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Groundwater Exploration Methods in West Africa: A Review.

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Abstract

The focus of groundwater research has evolved, expanded, and adapted to meet the water demands of society. In recent years, discernible trends have emerged in groundwater studies, particularly in the domains of exploration and exploitation. Groundwater exploration in West Africa has predominantly been driven by demand and ease of accessing water in its hosting environment. In light of the increasing dependence and the difficulty of groundwater accessibility in some environments, numerous methods have been employed to facilitate the rapid assessment of groundwater resources. This review explores into the diverse methods employed in groundwater exploration, placing particular emphasis on analyzing the evolution from geophysical methods to the application of machine learning in West Africa. The PRISMA technique was employed for data collection, screening, and verification of data eligibility. Researchers associated with Nigerian institutions contributed to 57% of all articles, followed by researchers from Ghanaian institutions. The predominant method employed in groundwater exploration, as evidenced by the highest number of published papers (18), was the electrical resistivity method followed by electromagnetic, and magnetic methodologies. Other techniques; such as induced polarization and gravity were employed in conjunction with other geophysical methods to enhance and/or corroborate the obtained results. Our research findings revealed that geophysical techniques played a crucial role in delineating the diverse geological environments relevant to groundwater accumulation and movement. In addition, Geographic Information Systems (GIS) and remote sensing have been integrated with geophysical methods to investigate the spatial distribution of groundwater resources. While these geophysical methods have demonstrated effectiveness, their interpretation relies on anomalies, which can be influenced by various factors. Incorrect interpretations may arise without thorough background studies on the geology of the area. Despite the fact that global trends are increasingly favoring the adoption of machine learning in groundwater exploration with great success in delineating potential groundwater reserves, our research reveals a notable scarcity of such endeavours in West Africa. Groundwater exploration in West Africa primarily revolves around the aforementioned geophysical methods and Geographic Information System (GIS). The review underscores the urgency for support, both financially and in terms of technological expertise, to promote research involving machine learning in West African countries. A key finding is the significant underrepresentation of machine learning studies by West African researchers in groundwater exploration, despite its demonstrated cost-effectiveness, time efficiency, and enhanced reliability.

Keywords: West Africa, Geophysical techniques, GIS, Machine learning, Groundwater.

1.0 Introduction

Groundwater remains a crucial resource, forming a substantial part of potable water essential for sustaining life on Earth; constituting over 90% of the readily available freshwater. Globally, groundwater contributes approximately one-third of freshwater withdrawals *(Raganal et al., 2017)*. Owing to escalating demands for potable water driven by factors such as population growth, enhanced living standards, socioeconomic development, mining operations, rural agro-industries, and agricultural and livestock needs, and the pollution of surface water bodies, groundwater has evolved into a principal source for domestic, irrigation, and industrial purposes *(Mulcherjee et al., 2012; Vaux, 2011; Ranganal et al., 2017).*

The dependence on groundwater is even more profound in most developing countries in Africa such as Ghana, where over two-thirds of the population rely on groundwater for various purposes *(Kortatsi et al., 2007)*. Surface water and rainfall, traditionally important water sources, have become increasingly unreliable due to the impacts of climate change and pollution. *Van de Giessan et al. (2001),* in their studies, observed a decline in annual rainfall, a significant source for groundwater recharge and other surface water bodies. The rapid change in climate patterns observed in the past decade, marked by elevated temperatures and precipitation variations, have led to a decline in water supplies, compromised water quality, and increased water demands. *Kumar (2012) and Salem et al. (2018)* have delved into the repercussions of escalating temperatures on the hydrologic cycle, elucidating how they directly augment the transpiration of vegetation and the evaporation of accessible surface water.

These indirectly influence the flow and storage of water in both surface and subsurface reservoirs, impacting the magnitudes, timings, and intensities of precipitation. *Lal et al. (2018)* and *Kumar (2012)* have examined how climate change assumes a central role among various factors jeopardizing the accessibility and sustainability of surface and groundwater resources. Concurrently, anthropogenic activities such as illegal mining, disposal of industrial waste, oil leaks, and spillages, among others, contribute to the pollution of surface water bodies. Addressing this pollution requires a substantial financial investment in water treatment and supply *(Dwivedi, 2017).* Poverty and insufficient institutional capacity to treat the accessible and abundant surface waters, as well as construction of the necessary infrastructure for storage and distribution, have prompted diverse governmental bodies, NGOs, and individuals to adopt cost-effective strategies. One such approach involves turning to groundwater development as an alternative source of potable water for settlements, particularly in rural communities. This shift has resulted in heightened exploration activities and subsequent exploitation of groundwater resources in West Africa.

The approaches to groundwater prospectivity mapping have predominantly been influenced by demand and accessibility. Traditional methods, including visual inspection of topography, site accessibility, and dowsing techniques *(Ndlovu et al., 2010)*, have been used for site selection for drilling. However, these methods lack a scientific foundation. their efficacy have been contested and they have resulted in a low borehole drilling success rate *(Betz & Betz, 1995)*. Recognizing the inefficiencies of these traditional approaches, various hydro-geophysical methods have been embraced and proven to be effective in assessing groundwater prospectivity. Although geophysical methods offer numerous advantages in terms of cost-effectiveness and the ability to investigate large areas compared to unconventional methods, the individual methods come with limitations that must be addressed for optimal results.

In order to enhance geological interpretations, researchers have increasingly turned to incorporating Geographic Information Systems (GIS) in groundwater exploration. GIS techniques do not only reveal spatial distribution but also provide a platform for the integration of geophysical and other hydrogeological factors, facilitating the generation of models for predicting groundwater potential. GIS, along with Remote Sensing techniques, has proven to be cost-effective and proficient in predicting groundwater potential sites *(Al-Bahrani et al., 2022; Epuh et al., 2022; Yusuf et al., 2022; Zimik et al., 2022)*. Moreover, GIS serves as a foundation for the integration of machine learning algorithms, in groundwater prediction.

Over the past decade, various studies have employed diverse Machine Learning models for GWL simulations. These techniques adopt simulation approaches to quantitatively and qualitatively predict groundwater accessibility. These methods encompass a broad spectrum of physically based conceptual models, exponential models, and numerical models (*Rasel et al., 2023*). These methods Artificial Neural Networks (ANNs), Fuzzy-based models *(Rajasekhar et al.,* 2019), Support Vector Machines (SVM), Tree-based models, Genetic Programming, and Gene Expression Programming models. More recently, in conjunction with the adoption of innovative AI models such as Deep Learning, Extreme Learning *(Kumar et al., 2020; Naghibi & Pourghasemi, 2015; Sharafati et al., 2020)*, and Long-Short Term Memory, novel strategies such as integrated and hybrid AI models, ensemble machine learning, and AI-GIS-based models have been implemented to model groundwater levels *(Naghibi et al., 2016)*.

