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Evaluation of saltwater intrusion in Groundwater at Bakana, Rivers State

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Abstract

Saltwater intrusion is a significant concern for coastal regions like Bakana, Rivers State, Nigeria, where freshwater resources are critical for the local population. This study evaluates saltwater intrusion into the groundwater system using Electrical Resistivity (ER) surveys at St. Andrew's Church, Bakana. The research aimed to delineate the freshwater-saltwater interface, identify freshwater aquifers, and assess potential contamination zones. Using advanced Electric Resistivity instruments such as the ADMT Digital Terrameter, data were collected along multiple survey lines and analyzed to create resistivity contour maps and 2D tomograms. The results revealed the presence of multiple freshwater-bearing formations at varying depths, ranging from 13 to 200 meters, with distinct layers of clay and silty clay overlying aquifer formations. Additionally, areas of potential saltwater intrusion and hydrocarbon contamination were identified, particularly in regions where resistivity values were lower. These findings provide critical insights for sustainable groundwater management in Bakana, offering a basis for informed decision-making in borehole drilling and the protection of freshwater resources. The study underscores the utility of electric resistivity surveys in coastal hydrogeological investigations, particularly in identifying and mitigating the impacts of saltwater intrusion.

Keywords: *Saltwater intrusion, Groundwater, Electrical resistivity surveys, Bakana, Freshwater aquifers, Hydrocarbon contamination, Resistivity contour maps, 2D resistivity tomograms, Coastal aquifers, Aquifer formations, Subsurface hydrogeology, Niger Delta, Groundwater management, Borehole drilling, Environmental geophysics.*

1. Introduction

Freshwater resources are crucial for sustaining the growing population of Bakana, a coastal region in Rivers State, Nigeria. However, saltwater intrusion poses a significant threat to existing freshwater supplies in these areas (Ojo, 2018). Effective management of groundwater resources requires a thorough understanding of the subsurface characteristics, particularly aquifer depths and potential saltwater encroachment.

The expanding population in Bakana necessitates a detailed examination of its water resources. Improper management of coastal freshwater resources can lead to saltwater contamination, jeopardizing the water supply's quality and suitability for various uses (Custodio & Langevin, 2016). Sound management decisions regarding groundwater extraction and utilization require comprehensive data on aquifer characteristics and potential threats. Electrical resistivity (ER) surveys provide a valuable tool for gathering this information in a cost-effective and non-destructive manner (McNeill, 1999).

Electrical Resistivity(ER) Surveys for Groundwater Exploration

ER surveys are a well-established geophysical technique used to map variations in electrical resistivity of the subsurface (Telford et al., 1990). This method involves injecting an electrical current into the ground through electrodes and measuring the resulting voltage at different locations on the surface (Reynolds, 2011). The measured electrical response is influenced by the resistivity of the various subsurface materials. Materials with high water content, such as saturated sands and gravels, typically exhibit lower resistivity values compared to drier formations or those containing clay minerals (Ward, Shirley, & Rovers, 1990). By analyzing the collected data and employing specialized software, geophysicists can create a model of the subsurface resistivity distribution, providing valuable insights into geological formations and water content (Dahlin, 2002).

ER surveys have been widely used in hydrogeological investigations for many decades, including borehole drilling programs (Fitterman & Stewart, 1986). They offer several advantages over traditional drilling methods. ER surveys are relatively inexpensive, particularly for large-scale investigations, and can be conducted rapidly, minimizing disruption to the target area (Nilsson et al., 2014). Additionally, ER surveys are non-destructive and environmentally friendly, making them a suitable option for sensitive environments (Chambers, Ogilvy, & McEwan, 2004).

Threats to Coastal Aquifers

Extensive use of coastal aquifers for water supply can lead to saltwater intrusion, a phenomenon where seawater migrates into the freshwater zone (Freeze & Cherry, 1979). This process reduces the quality of the groundwater and renders it unsuitable for various uses, including drinking water and irrigation (Custodio & Langevin, 2016). Several factors contribute to saltwater intrusion, including:

- **Over-pumping:** Excessive groundwater extraction can create a pressure gradient that draws saltwater inland).
- **Sea level rise:** Rising sea levels can increase the hydraulic head of seawater, further promoting its intrusion into coastal aquifers (Li et al., 2016).
- **Reduced recharge:** Decreases in natural groundwater recharge due to factors such as climate change or urbanization can exacerbate saltwater intrusion by limiting the freshwater available to push back against the encroaching saltwater (Sophocleous, 2002).

The combined effects of these factors can lead to a significant salinization of coastal aquifers, posing a serious threat to freshwater security in coastal regions.

ER is a valuable tool for monitoring the presence of iron-rich water and saltwater movement in coastal areas (Ward, Shirley, & Rovers, 1990). The distinct electrical resistivity signatures of saltwater and freshwater allow geophysicists to identify the interface between these two zones within the subsurface (Stewart, 1980). This information is crucial for understanding the extent of saltwater intrusion and for designing effective strategies to manage and protect coastal freshwater resources (Vacquier et al., 1977).

Objectives of this Study

This study aims to utilize ER instruments (ADMT: Digital Terrameter, Groundwater Resistivity Meter, and Pool Finder Plus) to define depths to freshwater aquifers, identify iron water presence, and assess the freshwater-saltwater interface at St. Andrew's Church, Rivers State. The findings of this study will provide valuable insights into the hydrogeological conditions of the area and inform the development of sustainable groundwater management strategies.

