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Groundwater exploration, management strategies and sustainability: Geophysical approaches

Joseph Omeiza Alao[a,*], Fahad Abubakar[b]

[a] Department of Physics, Air Force Institute of Technology, Kaduna, Nigeria
[b] Department of Geosciences, Confluence University of Science and Technology, Osara, Nigeria

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ABSTRACT

Groundwater is a hidden yet vital for life sustainable resource for billions across the world. However, it is often overlooked despite accounting for over one-third of global freshwater supplies. Geophysics plays a critical role in exploring, developing, and sustaining groundwater resources. This review article provides an in-depth analysis of the various roles of geophysics in groundwater development and sustainability, highlighting the importance of geophysical methods in mapping subsurface structures, characterizing aquifer properties, monitoring groundwater levels, detecting contamination, optimizing well siting, and assessing groundwater recharge processes. It also examines the transformative power of geophysical techniques, highlighting their effectiveness in mapping aquifer properties such as thickness, depth, volume, hydraulic conductivity, flow pathway, faults, and fractures to monitor groundwater levels and assess aquifer potential and vulnerability. Case studies demonstrate the efficacy of geophysical methods in groundwater studies across the globe. For instance, electrical resistivity (ER) surveys have been employed to identify promising aquifer zones with relative resistivity values ranging from 10 Ωm to 500 Ωm and transmissivity values ranging from 0.79 to 1203 m^2/day, occurring with depths of ≥ 5 m. Seismic surveys have accurately delineated aquifer depths from 24 to 150 m Furthermore, geophysical techniques have been instrumental in detecting and delineating groundwater contamination plumes, with studies revealing low resistivity zones (<15 Ωm) associated with contaminant plumes. The limitations and strengths of geophysical methods were also discussed alongside the other methods, such as geological observation, hydrogeological survey, test drilling, remote sensing (RS), and tracing its evolution from the era of blind exploration. While challenges exist, the future of groundwater management hinges on the continued development and application of geophysical methods. By integrating these techniques with the insights from hydrogeological and other methods, we can optimize well-siting, enhance aquifer recharge, and ensure long-term sustainable groundwater resource management (GWRM). This study underscores the vital role of geophysical methods in bridging the gap between knowledge and action, paving the way for a water-secure future.

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[*] Corresponding author.
E-mail address: alao.jo@afit.edu.ng (J.O. Alao).

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1. Introduction

Groundwater remains one of the most essential natural resources hidden beneath the Earth's surface, but is often the most undervalued component of global resources (Alao et al., 2024a). It is a vital lifeline, accounting for nearly one-third of the world's freshwater supplies, particularly in areas where surface water is limited or unpredictable (Foster and Chilton, 2003; Aslam et al., 2018). A recent study shows that while freshwater constituted only 3.5% of the available water on the earth, the oceans occupied about 96.5% (Singh et al., 2020). Groundwater is widely known to be found everywhere on the planet (UNESCO, 2022). However, it is unevenly distributed over the earth, occurring in abundance only in specific geologic formations and structures, which are hidden from the earth's surface. Investigating and exploring this hidden resource requires a variety of scientific methods (Alao, 2025). Geophysics stands as a cornerstone in the journey towards groundwater exploration, development, management, and sustainability, offering innovative solutions to the challenges of locating the exact position and depth of occurrence (Alao et al., 2024b, c). Groundwater exploration is becoming more and more crucial in both urban and rural areas of a nation, particularly in emerging nations, as a result of the diminishing groundwater levels in several parts of the world, especially in India (Shiksha, 2014). In the past decades, geophysics has been identified as a powerful scientific tool that transformed the landscape of groundwater exploration with different cutting-edge techniques to unveil the hidden aquifers, offering a beacon of hope for water-scarce regions (Alao et al., 2023a).

Groundwater security in the face of rising demand and climate change depends on the sustainable management of this essential resource (Alao et al., 2024a), which serves household, industrial, and agricultural demands. The study of the Earth using physical methods, such as geophysics, provides important information about conditions beneath the surface. Geophysical methods provide non-invasive and cost-effective tools for assessing subsurface hydrogeological conditions, mapping aquifer properties, and monitoring groundwater dynamics (Omeiza et al., 2023a). Geophysicists can map subterranean water supplies, locate aquifers, and track their health by using methods like ER, seismic surveys, magnetic resonance imaging, and ground-penetrating radar (GPR) (Sharma and Baranwal, 2005). The distribution, volume, and quality of groundwater reserves can be seen through the comprehensive subsurface images produced by these non-invasive techniques. For example, by detecting changes in subsurface resistivity, electrical resistivity tomography (ERT) aids in the delineation of groundwater-saturated zones (Loke et al., 2021; Alao et al., 2024d). Geophysics plays a part in more than only exploration. It includes the sustainable monitoring and management of groundwater resources. Remote sensing (RS) and geographic information systems (GIS) have been combined with geophysical data to create complete models that sustainably support groundwater management (Ojo et al., 2024). To comprehend recharge areas and identify possible zones for groundwater development, RS provides spatial data on topography, vegetation cover, and land use (Oyedele, 2019; Akinluyi et al., 2021). These disparate datasets may be integrated and analyzed using GIS, which promotes resource management and well-informed decision-making.

The methods and instruments required to get this knowledge are provided by geophysics, which offers an efficient means of visualizing and measuring subterranean water supplies. To sum up, geophysics is essential to the pursuit of sustainable GWRM through groundwater exploration, monitoring, and management because it can offer precise, in-depth insights into subsurface conditions (Sarma, 2009; Mohammed et al., 2023). As the world's water problems worsen, geophysics can provide precise insights into subsurface conditions, making groundwater exploration, monitoring, and management crucial. It will also play a growing role in ensuring the responsible assessment and management of groundwater resources for future generations. This systematic review aims to evaluate the role of geophysics in groundwater development and sustainability, highlighting its contributions, challenges, and potential for enhancing groundwater management practices. In addition, the transformative power of geophysics on groundwater exploration and sustainability, tracing its evolution from the era of blind exploration to the present day, stands as a beacon of hope for a water-secure future. This systematic review will identify relevant studies on geophysics applications in groundwater development and sustainability.

2. The scope and methodology of the study

The article explores how geophysical methods, like ER, seismic surveys, and GPR, are revolutionizing groundwater exploration. The investigation focuses on the diverse applications of geophysical methods, including ER, seismic surveys, GPR, etc., in:

(a) Mapping aquifers, faults, and fractures: the study examines how these techniques provide detailed subsurface images, enabling precise identification of potential groundwater sources and understanding their geological context.
(b) Characterizing aquifer properties: the study explores how geophysics quantifies key aquifer properties like porosity, permeability, and transmissivity, crucial for assessing groundwater availability and vulnerability.
(c) Monitoring groundwater levels: investigations on how geophysical methods track changes in groundwater levels over time, revealing the impact of climate change and human activities on aquifer dynamics, were discussed.
(d) Detecting and delineating groundwater contamination: analysis of how geophysics identifies contaminated zones and guides remediation efforts, ensuring the quality of this vital resource was discussed.
(e) Optimizing well siting: the study explores how geophysical surveys pinpoint optimal well locations, maximizing yield, minimizing costs, and promoting long-term aquifer health.

(f) Assessing groundwater recharge: examinations on how geophysical methods help to understand recharge processes, crucial for sustainable water management strategies.

The methodology of the study involves a comprehensive review of peer-reviewed articles, conference papers, and reports that discuss the use of geophysical methods in groundwater studies. A comprehensive search was conducted in electronic databases using keywords related to geophysics, groundwater, and sustainability. Inclusion criteria will focus on peer-reviewed articles, conference papers, and reports that discuss the use of geophysical methods in groundwater studies. Data extraction includes information on geophysical techniques, study objectives, key findings, and recommendations to provide a global perspective on the transformative power of geophysics in ensuring a water-secure future.

3. Groundwater exploration and the involvement of geophysics

Before the advent of geophysics, assessing groundwater potential relied heavily on empirical observations and indirect methods, which involved traditional or indigenous knowledge and local experience. Local communities often possessed valuable knowledge about water sources, well locations, and seasonal variations in groundwater availability. Historical records and accounts could also provide information about past water availability and usage. However, these methods primarily focused on surface observations and could not provide reliable information about groundwater (Shiksha, 2014). Therefore, reliance on visual observations and empirical relationships could lead to subjective interpretations and inaccurate assessments. In addition, traditional or indigenous knowledge cannot quantify groundwater potential (lack of quantitative data) and provide reliable estimates of water availability. Investigations of groundwater resources can be achieved site-scale, local scale or regional scale (Schwartz and Zhang, 2003). While investigation at the local scale covers an area of a few square kilometres, the investigation at the regional scale covers large-scale groundwater investigations, which typically cover hundreds or thousands of square kilometres (Shiksha, 2014). Site-scale investigation, on the other hand, covers the smallest scale for groundwater investigations with the highest in-depth field investigations of the site under study, which usually involves sites such as industrial sites, waste disposal sites, mining sites, a well field, etc. However, local-scale investigations provide more detailed information about aquifer characteristics, groundwater dynamics, water quality, and geology formation (Milsom, 2003). Irrespective of the scale, a detailed and reliable technique is required to ensure the utmost accurate predictions of findings.

Furthermore, groundwater exploration can be done via the earth's surface or subsurface investigations. While surface investigation involves exploration of groundwater from above-surface sites or the earth's surface, the subsurface investigation involves exploration of groundwater with the use of equipment and tools that extend underground (Lowrie, 2007). Surface examinations of groundwater typically do not yield adequate quantitative information or data about groundwater/aquifer conditions. Surface groundwater investigations are typically less costly and time-consuming compared to subsurface investigations. However, subsurface investigation can provide the necessary accuracy or interpretation to validate the results of surface investigations. According to a noteworthy study, there are two main categories of surface techniques used in groundwater exploration: (a) geology techniques, sometimes known as reconnaissance techniques, and (b) geophysical techniques. Geologic methods involve geology data and field reconnaissance utilizing (i) test pits and trenches, (ii) adits, (iii) continuous cone penetrometers, and (iv) augers, which are essential preliminary investigations of groundwater (Todd, 1980). On the other hand, geophysical explorations of groundwater involve the use of different geophysical techniques such as gravity, seismic, magnetic, ER and RS techniques to delineate and map groundwater repositories.

