Delineation of Aquifer Iron Content in Existing Borehole Using Joint Integrated Electrical Resistivity Imaging Technique, Ekeki, Bayelsa State

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Abstract
This study explores the use of Electrical Resistivity Imaging (ERI) to identify aquifers with varying iron levels in Ekeki, Bayelsa State, addressing the pressing issue of groundwater quality. High iron levels in drinking water can be a health and operational challenge, making it essential to pinpoint safe water sources. Using the Wenner-Schlumberger array, we examined two boreholes: Aquifer 1 (AQ1), containing clay-rich, fine-grained sediments at depths of 0–17.5 meters, and Aquifer 2 (AQ2), composed mainly of clean sands and gravel. The results revealed that AQ1 had low resistivity values (17.5–113 Ω·m), indicating the presence of iron-rich minerals, with lab tests confirming a high iron concentration of 4.0 mg/L, far exceeding the WHO guideline of 0.3 mg/L. In contrast, AQ2 exhibited higher resistivity (209–1345 Ω·m) and an iron concentration below 0.001 mg/L, making it a safer option. This study highlights how ERI can effectively map groundwater resources, providing a reliable tool to ensure safe and sustainable water supply for communities.
Keywords*: Aquifers, High iron level, Wenner-Schlumberger array, boreholes*

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1. Introduction

Access to clean and safe water is essential for human health and socio-economic growth, yet many communities in Bayelsa State, Nigeria, face challenges due to iron contamination in groundwater. Iron, commonly found in the region's geology, often appears in its ferrous form (Fe^{2+}) under reducing conditions, causing issues like staining, unpleasant odours, and metallic taste in water. Traditional methods for locating clean water, such as drilling and pumping tests, are costly and limited in scope. Electrical Resistivity Imaging (ERI), an innovative geophysical technique, offers a more efficient and detailed approach to understanding subsurface features. While ERI has proven successful in mapping aquifers and subsurface structures, its application to specifically address iron contamination remains underexplored. This study uses ERI to map aquifers with varying iron levels in Ekeki, Bayelsa State. By combining geophysical findings with hydrogeological data, it provides valuable insights into the causes of iron contamination and offers a practical pathway to identify safer groundwater sources for the community.

2. Methodology

2.1 Study Area

Ekeki is a densely populated community in Yenagoa, Bayelsa State, located within the Niger Delta. The region is characterized by extensive wetlands and relies predominantly on groundwater for domestic and industrial uses. The study focuses on two boreholes: one with high iron content and the other with low or negligible iron content, located at coordinates 4°55'30.42"N, 6°17'56.92"E and 4°55'31.28"N, 6°17'57.38"E, respectively (Fig. 1).

Fig.1: Image map of the survey area indicating the two points of the two boreholes

2.2.1 **2D Electrical Resistivity Imaging**

The electrical resistivity imaging survey employed a Wenner-Schlumberger array, providing detailed insights into the spatial distribution of subsurface resistivity. The Wenner and Schlumberger arrays according to Pazdirek and Blaha (1996), is a new hybrid the arising out of relatively recent works done with electrical imaging surveys. Measurements involve injecting current into the ground through current electrodes (C1 and C2) and recording potential differences with electrodes P1 and P2 (Fig. 2i (a and b) and 2ii (a and b). Apparent resistivity values are calculated using standard geometric factors. Electrical Resistivity Imaging (ERI) survey was conducted to map subsurface structures and delineate aquifer boundaries. In recent years, the use of 2-D electrical imaging or tomography surveys has become increasingly popular for mapping areas with moderately complex geology (Griffiths & Barker, 1993). The survey is typically conducted using an array of 25 or more electrodes connected to a multi-core cable. These electrodes are systematically positioned along a predetermined line at the surface. During the survey, electrical currents are injected into the ground through pairs of electrodes, and the resulting potential differences are measured by other pairs of electrodes. The data collected from these measurements are then processed to generate a two-dimensional resistivity model of the subsurface. The multi-core cable system, combined with advanced data acquisition equipment, automates the switching between electrodes, enhancing the speed and accuracy of the data collection process. The detailed methodology employed in this research work has been reported elsewhere (Chiemeke et al, 2014).