Scope of Work

This study will employ ER to explore depths to freshwater-bearing formations suitable for borehole drilling and evaluate zones of saltwater intrusion within the subsurface layers. The collected data will be analyzed and interpreted to generate a comprehensive picture of the subsurface hydrogeology, including aquifer depths, thicknesses, and potential saltwater contamination zones.

2. Study Area

The research area is around New Calabar River located in Rivers State is a part of the Niger Delta basin which covers all the land between latitude 4o14’N and 5o35’N and longitude 5^{o}26’E and 7^{o}37’E with a total area of 20,000 km2 (Figure 1) is situated within the Niger Delta of southern Nigeria (Olajire, 2024). This region exhibits an arcuate shape, characteristic of wave and tide-dominated prograding delta systems (Short & Stauble, 1970).

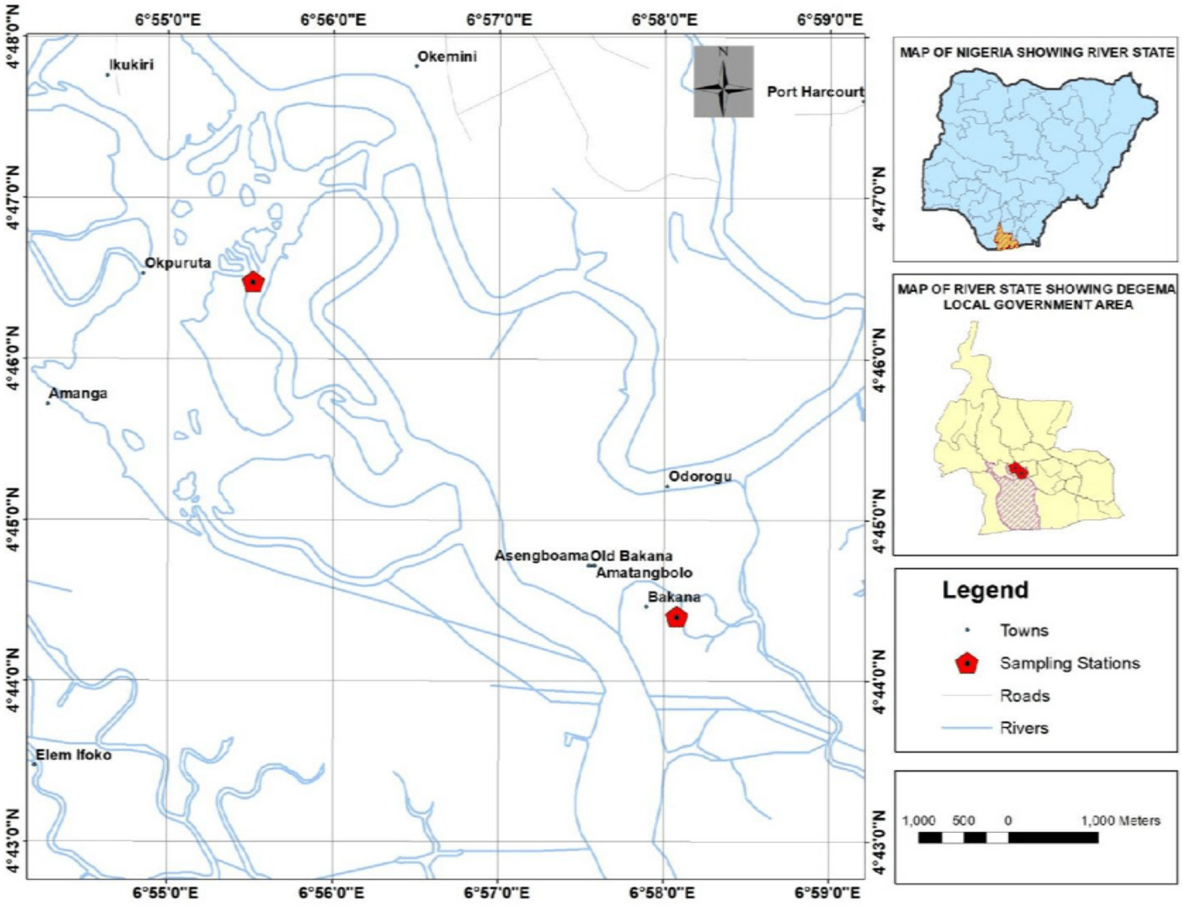


Figure 1: Map of the study area showing Rumuolumeni and Bakana Communities in Rivers State (Ugbomeh, et. Al.,2018)

The sedimentary sequence in the area spans from the Eocene to Quaternary periods (Akasi, 2010). Geologically, the Niger Delta is comprised of three primary formations: the Benin Formation, the Agbada Formation, and the Akata Formation (Doutrin et al., 2001).

The focus of this study is the Benin Formation, which serves as the principal source of groundwater for the region (Olajire, 2024). This formation consists of poorly sorted coastal sands that progressively become sandier and less consolidated towards the surface (Olajire, 2024). This gradual change in composition translates to increased porosity and permeability within the aquifer, enhancing its ability to store and transmit groundwater (Freeze & Cherry, 1979). Recharge of the Benin Formation in this area is primarily driven by surrounding water bodies, with limited contribution from rainfall infiltration due to the presence of dense vegetation cover (Olajire, 2024). These factors collectively contribute to the formation's designation as a prolific hydrologic unit.