This research aims to analyze the evolution of groundwater exploration in West Africa, examine the current methods adopted, and anticipate future trends in advancement. The objective is to shed light on the diverse methods employed, delineate their advantages and disadvantages, and guide research toward innovative and efficient approaches to groundwater exploration. Additionally, this work aspires to narrow the technological gap between West Africa and more technologically advanced nations.

2.0 Geophysical Methods in Groundwater Exploration

Geophysical techniques (electrical, IP, magnetic, and gravity) have played major roles in groundwater exploration. Of these, the electrical method stands out as the most prevalent and effective technique for groundwater exploration in Africa *(Mohamaden & Ehab, 2017)*. The electrical methods are employed to examine the electrical characteristics of subsurface geological units and identify anomalies within a specific area, utilizing direct currents or low-frequency alternating currents.

The ER method capitalizes on the fact that most rocks are poor conductors, and their resistivities are expected to be high. Therefore, low resistivities are considered anomalous and could be indicative of the porosity of the rocks and their infilling material, potentially water *(Mohamaden et al., 2016)* in consolidated rocks. In sandy and clayey sedimentary environments, points of high resistivity which mapped the areas of sand with high porosity serve as the area of potential aquifer. These techniques are generally conducted in Horizontal Electrical Profiling (HEP), Vertical Electrical Sounding (VES), and Electrical Resistivity Tomography (ERT) modes as discussed by Riwayat et al., (2018). Electrical Resistivity Tomography (ERT) is currently preferred due to its capability of producing 2D variations of resistivity along a survey profile *(Puspita & Suyanto, 2020).*

The electromagnetic method is employed to measure the conductivity of the subsurface. In conjunction with resistivity methods, it facilitates the examination of both horizontal and vertical discontinuities in the electrical characteristics of the ground. Additionally, it aids in identifying three-dimensional structures with abnormal electrical conductivity, as highlighted by *Nazifi and Gülen (2019a).*

In certain instances, induced polarization and self-potential methods are utilized to complement results obtained from electrical resistivity (ER) and electromagnetic (EM) methods. To enhance reliability in interpretation and minimize the risk of drilling dry wells, investigators often opt for a combination of two or more geophysical methods. For instance, by integrating resistivity and electromagnetic methods, a more comprehensive interpretation can be achieved.

The magnetic surveying technique stands as the second most frequently employed method in groundwater exploration. It involves measuring variations in the geomagnetic field caused by differences in rock magnetization or the presence of soils rich in magnetic oxide. The magnetic signatures aid in delineating various lithological units and delineating subsurface geological structures, which can influence the movement and accumulation of groundwater. In contrast, the gravity and seismic methods are infrequently used in groundwater exploration. This is because the variations observed in their measurements are negligible for groundwater exploration.

In addition to traditional geophysical methods, GIS has become an instrumental tool in groundwater exploration. GIS has demonstrated its reliability in this context by providing a platform for integrating various factors that influence groundwater accumulation and movement.

These factors include hydrogeomorphological data, geology, rainfall, drainage, slope, and land use/land cover and structural maps, as noted by *Escobar et al. (2023)*. The GIS platform allows for the analysis of logical conditions and the derivation of groundwater zones through thematic maps. These maps generate groundwater prospect zones based on their contribution to groundwater availability. *(Ganapuram et al., 2009).* The success in this has led to a noticeable shift in the groundwater exploration paradigm towards the integration of geophysics and GIS. These innovative approaches are actively sought to establish a comprehensive platform for the analysis of an area's true potential and the prediction of optimal drilling locations. Other numerical and conceptual models, such as MODFLOW and the Bayesian Network, have also found effective application in groundwater exploration.

3.0 Systematic Review Methodology

A systematic and transparent approach was employed in this literature review to identify, select, and critically evaluate relevant studies. The investigation adhered to a preferred reporting items for systematic reviews and meta-analyses (PRISMA) flow diagram, aligning with key steps, including formulating research questions, conducting a comprehensive literature search to identify relevant data, screening for eligibility based on research criteria, extracting, and synthesizing final data, and qualitatively evaluating the finding. The schematic workflow detailing the data screening process is illustrated in Figure 1.

Figure 1. Schematic workflow for data screening process.

Guided by the PRISMA-specific framework, a search string was developed to locate pertinent phrases within the abstracts, titles, and content of articles in four online databases (Dimensions, Scopus, Science Direct, and Google Scholar). The literature samples were drawn from journals published between January 2013 and August 2023, providing a decade-long perspective on the progress of groundwater exploration methods. Three review questions were formulated to serve as the foundational inquiries for this investigation (Table 1). Table 1 shows the reviews constructed the inquiries pursued in this paper.

KEYWORDS used for the search string include "groundwater", "Geophysical methods", "VES or West Africa", "Resistivity", "Aeromagnetic AND GIS AND Ghana AND Nigeria", "groundwater or modelling"," groundwater and machine learning", "numerical modelling or groundwater exploration"

Table 1. Review questions constructed for the inquiry.

	Research Questions	*Inspiration*
R1	What are the publication trends in the exploration of groundwater resources?	To determine the dominant areas of study based on the quantity of study and show the gaps in this domain.
R2	What are the advantages and disadvantages of the various approaches?	To identify and analyze the various methods being used in groundwater exploration and determine the most popular approach, the advantages, and disadvantages of these methods.
R3	What are future areas of focus?	To provide information about current subjects of interest in the domain, the new practices being utilized and the future ambition of researchers and practitioners.

A total of 573 articles were found: 385 from Dimensions, 68 from Scopus, 78 from Google Scholar, and 42 from Science Direct (Table 2). Key information, including title, keywords, abstract, and Digital Objective Identifier (DOI), among others, was extracted from the articles and saved in a comma-separated value (CSV) file generated by Scopus, Google Scholar, and Dimensions (Table 1). To streamline the dataset, duplicate files (258 papers, that is 45% of the total number of papers downloaded) were removed using Excel, resulting in 315 articles. The studies obtained from the literature search underwent further scrutiny through manual screening, involving a careful review of titles, abstracts, publication years, and the relevance of each article to the research questions.

Table 2. Databases and the number of items identified from the databases.

Database	**Number of articles**
Dimension	385
Scopus	68
Science Direct	42
Google Scholar	78
	573

Following the screening phase, the remaining 45 articles underwent a comprehensive assessment by reading their full texts. The selection process focused on choosing articles that fully met the eligibility criteria for further analysis. To ensure objectivity, the selected articles were then independently assessed by three additional reviewers. The three reviewers conducted independent evaluations of the full texts, and after collaborative discussions, a final set of 42 articles was identified for in-depth analysis, showing significant agreement among the reviewers.

Framework for Analysis

There were 42 papers after the full-text review. We analyze the articles using a specified data extraction methodology. The data extraction methodology used in this investigation is depicted in *Table 3*.

