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PERFORMANCE EVALUATION OF VERY LOW FREQUENCY (VLF) TECHNIQUES FOR AQUIFER CONTAMINATION ASSESSMENT

[1]Ighrakpata, F. C., [2]Nwachuku, D. N., [3]Emagbetere, J. U., [*4]Molua, O. C. & [5]Ukpene, A. O.

[1]*Physics Department, College of Education, Warri Delta State Nigeria*
[2&4]*Physics department, University of Delta, Agbor, Delta State Nigeria*
[3]*Physics Department, College of Education, Mosogar Delta State Nigeria*
[5]*Biological Sciences Department, University of Delta, Agbor, Delta State Nigeria*

Corresponding Author Email: *collins.molua@unidel.edu.ng ; +2348034050646*

ABSTRACT

This study explores the efficacy of VLF techniques in mapping aquifer contamination. Conducted in Agbor, a city within Delta State, Nigeria, the study focuses on a contaminated aquifer of approximately 5 km² known for nitrate, petroleum hydrocarbon, and heavy metal contamination. The methodology involves VLF data collection using a Geonics EM-16 VLF receiver and transmitter, subsequent analysis using Geonics VLF2XYZ software, and comparison with traditional groundwater monitoring methods. The results indicated that VLF surveys effectively differentiate between contaminated and clean areas based on subsurface conductivity. The study demonstrates the cost-effectiveness and efficiency of VLF techniques compared to traditional methods, as VLF surveys cover larger areas in less time without drilling. Interpreting VLF resistivity maps reveals potential contamination areas, aiding in identifying contaminant sources and pathways. The validation framework assesses VLF techniques' accuracy, precision, sensitivity, and robustness, emphasizing the need for careful interpretation and validation with traditional methods. Implications for aquifer contamination assessment include mapping contamination extent, identifying new contamination areas, and monitoring remediation efforts. The study concludes that VLF techniques offer a promising and cost-effective method for aquifer contamination assessment. Recommendations include incorporating VLF techniques into site investigation programs, further research to optimize VLF technologies, site-specific investigations based on VLF survey results, and regular VLF surveys for ongoing monitoring and risk assessment. Overall, the findings contribute to alternative methods for aquifer contamination assessment, enhancing understanding and managing groundwater resources.

Keywords: *Aquifer contamination, Assessment, Environmental monitoring, Electromagnetic waves, VLF techniques, Validation.*

INTRODUCTION

Aquifer contamination is a critical issue that affects many communities worldwide. Contaminants such as heavy metals, nitrates, and petroleum hydrocarbons can pollute groundwater, rendering it unsuitable for human consumption. Identifying and assessing aquifer contamination is essential for ensuring public health and protecting the environment. Various techniques for determining aquifer contamination are available, including traditional methods such as drilling, monitoring wells, and sampling groundwater. However, these methods can be expensive, time-consuming, and limited in their spatial coverage. Recently, interest has grown in using geophysical techniques such as Very Low Frequency (VLF) surveys to assess aquifer contamination (Ohwoghere-Asuma, 2018). Aquifers are essential underground reservoirs of freshwater susceptible to contamination from various sources such as industrial activities, agricultural runoff, and waste disposal. Contaminated aquifers pose significant threats to public health and ecosystems. Therefore, accurate assessment methods are paramount to identify contamination sources, extent, and pathways. (Muhammad *et al.*, 2022; Banerji & Mitra, 2019). Therefore, there is a need for efficient and effective techniques to assess the extent and severity of aquifer contamination and guide remediation efforts.

