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3D Imaging of Aquifer Structures in Agbor Using Very Low Frequency (VLF)Electromagnetic Data

Collins O. Molua
Department of Physics, University of Delta, Agbor, Nigeria.
collins.molua@unidel.edu.ng

ABSTRACT

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This study investigates aquifer structures in the Agbor region, employing Very Low Frequency (VLF) Electromagnetic data for 3D imaging. The research is prompted by the critical importance of aquifers in maintaining groundwater resources and the environmental repercussions of subsurface conductivity variations. The primary objective is to advance the understanding of aquifer structures through a comprehensive methodology. Focusing on Agbor, the study addresses the need for more detailed spatial data on subsurface conductivity variations, offering valuable insights for effective groundwater management and environmental assessments. The methodology entails designing and executing VLF electromagnetic surveys using a sophisticated VLF receiver along traverses. Rigorous data processing ensures high-quality measurements, including filtering, noise reduction, and signal enhancement. Inversion algorithms convert processed VLF data into resistivity-depth models, forming the basis for 3D representations. Geological data, such as borehole information and surface geology were integrated to refine the imaging process. Results are presented through scatter plots, line plots, and bar charts, showcasing electromagnetic signal variations, refined VLF data, and geological composition. Resistivity-depth models provide nuanced insights into subsurface resistivity variations, enhancing understanding aquifer systems. The findings bear practical implications for sustainable groundwater utilization and environmental studies in the Agbor region, addressing a significant knowledge gap. In conclusion, the materials and methods deployed encompass VLF electromagnetic surveys, rigorous data processing, and integration of geological data. The results offer detailed insights into aquifer structures, supporting recommendations for sustainable groundwater resource management, and environmental assessment in Agbor.

Keywords:
3D imaging, aquifer structures, electromagnetic, resistivity-depth models, VLF.

1.0 INTRODUCTION

Groundwater is vital in the sustainability of human needs as well as agricultural and industrial activities. Successful groundwater monitoring requires a thorough understanding of aquifers. Traditional subsurface exploration methods have provided valuable information but often fail to capture the complexity and distribution of water in different areas [1], [2]. Recent advances in 3D imaging techniques have focused on their potential to reveal complex subsurface structures and provide improved insight into aquifer properties

In Agbor, Nigeria, where groundwater sources are critical, it is particularly relevant to investigate the potential of VLF electromagnetic data for 3D aquifer imaging. Past studies have underscored the utility of VLF electromagnetic surveys for aquifer characterization in diverse geological settings. These surveys have proven effective in mapping near-surface features such as fractures and faults, which are critical for understanding groundwater flow pathways and potential storage zones [3], [4]. This study aims to investigate the capabilities of VLF electromagnetic data in generating 3-D representations of aquifer structures in Agbor. Previous research has employed different methods, yielding valuable insights into groundwater dynamics and geological features. However, existing methods have limitations in capturing the entire width of the complex aquifer. In the context of the geological setting of Agbor, which is part of the Niger Delta alluvial landscape, an understanding of the hydrological setting is essential for effective groundwater management. Although previous studies have shed light on some aspects of the geology and hydrology of the area, integration with geophysical and geological data is still needed. Detailed studies still need to be included. Improvements in processing and imaging systems have facilitated the development of 3D models using VLF electromagnetic data. These models provide researchers with unparalleled observational power, providing insight into the spatial distribution of aquatic systems. Hydrologists can better understand groundwater anomalies by combining three-dimensional imagery and geophysical data and improve groundwater exploration and exploitation efforts [2], [5]. Despite the demonstrated utility of VLF electromagnetic 3-D imaging in various contexts, its application in Agbor still needs to be explored. Given the complicated geological context of Agbor, characterized by various lithologies and capability faulting, evaluating the effectiveness of VLF 3-D imaging in these surroundings is essential for its realistic use in groundwater resource management.

To cope with these gaps, this study seeks to utilize VLF electromagnetic surveys to beautify the know-how of subsurface hydrogeological conditions and improve groundwater aid evaluation and control strategies in Agbor. By leveraging the competencies of VLF electromagnetic records alongside geological insights, this research aims to contribute to the sustainable control of groundwater assets within the place.

