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Cross Plot And Contour Closure Evaluation Of Resistive Zones For Groundwater Exploration In Parts Of Emuoha Local Government Area, Rivers State

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Abstract: Accelerated urbanization in Emuoha Local Government Area has escalated groundwater demand, yet borehole development remains challenged by intense lithological heterogeneity within the Tertiary Benin Formation. To eliminate geoelectric structural ambiguities that lead to dry holes, this study integrated conventional one-dimensional (1D) Vertical Electrical Sounding (VES) cross-plot analysis with high-resolution two-dimensional (2D) Advanced Digital Magnetic Tomography (ADMT) profiling. Using the Schlumberger array configuration, field data were acquired up to a maximum current electrode separation (AB/2) of 100m and inverted using computer-aided modeling. The 1D VES results resolved a four-layer, HK-type with the trend $\rho_1>\rho_2<\rho_3>\rho_4$, identifying a massive, clean, and highly resistive sand reservoir. Cross-validating these layers, the 2D ADMT tomograms mapped continuous, distinct low-resistivity contour closures that confirm prolific water-bearing channels at depths, alongside a secondary deep, high-pressure confined horizon at 110m. These closed contour signatures indicate optimized porosity, high transmissivity, and excellent fluid saturation shielded from surface contamination. This paper contributes a novel, field-verified predictive geophysical model that establishes a robust exploration template for sedimentary basins. Based on these findings, it is recommended that regional drilling operations prioritize targeting the deep, continuous 110 m contour closures to secure sustainable, maximum yield production and minimize borehole failure rates across the Niger Delta.

Keywords: Electrical Resistivity; Vertical Electrical Sounding; ADMT; Contour Closure; Benin Formation; Groundwater Exploration.

INTRODUCTION

The demand for potable water in the Niger Delta has escalated exponentially in recent decades, driven by rapid population growth, industrialization, and the rapid expansion of urban and semi-urban centers like Emohua (Oghonyon et al., 2025). In this region, groundwater hosted within the prolific Tertiary Benin Formation serves as the primary and most viable source of domestic and industrial water supply (Etu-Efeotor, 1981). However, despite the abundance of regional groundwater resources, the success rate of borehole development projects remains significantly low. This operational challenge is primarily due to the intense lithological heterogeneity of the coastal plain sands, which exhibit abrupt lateral and vertical variations, consisting of a complex mixture of high-permeability, fluid-bearing sand frameworks interrupted by tight, low-permeability clay matrices and localized high-salinity horizons (Short & Stauble, 1966).

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To mitigate drilling failures and systematically map these subsurface variations, surface electrical resistivity techniques particularly 1D Vertical Electrical Sounding (VES) have become standard industry practice due to the sharp contrast between the high resistivity of clean, coarse sand units and the low resistivity of clayey formations (Oghonyon et al., 2025). Nevertheless, conventional 1D interpretation workflows often yield ambiguous or non-unique structural models when relying solely on basic, isolated resistivity cross plots, which can misidentify productive zones. To resolve this ambiguity, advanced multi-dimensional imaging configurations and Digital Magnetic Tomography (ADMT) have emerged as powerful tools, capable of mapping continuous lateral and vertical variations by delineating distinct geoelectric patterns and structural closure boundaries (Oghonyon and Njoku 2024).

Consequently, the objective of this study is to deploy an integrated approach combining conventional VES cross-plot analysis with high-resolution ADMT contour closure evaluation to accurately delineate subsurface resistive zones in parts of Emohua Local Government Area. By correlating raw apparent resistivity values directly with precise depth profiles and lithological frameworks, this research aims to identify high-yield aquifer horizons and establish a reliable, field-verified geophysical template to optimize borehole positioning and minimize the risk of drilling failures in the region (Oghonyon and Ogaji, 2026).

MATERIALS AND METHOD

Description of the Study Area: Emohua L.G.A. is situated within the Tertiary Niger Delta Basin, specifically sitting on the Benin Formation, also known as the coastal plain sands (see figure 1). This formation consists of massive, poorly sorted, and unconsolidated sands ranging from fine to very coarse-grained, with localized occurrences of gravel, pebbles, and thin clay/lignite intercalations (Akpokodje, 1987; Oghonyon & Ogaji, 2026). The sediments were deposited under continental environments during the late Tertiary to Quaternary periods. The Benin Formation is a prolific, multi-aquifer system. In Emohua, the aquifers are generally unconfined to semi-confined. Transmissivity values are typically high (>1000m²/day), but the depth to the water table varies based on seasonal recharge and local topography (Etu-Efeotor, 1981). The presence of resistive zones in this area usually indicates clean, coarse-grained sand units that offer the best hydraulic conductivity.