Aside from the use of geological and geophysical groundwater exploration, "Test Drilling" is another powerful tool for groundwater exploration. This method typically involves the general practice of digging test wells in the investigated regions after reliable information from geological features is obtained from hydrogeological maps or geophysical investigations (Todd, 1980). Though test drilling is not without limitations, it can be costly and time-consuming, cause environmental disruption, and can only provide localized data, which may not present a broader aquifer condition (Todd, 1980). However, the involvement of Geophysics in the 20th centuries, armed with the power of physics and advanced technology, unveils the secrets of the Earth's subsurface, making it the most promising approach. This newfound understanding ushered in a new era of groundwater exploration, management, and sustainability. It empowered geoscientists, professionals, and engineers to locate promising aquifers, predict their yield, position/volume/depth of occurrence, and optimize well placement while ensuring efficient extraction and minimizing environmental impact (Telford et al., 1990). Geophysics continues to play a crucial role in safeguarding groundwater resources through the monitoring of groundwater levels, detecting contamination, and assessing the impact of climate change on aquifers (Alao et al., 2024e). Aquifers and confining layers can be identified through well or borehole logs, which offer trustworthy information about subsurface conditions (such as variations in subsurface materials and their thickness, the availability and kind of aquifers, the nature of other layers, etc.). Fig. 1 is a typical example of borehole or well

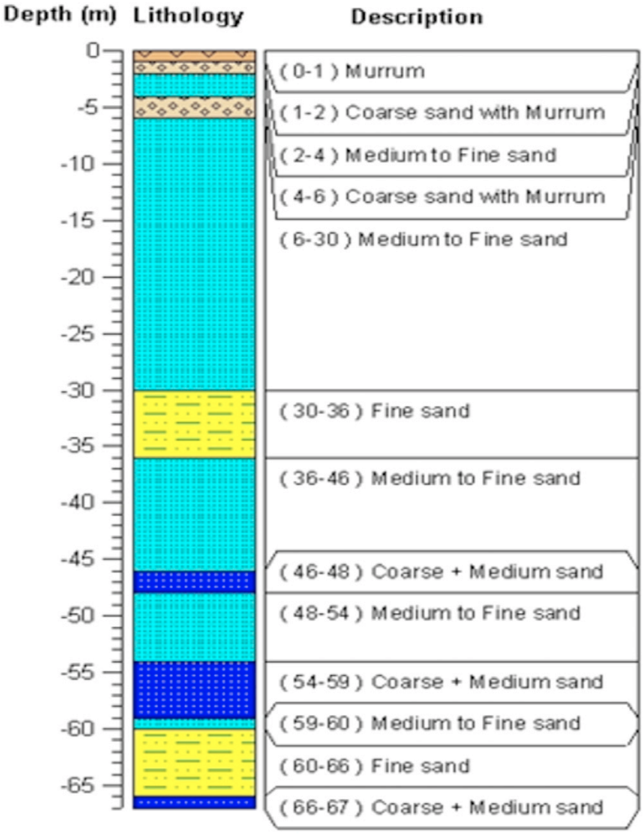

Fig. 1. Well log of a site created from geologic samples obtained in an unconsolidated formation during observation-well drilling (Shiksha, 2014).

logging of groundwater monitoring recorded in an unconsolidated aquifer formation. The data from this source is important and reliable for environmental projects, geologic research, foundation construction, well monitoring, and producing wells.

In addition to test drilling, hydrogeological surveys, RS, geochemical analysis, and piezometric surveys also play vital roles in groundwater exploration and sustainability. Hydrogeology involves the investigation of existing hydrological data, geological maps, and conducting field surveys, which is very effective for understanding the regional groundwater movement and locating potential aquifers. RS is another tool for groundwater exploration where groundwater samples are analyzed for physicochemical properties to infer the potential and quality of groundwater (Jha et al., 2007). On the other hand, the roles of Piezometric surveys in groundwater development cannot be overemphasised, it measures the pressure of groundwater in wells to understand the hydraulic gradient and flow direction (Shiksha, 2014). This technique is very effective for understanding groundwater recharge and movement. In conclusion, while these techniques provide information about groundwater, geophysical methods, which employ the service of ground penetrating radar (GPR), seismic refraction, and ER, remain the most effective method for groundwater exploration (Todd, 1980). However, for effective and comprehensive assessments, an integrated approach remains the best practice. For instance, geophysical methods can be utilized to select potential sites, followed by test drilling and geochemical analysis to confirm the presence and quality of groundwater.

3.1. A brief overview of geophysical techniques

Unveiling the mysteries of the subsurface, which contains a collection of invaluable information and treasures, remains a cardinal focus of Geophysics. While exploring and understanding the subsurface is crucial for a variety of applications, including exploration of groundwater resources, assessing geo-hazards, and managing environmental and engineering projects (Alao, 2025), geophysics has developed various methods of providing invaluable insights into subsurface conditions without distorting the ground structures. Among these methods, seismic surveys, ER, and GPR techniques stand out for their effectiveness in mapping subsurface structures such as aquifers, fractures, and faults (Lowrie, 2007). By introducing electrical current into the ground and measuring the voltage variations that ensue, a geophysical technique known as ER determines how subsurface materials respond to the passage of electricity (Telford et al., 1990). Geophysicists can create a stack resistivity profile of the subsurface, which is very effective in identifying changes in the resistivity of soil, rock, and water content (Alao, 2024a). For instance, low resistivity values often indicate the presence of water-saturated zones, making this technique ideal for groundwater exploration (Lowrie, 2007). ERS operates on the basic principle of Ohm's law, which is usually written as:

$$V = IR \tag{1}$$

Since the resistivity of the subsoil is inhomogeneous, the current flow responds to the subsoil materials in different ways, and the resistivity measured is expressed as apparent resistivity (ρ_a) in Eq. (2):

$$\rho_a = RK \tag{2}$$

where R is resistance and K is a factor that depends on the arrangement of the four electrodes (Telford, et al., 1990). K is also known as the geometrical factor or K-factor, which can be estimated from the electrode's arrangement in Fig. 2 and can be expressed as:

$$K = 2\pi\left[\left(\frac{1}{AC} - \frac{1}{CB}\right) - \left(\frac{1}{AD} - \frac{1}{BD}\right)\right]^{-1} \tag{3}$$

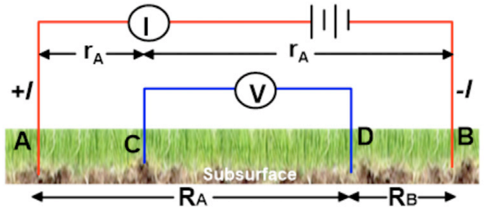

Fig. 2. Schlumberger configuration.

where BD, BC, A and AD are the distances between the separated electrodes measured in metres. Therefore, Eq. (3) can be reduced mathematical expression to simplify equation into Eq. (4) from the central-symmetric array where $BC = AD \; and \; AC = BD$ as shown in Fig. 2:

$$K = \pi\left[\frac{(AC)(AD)]}{(CD)}\right] \tag{4}$$

Seismic surveys involve generating seismic waves and recording their travel times and reflections through subsurface materials (Alao et al., 2025). These waves can be generated using explosives, mechanical impacts, or specialized equipment like vibroseis trucks (Engelsfeld et al., 2011). The recorded data are used to create seismic profiles, which reveal the subsurface's layered structure and help identify faults, fractures, and aquifers. Seismic surveys are widely used in oil and gas exploration, civil engineering, and environmental studies (Sharma and Baranwal, 2005). GPR uses high-frequency electromagnetic waves to image the shallow subsurface. A GPR system consists of a transmitting antenna that emits radar pulses and a receiving antenna that records the reflected signals. The time it takes for the radar pulses to return provides information about the depth and composition of subsurface features. GPR is highly effective for detecting changes in soil and rock layers, mapping buried objects, and identifying fractures and voids (Daniels, 2004). The changes in the Earth's magnetic field caused by the magnetic characteristics of subterranean materials are measured by the magnetic method (Telford et al., 1990). By delineating these magnetic anomalies, geophysicists can infer the presence of different rock types, faults, and other geological structures (Alao et al., 2024f). This method is specifically useful for mineral exploration and mapping geological features that affect groundwater flow. On the other hand, the very low frequency (VLF) method utilizes electromagnetic waves in the VLF range, typically transmitted by powerful naval communication stations. The VLF signals induce secondary electromagnetic fields in subsurface conductive structures, such as fault zones and mineral deposits. By measuring the strength and orientation of these secondary fields, geophysicists can map the subsurface conductivity and identify features like aquifers and faults (Alao et al., 2024g). However, the VLF technique is partially limited in terms of depth estimation, but the recent application of the rule of Thumb to the Fraser-filtered VLF-EM measurements indicates more strength in depth estimation, making it possible to infer the exact depth of underground conductive zones (Alao et al., 2024c).

3.2. Geophysical mapping of aquifers, faults, fractures and geological structures

Geophysical techniques are essential for identifying, characterizing, and mapping aquifers, which are critical sources of groundwater (Mohammed et al., 2024). ER surveys can delineate the extent of water-bearing formations by detecting zones of low resistivity (Fig. 3c; Alao et al., 2024d). Seismic surveys provide stacked figures of subsurface stratigraphy, helping to identify aquifer boundaries and thickness. GPR is effective for mapping shallow aquifers