3. Material and Method

This study employs electrical resistivity (ER) surveying techniques to investigate the subsurface hydrogeology at St. Andrew's Church, Rivers State. Electric Resistivity surveys are a geophysical method that measures variations in electrical resistivity of the subsurface (Telford et al., 1990). The specific instruments utilized in this study are the ADMT Digital Terrameter, Groundwater Resistivity Meter, and Pool Finder Plus, all part of the ADMT series manufactured by AIDU and Guilin Technology Hydrogeological Investigation Institute.

These ADMT instruments (Figure 2) represent a new generation of intelligent prospecting tools designed to streamline data collection, processing, and analysis. The system leverages mobile phone or tablet technology to perform complex data calculations and generate real-time inversion results and graphical representations. This allows for the swift generation of 2D/3D profiles, contour maps, and curve diagrams directly within a user-friendly mobile application. This technological advancement significantly simplifies the process of geophysical surveying compared to traditional methods.

Figure 2: ADMT digital Terrameter for Groundwater Exploration.

Figure 3: Geophysical operators of the ADMT Terra Meter

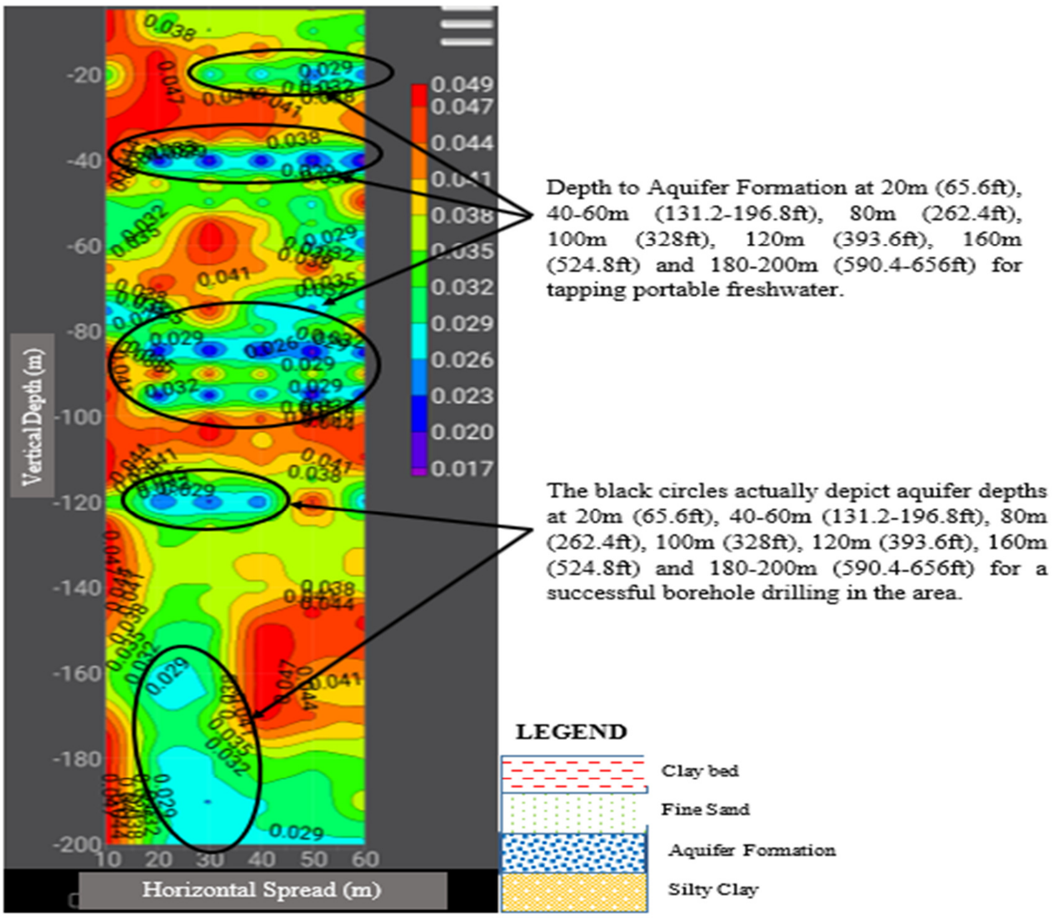
The key functionalities of the ADMT system include:

- **Instant Mapping:** The mobile application facilitates the immediate generation of 2D/3D resistivity maps upon data acquisition.
- **Simplified Operation:** Data collection involves a straightforward walking and stopping routine, eliminating the need for cumbersome cabling.
- **Enhanced Efficiency:** The wireless sensor probe technology enables a single operator to complete the entire survey, saving time and manpower.
- **Improved Precision:** The system incorporates robust anti-interference capabilities, field source correction techniques, and patented data processing algorithms to ensure accurate results.

The data collection process involves connecting the chosen instrument to the mobile application via Bluetooth. This app provides a central hub for all instrument operations, including measurement signal input, real-time data monitoring, and post-acquisition data processing. The wireless sensor probes employed by the system eliminate the need for extensive cabling, further streamlining field data collection and minimizing logistical requirements.

