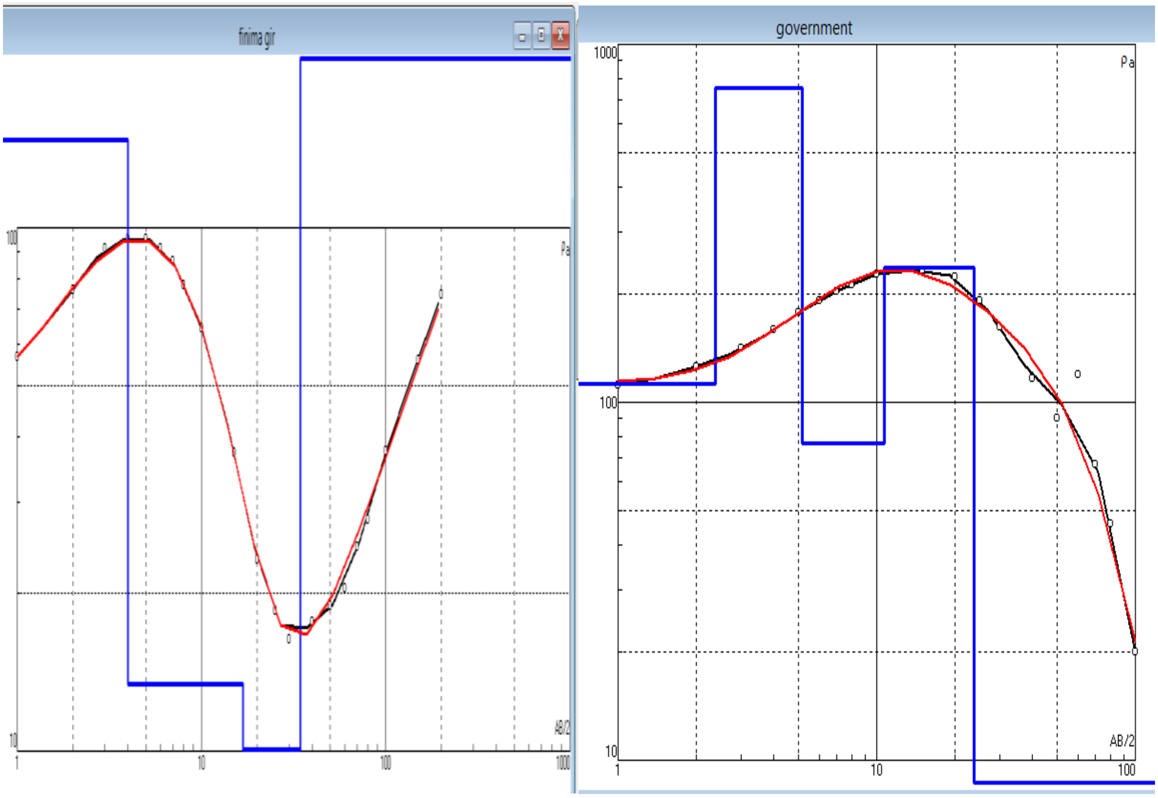

Fig. 5. VES3 (Finima Girls) VES 4 (Government School)

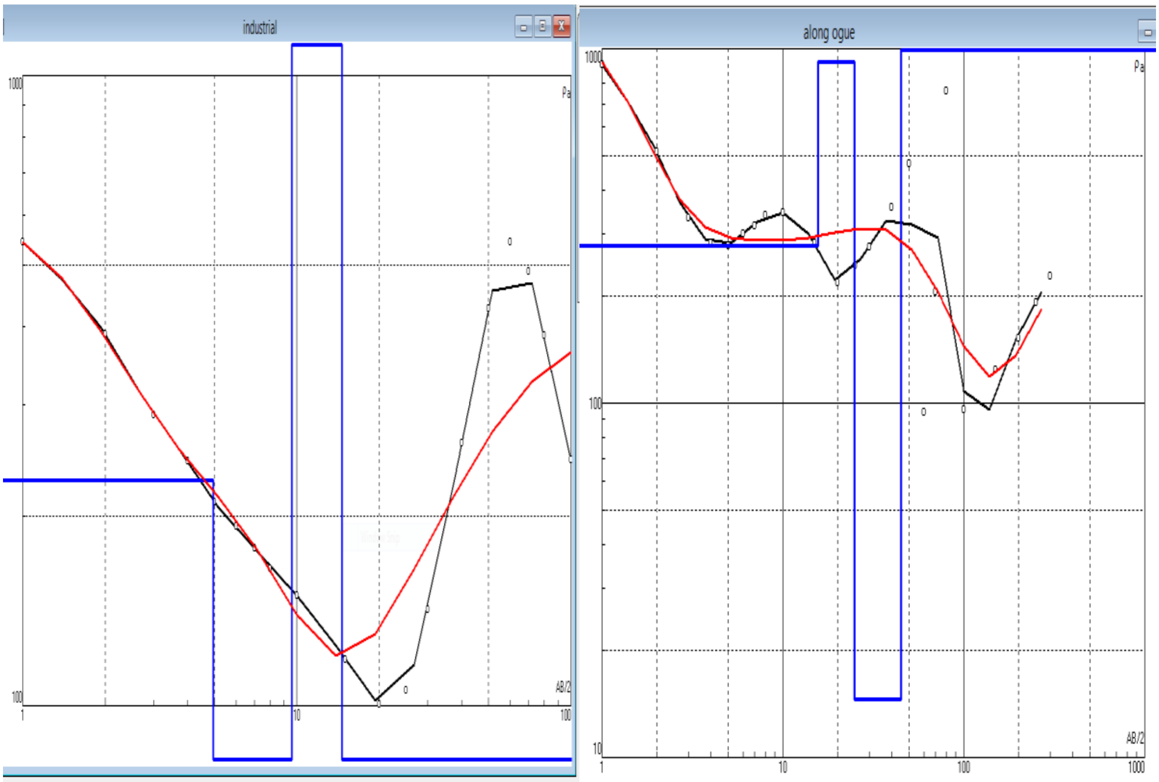

Fig. 6. VES 5 (Industrial Unit Field) VES 6 (Along Oguede Road)

