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A Review: The Role of Electrical Resistivity in Groundwater Exploration and Management

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Abstract

The review paper explores the use of electrical resistivity techniques to explore and manage groundwater, providing vital insights into aquifer properties and the behavior of groundwater. It delves into the principles and applications, limitations, and potential future developments. Groundwater is a very important water source for sustainable development, especially in dry areas thereby making effective groundwater exploration essential. Geophysical techniques like vertical electrical resistivity soundings (VES) and electrical resistivity tomography (ERT) are some of the methods used in analyzing subsurface characteristics and the behavior of aquifers. These methods allow the identification of hydrogeological parameters such as water saturation, porosity, and aquifer boundaries. This article further explores how instrumentation advancements, machine learning, and integrated approaches also improve accuracy in subsurface imaging despite geological complexities and interpretation ambiguities. The resistivity methods have proven effective in coastal aquifers, detecting saltwater intrusion, and monitoring groundwater quality.

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Keywords: Electrical Resistivity, Groundwater Exploration, Aquifer Mapping, Electrical Resistivity Tomography, Sustainable Water Management

Introduction

Groundwater exploration and management are important to sustain water resource utilization, especially in dry regions. Remote sensing and GIS technologies have emerged as efficient and cost-effective tools for mapping groundwater and exploration (Elbeih, 2014; Jha *et al.,* 2006). These methods allow for the delineation of potential groundwater targets and provide important interpretation for decision-making related to sustainable development and groundwater management (Elbeih, 2014). Interestingly, the success rate of these technologies remains limited despite the applications in groundwater studies since the 1990s, with most applications still in their infancy (Jha *et al.,* 2006). The risk of groundwater contamination from gas exploration is a major concern in society particularly in densely populated areas where groundwater is essential for drinking, agriculture, and industrial purposes. Effective groundwater management and exploration need an integrated approach combining various techniques. This includes geophysical methods (electrical resistivity surveys), remote sensing, and GIS (Elbeih, 2014; Jha *et al.,* 2006), and hydrogeochemical investigation (Aranguren-Díaz *et al.,* 2024). These approaches provide important information about the spatial and depth variation of the aquifers, helping in the prediction and enhancement of groundwater resource management.

Electrical resistivity methods are essential in hydrogeological studies, providing a non-invasive and economical way to assess subsurface characteristics and groundwater resources. These methods can effectively map subsurface structures and their properties. By measuring the distribution of electrical resistivity in the ground, which can vary from less than 1 Ohm.m to thousands of Ohm.m (Kumar, 2012), these techniques can infer different physical parameters like moisture content, soil structure, and fluid composition. This makes them particularly beneficial for groundwater investigations across various geological environments due to their broad resistivity range compared to other geophysical measures (Kumar et al., 2014). Moreover, electrical resistivity imaging (ERI) can be applied in coastal hydrogeological assessment and tracking seawater intrusion, as it can detect changes in pore-water salinity, hence aiding coastal groundwater investigation. Resistivity

imaging has also proven effective in the delineation of pollution plumes in bedrock environments, with research conducted on a sewage disposal site in Nigeria illustrating its capabilities. Additionally, because of the versatility of this technique, it has been employed to examine the vulnerability of the aquifer, characterize alluvial aquifers in mountainous regions, and understand the interplay between surface water and groundwater (Benabdelouahab et al., 2019; Koch et al., 2009).

Electrical Resistivity Tomography (ERT) is a method that provides 2D and 3D resistivity models of subsurface regions. It finds applications in numerous areas, including groundwater exploration, environmental assessments, engineering disciplines, and landslide studies (Drahor et al., 2006; Kumar, 2012). ERT is beyond resistivity techniques by offering denser data coverage and the capacity to unravel complex geological formations (Kumar, 2012). Enhancements in recent technology have improved ERT's effectiveness significantly, allowing for more precise and elaborate imaging of subsurface features (Abu-Zeid et al., 2005). Furthermore, ERT is an effective instrument for investigating various geological, environmental, and engineering challenges. Its sensitivity, and capability to produce high-resolution subsurface images make ERT crucial for a wide range of applications, from assessing groundwater resources to monitoring landslides and appraising the quality of restored foundations in construction (Abu-Zeid et al., 2005; Drahor et al., 2006). ERT in crystalline terrains is particularly advantageous for exploring alteration zones critical to groundwater accessibility in low-porosity areas (Briški et al., 2020). By integrating electrical resistivity methods with techniques such as magnetic resonance tomography, and electromagnetic, the reliability of interpretations related to complex geological, and hydrological issues can be enhanced. This multi-method approach, along with hydrochemical and hydrometric data, gives detailed insights into groundwater dynamics and subsurface attributes (Briški et al., 2020; Koch et al., 2009).