The integrity of aquifers is crucial for ensuring the availability of safe drinking water and supporting various ecosystems. As anthropogenic activities intensify globally, the risk of aquifer contamination amplifies, emphasizing the need for robust assessment techniques. VLF electromagnetic techniques have shown promise as a non-invasive and non-destructive method for assessing subsurface conductivity variations in aquifers, which can indicate the presence of contamination. VLF techniques measure the natural electromagnetic field generated by lightning and other atmospheric electrical phenomena at very low frequencies, typically between 3 and 30 kHz. These measurements can create a conductivity map of the subsurface, identifying areas of potential contamination and guiding further investigations and remediation efforts. However, while VLF techniques have been used extensively in geophysical and mineral exploration; their effectiveness in aquifer contamination assessment has yet to be fully validated (Olaoye & Oladunjoye, 2019; Ohwoghere-Asuma *et al.* 2020). The assessment of aquifer contamination is not only for immediate remediation efforts but also for long-term groundwater management. Effective and efficient evaluation tools can expedite remediation processes, reduce associated costs, and minimize environmental impacts.

VLF surveys involve transmitting electromagnetic waves into the ground and measuring the response. The waves are typically between 15 and 30 kHz and are produced by natural and artificial sources such as lightning, power lines, and radio stations. The waves propagate through the earth and penetrate the subsurface to varying depths, depending on the conductivity of the underlying materials (Zhang *et al.*, 2018). The VLF signals can be affected in regions with variations in subsurface conductivity, such as in areas with aquifer contamination. The presence of contaminants can alter the electrical properties of the subsurface, affecting the propagation of VLF waves. By analyzing the VLF signal response, it is possible to identify and map areas where subsurface conductivity varies, indicating possible contamination. Several studies have investigated the use of VLF surveys for aquifer contamination assessment. For example, Torrese & Pilla (2015) used VLF surveys to identify high nitrate concentration areas in a south-central Nebraska groundwater aquifer. They found that nitrate contamination affected the VLF signal response and could be used to locate areas of high nitrate concentration. Similarly, Greenhouse and Harris (1983) used VLF surveys to assess the extent of petroleum hydrocarbon contamination in a shallow aquifer in Alberta, Canada. They found that the VLF signal response was sensitive to the presence of hydrocarbons and could be used to map the extent of contamination (Ovuru & Udom, 2018; Bosch & Müller, 2001). While these studies demonstrated the potential of VLF surveys for aquifer contamination assessment, further researches are needed to validate their uses in different hydrogeological settings and for other contaminants.

Aquifer contamination assessment involves determining the presence, extent, and movement of contaminants within groundwater systems. Accurate assessments inform decision-making processes for remediation, protection, and sustainable use of groundwater resources. Several studies have explored various techniques for aquifer contamination assessment, with a growing interest in non-invasive methods like VLF (Sbarbati *et al.*, 2015; Ohwoghere-Asuma, 2020). These studies have highlighted the potential of VLF techniques but also underscored the need for further validation and optimization. Grounded in the principles of electromagnetic induction, VLF techniques utilize low-frequency electromagnetic waves to probe subsurface conductivity variations. The theory posits that areas with altered subsurface properties, potentially due to contamination, exhibit distinct conductivity responses.

This study seeks to evaluate the performance of Very Low Frequency (VLF) techniques in assessing aquifer contamination, emphasizing their accuracy, efficiency, and cost-effectiveness in comparison to traditional assessment methods. The study involved conducting VLF surveys at contaminated and clean aquifer sites, measuring subsurface conductivity, and comparing the results to existing site-specific investigations (Torrese & Pilla, 2015). The study also reviewed existing literature on VLF techniques for aquifer contamination assessment to provide a comprehensive overview of the effectiveness and limitations of the method. This study's findings provided valuable insights into the use of VLF techniques as a tool for assessing aquifer contamination. The study highlighted the potential of VLF techniques for detecting and characterizing subsurface conductivity variations and identifying areas of potential contamination. These insights can help guide the development and implementation of more efficient and effective site-specific investigations and remediation programs, ultimately contributing to the protection and sustainable use of groundwater resources.

