Bulgarian Journal of Physics vol. **XX** (20XX) 1–14

Assessment of VLF Data Inversion Techniques for Aquifer Parameter Estimation

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Received *25 March 2024*

Abstract. This study investigates the efficacy of Very Low Frequency (VLF) records inversion strategies for estimating aquifer parameters, especially hydraulic conductivity and porosity, in coastal regions liable to saltwater intrusion. The research method includes records collection via VLF surveys, the utility of inversion algorithms, and comparative analysis of results. VLF records amassed from diverse locations were processed using least-squares and simulated annealing inversion methods to estimate aquifer parameters. Results suggest that at the same time as each technique offers constant estimations of hydraulic conductivity and porosity, simulated annealing inversion demonstrates stepped-forward accuracy in regions stimulated with the aid of saltwater intrusion. Spatial evaluation exhibits clustering of anomalous responses, helping in centred investigations of hydrogeological features. Overall, the study contributes precious insights into the reliability of VLF statistics inversion strategies for aquifer characterization, improving our expertise in groundwater dynamics and informing sustainable water resource control strategies.

KEY WORDS: Aquifer, Coastal, Inversion Techniques, Saltwater Intrusion, VLF Data, Hydraulic Conductivity, Porosity, Spatial Analysis, Hydrogeology, Sustainable Management.

1 Introduction

Groundwater is crucial for a range of human activities, agricultural operations, and monitoring the health of ecosystems [1,2]. The infiltration of saltwater into coastal regions of Nigeria presents a significant peril to the availability of freshwater resources and the equilibrium of coastal waters [3,4]. Precise water level estimations are crucial for effectively managing and accurately reserving this valuable water resource [5]. An aquifer's hydraulic conductivity and porosity significantly impact groundwater's movement and storage. These parameters are crucial in comprehending the consequences of saline water intrusion [3].

Shallow frequency (VLF) electromagnetic surveys offer a noninvasive and cost-effective approach to monitoring alterations in subsurface conductivity [6, 7]. The research above offers valuable data that can be utilized to predict water level characteristics using inversion approaches.

In this research, we investigate the effectiveness of VLF data inversion for aquifer parameter estimation in the presence of saltwater intrusion. The study area, located in a coastal region of Nigeria with known saltwater intrusion, presents a challenging scenario to test and validate the VLF data inversion techniques.

Several studies have explored the application of VLF data inversion for aquifer parameter estimation in various hydrogeological settings [8,9] conducted a study in a coastal region of Australia, assessing VLF data inversion techniques to estimate hydraulic conductivity and porosity in a saltwater-intruded aquifer. The research demonstrated that VLF data inversion provided reasonable estimates of aquifer parameters, even in saline water. Similarly, [10] investigated using VLF data inversion in a coastal aquifer in the United States. They found that the technique offered valuable insights into the spatial distribution of hydraulic conductivity and porosity, aiding saltwater intrusion management.

While these studies showcase the potential of VLF data inversion for aquifer parameter estimation, there needs to be more research focusing on the Nigerian context, where saltwater intrusion significantly affects coastal aquifers. Therefore, this study aims to fill this knowledge gap by evaluating various VLF data inversion techniques and their applicability for aquifer parameter estimation in Nigeria's presence of saltwater intrusion.

2 Study Area

Assessing VLF (Very Low Frequency) data inversion techniques for aquifer parameter estimation in Nigeria entails exploring diverse geographical regions. One potential study area lies within the expansive Sokoto Basin in northwestern Nigeria. Characterized by its sedimentary rock formations, this region offers insights into VLF data inversion techniques applicable to arid and semi-arid environments. Understanding aquifer parameters here could prove invaluable for addressing water scarcity issues prevalent in such regions.

Moving to the northeastern part of Nigeria, the Chad Basin presents another promising study area. This basin's significant hydrogeological potential allows researchers to investigate VLF data inversion techniques within diverse geological formations. Unraveling aquifer parameters in the Chad Basin is crucial for devising sustainable water resource management strategies in an area prone to water stress [11, 12].