Table 3. Framework for data extraction used for analysis

	Information Extracted	**Description**
Bibliometric material	Year of Publication, Authors and their affiliations, number and type of institution.	Nationality of first/corresponding authors, the type of institution and the number of institutions.
Data and measurement	Geophysical method, purpose of the study, approach and analysis technique	Which methods were used? The aim of the study and the approach and technique used for the study
Results	Major findings	What were the results obtained?
Journal	Journal Name	Type of journal of publication

4.0 Results.

4.1 Publication trends on yearly basis

The yearly distribution of the articles from all the databases viewed from 2013 to 2023 is depicted in figure 2 below. The graph shows that the highest number of articles (9) were published in 2020, and the lowest being 2015 where no article was published with an average publication of 4 per year. Generally, no discernible pattern emerges from the analysis of the pattern of publications based on year of publication.

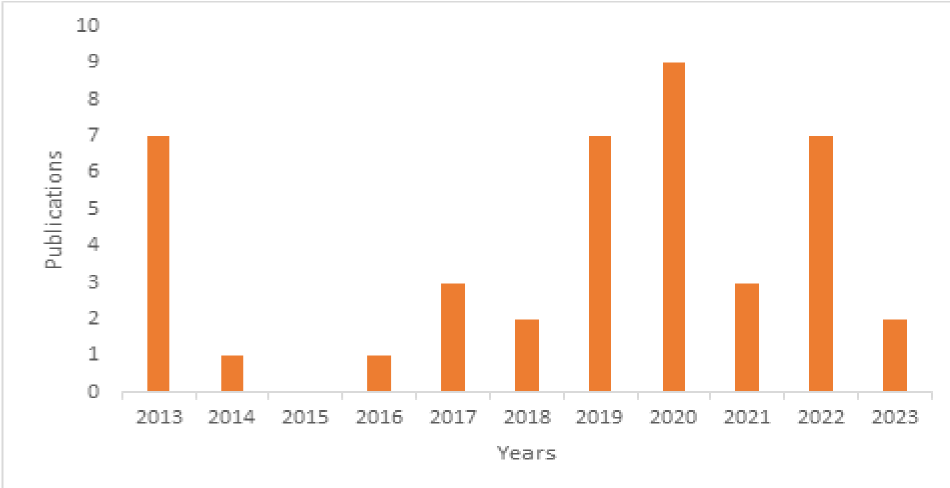

Figure 2. Frequency distribution of publications from 2013 to 2023.

4.2 Publication trends on country basis

The author and/or the corresponding authors were used to represent the country to which the paper was assigned. This was the approach used to determine the publication distribution by country. Figure 3 shows a pie chart of the distribution of publications by country. Nigeria had the highest number of publications with 57% authored articles, whereas Ghana came in second with 41% of authored papers. Researchers affiliated with Burkina Faso came in third with 2% authored articles. No other countries in West Africa were represented in the publication trends on country basis mainly because the search was done in English.

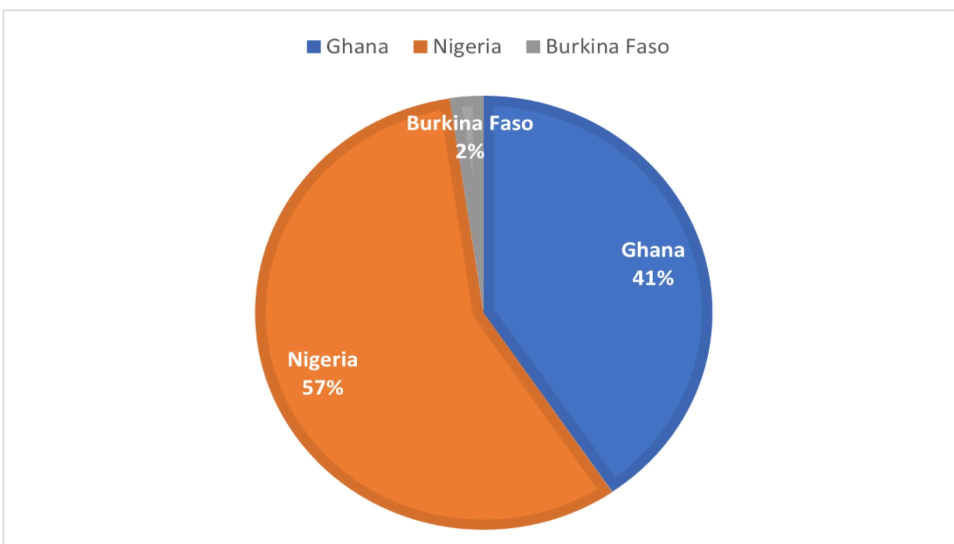

Figure 3. A pie chart depicting the proportion of articles by country of affiliation.

4.3 Publication trend on frequency of methods used.

The investigation revealed that the resistivity method was the most frequently employed, with a total of eighteen (18) publications out of the 42 analyzed. GIS ranked second, with a total of eight (8) publications, followed by the magnetic method with six (6) publications, and the electromagnetic method with four (4) publications. Induced polarization, density, hydrological, magneto telluric, and machine learning each had one publication.

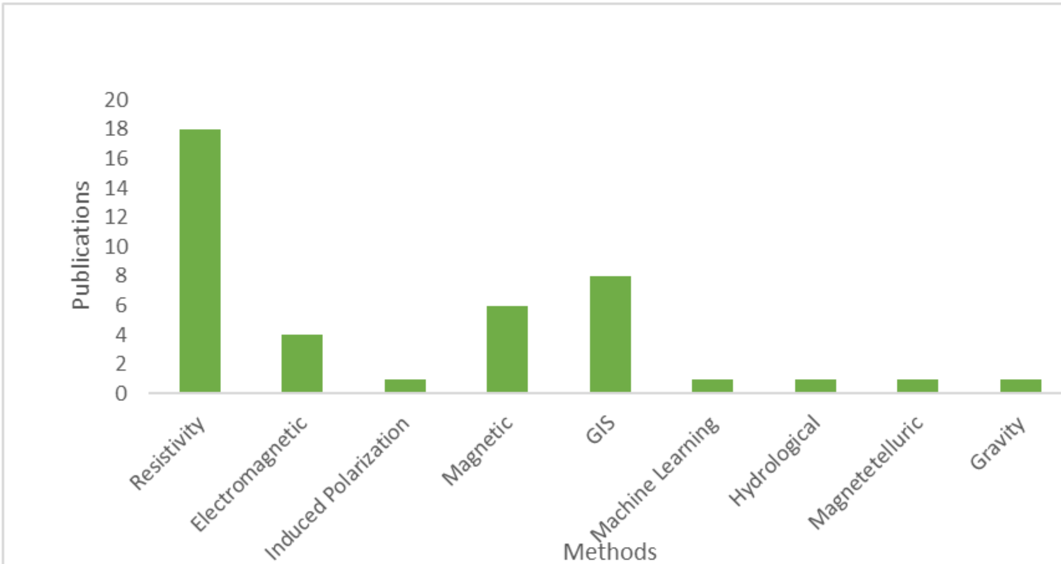

Figure 4. The frequency distribution of groundwater exploration methods used in West Africa.