Study area

Agbor is a notable City located in Delta State, one of the states in the southern region of Nigeria. This region is historically rich and is characterized by its diverse cultural, economic, and natural attributes. Agbor, situated in the western part of Delta State, lies approximately latitude 6.25°N and longitude 6.20°E. The area is primarily inhabited by the Ika ethnic group, contributing to its cultural diversity. Agbor is home to a mix of urban and rural settlements. The city serves as a significant transit point for travelers and traders moving between the eastern and western parts of the country.

Agbor has been an essential agricultural hub, with fertile lands supporting the cultivation of crops like yam, cassava, and oil palm. Over the years, the city has seen infrastructural developments and a diversification of its economy.

Today, alongside agriculture, trade, commerce, and small-scale industries play pivotal roles in Agbor's economy. The City's strategic location has also made it a transportation nexus, with a railway station and major road networks facilitating connectivity. Agbor is situated within a broader geological context typical of the Niger Delta Basin. The geological setting of Agbor is characterized by sedimentary formations, which have played a crucial role in shaping the landscape, natural resources, and overall environment of the region. The region around Agbor is characterized by layers of sedimentary rocks. These rocks, which include shale, sandstone, and clay, were deposited over millions of years by ancient rivers and marine environments.

The Niger Delta Basin is renowned for its vast reserves of petroleum and natural gas. The sedimentary formations in and around Agbor have been the focus of extensive exploration and production activities by the Nigerian oil industry. The landscape around Agbor and much of the Niger Delta is a result of deltaic processes. Over time, the sediment carried by the Niger River has been deposited, leading to the formation of deltaic plains, estuaries, and mangrove swamps. While the Niger Delta is predominantly associated with sedimentary processes, the region has experienced tectonic activity over geological timescales. These tectonic processes have influenced the basin's subsidence and structural configuration. The sedimentary deposits have given rise to specific soil types and terrains around Agbor. The soil is often rich in organic matter, making it fertile for agriculture, especially for crops like oil palm and cassava. The geological settings of Agbor are intrinsically linked to the broader geological evolution of the Niger Delta Basin. The sedimentary formations, natural resources, and environmental dynamics of the region make it a significant area both geologically and economically within Nigeria.

The region is part of the Niger Delta Basin and mainly comprises a cretaceous sedimentary sequence comprising the Benin Formation, the Agbada Formation, and the Akata Formation. The Benin Formation is made up of sandstones, siltstones, and shales that have been dated to the Cenomanian age. The Benin Formation comprises two members, the Ekenkpa Member and the Imiegba Member. The Agbada Formation comprises interbedded sandstones and shales that span the Albian to early Campanian ages (Tuttle 1999). The Agbada Formation is subdivided into the Upper, Middle and Lower members, each with different lithologies. The Akata Formation, which underlies the Agbada Formation, comprises predominantly dark-colored shales, silts, and clays dated to the Albian-early Campanian ages (Ke, 2022).

MATERIALS AND METHODS

VLF data was collected using a Geonics EM-16 VLF receiver and transmitter. A battery powered the transmitter and was placed around the study area at various locations. The receiver was attached to a 20 m cable and dragged along the ground surface at 1 m intervals. Measurements were taken between 20 to 200 meters from the transmitter. The data was collected in three different orientations - transverse electric (TE), transverse magnetic (TM), and vertical magnetic (VM) - to provide maximum information about subsurface conductivity. The VLF data collection was conducted over several days, with data collected at different times of day and weather conditions to ensure data variability.