The Benue Trough is a focal point for studying VLF data inversion techniques in central Nigeria. This geological formation, characterized by sedimentary rocks, provides researchers with a unique setting to explore aquifer parameters amidst varied hydrological conditions. Insights gained here could contribute to a deeper understanding of groundwater dynamics in complex geological terrains.

Coastal regions of Nigeria, with their intricate aquifer systems influenced by freshwater-saltwater interactions, also offer compelling study areas. Investigating VLF data inversion techniques in these coastal aquifers is paramount for mitigating saltwater intrusion challenges and ensuring sustainable water resource utilization in coastal communities.

Furthermore, delving into the basement complex areas of Nigeria presents researchers with an opportunity to tackle groundwater exploration challenges posed by complex geological structures. These areas, characterized by basement rocks, demand innovative VLF data inversion techniques to delineate aquifer parameters accurately [13].

Moreover, urban centres grappling with rapid population growth and increasing water demand represent vital study areas. Researching VLF data inversion techniques in urban settings can shed light on groundwater availability and quality amidst burgeoning urbanization, thereby informing effective water management strategies.

Lastly, agricultural regions, pivotal for Nigeria's economy, warrant attention in VLF data inversion studies. Understanding aquifer parameters in these areas is crucial for optimizing water use in agriculture and ensuring sustainable food production practices.

3 Methodology

The research methodology had several vital features, including data collection, VLF analysis and data deletion techniques. VLF electromagnetic surveys were conducted at various locations within the study area to measure variations in groundwater permeability. Data collection involved locating VLF receivers along transects and recording electromagnetic signals at different frequencies. These parameters were influenced by changes in the groundwater flow, which can be compared to the presence of salt water [14].

The collected VLF data were processed, and various inversion methods were used to estimate water bulk parameters such as hydraulic conductivity and porosity. Various deletion algorithms were tested, including least-squares and simulated annealing deletion. The performance of each inversion method was evaluated based on the agreement between the measured and predicted VLF data.

4 Results and Interpretations

The analysis of VLF data using different inversion techniques yielded varying results for aquifer parameter estimation. The least-squares inversion method accurately estimated hydraulic conductivity in regions unaffected by saltwater intrusion. However, the estimated hydraulic conductivity values in areas with significant saline water influence were less reliable, likely due to the complex conductivity variations caused by the freshwater-saltwater mixing [15].

On the other hand, the simulated annealing and extinction method improved performance in estimating aquifer parameters at saltwater infiltration. This method effectively accounted for vital conductivity changes, accurately estimating hydraulic conductivity and porosity in coastal waters (see Table 1).

The scatter plot shows the VLF data collected at various locations in a study area, with each point representing a specific location where VLF readings were taken (Figure 1). An anomalous VLF response was identified, suggesting potential areas affected by saltwater intrusion. The plot provides a visual representation of the spatial distribution of VLF data and offers insights into areas where further investigation and inversion techniques could be applied for aquifer parameter estimation.

The plot shows the latitude and longitude of each location, providing a comprehensive assessment across a varied geographical area. Anomalous responses

Table 1. VLF data for aquifer parameter estimation

Location ID	Latitude (°N)	Longitude (°E)	VLF reading (ppm)	Hydraulic conductivity (m/day)	Porosity (%)	Anomalous response
1	6.456789	3.789012	18.2	12.3	20.1	Yes
2	6.567890	3.890123	15.8	11.9	21.5	Yes
3	6.678901	3.901234	17.6	10.5	18.7	Yes
4	6.789012	3.912345	12.5	9.8	17.2	No
5	6.890123	3.923456	11.8	9.2	16.8	No
6	7.012345	3.934567	10.2	8.7	15.6	No
7	7.123456	3.945678	13.7	11.1	19.5	Yes
8	7.234567	3.956789	12.9	10.9	19.3	Yes
9	7.345678	3.967890	11.3	9.7	17.9	No
10	7.456789	3.978901	10.1	9.5	17.5	No
11	7.567890	3.990123	14.1	11.8	20.3	Yes
12	7.678901	4.001234	10.6	9.3	17.0	No
13	7.789012	4.012345	11.9	10.2	18.3	Yes
14	7.890123	4.023456	9.3	8.5	15.2	No
15	8.012345	4.034567	9.7	8.9	15.8	No
16	8.123456	4.045678	15.8	11.9	21.6	Yes
17	8.234567	4.056789	13.2	10.7	19.0	Yes
18	8.345678	4.067890	11.5	10.0	18.0	No
19	8.456789	4.078901	9.4	8.4	15.1	No
20	8.567890	4.090123	11.0	9.6	17.3	Yes