4. Results and Interpretations

The "Resistivity contour map" suggests the survey analyzed electrical resistance along a specific line. Freshwater generally has a higher resistivity than saltwater or clay. This electrical property helps pinpoint areas with potentially better-quality freshwater. The electrical resistivity survey, depicted in Figure 4, helps visualize potential freshwater zones at various depths. The black circles highlight these depths, ranging from a shallow 20 meters (65.6 feet) to a deeper 180-200 meters (590.4-656 feet). This provides flexibility in drilling depending on factors like cost and ease of access. The underground composition. The presence of an "Aquifer Formation" beneath clay and silty clay layers is encouraging, as aquifers typically store usable groundwater. The fine sand layer below the aquifer might also hold water, but further investigation might be needed. In conclusion, this data significantly improves the chances of a successful freshwater borehole. By analyzing the depths and locations identified in the survey, drilling efforts can be targeted more efficiently, maximizing the potential of obtaining clean drinking water.



Depth to Aquifer Formation at 20m (65.6ft), 40-60m (131.2-196.8ft), 80m (262.4ft), 100m (328ft), 120m (393.6ft), 160m (524.8ft) and 180-200m (590.4-656ft) for tapping portable freshwater.

The black circles actually depict aquifer depths at 20m (65.6ft), 40-60m (131.2-196.8ft), 80m (262.4ft), 100m (328ft), 120m (393.6ft), 160m (524.8ft) and 180-200m (590.4-656ft) for a successful borehole drilling in the area.

Figure 4: Resistivity contour map of Line-1 which shows zones of portable drinking water that can be tapped by a borehole.

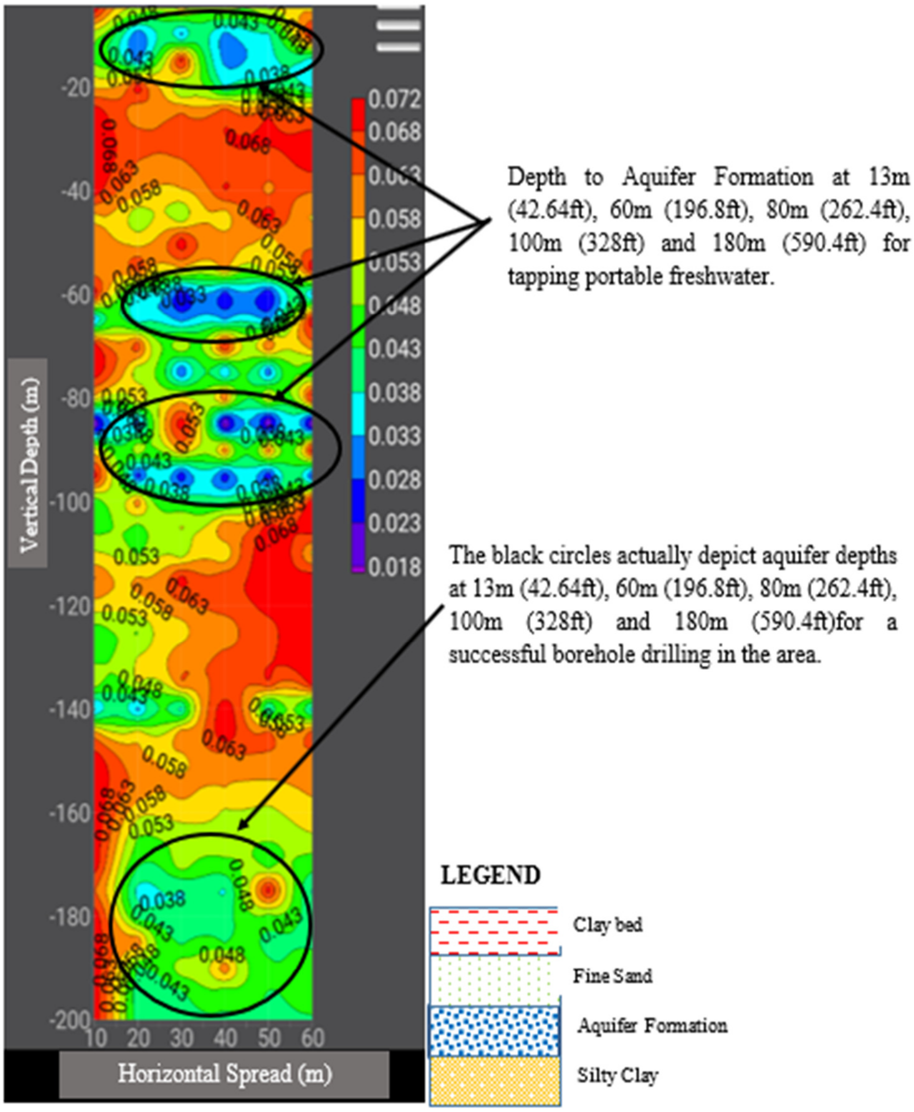
Figure 5 presents another resistivity contour map, from a separate survey line (Line 2) compared to Figure 4. This data provides valuable insights for drilling a freshwater borehole in this specific area.

The black circles on the map represent depths where freshwater can potentially be accessed. These depths differ slightly from Line 1, ranging from:

- 13 meters (42.64 feet) - A shallower option compared to Line 1.
- 60 meters (196.8 feet)
- 80 meters (262.4 feet)
- 100 meters (328 feet)
- 180 meters (590.4 feet)

This again offers flexibility in drilling based on project requirements. The results confirm the presence of an "Aquifer Formation" beneath clay and silty clay layers, a promising sign for finding usable groundwater.