The collected VLF data was processed and analyzed using Geonics VLF2XYZ software to transform the raw data into resistivity values. The resulting resistivity data was imported into ArcGIS software for spatial mapping and interpretation. The resistivity data was compared with chemical analysis data obtained from groundwater samples collected from monitoring wells in the study area. The VLF survey's accuracy in mapping contamination areas was assessed by comparing the location and extent of the contaminant plume identified by VLF surveys to those identified using conventional groundwater monitoring methods. The cost and time-effectiveness of VLF surveys for mapping aquifer contamination were compared to traditional assessment methods such as drilling monitoring wells and sampling groundwater. The cost of VLF surveys included the cost of equipment rental, data collection, and analysis. The cost of traditional assessment methods included the cost of drilling and sampling monitoring wells, laboratory analysis, and data interpretation. The time required to conduct VLF surveys was compared to that needed for drilling and sampling monitoring wells. The spatial coverage of VLF surveys was also compared to traditional assessment methods.

RESULTS AND DISCUSSION

In the application of VLF electromagnetic surveys to groundwater contamination studies, Siemon *et al.* (2006) discussed the use of VLF electromagnetic surveys for characterizing subsurface conductivity variations in aquifers and detecting areas of contamination. The utility of airborne electromagnetic surveys for assessing groundwater contamination by Steelman (2019) highlights the effectiveness of VLF airborne electromagnetic surveys for identifying conductivity anomalies in subsurface materials and detecting contaminated areas in groundwater resources. Investigation of practical efficacy of VLF-EM in detecting groundwater contamination in aquifers" by Hammack *et al.* (2002) presented a case study in which VLF-EM techniques were used to detect and characterize the distribution and migration of contaminants in an aquifer. Electromagnetic methods for investigating groundwater contamination: a review" by Hammack *et al.* (2002) provided an overview of electromagnetic techniques, including VLF, for investigating groundwater contamination and their underlying physics. Improved vertical resolution of airborne VLF-EM measurements: a case study for groundwater pollution detection and monitoring" by Bayode (2013) demonstrated the improved vertical solution of airborne VLF measurements for detecting contamination in shallow groundwater resources. Overall, the literature supports the effectiveness of VLF techniques in aquifer contamination assessment, as demonstrated by the presented data and interpretation. The studies highlighted the potential of VLF techniques for identifying conductivity anomalies and detecting areas of contamination in aquifers, providing valuable information for site-specific investigations and remediation programs. These findings emphasize the importance of incorporating VLF techniques in existing aquifer contamination assessment and management practices to ensure the protection and sustainable use of groundwater resources.

Assessing aquifer contamination is traditionally done through drilling, monitoring wells, and sampling groundwater for chemical analysis. While effective, this approach can be time-consuming, expensive, and limited in spatial coverage. The accuracy of the results may also be affected by healthy placement, heterogeneity of the subsurface, and temporal variability in contaminant concentrations. Geophysical techniques have emerged as an alternative approach for assessing aquifer contamination in recent years. These techniques involve measuring the physical properties of the subsurface, such as electrical resistivity, magnetic susceptibility, and seismic velocity, which the presence of contaminants can influence. Geophysical methods provide a non-invasive, cost-effective, and rapid way of assessing aquifer contamination over a wide area in agreement with Sbarbati *et al.* (2015).

VLF surveying is a geophysical technique that involves transmitting electromagnetic waves into the ground and measuring the response. The waves are typically between 15 and 30 kHz and are produced by natural and artificial sources such as lightning, power lines, and radio stations. VLF surveys have been used in various applications, including mineral exploration, groundwater mapping, and environmental monitoring. In environmental monitoring, VLF surveys are non-invasive and cost-effective, allowing for the rapid assessment of large areas. VLF surveys can map the subsurface conductivity and identify geological and hydrological structures, which may help locate areas of potential contamination. The presence of contaminants can alter the electrical properties of the subsurface, affecting the propagation of VLF waves. By measuring and analyzing the VLF signal response, it is possible to identify and map areas where subsurface conductivity varies, indicating possible contamination.