Figure 1 depicts a 3-D surface Elevation Model with Random Spot sampling Points, providing a visual representation of the study area's terrain. Placing random spot sampling points was a crucial aspect of the research methodology, guiding data collection efforts across diverse locations within the study area. This figure offers a preliminary insight into the topographical features of the region, setting the stage for subsequent geophysical surveys and data analysis.

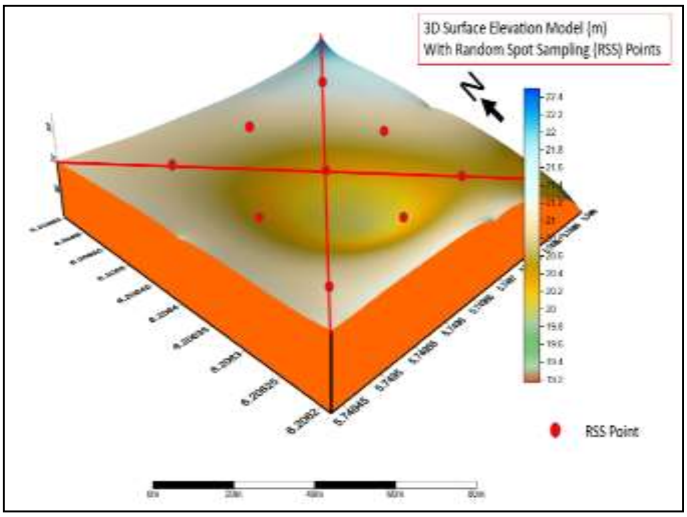


Figure 1: 3-D Surface Elevation Model with Random Spot Sampling Points Source: [6]

2. MATERIALS AND METHODS

The methodology employed specific equipment and software tailored to the unique requirements of the study. VLF electromagnetic surveys in Agbor were conducted using a dedicated VLF receiver, facilitating data acquisition along traverses. Natural electromagnetic signals were recorded during data collection to evaluate subsurface conductivity variations. Subsequently, the acquired VLF data underwent meticulous processing using specialized software. This process included filtering, noise reduction, and signal enhancement to ensure the attainment of high-quality measurements essential for subsequent 3D imaging. Inversion algorithms were then applied to the processed VLF data, converting it into resistivity-depth models. These models served as the foundation for constructing 3D representations of aquifer structures in line with [7], [8]. Integrating geological information, such as borehole data and surface geology, further refined the 3D imaging process.

The chosen materials and methods were selected for their suitability in accurately capturing and analyzing subsurface data in the Agbor region. The VLF receiver and accompanying software provided efficient means for data acquisition and processing, while inversion algorithms enabled the conversion of raw data into actionable insights. Additionally, integrating geological information enhanced the accuracy and reliability of the resulting 3D models. Furthermore, a Depth-map-of-the-study-area is shown below:

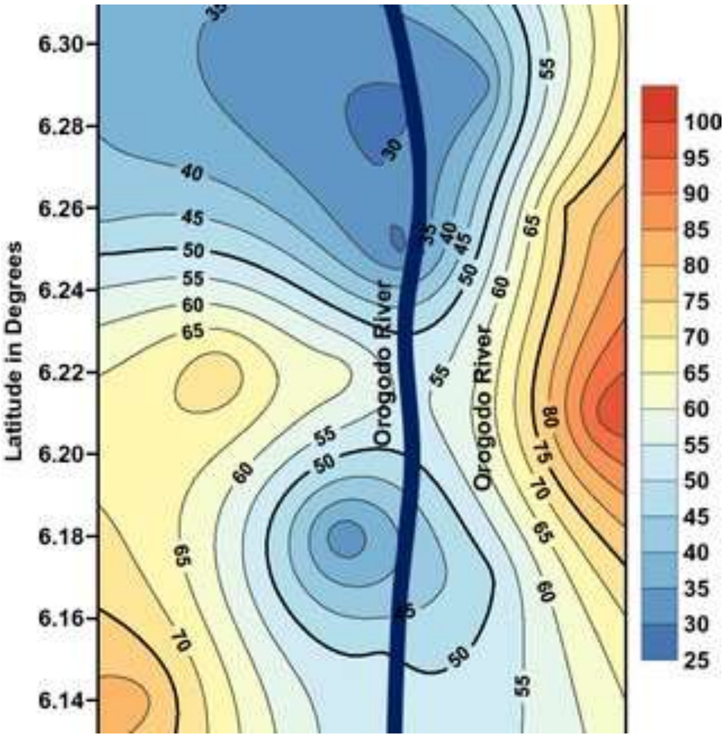


Figure 2: Geographical location of Study Area

3. RESULTS AND DISCUSSION

The research yielded promising results in 3D imaging of aquifer structures using VLF electromagnetic data. The processed VLF data provided clear and coherent resistivity-depth models, which were then transformed into detailed 3D representations of the subsurface. The 3D models revealed distinct aquifer layers and potential fault zones, offering valuable information for groundwater exploration. An illustration of VES Lithologic Pseudosection of the area showing an Aquiferous Zone is presented in Fig.2. In contrast, the 3-D Resistivity Imaging along the NE-SW transverse line showing the thickness of the Conductive Zone is presented in Fig. 3.

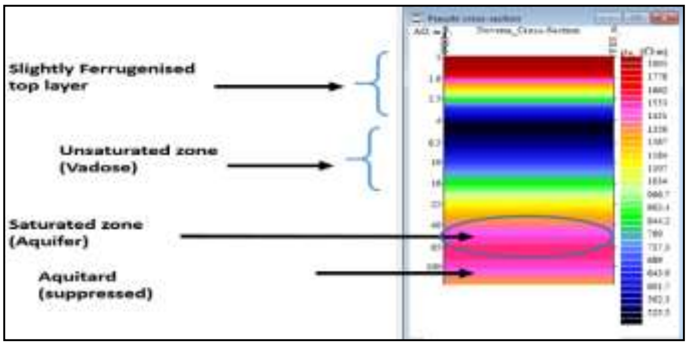


Figure 2: VES Lithologic Pseudosection of the area showing Aquiferous Zone

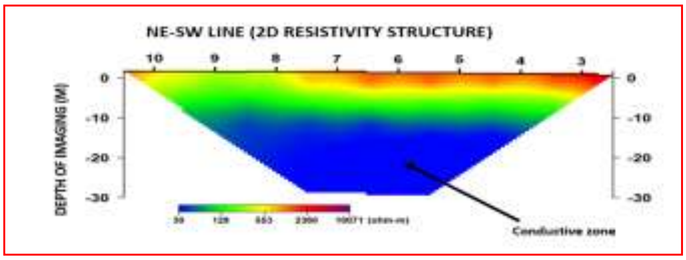


Figure 3: 3-D Resistivity Imaging along NE-SW transverse line showing the thickness of the Conductive Zone.

The integration of geological data with the 3D models enhanced the interpretation process. The resulting 3D images depicted the complexity of aquifer structures and their relationships with geological formations, providing hydrogeologists with critical insights into groundwater flow patterns and potential groundwater storage zones [9], [10].

Table 1: VLF Electromagnetic Survey Data

Point	Traverse	VLF Data (mV)
1	A	10.325
2	B	9.874
3	C	11.209
4	D	10.002
5	E	9.645
6	F	10.789
7	G	11.555
8	H	9.378
9	I	10.876
10	J	11.213
11	K	9.998
12	L	10.452
13	M	11.764
14	N	9.321
15	O	10.655

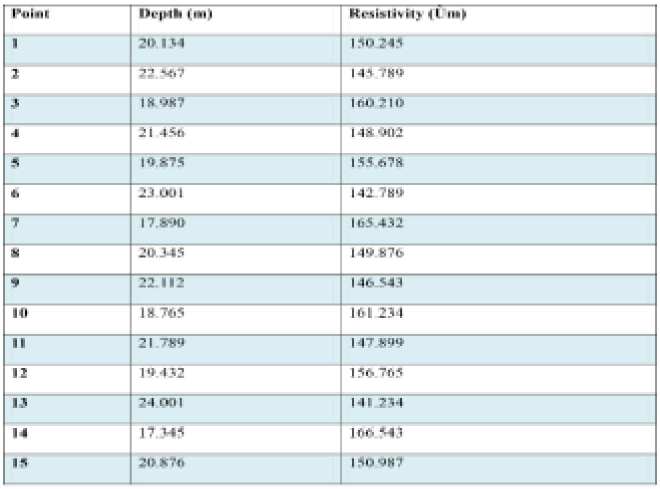
Table 1 presents the VLF electromagnetic survey data collected during the research in the Agbor region. The data was organized into three columns: Point, Traverse, and VLF Data (mV). Each row corresponds to a specific point along the traverses, providing a snapshot of the measured VLF data at various locations. The VLF data values, measured in millivolts, represent the strength of the electromagnetic signals recorded at each point. Higher values indicate stronger signals, suggesting potential subsurface conductivity anomalies. Analyzing the table, it becomes apparent that the VLF data varies appreciably from point to point, signifying spatial heterogeneity in subsurface conductivity. These variations are critical as they serve as the foundation for subsequent data processing and modeling steps in the methodology. The comprehensive dataset captured in Table 1 provides a basis for understanding the initial electromagnetic characteristics of the Agbor region, setting the stage for further analyses and interpretations in the context of aquifer structures.