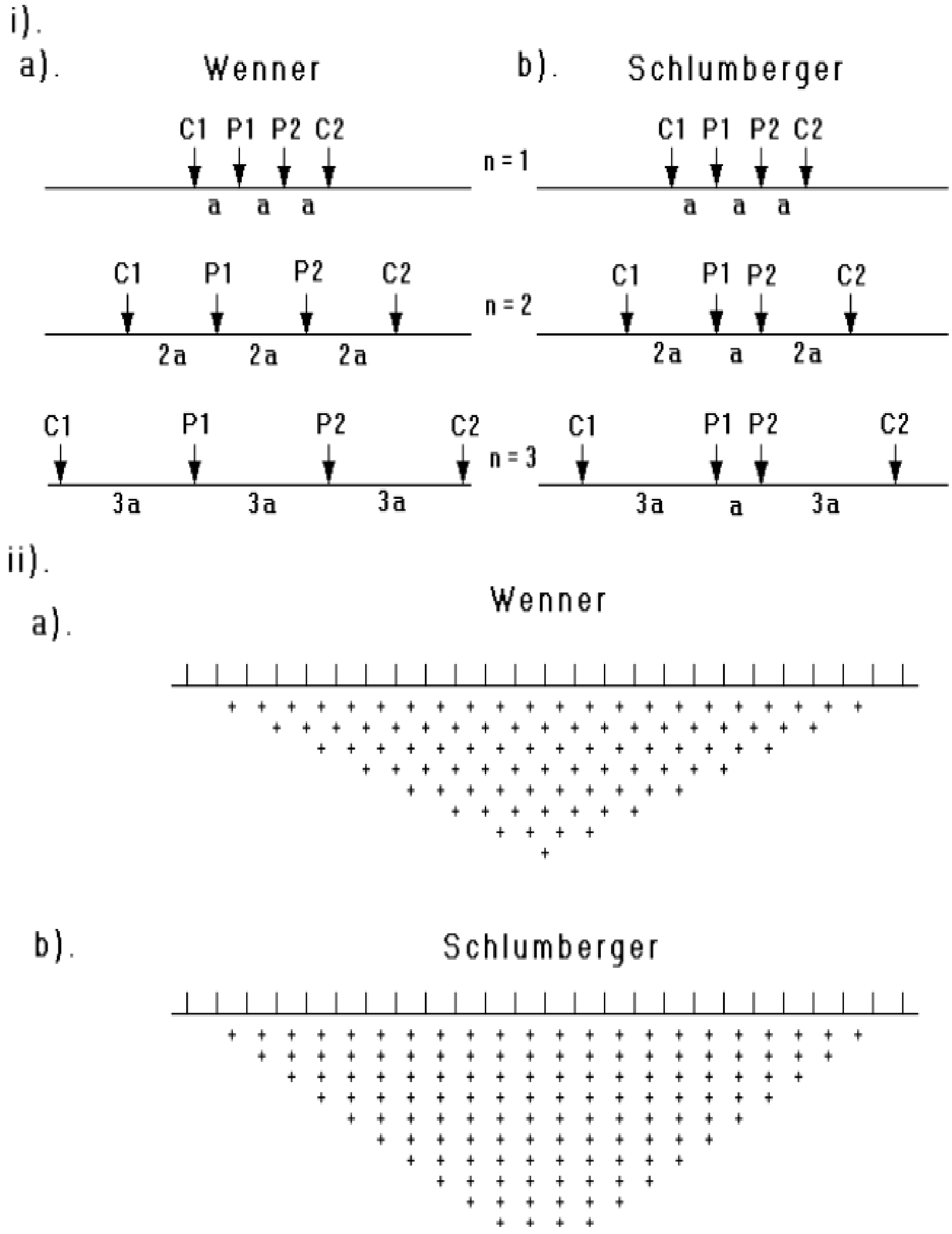

Fig. 2: A comparison of the (i) electrode arrangement and (ii) Resistivity Tomography Model data pattern for the Wenner and Wenner-Schlumberger arrays.