This study aims to investigate the principles and methodologies of electrical resistivity in groundwater exploration and management, focusing on the evaluation of key techniques such as Vertical Electrical Sounding (VES), Electrical Resistivity Tomography (ERT), and Time-Domain Electromagnetics (TDEM). It explores their applications in aquifer characterization, the integration of resistivity methods with complementary geophysical techniques, and their role in monitoring aquifer dynamics.

Principles and Applications of Electrical Resistivity in Groundwater Exploration

Electrical resistivity is a fundamental geophysical technique that determines the ability of a material to resist the flow of electric current. This principle plays a crucial in groundwater exploration, as it enables the identification of subsurface materials based on their electrical properties. The resistivity of geological structures is influenced by factors that include moisture content, composition, porosity, and structure. In hydrogeological investigations, electrical resistivity provides a non-invasive means to evaluate subsurface structures, making it useful in groundwater resources. Measurement techniques include the two-electrode and four-electrode methods, with the latter being preferred due to its ability to mitigate contact resistance issues (Cosoli et al., 2020). These techniques have been vital in evaluating aquifer properties and supporting groundwater management.

The relationship between electrical resistivity and moisture content is essential in groundwater exploration. Generally, resistivity decreases with increasing moisture and porosity, following a hyperbolic trend where significant drops occur at lower moisture levels before stabilizing at higher concentrations (Kibria and Hossain, 2012). These characteristics allow geosciences to deduce water saturation levels and distinguish between geological formations. Furthermore, oil presence has minimal impact on electrical resistivity, whereas open porosity plays a more vital role compared to closed porosity. A 40% increase in open porosity can lead to a 250% rise in resistivity, whereas a similar increase in closed porosity results in only a 25% rise. Understanding these relationships is critical for the accurate interpretation of resistivity data in groundwater investigations.

The resistivity methods are extensively employed for groundwater exploration, offering a cost-effective and efficient means of characterizing aquifers and underground structures (Kumar et al., 2014). These methods are particularly utilized in detecting changes in pore-water salinity, making them effective in coastal groundwater investigation. Techniques such as vertical electrical sounding (VES) and electrical resistivity tomography (ERT) are very reliable in delineating aquifers and estimating hydraulic properties (Ekanem et al., 2019). Advancements in microcomputer-controlled instruments like the GEA-58, have improved data acquisition and interpretation. However, complexities in geological structures can pose challenges, necessitating the integration of resistivity methods with other geophysical techniques such as electromagnetic and magnetic resonance tomography to enhance reliability and accuracy (Asfahani et al., 2023).

Electrical resistivity methods play a crucial role in sustainable groundwater resource management. They aid in identifying aquifer boundaries, detecting contamination, and mapping saltwater intrusion, which is important in coastal regions vulnerable to seawater encroachment (Batayneh, 2006; Himi et al., 2016). The application of ERT and frequency-domain electromagnetic methods has been particularly effective in mapping salinity variations and assessing water quality. In addition, the Horizontal to Vertical Spectral Ratio (HVSR) seismic method has been utilized to determine the relationship between resonance frequency and bedrock depth, which helps in delineating shallow aquifers. Integrated approaches, combining geophysical techniques with hydrochemical and isotopic analyses, provide a comprehensive understanding of complex aquifer systems and improve the accuracy of groundwater assessments (Abotalib et al., 2021). These methodologies are important in improving long-term groundwater management strategies, and ensuring the sustainability of water resources in diverse geological settings (Gottschalk et al., 2020).

Integration with other Geophysical Methods

Ground Penetrating Radar (GPR) can be effectively integrated with other geophysical methods to provide elaborate characteristics of subsurface structures. The integration of GPR with other geophysical methods including gravity methods of survey, seismic methods, electrical methods, and magnetic surveys offers complementary data that enhances the overall understanding of subsurface structures and properties. Combining GPR with seismic methods can yield valuable insights into subsurface structures. For instance, in the investigation at the Grimsel Test Site located in Switzerland, researchers combined ground-penetrating radar reflection imaging with seismic travel-time tomography to investigate rock volumes between boreholes and tunnels. This integration enables the identification of ductile shear zones imaged by GPR and showed increased seismic anisotropy, while regions of decreased seismic p-wave velocity correlated with high fracture density. Combining GPR with gravity and magnetic methods has proven effective in delineating underground cavities. A case study near Zaragoza, Spain, demonstrated the applications of geophysical techniques which include magnetic, low-frequency GPR, and microgravity techniques. The strong contrast in magnetic, electromagnetic, and density properties between surrounding rocks and doline fillings allowed for clear delineation of filled cavities. The benefits of integrated approaches are evident in various applications. According to Carbonel *et al.,* (2013), combining GPR with electrical resistivity tomography