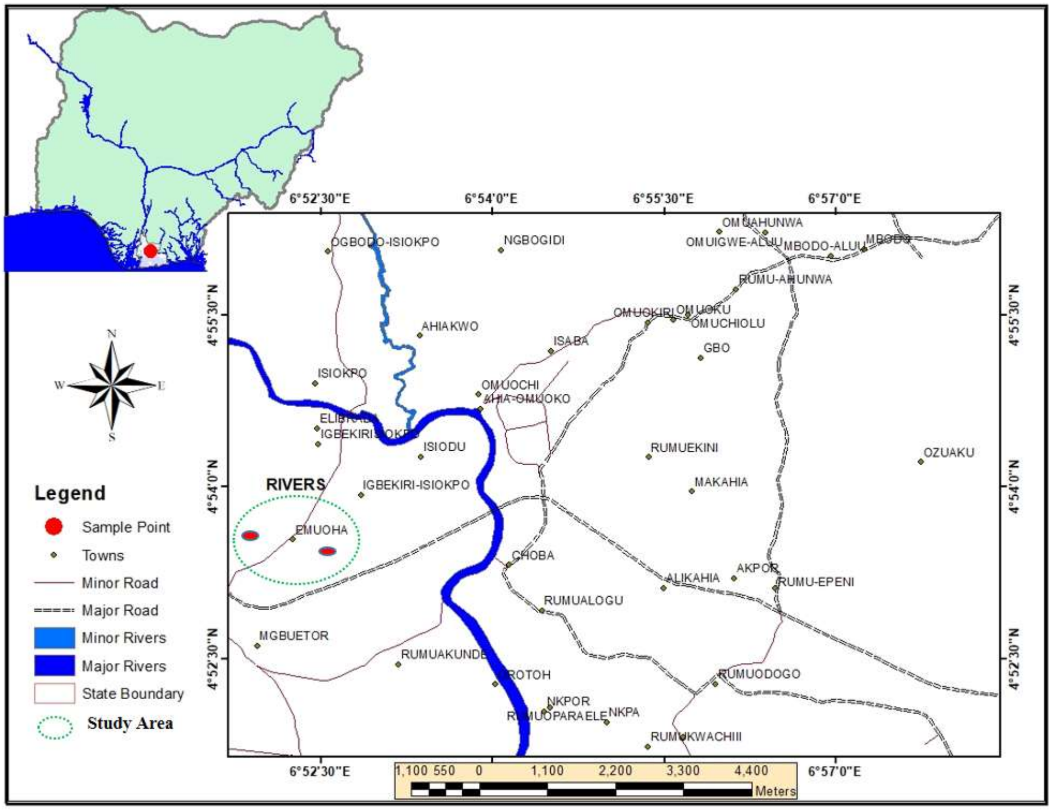

Fig. 1: Map of the study area (The map shows the regional distribution markers, local towns, and primary/secondary transit pathways across the Emuoha area).

The structural mapping and evaluation of subsurface resistive zones across Emuoha Local Government Area were executed using a high-resolution electrical resistivity survey design that seamlessly integrated one-dimensional (1D) Vertical Electrical Sounding (VES) and two-dimensional (2D) Advanced Digital Magnetic Tomography (ADMT). This hybrid geoelectric framework was systematically designed to characterize regional hydrogeological conditions and overcome structural interpretation ambiguities inherent to single-method configurations (Oghonyon et al., 2025). The investigative design was optimized for the complex, highly heterogeneous unconsolidated sedimentary sequence of the Tertiary Benin Formation, where high-permeability coarse sand bodies are laterally and vertically interrupted by low-permeability clay lenses and localized saline horizons (Short & Stauble, 1966).

Instrumentation and Technical Equipment Specifications: To acquire high-fidelity data capable of penetrating deep sedimentary targets while maintaining strict error controls, a hybrid digital and analogue terrameter unit was deployed. This configuration successfully integrated the operational stability of real-time analogue calibration with the rapid data logging and high-precision signal filtering of digital circuitry, ensuring excellent data reliability under variable field conditions and shifting contact resistances (Loke., 1996). The comprehensive field instrument kit comprised the following technical components:

i. A portable Global Positioning System (GPS) receiver utilized for precise geographical positioning, coordinate acquisition, and spatial geo-referencing of every sounding site.

ii. High-grade, non-polarizable stainless steel current electrodes driven deep into the ground to inject controlled direct current into the subsurface, alongside paired potential electrodes to measure the resultant voltage drops.

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iii. Heavy-duty, non-stretch graduated measuring tapes to establish exact geometric electrode layouts and ensure exact symmetrical spacing.

iv. Fully insulated, low-resistance connecting copper cables engineered to completely eliminate stray environmental noise, current leakage, and cable coupling artifacts.

v. A field data logging notebook for manual verification paired with a mobile digital processing interface for real-time tracking of digitized geoelectric signal curves.

vi. Digital and analog resistivity meters (terrameter).