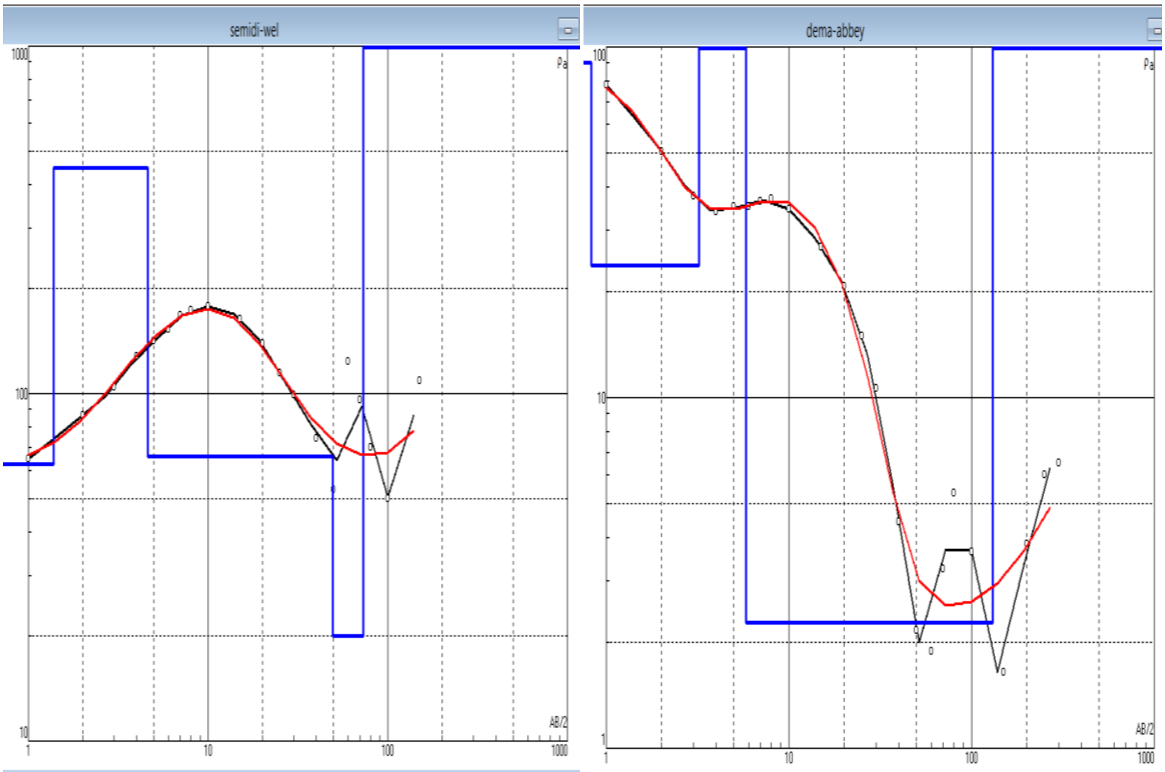

Fig. 7. VES 7 (Semidia Water Well 6) VES 8 (Dema Abbey Entrance)

