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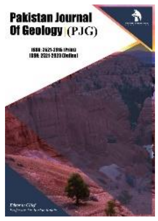

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RESEARCH ARTICLE

COMPREHENSIVE REVIEW OF GROUNDWATER ASSESSMENT TECHNIQUES: ENHANCING SUBSURFACE UNDERSTANDING THROUGH INTEGRATED METHODS

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ABSTRACT

Groundwater assessment methods have evolved significantly, revealing the effectiveness of various techniques and emphasizing the necessity of an integrated approach for a thorough understanding of groundwater resources. This review highlights Vertical Electrical Sounding (VES) as a foundational tool, which provides valuable insights into subsurface resistivity and aquifer characteristics. Despite its utility in profiling vertical resistivity, VES is limited in depth penetration and lateral variation capture. To address these constraints, the review explores advanced techniques such as Electrical Resistivity Tomography (ERT) and Ground Penetrating Radar (GPR). ERT enhances spatial resolution by offering detailed views of resistivity variations, which improve the understanding of aquifer boundaries and subsurface structures. GPR, with its high-resolution imaging capabilities, excels in shallow investigations, complementing VES data with detailed insights. Additionally, Seismic Refraction provides complementary information on subsurface layers and aquifer depths, adding another dimension to resistivity-based methods. The integration of these techniques, along with hydrogeological methods like drilling and well logging, offers a comprehensive framework for groundwater assessment. Remote sensing technologies, including satellite imagery and Geographic Information Systems (GIS), contribute valuable spatial and temporal data for understanding groundwater recharge areas and monitoring land use impacts. Hydrological modeling further supports predictive insights into groundwater flow and future scenarios. For Nigeria, applying these integrated methods is crucial due to its diverse geological and climatic conditions. Utilizing VES, ERT, GPR, Seismic Refraction, remote sensing, and GIS will enhance the understanding of groundwater resources, facilitate effective management strategies, and address issues such as over-extraction and contamination. Effective groundwater management policies should be informed by these comprehensive assessments and supported by research, development, and public awareness efforts to ensure sustainable use of groundwater resources.

KEYWORDS

Groundwater Assessment, Electrical Resistivity Tomography, Ground Penetrating Radar, Remote Sensing

1. INTRODUCTION

Groundwater is a cornerstone of Nigeria's water supply, essential for drinking, agriculture, and industry. With a population exceeding 200 million, the demand for water in Nigeria is immense, making groundwater a vital resource (Sikakwe, 2020; Abdullateef et al., 2021). This resource supplies approximately 50% of the country's total water needs, a crucial share given the uneven distribution and availability of surface water (Ewuzie et al., 2021). In many regions, where surface water is either scarce or unreliable, groundwater becomes the primary or even sole source of water. The significance of groundwater extends beyond basic consumption. It supports Nigeria's agriculture sector, which employs over 60% of the population and is a major contributor to the GDP (Adebayo et al., 2021). In areas where surface water is insufficient, groundwater supports irrigation systems that are critical for crop production and food security. Furthermore, in urban centers where rapid population growth and industrial demands exert pressure on surface water resources, groundwater acts as a crucial reserve, helping to meet the increasing water needs of these areas.

However, managing this vital resource presents several challenges. Groundwater is often overexploited due to unregulated drilling of boreholes, which leads to declining water tables and potential depletion of aquifers. Additionally, contamination from industrial activities, agricultural runoff, and inadequate sanitation facilities further compromises groundwater quality (Etuk et al., 2021). The situation is exacerbated by the lack of comprehensive and systematic groundwater monitoring, making it difficult to assess and manage the resource effectively. Given these issues, there is a pressing need for effective groundwater assessment methods to ensure the sustainable use of this resource (Barbosa et al., 2023). Proper assessment is essential for understanding groundwater availability and quality, forecasting future trends, and making informed decisions about water use and conservation. Effective assessment can help identify areas at risk of depletion or contamination and guide appropriate management strategies.

This review aims to provide a thorough examination of the current methods used for groundwater assessment in Nigeria and evaluate their effectiveness. The focus is on summarizing the various techniques employed to assess both the quantity and quality of groundwater, highlighting their strengths and limitations (Alabi et al., 2020). Through this analysis, the review seeks to identify existing gaps in groundwater assessment practices and propose an integrated approach to address these deficiencies. Current groundwater assessment methods in Nigeria

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include field-based techniques, laboratory analyses, and modeling approaches. Field-based methods involve the direct measurement of groundwater levels using piezometers and observation wells. These measurements provide critical data on the depth of the water table and its changes over time, which is important for understanding trends in groundwater availability and managing water extraction (Fajana, 2020). However, these methods can be limited by the spatial and temporal resolution of data collection and the costs associated with establishing and maintaining monitoring networks.

Laboratory analyses involve testing water samples for various chemical and biological parameters, such as pH, total dissolved solids (TDS), heavy metals, and microbial contaminants (Talabi et al., 2020). While these analyses offer detailed insights into groundwater quality, they are constrained by sampling frequency and the representativeness of the samples. Additionally, the resources required for laboratory testing, including time and cost, can limit the extent of monitoring efforts. Modeling approaches use mathematical models to simulate groundwater flow and predict future trends. These models, such as MODFLOW or Visual MODFLOW, integrate data from field observations and laboratory analyses to provide a comprehensive understanding of groundwater dynamics (Ibeh, 2020). Although modeling offers valuable predictions and insights, its accuracy depends on the quality of input data and the assumptions made during the modeling process. Each method has its strengths and limitations, and often, a combination of these methods is employed to gain a more comprehensive understanding of groundwater resources.