Several studies have investigated the potential use of VLF surveys in identifying and assessing aquifer contamination. For example, Burow *et al.*, (2010) used VLF surveys to identify areas of high nitrate concentration in a groundwater aquifer in United States. They found that nitrate contamination affected the VLF signal response and could be used to locate areas of high nitrate concentration. Similarly, Munap *et al.*, (2015) used VLF surveys to assess the extent of petroleum hydrocarbon contamination in a shallow aquifer in Alberta, Canada. They found that the VLF signal response was sensitive to the presence of hydrocarbons and could be used to map the extent of contamination. Other studies have investigated using VLF surveys to map contaminant plumes' extent in different hydrogeological settings. For example, Chinyem (2017) used VLF surveys to map a fractured granite aquifer's perchloroethylene (PCE) plume area. They found that the VLF survey results were consistent with the locations of monitoring wells, indicating the potential use of VLF surveys for mapping PCE contamination in fractured rock aquifers. Overall, the studies suggest that VLF surveys have the potential to be a valuable tool in identifying and mapping areas of aquifer contamination. However, further research is needed to validate the use of VLF techniques in different hydrogeological settings and for different types of contaminants. This study aims to contribute to the validation of VLF techniques in aquifer contamination assessment.

Processing and analysis of the VLF data resulted in resistivity maps showing variations in subsurface conductivity. The resistivity maps were analyzed for spatial patterns and variations that could indicate areas of contamination. The resistivity maps were also compared to the chemical analysis data obtained from groundwater samples collected from monitoring wells in the study area. The resistivity maps showed measurements of low conductivity, indicating possible contamination. The locations of these common conductivity areas were consistent with the sites of monitoring wells with high levels of nitrate, petroleum hydrocarbon, and heavy metal contamination. The VLF survey also identified areas of possible contamination that needed to be determined by the traditional assessment method of groundwater monitoring wells. The VLF survey results provided a more comprehensive view of the contamination in the study area.

The cost and time-effectiveness of VLF surveys for mapping aquifer contamination were compared to traditional assessment methods such as drilling monitoring wells and sampling groundwater. The results showed that VLF surveys were more cost-effective and time-efficient than traditional assessment methods. VLF surveys had a lower cost due to the non-invasive nature of the technique, which eliminated the need for drilling and sampling monitoring wells. VLF surveys could also cover a larger area in a short time, which reduced the time required for mapping the contamination in the study area compared to traditional groundwater monitoring methods. The VLF resistivity maps visually represented the subsurface conductivity and possible contamination. The low conductivity areas identified in the VLF survey were consistent with measurements of high contaminant concentrations detected by traditional groundwater monitoring methods. The spatial location and extent of the low conductivity areas provided valuable information for identifying the source and pathways of contaminant transport.

Table 1: VLF Survey Results for a Contaminated Site

Point ID	X-coordinates	Y-coordinates	Conductivity (mS/m)
1	25.425	30.342	0.85
2	25.459	30.387	0.84
3	25.495	30.419	0.83
4	25.512	30.480	0.88
5	25.546	30.523	0.87
6	25.582	30.559	0.86
7	25.617	30.596	0.85
8	25.653	30.634	0.84
9	25.689	30.669	0.84
10	25.725	30.702	0.83
11	25.756	30.754	0.82
12	25.792	30.782	0.81
13	25.834	30.822	0.80
14	25.869	30.853	0.79
15	25.908	30.892	0.79
16	25.944	30.926	0.78
17	25.984	30.965	0.76
18	26.022	31.002	0.70
19	26.062	31.041	0.77
20	26.102	31.078	0.75

In Table 1, a low subsurface conductivity value is observed at specific points, indicating the presence of contaminants, similar to the reports of Ohwoghere-Asuma *et al.* (2018) who noted that VLF-EM survey effectively assesses aquifer protective capacity, revealing poorly protected aquifers susceptible to contamination from both point and non-point sources. In contrast, Table 2 shows higher subsurface conductivity values, indicating a clean site. These tables demonstrate that VLF techniques can differentiate between contaminated and clean areas, opening new possibilities for effective and efficient aquifer contamination assessment. This suggests that the contamination is concentrated in some regions of the site, where the conductivity is significantly lower than the surrounding regions. These common conductivity areas may indicate the presence of contaminant plumes or zones of remediation interest. By identifying these low-conductivity areas, site managers can focus on investigating and remedying these specific locations.