4.4 Groundwater Exploration Methods in West Africa.

Groundwater exploration methods are constantly evolving. A compelling number of articles have been written on the various methods used in groundwater exploration. Table 4 shows the various methods used and articles written in West Africa.

Table 4. Various methods used in exploring groundwater.

METHODS USED	PUBLISHED PAPERS
Resistivity	*(Adadzi et al., 2018; Agyemang, 2021, 2022; Akanji, 2013; Anomohanran, 2013; Choudhury et al., 2017; Dailey et al., 2015; Ekwok et al., 2020; Fadele et al., 2013; Mainoo et al., 2019; Manu et al., 2019; Menyeh & Sarpong Asare, 2013; Millogo et al., 2019; Mohammed Nazifi & Gülen, 2019a; Raji & Abdulkadir, 2020b, 2020a; Seidu et al., 2019; Umeh & C, 2014)*
IP	*(Aizebeokhai et al., 2016)*
GIS	*(Epuh et al., 2022; Fashae et al., 2014; Ogungbade et al., 2021; Omolaiye et al., 2020; Oyedele, 2019; Yusuf et al., 2022, Danso & Ma., 2023)*

Magnetic	*(Aroyehun, 2022; Ishola et al., 2023; JONATHAN, 2022; Ndikilar et al., 2019; Nur, 2020; Okpoli & Akinbulejo, 2022)*
Electromagnetic	*(Adelusi et al., 2014; Manu et al., 2016; Mohammed Nazifi & Gülen, 2019a; Nazifi & Lambon, 2021)*
Magnetotelluric	*(Agyemang, 2020)*
Density	*(Epuh et al., 2020)*
Machine Learning	*(Siabi et al., 2022)*

Electrical methods

In groundwater exploration, the electrical method is the most sought-after method in terms of work done in West Africa. The electrical methods include resistivity, electromagnetic, induced polarization, and self-potential methods *(Alisiobi & Ako, 2012)*.

These methods have other applications, including mineral exploration, monitoring groundwater pollution, locating surface cavities, and archaeological mapping of the extent of finding remnants of buried foundations of ancient buildings.

Resistivity Methods

The resistivity method has been the most used method in groundwater exploration in West Africa according to our survey. Resistivity methods leverage the characteristic that most consolidated rocks exhibit poor conductivity, resulting in high resistivities *(Rolia & Sutjiningsih, 2018)*. Consequently, low resistivities are deemed anomalous, potentially indicating the porous rocks filled with water. In this section, papers retrieved on how the resistivity method was used for groundwater exploration were analyzed. The most common mode of data collection used in the resistivity from our research was the Vertical Electrical Sounding,

Menyeh & Sarpong Asare (2013) discussed the use of the electrical resistivity method to locate underground aquifers and develop productive boreholes for groundwater extraction. The study area was located in the Northeastern part of the Northern Region, within the ″Middle Voltaian Basin‶, ″dominated by the Voltaian system and the crystalline basement and aquifers of the consolidated sedimentary rocks‶. The geophysical targets for groundwater potential zones were characterized as depressions or troughs, located mostly beyond 20 meters from the ground surface. The VES curves provided depth information and geophysical signatures of subsurface groundwater potential zones, allowing for the identification of sustainable sources of groundwater. The combination of the electrical resistivity method with geological and hydrological site investigations can successfully locate and develop productive boreholes for groundwater extraction. The study concluded that potable water abstracted from boreholes in these areas may not be found shallower than 20 meters.

Anomohanran (2013) presented a geoelectrical investigation conducted in Oleh, Nigeria to assess the groundwater condition of the area. The study used the Vertical Electrical Sounding (VES) technique with the Schlumberger configuration to collect data. The data obtained were interpreted using a computer iteration process and compared with lithologic logs from existing boreholes. The results indicate a four-layered formation, with the first aquifer layer identified along the second layer and the second aquifer located in the fourth layer. The first aquifer was unconfined and prone to pollution, while the second aquifer in the fourth layer is a viable source of potable water. Boreholes for potable groundwater are recommended to be sunk to the fourth layer, with a depth range of 21.8 to 27.9 m.

Adadzi et al (2018) discussed the importance of geophysical surveys in the construction and development of boreholes for rural water supply in Ghana. Vertical Electrical Sounding (VES) mode was used to investigate the subsurface geology and aquifer potentials in the study area. The resistivity measurements were conducted using ABEM SAS 100C Terrameter with Schlumberger electrode configuration. The hydrogeological information obtained from the surveys was used to estimate the depth of groundwater and aquifer geology. The study provides guidelines and data to evaluate borehole options and future drilling and development campaigns in rural settings. The conclusions of the study suggest that the Eleme community in Ghana is underlain by Dahomeyan gneisses and Schists with a thick clay and sand overburden. The groundwater potential in the area was estimated to be medium. Recommendations include drilling points to confirm the existence of aquifer systems and suggesting borehole depths between 55 and 65m below ground level. Mud-drilling technique was recommended due to low resistivity values with increasing depth.

Fadele et al (2013) conducted electrical resistivity at Nigerian College of Aviation Technology (NCAT) to study the groundwater potential and determine the depth to the bedrock and thickness of the overburden. Schlumberger array was used for data collection at fifteen VES stations. ABEM Terrameter (SAS 300) was used for data acquisition. The VES results revealed a heterogeneous nature of the subsurface geological sequence, consisting of topsoil, weathered layer, partly weathered (fractured basement), and fresh basement. The resistivity values and thickness of each layer were determined. The resistivity values for the topsoil layer ranged from 20 Ωm to 600 Ωm, the weathered basement ranged from 15 Ωm to 593 Ωm, the fractured basement ranged from 201 Ωm to 835 Ωm, and the fresh basement ranged from 1161 Ωm to 3115 Ωm. The depth from the earth's surface to the bedrock surface varied between 2.5 m to 37.75 m. The study area was vulnerable to pollution due to its shallow depth of the aquiferous zone, and caution should be taken to prevent contamination.

Umeh & Ezeh (2014) also focused on the use of Vertical Electrical Sounding (VES) method to delineate sub-surface layers, aquifers, and sub-surface structures in Lokpaukwu and its environs. The study area in Lokpaukwu is characterized by isolated hills with intrusion of rocks. It is underlain by the Asu River Group and Nkporo Formation. Data from ten VES stations were acquired in the study area, and the resistivity-sounding curves were interpreted quantitatively using a partial curve matching technique and computer iteration. Eight out of the ten resistivity curves obtained from the study showed 3-layer H-type curves, indicating the presence of aquifer units. VES 1, 5, 8, and 10 are recommended for groundwater development, with drilling a recommended depth of 40-80m.