Despite the availability of these methods, significant gaps remain in groundwater assessment in Nigeria. A major gap is the lack of comprehensive and systematic monitoring networks, particularly in rural and underserved areas, leading to insufficient data for effective management (Omosuyi et al., 2020). Additionally, there is limited integration of groundwater data with other hydrological and environmental data, which hinders a holistic understanding of groundwater dynamics. Another gap is the underutilization of advanced technologies for groundwater assessment. Remote sensing and geospatial technologies, which have been effective in other regions, are not widely used in Nigeria (Ogungbade et al., 2022). These technologies can offer valuable data on land use, vegetation cover, and changes in groundwater levels over large areas, enhancing the monitoring and management of groundwater resources.

To address these gaps, an integrated approach to groundwater assessment is necessary. This approach should combine traditional field-based methods with advanced technologies and modeling techniques. Enhancing monitoring networks to cover both urban and rural areas is crucial, as is the integration of remote sensing and GIS technologies to complement existing data (Oni et al., 2020). Developing robust data management systems to integrate and analyze groundwater data from various sources is also essential. Furthermore, improving the technical capacity of personnel involved in groundwater assessment and management through training and skill development will support the effective implementation of advanced techniques. By adopting an integrated approach, Nigeria can improve its groundwater assessment efforts, address existing gaps, and ensure the sustainable management of this critical resource.

2. Overview of Groundwater Potential in Nigeria

Nigeria's groundwater potential is deeply influenced by its diverse geological and hydrogeological context. The country's geology varies significantly across different regions, affecting the distribution and quality of groundwater resources. Nigeria's geological formations are primarily divided into three broad regions: the Basement Complex, the Sedimentary Basins, and the Coastal Plain Sands. The Basement Complex, which covers much of northern and central Nigeria, is characterized by Precambrian rocks such as granites, gneisses, and schists. These rocks are typically hard and crystalline, resulting in lower porosity and permeability (Osinowo and Arowoogun, 2020). Consequently, groundwater in this region is usually found in weathered and fractured zones rather than in extensive, continuous aquifers. Groundwater yields in the Basement Complex can be modest unless there is significant fracturing or weathering.

In contrast, the Sedimentary Basins, which include the Niger Delta, the Benue Trough, and the Sokoto Basin, cover large parts of southeastern, central, and northern Nigeria. These basins are composed of sedimentary rocks such as sandstone, limestone, and shale, which generally exhibit higher porosity and permeability compared to the Basement Complex (Oke, 2020). This makes these areas more conducive to productive aquifers. For instance, the Niger Delta features extensive alluvial and deltaic sediments that form highly productive aquifers, significantly contributing to the country's groundwater resources. The Coastal Plain Sands, located in southwestern Nigeria, are composed of unconsolidated sandy deposits with high permeability. This region benefits from excellent groundwater potential due to the sands' high porosity and ability to store and transmit water efficiently (Aladejana et al., 2020). Additionally, the Coastal Plain Sands area experiences high recharge rates due to its proximity to the Atlantic Ocean and abundant rainfall, further enhancing its groundwater resources.

Nigeria's major aquifers are influenced by these geological formations and are crucial to the country's groundwater supply. The Ogallala Aquifer system, found in the north-central region, particularly within sedimentary basins, represents a significant source of groundwater. It consists mainly of sandstone formations with favorable aquifer properties, contributing substantially to regional water supplies (Akinwumiju, 2020). Similarly, the Niger Delta Aquifer is one of the most productive groundwater systems in Nigeria, characterized by high porosity and permeability due to its alluvial and deltaic sediments (Salawu et al., 2020). In the northern part of the country, the Sokoto Basin also contains significant aquifer systems within its sedimentary rocks, accessed through deep wells and boreholes. The Coastal Plain Sands Aquifer system in southwestern Nigeria is renowned for its high productivity, owing to its sandy sediments that provide excellent conditions for groundwater storage and movement (Oyeyemi et al., 2021). This aquifer system is vital for meeting the water needs of the region. The groundwater potential across Nigeria varies greatly, influenced by regional differences in geological formations, climate, and recharge conditions. Understanding this variability is essential for effective groundwater management and resource allocation.

In northern Nigeria, where the Basement Complex predominates, groundwater resources are often constrained by the low permeability of the underlying rocks. This region has a semi-arid to arid climate with limited rainfall, which restricts groundwater recharge. Despite these challenges, groundwater can be found in sufficient quantities in areas with significant fracturing or weathering (Wali et al., 2020). Notable exceptions include the Sokoto Basin and parts of the Benue Trough, where sedimentary formations provide more productive aquifers. Central Nigeria, located at the boundary between the Basement Complex and sedimentary basins, exhibits a mixed groundwater potential. This region includes both hard rock and sedimentary formations, leading to a variable groundwater profile. The sedimentary basins in central Nigeria, such as parts of the Benue Trough, generally offer better groundwater conditions compared to the Basement Complex areas (Lawal et al., 2020).

Southern Nigeria, characterized by sedimentary and Coastal Plain Sands formations, generally has high groundwater potential. The Niger Delta, with its extensive alluvial deposits, is particularly notable for its abundant groundwater resources (Abdullateef et al., 2021). The Coastal Plain Sands region also benefits from high rainfall and good recharge conditions, resulting in significant groundwater availability. These areas are characterized by high porosity and permeability, which support substantial groundwater extraction and storage.