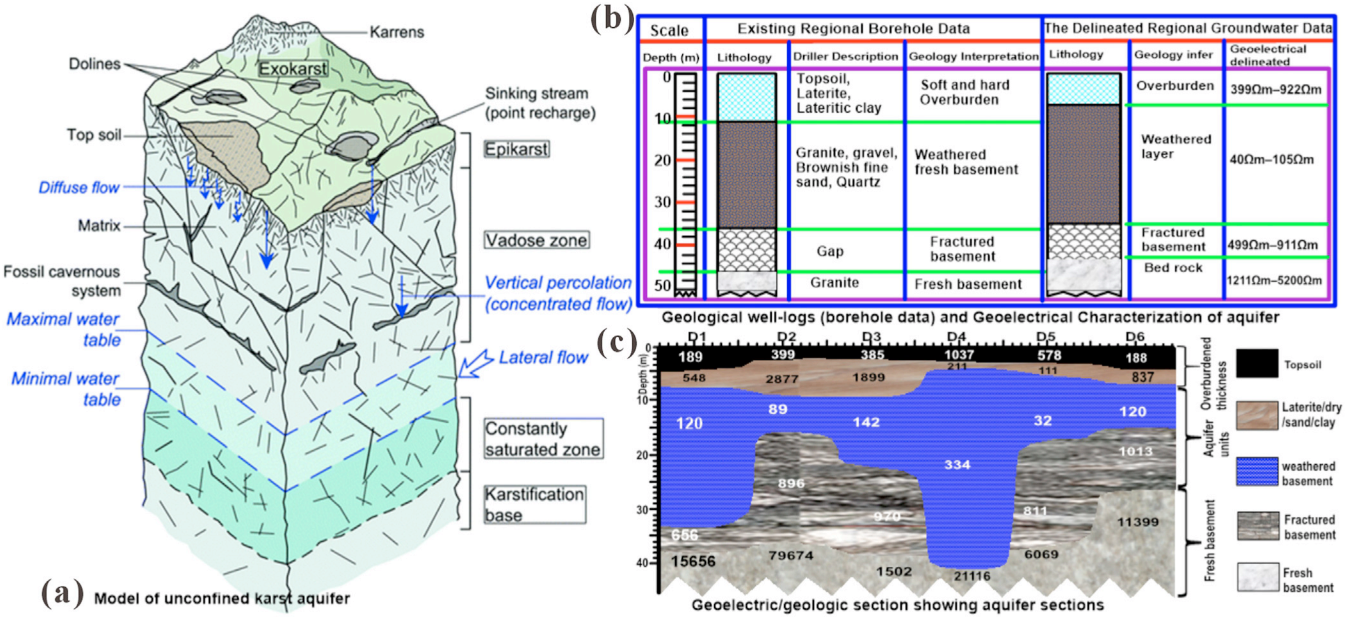

Fig. 3. Characterization of aquifer potential.

and detecting changes in groundwater levels. Magnetic and VLF methods can complement these techniques by identifying geological features that influence groundwater flow, such as fractures and faults. Fractures and faults play a crucial role in groundwater movement and storage (Todd, 1980). Geophysical methods are invaluable for mapping these features and understanding their impact on hydrogeology. Seismic surveys can detect fault planes and fracture zones by identifying discontinuities in seismic reflections. ER and GPR can map the extent of fault zones and detect variations in subsurface conductivity associated with fractures. Magnetic and VLF methods can highlight conductive anomalies associated with fault zones, providing additional information for subsurface mapping. The particular geological and hydrological circumstances of the region frequently determine the best approach for groundwater investigation. Through a huge crack in the zone of lower aquifers, the seepage flow in the top sections has been distinguished from vertical drainage by examining the epikarst flow to the underlying vadose zone (Stevanović, 2015). Nonetheless, seismic refraction and ER techniques are generally thought to be quite successful. The ER of subsurface formations is measured using the ER method. It assists in determining the existence and quality of groundwater by running an electrical current through the earth and detecting the potential difference. It's very helpful for identifying contamination and charting aquifer borders (Abdullahi et al., 2013; Adagunodo et al., 2023; Alao et al. 2024h). Seismic Refraction Method: This technique maps subsurface structures using seismic waves. The depth and thickness of aquifers can be determined by measuring the transit time of seismic waves. It works well in places where the subsurface materials vary greatly. Both techniques offer useful information for groundwater investigation and are non-invasive. By combining these techniques with RS and geological field reconnaissance, groundwater exploration accuracy can be further increased. In addition to mapping stratigraphy and subsurface structure, ER data could be used to infer hydrogeological parameters and lithological information required for groundwater mapping Fig. 3). Identifying interstices, void spaces, linked pore spaces, and fractures in water-filled rocks that result in low resistivity values and high conductivity is important in this case (Salako and Adepelumi, 2017). More details are still required because a variety of factors, such as the presence of clay minerals, pollution plumes, etc., can cause high conductivity inside rock formations or units.

3.3. Depth and volume estimation of groundwater

Geophysical estimation of depth and volume of subsurface targets such as groundwater from the ground surface remains one of the most important transformative power geophysical methods in exploration (Ebrahimi et al., 2019; Alao et al., 2024b), providing precise location, volume and depth of groundwater reservoir. Determining and mapping aquifer repositories, volumes, and depths under current stress and growing demand on water resources is quite essential (Rao et al., 2013). Geophysical methods leverage the physical properties of subsurface materials to identify groundwater reservoirs, making them indispensable in regions where water scarcity poses significant challenges. ER is particularly effective in identifying discontinuities and weak zones, which are crucial for drilling high-yield boreholes (Ewusi et al., 2020). For instance, studies conducted in the Volta Basin of Ghana demonstrated the efficacy of ERI in pinpointing groundwater accumulation zones, leading to improved success rates in borehole drilling (Alao et al., 2024d).

The electrokinetic system (EKS) is another powerful method, which assesses the hydraulic conductivity of subsurface materials, is another effective technique. This method is crucial for comprehending how groundwater moves through aquifers and how much of it can be stored. Researchers can determine regions with high yield potential and estimate the volume of groundwater by examining electrokinetic parameters (Ewusi et al., 2020). By identifying areas of water circulation, the Radon (222Rn) approach offers an additional degree of accuracy. Active groundwater flow zones are identified using radon, a naturally occurring radioactive gas, as a tracer. In difficult terrains where conventional methods might not be effective, this approach is especially helpful (Ewusi et al., 2020). In addition to being efficient, geophysical techniques are also reasonably priced. They lessen the need for significant drilling, which can be costly and harmful to the environment. These methods enhance rural water delivery projects and allow for sustainable management of water resources by offering precise data on groundwater volume and depth. To sum up, geophysical techniques like

ERI, EKS, and Radon have demonstrated their effectiveness in determining the volume and depth of groundwater. Their capacity to offer accurate, economical, and ecologically sustainable solutions renders them indispensable instruments in tackling worldwide water issues. These techniques will surely become even more important in guaranteeing access to dependable and clean water sources as technology develops.

3.4. Case studies demonstrating the effectiveness of geophysical methods

Geophysical methods have proven to be invaluable tools in addressing complex environmental, engineering, and resource management challenges. Their efficacy in a variety of applications is demonstrated by recent case studies. To ensure the stability of geothermal infrastructure, for example, ERT and SRT were used at the Olkaria V Geothermal Project in Kenya to determine bedrock depth and weak zones (Ayipa, 2024). Similarly, the University of Benin in Nigeria employed integrated geophysical techniques, such as seismic refraction and ER, to identify underlying geological features and evaluate groundwater potential. High-yield aquifer zones were identified by this study, which also offered vital information for sustainable resource management (Saqr et al., 2021; Maju-Oyovwikowhe, et al., 2024). Another noteworthy instance is the Hanford 300 Area in Washington, USA, where uranium pollution in groundwater was monitored using geophysical techniques. Informed cleanup solutions and the tracking of pollutant transport were made possible by methods like hydrogeological characterisation and time-lapse imaging (Slater, 2022). These case studies highlight how flexible geophysical techniques are for imaging subsurface structures, tracking changes in the environment, and assisting in decision-making and stakeholders in water resource management. These studies show that combining many geophysical techniques improves data dependability and accuracy. To overcome constraints and accomplish thorough subsurface characterization, researchers might combine techniques such as ERT, GPR, and SRT surveys. These developments demonstrate how important geophysics is to solving global issues, including infrastructure development, environmental cleanup, and groundwater management. The ongoing use of geophysical techniques promises creative answers for environmental stewardship and sustainable development in groundwater exploration.

3.5. Characterization of aquifer properties

Characterization of aquifer properties such as thickness, porosity, hydraulic conductivity, permeability, transmissivity, etc., is essential for understanding groundwater availability and quality (Alao et al., 2023b; Yang et al., 2024). Thickness determines the volume of water an aquifer can store. Porosity, the measure of void spaces in rocks or sediments, affects how much water an aquifer can hold, while permeability, the ability of the material to transmit water, influences the rate and ease of groundwater flow (Alao et al., 2024i). Geophysical methods like seismic surveys, GPR, and ER provide non-invasive means to assess these properties. ER surveys can identify zones of high and low resistivity, correlating with changes in porosity and permeability (Alao et al., 2023b). Seismic surveys help determine the thickness and stratigraphy of aquifers, providing insights into subsurface geology. GPR is effective in mapping shallow subsurface features, including delineating aquifer boundaries and identifying variations in porosity and permeability.

Several geophysical methods have been utilized to delineate aquifer properties such as permeability, porosity, hydraulic conductivity, and transmissivity globally. A study in Edem, Nigeria, revealed aquifer resistivity ranging from 34.8 to 561.2 Ωm and a thickness of 24.8–147.6 m. Porosity values ranged from 25.6 to 32.6%, while transmissivity was 0.86–458.07 m^2/day (Omeje et al., 2022). Similarly, in Ota, Nigeria, Schlumberger resistivity surveys estimated aquifer porosity and transmissivity, highlighting high porosity zones vulnerable to contamination (Oyeyemi, et al., 2018). In Uyo, Nigeria, ER surveys characterized aquifers with resistivity values of 2.4–4393 Ωm. Hydraulic conductivity ranged from 0.1 to 1.5 m/day, while transmissivity values were mapped using contour models (Udosen, et al., 2024). In India, resistivity methods identified aquifers with transmissivity values of 50–200 m^2/day and porosity exceeding 30%, aiding sustainable groundwater management. In Gombe, Nigeria, a study applied ER surveys to 32 vertical electrical soundings (VES), which identified four groundwater potential zones, with medium-grained sandstones being the most prevalent (Kwami et al., 2019). The computed Dar Zarrouk parameters show an average transverse resistance of 1789.50 Ωm, longitudinal conductance of 2.002 Ωm, hydraulic conductivity of 20.662 m/day, and transmissivity of 893.57 m^2/day. The aquifers were found to have moderate to good protective capacity, indicating a low risk of contamination. A similar study applies VES techniques to evaluate aquifer characteristics and groundwater potential where thirty Schlumberger soundings were acquired with a maximum electrode spacing (AB/2) of 50 m (Ogundana and Falae, 2024). Aquifer resistivity ranged from 17 to 678 Ωm, hydraulic conductivity from 0.004 to 0.047 m/s, transmissivity from 0.003 to 1.130 m^2/day, and porosity from −9.71 to 11.73. The groundwater potential index (GWPI) map revealed that 56% of the area has medium potential, 32% low, 10% high, and 2% very low. The study highlights low groundwater potential and offers a strategic roadmap for groundwater exploration and management.