Similar to Figure 4, the "Resistivity contour map" shows the analysis focused on electrical resistance variations along Line 2. As with the previous map, freshwater's higher resistivity compared to saltwater or clay aids in identifying zones with potentially better-quality drinking water.



Depth to Aquifer Formation at 13m (42.64ft), 60m (196.8ft), 80m (262.4ft), 100m (328ft) and 180m (590.4ft) for tapping portable freshwater.

The black circles actually depict aquifer depths at 13m (42.64ft), 60m (196.8ft), 80m (262.4ft), 100m (328ft) and 180m (590.4ft)for a successful borehole drilling in the area.

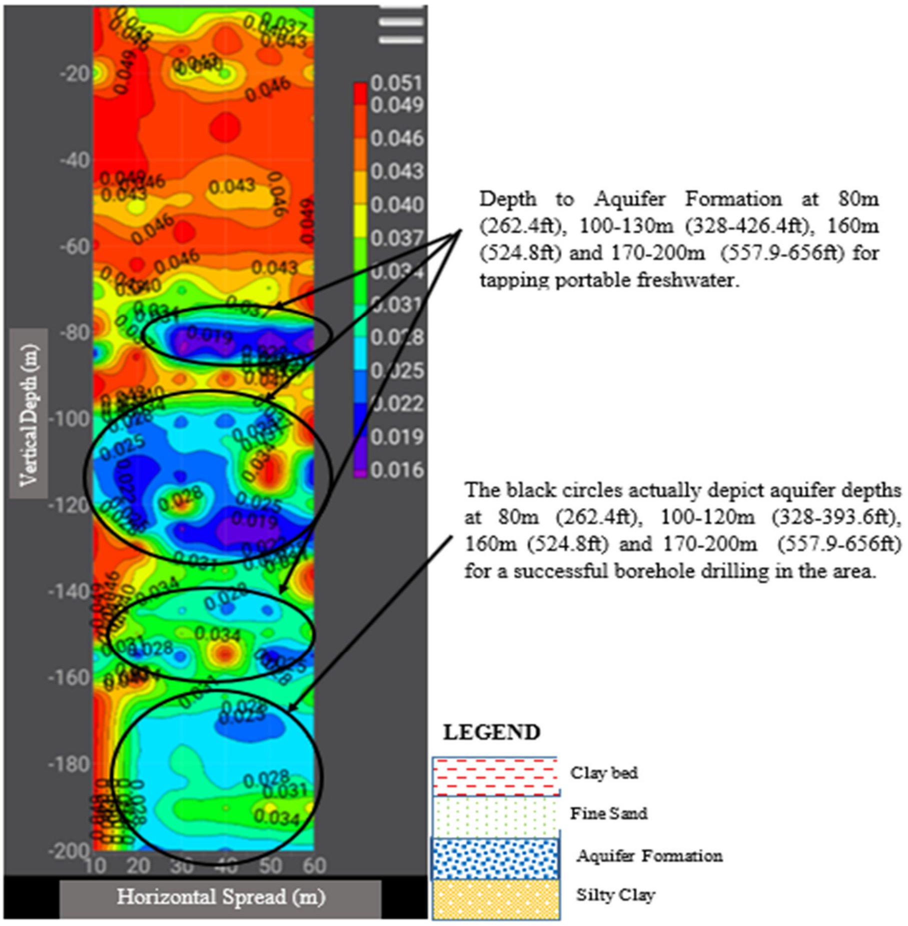
Figure 5: Resistivity contour map of Line-2 which shows zones of portable drinking water that can be tapped by a borehole.

Figure 6 showcases a "geophysical model" of Line 3, depicting the subsurface structure based on Electric resistivity. This information gotten is crucial for planning a successful freshwater borehole in this area. The black circles on the model represent depths where freshwater can potentially be found. Compared to Lines 1 and 2, the depths here are generally deeper, ranging from:

- 80 meters (262.4 feet) - Similar to the shallowest option from Lines 1 and 2.

- 100-130 meters (328-426.4 feet) - A wider range offering more flexibility.
- 160 meters (524.8 feet)
- 170-200 meters (557.9-656 feet) - The deepest option presented so far.

The result shows that freshwater might be present at deeper levels in this specific location. The result confirms the familiar layering of "Clay bed" and "Silty Clay" above the crucial "Aquifer Formation," and a "Fine Sand" layer below.



Depth to Aquifer Formation at 80m (262.4ft), 100-130m (328-426.4ft), 160m (524.8ft) and 170-200m (557.9-656ft) for tapping portable freshwater.