Eastern Nigeria features a mix of sedimentary and Basement Complex rocks. The groundwater potential in this region varies accordingly, with sedimentary areas such as parts of the Benue Trough showing moderate to high potential. The Basement Complex areas in eastern Nigeria have more limited groundwater resources, similar to those in the northern region (Awosika et al., 2020). In Western Nigeria, the Coastal Plain Sands dominate, offering high groundwater potential due to the highly permeable sandy sediments (Badmus et al., 2020). This region benefits from substantial rainfall and high recharge rates, contributing to the abundance of groundwater resources.

Nigeria’s groundwater potential is shaped by its complex geology and regional climatic conditions (Igwe et al., 2020). While the Basement Complex areas in the north and central regions generally have more limited groundwater resources due to lower permeability, the sedimentary basins and Coastal Plain Sands in the south and southwest provide more prolific aquifers. Understanding these regional variations is essential for effective groundwater management and ensuring sustainable use of this crucial resource across the country.

3. Methodologies for Assessing Groundwater Potential

Groundwater plays a pivotal role in supporting various sectors, including agriculture, drinking water supplies, and industry, especially in regions like Nigeria. Assessing groundwater potential is crucial for effective management and sustainable use. This assessment relies on a range of methodologies, each providing unique insights into groundwater resources (Anomohanran et al., 2020). The following discussion covers the key techniques used, including VES, geophysical methods, geological and hydrogeological surveys, remote sensing and GIS, hydrological modeling, and water quality analysis. VES is a widely recognized geophysical method that measures the resistivity of subsurface materials to infer the presence and characteristics of groundwater. The principle behind VES is based on the fact that different geological materials exhibit varying resistivities, primarily influenced by their water content. In VES, an electrical current is introduced into the ground through two current electrodes, while the resulting voltage is measured using two potential electrodes (Joel et al., 2020). By adjusting the distance between the electrodes, VES can probe different depths of the subsurface.

Typically, VES involves placing four electrodes in a linear arrangement on the surface (Oguama et al., 2020). The current electrodes are positioned at a set distance apart to inject the current, while the potential electrodes are placed between them to measure the resulting voltage. As the distance between the current electrodes increases, the depth of investigation also increases. The resistivity data collected is plotted against depth to produce a vertical profile of the subsurface. This profile reveals the depth, thickness, and extent of aquifers, as well as the presence of other geological formations. VES is crucial for assessing various properties of aquifers. It helps determine the depth to the water table or the top of the aquifer, which is essential for planning drilling operations. VES also estimates the thickness of an aquifer, providing insights into its potential yield and capacity (Iserhien-Emekeme et al., 2020). Additionally, it delineates the lateral extent of an aquifer, which is vital for understanding its spatial distribution and suitability for groundwater extraction. While VES primarily measures resistivity, it can also offer indirect indications of water quality, such as the presence of saline or highly conductive water.

In Nigeria, VES has been applied in various regions to explore groundwater resources. For instance, in northern Nigeria, where the Basement Complex is prevalent, VES has been used to investigate groundwater potential in areas with hard, crystalline rocks (Ezema et al., 2020). In the Sokoto Basin, VES surveys revealed productive sedimentary aquifers within these formations, providing essential data for groundwater management. In central Nigeria, particularly within the Benue Trough, VES has been employed to explore sedimentary aquifers, helping to map their thickness and depth for effective groundwater extraction planning. Southern Nigeria, known for its sedimentary and Coastal Plain Sands formations, has also benefited from VES applications. In the Niger Delta, VES played a crucial role in identifying high-yield groundwater zones within alluvial and deltaic sediments. Similarly, in southwestern Nigeria, VES provided insights into the sandy sediments of the Coastal Plain Sands region, facilitating the identification of productive aquifers (Ameh et al., 2020).

While VES is effective in providing detailed resistivity profiles, it does have limitations. The resistivity data can be influenced by factors such as soil moisture content and mineral composition, which may lead to ambiguous results or misinterpretations. For example, high resistivity values might indicate either dry materials or saline water, complicating the assessment of groundwater types (Mohammed and Taofiq, 2021). Additionally, the depth of investigation depends on the electrode spacing and current used, which might not always be sufficient to reach deeper aquifers or provide high resolution. The successful implementation of VES also requires expertise in data acquisition and interpretation, which may be limited in remote areas.

Geophysical methods complement VES in assessing groundwater potential. ERT is one such method, offering a two-dimensional image of subsurface resistivity variations. Unlike VES, which provides a vertical profile, ERT provides a continuous resistivity profile along a horizontal line, allowing for a more detailed spatial representation of subsurface conditions. ERT involves deploying a series of electrodes along a survey line and systematically measuring resistivity at various positions and depths (Mohammed and Taofiq, 2021). The data collected are used to create a tomographic image of the subsurface, revealing detailed information about the distribution and extent of groundwater-bearing formations. ERT is particularly useful for identifying lateral variations in resistivity, which can help delineate aquifer boundaries and detect features such as fault zones or contamination plumes.

GPR is another geophysical method employed for shallow subsurface investigations. GPR uses radar pulses to detect variations in the electromagnetic properties of subsurface materials. This method is especially effective for mapping shallow aquifers, detecting changes in water content, and identifying structures like buried channels or voids (Ganiyu et al., 2020). GPR provides high-resolution images of subsurface features, enabling the identification of water table depths and delineation of aquifer boundaries. However, GPR is most effective in environments with low electrical conductivity, as high conductivity materials, such as clay-rich soils, can attenuate radar signals.