Akanji (2013) in an attempt to address the increase in demand for improved water supply in Alakuta-Awotan area in Ibadan, Nigeria due to the rapid development and increased population, focused on delineating the area into hydrogeologic zones to increase the number of productive boreholes. Twenty-two Vertical Electrical Soundings (VES) survey were conducted to generate geoelectrical parameters and delineation of aquiferous zones in the subsurface. The resistivity data were utilized to estimate the typical fracture characteristics, fracture strike, coefficient of anisotropy, and mean resistivity at each measurement site. The study found two aquiferous zones in the area: thus, the weathered basement and fractured basement rocks. The weathered basement relief map identified depressions and fracture zones as priority areas for groundwater development.

Raji & Abdulkadir (2020b, 2020a) presented data on the electrical resistivities of soil and rocks in a study area in Ilorin, Nigeria, obtained using the Vertical Electrical Resistivity Sounding (VES) method. The study area covers approximately 110 km^2. The data was collected using the SAS 3000 ABEM Resistivity Meter, metallic electrodes, electrical cables, and GPS devices. The raw data was stored in MATLAB and CVS files, and processed data images were available in TIFF format. The first layer was found to be a weathered zone with a thickness ranging from 1.4 m to 49.2 m, while the resistivity values ranged from 10.1 Ωm to 421 Ωm. There was differential weathering and areas with thick weathering were chosen for drilling. The paper also includes geo-referencing data obtained using a portable GPS device, which can be used for field validation and combining with other geophysical data.

Manu et al. (2019) focused on delineating groundwater-bearing zones in the Cape Coast municipality for sustainable water supply using the vertical electrical sounding (VES) technique. A total of 25 VES points were conducted, and 13 test boreholes were drilled. The VES data were processed and interpreted using the ZONDIP resistivity inversion software. The study found four major groundwater-bearing zones in the terrain, ranging from 12 to 28 m, 31 to 40 m, 43 to 59 m, and 80 to 104 m. The bedrock resistivity values most likely to yield productive boreholes range from 54 to 845 ohm-m. Areas with decreasing resistivity trend from the overburden to the bedrock are more likely to produce productive wells. The survey resulted in a drilling success rate of 90% with an average borehole yield of 118 l/m. The study demonstrated the efficacy of the VES technique in delineating groundwater potential zones for borehole drilling. revealed a drilling success rate.

Choudhury et al. (2017) in their prospect for groundwater conducted twelve VES surveys, each with an AB spacing of 400 m, in lateritic and granitic rock formations to examine layer response and designate prospective zones. Their results revealed that the top sand layer (2-15 m) showed high resistivity contrast at all sites, although a drop in resistivity parameter suggests saturated and/or heavily weathered material, which is consistent with the interpreted resistivity models. They then delineated a very shallow aquifer which influenced the layers resistivity response. It was observed in all the sites that the high resistive layer was inferred to be granite reaching up to 80 m and beyond. The formations had few expected fractures from the sounding response. The borehole data analyzed correlated well with the interpreted resistivity models.

Agyemang (2021, 2022) presented a hydrogeophysical assessment of aquifers in the Upper Denkyira East and West Districts of Ghana for groundwater potential and protective capacity determination. The hydrological data was obtained from the Regional Office of Community Water and Sanitation Agency (CWSA) and thirty-seven Vertical Electrical Sounding (VES) surveys were conducted. The interpretation of the data revealed the presence of three-to-six layers, including laterite, clay, sandy-clay, and slightly to highly weathered bedrock, indicating high heterogeneity of electrical resistivity in the study area. The aquiferous zones were found within the weathered layers, with varying groundwater potentials across the study area. The western and southeastern corners, underlain by the Birimian and Tarkwaian formations, respectively, showed higher groundwater potentials. The study also assessed the protective capacity of the aquifer, indicating that the study area is mostly overlain by materials with different protective capacities. The Birimian formation was found to have a better aquifer protective capacity than the Tarkwaian formation. The paper highlights the effectiveness of using geophysical techniques for groundwater exploration and provides valuable information for ground investigation.

Millogo et al (2019) discussed the success rate of water drilling in different geological formations, such as shale, granitoids, and schists in Burkina Faso. It was revealed that the success rate in shale is generally higher than in granitoid rocks, but the presence of quartz veins or pegmatite can improve the success rate regardless of lithology. The paper highlights the difference between theoretical alteration thicknesses deduced from electric-sounding curves and the actual alteration thicknesses from boreholes. Parameters like depth of deterioration, global static level, and topography should be considered in evaluating the success of a borehole. The best flow rates are obtained in both granitoids and schists, but there was no well-defined correlation between flow and depth of weathering. The framework for evaluating borehole success based on lithology and geophysical data may vary in different geological or climatic contexts.

Electrical Resistivity Tomography (ERT)

With the advancement in geophysical methods, the ERT method has become the most prominent data collection technique used in groundwater exploration. It has also proven to be effective and successful in other geotechnical applications such as mapping out geothermal reservoirs *(El-Qady et al., 2000),* as well as in environmental engineering applications *(Dahlin, 1996),* such as the detection of buried faults *(Zhu et al., 2009; Rizzo et al., 2004),* and landfill investigations

(Zume et al., 2006). While Electrical Resistivity Tomography (ERT) investigates both the lateral and vertical change in resistivities of an area, the VES method offers a one-dimensional delineation of subsurface aquifer characteristics (usually for discrete locations). The ERT provides a two-dimensional mapping of the subsurface geological formation (Hasan et al., 2019). Furthermore, owing to its more advanced instrumentation, Electrical Resistivity Tomography (ERT) can efficiently take measurements over a vast area within a shorter time frame. The study by *LaBrecque and Yang (2001)* demonstrates a three-dimensional inversion approach for Electrical Resistivity Tomography (ERT). This approach has proven to be faster, reducing systematic errors. Additionally, the results can better fit the different data than individual potentials, leading to improved resolution.

Mainoo et al., (2019) emphasized the importance of applying the electrical resistivity tomography (ERT) technique professionally in hydro-geologically difficult terrains like the Voltaian Supergroup of Ghana. Groundwater occurrence within the Voltaian formation is characterized by the presence of secondary porosities caused by faulting, fracturing, jointing, and weathering. The most productive aquifers are found in areas where both weathered zone and fractured bedrock are present. The survey was conducted using the ERT technique and found that the sandstone unit in the study area contains aquifers at different depths. The ERT data shows the area predominantly has low resistivities (< 40 Ωm). A relatively high range of resistivities (greater than 140 Ωm) was also recorded. The aquifers in the sandstone unit yielded a relatively large volume of water, while the aquifer zone within clayey material (shale, mudstone and siltstones) had low yield due to limited interconnectedness of pores. The recommended groundwater potential zones were based on an in-depth understanding of the bedrock geology in the study area.