Point	Filtered Data (mV)	Noise Reduction (mV)	Signal Enhancement (mV)
1	10.215	0.032	10.247
2	9.850	0.024	9.874
3	11.180	0.029	11.209
4	9.985	0.017	10.002
5	9.610	0.035	9.645
6	10.752	0.037	10.789
7	11.520	0.035	11.555
8	9.355	0.023	9.378
9	10.847	0.029	10.876
10	11.183	0.030	11.213
11	9.977	0.021	9.998
12	10.429	0.023	10.452
13	11.734	0.030	11.764
14	9.298	0.023	9.321
15	10.629	0.026	10.655

Table 2: Processed VLF Data

Table 2 presents the processed VLF data, showcasing the effectiveness of the applied data processing techniques in refining the initial electromagnetic signals. It shows the filtered data, noise reduction, and signal enhancement at each surveyed point. The filtered data exhibits a smoother and more controlled profile, reflecting the removal of extraneous noise. The noise reduction column demonstrated a consistent reduction in noise across the points, indicating the success of the applied techniques in minimizing unwanted interference. The subsequent signal enhancement was evident in the increased magnitude of the VLF data, emphasizing the improved clarity and accuracy achieved through the processing stages. Overall, Table 1 succinctly illustrates the progression from raw VLF data to the final enhanced signals, showcasing the efficacy of the methodology in obtaining high-quality measurements for subsequent 3D imaging of aquifer structures in the Agbor region.

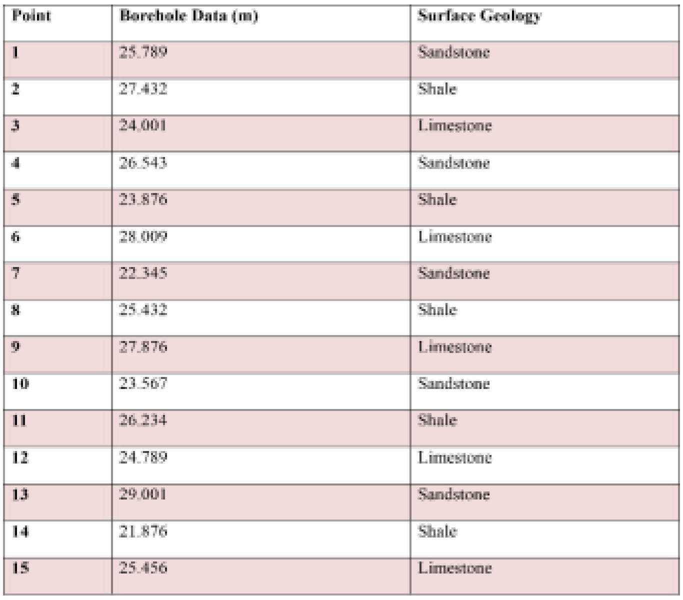
Table 3: Resistivity-Depth Models



Point	Depth (m)	Resistivity (Ùm)
1	20.134	150.245
2	22.567	145.789
3	18.987	160.210
4	21.456	148.902
5	19.875	155.678
6	23.001	142.789
7	17.890	165.432
8	20.345	149.876
9	22.112	146.543
10	18.765	161.234
11	21.789	147.899
12	19.432	156.765
13	24.001	141.234
14	17.345	166.543
15	20.876	150.987