Seismic Refraction is another technique used to assess subsurface layers and aquifer depths. This method involves measuring the arrival times of seismic waves that travel through different geological layers. By analyzing the speed at which seismic waves travel, Seismic Refraction can provide insights into the depth and composition of subsurface layers (Adewoyin et al., 2021). This technique is particularly useful for estimating the depth to bedrock or the top of an aquifer, helping determine the thickness of overlying materials and identifying variations in subsurface conditions that may affect groundwater flow.

Geological and hydrogeological surveys are also crucial in assessing groundwater potential. Field mapping involves creating detailed maps that illustrate the distribution of geological units and groundwater conditions. Geological maps provide information on rock types, structures, and formations, while hydrogeological maps focus on groundwater occurrence, flow patterns, and recharge areas. Field mapping is essential for understanding the spatial distribution of groundwater resources and guiding management strategies (Olaolu and Abiola, 2021). It helps identify areas with favorable conditions for groundwater extraction and assess potential impacts of land use changes on water resources.

Drilling and well logging are direct methods for obtaining data on subsurface conditions and aquifers. Drilling involves boring holes into the ground to access groundwater and collect samples from different depths. Well logging measures various properties of subsurface materials encountered during drilling, such as electrical resistivity, gamma radiation, and lithology (Sunday, 2021). These techniques provide accurate, site-specific data on aquifer characteristics, including depth, thickness, and quality. They are crucial for validating geophysical and geological models and obtaining direct measurements of groundwater levels and properties.

Remote sensing and GIS offer additional tools for assessing groundwater potential. Satellite imagery provides broad-scale observations of land surface conditions, which can be used to identify recharge areas, analyze land use patterns, and monitor changes in vegetation and soil moisture (Omolaiye et al., 2020). By integrating satellite imagery with other data sources, such as geological and hydrogeological maps, it is possible to gain insights into factors influencing groundwater recharge and availability. Satellite imagery also helps identify areas of land use change that may impact groundwater resources.

GIS facilitates the integration, analysis, and visualization of spatial data related to groundwater resources. It combines various data layers, including geological maps, hydrological data, and remote sensing information, to create comprehensive models of groundwater systems. GIS enables spatial analysis, such as identifying recharge areas, assessing groundwater flow patterns, and evaluating the impacts of land use changes. It also aids decision-making by providing visual representations of groundwater data and scenarios (Falebita et al., 2020).

Hydrological modeling is another critical approach for assessing groundwater potential. Water Balance Models assess the inputs, outputs, and storage of groundwater in a given area by considering factors such as precipitation, evaporation, surface runoff, and groundwater recharge (Boubacar et al., 2020). These models provide valuable insights into groundwater dynamics, evaluate the sustainability of water resources, and predict the impacts of changes in land use or climate.

Numerical Groundwater Models simulate groundwater flow and predict future scenarios based on various input parameters (Akintorinwa et al., 2020). These models use mathematical equations to represent groundwater movement through different geological formations and can simulate the effects of pumping, recharge, and other factors on groundwater levels and flow patterns. Numerical models are useful for predicting the impacts of groundwater extraction, assessing contamination risks, and planning for future water demands. They offer a detailed understanding of groundwater dynamics and support informed decision-making regarding groundwater management.

Water quality analysis is crucial for evaluating the suitability of groundwater for various uses. Chemical analysis measures the concentrations of substances in groundwater, such as salts, heavy metals, and nutrients. Isotopic analysis provides information on the origin and age of groundwater, as well as processes affecting its quality. These analyses are essential for identifying contamination sources, assessing water quality, and monitoring changes over time, ensuring that groundwater resources are safe and suitable for consumption and other uses

(Eyankware et al., 2020). Assessing groundwater potential involves a diverse range of methodologies, each contributing valuable insights into groundwater resources. From geophysical methods like VES and ERT to geological surveys, remote sensing, and hydrological modeling, these techniques collectively provide a comprehensive understanding of groundwater characteristics and dynamics. By integrating these methods, it is possible to effectively manage and protect groundwater resources, supporting sustainable development and addressing water supply challenges.

4. Comparative analysis of methods

Assessing groundwater potential is a critical endeavor, given the significant role groundwater plays in various sectors such as agriculture, drinking water, and industry. In Nigeria, as in many other regions, different methodologies are used to explore and evaluate groundwater resources. Among these, VES is a widely employed technique. However, it is often compared and complemented by other geophysical and hydrogeological methods (MS and GI, 2020). This analysis examines the effectiveness of VES in relation to other techniques and explores how various methods perform across different regions of Nigeria.

VES is a geophysical technique that measures subsurface resistivity to infer the characteristics of groundwater-bearing formations. VES is valued for its simplicity and cost-effectiveness. It provides a vertical profile of resistivity, which helps in determining the depth, thickness, and lateral extent of aquifers (Sunkari et al., 2021). Additionally, VES can offer indirect information about groundwater quality, such as the presence of saline or conductive water. One of the primary advantages of VES is its straightforward implementation. The method requires basic field equipment and the data collection process is relatively simple compared to other methods. VES is adaptable to various geological settings, making it a versatile tool for groundwater exploration.

Despite its advantages, VES has limitations. The accuracy of resistivity measurements can be influenced by factors like soil moisture content, temperature, and mineral composition, which may lead to potential misinterpretations. For instance, high resistivity values might indicate either dry materials or saline water, complicating the assessment of groundwater types. Additionally, the depth of investigation in VES is dependent on electrode spacing and current, which might not always be sufficient to reach deeper aquifers or provide high-resolution data. VES also requires expertise in data acquisition and interpretation, which can be a challenge in remote or underserved areas (Olanrewaju et al., 2020).

