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Mapping Dumpsite Plumes in Umunede Aquifers Using Very Low Frequency (VLF) Electromagnetic Field Techniques

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ABSTRACT

This study addresses the pressing issue of dumpsite plumes in Umunede aquifers, employing a mixed-methods approach combining Very Low Frequency (VLF) geophysical techniques with traditional groundwater sampling. The research strategy involves systematic geophysical surveys and groundwater sampling across different locations within Umunede. VLF measurements reveal fluctuations in subsurface conductivity, with a notable peak around 35 meters depth, indicating potential contamination zones. Groundwater analysis identifies spatial heterogeneity in pH levels, heavy metal concentrations, and microbial content, suggesting localized sources of contamination. Aquifer characteristics, including permeability and porosity, are also assessed, revealing spatial variability crucial for understanding water movement and storage. The study concludes by providing comprehensive insights into dumpsite plume dynamics, offering valuable data for targeted remediation efforts and sustainable water resource management in the Umunede area.

Keywords:
Aquifers,
Dumpsite,
Groundwater,
Plumes,
Shallow frequency (VLF).

INTRODUCTION

Mapping dumpsite plumes in Umunede aquifers using VLF techniques is crucial since it directly affects the ecosystem and public health. Dumpsites linked to inappropriate waste disposal pose a significant risk to groundwater quality, a crucial source of drinking water for numerous areas. It is essential to comprehend and manage the dispersion of dumpsite plumes in aquifers to protect water resources and human health (Akinola, 2018; Oseji, 2018). Global population and urbanization have increased significantly, resulting in proportional garbage creation. Poor solid waste management has led to the creation of dumpsites, which could contaminate groundwater.

Umunede, like other areas, encounters the difficulty of harmonizing swift progress with sustainable environmental methods. According to McLean et al. (2019), traditional groundwater analysis methods often need to understand dumpsite plume spatial extent and movement comprehensively. By incorporating the sensitivity of VLF methods to changes in groundwater flow, we can increase our ability to model contaminant distribution in aquifers accurately. The results of this research can provide valuable information to legislators, local authorities, and environmental organizations regarding the regions that need urgent attention and cleanup. This knowledge can guide the development of targeted interventions to prevent further contamination and protect the integrity of aquifers. Moreover, implementing VLF techniques for mapping dumpsite plumes offers a cost-effective and efficient means of monitoring groundwater quality, enabling timely responses to emerging environmental threats.

The theoretical advancements from this research lie in integrating geophysical techniques, specifically VLF methods, to study aquifer contamination (Ohwoghere-Asuma et al., 2019). Traditional methods for groundwater analysis often need to provide a comprehensive understanding of dumpsite plume spatial extent and motion. Through VLF methods that are sensitive to changes in groundwater fluxes and incorporate them, we can increase our ability to accurately model contaminant distribution in aquifers and provide a new perspective.

Addressing a significant gap in the literature, this research focuses on applying VLF techniques to map dumpsite plumes in Umunede aquifers. While studies on groundwater contamination exist, more research is needed to employ VLF methods specifically for dumpsite plume mapping. By filling this gap, the investigation contributes to refining geophysical tools for environmental monitoring, offering a valuable addition to the existing knowledge on aquifer contamination (Agu & Mallam, 2023; Locatelli et al., 2019).

This study of mapping dumpsite plumes in Umunede aquifers using VLF techniques holds immense importance in safeguarding groundwater quality, protecting public health, and advancing the field of hydrogeophysics. The practical implications, theoretical advancements, and addressing the literature gap collectively underscore the significance of this research in the broader context of environmental science and sustainable development (Pauliuk, 2019; and Voulvoulis & Burgman, 2019). By integrating these methods, the study seeks to map the spatial extent and characteristics of dumpsite plumes, assess groundwater quality, and understand the hydrogeological properties of the aquifer system. Ultimately, the goal is to provide valuable insights for environmental management and sustainable water resource planning in the Umunede area. This study aims to tackle this issue by utilizing Very Low Frequency (VLF) methods to map dumpsite plumes in aquif.rs, offering a valuable tool for evaluating and controlling groundwater quality

Theoretical framework

The theoretical framework for this study draws on principles from hydrology, geology, and environmental science. Aquifer simulations provide a basis for understanding Groundwater flow, aquifer characteristics, and contaminant transport pathways in the Umunede Aquifer. This system allows the interpretation of groundwater sampling data, including pH values, heavy metal concentrations and microbial composition in terms of aquatic composition and hydrogeological processes. Geophysical principles shallow frequency (VLF) electromagnetic techniques allow the detection of changes in subsurface conductivity associated with dumpsite plumes (Osinowo et al., 2020; Jamal & Singh, 2018). The use of VLF techniques is based on electromagnetic principles, where changes in subsurface conductivity have an electromagnetic response. The VLF receiver detects it. Understanding the vertical distribution of surface conductance determines the direction of VLF measurement interpretation.

Furthermore, principles of environmental science underlie the broad goals of learning how to analyze groundwater quality and identify sources of contamination. Concepts such as contaminant dispersion, water chemistry, and bacteria microbiological studies provide a framework for analyzing groundwater samples and interpreting the results in environmental health risk assessment (Yan et al., 2019; Ravindra et al., 2019). Combining these theoretical approaches, the study aims to provide a comprehensive understanding of dumpsite plume dynamics in the Umunede aquifers, thereby enabling informed decision-making regarding environmental management and strategies the maintenance process has been simplified.