In Ode Aye, southwestern Nigeria, geophysical techniques were employed to delineate and characterize shallow aquifers using Schlumberger vertical electrical sounding (VES), which identified three distinct geological units: topsoil lateritic/sand layer, sandstone/loose sand layer, and sandy/shale layer (Ozegin and Oseghale, 2012). The middle layer, ranging from 7.5 to 32.1 m in thickness, was delineated as the aquifer unit. This study highlighted the importance of proper casing for boreholes to prevent contamination. In the same region, a study utilized 16 Schlumberger VES with a maximum electrode separation of 900 m to analyze the groundwater potential of Ijebu Ode, Southwestern Nigeria (Oladele and Odubote, 2017). Of the soundings, only VES 9 indicated a saturated aquifer. Four subsurface layers were identified within an 80 m depth. The topsoil layer, composed of dry clay, has a thickness of 0.8–1.5 m. The second layer, sandy clay with resistivity values of 53–1895 Ωm, varies in thickness from 0.8 to 34.5 m. A thick sand layer, with high resistivity values of 1208–7350 Ωm, spans 2.4–55.3 m. The basement layer, with resistivity values of 3155–39,529 Ωm, occurs at depths of 3–63 m. The saturated aquifer beneath VES 9, with 8–10% clay content and 40% porosity, contains fresh water with a resistivity of 122 Ωm and TDS of 53 ppm. The findings emphasize low groundwater potential and the importance of geophysical studies for erratic aquifer detection.

In the Mississippi Delta, USA, geophysical methods were used to characterize sedimentary aquifers. Techniques such as facies analysis, sequence stratigraphy, and advanced borehole geophysics were applied to understand aquifer heterogeneity (Maliva, 2016). This comprehensive approach allowed for improved groundwater models and successful water management solutions, including contaminant remediation and managed aquifer recharge systems. At the University of Nigeria, Nsukka, geophysical methods were used to assess aquifer vulnerability. 17 VES and 7 ERT profiles were conducted. The study employed Schlumberger and Wenner electrode configurations to determine the vulnerability of hydrogeological units. The results helped delineate aquifer protective zones and guide groundwater resource exploration and management (Obiora and Ibuot, 2020). In remote and arid parts of South Australia, geophysical methods were used to locate groundwater resources for Aboriginal communities. Techniques such as resistivity arrays and vertical seismic reflection were employed to map subsurface structures and identify potential aquifers. This study provided valuable information for sustainable groundwater management in the region (Hanafy, 2013). Geophysical methods have also been applied in urban areas to assess groundwater quality and potential contamination. In a study conducted in an urban setting, ER and GPR were used to map subsurface structures and identify potential contamination sources (Hanafy, 2013). The results provided valuable information for groundwater management and environmental protection in the urban environment. In Southeast Spain, an integrated geophysical approach was used to characterize shallow aquifers. Techniques such as ERT, time-domain electromagnetics (TDEM), and vertical seismic reflection were applied (Alcalá et al., 2021).

Recently, research was conducted to investigate fractures and groundwater pathways in a hard rock area in India using airborne electromagnetic (AEM) surveys. The study found a strong correlation between well yield and depth of investigation beyond 80 m, suggesting a threshold groundwater horizon (TGWH). The study analyzes various lineaments, including magnetic, satellite, and hydrological lineaments, and finds that hydrological lineaments (Hydrolins) are the most effective indicators of groundwater occurrence. The study also reveals that Hydrolins are not influenced by any particular regional structural lineaments. The study concludes that AEM surveys, in combination with borehole data and geological information, provide a valuable tool for locating sustainable groundwater sources in hard rock terrains (Fig. 4). These case studies demonstrate the effectiveness of geophysical methods in quantifying aquifer properties globally. It also allowed for detailed mapping of aquifer properties and improved understanding of groundwater flow dynamics. Together, these methods offer a comprehensive understanding and characteristics of aquifers, providing valuable insights for efficient groundwater exploration, management and sustainability.

3.6. Mapping of aquifer promising zones

Geophysical methods are invaluable for mapping aquifer promising zones, offering non-invasive, cost-effective, and accurate subsurface characterization. Geophysical methods, such as have been effectively used to delineate aquifer potential zones. For instance, in Kangonde, Kenya, resistivity values of 10–100 Ωm identified highly conductive zones at depths of 70–160 m, indicating promising aquifers (Lucy et al., 2016). Similarly, in Lokoja, Nigeria, VES revealed hydraulic conductivity ranging from 0.37 to 56.87 m/day and transmissivity of 4.45–917.73 m²/day, highlighting aquifer potential. These methods provide critical quantitative data for groundwater exploration and management (Omali and Arogundade, 2022). In the Tata Basin, Morocco, ER profiling revealed aquifer resistivity values ranging from 10 to 100 Ωm, indicating promising groundwater zones. In India, the Multiple Influence Factor (MIF) and Analytical Hierarchy Process (AHP) methods, combined with GIS, mapped groundwater potential zones, categorizing areas into poor, moderate, good, and very good potential, with AHP showing an accuracy of 93% (Shinde et al., 2024). In Portugal, integrated geophysical methods, including ERT and seismic surveys, characterized aquifers with resistivity values of 20–200 Ωm, providing insights into aquifer geometry and salinity (Alcalá et al., 2021).

These other case studies highlight the effectiveness of geophysical methods in providing quantitative data for aquifer mapping, ensuring sustainable groundwater management in diverse geological settings. For instance, a study investigates groundwater resources in Central Sinai, Egypt, using a combination of RS, geoelectric, and well-logging data (Araffa et al., 2023). The study identified two aquifers: a shallow aquifer in fractured limestone (35–250 m thick) and a deep aquifer in Nubian sandstone (660–1030 m deep). Eighteen deep VES stations were used to analyze the upper portion of the aquifer or groundwater, revealing three zones with significant storage and recharge potential. The study also used gravity data to identify subsurface faults and structural patterns, which likely act as recharge conduits connecting the deep and shallow aquifers. The

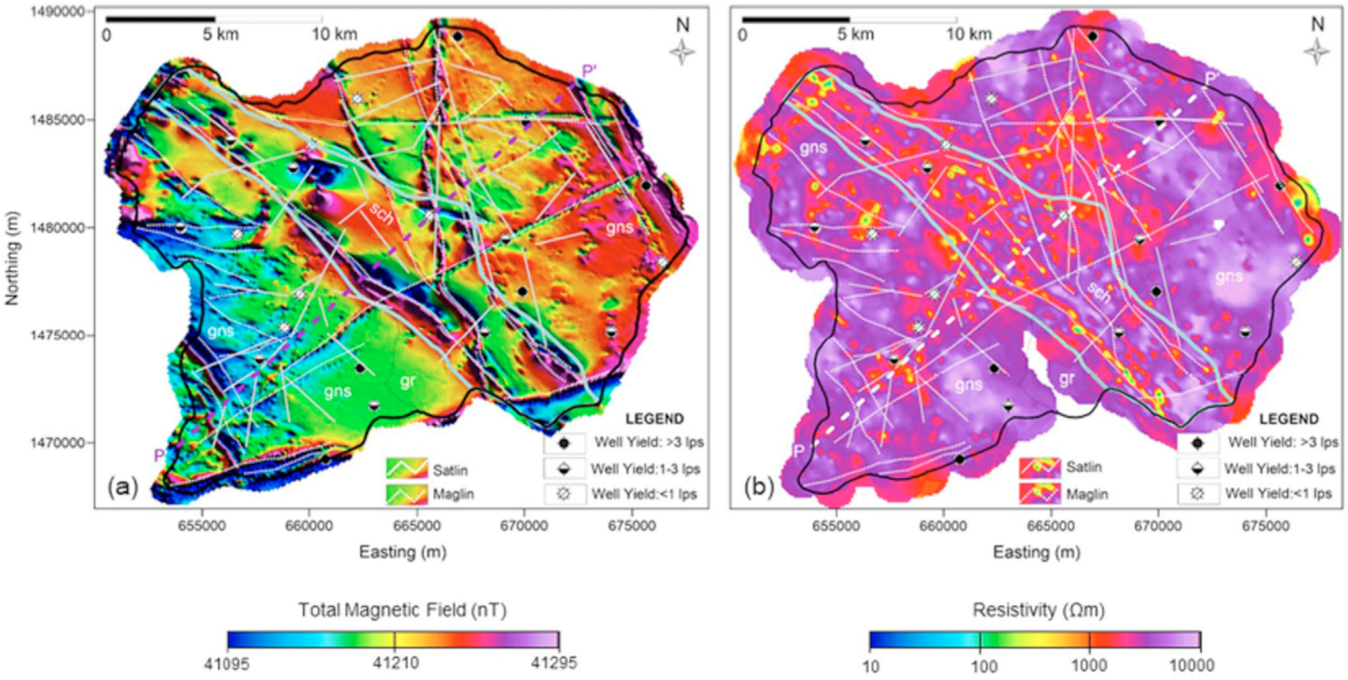

Fig. 4. (a) Map of the intensity of the total magnetic field (nT). Contact between gneiss and schist is indicated by the grey line (with schist in the middle). The magnetic lineaments are indicated by the white dashed lines. (b) Map of mean resistivity at a depth of 100–110 m. Three yielding categories: high (>3 lps), moderate (1–3 lps), and low (<1 lps), are applied to the 21 wells (Chandra et al., 2019).

research concludes that the NW-SE and NE-SW faults provide sites with acceptable groundwater potential for various uses in Sinai. Similar investigation on groundwater potential zones (GWPZs) in Wadi Abu Marzouk, Egypt, using a combination of RS, GIS, and geophysical techniques. The study identified five GWPZ categories based on eight parameters, with good and very good zones covering 49% of the area. Thirty-five VES and four ERT profiles were conducted, revealing a freshwater-bearing layer at depths between 27 and 51 m, primarily in the northern and northwestern regions. The study highlights the effectiveness of integrating these methodologies for accurate and comprehensive groundwater assessments.