Seidu et al. (2019), The major source of potable water in Tarkwa is the Bonsa Treatment Plant, but pollution from illegal mining activities along the Bonsa River has led to high treatment costs and irregular water supply. Due to the population increase and water demand in Tarkwa, residents resorted to constructing boreholes and hand-dug wells, but success rates and yields are low in hydrogeologically difficult terrains. The research investigated the hydrogeological conditions of the Tarkwa area of Ghana using Electrical Resistivity Imaging (ERI) and Electromagnetic (EM) geophysical techniques to identify potential water-bearing zones. The electrical resistivity and electromagnetic results show the resistivity and conductivity distribution in the area. The results were used to map water-bearing zones in the Huni Sandstone, Tarkwa Phyllite, Banket Series, and Kawere Conglomerate, at varying depths. The combination of electrical resistivity and electromagnetic techniques improves the success rate of identifying potential water-bearing zones to 86%. The paper highlighted the importance of geophysical techniques for borehole siting in the Tarkwa area.

Induced Polarization Method

This method is usually utilized with the resistivity method to give a more in-depth interpretation. It has evolved into one of the most widely used exploration methods for mineral and groundwater prospecting, especially for examining dispersed sulfide and clay deposits. Most often, this method is used alongside other geophysical methods to validate results.

Aizebeokhai et al. (2016) discussed the use of geoelectrical resistivity data and induced polarization imaging in mapping groundwater potential zones in the Ilaro Formation in Nigeria. The results were inverted to produce a 2D model of apparent resistivity and IP effect (chargeability) for the data. The high resistive unit in the formation was composed of swelling clay rich in kaolin and intercalated with phosphate minerals, which contributed to its high resistivity values. The unconsolidated sand unit in the formation had lower resistivity values and was identified as the main aquifer.

Electromagnetic Method (EM)

The electromagnetic method is conducted in a similar approach to the resistivity method but the physical property measured is conductivity. The EM method relies on the principle of electromagnetic induction. When an alternating current (AC) is passed through a transmitter coil, it generates a time-varying magnetic field. This changing magnetic field induces electrical currents in conductive materials underground (ie; Primary current attenuated producing secondary current in geological medium producing secondary which is measured by the receiver). This is done either in time domain or in frequency domain. Frequently, the EM method is often used in conjunction with other geophysical approaches.

Adelusi et al (2014) reported on using Very Low Frequency Electromagnetic (VLF-EM) and Vertical Electrical Sounding (VES) methods for groundwater exploration in a Precambrian basement terrain in southwestern Nigeria. VLF-EM was found to be effective in mapping basement structures relevant to groundwater development. The investigation used a total of 2100 VLF-EM data points and selected VES points over 7 traverses. The results showed that the main aquifer unit is the fractured basement layer with a thickness of 20-25 m. The layer resistivity and thickness ranges for the five subsurface layers were determined. The geoelectric results were compared favorably with drilling information. The study area was characterized by surface manifestations of rocks, making groundwater abstraction difficult.

Mohammed Nazifi & Gülen (2019a) discussed the use of electromagnetic (EM) profiling and vertical electrical sounding (VES) methods for groundwater exploration in selected communities in the Twifo-Hemang Lower Denkyira Districts of Ghana. The electromagnetic results revealed that the three communities studied were underlain by two layers, with the first layer having a thickness range of 2 to 10 m. The VES studies indicate that Achiase Community and Mbaa Mpe Hia No. 2 Community are underlained by three geoelectrical layers, while Moseaso Community was underlain by four geoelectrical layers. Based on the study, Moseaso Community had the highest groundwater potential, followed by Achiase Community and Mbaa Mpe Hia No. 2

Community. Several sites were recommended for drilling boreholes for water supply in these communities.

Nazifi & Lambon (2021) used geophysical data, including electromagnetic (EM) profiling, electrical resistivity profiling, and vertical electrical sounding (VES), to map groundwater aquifers in Beseadze and Nyamebekyere No. 2 in the Central Region of Ghana. The EM profiling was conducted using the Geonics EM43-3 ground conductivity meter, while the electrical resistivity profiling and VES were carried out with the ABEM Terrameter SAS 1000C using the Schlumberger electrode array. The resistivity profile data were processed and analysed using the ProfileR inversion computer program, while the VES data were analysed and interpreted using Zondip1D and Surfer 13. Short resistivity profiling measurements were conducted around the points where EM profiles displayed anomalies, and the short resistivity profiling was used to confirm the conductive zones picked by the EM equipment. The results showed that the surveyed areas are underlain by three to four layers, with the depth to the aquifer ranging from 0.48 to 7.42 m and an average aquifer thickness of about 14.78m. These results were used to determine the drilling locations for boreholes in the area. The use of multi-geophysical methods for groundwater exploration proved to be effective in saving time and resources and reducing ambiguous interpretation of results.

Bienibour et al (2016) used electromagnetic and electrical resistivity methods to identify potential groundwater sites for borehole drilling in Adoe, Ghana. The geophysical data revealed four subsurface geological layers with varying resistivity and thickness ranges. These layers include quartzitic sandstone with clay, sandy clay with silt, lateritic sandstone, and clayey shale. The overburden thickness ranged from 14 m to 24 m. The VES points within the appropriate range were selected for drilling. The resistivity values of layers 3 and 4 were 27 and 20 Ωm, respectively, indicating the potential for sustainable groundwater in the fourth layer. Stations with the lowest VES values and continual decrease in resistivity with depth were identified as the best location for borehole drilling. Following the identification of potential groundwater zones, two sites were chosen for borehole drilling. These sites were ranked as first and second, with priority given to the first-ranked location. Upon drilling, the selected aquifers were found at depths ranging from 14 meters to 24.3 meters, with thicknesses varying between 1 meter and 14 meters. Subsequently, a borehole was successfully drilled at the first-ranked site, where the aquifer was encountered in the fourth layer. The yield from this borehole was found to be approximately $12m^3/h$, indicating a substantial groundwater resource.

Magnetic Method

In groundwater exploration, the magnetic method is used mainly to delineate the lithologies and structures which have major control on groundwater occurrences. The magnetic method aims to investigate the subsurface geology based on the magnetic signatures produced from the rocks due to the different composition of the magnetic mineral content of these rocks *(Telford et al., 2010).*

Nur (2020) focused on the analysis of lineaments and their potential for groundwater exploration in a specific study area (Abuja and its environs). The study aimed to use high-resolution aeromagnetic data analysis to delineate areas of groundwater potential. High-resolution aeromagnetic survey conducted by Nigerian Geological Survey Agency (NGSA). Terrain clearance was 80 m, flight lines spacing of 500 m and a tie line spacing of 2000 m. A regional-residual separation using first order polynomial method was done, then lineaments were extracted from 1VD map using ArcGIS software. The residual magnetic values in the study area ranged from -104.390 to 87.8889 nT, with areas of high and low values observed. The magnetic data revealed important structural patterns in the study area. Application of 1VD technique identified joints, fractures, faults, and folds. Lineament analysis was conducted using rose diagrams and lineament density maps from these major lineaments trending in NE-SW direction were identified. Areas with long lengths and high lineament densities were mapped as suitable for groundwater exploration.