2.3 Determination of Iron in the Boreholes

Iron (Fe) in the groundwater was determined using Atomic Absorption Spectroscopy (AAS) in ASTM D1068 with slight modification. Water samples were collected from the two boreholes of the first aquifer suspected to have high resistivity with high Fe (AQ1) and the second aquifer also suspected to have low resistivity and low or no Fe (AQ2), acidified with nitric acid to a pH of less than 2. This preserves the sample and ensures that all iron remains dissolved. Standard solutions with known Fe concentrations were prepared to create a calibration curve, which were used to calibrate the AAS instrument. The prepared sample was aspirated into the flame of the AAS instrument, where it was atomized. A light beam with a wavelength specific to iron (usually around 248.3 nm) passes through the atomized sample. The Fe atoms absorb this light, reducing its intensity. The reduction in light intensity was measured and compared against the calibration curve to determine the Fe concentration in the water sample.

3. Results and Discussion

3.1 2D Electrical Resistivity Imaging Results

The results of the 2D electrical resistivity Imaging (ERI) using Wenner – Schlumberger array are presented in Fig. 3. The Resistivity Tomography Model analysis of regions of low resistivity (potentially indicative of iron-bearing formations) and high resistivity (obviously indicative of low or no iron iron-bearing formations), is presented as follows:

3.1.1 Measured Apparent Resistivity

This observed Model shown in Fig. 3 represents the raw data obtained during the field survey. The colour scale corresponds to different apparent resistivity values, with shades of blue representing lower resistivity and shades of red representing higher resistivity. The resistivity values vary across the section, with a significant high-resistivity anomaly seen on the right side, particularly between 50 to 80 m. This suggests the presence of a material with higher resistivity, which could be indicative of non-conductive soil materials or possibly lower iron content. Lower resistivity areas, seen in blue and green, might indicate zones with higher moisture content or higher iron concentrations, as iron typically reduces resistivity due to its conductive properties.

3.1.2 Calculated Apparent Resistivity

The calculated model shown in Figure 3, depicts the resistivity distribution after data processing and inversion. The resistivity model that fits the measured data was generated. The resistivity distribution remains similar to the measured section but the anomalies are more refined. The high-resistivity anomaly is still present on the right side, while the lower resistivity zones are more clearly delineated. The processing seems to have slightly smoothed out the variations, further making clearer interpretation of the underlying subsurface structures and materials.

3.1.3 Inverse Model Resistivity Section

The true resistivity model section shown in Figure 4.1, represents the final model resistivity after inversion, indicating the subsurface resistivity distribution within a long range of resistivity values from 17.5 to 1345 Ω.m. The low-resistivity zones which ranged from 17.5 and 113 **Ω**., corresponds to Aquifer 1 (otherwise known as borehole with high-iron content) in this study. This zone is indicated by blue and green on colour scale bar below the ERT model, correspond to regions are indicative of conductive materials, likely due to the presence of iron-rich minerals or iron-contaminated groundwater. Iron-bearing minerals, such as hematite or magnetite, significantly lower the resistivity, particularly in water-saturated zones where iron dissolves into the groundwater. The identified resistivity range (17.5 to 113 Ω.m) in the study aligns with the typical low resistivity values for iron-rich clays, shales, and water-bearing formations (Fig. 4). The water in this borehole might have a high dissolved iron content, potentially leading to iron-rich deposits or staining in the surrounding sediments. This can affect the utility of borehole for drinking water purposes, as high iron content can cause staining and poor water quality (Saana et al, 2016).