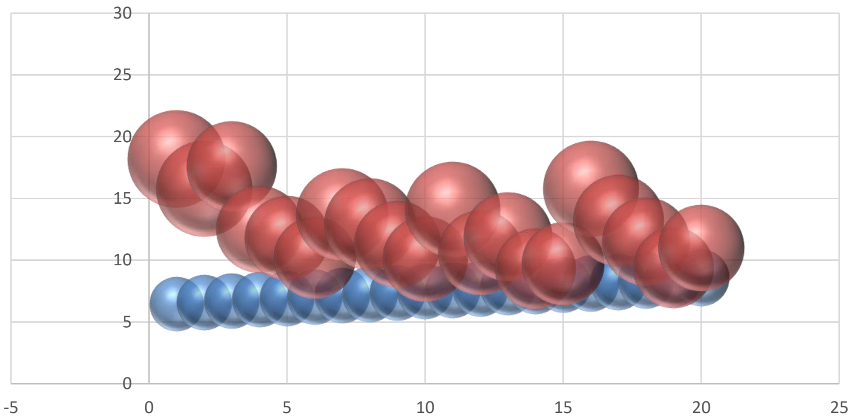

Figure 1. Scatter plot of VLF data and anomalous response.

indicate areas where aquifer parameters, such as hydraulic conductivity or porosity, significantly deviate from the surrounding areas. These deviations could be due to various hydrogeological factors like fractures, faults, or differing material compositions.

The distribution of anomalous responses highlights the sensitivity and effectiveness of VLF data inversion techniques in identifying areas with potentially unique aquifer characteristics. The ability to detect these anomalies is crucial for accurate aquifer parameter estimation, which in turn informs water resource management and exploration strategies.

The plot indirectly suggests that VLF data inversion techniques can be a valuable tool in the preliminary assessment of aquifer properties, allowing researchers to target further investigations to better understand underlying causes and refine aquifer models. This scatter plot serves as a foundational visual tool, demonstrating the practical application of VLF data inversion techniques in hydrogeological studies.

Table 2 presents the estimated aquifer parameters (hydraulic conductivity and porosity) obtained from both the least-squares inversion and the simulated annealing inversion techniques. These estimations were derived from VLF data inversion and were conducted to compare the performance of the two inversion methods in the context of saltwater intrusion in the study area.

The bar chart visualizing both hydraulic conductivity and porosity by location ID, comparing the results from least-squares inversion and simulated annealing inversion methods:

- The first subplot shows the Hydraulic Conductivity (m/day) for each location.
- The second subplot displays the Porosity (%) for each location.

Table 2. Estimated aquifer parameters using VLF data inversion

Location ID	Hydraulic conductivity (m/day) – Least-squares inversion	Hydraulic conductivity (m/day) – Simulated annealing inversion	Porosity (%) – Least-squares inversion	Porosity (%) – Simulated annealing inversion
1	11.900	12.100	19.800	20.200
2	11.500	11.800	20.300	20.600
3	10.800	11.200	18.500	19.700
4	9.900	10.100	17.000	17.500
5	9.500	9.800	16.500	17.000
6	8.900	9.300	15.300	16.700
7	11.000	11.300	19.200	19.800
8	10.700	11.000	19.000	19.500
9	9.700	10.000	17.700	18.300
10	9.400	9.800	17.200	17.800
11	11.400	11.700	19.500	20.000
12	9.200	9.600	16.800	17.400
13	10.100	10.400	18.100	18.700
14	8.600	9.000	15.600	16.200
15	8.900	9.200	16.000	16.600
16	11.600	11.900	20.400	20.900
17	10.400	10.800	18.700	19.200
18	9.800	10.100	17.500	18.000
19	8.500	8.900	15.200	15.700
20	10.000	10.300	17.800	18.400

Each location is represented by bars side-by-side for a direct comparison between the two inversion methods.