In Southern China, a study applies a combined geophysical approach to determine weathered/fault zones for groundwater potential (Hasan et al., 2018). The study combines 2D ERT and magnetic methods, revealing six main faults and three distinct layers: topsoil, unweathered layer, and weathered layer. The ERT data shows resistivity ranges of 18–345 Ωm for topsoil, 18–928 Ωm for the weathered layer, and 906–2595 Ωm for the unweathered layer. Magnetic intensity varies from −38 to −4 nT, with lower values indicating weathered rock. The integrated results suggest that groundwater reserves are primarily located within the weathered/fault zones, highlighting the effectiveness of this approach for groundwater exploration in complex geological settings. A similar study applied the AHP and MIF methods to map groundwater potential zones using nine thematic layers integrated in ArcGIS 10.5 (Shinde et al., 2024). AHP classified zones as 241.50 ha (poor), 285.64 ha (moderate), 408.31 ha (good), and 92.75 ha (very good), while MIF classified them as 351.29 ha (poor), 511.18 ha (moderate), 123.95 ha (good), and 41.78 ha (very good). Validation with water yield data yielded ROC-AUC values of 0.93 (AHP) and 0.80 (MIF), highlighting AHP's superior performance. The study emphasizes the importance of groundwater for drinking, providing a framework and practical insights for irrigation efficiency, rainwater conservation, economy, and ecosystem sustainability in India's basaltic, drought-prone areas. Another study employed RS and resistivity methods to evaluate groundwater-promising zones in a hard-rock terrain of Ondo State, Nigeria (Akinluyi et al., 2021). Using Landsat ETM+, Aster DEM, and ArcGIS 10.5, maps of geomorphology, lineament density (0.00–69.48 km/km^2), and lineament-intersection density (0.00–72.92 km/km^2) were produced. Aquifer thicknesses ranged from 0.2 to 79 m, with coefficients of anisotropy (1.0–2.88 units) derived from geoelectric parameters. Identified aquifer types included weathered and fractured layers, both confined and unconfined. Landforms ranged from residual hills (677–980 m.a.s.l) to pediplains with alluvium (74–226 m.a.s.l). Four groundwater-promising zones, from very low to high were delineated, with the area's overall potential rated low to moderate.

In Varde, Denmark, a combination of seismic and resistivity methods was used to assess groundwater potential in glacial terrain. The seismic and resistivity data were combined to delineate groundwater-bearing and groundwater-barrier layers down to a depth of 150 m (Wiederhold et al., 2021). This approach enabled the identification of thrust structures and channel structures, providing valuable information for groundwater exploration. A detailed ground magnetic survey was conducted in Modomo, Southwest Nigeria, to delineate subsurface structures and estimate overburden thicknesses. The magnetic survey identified 24 lineaments with lengths varying between 150 and 777 m (Oni et al., 2020). These lineaments were validated with resistivity survey data and borehole log data, demonstrating the effectiveness of the magnetic method in groundwater potential assessment. In the Pydibhimavaram Industrial Area, Andhra Pradesh, India, VES using the Schlumberger array was carried out in 13 stations to determine subsurface layer parameters and categorize groundwater potential (Venkata Rao et al., 2014). The findings demonstrated that three-layer formations with a variety of resistivities and associated thicknesses were present in the majority of the research region. The region's groundwater potential was demonstrated by pseudo-sections and geo-electric sections produced from the data (Venkata Rao et al., 2014).

In the plateau slope zone, a groundwater investigation was conducted using an integrated geophysical strategy that combined k-reflection coefficient methods, composite profiling, audio frequency magnetotelluric (AMT), ER tomography, microtremor, and apparent resistivity sounding (Zheng et al., 2024). The combination of these methods proved effective in identifying groundwater sources in the region. Geophysical methods have also been applied in urban areas to assess groundwater quality and potential contamination (Kanli, 2019). In a study conducted in an urban area, ER and GPR were used to map subsurface structures and identify potential contamination sources (Kanli, 2019). The results provided valuable information for groundwater management and environmental protection in the urban setting. These case studies demonstrate the effectiveness of geophysical methods in subsurface mapping for groundwater exploration and management. By leveraging these techniques, we can better understand subsurface conditions, locate potential groundwater sources, and ensure sustainable management of this vital resource. Similarly, a study employed seismic refraction surveys to effectively delineate groundwater-bearing zones along two traverse lines of 155 m and 140 m in length (Sunkpal et al., 2022). Subsurface velocities ranged from 470.10 to 1623.50 m/s for traverse one and 463.35–4050.31 m/s for traverse two, with layer thicknesses spanning 0–51.67 m and 0–46.67 m, respectively. The generated subsurface models captured lateral and vertical variations, revealing high groundwater potential zones. The findings, aligning with borehole logs, underscore the method's precision in groundwater exploration, offering valuable insights for efficient resource extraction and management.

In California, USA, geophysical methods have been extensively used to map faults and assess seismic hazards (Mualchin, 2005). A notable example is the use of seismic surveys to map the San Andreas Fault. High-resolution seismic imaging revealed detailed fault structures and provided insights into the fault's geometry and behaviour (Kim et al., 2016). This study investigates fault geometry in Parkfield, California, using seismicity data and velocity residuals. Low seismic velocities are observed east of the fault, with high velocities to the west. Shallow depths exhibit large velocity anomalies, while depths of 3–8 km show smaller anomalies in the central zone but larger ones in the northern and southern zones. Beyond 8 km, low velocities dominate the northern zone. The fault's spiral geometry dips NE in the north, vertically in the central, and SW in the south. A rapid twist occurs over 50 km, linked to periodic M6 events. These geophysical studies have been critical for understanding seismic risks and guiding infrastructure development in the region. The Appalachian Basin in the USA is characterized by complex geological structures, including numerous fractures that influence groundwater flow. Geophysical methods, including seismic surveys, ER, and magnetic techniques, have been employed to map these fractures. Seismic surveys provided detailed images of subsurface structures, while resistivity surveys identified conductive fractures and fault zones (Ettensohn, 2007). Magnetic surveys detected variations in the Earth's magnetic field associated with fracture zones. This integrated approach helped characterize the basin's hydrogeology and guide groundwater management practices. In conclusion, geophysical methods play a crucial role in mapping subsurface structures, providing valuable information for locating potential groundwater sources, identifying aquifers, and understanding the hydrogeological setting. The applications of these methods in mapping aquifers, faults, and fractures demonstrate their effectiveness in subsurface exploration and management. Case studies from around the world highlight the practical benefits of geophysical techniques in addressing real-world challenges. As the demand for groundwater resources continues to grow, the role of geophysics in sustainable groundwater development and management will become increasingly important.

3.7. Monitoring groundwater levels

Geophysics plays a crucial role in monitoring changes in groundwater levels, providing valuable data for sustainable GWRM without invasively tracking groundwater fluctuations over time (Alao et al., 2024a). These techniques help in understanding aquifer dynamics, assessing the impact of climate change, and managing human activities that affect groundwater levels. In the Columbia River region, the U.S. Geological Survey (USGS) used a floating transient electromagnetic (FloaTEM) system to monitor groundwater/surface water exchange (USGS, 2019). This method provided high-resolution ER mapping, revealing groundwater levels and flow dynamics beneath large water bodies (USGS, 2019). The data helped in predicting groundwater/surface water interactions and managing water resources effectively. In Shuangnuo Village, Yunnan Province, China, an integrated geophysical approach was employed to monitor groundwater levels. Techniques such as ERT and AMT methods were used to map subsurface structures and track groundwater fluctuations (Zheng et al., 2024).

This approach helped in identifying water-rich blocks and optimizing borehole locations. In Delta State, Nigeria, a combined approach using resistivity techniques with RS and geographic information system (GIS) methods was used to monitor groundwater levels. The study delineated aquifers and assessed groundwater resources, providing valuable insights for sustainable water management (Ojo et al., 2024). This integrated approach provided a comprehensive understanding of aquifer dynamics and supported effective water resource management. According to a recent report, less rainfall is causing severe water shortages in many cities worldwide, particularly in India. This has inevitably resulted in the depletion of groundwater as a result of a drop in groundwater level (Kumari and Singh, 2016). Consequently, naturally occurring springs dried up, causing a decline in groundwater levels. Additionally, excessive groundwater extraction in some areas of Egypt, the groundwater level has been dropping between 50 m and 60 m (Foster and Loucks, 2006).

According to a different analysis, a country with an irrigation-based economy and streams that rely heavily on groundwater, where >2.3 million people live, may cause groundwater levels to drop quickly, reaching 50 m (Gleeson et al., 2010). According to a study conducted in Marrakech, Morocco, the semiarid climate and ongoing drought are causing groundwater depletion. The amount of water in Marrakesh's shallow aquifer and its surrounding environment, according to the results, indicates a slow decline in the water table over the previous 40 years, which could reach a sharp decline in the early 2000s (Analy and Laftouhi, 2021). Based on the continuous excessive reliance on groundwater resources, all signs point to the possibility that the declining event could result in severe water scarcity or complete aquifer depletion, which could be even more detrimental to the socioeconomic activities of the area (Analy and Laftouhi, 2021). In conclusion, three major factors have been identified for the constant changes in groundwater levels, which include low rainfall, hot climate, especially in an arid area, and over-extraction of groundwater due to population expansion, which has impacted aquatic populations and the human environment.

3.8. Groundwater hydraulic conductivity and vulnerability

Geophysical methods have been effectively utilized worldwide to delineate hydraulic conductivity and assess aquifer vulnerability, providing critical insights for sustainable groundwater management. Because it shows the direction of groundwater movement (Fig. 5), the water table's slope is significant from a hydrological perspective (Hussain et al., 2022). Given the risk of contaminating groundwater supplies, understanding the direction of groundwater movement has become more and more crucial. Groundwater flows in a downward direction relative to the total head (Alao, 2024b). To assist in determining the groundwater flow metrics of the research area, physical measurements were taken for wells drilled at the sampling locations (Ahmad et al., 2020). For instance, in Ngor-Okpala, Nigeria, VES was employed to estimate transmissivity and hydraulic conductivity. Hydraulic conductivity ranged from 9.21 to 10.27 m/day, while transmissivity values varied between 310.72–1203 m²/day. These findings highlighted high water-yielding capacity and vulnerability to contamination (Obiora and Ibuot, 2020). In Portugal, ER tomography (ERT) was used to evaluate coastal aquifers. Hydraulic conductivity values ranged from 1.5 to 3.0 m/day, while vulnerability assessments identified areas at risk of seawater intrusion, aiding groundwater protection strategies (Bentley et al., 2011). In India, resistivity surveys in Rajasthan revealed aquifers with hydraulic conductivity values of 0.5–1.2 m/day. Vulnerability mapping highlighted zones prone to contamination, supporting sustainable groundwater management in arid regions (Tyagi and Haritash, 2024).