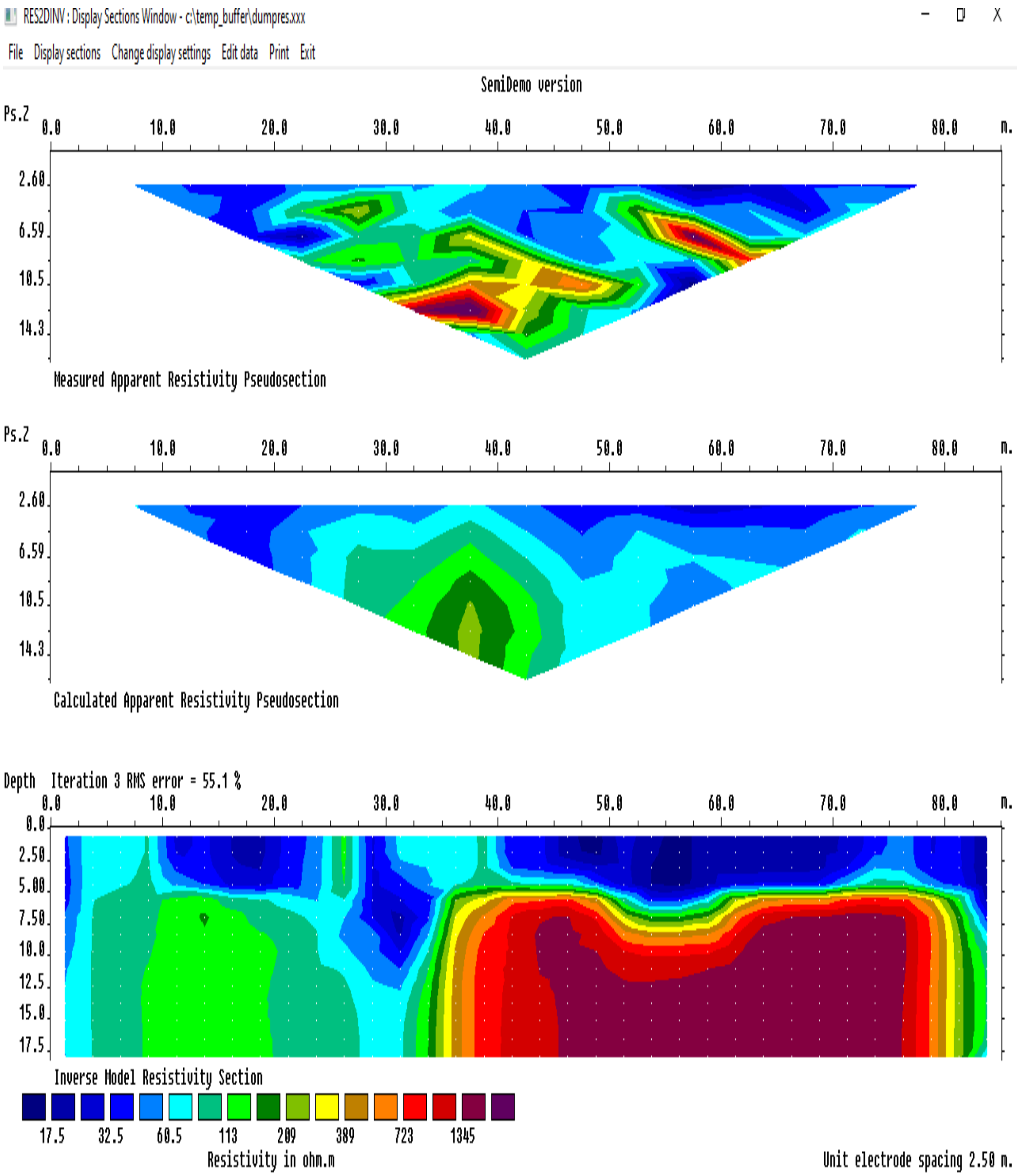

Fig. 3: Resistivity Tomography Models of Wenner-Schlumberger array from a geophysical survey of existing boreholes at Ekeki, Bayelsa