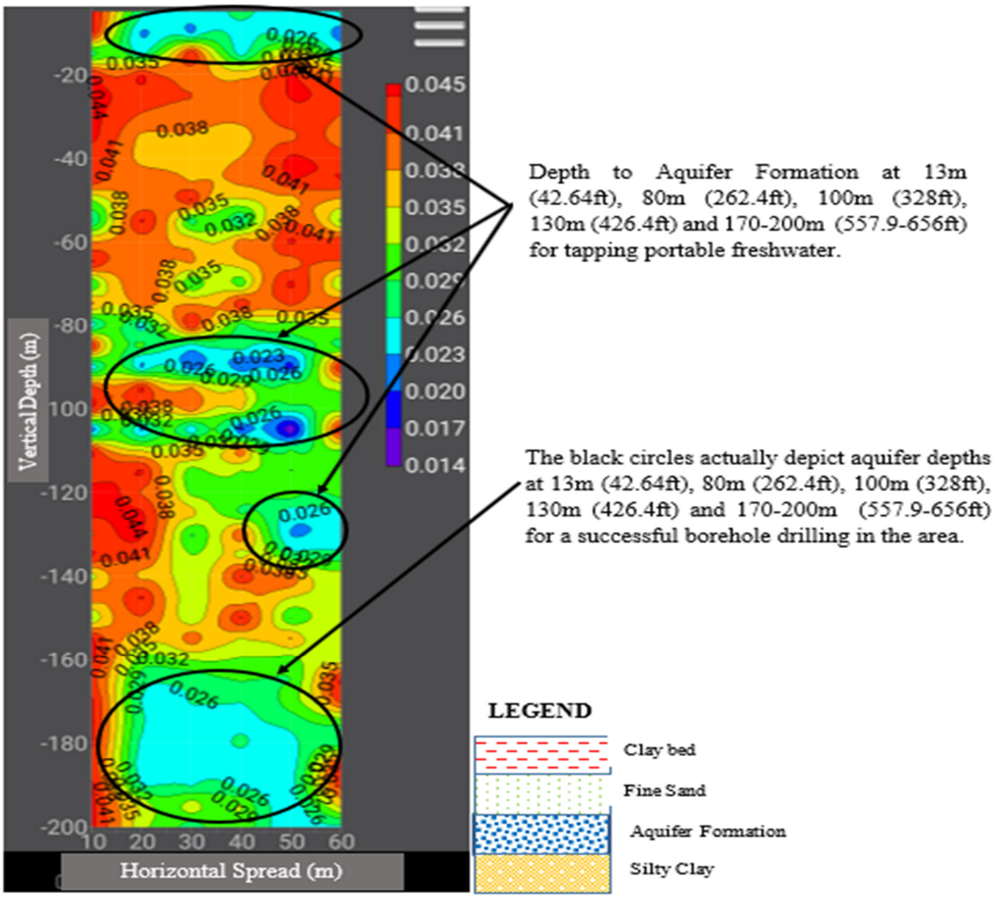
The black circles actually depict aquifer depths at 80m (262.4ft), 100-120m (328-393.6ft), 160m (524.8ft) and 170-200m (557.9-656ft) for a successful borehole drilling in the area.

Figure 6: A geophysical model of Line-3 and portable water zones.

Figure 7 presents a "resistivity model" of Line 4, which depicts the subsurface structure based on electrical resistivity measurements. This data is valuable for strategically planning a freshwater borehole in this area. The black circles on the model highlight depths where freshwater can potentially be accessed. This line offers a unique perspective compared to the previous lines:

- 13 meters (42.64 feet) - The shallowest option across all four lines, potentially allowing for a more cost-effective and quicker borehole.
- 80 meters (262.4 feet) - Consistent with depths found in Lines 1, 2, and 3.
- 100 meters (328 feet) - Also consistent with previous lines.
- 130 meters (426.4 feet) - A new depth not identified on the other lines.
- 170-200 meters (557.9-656 feet) - Consistent with the deepest option on Line 3.

The result shows the presence of multiple potential freshwater zones at varying depths along Line 4. The results confirm the familiar underground layering with "Clay bed" and "Silty Clay" on top, followed by the "Aquifer Formation," and "Fine Sand" below.



Depth to Aquifer Formation at 13m (42.64ft), 80m (262.4ft), 100m (328ft), 130m (426.4ft) and 170-200m (557.9-656ft) for tapping portable freshwater.

The black circles actually depict aquifer depths at 13m (42.64ft), 80m (262.4ft), 100m (328ft), 130m (426.4ft) and 170-200m (557.9-656ft) for a successful borehole drilling in the area.