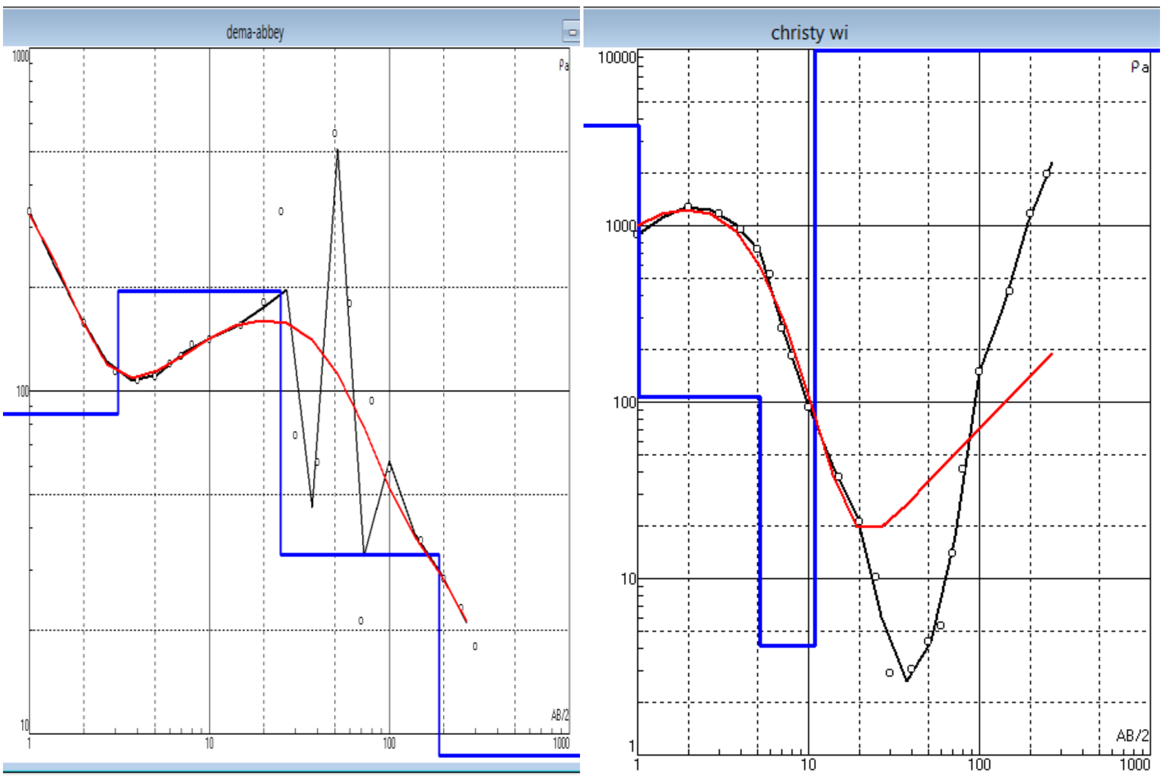

Fig. 8. VES 9 (Dema Abbey Old Settlement) VES 10 (Christy Wilcox – Halliday Road)

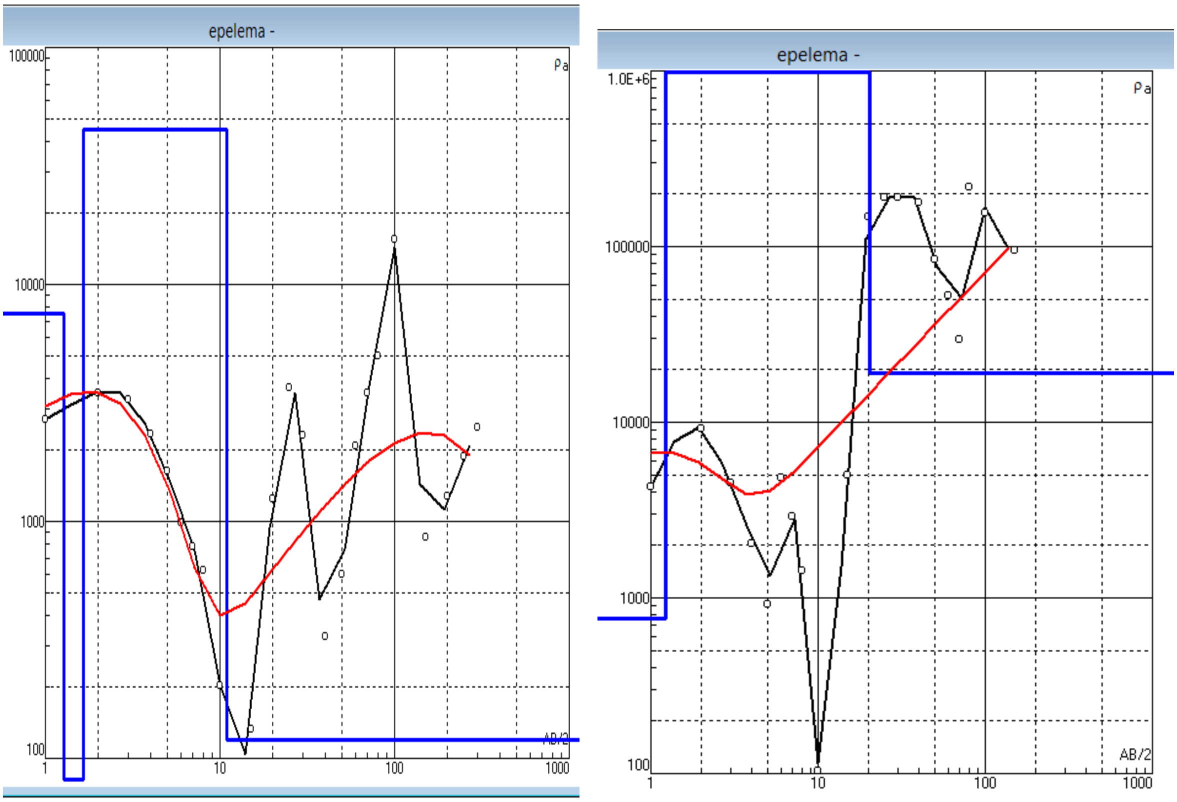

Fig. 9. VES 11 (Epelema – Oloma Road) VES 12 (Epelema - Minima Road)