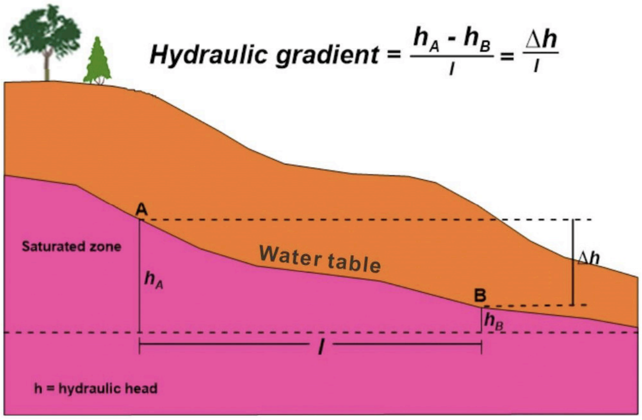

Fig. 5. Direction of groundwater movement.

Similarly, an investigation was conducted in Kaduna Millennium City, Nigeria, to evaluate groundwater vulnerability to surface contaminants using VES (Omeiza and Dary, 2018). The study identified zones with varying aquifer protective capacities and found that 80% of the area has moderate to good protective capacity, with an average longitudinal conductance of 0.210–0.559 Ω. However, 20% of the area, particularly in the northeast and central regions, has weak protective capacity (0.114 - 0.194 Ω). The research recommends avoiding waste and sewage disposal in areas with weak protective capacity and suggests siting boreholes in areas with good protective capacity. A similar investigation in the same city of Kaduna, Nigeria, applies an ER survey to identify a promising aquifer zone with high protective capacity, characterized by weathered and fractured basement rocks at depths between 30 and 59 m. The overburden thickness, ranging from 3 to 20 m, provides good protection against surface contamination. The study also determined the aquifer's hydraulic conductivity, which varies from 0.33 to 10.6 m/day, indicating good groundwater movement, which plays an important role in contaminant mobility and aquifer recovery (Alao et al., 2023b). These case studies demonstrate the versatility of geophysical techniques in quantifying hydraulic conductivity and assessing aquifer vulnerability, ensuring effective groundwater exploration and management across diverse geological settings.

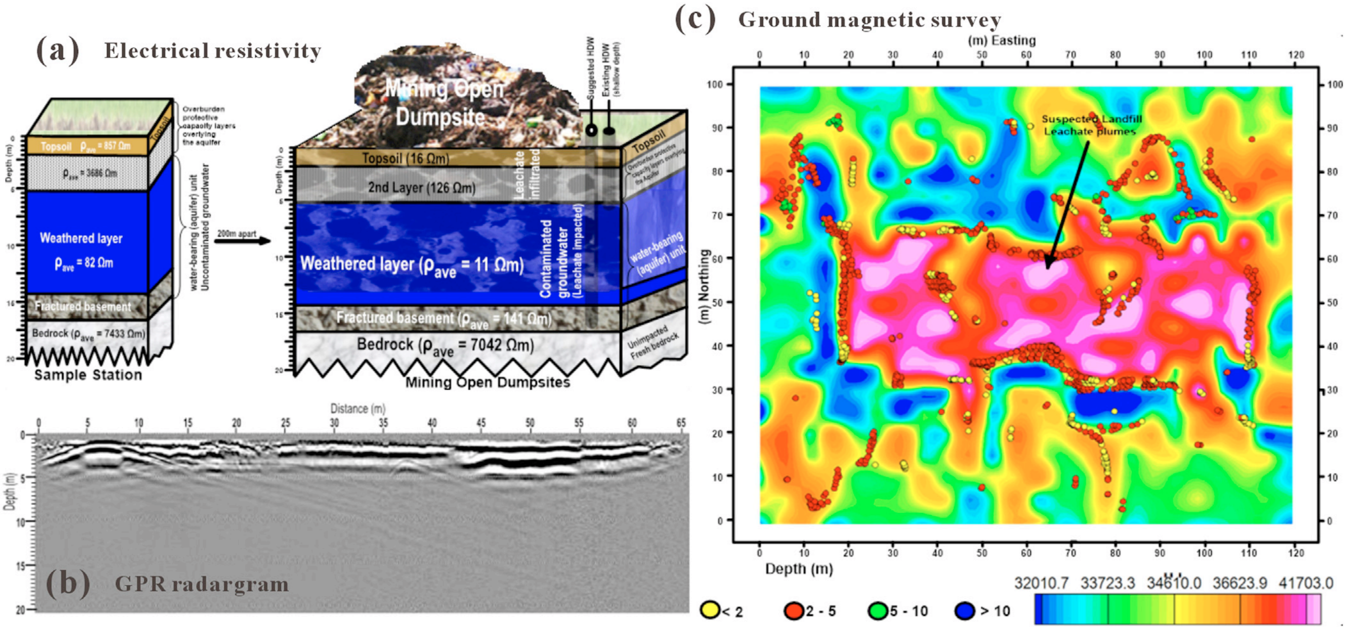

Fig. 6. Visual illustrating the results of geophysical methods for mapping groundwater contamination.

3.9. Detection and delineation of groundwater contamination

Geophysical methods have been effectively used to detect and delineate groundwater contamination plumes using different techniques (Adiat et al., 2019; Omeiza et al., 2022) and facilitating remediation efforts to promote groundwater quality in various parts of the world. In Kaduna, Nigeria, geophysical techniques have been employed to explore and manage groundwater resources. A remarkable study utilized ER surveys to assess the impact of unlined dumpsites on groundwater quality (Omeiza et al., 2023b). The resistivity surveys identified contaminated zones with low resistivity values between 2.4 Ωm to 12 Ωm within the 15 m depth (Figs. 6 and 7; Alao, 2023). This technique provided detailed images of the subsurface stratigraphy to delineate aquifers and assess the extent of contamination, guiding efforts to protect and manage groundwater resources. In Hanford Site, USA: At the Hanford 300 Area in Washington, ERT was employed to monitor uranium contamination in groundwater. The study revealed lithological variability and its influence on contaminant transport, aiding in the management of contaminated aquifers (Slater, 2022). This information supported remediation planning. VES and horizontal profiling methods were employed to detect and map hydrocarbon contamination from oil spills in Ahoada, Nigeria (Nwankwo and Emujakporue, 2012). High resistivity zones (>200 Ωm) were identified as contaminated, while clean aquifers were located at depths beyond 30 m.

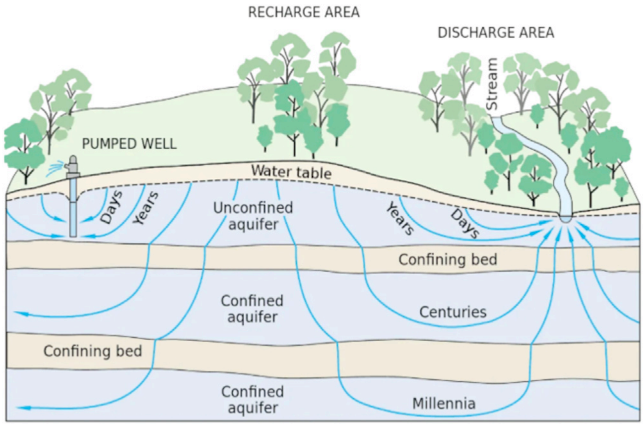

Fig. 7. Natural groundwater recharge by precipitation, ice, and snowmelt (Zac, 2023).

In the Northern Territory, Australia, a study used advanced geophysical techniques, including SP, DC resistivity, IP, and TEM, to monitor seepage at the Ranger mine site (Buselli and Lu, 2021). Utilizing a 64-channel system, SP responses were mapped over a 200 × 300 m area, minimizing telluric noise. In-line DC resistivity and IP soundings at 10-m intervals across 30 stations were completed in half a day. Results revealed increasing chargeability toward a fault, pinpointing it as the main seepage path. The reproducibility of SP anomalies at fault intersections highlights the methods' effectiveness for seepage detection, while DC resistivity and TEM resolved hydrogeological structures impacting seepage dynamics. In southwestern Nigeria, a study utilized ERT, GPR, and geochemical analysis to unveil significant groundwater contamination risks near a waste disposal site (Isah et al., 2024). GPR identified a "shadow zone" at 1–1.5 m with anomalies, while an intermittent reflection zone at 1.5–3.5 m suggested leachate-impacted groundwater. ERT revealed low-resistivity zones (6.80–47.62 Ωm) corresponding to elevated water conductivity (21–147 mS/m) and a leachate plume at depths of 2–10 m. Heavy metal concentrations, such as cadmium and mercury (641–1175 ppb), exceeded safe limits. This innovative geophysical-geochemical approach highlights urgent contamination risks and the importance of risk assessment in fractured geological settings.

Another case study in Brazil investigates contamination behaviour in groundwater and soil from an inactive dumpsite using a frequency-domain electromagnetic survey to map electrical conductivity anomalies, which are then correlated with soil and groundwater samples (Netto et al., 2024). The study found high electrical conductivity values in the central area of the dump, indicating the presence of leachate. Chemical analysis revealed elevated levels of aluminium, arsenic, and iron in topsoil samples, exceeding USEPA guidelines. Groundwater analysis showed elevated levels of barium, nitrate nitrogen, nitrite, cyanide, iron, and chloroform, exceeding Brazilian and USEPA guidelines. The study highlights the effectiveness of electromagnetic methods in identifying and understanding contamination behaviour in dumpsite environments. Turkey investigates groundwater and soil pollution at two open waste disposal sites using geophysical methods such as DC resistivity, VLF-EM, and SP methods to map the extent of contamination (Kaya and Ağaçgözgü, 2017). In Isparta, a zone of low resistivity contrast (<5 Ωm) was identified, indicating leachate-accumulated zones from the open dumpsite. The VLF-EM and SP methods supported these findings. In Çanakkale, the study found a good correlation between the geophysical data and previous geochemical and hydrochemical measurements, confirming the effectiveness of these methods in detecting contamination. A similar study investigates groundwater contamination in the Wadi Bani Malik dam area in Jeddah, Saudi Arabia, employing geophysical techniques like ERT, VES and ground magnetic surveys, along with hydrochemical analysis of water samples (Rehman et al., 2021). The results show significantly higher total dissolved solids (TDS) values in the upstream area of the dam compared to the downstream, indicating a contamination source upstream. The study also found that the dam was not completely successful in blocking contamination due to an improper base. The research concludes that the groundwater in the area is not suitable for drinking purposes.