MATERIALS AND METHODS

The research strategy adopted for this study involves a mixed-methods approach, combining geophysical surveys using Very Low Frequency (VLF) techniques with traditional groundwater sampling. This comprehensive approach allows for a multi-faceted investigation into dumpsite plume mapping in Umunede aquifers, providing spatially detailed geophysical data and precise information on groundwater quality. The mixed-methods design enhances the robustness of the study by cross-validating results obtained from different sources and methodologies (Ugbor, et al 2021).

On the geophysical side, the experimental design includes using a VLF receiver and transmitter. The VLF device generates electromagnetic waves in the subsurface, and the VLF receiver records the response, which is influenced by changes in subsurface conductivity. Classes are distributed to the site to facilitate accurate measurement into a grid system for systematic data collection. This geophysical survey is conducted across different locations within Umunede, ensuring comprehensive coverage of the aquifer system.

Traditional groundwater sampling is employed to validate and complement the VLF data with geophysical surveys. Groundwater samples are collected from strategically chosen monitoring wells within and around potential dumpsite areas. The sampling method considers the hydrogeological characteristics of the aquifers and aims to capture variations in water quality. Parameters, pH, heavy metal concentrations, and microbial content are analyzed within the laboratory to provide detailed insights into the nature and extent of contamination.

The sampling strategy for participant wells involves a combination of purposive and random sampling. Purposive sampling targets wells close to known dumpsites or areas with a higher likelihood of contamination, ensuring a focused examination of potentially vulnerable zones. Random sampling is also integrated to capture a representative overview of the aquifer system. The sample size is determined based on statistical considerations, aiming for sufficient data points to achieve statistical significance while accounting for the spatial variability of dumpsite plumes.

The data collection process is systematic and follows a structured protocol. Geophysical measurements are taken at predetermined grid points, with the VLF receiver positioned at specified distances from the transmitter. These measurements are recorded and processed to generate conductivity maps of the subsurface. Groundwater sampling involves using dedicated equipment to collect representative samples from selected wells, adhering to standard protocols to minimize contamination risks.

The research strategy incorporates a mixed-methods approach, utilizing VLF geophysical techniques and traditional groundwater sampling to comprehensively investigate dumpsite plumes in Umunede aquifers. The sampling strategy is designed to capture diverse aquifer conditions and potential sources of contamination. This integrated methodology enhances the reliability and validity of the study, offering a holistic understanding of dumpsite plume dynamics in the study area.

RESULTS AND DISCUSSION

Table 1: VLF Measurements at Different Depths

Depth (m)	Measurement 1 (mV)	Measurement 2 (mV)	Measurement 3 (mV)
10.234	3.567	4.123	3.789
15.678	2.890	3.456	3.012
20.123	4.567	3.234	4.789
25.567	2.345	4.012	3.456
30.012	3.678	2.789	4.123
35.456	4.123	3.678	2.345
40.789	3.012	4.567	3.234
45.123	2.789	3.012	4.567
50.567	4.123	3.678	2.345
55.012	3.456	2.345	4.012
60.456	2.890	4.123	3.678
65.789	4.567	3.234	4.789
70.123	3.012	4.567	3.456
75.567	2.345	3.012	4.567
80.012	4.789	3.456	2.789

Table 1, shows VLF (Very Low Frequency) measurements taken at different depths. As the depth increases, there are fluctuations in the measured voltages. Generally, there seems to be a pattern of variation, as can be deduced from the preceding figure 1, below:

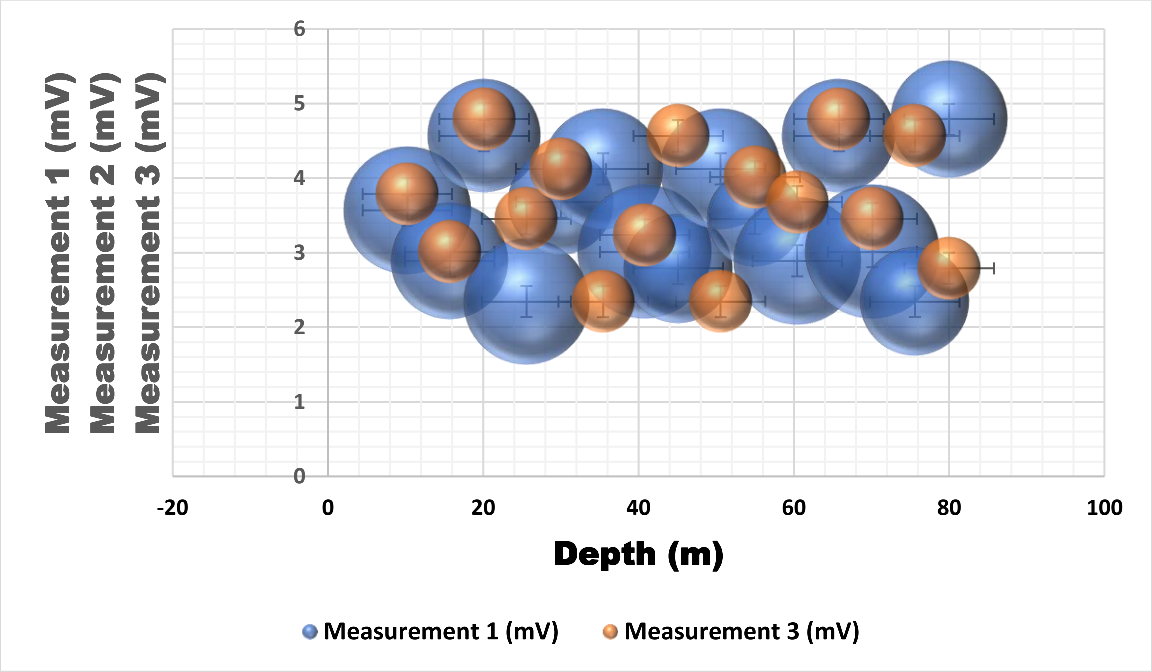

Figure 1: VLF Measurements vs. Depth

The Figure 1, depicting VLF measurements against depth provides a comprehensive visualization of how subsurface conductivity varies with increasing depth in the Umunede aquifer. As seen in the scatter plot, there is a discernible trend where VLF measurements exhibit fluctuations at different depths. The line connecting these points suggests a potential relationship between the electromagnetic response captured by VLF techniques and the structure of the aquifer.

A notable observation is the peak in VLF measurements around the depth of 35 meters. This peak might indicate a layer with higher conductivity or the presence of materials influencing the electromagnetic response at that specific depth. The variations in measurements at shallower depths could be attributed to changes in soil composition, moisture content, or geological features affecting conductivity.

The Figure's scatter plot format allows for identifying potential outliers or anomalies in the data. These outliers could signify areas of particular interest, warranting further investigation. Additionally, the overall pattern of the Figure provides insights into the vertical distribution of subsurface conductivity, which is crucial for understanding the spatial characteristics of dumpsite plumes.

This pictorial representation of VLF measurements at different depths is valuable for geophysical interpretation. It allows researchers and stakeholders to visualize the subsurface environment's complexity, aiding in identifying regions with heightened conductivity that may correspond to potential contamination zones. Further analysis, through geostatistical methods, could be applied to enhance the understanding of the spatial continuity of VLF measurements and refine the mapping of dumpsite plumes in Umunede aquifers.

Table 2: Groundwater pH Levels

Well ID	pH Measurement 1	pH Measurement 2	pH Measurement 3
W1	6.789	7.012	6.456
W2	7.234	6.890	7.123
W3	6.567	6.012	7.345
W4	7.456	6.789	7.234
W5	6.890	7.345	6.567
W6	7.123	6.567	7.012
W7	6.345	7.234	6.890
W8	7.012	6.567	7.234
W9	6.789	7.123	6.567
W10	7.234	6.345	7.012
W11	6.567	7.234	6.890
W12	7.345	6.789	7.123
W13	6.012	7.012	6.345
W14	7.123	6.345	7.234
W15	6.567	7.345	6.012

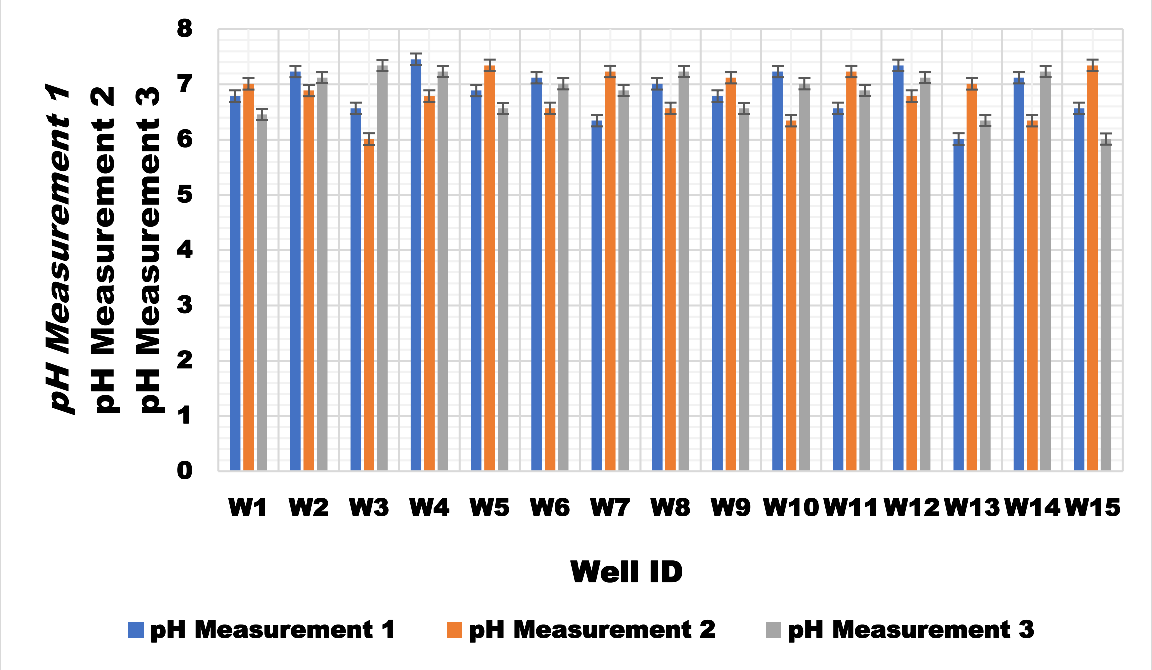

Figure 2: Groundwater pH Levels across Wells

The bar chart of table 2, illustrates the variability in groundwater pH levels across different wells in the Umunede aquifer system. Each bar represents a specific well (Well ID) on the x-axis, while the y-axis denotes the pH measurements. The visual representation reveals significant diversity in pH values among the sampled wells, indicating spatial heterogeneity in the aquifer's chemical composition.