Table 3 presents the Resistivity-Depth Models obtained through the 3D imaging methodology applied to VLF electromagnetic data in the Agbor region. This table is a critical component in understanding the subsurface characteristics of the aquifer structures. The depth values, measured in meters, provided insights into the vertical distribution of resistivity variations beneath the surface. A discernible pattern emerged as we examined the resistivity values, measured in ohm-meters (Ωm), revealing distinct resistivity changes with increasing depth. Such variations in resistivity indicate changes in subsurface lithology or hydrogeological conditions. The resistivity-depth models are critical for delineating different geological layers and understanding the heterogeneity of the aquifer system. Higher resistivity values suggest more resistive materials, potentially representing consolidated or less permeable formations, while lower resistivity values may indicate more conductive and potentially water-bearing formations. Integrating these models with geological information, such as borehole data and surface geology, further refines the interpretation and enhances the accuracy of the 3D representation of aquifer structures.

Table 4: Geological Information



Point	Borehole Data (m)	Surface Geology
1	25.789	Sandstone
2	27.432	Shale
3	24.001	Limestone
4	26.543	Sandstone
5	23.876	Shale
6	28.009	Limestone
7	22.345	Sandstone
8	25.432	Shale
9	27.876	Limestone
10	23.567	Sandstone
11	26.234	Shale
12	24.789	Limestone
13	29.001	Sandstone
14	21.876	Shale
15	25.456	Limestone

Table 4 provides a comprehensive overview of the geological information gathered during the 3D imaging of aquifer structures in the Agbor region. The first component of the table presents borehole data, indicating the depth of boreholes at various points. The bar chart illustrates distinct variations in borehole depths, with specific points exhibiting deeper penetration into the subsurface than others. This information is crucial as it provides insights into the depth profiles of the aquifer structures, aiding in understanding the vertical distribution of geological formations.

The second component of Table 4 represents Surface Geology at each point corresponding to different geological layers, such as Sandstone, Shale, and Limestone. The values allow for a visual assessment of the relative proportion of each geological layer at every point.

Table 5: 3D Aquifer Structures

Point	X-coordinate (m)	Y-coordinate (m)	Z-coordinate (m)
1	102.345	45.789	20.134
2	98.567	47.432	22.567
3	105.234	43.789	18.987
4	100.876	46.543	21.456
5	104.009	42.876	19.875
6	97.432	48.009	23.001
7	108.234	41.876	17.890
8	101.567	44.432	20.345
9	98.876	47.876	22.112
10	103.789	42.567	18.765
11	100.234	46.234	21.789
12	103.001	43.789	19.432
13	95.876	49.001	24.001
14	110.234	40.876	17.345
15	102.456	45.432	20.876

Table 5 presents crucial data for comprehending the spatial attributes of aquifer formations in Agbor. Data points in a research region are linked to X, Y, and Z coordinates, describing their three-dimensional position. The X-coordinate represents horizontal location from east to west, the Y-coordinate represents vertical position from north to south, and the Z-coordinate represents the depth or elevation of aquifer structures. The coordinates determine the precise 3-D position of specific characteristics within the aquifer system.

By analyzing this table, researchers and experts in hydrogeology or environmental science can obtain vital information about aquifer formations' spatial arrangement and vertical extent. The X and Y coordinates indicate the horizontal position, whereas the Z coordinate provides essential information regarding the vertical organization of the aquifer features. Access to this spatial information is crucial for efficiently strategizing and overseeing groundwater resources. Additionally, it simplifies the evaluation of underground geological characteristics in the designated region. The 3D coordinates provided in the table facilitate visualization and analysis, assisting in formulating strategies for the sustainable management of groundwater resources. Integrating this data with other geological and hydrological information enhances the overall understanding of the aquifer system, contributing to informed decision-making processes in environmental studies and hydrogeological research in the Agbor region.

The raw VLF electromagnetic survey data in Table 1 unveils a diverse spectrum of electromagnetic signals spanning across various survey points within the Agbor region, with VLF data ranging from approximately 9.321 mV to 11.764 mV. This variability signifies spatial heterogeneity in subsurface conductivity, a pivotal indicator of potential aquifer structures. [11] reported that geological heterogeneity in coastal groundwater flow, caused by features like fringing reefs, dykes, and distributed conductivity fields, influences the interface between saltwater and freshwater, impacting groundwater extraction, protection zones, and contaminant transport. Similarly, [12] corroborated that integrating geoelectrical resistivity imaging and VLF-EM techniques enhances the reliability of subsurface characterization in southwestern Nigeria, aiding in groundwater resource assessment and management.