When compared to other geophysical methods, such as ERT, GPR, and Seismic Refraction, VES offers a more limited perspective of subsurface conditions. ERT provides a two-dimensional image of resistivity variations along a horizontal line, offering a more detailed spatial representation of subsurface features than the vertical profile obtained from VES (Akinbiyi et al., 2020). ERT is particularly effective in identifying lateral resistivity variations and detecting features like fault zones or contamination plumes, which VES might not reveal as effectively.

GPR complements VES by offering high-resolution images of shallow subsurface structures. GPR uses radar pulses to detect variations in electromagnetic properties and is effective in mapping shallow aquifers, detecting changes in water content, and identifying structures such as buried channels or voids. However, GPR's effectiveness can be limited in environments with high electrical conductivity, such as clay-rich soils, where radar signals may be attenuated (Oladunjoye et al., 2020). VES, in contrast, can be employed across a broader range of geological settings, although it may not provide the same level of detail as GPR in shallow investigations.

Seismic Refraction is another method used to assess subsurface layers and aquifer depths by measuring the arrival times of seismic waves traveling through different geological layers. This technique can estimate the depth to bedrock or the top of an aquifer and determine the thickness of overlying materials (Adizua et al., 2021). While Seismic Refraction offers valuable depth information, it may not be as effective in delineating the lateral extent of aquifers or detecting smaller-scale features compared to ERT.

Hydrogeological techniques, such as drilling and well logging, provide direct, site-specific data on subsurface conditions (Akinsete et al., 2020). Drilling involves boring holes into the ground to access groundwater and collect samples from various depths, while well logging measures properties like resistivity and lithology. These methods offer accurate information on aquifer characteristics and help validate geophysical and geological models. However, they are more invasive and costlier compared to VES and may not be feasible for large-scale or preliminary surveys. The effectiveness of VES and other methods varies significantly across different regions of Nigeria, reflecting the diverse geological and hydrogeological conditions present in the country. In northern Nigeria, characterized by the Basement Complex with its hard, crystalline rocks, VES has been instrumental in identifying productive sedimentary aquifers. For example, in the Sokoto Basin, VES was used to delineate aquifer zones that were not easily detectable with other methods (Bayowa et al., 2020). However, the depth of investigation provided by VES might be limited in this region due to the complex geology and the presence of hard rock formations, where ERT or Seismic Refraction might offer additional insights.

In central Nigeria, within the Benue Trough, VES has been effectively used to explore sedimentary aquifers. The resistivity profiles obtained have assisted in understanding aquifer thickness and depth, supporting groundwater extraction planning (Eyankware et al., 2020). In this region, ERT could provide a more detailed spatial view of resistivity variations, while GPR might offer high-resolution images of shallow aquifers. Southern Nigeria, known for its sedimentary and Coastal Plain Sands formations, has also seen benefits from VES. In the Niger Delta, VES played a crucial role in identifying high-yield groundwater zones within alluvial and deltaic sediments. Despite this, the effectiveness of VES might be enhanced by GPR for shallow investigations or ERT for detailed spatial mapping of aquifer boundaries (Thomas et al., 2020).

In southwestern Nigeria, the Coastal Plain Sands region has similarly benefited from VES applications. VES provided insights into the sandy sediments, facilitating the identification of productive aquifers. However, combining VES with other methods, such as ERT or GPR, could improve the accuracy of aquifer delineation and support better groundwater management strategies (Inim et al., 2020). In eastern Nigeria, where a mix of sedimentary and Basement Complex rocks is present, VES has been used to understand groundwater potential. The diverse geological conditions in this region highlight the need for a multi-method approach (Olaseeni et al., 2020). VES, when complemented by techniques such as Seismic Refraction for depth estimation and GPR for shallow investigations, can provide a more comprehensive assessment of groundwater resources.

The comparative effectiveness of VES and other methods depends on specific geological and hydrogeological conditions. While VES offers valuable insights into subsurface resistivity and aquifer properties, its limitations can be addressed by integrating other geophysical methods like ERT, GPR, and Seismic Refraction. Hydrogeological techniques such as drilling and well logging provide direct, site-specific data but are more invasive and costlier (Lawal et al., 2020). By combining these methodologies and tailoring them to regional characteristics, a more comprehensive understanding and management of groundwater resources can be achieved across Nigeria.

5. Integration of methods for comprehensive assessment

Assessing groundwater potential effectively is crucial for sustainable water resource management, especially in regions with diverse geological and hydrological conditions like Nigeria. Relying on a single assessment method often limits the accuracy and depth of understanding that can be achieved (Okpoli and Ozomoge, 2020). Integrating multiple methodologies, including VES, with other geophysical and hydrogeological techniques, offers a more holistic approach to groundwater evaluation. This integration enhances the accuracy and reliability of assessments, providing a comprehensive view of groundwater resources. VES is a widely used technique that measures subsurface resistivity to infer the properties of groundwater-bearing formations. It provides valuable information about the vertical profile of resistivity, which helps in identifying and characterizing aquifers (Babaiwa et al., 2020). Despite its strengths, such as simplicity and cost-effectiveness, VES has limitations including its resolution and depth constraints. These limitations can be effectively addressed by combining VES with other methods.