Fig. 2: Resistivity equipment for subsurface investigation (Field array setup showing terrameter hub, cable reels, hammers, and grounding electrodes)

Field Survey Configuration and Data Acquisition Procedure: The direct current resistivity survey was executed based on fundamental governing field equations where an electric current (I) is introduced into the earth through current electrodes (A and B), and the resulting potential difference (V) is recorded across potential electrodes (M and N) to derive the apparent resistivity ($\rho \boldsymbol{a}$) via the geometric factor (K) specific to the array geometry (see Eq. 1,2,3,4, 5, and 6 below)

$$\rho \boldsymbol{a} = \boldsymbol{k} \times \boldsymbol{R} \ldots\ldots\ldots (\mathbf{1})$$

Where $\rho \boldsymbol{a}$= Apparent Resistivity, $\boldsymbol{k}$=Geometric factor, $\boldsymbol{R}$=Resistance.

But geometric factor $\boldsymbol{k}$, is calculated using the equation (modified from Oghonyon et al., 2025):

$$\mathbf{k} = \frac{\boldsymbol{\pi}}{\mathbf{4}}\left(\frac{\boldsymbol{L}^2 - \boldsymbol{a}^2}{\boldsymbol{a}}\right) \ldots\ldots\ldots (\mathbf{2})$$

Where 'L' is the current electrode spacing from A-B (see figure 3) and is calculated using the equation (modified from Oghonyon et al., 2025):

$$\mathbf{L} = \boldsymbol{AB} \ldots\ldots\ldots (\mathbf{3})$$

But,

$$\mathbf{AB} = \mathbf{2}\boldsymbol{n} \ldots\ldots\ldots (\mathbf{4})$$

Where 'n' is the halve current electrode spacing (AB/2);

'a' is the product of the potential electrodes between A, M, N, and B (see Figure 3).

Mathematically; $a = MN \ldots\ldots\ldots (5)$

But, $MN = 2n \ldots\ldots\ldots (6)$

Where ‘n’ is the halve potential electrode spacing (MN/2) that is $n = MN/2$

The Schlumberger array configuration (see figure 3 below) was strictly maintained for all VES profiles due to its superior vertical resolution, deep depth of investigation, and high labor efficiency, which makes it remarkably suited for groundwater mapping within thick sedimentary basin sequences (Loke., 1996).

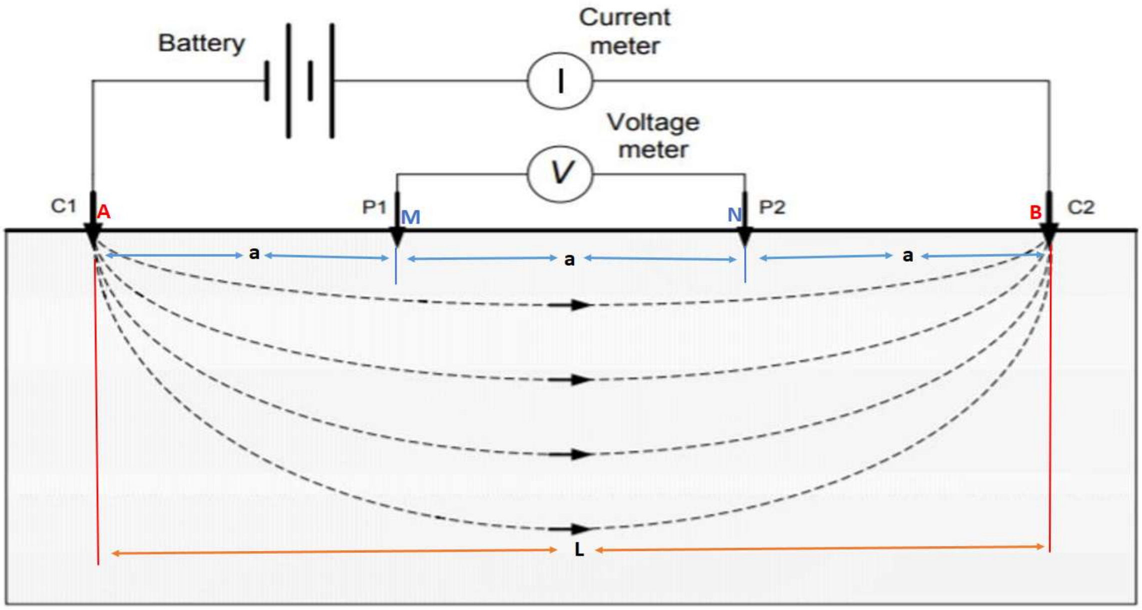


Fig. 3: A hypothetical diagram for Schlumberger array configuration (Schematically displaying the layout of current (A, B) and potential electrodes (M, N), current flow lines, and geometric spacing variables).