(ERT) and trenching techniques in karst areas has proven advantageous for sinkhole characterization (Carbonel *et al.,* 2013). While ERT provided information on the approximate location of sinkhole edges, GPR surveys revealed the 3D internal geometry and dominant subsidence mechanisms. Similarly, in cave mapping, the integration of GPR and microgravimetric surveys has been shown to provide better constraints on interpreted geological models than using either method alone (Beres *et al.,* 2001). Furthermore, the integration of GPR with other geophysical techniques provides more elaborate and accurate characteristics of the subsurface. This integrated approach allows for the validation of geophysical results, provides complementary data, and helps overcome the limitations of individual techniques, thereby leading to more reliable interpretations of complex subsurface environments.

Case Studies

A Case History of the Use of the Electrical Resistivity Method in Assessing Groundwater Iron Concentration in Otuoke and its Environs

To enhance understanding of the electrical resistivity method in the investigation of groundwater, we present a case study of Oghale and Arekumo (2023), who outline a comprehensive assessment of groundwater iron concentration in Otuoke and its Environs by integrating electrical resistivity methods with hydrogeochemical and borehole data to enhance the reliability of subsurface assessments. The electrical methods, including eight (8) vertical geoelectrical soundings were used, geochemical analysis, including eight (8) groundwater samples, and 1 borehole log to analyze subsurface structures. The results revealed a clay topsoil layer (0.5-1.3 m depth, 15.8-112 Ωm resistivity) and a coarse sand aquiferous layer (1.7-3.5 m depth, 84.5-225 Ωm resistivity) separated by a sandy-clay transition zone, while also establishing a significant correlation between high iron concentrations and low resistivity values in shallow groundwater.

According to research by Oghale and Arekumo (2023), the integration of multiple geophysical and geochemical techniques yielded robust insights into subsurface characterization, demonstrating a valuable inverse correlation between electrical resistivity values and groundwater iron concentrations. Through the synthesis of electrical resistivity methods, hydrogeochemical analyses, and stratigraphic data from borehole logging, we successfully delineated the vertical succession of lithological units, comprising a clay-rich

topsoil underlain by a productive coarse-grained aquifer system. These integrated methods enhanced the resolution of subsurface imaging and established a cost-effective framework for groundwater quality assessment. This integrated approach is important to regions like Otuoke, Nigeria, where accurate delineation of aquifer properties is essential for sustainable water resource management

Role in Groundwater Management

Groundwater management relies heavily on continuous monitoring of aquifer dynamics, assessing recharge and discharge processes, and assessing the effectiveness of artificial recharge. These aspects are important for sustainable water resource management, especially in semi-arid and arid areas where water scarcity presents a significant challenge. Monitoring aquifer dynamics, and assessing groundwater recharge and discharge patterns are paramount for understanding the groundwater system's behavior. Remote sensing and GIS techniques have proven effective in mapping recharge and discharge areas. These methods provide the identity of surface indicators like vegetation activity, terrain analysis, and infiltration capacity, providing a framework for systematic mapping across catchments. Additionally, groundwater flow and solute transport models like MODFLOW and MT3DMS are essential tools for simulating aquifer dynamics and assessing the impact of various management strategies. Artificial recharge has emerged as a key strategy for groundwater management, especially in areas experiencing depletion or seawater intrusion. Evaluating the effectiveness of artificial recharge interventions is vital in ensuring their long-term viability. Studies have shown that artificial recharge can significantly improve groundwater levels and quality. For instance, in the Korba aquifer of Tunisia, artificial recharge using treated wastewater resulted in a groundwater level increase of up to 2.7 m and a reduction in salinity by 5.7 g/L.

Similarly, in Iraq's Dibdibba unconfined aquifer, artificial recharge using reclaimed water increased groundwater levels and significantly improved the quality, with TDS decreasing by over 55% (Hassan *et al.,* 2023). Moreover, effective groundwater management requires a comprehensive approach that integrates monitoring, assessment, and evaluation of artificial recharge. Remote sensing, GIS applications, and groundwater modeling collectively improved our understanding of complex aquifer interactions, enabling informed decision-making for sustainable water resource management. The synergy between these methods

provides valuable insights into the complex interactions within groundwater systems and helps in developing targeted strategies for recharge and conservation.