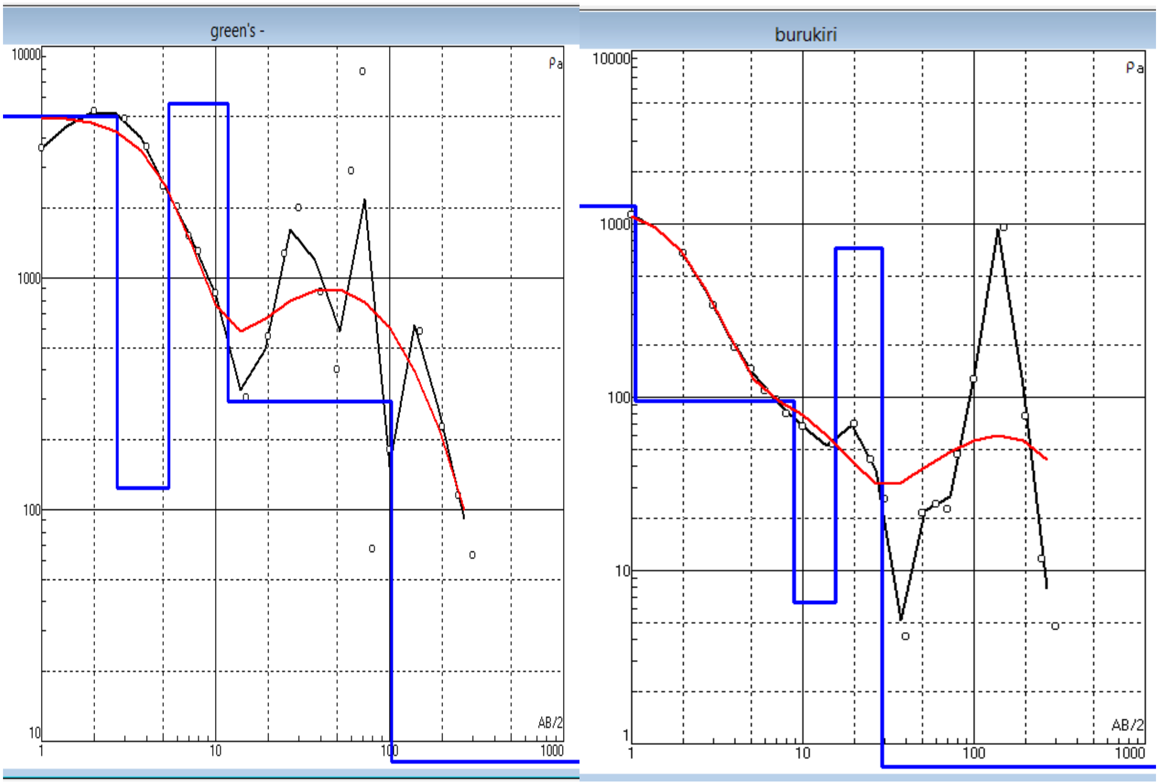

Fig. 10. VES 13 (Greens - William Jumbo) VES 14 (Burukiri)

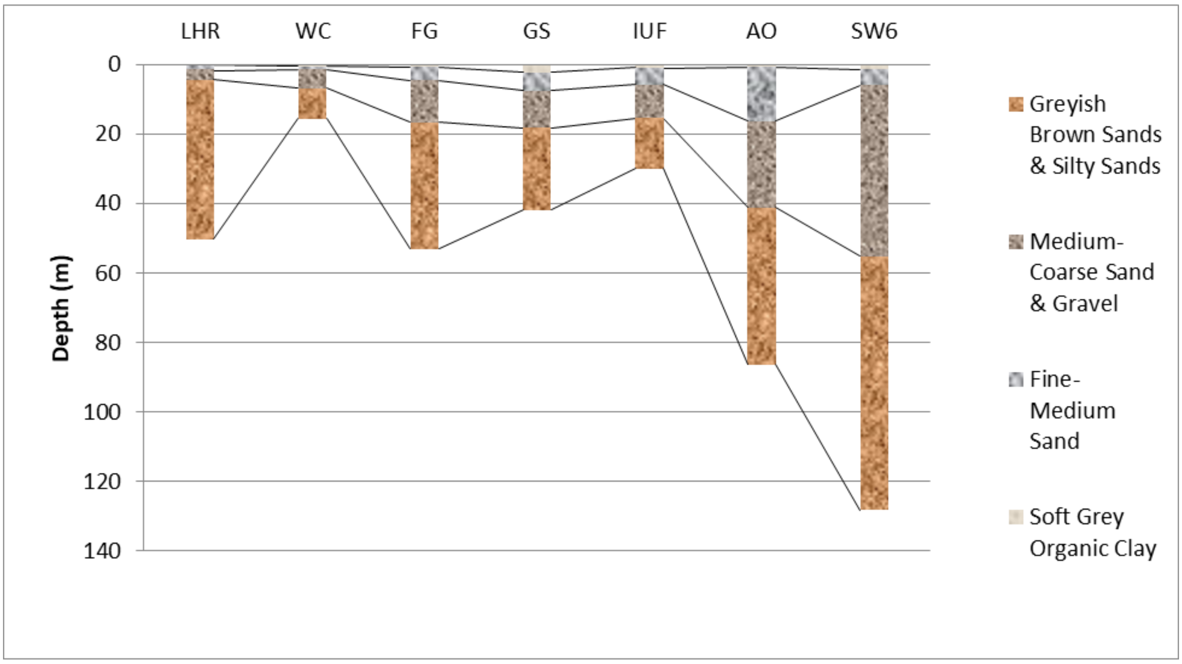

Fig. 11. Geoelectric section of the bonny mainland

LHR = Light House Road, WC = Workers Camp, FG = Finima Girls, GS = Government School, IUF = Industrial Unit Field, AO = Along Oguede Road, SW6 = Semidia Water Well 6.