Prior to driving the electrodes, the survey lines were cleared of all surface debris, metallic conductors, and organic materials to reduce contact resistance and prevent cultural noise from corrupting the raw signal response (Loke., 1996). Field acquisition commenced with small current electrode spacing (AB/2) to map thin surficial layers and was systematically increased in a stepwise, logarithmic manner up to a maximum current electrode separation of 100m to guarantee deep vertical penetration into the primary aquifer body. The potential electrode spacing (MN/2) was adjusted progressively only when the measured potential drop approached the lower detection limits of the terrameter unit. To safeguard data integrity, every measurement loop was recorded automatically by the digital unit and cross-verified against the analogue scale; any reading exhibiting a standard deviation exceeding 2% due to poor coupling or ambient electrical noise was immediately discarded and re-measured after moisturizing the electrode ground contact with saline water to restore low-resistance coupling (Loke., 1996). Simultaneously, 2D ADMT profiling was executed along the established survey lines, utilizing high-frequency magnetic fields to continuously track and log lateral and vertical electromagnetic variations across the subsurface, thereby providing the necessary continuous dataset to construct 2D tomographic profiles.

Data Processing, Inversion Modeling, and Validation: The collected apparent resistivity values were compiled, formatted, and loaded into computer-assisted geoelectric processing software for qualitative and quantitative inversion modeling. The raw datasets were plotted as 1D geoelectric sounding curves on log–log coordinate graphs, tracking apparent resistivity ($\rho_{\boldsymbol{a}}$) against half-current electrode spacing (AB/2) to evaluate discrete geoelectric layer boundaries (Olorunfemi & Olorunniwo, 2021). Computer-aided iterative inversion loops were executed to match the field curves with synthetic multi-layer models, minimizing the root-mean-square (RMS) error down to a mathematically acceptable limit below 5% to yield true layer resistivity, precise thicknesses, and structural depths (Oghonyon et al., 2025).

The 1D geoelectric models were subsequently integrated with the raw continuous ADMT profiles to generate two-dimensional (2D) high-resolution resistivity contour tomograms using advanced spatial interpolation algorithms (Oghonyon. et al., 2025). These 2D contour maps display continuous vertical cross-sections of the subsurface down to depths exceeding 200m. To isolate high-yield groundwater exploration prospects, the interpretation focused on identifying localized, low-resistivity contour closures embedded within the highly resistive, coarse-grained sand frameworks of the Benin Formation. These distinct contour closures are indicative of high fluid saturation, enhanced effective porosity, and high transmissivity values. Synthesizing the 1D structural layer depths from the VES models with the lateral geometric boundaries resolved by the 2D ADMT contour closures provided a robust, cross-validated interpretation framework that eliminated geoelectric ambiguity and delivered an empirical template for sustainable borehole positioning (Oghonyon et al., 2025).

RESULTS AND DISCUSSIONS

The geoelectric inversion model for Line 1 (see figure 4, and 5) displays a characteristic four-layer, HK-type curve with resistivity trend $\rho_1>\rho_2<\rho_3>\rho_4$, which reflects a highly structured vertical variation in subsurface lithology. The top layer exhibits a moderate resistivity of 291.9Ωm at a shallow thickness of 1.114m, representing the dry, aerated surficial topsoil. This is underlain by a conductive second layer with a lower resistivity of 149.9Ωm and a thickness of 3.26m, which signifies an increase in moisture or fine-grained clay content within the shallow vadose zone. The third layer reveals a very prominent, highly resistive trend peaking at 2,829Ωm with a substantial thickness of 23.41m. This thick, high-resistivity zone corresponds to a massive, clean, and coarse-grained unconsolidated sand unit within the Benin Formation, acting as a highly viable unconfined to semi-confined aquifer layer. Below this reservoir, the resistivity drops to 1,264Ωm in the infinite fourth layer, indicating a transition into a more saturated sand horizon or a sequence with minor clay intercalations that naturally lowers the bulk subsurface resistivity.