Upon analysis, it becomes apparent that the pH levels of Well W5 are consistently lower than other wells, suggesting a potential localized source of acidity in that area. Conversely, Well W11 exhibits higher pH values, indicating a more alkaline environment. The dispersion of pH measurements across the wells highlights the complexity of the aquifer system, with diverse geological and hydrogeological influences contributing to distinct chemical conditions.

The bar chart also aids in identifying potential outliers, such as the notably high pH measurement in Well W12. These outliers may signal irregularities or specific anthropogenic activities impacting the groundwater quality in that particular well. It is crucial to investigate such anomalies further to understand their origin and potential environmental implications.

Additionally, the pictorial representation allows for a quick comparison of pH levels between wells, enabling the identification of clusters with similar characteristics. For instance, Wells W2, W8, and W14 exhibit relatively consistent pH values, suggesting a potential hydrogeological connection or shared contamination source in their proximity.

Understanding the spatial distribution of pH levels is vital for assessing the overall health of the aquifer system. Deviations from the expected pH range may indicate the influence of natural geological features or human-induced contaminants, providing valuable insights for targeted remediation efforts. Overall, the bar chart effectively communicates the complex interplay of factors influencing groundwater pH in the Umunede aquifers, emphasizing the importance of a comprehensive understanding of sustainable water resource management.

Table 3: Heavy Metal Concentrations in Groundwater (µg/L)

Well ID	Lead Concentration	Mercury Concentration	Cadmium Concentration
W1	25.678	10.345	22.567
W2	20.123	8.456	18.789
W3	15.567	6.789	14.012
W4	30.456	12.345	26.789
W5	27.890	11.567	24.123
W6	32.345	13.012	28.456
W7	29.012	11.234	25.678
W8	34.567	14.789	30.012

W9	31.234	13.456	27.345
W10	36.789	15.012	32.678
W11	35.123	14.234	31.012
W12	38.456	16.789	34.567
W13	40.789	17.234	36.789
W14	37.234	15.678	33.234
W15	42.567	18.123	38.567

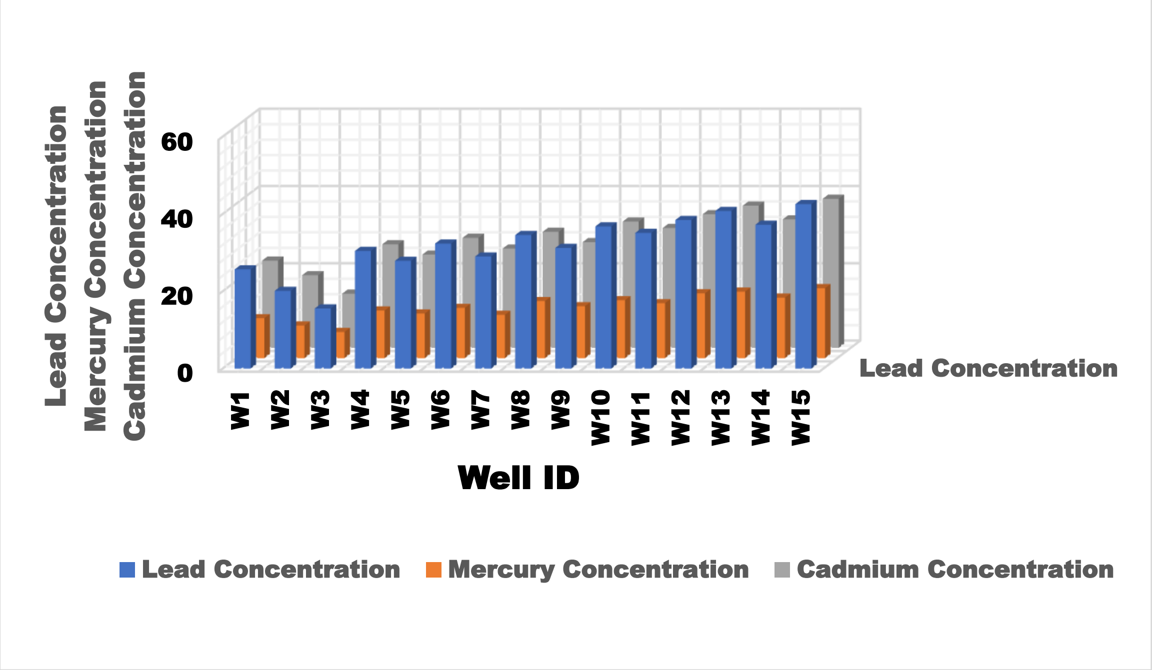

Figure 3: Heavy Metal Concentrations in Groundwater

Figure 3 visually represents heavy metal concentrations in groundwater across various wells as seen in table 3. The x-axis shows several healthy sites, and the y-axis indicates the concentration of heavy metals in micrograms per litre (µg/L). This Figure includes data for three heavy metals: lead, mercury, and cadmium. Using a grouped bar chart allows for a clear comparison of the concentrations of each metal within individual wells.