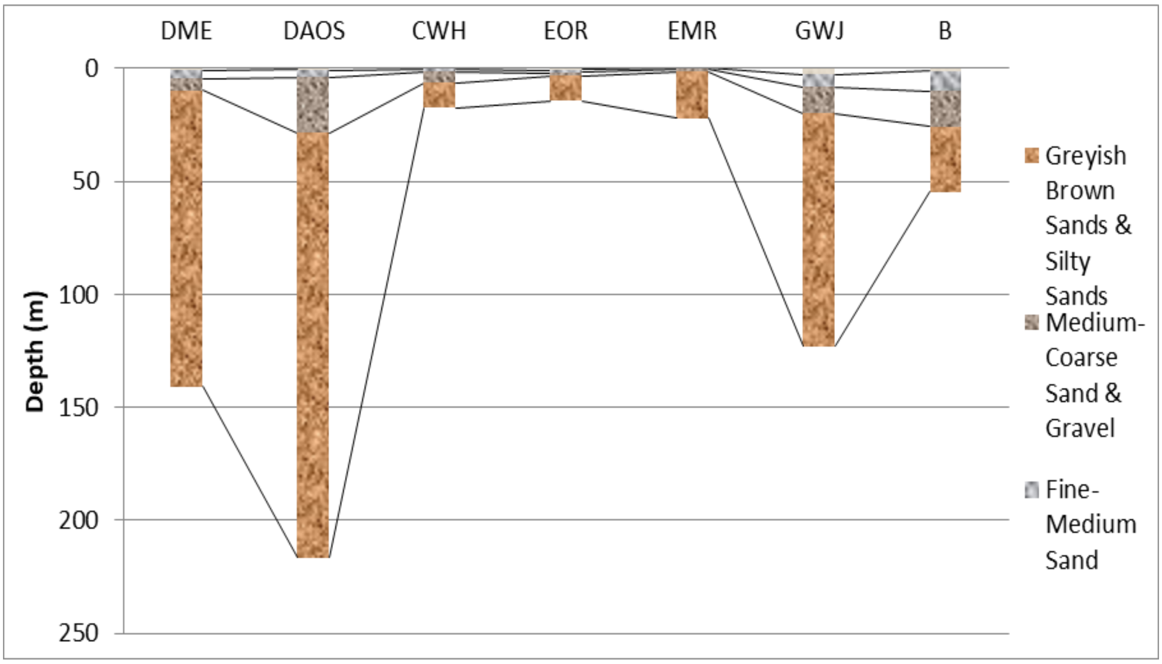

Fig. 12. Geoelectric Section of the Bonny Villages

DME = Dema-Abbey Entrance, DAOS = Dema-Abbey Old Settlement, CWHR = Christy Wilcox – Halliday Road, EOR = Epelema - Oloma Road, EMR = Epelema-Minima Road, GWJ = Greens - William Jumbo, B = Burukiri.

4.2 VES 2: Workers Camp

In this station, five subsurface layers were delineated (Table 1 and Fig. 4, 11), and the geoelectric curve is HKH-type. The topsoil which is the first layer has an apparent resistivity of 164 Ωm at a depth of 0.466 m and thickness of 0.466 m, indicating a layer composed of low-conductive materials such as dry sand. The second layer has an apparent resistivity of 12.5 Ωm at a depth of 0.916 m and thickness of 0.45 m, indicating the presence of more conductive materials likely clay or silt. The third layer has an apparent resistivity of 149 Ωm at a depth of 5.46 m and a thickness of 4.54 m, indicating the presence of a less conductive material, possibly a sandy or gravelly aquifer, with a deeper layer. The fourth layer has an apparent resistivity of 3.59 Ωm at a depth of 8.77 m and thickness of 3.31 m, indicating the presence of highly conductive materials likely a clay or shale formation that acts as an aquitard, separating the upper aquifer from a deeper aquifer. The fifth layer has an apparent resistivity of 8.76 Ωm at an infinite depth, likely representing the presence of conductive materials at an infinite depth. From the above data, the third layer indicates the presence of a freshwater aquifer. However, because of depth and thickness, it may be prone to contamination shortly, and dry up in the dry season. Upon the above findings, a borehole can be drilled in this station only for domestic uses to a depth range of 5 m to 7 m.

4.3 VES 3: Finima Girls' School

In this station, five subsurface layers were delineated (Table 1 and Fig. 5, 11), and the geoelectric curve is HKH-type. The topsoil which is the first layer has an apparent resistivity of 46.4 Ωm at a depth of 0.713 m and thickness of 0.713 m, indicating a layer composed of highly conductive materials such as moist sand at a shallow depth. The second layer has an apparent resistivity of 147 Ωm at a depth of 3.98 m and a thickness of 3.27 m, indicating the presence of less conductive materials, possibly a sandy or gravelly formation. The third layer has an apparent resistivity of 13.4 Ωm at a depth of 16.8 m and a thickness of 12.8 m and the fourth layer has an apparent resistivity of 10.1 Ωm at a depth of 34.3 m and thickness 17.5 m. Both layers indicate the presence of highly conductive materials like clay or shale at relatively deep layers. The fifth layer has an apparent resistivity of 10773 Ωm at an infinite depth, likely representing the presence of very low conductive materials, likely sands/sandstones, or a highly resistive layer that extends to great depths. From the above data, the second layer indicates the presence of a freshwater aquifer. However, because of depth and thickness, it may be prone to contamination shortly, and dry up in the dry season. Upon the above findings, a borehole can be drilled in this station only for domestic uses to a depth range of 3 m to 12 m.

4.4 VES 4: Government School

In this station, five subsurface layers were delineated (Table 1 and Fig. 5, 11), and the geoelectric curve is KHK-type. The topsoil, which is the first layer has an apparent resistivity of 113 Ωm at a depth of 2.37 m and thickness of 2.37 m, suggesting a layer composed of low-conductive material like sand. The second layer has an apparent resistivity of 753 Ωm at a depth of 5.16 m and thickness of 2.79 m, indicating the presence of highly resistive materials, like medium-coarse sand and gravel formations. The third layer has an apparent resistivity of 77 Ωm at a depth of 10.7 m and a thickness of 5.53 m, indicating the presence of more conductive materials, possibly a clay or shale formation. The fourth layer has an apparent resistivity of 239 Ωm at a depth of 23.7 m and a thickness of 13.1 m, indicating the presence of less conductive materials, possibly a sandy or gravelly formation. The fifth layer has an apparent resistivity of 0.277 Ωm at an infinite depth. This value is a clear indication of saline water intrusion. From the above data, the second and fourth layers indicate the presence of freshwater aquifers. However, the second layer, because of depth may be subject to contamination in a short period. Therefore, the fourth layer is more indicative of a freshwater/potable aquifer due to its depth and thickness; the thickness also makes it more prolific and sustainable/durable. Upon this, a borehole can be drilled in this station for both domestic and industrial uses for a depth above 15 m to 30 m.