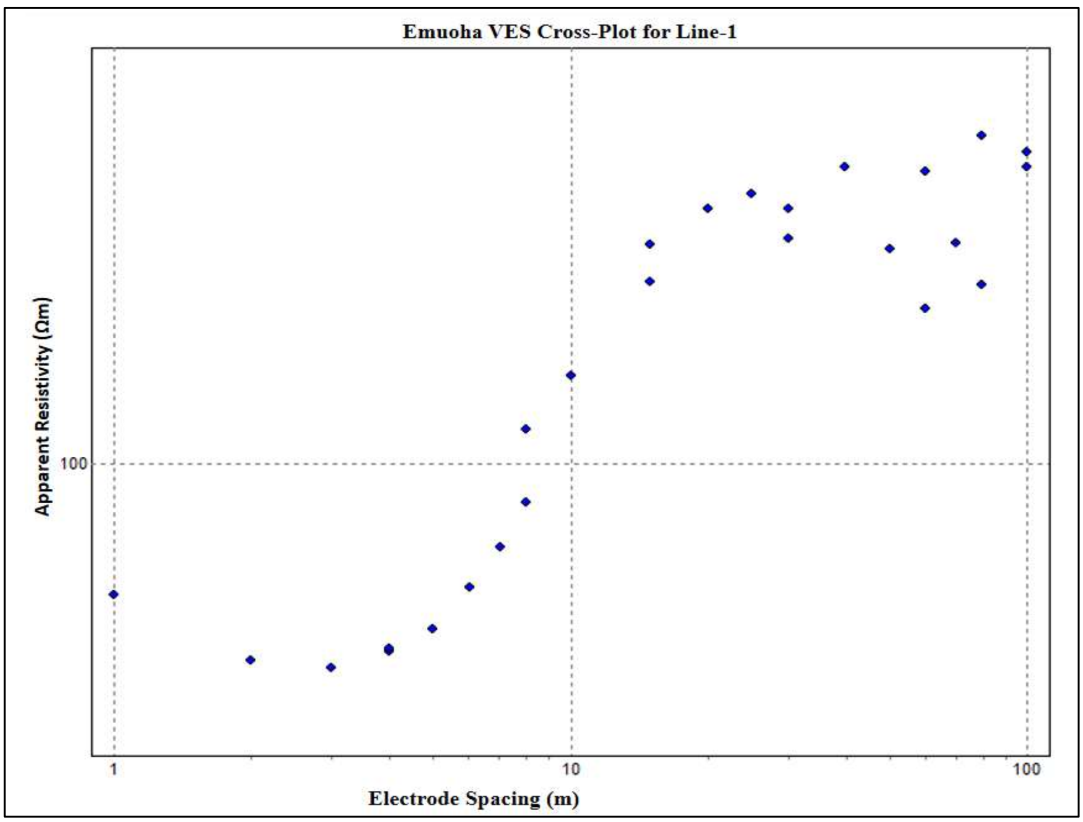
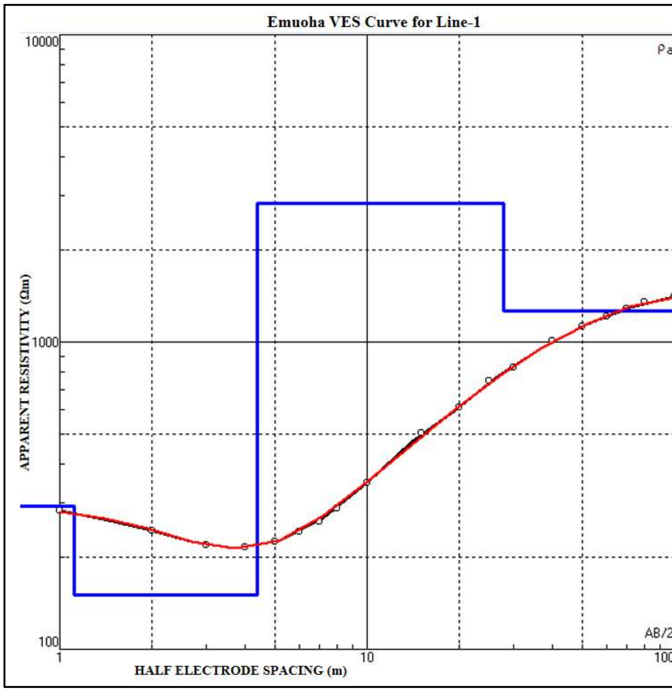


Fig. 4: Resistivity cross-plot for line-1



S/N	Resistivity (Ωm)	Thickness (m)	Depth (m)
1	291.9	1.114	1.114
2	149.9	3.26	4.374
3	2829	23.41	27.79
4	1264		

Fig. 5: Resistivity profile of an HK-type curve for VES line-1.

Line 2 (see figure 6, and 7 below) also demonstrates a matching HK-type geoelectric curve with resistivity trend $\rho_1>\rho_2<\rho_3>\rho_4$ distributed across four distinct subsurface layers, confirming excellent lateral continuity of the local stratigraphic framework. The uppermost layer consists of a dry sandy loam topsoil with a resistivity of 342.2Ωm and a thickness of 1.114m. Below this, the second layer exhibiting a distinct drop in resistivity to 284Ωm over a thickness of 3.626m, marking a damp, finer-grained clayey sand horizon. The core of this profile is defined by the third layer, which exhibits a sharp upward resistivity trend of 1,790Ωm and spans a significant thickness of 21.42m. Geologically, this major resistive horizon represents a highly permeable, fluid-bearing coastal plain sand body characterized by optimal porosity and low clay matrix conduction, making it a prime hydrogeological target for sustainable water abstraction. The baseline terminates into an open-ended fourth layer with a reduced resistivity of 843Ωm, which geologically implies either a deeper fully saturated zone with enhanced fluid pathways or an influx of silty intercalations within the deeper sedimentary bedding.