Limitations and Challenges

Interpretation of geophysical data faces several limitations and challenges, particularly in geologically complex and urban environments. A primary limitation in geophysical inversion is ambiguity, emanating from the non-uniqueness of potential field solutions, which leads to multiple plausible subsurface models, making it difficult to estimate the true subsurface structure. This ambiguity is further exacerbated by the lack of large, labeled datasets for validating or training machine learning and inversion schemes in geosciences (Jessell *et al.,* 2022). To mitigate these ambiguities, cooperative inversion approaches that combine multiple data types, such as surface seismic, sonic logs, and gravity data, can be employed to reduce uncertainties. Urban settings and intricate geological formations present additional site-specific difficulties. In densely built environments, the acquisition and interpretation of LiDAR data are complicated by obstructions like high-rise buildings and heavy traffic (Jeong *et al.,* 2018). Geological complexities, such as the interbedding of stiff gravels and soft sediments in Christchurch, New Zealand, complicate the interpretation of surface wave data and compound optimal parameterization for inversion. Similarly, in regions with high magnetic susceptibility, self-demagnetization effects can significantly distort magnetic data interpretation.

Data processing and inversion methodologies also pose substantial challenges in geophysical studies. The lack of extended quantitative techniques for analyzing natural geomorphological patterns and structures limits the interpretation of complex terrains (Baas, 2007). Traditional 2D minimum-structure inversions tend to produce models with spatially smooth resistivity transitions, obscuring critical layer boundaries in sedimentary environments (Auken & Christiansen, 2004). To overcome these limitations, advanced approaches such as the joint inversion of gravity and magnetic data, as well as resistivity inversion techniques incorporating lateral constraints and sharp boundary definitions, have been developed to improve model accuracy and subsurface characterization (Auken & Christiansen, 2004).

Emerging Trends and Future Directions

Remote sensing and Geographic Information Systems (GIS) have emerged as indispensable tools for data acquisition and processing in various fields, including geomorphology, hydrology, and environmental monitoring. Integrating remote sensing, GIS, and Global Positioning System (GPS) has transformed groundwater hydrology, resource management, and environmental monitoring. Recent advancements in these fields have facilitated more efficient and cost-effective data handling, allowing for the simultaneous processing of large datasets.

Machine learning (ML) and artificial intelligence (AI) have significantly enhanced the interpretation of resistivity data and the development of real-time monitoring systems for groundwater management. These technologies enhance the accuracy and efficiency of underground analysis, enabling the detection of complex hydrogeological patterns. Machine learning algorithms are now being used to assess surface water, groundwater, and seawater quality across different environments. Techniques such as distribution-guided clustering (DGC) provide automated identification of variation in resistivity sections, correlating well with direct groundwater observations. Such improvement streamlines data interpretation and enhances automated groundwater monitoring by setting alarm thresholds for rapid environmental changes.

Groundwater monitoring has been transformed by artificial intelligence approaches, such as Automated Time-Lapse Electrical Resistivity Tomography (ALERT) systems. These systems generate continuous, remote monitoring of coastal aquifers, generating high-resolution geoelectric images at regular intervals without the need for repeated surveys. The integration of AI into resistivity data analysis, enhanced spatial and temporal resolution, improved automated data processing, and refined predictive models. These new technologies are transforming groundwater management by enabling proactive decision-making, protecting water resources, and ensuring sustainable environmental practices. As ML and AI continue to advance, their integration with geophysical methods will further optimize resource management strategies, ensuring more efficiency and effectiveness.

Conclusion

Electrical resistivity methods are highlighted as essential tools in groundwater exploration, providing a non-invasive and cost-effective means to characterize subsurface properties.

These techniques leverage the relationship between electrical resistivity and hydrogeological characteristics such as porosity, clay content, and water saturation. The versatility of electrical resistivity methods allows for their application across various geological settings, making them particularly valuable for mapping aquifers, detecting pollution plumes, and monitoring seawater intrusion in coastal areas. The integration of electrical resistivity with other geophysical methods enhances the reliability of interpretations, thereby improving groundwater management strategies. Overall, these methods facilitate a better understanding of aquifer dynamics, which is crucial for sustainable groundwater resource management.

Looking ahead, the document indicates that advancements in electrical resistivity technologies will likely enhance their effectiveness in groundwater exploration. The development of more sophisticated instruments and data processing techniques will improve the accuracy of subsurface imaging and characterization. As water scarcity becomes an increasingly pressing issue globally, the ability to efficiently locate and manage groundwater resources will be paramount. The ongoing integration of electrical resistivity methods with remote sensing and GIS technologies is expected to yield significant benefits for decision-making processes related to sustainable water resource management. Ultimately, these advancements can lead to more effective strategies for safeguarding freshwater resources against over-exploitation and contamination, ensuring their availability for future generations.

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