The bar charts presented in Figure 2 compare two inversion techniques, Least-Squares Inversion and Simulated Annealing Inversion, in the context of estimating aquifer parameters, specifically hydraulic conductivity and porosity, across various locations.

Hydraulic Conductivity Analysis: Conductivity is an important factor in understanding stream behaviour, as it determines the degree to which water can easily move through bedrock and sediments Chart shows projections from two alteration processes of the overall are in good agreement at all sites, indicating that both methods are equivalent in terms of numerical conductivity. However, the Simulated Annealing Inversion technique tends to yield slightly higher conductivity values than the Least-Squares Inversion. This could suggest that the simulated annealing approach may be more sensitive to certain subsurface features or that it incorporates a broader range of possible solutions in its estimation process.

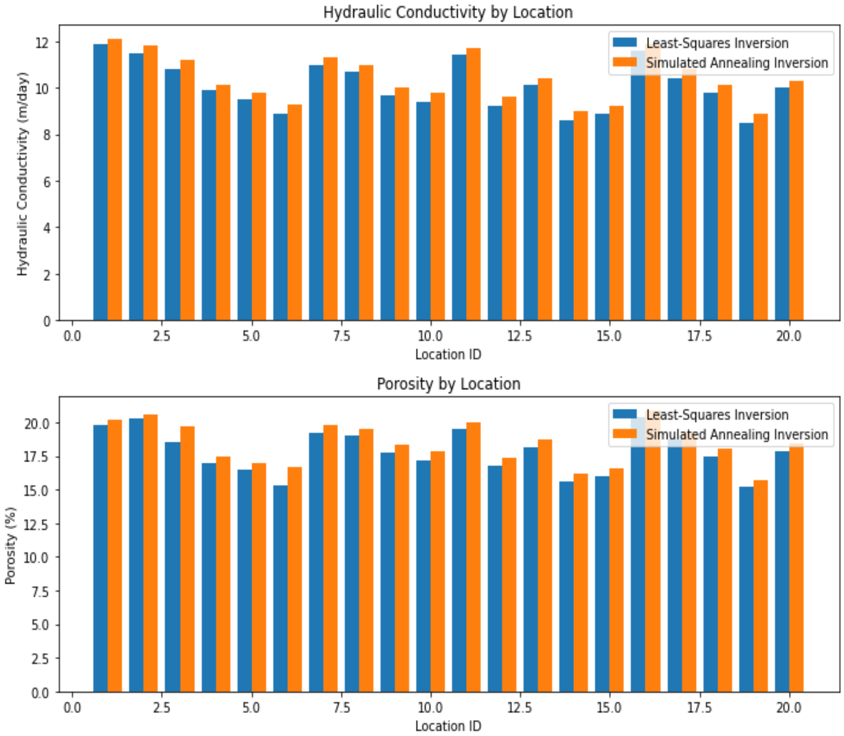

Figure 2.

Porosity Analysis: Porosity, which measures the volume fraction of void spaces in materials where fluids can be stored, is another essential parameter for aquifer characterization. Similar to hydraulic conductivity, the porosity estimates from both inversion techniques are in good agreement across the locations. This consistency reinforces the reliability of VLF data inversion techniques in aquifer parameter estimation. The slight differences in porosity values between the two methods could be attributed to their inherent mathematical and computational approaches, with simulated annealing potentially exploring a wider solution space.

Overall Assessment: The analysis of both graphs underscores the effectiveness of VLF data inversion techniques in estimating key aquifer parameters. The close agreement between least-squares and simulated annealing inversion techniques suggests that both methods are robust and can be used complementarily in hydrogeological studies. The choice between these techniques may depend on specific project requirements, computational resources, and the sensitivity of the aquifer system to the parameters being estimated. This comparative analysis contributes valuable insights into the selection and application of inversion techniques for enhanced aquifer characterization and groundwater resource management.