Ekwok et al (2020) assessed the groundwater potential in parts of Cross River State, Nigeria, using vertical electrical sounding (VES) and high-resolution aeromagnetic methods (HRAM). The VES and HRAM data were used to identify hydro-lithostratigraphic units and to map geologic structures, respectively. The unsaturated top layer of the area consists of shales, marl, clay, silt, gravel, and lateritic materials, while the aquifer units include sandstones, siltstones, fractured shales, limestone/marl, and fractured/weathered basement. The Calabar Flank, Oban Massif, and Ikom-Mamfe Embayment showed varying apparent resistivity values for the hydro-lithostratigraphic units, indicating different groundwater potential. The HRAM results revealed the presence of geologic structures like faults, fractures, fissures, and dyke swamps, which enhance permeability and create secondary porosity. Overall, the Oban Massif and Ikom-Mamfe Embayment represent areas with moderate groundwater potential, while the Calabar Flank has low groundwater potential due to the dominance of argillites and lack of significant geological structures.

Ndikilar et al (2019) investigated mapping the groundwater potential of Dutse, Jigawa State, Nigeria using integrated geophysical survey techniques. Spectral analysis of aeromagnetic data was used to map the crystalline basement rock, while the vertical electric sounding technique was used to detect the depths to the top of the aquifer. The aquifer depth ranged from 5 to 15 m with a mean value of 10 m, while the magnetic crystalline basement depth ranged from 6 to 69 m with a mean value of 24 m. The IVD map revealed structures within the basement rock that are considered favorable zones for groundwater accumulation. The spatial distribution of groundwater potential was mapped into three zones: high, moderate, and low based on geology and extracted lineaments. The study provided a vital tool for groundwater exploitation and management strategies in the area.

Okpoli & Akinbulejo (2022) investigated the groundwater potential in the Ijano area of southwestern Nigeria using aeromagnetic and vertical electrical sounding techniques. Aeromagnetic data was acquired and processed using software like Oasis Montaj, and Arc GIS.

Magnetic image-enhancing filters were applied to the aeromagnetic data to define lithological boundaries, geological structures, faults, folds, and contacts. Lineament maps were generated from derived field intensity gradients and Euler deconvolution, showing the trends of lineaments in the study area. Hydro-lineament density maps were produced based on lineament trends, indicating areas with high concentrations of lineament density for groundwater prospecting. Vertical electrical-sounding data was collected and interpreted using qualitative and quantitative techniques. The interpretation of the VES curve involved visual inspection and quantitative analysis using a partial curve matching technique and resistivity inversion algorithm. The vertical electrical sounding data revealed different curve types, with areas of high hydro-lineament density identified as promising for groundwater prospect and development. The study demonstrated the capability of the aeromagnetic technique in extracting lineament trends in inaccessible tropical forests.

Ishola et al (2023) used remote sensing and geospatial data integration on the analysing lineament and their potential for groundwater exploration in Nigeria. The study area is geologically within the Precambrian basement complex of north central Nigeria and is characterized by diverse landforms with few elevated landscape features of igneous rocks. The study aimed to use high-resolution aeromagnetic data analysis to delineate areas of groundwater potential and the study area exhibit polyphase deformation in the form of joints, fractures, faults and folds. The residual magnetic values in the study area ranged from -104.390 to 87.8889 nT, with areas of high and low values observed. Lineament analysis was conducted using rose diagrams and lineament density maps. The distribution of lineaments in the study area showed trends mainly in the NNE-SSW, NE-SW, and ENE-WSW directions, corresponding to Pan-African and pre-Pan-African deformational episodes. The Analytical hierarchy process (AHP) technique for data prioritization was used in ranking evidential layers which were integrated in the GIS platform to map the groundwater potential zone (GWPZ) in the area. Multiple validation including magnetic anomalies maps, borehole groundwater potential indices (GWPI), and receiver operating characteristic (ROC) curves were used in validation of GWPZ.

Ogungbade et al (2021) delineated groundwater potential zones in Ilora, Nigeria. The paper employed lineament analysis and high-resolution aeromagnetic data analysis to investigate the hydrogeological framework and groundwater potential in the study area. Primary data included Landsat 8 OLI, ASTER DEM, and aeromagnetic data. Secondary data included geology, soil, and topographical maps. High-resolution aeromagnetic data analysis was conducted to map the depth and spatial distribution of hydro-lithostratigraphic units and geologic structures such as faults and fractures. Eight thematic layers including geology, elevation, slope, land use, lineament density, fault proximity, soil, and drainage density were used to map groundwater potential zones. ArcGIS, Rockworks, ENVI, and PCI Geomatica Software were used for data processing. The enhanced HRAM data showed a high concentration of short-wavelength anomalies in certain regions, suggesting the presence of geologic features that could enhance subsurface rock porosity and permeability. Lineament analysis involved the use of rose diagrams and lineament density maps to identify potential groundwater recharge areas and exploration targets. The study revealed the presence of aquifer layers composed of fractured/weathered crystalline basement, sandstones, siltstones, sandy shales, and highly baked and fractured shales at different depths. The electrical resistivity of the hydro-lithostratigraphic units varied in different regions, indicating variations in porosity and permeability. Groundwater potential was classified into five classes: very high, high, moderate, low, and very low. The results were cross-validated with well data, achieving 89% correlation. The groundwater potential map can be used to select suitable sites for groundwater resource exploitation. The findings provided valuable insights into the hydrogeological framework, groundwater potential, and subsurface geological features in the study area.

Jonathan (2022) explored potential areas for groundwater occurrence in part of the north-central Basement Complex of Nigeria using high-resolution aeromagnetic and land satellite imagery data. The analysis of the data involved magnetic residual separation and analytical signal for the aeromagnetic data, and false colour composite analysis for the land satellite imagery data. The mapping of lineaments from the analytical signal and land satellite images revealed high-density lineaments around Wushishi, Zungeru, Tegina Kagara, Pandogari, Alawa, and Gurmana, and low-density lineaments around Bobi, Kuta, Guni, Minna, and Tenenge. These lineaments were interpreted as joints, veins, faults, foliations, and lineation of outcrops. Field studies in Tegina, Zungeru, and Wushishi, which had high lineament density, showed good groundwater yield, while an area with low lineament density, Gidan Gwari, had limited groundwater productivity. The study provided valuable information for groundwater exploration in the study area, considering the significance of groundwater to population growth.

Ejepu et al (2017) investigated hydrogeological structures in Paiko region, North-Central Nigeria using aeromagnetic data, Landsat ETM+ data, and SRTM DEM. Lineaments were extracted from derivative maps of the datasets, and ground geophysical investigation was conducted using Radial Vertical Electrical Sounding (RVES) in nine transects. Source Parameter Imaging (SPI) was used to map average depths of structures from the aeromagnetic dataset. Thematic layers were integrated and modelled using ArcGIS to generate a groundwater potential map. The area groundwater zones were classified into four categories based on potential. RVES survey was correlated with surface structural mapping and remotely sensed data and areas of recharge regions were identified with high lineament density. The results showed a good correlation between lineaments delineated from surface mapping, remotely sensed datasets, and RVES survey. Regions with high lineament density and fractured basements had better groundwater potential. The research also highlighted the importance of considering water quality issues associated with mineralization in deep water wells in weathered igneous rocks. The study emphasized the significance of rock type, fractures, and slope in controlling groundwater flow and storage. GIS analysis and field investigations were crucial for understanding the hydrogeological nature of hard rock aquifers.