Our finding is comparable to the findings of Amadi et al, (2012) who studied resistivity values for aquifers ranging from 20 to 100 Ω.m, and obtained lower values linked to higher salinity and potential iron content, suggesting similar geological and hydrogeological conditions in the Niger Delta. Omosuyi, G.O. et al. (2008) studying groundwater potential via geoelectrical sounding techniques in Akure, Nigeria, obtained similar report as identified aquifer with potential contamination, including iron, showing resistivity values between 10 and 150 Ω.m, corroborating our findings in this report for the aquifer with higher conductivity. Report by Ezersky et al, (2010) investing iron-rich sediments in the Coastal Plain of Israel, identified iron-bearing formations with low resistivity values ranging from 15 to 100 Ω.m, attributing to the presence of iron oxides and hydroxides in the sediments. Other studies in Niger Delta [Edet et al. (2003); Onwuka et al, (2014); Amadi et al, (2012); Ehirim et al, (2009); Oseji et al, (2006); Ofomola et al, (2012); Etu-Efeotor (1983)], in Malayia [Sundararajan et al, (2003) and Iran [Khazai et al (2013)], in using resistivity surveys to map groundwater quality further corroborate our report of low resistivity ranges with high Fe contents. Similarly, with respect to depth (0 – 5.0m), borehole 1 (Fig. 3) depicts formation with low resistivity, clay-rich layer and high Fe content. At the depth of 5.0 – 17.5 meters, it further indicates higher resistivity, sandy clay and moderate Fe level.

On the other hand, the second borehole (Aquifer 2: otherwise known as low or no iron borehole) exhibits higher resistivity values, ranging from 209 t0 1345 Ω.m which suggests a lack of conductive minerals like iron. The high-resistivity area observed in the earlier sections corresponds to the zone in red and purple near the right side of the section, especially at depths below 10 meters (Fig. 3). These resistivity values are more typical of clean sands, gravels, or consolidated layer, with little to no iron contamination (Fig. 4). The absence of iron could be due to the lack of iron-bearing minerals or well-oxidized conditions that prevent iron from remaining in a dissolved state. This borehole is likely to yield better-quality water with low iron content, suitable for drinking and other uses. Studies conducted at Ibeno, Akwa Ibom State (Akpan et al, 2012) reflected resistivity value above 120 Ω.m with clean fresh water in sandy aquifers, with minimal iron content. Similar findings by Amadi et al, (2011) indicated aquifer with high resistivity values (above 150 Ω.m) were linked to clean aquifers, primarily composed of coarse sands and gravels, with negligible iron content. Also corroborating our claims of the report of high resistivity aquifer with minimal Fe potential are globally reported [Obasi et al, (2015); Lue et al (2004); Khalil et al, (2013); Zohdy et al, (1993)]. In affirmation, with respect to depth of the aquifer (0 – 5.0m), borehole 2 (Fig. 3) is encapsulated in a moderate resistivity region, sandy layer with no Fe content. There is very high resistivity, coarse sands/gravel, bedrock with no Fe content, as we progress along the depth (5 - 17.5 m) of the aquifer.