In Moshi, India, a study investigates groundwater contamination at a landfill site using the Wenner Array geophysical method, which involved three profiles with 54 station measurements (Chougale et al., 2023). The results show a high resistivity zone (>155 Ωm) at depths of 1–16 m in the control area, indicating uncontaminated groundwater. However, a highly conductive zone (3.0–6.0 Ωm) was identified at the landfill surface, suggesting leachate infiltration. The study also reveals a clay layer with low hydraulic conductivity, acting as a barrier to leachate contamination of the underlying aquifer. The paper provides quantitative data on resistivity values for various materials, including leachate, sand, soil, and clay, which are crucial for understanding the extent of contamination. Another remarkable study from Oyo Town, Nigeria, applies ERT and VES surveys at active dumpsites and revealed low resistivity zones (<15 Ωm) associated with contaminant plumes (Suleman et al., 2024). The study emphasized the importance of geophysical methods in urban groundwater management. In Coastal Portugal, integrated geophysical methods such as ERT and EM surveys were applied to detect and map seawater intrusion into coastal aquifers, showing zones of low resistivity values of 1.5–3.0 Ωm, which indicated contamination, for guiding sustainable groundwater use (Zhang and Yang, 2024).

In a similar move, a study at a landfill site in Alice, South Africa, employed ER and induced polarization methods (Mepaiyeda et al., 2019), revealing a four subsurface layer with a shallow bedrock depth (<10 m), low resistivity (34–80 Ωm), and low charge ability (0.05–5.75 ms) were discovered in the contaminants, suggesting both dense aqueous phase liquid contaminants and unsaturated trash with a high ion content. Because of its high resistivity (≥1000 Ωm), the bedrock presents little risk of contaminating groundwater. However, the potential for pollutant migration is increased by the landfill's steep terrain. The study suggests building containment structures to enhance waste management procedures. These case studies have successfully demonstrated the versatility of geophysical methods, especially the combined methods in identifying and managing groundwater contamination in addition to comprehensive subsurface characterization, to ensure adequate and effective remediation for sustainable water resource management.

3.10. Groundwater recharge

Geophysical methods can be used to assess groundwater recharge processes by monitoring changes in subsurface moisture content and flow patterns. Therefore, understanding subsurface geology structures and how the geology either promotes or inhibits regulated aquifer recharge rates is made easier with the use of geophysical technologies (Sheng and Zhao, 2015). In managed aquifer recharge (MAR) projects, geophysical methods are employed to address critical concerns about the subsurface movement of water because they provide cost-effective, non-invasive, and precise insights into subsurface dynamics, enabling sustainable groundwater management. A recent study emphasized the main causes of groundwater depletion, how the hydrologic cycle naturally replenishes groundwater, and how artificial groundwater recharge can assist in combating groundwater depletion (Fig. 7; Zac, 2023). For instance, in Alaba and Apatapiti, Akure, Nigeria, a study masterfully addressed groundwater development through the determination of groundwater flow pattern and the need to combine hydrogeologic data from 72 wells and 42 geoelectric soundings (Adeyemo et al., 2014). Results revealed groundwater flow from the centre and north-central regions to the southwest, with aquifer resistivity and elevation maps supporting this pattern. Resistivity values illuminated critical flow paths, emphasizing the synergy between hydrogeologic and geoelectric data. The study's findings affirm the reliability of geoelectric soundings in determining groundwater flow where well data are limited, providing invaluable insights for effective water resource planning in rapidly growing urban areas.

A recent noteworthy study in Amravati District, Maharashtra, India, investigates the effectiveness of artificial recharge structures (percolation tanks and Kolhapuri weirs) in different geological settings using the ER method (Tohare and Jadhav, 2022). The study analyzed 38 VES using the Schlumberger array in Amravati District, Maharashtra, India. The results show that the first layer thickness for Kolhapuri weirs varied from 0.14 to 5.14 m, while for percolation tanks it ranged from 0.13 to 1.53 m The resistivity values were generally higher for percolation tanks compared to Kolhapuri weirs, suggesting that the latter may be more effective in areas with low resistivity layers. A similar study in Naya Raipur, Chhattisgarh, India, investigates groundwater recharge potential utilizing VES to map subsurface layers and identify fracture zones, which are crucial for groundwater storage (Kumar et al., 2021). Nine VES were conducted, revealing multiple layers with varying resistivity and thickness. The study identifies a weathered layer ranging from 9.21 to 11 m thick with resistivity between 21.7 and 33.4 Ωm. Fracture zones are identified at depths between 12–15 m and 80–85 m The study concludes that the area holds potential for groundwater recharge, emphasizing the need for further research and integrated mapping of groundwater parameters.

Another study emphasizes the growing reliance on MAR to combat escalating water stress, with drilling costs surging by over 30% post-COVID-19 (Parker et al., 2022). It highlights advanced geophysical methods, including airborne time-domain electromagnetic (AEM) surveys, which efficiently collect data over vast areas, and ER, offering comparable resolution. Seismic reflection, though more expensive, provides exceptional penetration depth and aquifer detail. Borehole geophysics delivers near-hole data and surface techniques. These methods collectively outperform traditional drilling, delivering cost-effective, high-resolution insights into hydrogeologic properties, aquifer geometry, and storage zones, ensuring MAR's efficacy in resilient water supply strategies. A similar investigation conducted on the West Coast, South Africa, showcases the transformative potential of integrating hydrogeophysics and diagnostic plots for MAR utilizing SkyTEM and ERT, to delineate subsurface pathways while pumping tests identified flow regimes and boundary conditions (Igwebuike, et al., 2023). Results revealed recharge pathways and critical avoidance zones, with geophysics uncovering precise subsurface structures. By improving operations and maintenance, this approach addresses aquifer dynamics scientifically. The study emphasizes that incorporating hydrogeophysics during MAR planning enhances groundwater management and decision-making, particularly in South Africa, where MAR remains underutilized. Its findings underline the pivotal role of advanced geophysical tools in sustainable water resource management.

In addition, a new geophysical imaging method, towed time-domain electromagnetic (TEM) was employed to assess managed aquifer recharge (MAR) sites in California's Central Valley, acquiring data over 2 days at seven sites, including almond and pistachio groves, an open field, and two active recharge basins (Behroozmand et al., 2018). The TM system provided high-resolution 3D resistivity models down to 60 m, allowing for detailed characterization of both unsaturated and saturated zones. The study found that five out of the seven sites were suitable for MAR based on the presence of coarse-grained sediments in the unsaturated zone. Another noteworthy study in Italy, investigates the use of geophysical methods to support aquifer recharge, focusing on a specific aquifer in Italy, analyzing data from three geophysical methods such as GPR, ERT, and Induced Polarization (Affatato et al., 2013). The study found that GPR was effective in identifying the aquifer's geometry and thickness, while ERT and IP helped determine the aquifer's hydraulic properties. The results suggest that these methods can be valuable tools for optimizing aquifer recharge strategies. Similarly, in Israel, laboratory experiments using GPR with an 800 MHz antenna mapped soil moisture content in agricultural soils achieved an average volumetric soil moisture content (VSMC) accuracy of 1.5%, correlating well with standard oven-drying methods (Shamir et al., 2018). This approach optimized irrigation plans and enhanced water-use efficiency. These case studies highlight the versatility of geophysical techniques in evaluating recharge processes, monitoring moisture content, and mapping flow patterns. By integrating geophysical data with hydrogeological insights, valuable tools for understanding and managing groundwater recharge. It also provides detailed insights into subsurface moisture content, flow patterns, and recharge dynamics, these methods contribute to the sustainable groundwater resource and develop effective management strategies to ensure the long-term health of our aquifers.

3.11. Optimization of well siting

Geophysical surveys can aid in optimizing the siting of groundwater extraction wells by providing information on subsurface geology, hydrogeological conditions, and potential drilling hazards. Optimizing well siting for efficient groundwater extraction remains one of the fundamental powers of geophysics because selecting the right location maximizes yield, minimizes operational costs, and ensures long-term sustainability. Geophysical surveys play a crucial role in identifying suitable well locations by providing detailed subsurface information because wells placed in areas with high aquifer transmissivity and storage capacity yield more water will produce maximal yield, while drilling wells in areas with less overburden and fewer geological complexities reduce drilling costs and minimize pumping energy requirements. Geophysical surveys can also identify potential sources of contamination, allowing for good placement in contaminant-free zones to ensure high water quality, reduce over-extraction and promote long-term aquifer health. Geophysical investigations have been successfully conducted across the globe for well-siting for optimal yield. A recent study illuminates the complexities of well placement optimization in oil field developments, where decision variables, constraints, and computational challenges abound (Mahmood and Al-Fatlawi, 2022). Highlighting advancements from conventional to cutting-edge AI techniques, it categorizes methods based on precision and simulation efficiency. The paper emphasizes maximizing net present value while addressing constraints. It showcases the evolution of optimization methods, offering strategies tailored for diverse scenarios. By bridging traditional and AI-driven approaches, this comprehensive review equips petroleum engineers with tools to enhance operational efficiency and drive innovation in oil field management.

A noteworthy study in Beijing, China, presents two case studies using CSAMT and NSAMT methods for groundwater exploration (Carlson and Bushner, 2011). In the Tule Desert project, a resistive feature identified by the survey led to a well producing 4540 litres per minute of low TDS water. In the Dry Lake Valley project, a CSAMT survey guided the drilling of a well producing over 6800 litres per minute of good quality water. The surveys involved over 2000 stations at 76 m intervals, covering 158 km in the Tule Desert project. The Dry Lake Valley project used 61 m electric field dipoles and one magnetic field measurement per five electric fields. A PhD thesis on well placement optimization in the oil and gas industry proposes new algorithms based on CMA-ES, a powerful derivative-free optimizer, to find optimal well locations and trajectories (Bouzarkouna, 2012). The thesis demonstrates significant reductions in the number of reservoir simulations needed for optimization. For example, using partially separated meta-models (p-sep lmm-CMA) reduces simulations by 60% compared to standard CMA-ES. The thesis also introduces a new approach to handling geological uncertainty, achieving an 81% reduction in simulations compared to using the mean of samples. These results highlight the potential of the proposed methods for improving efficiency and accuracy in well placement optimization.