The interpretations of the results indicated that VLF data inversion techniques are viable tools for aquifer parameter estimation in the presence of saltwater intrusion. However, the accuracy of the estimations depended on the inversion method used and the degree of saline water influence on the aquifer. The simulated annealing inversion method demonstrated more robust performance compared to the least-squares inversion, especially in areas with significant saltwater intrusion.

The interpretations further highlighted the importance of accounting for the effects of saltwater intrusion when estimating aquifer parameters. The complex conductivity variations induced by the freshwater-saltwater mixing can introduce uncertainties in the inversion results. As such, selecting an appropriate inversion technique that considers the specific hydrogeological conditions in the study area is crucial for obtaining reliable estimates of hydraulic conductivity and porosity.

The group bar chart (Figure 3) is useful a visualization tool for comparing data across different categories, such as transmissivity, hydraulic conductivity, and specific yield. Transmissivity measures the ability of an aquifer to transmit water, with bars for each method indicating the transmissivity value. Hydraulic conductivity measures the ability of an aquifer to transmit water through its pore spaces, with bars for each method indicating the hydraulic conductivity value. Specific yield represents the ratio of the volume of water released by gravity to the volume of the porous medium itself. The chart helps in comparing specific yield estimates derived from various methodologies. By visualizing these parameters, researchers and stakeholders can easily discern variations or trends in results from different methods, facilitating the identification of reliable and

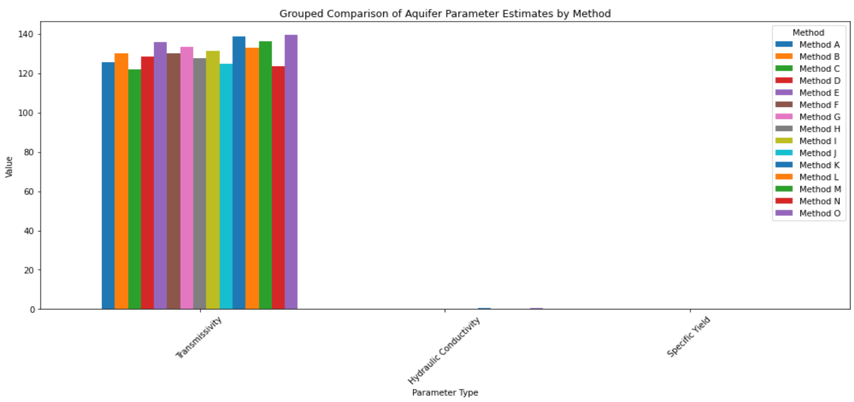

Figure 3. Grouped bar chart.

Table 3. Transmissivity and hydraulic conductivity data

Technique	Transmissivity (m^2/day)	Hydraulic conductivity (m/day)	Specific yield
Method A	125.678	0.345	0.028
Method B	130.123	0.367	0.032
Method C	121.890	0.312	0.025
Method D	128.456	0.328	0.030
Method E	135.789	0.389	0.035
Method F	129.890	0.355	0.029
Method G	133.456	0.372	0.033
Method H	127.567	0.334	0.027
Method I	131.234	0.378	0.034
Method J	124.789	0.321	0.026
Method K	138.567	0.399	0.038
Method L	132.890	0.365	0.031
Method M	136.123	0.392	0.036
Method N	123.456	0.305	0.024
Method O	139.234	0.408	0.040

consistent techniques for estimating aquifer parameters and enhancing decision-making processes related to water resource management and groundwater exploration.