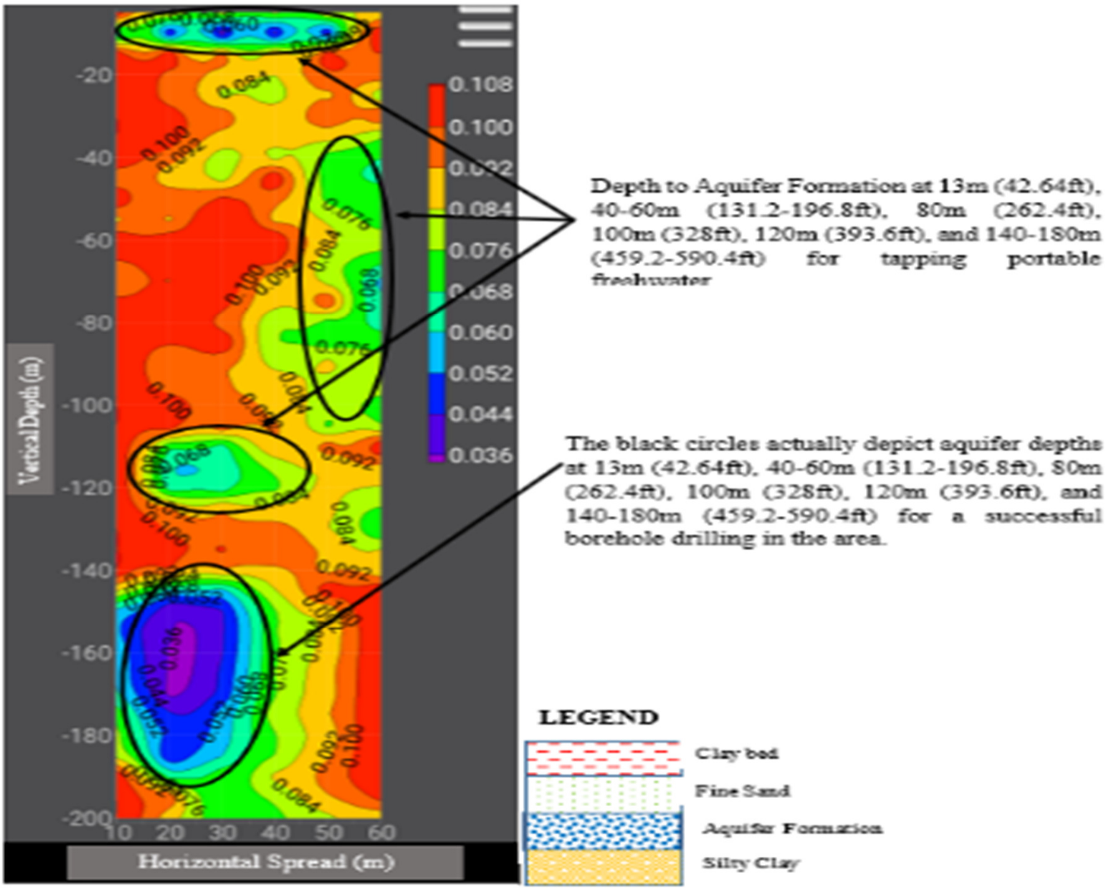
Figure 7: A resistivity model of Line-4 and Aquifer zones.

Figure 8 showcases a "resistivity contour map" of Line-5, depicting variations in a geophysical property (electrical resistivity) across this specific survey line. This data is valuable for strategically planning a freshwater borehole in the area.

The black circles on the map represent depths where freshwater can potentially be accessed. Line 5 offers a good mix of shallow and deeper options compared to previous lines:

- 13 meters (42.64 feet) - Similar to the shallowest option on Lines 4 and 7, potentially allowing for a more cost-effective and quicker borehole.
- 40-60 meters (131.2-196.8 feet) - A range not identified on other lines, offering additional flexibility.
- 80 meters (262.4 feet) - Consistent with depths found in Lines 1, 2, 3, and 4.
- 100 meters (328 feet) - Also consistent with previous lines.
- 120 meters (393.6 feet) - Consistent with Line 1.
- 140-180 meters (459.2-590.4 feet) - A range overlapping with Line 3, offering deeper possibilities.

The result shows multiple potential freshwater zones at varying depths along Line 5. The results confirm the familiar underground layering with "Clay bed" and "Silty Clay" on top, followed by the "Aquifer Formation," and "Fine Sand" below.



Depth to Aquifer Formation at 13m (42.64ft), 40-60m (131.2-196.8ft), 80m (262.4ft), 100m (328ft), 120m (393.6ft), and 140-180m (459.2-590.4ft) for tapping portable freshwater

The black circles actually depict aquifer depths at 13m (42.64ft), 40-60m (131.2-196.8ft), 80m (262.4ft), 100m (328ft), 120m (393.6ft), and 140-180m (459.2-590.4ft) for a successful borehole drilling in the area.

Figure 8: A contour map of Line-5 and depths to Aquifers.

Figure 9, unlike previous figures, presents a "2D resistivity tomogram" which provides a more detailed cross-sectional view of the subsurface based on electrical resistivity measurements. This result offers valuable insights but also raises concerns regarding potential water contamination, which needs to be considered when planning a borehole in this area.

Freshwater Potential:

The tomogram depicts changes in resistivity, with blue zones indicating areas of potential freshwater presence. These zones are located where the electrical resistance is higher. However, unlike previous figures with black circles marking specific depths, this tomogram provides a more continuous image.

Contamination Concerns:

- **Red-coloured zones:** These zones represent areas with higher conductivity, potentially indicating the presence of "conductive fluid" within the subsurface layers. This fluid might not be suitable for drinking water. zones to the presence of "hydrocarbon contaminants" causing an offensive odour in the extracted water. These contaminants are suspected to originate from "illegal refinery activities" near the surface.

- **Black arrows on the left:** These arrows suggest the potential "influx of contaminants" from an external source into the freshwater zones. This raises concerns about the water quality.

- **Blue zone:** The Blue zones represent possible freshwater water zones and Areas with very high resistivity.