A review study on the application of geophysical well logs in solving geological issues highlights the evolution of well logging technology, emphasizing the increasing vertical resolution and depth of investigation of modern tools (Lai et al., 2024). The paper provides quantitative data on various well-log parameters, including vertical resolution, depth of investigation, and fracture properties. It also discusses the use of well logs in determining in-situ stress, predicting lithology and lithofacies, and evaluating unconventional oil and gas reservoirs. The review concludes by exploring the potential of artificial intelligence in enhancing well-log interpretation and analysis. In conclusion, geophysical techniques have revolutionized well and borehole siting, combining precision and cost-efficiency to enhance groundwater and resource exploration. Several case studies have effectively demonstrated the success of geophysical methods like ER, and seismic surveys in identifying aquifer depths (24–150 m), resistivity values (10–561 Ωm), and transmissivity ranges (0.79–1203 m^2/day). These technologies enable accurate siting in diverse terrains, minimizing drilling risks and maximizing yields. Recent applications in India, Nigeria, and Kenya highlight their global relevance, underscoring their role in sustainable water resource management and optimized extraction strategies for agricultural, industrial, and urban demands. This information can help in improving the efficiency of groundwater extraction and minimizing the risk of well failure. Therefore, geophysical surveys remain essential tools for optimizing well siting, leading to increased water yield, reduced operational costs, and improved groundwater sustainability, which will enable informed decision-making, ensuring the efficient and responsible utilization of groundwater resources.

4. Applications of geophysics: challenges and opportunities

The involvement of geophysics in groundwater exploration, management, and sustainability in the 20th and 21st centuries remains a masterstroke in human development (Omeiza et al., 2023a). The geophysical exploration and management of groundwater resources have enhanced the delineation of aquifers, groundwater management, assessment of hydraulic conductivity, and monitoring of aquifer recharge zones with high precision, which enables sustainable groundwater allocation, particularly in arid regions. However, the application of geophysical methods can be very challenging, especially in waterbodies, thick forests, and urban areas. While geophysical methods remain powerful tools for groundwater exploration, management, and sustainability, some inherent limitations should be considered. For instance, the resolution of geophysical methods is limited by the wavelength of the energy employed (Alao et al., 2025), which means that smaller features, like thin aquifers or fractures, may not be detected (Alao et al., 2023a). The depth of penetration varies significantly between methods. For instance, methods like GPR are only effective in shallow depths (Poluha et al., 2017), while others like seismic reflection can reach deeper targets but struggle to capture the complex geological structures (Alao et al., 2025). While geophysics may not directly measure these parameters, such as water quality assessment, treatment planning, flow direction, or recharge rates, it can provide valuable data that can be used to infer these parameter. In addition to these challenges, other common challenges that may arise from the utilization of geophysical tools due to the dynamic and complex nature of the landscape and subsurface environment include (i) limited access, (ii) high levels of noise, (iii) inadequate skilled personnel, (iv) subsurface heterogeneity, (v) electromagnetic interference, (vi) data interpretation complexity, (vii) cost-effective considerations, and (viii) regulatory compliance. By acknowledging these limitations and integrating geophysical data with other information, geophysical methods can be maximized to ensure suitable application in groundwater exploration, management, and sustainability efforts, leading to better resource utilization and protection.

Despite the obstacles and limitations, geophysical methods remain the most effective methods for exploring and managing groundwater resources because they provide: (i) cost-effective survey, (ii) non-invasive investigation, (iii) high-resolution imaging, (iv) rapid data acquisition, and (v) predicting the exact position and depth aquifer or groundwater repository. Additionally, the geophysical methods of groundwater exploration are not limited to determining aquifer recharge rate, characterization of the aquifer, the identification of groundwater promising zones, and assessment of groundwater vulnerability, but they can also evaluate groundwater quality. The recent advancements in geophysical methods, such as electromagnetic surveys and 3D modelling, have enhanced the precision and efficiency of groundwater management (Bhattacharya, 2019), which holds a promising approach for sustainable GWRM, particularly in regions facing water scarcity. Therefore, leveraging geophysical tools in conjunction with community engagement and innovative financing mechanisms can mitigate costs and expand access. By fostering collaboration between scientists, policymakers, and stakeholders, the geophysical field holds the key to sustainable water resource management in the face of growing global demand. Ultimately, these technologies bridge gaps in knowledge, empowering humanity to secure its most vital water resource for generations to come.

5. Discussion: findings, implications, economic significance, and future directions

Geophysics revolutionizes groundwater exploration and management for sustainability is crucial because this hidden treasure (groundwater) lies beneath the Earth's surface. However, groundwater resources are often undervalued and increasingly threatened by growing demand, contaminants, and climate change. The involvement of geophysics as a powerful tool for transforming groundwater exploration and sustainability remains second to none. This review highlights the remarkable contributions of geophysics in revealing the secrets of the subsurface, offering a glimpse into the efficacy of geophysical methods such as GPR, seismic, and ER, which have proven invaluable in mapping aquifer zones, faults, fractures, and geological structures with vital quantitative data for informed decision-making and stalkhoders in groundwater development. The knowledge and information also enpower stakeholders to implement effective strategic plannning for sustainable groundwater management, ensuring wter security for the next generations.

Geophysical methods are not just about identifying the presence of groundwater; they also provide crucial quantitative data for understanding aquifer properties and dynamics. For instance, ER surveys can delineate zones of high and low resistivity, correlating with changes in porosity and permeability (Alao et al., 2023b). This information is essential for determining the volume of water an aquifer can hold and the rate at which it can flow. Seismic surveys, on the other hand, provide detailed images of subsurface stratigraphy, helping to identify aquifer boundaries and thickness (Alao et al., 2025). Geophysical methods are also proving highly effective in mapping aquifer promising zones, offering a cost-effective and accurate way to identify areas with high groundwater potential. Studies in Kenya, Nigeria, and Morocco have successfully used ER surveys to identify zones with resistivity values ranging from 10 to 100 Ωm, indicating promising aquifers (Lucy et al., 2016; Omali and Arogundade, 2022). This information is crucial for guiding well-siting and maximizing groundwater extraction. Geophysics plays a vital role in monitoring changes in groundwater levels, providing valuable data for sustainable water resource management. Techniques like floating transient electromagnetic (FloaTEM) systems and ER tomography (ERT) are being used to track groundwater fluctuations over time, revealing the impact of climate change and human activities on aquifer dynamics (USGS, 2019; Zheng et al., 2024).

Furthermore, geophysical methods are proving effective in detecting and delineating groundwater contamination plumes, facilitating remediation efforts and promoting groundwater quality. Studies in Nigeria, the USA, and Australia have successfully used ER surveys, GPR, and other techniques to identify contaminated zones and guide cleanup strategies (Buselli and Lu, 2021; Slater, 2022; Alao, 2023). However, the financial constraints often hinder groundwater exploration, with the cost of drilling a new production well reaching up to $1 million (Foster, 1988). Geophysical methods mitigate these costs by reducing the risk of dry wells and guiding the placement of wells in the most promising locations. This cost-effectiveness is a game-changer for groundwater development projects (Alao et al., 2024j). Therefore, the economic significance of geophysics in groundwater management is undeniable because it provides accurate and detailed subsurface information that enables decision-makers and stakeholders in GWRM to: (i) optimize well siting for maximizing yield, minimizing operational costs, and ensure long-term sustainability (Mahmood and Al-Fatlawi, 2022), (ii) effectively extract groundwater which promotes aquifer health, (iii) reduce contamination risks by Identifying potential contamination sources and allowed proper wells/boreholes placement in contaminant-free zones to ensure high water quality, (iv) enhance cost-effective exploration compared to traditional drilling methods, particularly for large-scale exploration projects.

Going forward, the future of geophysics in groundwater management cannot be overemphasised, especially as the demand for groundwater resources continues to grow. It is therefore important for future research and development to focus on: (i) integration of geophysical methods to provide an adequate understanding of subsurface conditions, (ii) development of advanced technologies such as AEM surveys and tTEM systems, enabling faster and more efficient data acquisition over large areas (Behroozmand et al., 2018), (iii) improved or sophisticated data interpretation and algorithms that will enhance the accuracy and reliability of geophysical surveys, integrating artificial intelligences such as such as maching learning, deep learning, geospatial analysis, AI-enhanced hydrological modeling, data fusion techniques, predictive analysis, etc. for advanced groundwater exploration, and (iv) collaboration and stakeholder engagement to inform decision-making and promote sustainable groundwater management. Finally, geophysics is revolutionizing groundwater management, providing a powerful tool for understanding and managing this vital resource. By providing precise, quantitative data about subsurface conditions, these methods are enabling more efficient exploration, sustainable extraction, and effective contamination mitigation. As the world faces increasing water scarcity, geophysics will play a crucial role in ensuring that groundwater remains a reliable and sustainable source of water for generations to come.

6. Conclusions

The Earth's hidden treasure, groundwater, is crucial for a water-secure future. This review article has demonstrated how geophysics, armed with advanced technology, is unlocking the secrets of this vital resource. From identifying and mapping promising aquifers through the geophysical evaluation of aquifer properties such as resistivity, thickness, permeability, porosity, etc. to provide precise insights into subsurface conditions. Geophysical techniques are not only revealing the location and extent of aquifers but also helping us understand their properties, such as hydraulic conductivity and transmissivity, which are crucial knowledge for sustainable GWRM, particularly in arid regions where groundwater is a lifeline. Based on the reports from various literature, the future of groundwater exploration and management lies in integrating geophysical methods with other technologies like RS and GIS. This integrated approach, coupled with community engagement and innovative financing mechanisms, can overcome challenges like cost and access, making geophysics a powerful tool for sustainable GWRM. For instance, one of the studies demonstrates a critical connection between waste management and water source integrity, emphasizing the transformative potential of integrating community knowledge into scientific research, prioritizing education, infrastructure, and reformed water management skills as essential to safeguard water resources and public health. Geophysical methods offer cost-effective, non-invasive solutions, reducing the risk of dry wells and guiding efficient extraction. As the world faces increasing water stress, geophysics stands as a vital tool for unlocking the secrets of hidden subterranean water treasure. By embracing these technologies, we can unlock the potential of groundwater, safeguarding water-secure future.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Joseph Omeiza Alao: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Fahad Abubakar:** Writing – review & editing, Writing – original draft, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation.

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