ERT is a technique that complements VES by offering a detailed, two-dimensional spatial view of resistivity variations along a survey line. While VES provides vertical profiles of resistivity, ERT extends this by mapping lateral variations, allowing for a more comprehensive understanding of subsurface features (Ossai, 2020). This combination enables the creation of a detailed resistivity model that captures both vertical and horizontal variations, improving the accuracy of aquifer delineation. GPR provides high-resolution images of shallow subsurface structures and water content variations (Oladunjoye et al., 2021). By integrating GPR with VES, it is possible to obtain detailed insights into both shallow and deeper subsurface conditions. GPR is particularly useful for mapping the depth to the water table and detecting features such as buried channels or voids, which VES alone might not reveal.

Seismic Refraction is another method that can be integrated with VES to enhance groundwater assessments. This technique measures the arrival times of seismic waves to estimate subsurface layers and aquifer depths. While VES offers information on resistivity, Seismic Refraction provides depth information and insights into the mechanical properties of subsurface layers. Combining these methods allows for the confirmation and refinement of depth estimates, improving the understanding of aquifer thickness and the depth to significant geological boundaries (Abdulrazzaq et al., 2020). Incorporating geological and hydrogeological surveys, such as field mapping, drilling, and well logging, further enriches the integrated approach. Drilling and well logging provide direct, site-specific data on subsurface conditions and aquifer properties, which can validate and complement the geophysical data obtained through methods like VES and ERT (Olaseeni et al., 2020). Field mapping adds valuable context regarding geological formations and groundwater occurrence, aiding in the interpretation of geophysical results and the identification of recharge areas and potential contamination sources.

Remote sensing and GIS play a crucial role in integrating groundwater assessment methods. Satellite imagery and GIS facilitate the analysis of land use, vegetation, and recharge areas (Sikakwe, 2020). By incorporating these data into the assessment, it is possible to gain a comprehensive view of groundwater systems. GIS supports the spatial analysis and visualization of groundwater data, integrating various datasets and enhancing decision-making in groundwater management. The benefits of integrating these methods are substantial (Olawuyi, 2021). One major advantage is the improvement in data accuracy. Each technique provides different types of information and has its strengths and limitations. While VES is effective for determining resistivity profiles, it may not capture lateral variations or shallow features as well as ERT or GPR. By combining these methods, data can be cross-validated and refined, leading to a more accurate assessment of aquifer characteristics, depth, and spatial distribution.

Reliability is another significant benefit of an integrated approach. Relying on a single dataset can lead to errors or misinterpretations influenced by various factors such as soil moisture or mineral composition (Nebeokike et al., 2020). By integrating multiple methods, inconsistencies in one dataset can be cross-checked and corrected using information from other techniques, ensuring that the results are robust and reliable. An integrated approach also addresses complex geological and hydrological conditions more effectively. In regions with diverse formations or challenging subsurface environments, no single method may provide a complete picture (George, 2021). By combining different types of data—such as resistivity profiles, seismic velocity, and shallow subsurface images—a more comprehensive understanding of groundwater resources is achieved. This holistic view is essential for identifying potential issues, such as contamination or depletion, and developing appropriate management strategies.

Furthermore, integration supports better decision-making and resource management. A more detailed and accurate assessment of groundwater potential enables stakeholders to make informed decisions regarding groundwater extraction, conservation, and development (Ewuzie et al., 2021). For example, integrated data can help identify high-yield aquifer zones, assess the impacts of land use changes on recharge areas, and evaluate the sustainability of groundwater resources. This information is crucial for planning and implementing effective groundwater management strategies that balance resource use with conservation.

Integrating VES with other geophysical and hydrogeological methods provides a comprehensive assessment of groundwater potential. By combining the strengths of each technique and addressing their individual limitations, this approach enhances the accuracy, reliability, and overall understanding of subsurface conditions. The benefits of integration, including improved accuracy, reliability, and the ability to address complex conditions, highlight the value of employing multiple methodologies in groundwater assessment (Ugbaja, 2021). This integrated approach not only improves the assessment process but also supports more informed decision-making and sustainable groundwater management.

6. Challenges and Limitations

Effective groundwater assessment is crucial for sustainable water management, yet it is fraught with challenges that can impact the accuracy and reliability of various methodologies (Akinlalu et al., 2021). Both methodological and regional factors contribute to these difficulties, highlighting the need for an understanding of these challenges to improve assessment practices and strategies for groundwater management. VES is a commonly used technique for groundwater assessment, valued for its ability to provide information on subsurface resistivity. However, VES is not without its challenges. One major issue is the potential for misinterpretation of resistivity data, as resistivity can be influenced by factors such as soil moisture content, temperature, and the presence of conductive materials like clay or saline water (Kasidi and Victor, 2021). These factors can lead to ambiguities in identifying aquifer boundaries or determining groundwater quality. For instance, high resistivity values might be mistaken for either dry conditions or saline water, complicating the assessment of groundwater resources.

Another significant limitation of VES is its depth of investigation. The technique's effectiveness depends on electrode spacing and current applied, which can restrict the depth to which resistivity measurements can penetrate. This limitation becomes particularly problematic when dealing with deeper aquifers or complex geological structures where VES may not provide sufficient data (Ekwe et al., 2021). The primarily vertical profiles offered by VES may also fall short in capturing lateral variations in subsurface conditions, which are crucial for understanding the full extent of aquifers and their boundaries. Other geophysical methods used in groundwater assessment, such as ERT, GPR), and Seismic Refraction, each come with their own set of challenges (Aduojo and Adebowole, 2020). ERT, while providing a spatial view of resistivity, involves complex data processing and interpretation, which can be resource-intensive. GPR, though useful for high-resolution imaging of shallow subsurface structures, may suffer from signal attenuation in high-conductivity environments. Seismic Refraction, which estimates depths and mechanical properties of subsurface layers, may not always effectively delineate aquifer boundaries or provide detailed information on water quality.