From Figure 9, it's obvious that there is a clear delineation between the freshwater zone (blue zone areas with low resistivity) and the Contaminated zones (Red zone areas with high resistivity) those green zones that serve as a protective layer. Hence the freshwater appears to be uncontaminated

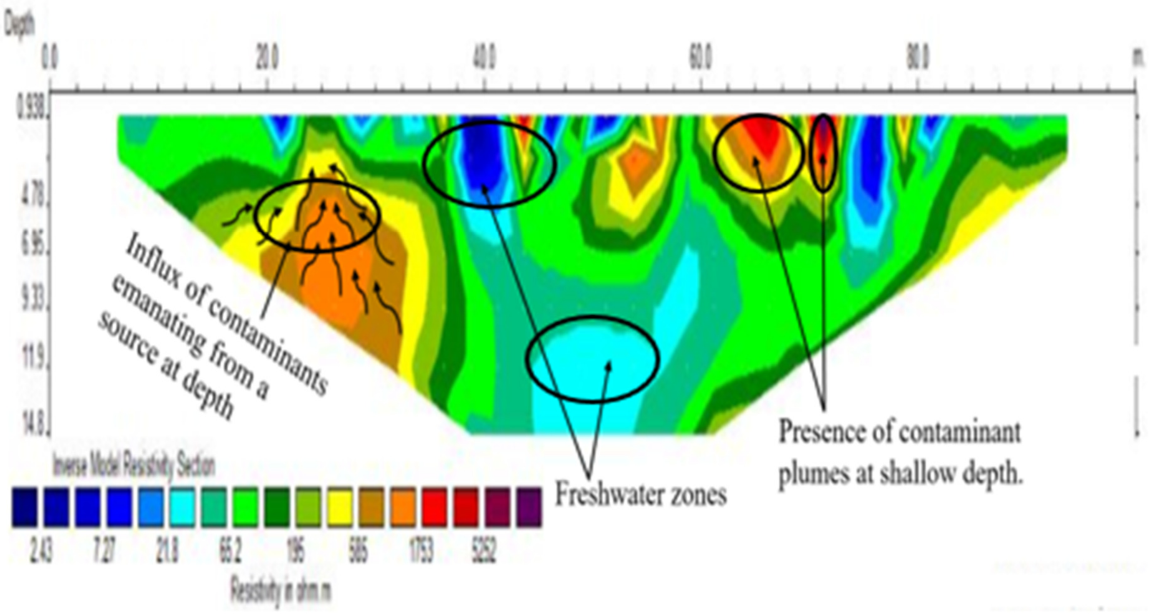


Figure 9: A 2D resistivity tomogram of the subsurface layers produced from the Wenner profile.

Discussions

This series of figures (Figures 4-9) presents geophysical data, collected using electrical resistivity surveys, from six different lines (Lines 1-5) in an area. The analysis aims to identify potential locations for drilling boreholes to access freshwater.

Encouragingly, all figures depict zones with potential freshwater presence at various depths. These depths range from a shallow 13 meters (42.64 feet) up to a deeper 200 meters (656 feet). This variability offers flexibility in drilling depending on project needs and cost considerations. The figures consistently show an

"Aquifer Formation" beneath clay and silty clay layers, a promising sign for finding usable groundwater. Additionally, variations in electrical resistivity, often depicted by black circles or blue zones, help pinpoint areas with potentially better-quality freshwater within the aquifer.**:**

While all figures identify potential freshwater, some variations exist. Lines 1, 2, and 3 offer similar depth ranges, while Lines 4 and 5 present additional shallower or deeper options. The tomographic image in Figure 9, raises a crucial concern: potential contamination of the freshwater zones. The presence of red zones indicating conductive fluids, black arrows suggesting contaminant influx, and mentions of hydrocarbon and iron contamination necessitate further investigation.

By combining data from all six lines, a comprehensive picture of the area's freshwater potential emerges. This information is invaluable for planning a successful borehole drilling project. However, for Line-6(tomogram) specifically, addressing potential contamination through source identification, mitigation strategies, and water quality testing is crucial before relying on this water source.

5. Conclusions and Recommendations:

The geophysical investigation employing electrical resistivity at St. Andrew's Church in Bakana, Rivers State, has proven to be a valuable tool. It provided valuable insights into the subsurface layers, revealing promising locations for drilling boreholes to access fresh water. The analysis of multiple 2D contour maps successfully identified depths where freshwater is likely present within porous and permeable underground formations. These depths vary, ranging from a shallow 13 meters (42.64 feet) to a deeper 200 meters (656 feet). The identified aquifers exhibited high resistivity properties, a strong indicator of the presence of freshwater within the soil layers and also a strong indicator of no saltwater intrusion into freshwater zones in the study area.

Recommendations for Borehole Drilling:

Based on the findings from the geophysical survey, the following recommendations are made for a successful borehole drilling project:

- **Target Depths:** Borehole drilling should target specific depths with high freshwater potential:
    - **(a)** 13 meters (42.64 feet)
    - **(b)** 14 meters (45.92 feet)
    - **(c)** 40-60 meters (131.2-196.8 feet)
    - **(d)** 80 meters (262.4 feet)
    - **(e)** 100 meters (328 feet)
    - **(f)** 170-200 meters (557.9-656 feet)
- **Screen Installation:** To optimize water yield from the borehole, screens should be installed within these targeted depth ranges.

Additional Considerations:

While these depths offer promising freshwater access, further investigation might be necessary depending on specific project requirements. This could include:

- **Water Quality Testing:** Before relying on this water source, a thorough water quality test is essential to ensure it meets safe drinking water standards.

- **Project Priorities:** Depending on project priorities, such as budget or desired well capacity, a specific depth from the recommended range might be chosen.

Overall Significance:

This geophysical survey provides valuable data to strategically plan a borehole drilling project at St. Andrew's Church. By targeting the recommended depths and incorporating screens, the project has a high chance of success in obtaining clean and sustainable freshwater for the community.

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