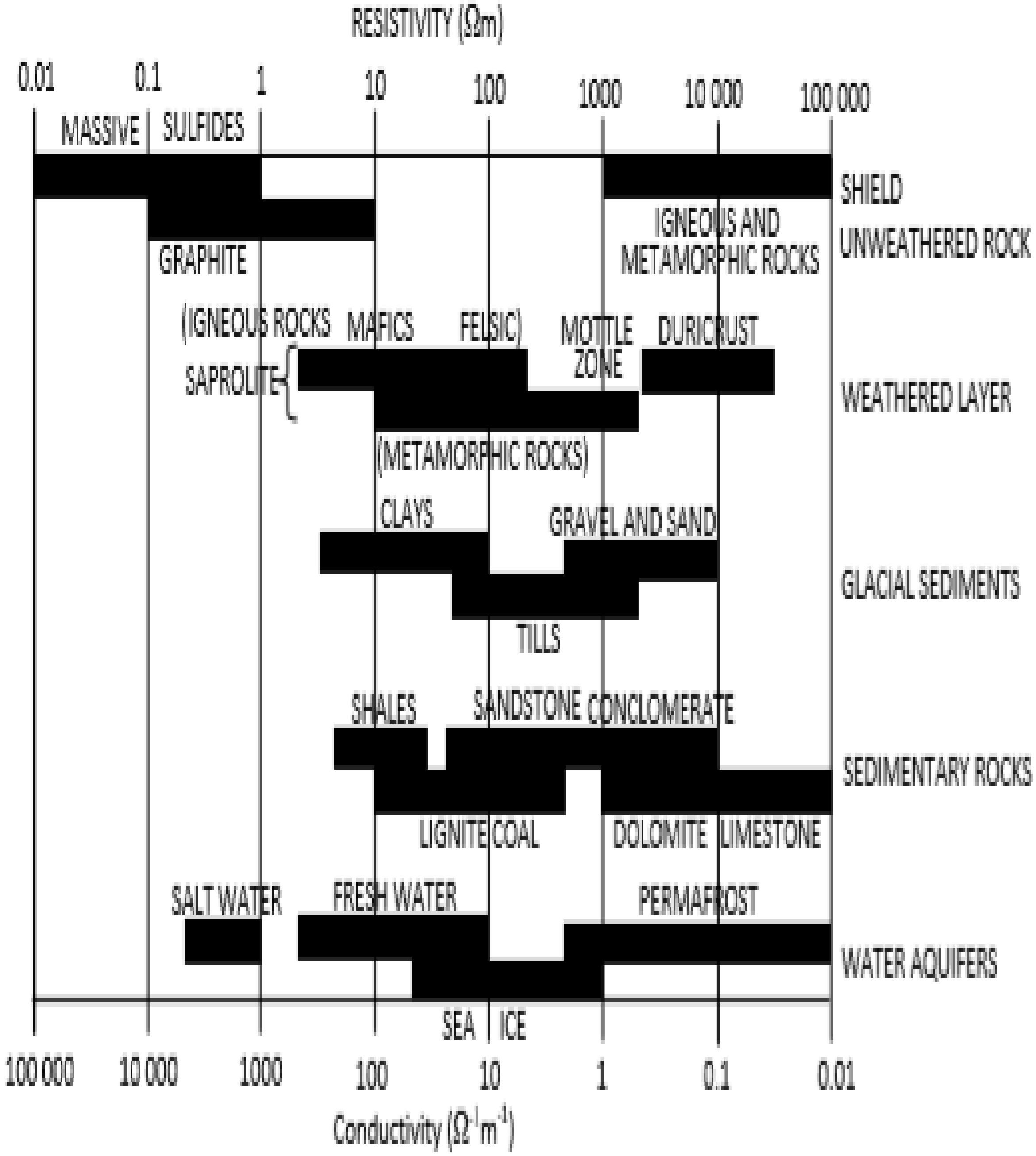

Fig. 4: Standard resistivity values of most subsurface materials

3.2 Iron Level in the Boreholes

The result of iron (Fe) concentration in the groundwater obtained from the two aquifers under study, denoted by AQ 1 (Aquifer 1) and AQ 2 (Aquifer 2), separated 30m apart and AQ (Control), a control sample taken randomly from Otuoke, a surburb area from the study site, is presented in Table 1. Result showed that AQ 1 has an Fe concentration of 4.0 mg/L, which is substantially higher than the WHO acceptable limit of 0.3 mg/L for drinking water (WHO, 2017). AQ 2 shows an Fe concentration of less than 0.001 mg/L, which is well below the WHO acceptable limit of 0.3 mg/L for drinking water. AQ Control has an Fe concentration of 1.0 mg/L, which is more than three times the WHO limit. Considering the aquifer with low resistivity and high conducting potential (AQ 1), the laboratory analysis of Fe content revealed expected high conducting Fe level, which is is alarmingly high. Iron concentrations at this level are not uncommon in the Niger Delta, particularly in areas with specific geological formations such as our finding. Most studies in Yenagoa, Bayelsa State, have reported Fe concentrations exceeding 0.3 mg/L, with some locations showing values similar to or even higher than 4.0 mg/L (Ehirim and Ebeniro, 2010; Okiongbo & Douglas, 2013); Nwankwoala & Udom, 2011). Such elevated levels are often associated with the iron-rich sediments in the region, particularly within the Benin Formation, which comprises unconsolidated sands with significant iron content. High Fe levels can cause staining of plumbing fixtures, a metallic taste in water, and potential health impacts if consumed over prolonged periods. AQ 2, on the other hand, has a very low Fe concentration from the laboratory result, indicating that it is sourced from an aquifer with minimal iron content. Of course, from our finding from ERI, the aquifer is made of high resistivity with low or no Fe contents. The lab results further validate our claims that the aquifer is composed of different geological setting (sandy clay) enhancing a more effective natural filtration for the groundwater. The low Fe concentration is ideal for drinking water and aligns with WHO guidelines, ensuring no adverse effects associated with iron consumption. The Fe concentration in the control sample is moderately high but not as extreme as AQ 1. However, it still exceeds the WHO acceptable limit of 0.3 mg/L (WHO, 2017), which could indicate moderate iron enrichment. Similar concentrations have been reported in other studies across the Niger Delta, where Fe levels in some regions exceed 1.0 mg/L (Nkereuwem et al, 2014). This could be due to varying lithological compositions, water table depths, or anthropogenic influences such as the interaction of groundwater with iron-rich materials.