4.5 VES 5: Industrial Unit Field

In this station, five subsurface layers were delineated (Table 1 and Fig. 6, 11), and the geoelectric curve is QHK-type. The topsoil, which is the first layer has an apparent resistivity of 622 Ωm at a depth of 0.814 m and thickness of 0.814 m, suggesting the presence of low-conductive materials such as clay or dry sand. The second layer has an apparent resistivity of 228 Ωm at a depth of 4.96 m and thickness of 4.15 m, indicating the presence of conductive materials possibly shale or moist sand formation with a slightly deeper layer. The third layer has an apparent resistivity of 35.6 Ωm at a depth of 9.59 m and thickness of 4.63 m, indicating the presence of highly conductive materials, possibly a clay or shale formation. The fourth layer has an apparent resistivity of 9665 Ωm at a depth of 14.63 m and thickness of 5.04 m, indicating the presence of low conductive materials, possibly a sandy or gravelly formation. The fifth layer has an apparent resistivity of 27.1 Ωm at an infinite depth. This layer indicates highly conductive materials. From the above data, the second and fourth layers indicate the presence of freshwater aquifers. However, the second layer because of depth may be subject to contamination in a short period. Therefore, the fourth layer is more indicative of a freshwater/potable aquifer due to its depth and thickness; the thickness also makes it more prolific and sustainable/durable. Upon this, the borehole can be drilled from a depth above 10 m.

4.6 VES 6: Along Oguede Road

In this station, five subsurface layers were delineated (Table 1 and Fig. 6, 11), while the geoelectric curve is HKH-type. The topsoil, which is the first layer has an apparent resistivity of 1241 Ωm at a depth of 0.644 m and thickness of 0.644 m, suggesting the presence of low-conductive materials, possibly soil or alluvial layer. The second layer has an apparent resistivity of 278 Ωm at a depth of 15.7 m and thickness of 15 m, indicating the presence of conductive materials possibly shale or moist sand formation with a slightly deeper layer. The third layer has an apparent resistivity of 921 Ωm at a depth of 24.9 m and thickness of 9.21 m, indicating the presence of less conductive materials, possibly a sandy or gravelly formation. The fourth layer has an apparent resistivity of 14.6 Ωm at a depth of 45.1 m and thickness of 20.2 m, indicating the presence of highly conductive materials, possibly saline water since the sea is less than 50 m to the survey point. The fifth layer has an apparent resistivity of 16010 Ωm at an infinite depth. This layer indicates very less conductive materials, such as sand or sandstone. From the above data, the second and third layers indicate the presence of freshwater aquifers. However, the second layer because of its depth may be considered a shallow aquifer while the third, is a deep aquifer; their thicknesses also make them more prolific and sustainable/durable. Upon this, boreholes can be drilled in this station for both domestic and industrial uses to a depth ranging from 15 m to 35 m.

4.7 VES 7: Semidia Water Well 6

In this station, five subsurface layers were delineated (Table 1 and Fig. 7, 11), and the geoelectric curve is KQH-type. The topsoil, which is the first layer has an apparent resistivity of 62.5 Ωm at a depth of 1.38 m and thickness of 1.38 m, suggesting a layer composed of highly conductive materials like clay or shale formation. The second layer has an apparent resistivity of 447 Ωm at a depth of 4.61 m and thickness of 3.22 m, indicating the presence of highly resistive materials, like medium-coarse sand and gravel, and sands and silty sands. The third layer has an apparent resistivity of 66.2 Ωm at a depth of 49.3 m and thickness of 44.7 m, indicating the presence of highly conductive materials, possibly a clay or shale formation. The fourth layer has an apparent resistivity of 20.1 Ωm at a depth of 73.1 m and thickness of 23.8 m, indicating the presence of highly conductive materials, possibly a clay or shale formation. The fifth layer has an apparent resistivity of 9355 Ωm at an infinite depth. From the above data, the second and third layers indicate the presence of freshwater aquifers. The second layer is more indicative of a freshwater/potable aquifer. However, due to its depth, it may be prone to contamination in a short period. Additionally, it is not prolific and sustainable because of its limited thickness. The third layer may be more prolific but may require some level of treatment. Upon this, a borehole can be drilled for both domestic and commercial uses for a depth ranging from 5 m to 60 m.

4.8 VES 8: Dema-Abbey Entrance

In this station, five subsurface layers were delineated (Table 1 and Fig. 7, 12), and the geoelectric curve is HKH-type. The topsoil, which is the first layer has an apparent resistivity of 89.9 Ωm at a depth of 0.825 m and thickness of 0.825 m, suggesting a layer composed of high conductive materials like clay or shale. The second layer has an apparent resistivity of 23.8 Ωm at a depth of 3.21 m and thickness of 2.38 m, indicating the presence of highly conductive materials like stone-based rock due to the ongoing road construction (Bodo-Bonny road). The third layer has an apparent resistivity of 116 Ωm at a depth of 5.82 m and thickness of 2.61 m, indicating the presence of less conductive materials, possibly a medium-coarse sand and gravel formation. The fourth layer has an apparent resistivity of 2.28 Ωm at a depth of 131 m and thickness of 125 m, indicating the presence of more conductive materials, possibly clay or shale formations. The fifth layer has an apparent resistivity of 284 Ωm at an infinite depth. From the above data, the third layer is more indicative of a freshwater/potable aquifer due to its depth and thickness; the thickness also makes it more prolific and sustainable/durable.