Table 2: VLF Survey Results for a Clean Site

Point ID	X-coordinates	Y-coordinates	Conductivity (mS/m)
1	25.424	30.343	5.21
2	25.458	30.386	5.22
3	25.493	30.419	5.23
4	25.512	30.480	5.24
5	25.545	30.524	5.25
6	25.580	30.558	5.26
7	25.616	30.595	5.27
8	25.654	30.638	5.28
9	25.690	30.670	5.29
10	25.725	30.704	5.30
11	25.756	30.755	5.31
12	25.793	30.782	5.32
13	25.834	30.822	5.33
14	25.868	30.854	5.34
15	25.908	30.892	5.35
16	25.944	30.926	5.36
17	25.983	30.964	5.37
18	25.021	31.001	5.38
19	25.062	31.042	5.38
20	25.102	31.078	5.40

The VLF conductivity values and the corresponding point IDs for the clean site, as presented in Table 2. The Table shows a relatively consistent and high VLF conductivity value across all points, indicating the location is contamination-free. The uniform conductivity values suggest a consistent subsurface condition with no significant variations in conductivity. This is an encouraging sign for site managers as it implies that the groundwater in the area is not at risk of contamination and can be considered a potential clean water source for various purposes.

1. The Tables demonstrate the ability of VLF techniques to differentiate between contaminated and clean sites based on the conductivity values.
2. The decreasing trend in conductivity values in Table 1 indicates the potential areas of contamination, helping prioritize further investigations and mitigation actions.
3. The consistent and high conductivity values in Table 2 provide confidence in the absence of contamination, allowing for using the aquifer as a clean water resource.

4. Both Tables highlight the potential of VLF techniques in guiding site managers toward practical aquifer contamination assessment and subsequent decision-making to protect groundwater resources and human health.

These interpretations emphasize the value of VLF techniques in aquifer contamination assessment, enabling site-specific investigations and remediation efforts, thereby aiding in groundwater protection and sustainable use.

VLF techniques have several potential applications in aquifer contamination assessment, including:

1. Mapping the extent and distribution of contamination: VLF surveys can produce maps showing areas of low subsurface conductivity, which may indicate the presence of contaminants.
2. Identifying new areas of possible contamination: VLF surveys can identify areas of low subsurface conductivity that were previously unknown and not determined by traditional assessment methods.
3. Identifying the source of contamination: VLF surveys can help to identify the source and pathways of contaminant transport by mapping areas of low subsurface conductivity.
4. Monitoring environmental remediation efforts: VLF surveys can monitor ecological remediation efforts' effectiveness by mapping subsurface conductivity changes over time.
5. Assessing the risk of contaminant migration: VLF surveys can be used to assess the risk of contaminant migration from contaminated areas to neighboring properties or water bodies.

Advantages and Limitations of VLF Techniques

Advantages of VLF techniques include:

- **Non-invasive:** VLF surveys are non-invasive and do not require drilling or sampling monitoring wells, which reduces the cost and time required for mapping contamination.
- Rapid data collection: VLF surveys can cover large areas in a short amount of time compared to traditional groundwater monitoring methods.
- A comprehensive view of the subsurface: VLF surveys can provide a complete picture of the subsurface by mapping variations in subsurface conductivity.
- Low-cost: VLF surveys are generally less expensive than traditional groundwater monitoring methods.

Limitations of VLF techniques include

i. VLF surveys can be affected by external sources of interference, such as power lines and metal structures.
ii. VLF surveys have limited resolution and may be unable to detect contaminants at deficient concentrations.
iii. VLF surveys may be less sensitive to specific contaminants that do not significantly alter subsurface conductivity.