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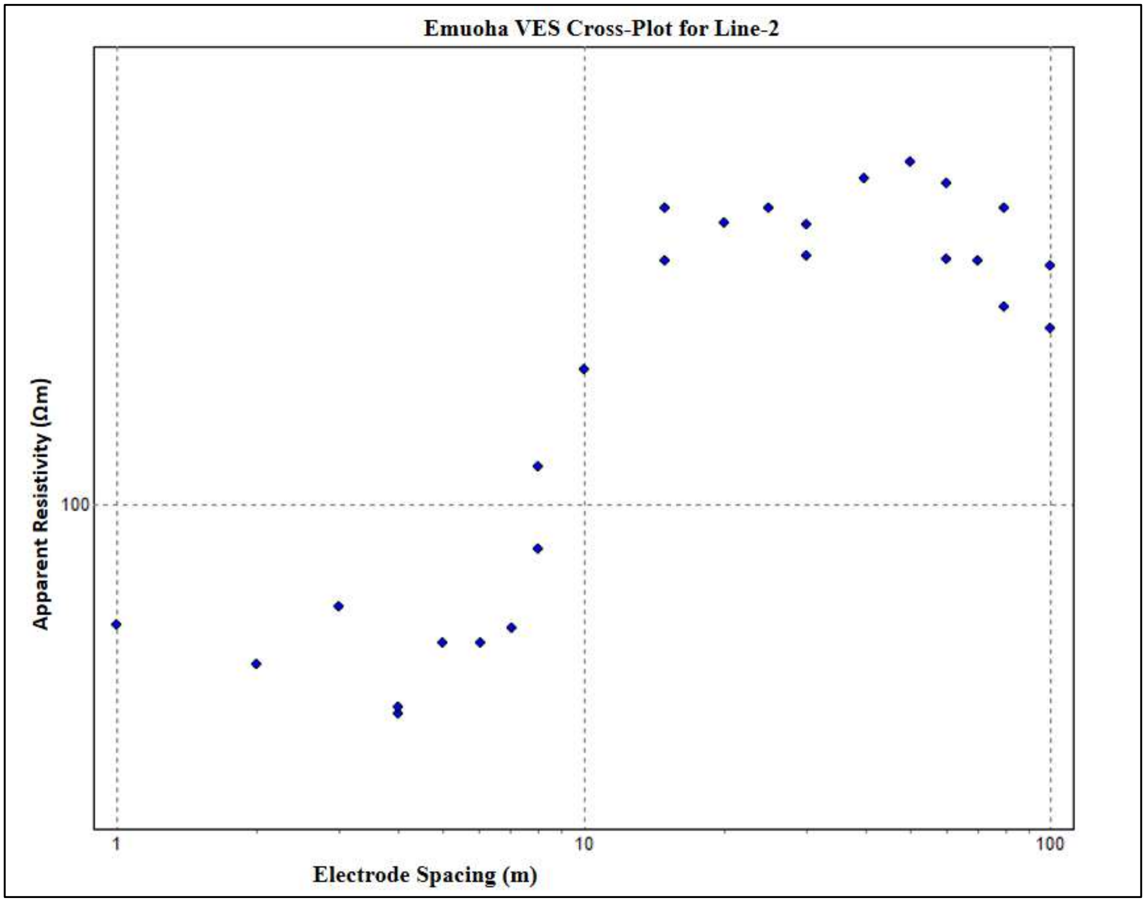
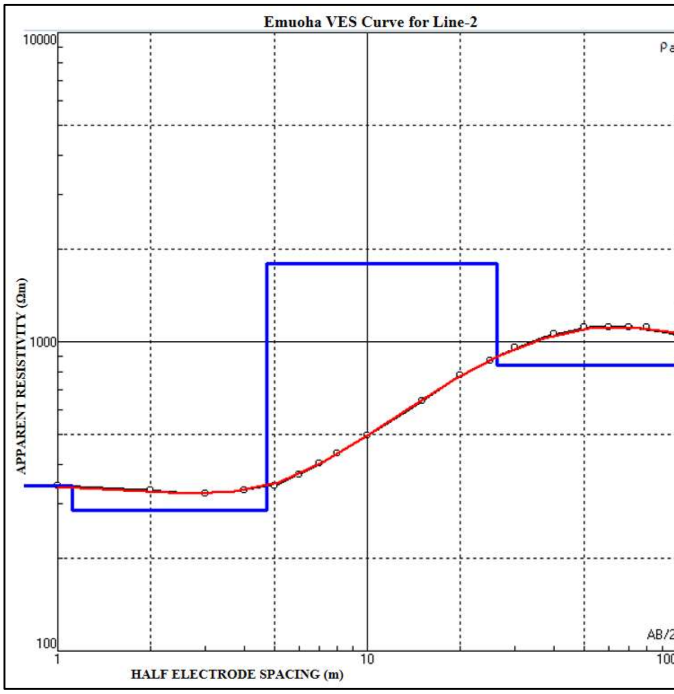


Fig. 6: Resistivity cross-plot for line-2



S/N	Resistivity (Ωm)	Thickness (m)	Depth (m)
1	342.2	1.114	1.114
2	284	3.626	4.741
3	1790	21.42	26.16
4	843		

Fig. 7: Resistivity profile of a HK-type curve for VES line-2.

The 2D ADMT resistivity tomogram for Line 1 (see figure 8 below) provides a high-resolution spatial mapping of the subsurface, characterized by prominent, localized low-resistivity contour closures set against a broader resistive background matrix. These distinct contour closures are indicative of high fluid saturation, enhanced effective porosity, and high hydraulic conductivity within the coarse sedimentary frameworks. The primary hydrogeological target zones are isolated as high-yield anomalies. Geologically, these closed contour patterns are the presence of continuous, prolific sand-rich water channels that are protected from rapid surface contamination. This specific distribution offers an empirical template for Aquifer prospect zone, ensuring long-term yield stability while avoiding dry, tightly packed sandy clay layers.