Upon this, a borehole can be drilled both for domestic and commercial uses for a depth ranging from 5 m to 125 m.

4.9 VES 9: Dema-Abbey Village

In this station, five subsurface layers were delineated (Table 1 and Fig. 8, 12), and the geoelectric curve is HKQ-type. The topsoil, which is the first layer has an apparent resistivity of 481 Ωm at a depth of 0.6 m and thickness of 0.6 m, suggesting a layer composed of low conductive materials like sand or fine-medium sand. The second layer has an apparent resistivity of 85.7 Ωm at a depth of 3.11 m and thickness of 2.52 m, indicating the presence of conductive materials like clay or shale formation. The third layer has an apparent resistivity of 196 Ωm at a depth of 24.9 m and a thickness of 21.8 m, indicating the presence of less conductive materials, possibly fine-medium sand, medium-coarse sand, and silty sand formations. The fourth layer has an apparent resistivity of 33.3 Ωm at a depth of 188 m and thickness of 163 m, indicating the presence of more conductive materials, possibly clay or shale. The fifth layer has an apparent resistivity of 0.21 Ωm at an infinite depth; this indicates the presence of saline water intrusion. From the above data, the third layer is more indicative of a freshwater/potable aquifer due to its resistivity, depth, and thickness. Its considerable thickness makes it more prolific and sustainable, while its depth helps protect it from contamination. Upon this, a borehole can be drilled both for domestic and commercial uses for a depth ranging from 5 m to 125 m.

4.10 VES 10: Christy Wilcox – Halliday

In this station, five subsurface layers were delineated (Table 1 and Fig. 8, 12), and the geoelectric curve is KQH-type. The topsoil, which is the first layer has an apparent resistivity of 413 Ωm at a depth of 0.286 m and thickness of 0.286 m, suggesting a layer composed of less conductive materials like fine-medium sand and silty sand. The second layer has an apparent resistivity of 3699 Ωm at a depth of 1.01 m and thickness of 0.726 m, indicating the presence of highly resistive materials like sands and silty sands, and medium-coarse sand and gravel. The third layer has an apparent resistivity of 107 Ωm at a depth of 5.17 m and thickness of 4.16 m, indicating the presence of more conductive materials, possibly medium-coarse sand and gravel formations. The fourth layer has an apparent resistivity of 4.17 Ωm at a depth of 10.9 m and thickness of 5.72 m, indicating the presence of more conductive materials, possibly clay or shale. The fifth layer has an apparent resistivity of 17675 Ωm at an infinite depth. From the above data, the second and third layers indicate the presence of freshwater aquifers. The second layer is more indicative of a freshwater/potable aquifer. However, due to its depth, it may be prone to contamination in a short period. Additionally, it is not prolific and sustainable because of its limited thickness. The third layer is more prolific but may require some level of treatment. Upon this, a borehole can be drilled in this station for only domestic uses for a depth ranging from 1 m to 7 m.

4.11 VES 11: Epelema - Oloma Road

In this station, five subsurface layers were delineated (Table 1 and Fig. 9, 12), and the geoelectric curve is KHK-type. The topsoil, which is the first layer, has an apparent resistivity of 1671 Ωm at a depth of 0.335 m and thickness of 0.335 m, suggesting a layer composed of low conductive materials like fine-medium sands formation. The second layer has an apparent resistivity of 7552 Ωm at a depth of 1.28 m and thickness of 0.942 m, indicating the presence of highly resistive materials, likely fine-medium sands, medium-coarse sand and gravel formations. The third layer has an apparent resistivity of 12.3 Ωm at a depth of 1.65 m and thickness of 0.374 m, indicating the presence of highly conductive materials, possibly clay or shale formation. It also suggests the presence of a buried pipeline that cut across the survey line, as informed and seen. The fourth layer has an apparent resistivity of 45195 Ωm at a depth of 11 m and thickness of 9.35 m, indicating the presence of low conductive materials, possibly medium-coarse sand and gravel formations. The fifth layer has an apparent resistivity of 119 Ωm at an infinite depth. From the above data, the second and fourth layers indicate the presence of freshwater aquifers. However, the second layer because of depth may be subject to contamination in a short period. The fourth layer is more indicative of a freshwater/potable aquifer due to its depth and thickness; the thickness also makes it more prolific and sustainable/durable. Upon this, boreholes can be drilled in this station for both domestic and small industrial uses to a depth ranging from 9 m to 25 m.

4.12 VES 12: Epelema-Minima Road

In this station, five subsurface layers were delineated (Table 1 and Fig. 9, 12), and the geoelectric curve is KHK-type. The topsoil, which is the first layer has an apparent resistivity of 32.2 Ωm at a depth of 0.0025 m and thickness of 0.0025 m, suggesting the presence of highly conductive materials like moist soil or clay formation. It also suggests the presence of a buried pipeline that cut across the survey line, as informed and seen. The second layer has an apparent resistivity of 34491 Ωm at a depth of 0.243 m and thickness of 0.24 m, indicating the presence of dry, compact rock or an impermeable layer. The third layer has an apparent resistivity of 758 Ωm at a depth of 1.23 m and thickness of 0.987 m, indicating the presence of less conductive materials, possibly fine-medium sand formations. The fourth layer has an apparent resistivity of 78000000 Ωm at a depth of 20.4 m and a thickness of 19.2 m, indicating the presence of less conductive materials, possibly a sandy or gravelly aquifer. The fifth layer has an apparent resistivity of 19082 Ωm at an infinite depth. From the above data, the second, third, and fourth layers indicate the presence of freshwater aquifers. However, the second and third layers because of depths may be subject to contamination in a short period. The fourth layer is more indicative of a freshwater/potable aquifer due to its depth and thickness. The thickness also makes it more prolific and sustainable. Upon this, boreholes can be drilled in this station for both domestic and small industrial uses to a depth ranging from 3 m to 25 m.