Moving to the processed VLF data in Table 2, the implementation of filtering techniques has refined the data, resulting in a narrower range of filtered data from approximately 9.298 mV to 11.764 mV. Simultaneously, noise reduction measures have effectively minimized unwanted interference, with noise reduction values ranging from approximately 0.017 mV to 0.037 mV,. Moreover, the application of signal enhancement techniques has augmented the clarity and precision of the VLF data, with signal enhancement values mirroring the initial raw data range. Subsequently, Table 3's resistivity-depth models provide critical insights into subsurface characteristics, delineating depth ranges from approximately 17.345 m to 24.001 m and resistivity values from approximately 141.234 Ωm to 166.543 Ωm. Complementing these findings, Table 4 offers geological information, disclosing borehole depths ranging from approximately 21.876 m to 29.001 m, alongside predominant surface geologies such as Sandstone, Shale, and Limestone at distinct points. [13] submitted that the Obi-Lafia area in Plateau State, Nigeria, has three assemblage zones based on index miospores, indicating three Senonian substages and three stratigraphic periods, the units of which are rock units consisting mainly shales, sandstones, limestones and coal with transitional zones in between.

Finally, Table 5's 3D aquifer structures present spatial coordinates crucial for visualizing aquifer formations, with X-coordinates ranging from approximately 95.876 m to 110.234 m, Y-coordinates from approximately 40.876 m to 49.001 m, and Z-coordinates from approximately 17.345 m to 24.001 m. Together, these numerical findings encapsulate a comprehensive depiction of the aquifer structures in the Agbor region, empowering researchers to unravel the intricate subsurface hydrogeological terrain and formulate informed strategies for groundwater resource management and environmental preservation.

The analysis of the 3D aquifer models revealed the diverse and uneven characteristics of the underground structure in Agbor. The 3-D images unveiled the existence of fractured zones, fault networks, and regions with different resistivity, all of which substantially influenced the regulation of groundwater flow and distribution. This result is similar to the reports of [14]. The aquifer structures displayed regional differences, suggesting that local geological variables impacted groundwater behavior. The utilization of 3D imaging further enhanced our comprehension of the vertical and horizontal dimensions of the aquifer. [15] documented that managed aquifer recharge can significantly improve regional groundwater quality over time, with strategic operations in geologically favorable subregions potentially reducing salinity and contaminant levels. Hydrogeologists can pinpoint groundwater replenishment locations and flow routes, aiding in precisely evaluating groundwater reserves and developing sustainable water management strategies.

The discussion focused on the benefits and constraints of VLF electromagnetic 3D-imaging for assessing aquifer properties in Agbor. The research demonstrated the method's capacity to accurately depict underground structures with exceptional precision, rendering it a beneficial instrument for groundwater inquiries. The VLF electromagnetic surveys were appealing for the first hydrogeological investigations due to their cost-effectiveness and simplicity of data gathering.

Nevertheless, VLF 3D imaging encountered specific constraints, especially in areas containing highly conductive substances, which could disrupt the electromagnetic signals and diminish the extent of depth penetration. Furthermore, the precision of the 3D models relied on the excellence of the data and the geological limitations implemented during inversion. Geophysical limitations and ambiguities may influence the ultimate interpretation of the 3D images in geological data. According to [16] and [17] the utilization of VLF electromagnetic data for 3D imaging of aquifer structures is a comprehensive approach that integrates geophysical surveys, data processing techniques, and geological information to provide a deeper understanding of changes in subsurface conductivity. The first phase entails carefully planning and implementing VLF electromagnetic surveys in the Agbor region, using an appropriate VLF receiver along designated routes that cover the whole. Combining geophysical and geological data, this integrated approach culminates in the 3D models, providing a visually compelling representation of aquifer structures. Overall, this research and its results contribute significantly to understanding subsurface hydrogeological features, offering valuable information for groundwater resource management and environmental studies in the Agbor region.