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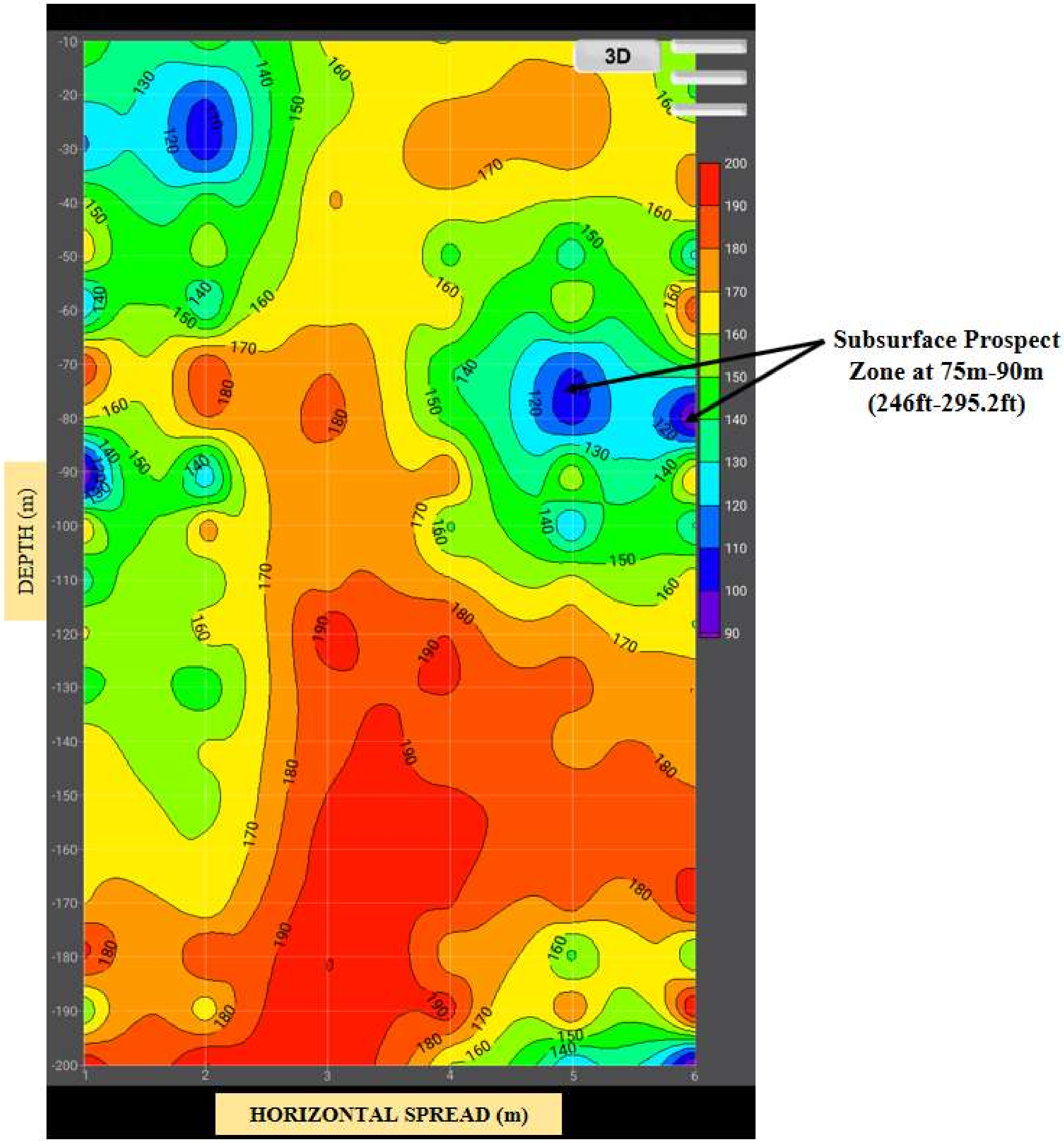

Fig. 8: ADMT resistivity contour map for line-1 and contour closures.

The 2D ADMT contour closure map for Line 2 (see figure 9 below) reveals well-defined, continuous contour closures that map the lateral expansion and structural depth limits of the regional multi-aquifer system. On this profile, low-resistivity and high-yield contour loops form a prominent, elongated prospect zone between. These expansive contour closures are the confirmation of a massive, connected groundwater reservoir characterized by excellent fluid transmissivity values. The vertical distribution of these closures demonstrates that drilling into the deeper target can access confined, high-pressure water horizons, which significantly mitigates the risk of borehole failure and localized drawdown during sustained regional pumping operations.