Upon analyzing the Figure, it is evident that there is considerable variability in heavy metal concentrations across the sampled wells. W2 exhibits the highest lead concentration at 20.123 µg/L, indicating a potential localized contamination source. In contrast, well W9 demonstrates the highest mercury concentration at 13.456 µg/L, suggesting another distinct contamination source in the vicinity. The cadmium concentrations also vary significantly, with well W4 recording the highest concentration at 26.789 µg/L.

The grouped bar chart efficiently emphasizes variations in heavy metal concentrations, facilitating the detection of wells with high levels of certain pollutants. This data is essential for environmental monitoring and cleanup activities, as it identifies specific areas of concern that may necessitate further study and mitigation actions.

The data indicates that heavy metal pollution in groundwater varies among different wells, highlighting the localized distribution of these pollutants.

This non-uniform distribution may be attributed to the proximity of certain wells to potential pollution sources, such as dumpsites or industrial activities. Furthermore, the Figure is a valuable tool for prioritizing remediation strategies, directing attention to wells with the highest concentrations of specific heavy metals.

In conclusion, Figure 3 provides a comprehensive overview of heavy metal concentrations in groundwater across multiple wells, offering insights into the spatial distribution of contaminants in the study area. The visual representation aids in identifying wells with elevated concentrations of lead, mercury, and cadmium, facilitating targeted environmental management strategies to address the potential health risks associated with heavy metal contamination in Umunede aquifers.

Table 4: Aquifer Characteristics

Location	Aquifer Type	Permeability (m/day)	Porosity (%)
L1	Confined	0.025	15.678
L2	Unconfined	0.034	20.123
L3	Semi-Confined	0.028	18.567
L4	Confined	0.021	14.890
L5	Unconfined	0.036	22.345
L6	Semi-Confined	0.030	21.012
L7	Confined	0.018	13.234
L8	Unconfined	0.032	19.456
L9	Semi-Confined	0.027	17.789
L10	Confined	0.022	15.012
L11	Unconfined	0.038	23.567
L12	Semi-Confined	0.029	20.789
L13	Confined	0.019	14.345
L14	Unconfined	0.033	18.012
L15	Semi-Confined	0.026	16.234

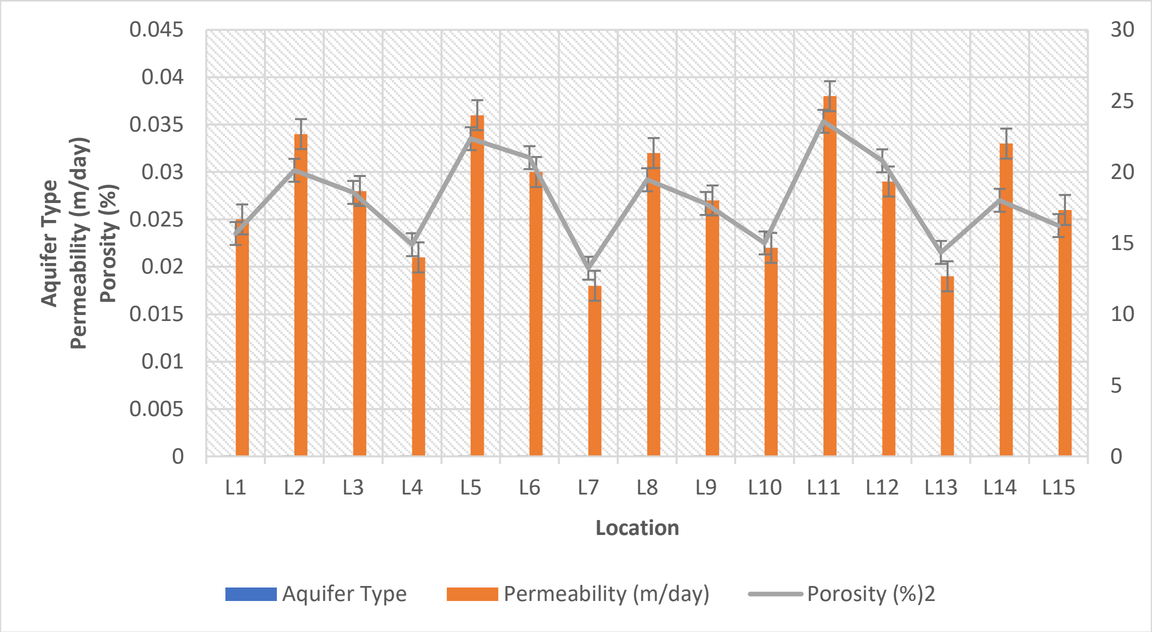

Figure 4: Aquifer type permeability

The combination graph of Table 4 illustrates the aquifer's permeability and porosity at several sites, providing a detailed overview of the study area's physical attributes. This graph displays permeability as a line chart and porosity as a bar chart, allowing for a detailed analysis of the variations in these important properties across different sites.

The graph represents each location along the x-axis, providing a clear spatial context for the aquifer characteristics. The left y-axis corresponds to the permeability values measured in meters per day, showcasing a range of values across the locations. The line connecting these points enables the identification of trends or patterns in permeability. Meanwhile, the right y-axis corresponds to the percentage values of porosity, with individual bars representing the porosity levels for each location.