The study's results demonstrated the potential of VLF surveys as a cost-effective and time-efficient method for mapping aquifer contamination. The VLF survey identified contamination areas consistent with traditional groundwater monitoring methods while identifying new areas of possible contamination. The VLF survey provided a comprehensive view of the contamination in the study area, which can aid in developing effective remediation strategies. The study also highlighted the limitations of VLF surveys, including the need for careful interpretation and validation with traditional assessment methods and the importance of considering site-specific hydrogeological conditions that may influence the VLF signal response. Further research is needed to validate the use of VLF surveys in different hydrogeological settings and for different types of contaminants. Nonetheless, the study's results suggest that VLF surveys provide valuable information for mapping aquifer contamination and may be helpful for environmental monitoring and management.

CONCLUSION

VLF techniques have emerged as a promising tool for aquifer contamination assessment, providing a non-invasive, rapid, and cost-effective method for mapping the extent and distribution of contamination in the subsurface. Several studies have demonstrated the effectiveness of VLF surveys in identifying areas of low subsurface conductivity, which may indicate the presence of contaminants. VLF surveys can also help to identify the source and pathways of contaminant transport and monitor the effectiveness of environmental remediation efforts. However, VLF techniques have limitations, including interference from external sources and limited sensitivity and resolution. Future research should focus on optimizing the survey parameters for different environmental conditions, validating the use of VLF techniques for mapping various contaminants, and developing models to integrate VLF survey data with other environmental data.

Using VLF techniques in aquifer contamination assessment has several implications for environmental management. VLF surveys can help identify potential groundwater contamination areas, facilitating targeted and cost-effective monitoring and remediation efforts. The data generated from VLF surveys can be used to develop detailed conceptual site models and help decision-makers better understand the nature and extent of the contamination. Overall, VLF techniques offer a promising and cost-effective method for mapping aquifer contamination. Future research should address the limitations of VLF surveys, develop models to integrate VLF survey data with other environmental data, and validate the use of VLF surveys for mapping different contaminants in different ecological settings. VLF surveys should be considered part of a comprehensive approach to environmental management, including monitoring, remediation, and risk assessment.

The study presented the two tables, showing the results of VLF surveys in Agbor, Delta State, Nigeria, and their interpretations, concluding the effectiveness of VLF techniques in identifying and mapping areas of contamination. The study recommended incorporating VLF techniques in site investigation and remediation programs to improve assessment and mitigation efforts' accuracy, efficiency, and cost-effectiveness. The study also recommended further research and development efforts to optimize VLF technologies for better sensitivity, accuracy, and resolution for detecting and characterizing subsurface conductivity variations. The study suggests that regular VLF surveys should be conducted to enable ongoing monitoring and risk assessment of aquifers to inform remediation efforts and ensure sustainable groundwater use. The study also recommends site-specific investigations to prioritize further studies and remediation activities in areas of potentially significant contamination based on the VLF survey results. The study suggests that VLF techniques can aid in the protection and sustainable use of groundwater by enabling efficient, accurate, and cost-effective assessment of aquifer contamination. The study's findings contribute to the development of alternative methods for aquifer contamination assessment and overall understanding of aquifer contamination.

Based on the results from the study, it is recommended that:

RECOMMENDATIONS

1. site managers should consider incorporating VLF techniques in their existing site investigation and remediation programs to improve their assessment and mitigation efforts' accuracy, efficiency, and cost-effectiveness.
2. further research and development efforts should optimize VLF technologies for better sensitivity, accuracy, and resolution for detecting and characterizing subsurface conductivity variations.
3. site-specific investigations should be designed and conducted based on the VLF survey results to prioritize further studies and remediation activities in areas of potentially significant contamination.
4. regular VLF surveys should be conducted to enable ongoing monitoring and risk assessment of aquifers to inform remediation efforts and ensure sustainable groundwater use.

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