Hydrogeological methods, including drilling and well logging, are direct but not without their issues. Drilling is often costly and invasive and may not be feasible for preliminary surveys. Well logging, while providing valuable data, requires careful interpretation and might not always reflect broader groundwater conditions accurately. Regional factors further complicate groundwater assessment. In northern Nigeria, characterized by the Basement Complex, the hard, crystalline rock formations present considerable challenges (Popoola et al., 2020). The complex geology and highly resistive rocks can limit the depth and resolution of VES measurements. The arid to semi-arid climate in this region can also cause variations in soil moisture that affect resistivity readings, adding complexity to the accurate assessment of groundwater potential. This situation often necessitates integrating additional methods, such as Seismic Refraction or drilling, to obtain a clearer understanding of groundwater resources.

Central Nigeria, with its sedimentary formations in the Benue Trough, presents its own set of challenges. The sedimentary layers in this region are often complex, with varying resistivity that complicates the interpretation of VES data (Okon et al., 2020). The presence of different sediment types and potential contamination sources can affect the accuracy of resistivity measurements. To address these complexities, combining VES with techniques such as ERT and GPR can provide a more detailed understanding of subsurface conditions. Southern Nigeria, particularly in the Niger Delta, faces challenges related to its alluvial and deltaic sediments. The high-water content and variable sediment composition in this region can impact the effectiveness of VES, as high resistivity values might not accurately reflect the presence of groundwater. Coastal and swampy conditions also pose difficulties for methods like GPR, where signal attenuation can be problematic (Ogbe et al., 2020). In this environment, employing a multi-method approach, integrating VES with techniques that handle high conductivity environments, such as Seismic Refraction or advanced hydrogeological surveys, becomes crucial.

In southwestern Nigeria, known for its Coastal Plain Sands, groundwater assessment methods must address the challenges posed by sandy sediments. The high permeability and variability of these sediments can complicate resistivity measurements from VES and GPR. Additionally, the region's proximity to the coast introduces issues related to saltwater intrusion, which affects groundwater quality and complicates the assessment of freshwater resources (Coker et al., 2021). To effectively address these challenges, integrating VES with methods that can manage saltwater intrusion and provide detailed spatial information, such as ERT and GIS, is important.

Eastern Nigeria, with its mix of sedimentary and Basement Complex formations, presents unique challenges due to its diverse geological settings. VES may struggle with the varied resistivity of different formations, necessitating the integration of methods like Seismic Refraction and GPR. The region's climatic conditions, including varying rainfall and humidity, also impact resistivity readings and require careful calibration and interpretation of geophysical data (Bute et al., 2019).

Groundwater assessment faces several challenges that stem from both methodological limitations and regional factors. Issues such as data interpretation, depth limitations, and method-specific constraints impact the effectiveness of techniques like VES and its counterparts. Additionally, geological diversity and climatic conditions across different regions introduce specific difficulties that can affect assessment accuracy. Addressing these challenges involves a multi-method approach that integrates various techniques to provide a more comprehensive and accurate understanding of groundwater resources (Danga et al., 2021). By acknowledging and overcoming these limitations, groundwater assessment practices can be improved, leading to more effective management and sustainable use of this critical resource.

7. Future directions and recommendations

Groundwater assessment is essential for effective water resource management, yet it faces a myriad of challenges that necessitate ongoing research, technological innovation, and refined policy-making (Ohwoghere-Asuma et al., 2020). As demand for groundwater grows and environmental issues intensify, addressing these areas becomes increasingly critical. The future of groundwater management hinges on bridging research gaps, harnessing emerging technologies, and implementing strategic policies.

Research into groundwater assessment continues to reveal important gaps. One significant area in need of further exploration is the understanding of complex subsurface environments. Despite advancements in techniques like VES and ERT, the interactions between groundwater and various geological formations are not fully understood. Detailed studies on how different sediment types affect resistivity measurements could improve the accuracy of these techniques. Additionally, research into the impacts of extreme weather events and long-term climate change on groundwater resources is vital for developing adaptive management strategies that can withstand environmental shifts (Akingboye and Osazuwa, 2021).

Another pressing research gap involves groundwater quality and contamination sources. While chemical and isotopic analyses provide valuable insights, more comprehensive studies are needed to understand the origins and pathways of contaminants. This includes examining the effects of land use changes, industrial activities, and agricultural practices on groundwater quality (Olalekan et al., 2022). Enhanced methods for detecting and monitoring contaminants, especially in regions with complex hydrogeological settings, are crucial. This will help in identifying potential pollution sources and developing strategies to mitigate their impact on groundwater resources. The integration of data from various assessment methods also presents an area ripe for development. Combining techniques such as VES, GPR, and Seismic Refraction offers a more complete view of groundwater resources, but there is a need for improved methods to integrate and analyze this multi-source data effectively (Ibuot et al., 2020). Advances in data fusion techniques and machine learning algorithms hold promise for interpreting complex datasets more accurately, leading to better assessments of groundwater potential and quality.