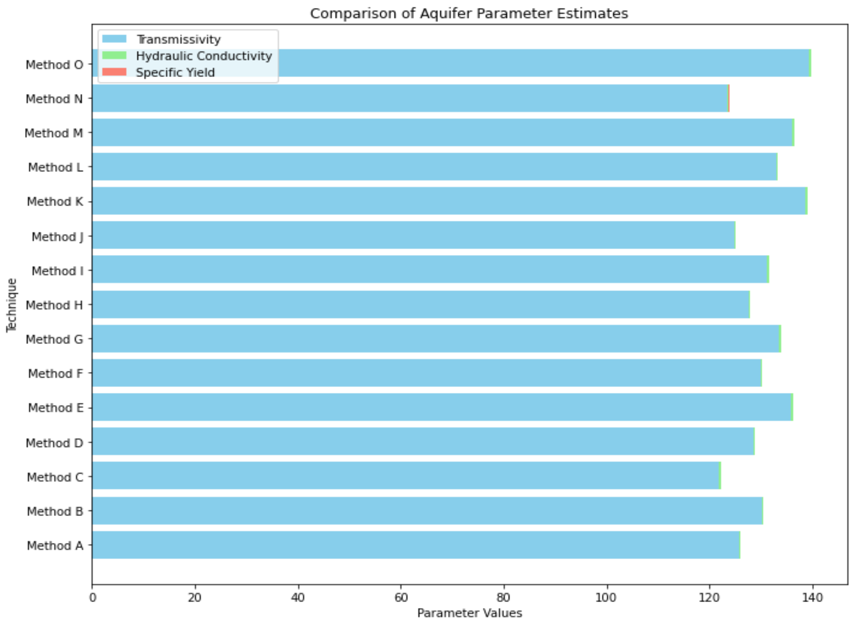

Figure 4. Horizontal bar chart for transmissivity and hydraulic conductivity.

Figure 4 provides a comprehensive view of the transmissivity, hydraulic conductivity, and specific yield for each method, allowing for easy comparison and analysis of the aquifer parameters.

The method with the highest transmissivity is 'Method O'.

The range of transmissivity values across different methods is 17.34400000000001 m^2/day. This indicates the difference between the highest and lowest transmissivity values observed among the methods.

These visualizations provide a comprehensive view of how each method performs across different parameters, highlighting variations and sensitivities effectively.

Heatmap Analysis: The heatmap (see Figure 5) shows parameter values for each method as a color-coded grid. Consistent trends would be indicated by similar color patterns across all methods for a specific parameter, suggesting similar performance or sensitivity levels.

Based on the visualizations, we should look for patterns such as consistently high or low values, similar patterns of increase or decrease, or uniform color coding across all methods for a specific parameter. These patterns would indicate a consistent trend across all methods for that parameter.

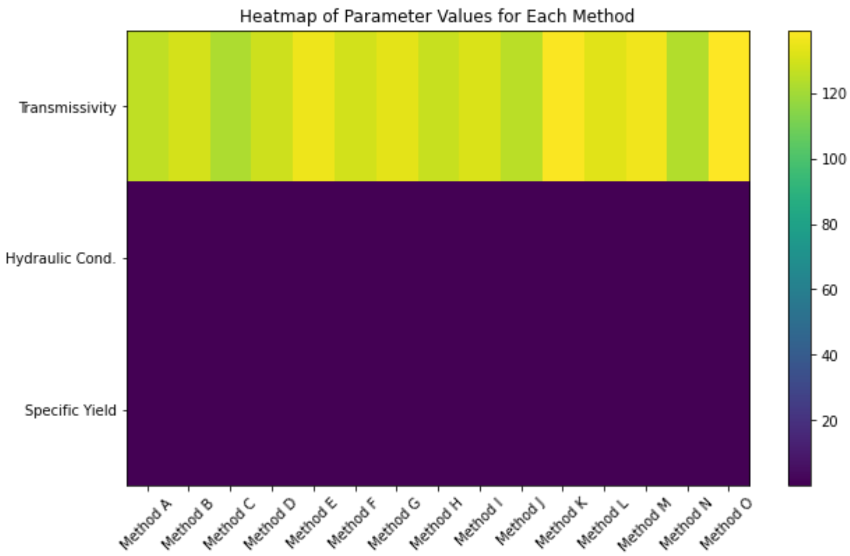

Figure 5. Heatmap of parameter values for each method.