Table 1: Iron concentrations in high resistivity, low resistivity and control boreholes

S/N	**Sample ID**	**Fe Level (mg/L)**	**WHO limit (mg/L)**
1	AQ 1	4.0	0.3
2	AQ 2	<0.001	0.3
3	AQ Control	1.0	0.3

Conclusions and Recommendations

Conclusions

The following conclusions have been drawn from this study:

1. The Wenner-Schlumberger Resistivity Tomography Models comprising of the low resistivity zones coloured blue and green in the study area, are indicative of iron-rich zones, responsible for the high iron content in most part oof the state.
2. The high-resistivity area observed in the earlier sections corresponding to the zone with red and purple colour (depths <10m), are typical of clean sands, gravels, or consolidated layer, with little to no iron contamination
3. Borehole 1 encounters more clay-rich and fine-grained sediments in the 0 to 17.5 meters depth, which contributes to high Fe content due to the interaction of groundwater with iron-bearing minerals in these formations.
4. Borehole 2, on the other hand, predominantly taps into clean sands and gravels across the entire 0 to 17.5 meters depth, which results in no Fe content due to the lack of iron-bearing clays or fine sediments.
5. Laboratory analysis of Fe level in groundwater samples from low and high resistivity aquifers (AQ1 and AQ 2) gave values of Fe alarmingly high (4.0 mg/L) and below instrument detection, respectively, and AQ 1 was well above WHO acceptable limit of 0.3 mg/L for drinking water.

Recommendations

1. We recommend that prior to groundwater drilling, geophysical investigation should be carried out via wenner – schlumberger array in order to identify clearly zones that have low and high resistivities. This would guide decision making towards hitting aquifer with clean, safe and Fe – free water at a reduced cost.
2. We also recommend that experts who understand ERI concepts be consulted each time groundwater extraction is to be carried out rather than patronize quacks.
3. Data obtained from this study should serve as indices for informed polcy formulation by the regulatory agencies.

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