The line chart reveals distinctive variations in permeability, indicating spatial heterogeneity in the ability of the aquifer to transmit water. Peaks and troughs in the line suggest higher and lower permeability areas, respectively. Such variations can indicate geological features, such as fractures or varying degrees of sedimentary deposits, significantly influencing fluid flow within the aquifer.

Simultaneously, the bar chart for porosity provides insights into the aquifer's capacity to store water within its pore spaces. The varying heights of the bars represent differences in porosity percentages across locations. High porosity suggests a more significant potential for water storage, while lower values may indicate more compacted or less porous subsurface materials.

The combo graph facilitates the identification of potential correlations or inverse relationships between permeability and porosity. For instance, a location with high permeability might exhibit lower porosity, reflecting a trade-off between water flow and storage capacity. Conversely, locations with low permeability may display higher porosity, indicating reduced water transmission but increased storage potential.

In summary, the combo graph for Table 4 effectively communicates the spatial distribution and interrelation of aquifer permeability and porosity in Umunede. The integration of line and bar charts offers a comprehensive visualization that aids in deciphering the complex geological characteristics of the aquifer, which is crucial for understanding water movement and storage within the study area.

Table 5: Microbial Content in Groundwater (CFU/mL)

Well ID	Measurement 1	Measurement 2	Measurement 3
W1	1200	900	1050
W2	980	1150	850
W3	1350	870	950
W4	1100	800	1200
W5	950	1250	890
W6	1050	920	1100
W7	880	1100	930
W8	1150	950	1050
W9	950	1030	900
W10	1220	880	1130
W11	1180	920	990
W12	1280	950	1080
W13	1350	880	1170
W14	1120	940	1020
W15	1260	970	1100

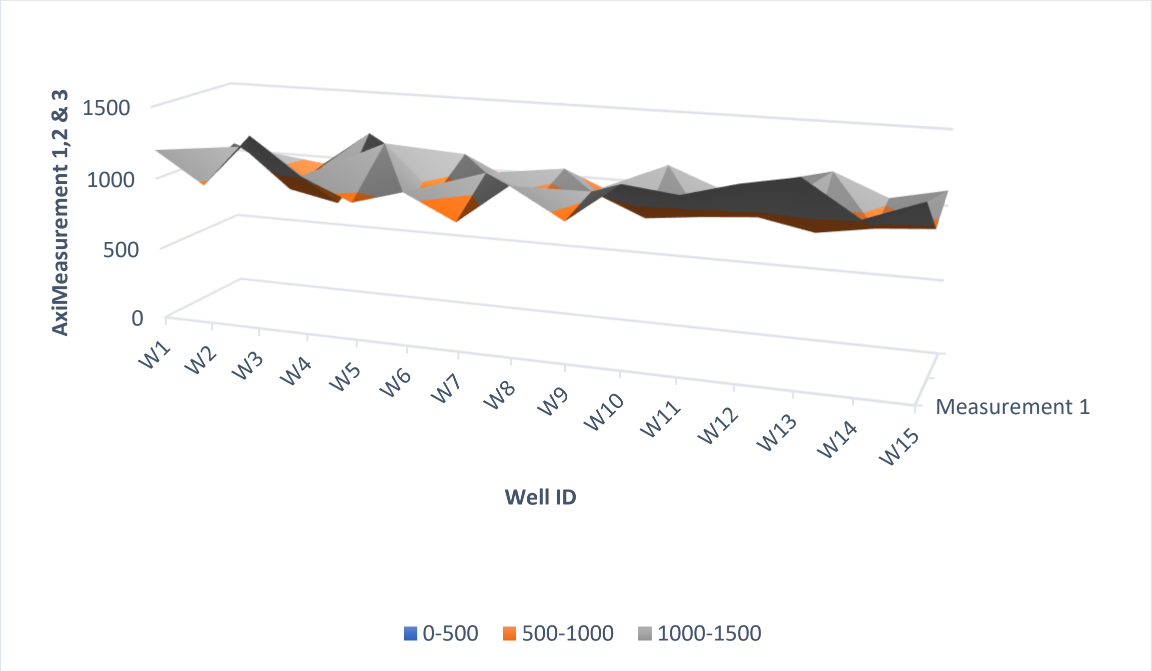

Figure 5: Microbial Content in Groundwater (CFU/mL)

The 3D surface graph of table 5, represents the microbial content (measured in Colony Forming Units per millilitre - CFU/mL) across different wells (Well ID) and measurements. The x-axis corresponds to the Well ID, the y-axis represents the three individual measurements for microbial content, and the z-axis depicts the actual microbial content values in CFU/mL.

Upon observing the graph, we can discern clear patterns and variations in microbial content across the wells. Each peak or trough on the surface graph signifies a particular well's microbial content concerning the three measurements taken. The variations in the surface indicate the heterogeneity in microbial presence among the sampled wells.

The peaks in the graph denote wells with higher microbial content, while troughs represent wells with lower microbial counts. Wells with consistently elevated microbial content across all three measurements are visually distinct, forming identifiable peaks in the 3D landscape. Similarly, wells with consistently lower microbial content contribute to the lower areas in the graph.