Technological advancements are paving the way for more effective groundwater assessment and management. Emerging technologies such as advanced remote sensing, including satellite-based sensors and drones, offer high-resolution imaging and real-time data collection capabilities (Epuh et al., 2020). These technologies can monitor groundwater recharge, land use changes, and surface-water interactions, providing valuable insights for managing groundwater resources. For instance, satellites equipped with synthetic aperture radar (SAR) can track soil moisture and surface deformation, which can be correlated with groundwater levels and quality. The use of smart sensors and Internet of Things (IoT) devices for real-time groundwater monitoring is another promising development (Massazza et al., 2021). These sensors, installed in wells and monitoring stations, can provide continuous data on groundwater levels, temperature, and quality. When integrated with data analytics platforms, they enable real-time monitoring and early detection of issues such as contamination or declining water levels. This capability can significantly enhance the responsiveness of groundwater management systems and facilitate proactive management strategies.

Advancements in numerical modeling and simulation also offer potential benefits. Improved computational models that incorporate high-resolution data and sophisticated algorithms can simulate groundwater flow and quality with greater accuracy (Ibrahim et al., 2021). These models can predict future scenarios, assess the impacts of various management strategies, and support decision-making processes. User-friendly modeling tools and platforms can further enhance their accessibility and application, providing valuable insights for groundwater management. In terms of policy and management, several recommendations can improve groundwater management practices. Implementing integrated groundwater management frameworks that combine data from various assessment methods is crucial. Such frameworks should include collaboration among stakeholders—government agencies, researchers, and local communities—to ensure that groundwater management strategies are both effective and inclusive (Barbosa et al., 2022). By integrating diverse data sources and perspectives, these frameworks can provide a more comprehensive understanding of groundwater resources and support better decision-making.

Strengthening regulatory frameworks and enforcement mechanisms related to groundwater use and protection is also essential. Policies should address issues such as over-extraction, contamination, and the impacts of land use changes on groundwater resources. For example, regulations could limit groundwater extraction in critical areas, enforce best practices for agricultural and industrial activities, and promote sustainable water management practices (George, 2020). Effective enforcement of these regulations is crucial to ensuring their success.

Investing in research and development is key to advancing groundwater assessment methods and technologies. Supporting research initiatives that focus on improving assessment techniques, understanding contamination sources, and developing new technologies will drive progress in groundwater management (Ogwah and Eyankware, 2020). Collaboration between research institutions, technology developers, and policymakers can facilitate the translation of research findings into practical solutions, enhancing groundwater management practices.

Public awareness and education play a vital role in groundwater management. Educational programs and outreach initiatives can raise awareness about the importance of groundwater, the impacts of human activities on groundwater resources, and the need for sustainable management practices. Engaging communities in groundwater management efforts can lead to better outcomes and promote responsible water use. Adopting adaptive management approaches is crucial for effective groundwater management (Akakuru et al., 2021). This involves regularly reviewing and updating management strategies based on new data and insights and being flexible in responding to changing conditions and emerging challenges. An adaptive management approach ensures that groundwater resources are managed sustainably and resiliently, accommodating both current and future needs.

Addressing research gaps, leveraging technological advancements, and refining policy and management practices are essential for improving groundwater assessment and management (Babika et al., 2020). By focusing on these areas, we can enhance the accuracy and effectiveness of groundwater assessments, develop more robust management strategies, and ensure the sustainable use of this critical resource. The future of groundwater management relies on continued innovation, collaboration, and a commitment to overcoming the challenges and seizing the opportunities that lie ahead.

8. Conclusion

The investigation into groundwater assessment methods has highlighted several effective techniques and underscored the value of an integrated approach for a comprehensive understanding of groundwater resources. VES has long been a fundamental tool, offering insights into subsurface resistivity and aquifer characteristics. While VES is useful for initial assessments due to its ability to profile vertical resistivity, it has limitations regarding depth penetration and the capture of lateral variations in groundwater conditions. To address these limitations, techniques such as ERT and GPR offer significant advantages. ERT improves spatial resolution by providing a detailed view of resistivity variations, enhancing the understanding of aquifer boundaries and subsurface structures. GPR, with its high-resolution imaging, excels in shallow investigations, revealing details that complement the data provided by VES.

Together, these methods offer a more complete picture of subsurface conditions. Seismic Refraction adds another layer of insight by providing information about subsurface layers and aquifer depths, complementing the resistivity-based methods with a different perspective. When combined with hydrogeological techniques like drilling and well logging, which offer direct data on aquifer properties and groundwater quality, these methods contribute to a robust and detailed assessment framework. Furthermore, remote sensing technologies, including satellite imagery and GIS, enhance groundwater assessments by supplying valuable spatial and temporal data. This data helps in understanding groundwater recharge areas and monitoring land use impacts. Hydrological modeling, through water balance and numerical models, provides predictive insights into groundwater flow and future scenarios, aiding in the development of informed management strategies.

The integration of these methods offers a holistic approach that addresses the limitations of individual techniques, resulting in a more accurate and thorough understanding of groundwater resources. This comprehensive perspective is crucial for effective groundwater management. For Nigeria, the implications of these findings are profound. The country's diverse geological and climatic conditions require tailored assessment approaches that consider regional variations.

By utilizing a combination of techniques such as VES, ERT, GPR, Seismic Refraction, remote sensing, and GIS, Nigeria can achieve a more detailed understanding of its groundwater resources. This integrated approach will facilitate the identification of critical areas for groundwater development, enable monitoring of resource changes over time, and assess the impacts of human activities. Integrating various groundwater assessment methods provides a more complete and accurate understanding of groundwater resources. For Nigeria, adopting these integrated approaches and supporting effective policy frameworks will ensure the sustainable management of groundwater resources, meeting the needs of its population and safeguarding this vital resource for future generations.

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