4.13 VES 13: Greens-William Jumbo

In this station, five subsurface layers were delineated (Table 1 and Fig. 10, 12), and the geoelectric curve is HKQ-type. The topsoil, which is the first layer, has an apparent resistivity of 4987 Ωm at a depth of 2.73 m and thickness of 2.73 m, suggesting a layer composed of highly resistive materials such as sand, gravel, or dry rock. The second layer has an apparent resistivity of 123 Ωm at a depth of 5.39 m and a thickness of 2.66 m, indicating the presence of more conductive materials, likely water-saturated soils or fractured rocks. The third layer has an apparent resistivity of 5666 Ωm at a depth of 11.8 m and thickness of 6.38 m, indicating the presence of less conductive materials, possibly a medium-coarse sand and gravel formation. The fourth layer has an apparent resistivity of 292 Ωm at a depth of 103 m and thickness of 91 m, indicating the presence of less conductive materials, possibly a sand and silty sandy formation. The fifth layer has an apparent resistivity of 2.01 Ωm at an infinite depth. A highly conductive material was delineated in the fifth layer, likely high salinity or clay-rich sediments. From the above data, the second, third, and fourth layers indicate the presence of freshwater aquifers. However, the second layer because of depth may be subject to contamination in a short period. Therefore, the third and fourth layers are more indicative of a freshwater/potable aquifer due to their resistivity values. By their depths, they may not easily be contaminated. Additionally, their thicknesses make them more sustainable. Upon this, boreholes can be drilled in this station for both domestic and industrial uses to a depth ranging from 6 m to 120 m.

4.14 VES 14: Burukiri

In this station, five subsurface layers were delineated (Table 1 and Fig. 10, 12), and the geoelectric curve is QHK-type. The topsoil, which is the first layer, has an apparent resistivity of 1268 Ωm at a depth of 1.05 m and thickness of 1.05 m, suggesting that the layer is composed of low conductive materials like fine-medium sand formations. The second layer has an apparent resistivity of 94.8 Ωm at a depth of 8.92 m and thickness of 7.87 m, indicating the presence of conductive materials like wet clay-rich soil or weathered rocks. The third layer has an apparent resistivity of 6.71 Ωm at a depth of 15.6 m and thickness of 6.65 m, indicating the presence of highly conductive materials, possibly clay and shale formations, and saline water intrusion. The fourth layer has an apparent resistivity of 728 Ωm at a depth of 29.2 m and thickness of 13.6 m, indicating the presence of less conductive materials, possibly a sandy or gravelly aquifer. The fifth layer has an apparent resistivity of 0.624 Ωm at an infinite depth. From the above data, the second and fourth layers indicate the presence of freshwater aquifers. However, the second layer because of depth may be subject to contamination in a short period. Therefore, the fourth layer is more indicative of a freshwater/potable aquifer due to its resistivity value. By its depth, it may not easily be contaminated. Additionally, its thickness makes it more sustainable. Upon this, boreholes can be drilled in this station for both domestic and small industrial uses to a depth ranging from 13 m to 40 m.

5. CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The exploration and delineation of potable and prolific aquifers in the Bonny Kingdom using the

Vertical Electrical Sounding (VES) method was carried out. This method provided valuable insights into the subsurface resistivity distribution and its implications for groundwater potential. The study identified various geoelectric layers across multiple sites and obtained information on the presence of freshwater aquifers and the conditions of different subsurface materials. The results indicate that the aquifers in Bonny Kingdom are generally composed of materials such as soft grey organic clay, fine-medium sand, medium-coarse sand and gravel, and greyish brown sands and silty sands, at varying depths and thicknesses. The depth and thickness of these aquifers suggest the potential for both domestic and industrial water supply, though the risk of contamination and salinity intrusion varies across locations. The findings highlight the critical need for strategic drilling to maximize potable water extraction and minimize contamination risks. For the fact that the mainland and the villages are on different topography, the depth to which boreholes can be drilled varies. Furthermore, it is observed that there are more prolific freshwater aquifers on the mainland than in the villages.

5.2 Recommendations

Based on the findings, the following recommendations are proposed to optimize potable and prolific groundwater exploration and utilization in Bonny Kingdom:

1. Regular monitoring and protective measures should be implemented to prevent contamination, especially for shallower aquifers. Locations such as Workers Camp and Finima Girls School, where aquifers are closer to the surface, require stringent contamination control measures.
2. Tailor the drilling depth to match the aquifer characteristics of each site. For example, boreholes at Light House Road should target depths between 4m and 20m, while those at Dema-Abbey Entrance should aim for depths ranging from 5m to 125m.
3. Develop specific plans for water usage, distinguishing between domestic and industrial needs. Industrial wells should not be drilled in areas identified for domestic aquifers.
4. Stations with depth ranging from 3 to 7 m are recommended for shallow boreholes.
5. Employ more advanced and continuous geophysical survey methods alongside VES to enhance the accuracy of aquifer delineation and to identify potential aquifers that were not detected in the initial survey.
6. Conduct further research to expand our understanding of aquifer dynamics, recharge mechanisms, and potential impacts of climate change on groundwater resources in Bonny Kingdom.

By implementing these recommendations, Bonny Kingdom can effectively improve its groundwater resources, ensuring a reliable and sustainable supply of potable water for its residents and industries.

Conflict of Interest

The authors declare that there is no conflict of interest.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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