The graph also allows for the identification of potential outliers or anomalies. Any irregularities, such as a sudden spike or dip in microbial content for a specific well, may indicate localized contamination sources or unique hydrogeological conditions influencing microbial proliferation.

The colour gradient on the surface adds another layer of information, representing the magnitude of microbial content. Darker regions indicate higher microbial counts, while lighter regions correspond to lower counts. This colour representation aids in quickly identifying wells with extreme microbial variations.

The 3D surface graph comprehensively visualizes microbial content across wells and measurements. It not only highlights patterns and trends but also facilitates the identification of potential hotspots or areas with distinctive microbial characteristics. This graphical representation enhances the understanding of groundwater microbial dynamics, which is crucial for assessing water quality and identifying areas requiring targeted remediation efforts.

Discussion

The results of this study provide valuable insights into the dynamics of dumpsite plumes in the Umunede aquifers, as well as the associated groundwater quality and hydrogeological characteristics.

Firstly, the geophysical surveys using Very Low Frequency (VLF) techniques have revealed subsurface conductivity fluctuations, particularly around 35 meters. This is in line with Musa et al. (2019), who stated that this peak in conductivity measurements suggests the presence of materials or conditions influencing electromagnetic response, potentially indicating the presence of contaminant plumes or geological features affecting conductivity. Moreover, Watts et al (2022) opined that a geophysical survey identified three distinct layers of overburden, weathered, and fresh basement in Shika, Nigeria, with higher seismic velocities at deeper depths and resistivity > 1500 m. This finding underscores the effectiveness of VLF techniques in identifying potential contamination zones and mapping the spatial extent of dumpsite plumes within the aquifer system.

Second, analysis of groundwater samples provides detailed information on water quality parameters such as pH, heavy metal concentrations, and microbial composition, with observed spatial differences in pH across wells indicating changes in the chemical composition of water bodies, which may have an impact on the availability of local soil hydrologic resources, elevated levels of copper, mercury and cadmium. It has been shown that these parameters occur if ongoing monitoring and improvement efforts are needed to emphasize groundwater quality and public health protection.

Furthermore, the analysis of aquifer characteristics, including permeability and permeability, provides insights into the hydraulic properties of the Umunede aquifer. Changes in permeability indicate spatial variations in flow rates, which may influence contaminant transport in the aquifer system. As demonstrated by Qin et al. (2020). Porosity data provide information about the storage and transport capacity of the aquifer, thus affecting groundwater availability and recharge strategies.

In addition, analyses of microorganisms in groundwater samples reveal spatial variations in microbial densities, with a well consistently showing higher or lower microbial densities. Similarly, Meng et al. (2019) reported that microbial diversity in groundwater decreases along the groundwater flow path, with unsaturated zones having higher richness and diversity and physiochemical parameters affecting their composition.

Variations may indicate regions where pollution sources or unique aquatic conditions affect bacterial growth. Understanding microbial dynamics is essential for assessing water quality and identifying potential health risks associated with microbial contamination.

Overall, the results of this study highlight the complex interplay of hydrochemical, geochemical, and biological factors influencing dumpsite plume dynamics and groundwater quality in the Umunede aquifers in the 1990s. These findings provide valuable environmental management and decision-making information, guiding targeted remediation efforts and sustainable water resource planning in the study area.

CONCLUSION

The study on dumpsite plumes in Umunede aquifers, using various VLF techniques, groundwater sampling, and aquifer characterization, has provided valuable insights into environmental dynamics and groundwater quality. VLF measurements at various depths revealed distinct conductivity patterns, guiding targeted environmental monitoring efforts. Groundwater analysis revealed different pH levels and heavy metal levels, providing insight into contamination levels and potential sources in the aquifer system. Aquifer properties such as permeability and porosity revealed the variability of underground conditions, impacting groundwater movement and storage. Microbial content examinations provided crucial information on the biological quality of groundwater, essential for public health issues.

This research provides valuable approaches and insights for similar environmental studies worldwide, demonstrating the effectiveness of integrating geophysical and hydrogeological data in dumpsite plume mapping. The methodological improvements in hydrogeophysics and environmental geophysics improve tactics for measuring and maintaining groundwater quality. The study fills a significant vacuum in the literature by examining dumpsite plume mapping with VLF techniques, providing a distinct viewpoint that enhances current understanding of hydrogeophysics and environmental monitoring.

The study makes several recommendations for environmental management and mitigation in the Umunede watershed, including continuous groundwater quality monitoring, targeted mitigation, watershed protection, public awareness and education, collaboration, research, and innovation. Land regular monitoring of bottom water quality is essential to monitor changes and identify pollution issues.

REFERENCES

Agu, R., & Mallam, A. (2023). Investigation of Leachate Plume and Groundwater Pollution using Geophysical and Physio-chemical Methods in an Open Dumpsite at Idugosa, Federal Capital Territory (FCT), Abuja, Nigeria. PHYSICS ACCESS. https://doi.org/10.47514/phyaccess.2023.3.2.004.

Akinola, B., Awoyemi, M., Matthew, O., & Adebayo, A. (2018). Geophysical and hydro-chemical investigation of contamination plume in a basement complex formation around Sunmoye dumpsite in Ikire, Southwestern Nigeria. MODELING EARTH SYSTEMS AND ENVIRONMENT, pp. 4, 753–764. https://doi.org/10.1007/s40808-018-0455-8.