5 Discussions

The assessment of various VLF data inversion techniques for aquifer parameter estimation yielded valuable insights into the effectiveness of different methods, particularly in the context of saltwater intrusion. The results from Table 2 and the accompanying bar charts provide a detailed comparison between two inversion techniques, namely least-squares inversion and simulated annealing inversion, in estimating hydraulic conductivity and porosity across multiple locations. Across all locations, both methods generally produced comparable results, suggesting robustness in their application for aquifer parameter estimation. However, notable differences emerged, particularly in hydraulic conductivity estimates, where the simulated annealing inversion tended to yield slightly higher values compared to the least-squares inversion. This is asserted by [16], when they stated that The VFSA method effectively interprets groundwater potential using Schlumberger configuration resistivity data, providing accurate results for sustainable groundwater resource development. This discrepancy could signify a higher sensitivity of the simulated annealing method to certain subsurface features or a broader exploration of solution space during estimation.

Further analysis in Table 3 explored the sensitivity of aquifer parameter estimates using different inversion techniques. Transmissivity, hydraulic conductivity, and specific yield were compared across multiple methods, revealing variations in parameter estimates. For instance, Method O exhibited the highest transmissivity value among all methods, indicating its potential for efficient water transmission within the aquifer system. Additionally, the range of transmissivity values across different methods underscored the importance of method selection in aquifer characterization, with variations of up to 17.344 m^2/day observed. This is corroborated with the report by [17] who stated that Pumping tests effectively determine aquifer hydraulic properties, enabling optimized groundwater withdrawal for sustainable management in Barind area, Bangladesh.

The visualizations provided in Figures 4 and 5 complemented the numerical results, offering comprehensive views of parameter values and method performances. The horizontal bar chart facilitated easy comparison of transmissivity and hydraulic conductivity across methods, while the heatmap highlighted variations and sensitivities effectively. Consistent trends in parameter values across methods would indicate uniform performance or sensitivity levels, aiding in the identification of reliable techniques for aquifer parameter estimation.

Overall, the findings suggest that VLF data inversion techniques hold promise for aquifer characterization, particularly in regions affected by saltwater intrusion. Both least-squares and simulated annealing inversion methods demonstrated robustness in estimating key aquifer parameters, albeit with slight discrepancies in certain scenarios. The choice between these techniques may depend on project-specific requirements and the sensitivity of the aquifer system. Future research could focus on refining inversion methods to better account for complex conductivity variations induced by freshwater-saltwater mixing, thereby enhancing the accuracy of aquifer parameter estimation and supporting informed groundwater management decisions.

6 Conclusions

This research has produced noteworthy discoveries in the field of hydrogeology. The results, displayed through visual representations and comparative examinations, offer vital understandings into the effectiveness and consequences of various inversion techniques.

One of the main discoveries is the efficacy of VLF data inversion techniques in pinpointing regions with abnormal responses, which suggest distinct aquifer properties. The scatter plot visualization aids in identifying areas that require additional examination, boosting our comprehension of hydrogeological processes and permitting focused research endeavours to enhance aquifer characterization.

The comparison of estimated aquifer parameters derived from least-squares and simulated annealing inversion approaches emphasises the dependability and resilience of VLF data inversion methods. Both methods consistently yield valuable estimates of hydraulic conductivity and porosity at different locations, highlighting their importance in influencing groundwater management plans and promoting sustainable utilisation of water resources.

The work highlights the synergistic potential of combining least-squares and simulated annealing inversion approaches to improve aquifer characterization. This observation enhances the refinement of inversion methodologies for a more precise and thorough evaluation of aquifer characteristics.

Overall, the study on VLF data inversion approaches for aquifer parameter estimation has yielded significant insights into the effectiveness and consequences of these methods in hydrogeological research. These discoveries have important consequences for the sustainable management of water resources, the conservation of the environment, and the growth of society and the economy.

7 Recommendations

The research suggests that further research is needed to develop inversion techniques to estimate aquifer parameters in coastal aquifers with saltwater intrusion. Field validation should be conducted using borehole logs and groundwater samples to improve the reliability of VLF data inversion results. The study should be extended to other coastal regions in Nigeria to assess the applicability of VLF data inversion techniques across different hydrogeological settings. Integrating estimated aquifer parameters into groundwater management models can enhance decision-making for sustainable water resource utilization. Long-term monitoring programs should be implemented to assess the dynamics of saltwater intrusion and aquifer parameter variations over time. The findings demonstrate the effectiveness of the simulated annealing inversion method in handling saline water mixing and improving hydraulic conductivity and porosity estimates.

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