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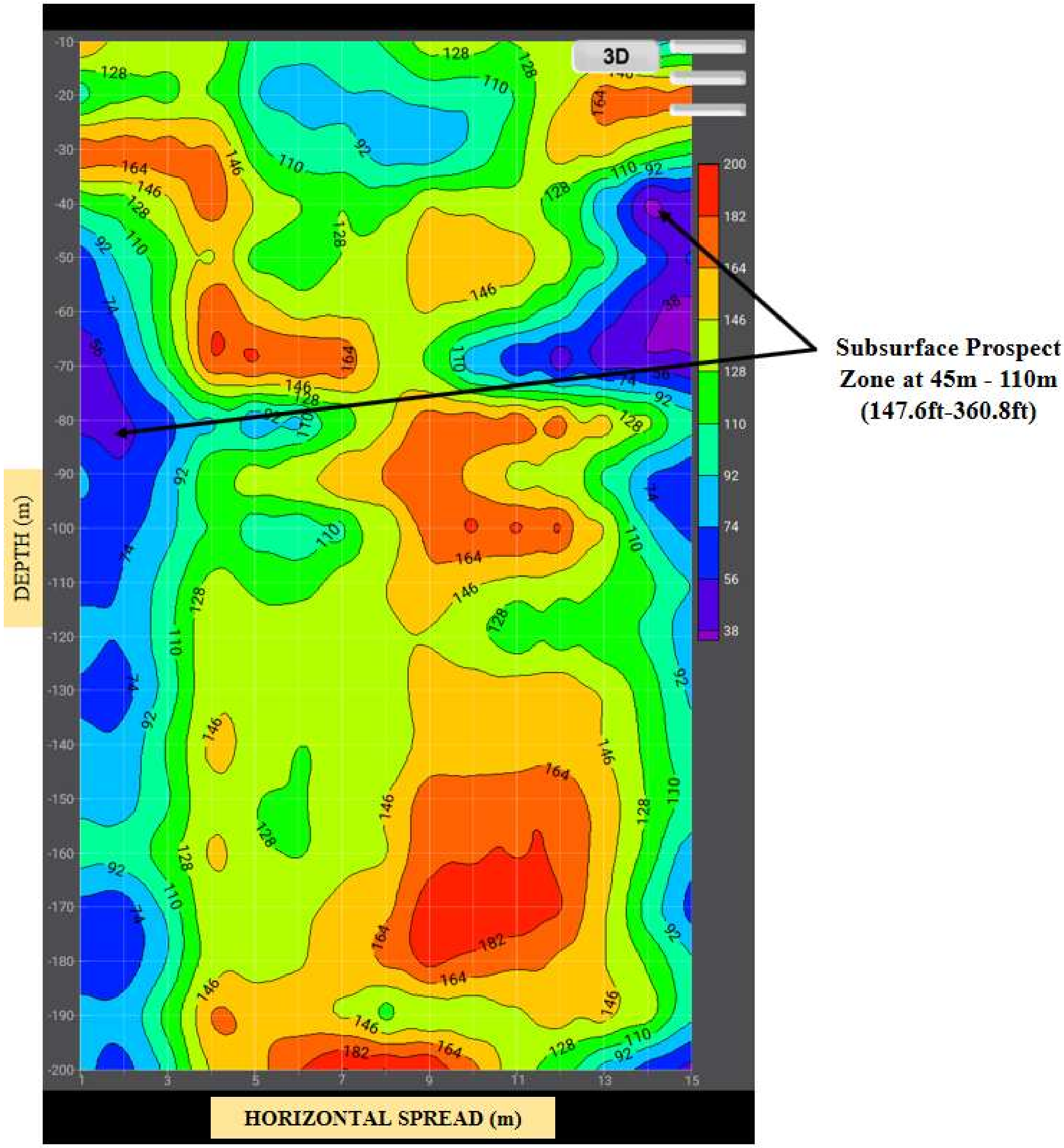

Fig. 9: ADMT resistivity contour map for line-2 and contour closures

Conclusion: This paper advances regional hydro-geophysics by developing an integrated 1D VES and 2D ADMT framework that eliminates structural ambiguity in highly heterogeneous sedimentary environments. By validating the lateral continuity of multi-layer HK-type aquifers and mapping continuous resistivity contour closures within the Benin Formation, this study provides a field-verified template for locating high-yield groundwater channels. Ultimately, these findings contribute a predictive geophysical model that optimizes borehole placement and minimizes drilling failures across the Niger Delta.

DECLARATIONS:

Ethical Approval: This study did not involve human participants or animal experimentation and therefore did not require formal ethical approval. All procedures involving data handling and analysis were conducted responsibly and in accordance with standard academic and institutional guidelines.

Disclaimer (Artificial Intelligence): Author(s) hereby declare that no generative Artificial Intelligence (AI) technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during writing or editing of this manuscript.

Declaration of Conflict of Interest: The authors declare that no known conflict of interest or personal relationships that could have influence the work reported in this paper.

Declaration of Data Availability Statement: Data are available upon request from the Second Author.

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