Jamal, N., & Singh, N. (2018). Identification of fracture zones for groundwater exploration using shallow frequency electromagnetic (VLF-EM) and electrical resistivity (ER) methods in the hard rock area of Sangod Block, Kota District, Rajasthan, India. GROUNDWATER FOR SUSTAINABLE DEVELOPMENT. https://doi.org/10.1016/J.GSD.2018.05.003.

Locatelli, L., Binning, P., Sanchez-Vila, X., Søndergaard, G., Rosenberg, L., & Bjerg, P. (2019). A simple contaminant fate and transport modeling tool for management and risk assessment of groundwater pollution from contaminated sites. JOURNAL OF CONTAMINANT HYDROLOGY, 221, 35-49. https://doi.org/10.1016/j.jconhyd.2018.11.002.

McLean, M., Evers, L., Bowman, A., Bonte, M., & Jones, W. (2019). Statistical modeling of groundwater contamination monitoring data: A comparison of spatial and spatiotemporal methods. THE SCIENCE OF THE TOTAL ENVIRONMENT, p. 652, 1339–1346. https://doi.org/10.1016/j.scitotenv.2018.10.231.

Meng, L., Zuo, R., Wang, J., Yang, J., Li, Q., & Chen, M. (2019). The spatial correlation variations between microbial diversity and groundwater quality derived from a riverbank filtration site in northeast China. THE SCIENCE OF THE TOTAL ENVIRONMENT, 706, 135855. https://doi.org/10.1016/j.scitotenv.2019.135855.

Musa, Z., Jimoh, R., & Eshimiakhe, D. (2019). A two-dimensional image of seismic refraction and electrical resistivity tomography survey in a proposed geophysical test site at Shika, Ahmadu Bello University Zaria, Nigeria. GOMBE JOURNAL OF ENVIRONMENTAL SCIENCE, 4, 56-66. https://doi.org/10.31248/GJEES2019.031.

Ohwoghere-Asuma, O., Aweto, K., Chinyem, F., & Nwankwoala, H. (2018). Assessing the Protective Capacity of Aquifers Using Very-Low-Frequency Electromagnetic Survey. GEOSCIENCES, 8, 150. https://doi.org/10.3390/GEOSCIENCES8050150.

Oseji, J., Egbai, J., Okolie, E., & Ese, E. (2018). Investigation of the Aquifer Protective Capacity and Groundwater Quality around Some Open Dumpsites in Sapele Delta State, Nigeria. APPLIED AND ENVIRONMENTAL SOIL SCIENCE. https://doi.org/10.1155/2018/3653021.

Osinowo, O., Agbaje, M., & Ariyo, S. (2020). We integrated geophysical investigation techniques for mapping cassava effluent leachate contamination plume at a dump site in Ilero, southwestern Nigeria. SCIENTIA AFRICANA, 8. https://doi.org/10.1016/j.sciaf.2020.e00374.

Pauliuk, S. (2019). Making sustainability science a cumulative effort. NATURE SUSTAINABILITY, pp. 3, 2–4. https://doi.org/10.1038/s41893-019-0443-7.

Qin, X., Hua, Y., Sun, H., Xie, J., & Zhao, Y. (2020). Visualization study on aniline-degrading bacteria AN-1 transport in the aquifer with the low-permeability lens. WATER RESEARCH, p. 186, 116329. https://doi.org/10.1016/j.watres.2020.116329.

Ravindra, K., Thind, P., Mor, S., Singh, T., & Mor, S. (2019). Evaluation of groundwater contamination in Chandigarh: Source identification and health risk assessment.. ENVIRONMENTAL POLLUTION, 255 PT 1, 113062. https://doi.org/10.1016/J.ENVPOL.2019.113062.

Ugbor, C., Ikwuagwu, I., & Ogboke, O. (2021). 2D inversion of electrical resistivity investigation of contaminant plume around a dumpsite near Onitsha expressway in southeastern Nigeria. SCIENTIFIC REPORTS, 11. https://doi.org/10.1038/s41598-021-91019-3.

Voulvoulis, N., & Burgman, M. (2019). The contrasting roles of Science and technology in environmental challenges. CRITICAL REVIEWS IN ENVIRONMENTAL SCIENCE AND TECHNOLOGY, 49, 1079 - 1106. https://doi.org/10.1080/10643389.2019.1565519.

Watts, H., Booth, A., Reinardy, B., Killingbeck, S., Jansson, P., Clark, R., Chandler, B., & Nesje, A. (2022). An Assessment of Geophysical Survey Techniques for Characterizing the Subsurface Around Glacier Margins, and Recommendations for Future Applications. https://doi.org/10.3389/feart.2022.734682.

Yan, X., Dong, W., An, Y., & Lu, W. (2019). A Bayesian-based integrated approach for identifying groundwater contamination sources. JOURNAL OF HYDROLOGY, 579, 124160. https://doi.org/10.1016/j.jhydrol.2019.124160.

Ugbor, C., Ikwuagwu, I., & Ogboke, O. (2021). 2D inversion of electrical resistivity investigation of contaminant plume around a dumpsite near Onitsha expressway in southeastern Nigeria. SCIENTIFIC REPORTS, 11. https://doi.org/10.1038/s41598-021-91019-3