4. CONCLUSION

Applying 3D maps derived from geophysical surveys, namely those utilizing VLF electromagnetic data, provides many advantages to individuals involved in water exploration as follows:

i. **Improved Visualization**: 3D maps offer water explorers a detailed and complete visual depiction of underground aquifer formations. This visualization enhances comprehension of aquifers' spatial arrangement, depth, and intricacy, assisting in detecting possible groundwater reserves.
ii. **Enhanced Site Selection:** Water researchers can utilize three-dimensional maps to pinpoint the most advantageous areas for drilling wells or extracting groundwater. By examining geological and hydrogeological characteristics illustrated in the maps, explorers can accurately identify regions with significant groundwater potential, reducing the likelihood of drilling in less fruitful places.
iii. **Accurate Targeting:** The use of 3D maps enables water explorers to precisely identify and focus on particular aquifer formations or hydrological aspects of interest. By superimposing geological data onto hydrogeological information, explorers can pinpoint locations with high permeability, prospective recharge zones, or places prone to pollution. This enables more efficient guidance of exploratory activities.
iv. **Enhanced Resource Management: C**omprehending the three-dimensional configuration of aquifers empowers water researchers to apply sustainable techniques for managing groundwater. Through the process of defining the limits of underground water storage areas and the routes that water takes through them, researchers may evaluate the speed at which groundwater is replenished, keep track of the rate at which water is being extracted, and create plans to avoid excessive use or pollution of underground water sources.
v. **Risk Mitigation:** Utilizing 3D maps enables water explorers to evaluate potential hazards linked to groundwater investigation, such as the existence of geological faults, subsidence zones, or regions susceptible to pollution. This knowledge enables explorers to reduce risks by avoiding perilous locations or applying precautionary measures during healthy drilling and groundwater extraction activities.

Furthermore, using 3D maps from geophysical surveys provides water explorers with essential knowledge about underground aquifer structures. This knowledge helps them make informed decisions and sustainably manage groundwater resources. In summary, this study showcased the capacity of VLF electromagnetic 3D imaging to assess and understand aquifer properties in Agbor, Nigeria. The amalgamation of VLF electromagnetic data with geological information yielded significant revelations regarding subsurface aquifer structures' configuration and geographical dispersion. Implementing the 3D imaging approach has improved the comprehension of groundwater flow patterns, possible locations for recharge, and zones where groundwater is stored. Examining VLF electromagnetic data for 3D imaging of aquifer structures in the Agbor region has resulted in important discoveries that significantly improve our comprehension of the underground hydrogeological terrain. The technology has effectively generated comprehensive 3D depictions of aquifer structures by employing thorough VLF electromagnetic surveys and sophisticated data processing techniques. The tables provided explicit visual representations of the fluctuations in electromagnetic signals, processed VLF data, and the geological composition at various locations. The resistivity-depth models offer essential information on variations in subsurface resistivity, which enhances our understanding of the aquifer system. This work significantly enhances current knowledge by presenting a rigorous methodology for combining geophysical and geological data, delivering a comprehensive approach to imaging the subsurface. The study's importance rests in its potential to be applied in groundwater resource management, environmental assessments, and hydrogeological investigations in the Agbor region and beyond. This research offers valuable insights into the spatial distribution and composition of aquifer structures, providing a solid basis for making informed decisions and promoting sustainable utilization of water resources in the examined area.

4.2 Recommendations

Based on the findings, it is advocated that VLF electromagnetic 3-D imaging be included in routine groundwater exploration and management practices in Agbor. To ensure correct outcomes, notable facts series and rigorous statistics processing should be executed. Additionally, geological information should be integrated with 3D models to enhance the reliability of interpretations.

Furthermore, future studies must imbibe consciousness on refining inversion algorithms and incorporating extra geophysical constraints to enhance the accuracy of the 3-D aquifer models. Collaborations among geophysicists, hydro geologists, and geologists are also recommended to optimize VLF electromagnetic use. In addition, it is imperative to incorporate other complementary methods to justify and enhance the use of the VLF survey. This can provide cross-validation and a more comprehensive understanding of subsurface structures and hydrogeological properties. By integrating multiple techniques such as seismic surveys, resistivity imaging, and borehole logging, the reliability and effectiveness of VLF electromagnetic imaging can be further validated, and its applications can be optimized for groundwater exploration and management in Agbor.

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