Ilugbo et al (2023) employed structural analysis for groundwater potentiality using satellite remotely sensed, aeromagnetic dataset, and vertical electrical sounding (VES) in Ilesha Schist Belts, Southwestern Nigeria. Landsat 8 OLI satellite imagery and aeromagnetic dataset were analyzed to generate lineaments maps for groundwater prospects. Landsat 8 OLI satellite imagery and SRTM DEM were filtered and processed using edge detection tools. Processing of aeromagnetic data was also done using Oasis Montaj software. Data enhancement techniques were applied to the magnetic data. Extraction of lineaments from the filtered image was done using a LINE module. The horizontal derivative was applied to enhance the magnetic pattern of linear fissures and the use of Total Horizontal Derivative to determine the edges of the magnetized structure. The 3D Euler deconvolution was used to determine the locations and depths of geologic sources. Generation of an aeromagnetic lineament map was done, and lineament density was calculated using a line density tool in GIS environment. The lineaments were predominantly NE-SW orientations. Lineament intersection density was categorized into four categories: very low, low, moderate, and high. VES data was acquired and interpreted quantitatively using the partial curve matching method and computer-assisted 1-D forward modelling. VES data validated the areas of high lineament intersection density have better prospects for groundwater occurrences. The results validated the accuracy of the categorized lineament intersection density in terms of groundwater potentiality. The lineament intersection map showed that the intersected structures concentrated most in the northeastern regions, indicating high prospects for groundwater potential.

Geographic Information System (GIS)

The development of GIS technology has now made it possible to explore groundwater quickly and affordably, even in remote locations. This approach enables both regional and even national exploration of the spatial distribution of groundwater. GIS helps us to locate features on and in the earth's surface and helps to generate the attribute map of a particular location. These features can serve as indications for groundwater sources. *Jha et al. (2007)* divided the use of remote sensing and GIS in hydrogeology into six categories: the exploration and evaluation of groundwater sources, the choice of artificial recharge sites, subsurface flow, and pollution modelling, the assessment and planning for groundwater pollution hazards, the estimation of the distribution of natural recharge, and the analysis and processing of hydrogeologic data.

Forkuor et al (2013) assessed the groundwater development potential for agriculture in northern Ghana using GIS/RS techniques. The study used a multi-criteria analysis approach to assess groundwater development potential in northern Ghana by combining spatial layers for five critical factors: recharge rate, regolith thickness, transmissivity, borehole success rate, and static water level. GIS raster layers were created for each factor and standardized into comparable units using fuzzy set theory. The weighted linear combination method was used to combine the standardized factors, with equal importance given to each factor. The study found a high potential for groundwater development in the study area, with about 70% of the area having high to moderate groundwater availability and 83% having high to medium groundwater accessibility.

The Precambrian Basement rocks (PCB) area generally had higher groundwater development potential than the Voltaian Sedimentary rocks (VSB). The VSB was found to produce a small proportion of exceptionally high-yielding boreholes. The PCB had a thicker regolith, superior borehole success rate, and slightly higher transmissivity compared to the VSB. The reliability of the results was tested against measured data, with borehole yields used to validate the groundwater availability map and borehole depths and field observations used to validate the groundwater accessibility map.

Danso & Ma (2023) utilized geospatial techniques to map groundwater potential zones (GWPZ) in the Komenda-Edina-Eguafo-Abrem (KEEA) Municipal, Ghana. Eight predictors were considered: lineament density, slope, topographic wetness index (TWI), drainage density, land use/land cover (LULC), normalized difference vegetation index (NDVI), geology, and soil type. Raster and vector data were obtained from various sources, including ASTER GDEM and Landsat 8 imagery. The data were processed and standardized using GIS. The study classified the groundwater potential zones into five categories: very poor, poor, good, very good, and excellent. Most of the study area (36%) fell within poor groundwater zones, while 27% were identified as very good locations for groundwater prospecting. Areas close to the coast were mostly found within poor zones. Validation using functional boreholes confirmed that 76.5% of the boreholes are within suitable sites for groundwater discovery. These results have implications for policymaking, sustainable planning, and water resource management in the KEEA Municipal

Amponsah et al (2023) investigated groundwater prospects in the Akatsi Districts of the Volta Region of Ghana by integrating ten predictors extracted from geological and remote sensing datasets to generate a groundwater prospectivity model (GPM). The frequency ratio approach was applied to examine the coherence between the classes of evidential layers (predictors) and groundwater occurrences, with the soil type evidential layer having the greatest influence on the GPM. Ten predictors, including slope, topographic wetness index, stream power index, lineament density, drainage density, elevation, slope aspect, geology, land cover, and soil type, were extracted from geological and remote sensing datasets. The frequency ratio approach was applied to assess the association between the classes of each predictor and groundwater occurrences. The elevation predictor played a significant role in groundwater potential modeling, as it influences infiltration capacity, runoff potential, flow aggregation, and water resource transport. The groundwater prospectivity model (GPM) was created by synthesizing the predictors using the frequency ratio values obtained for each predictor. The GPM was normalized to constrain the range of prospectivity scores up to 1. The performance of the GPM was evaluated using the area under the receiver operating characteristics curve, which indicated a good accuracy score of 0.876. The prediction-area plot showed that 76% of known groundwater occurrences were within the prospectively delineated zones of groundwater over the study area. The stream power index (SPI) was used as a predictor, with higher SPI values indicating low groundwater prospects and vice versa.

Oyedele (2019) explored using remote sensing and GIS techniques for sustainable groundwater development in Ado-Ekiti, Nigeria, which has a challenging hard rock terrain. The study utilized Landsat imageries for land-use/landcover mapping and lineament analysis, as well as the Shuttle Radar Topographic Mission Digital Elevation Model for drainage network extraction and geomorphological analysis. A landuse / landcover (LULC) map was produced using Landsat 8 imagery, and image classification was done using Ecognition Developer software. Geological map and topographical sheet data were used for data preparation, pre-processing, processing, and analysis. Thematic layers including lithology, geomorphology, drainage density, slope, lineaments, and landuse/landcover were generated and reclassified based on hydrogeological importance and characteristics of the basement terrain, aiding in the planning and management of groundwater resources. Weightage factors were assigned to themes and categories according to groundwater prospects. The reclassified layers were integrated into a GIS environment to produce a composite groundwater potential map. The generated groundwater potential zones were validated with field checks and existing groundwater yield data. Lineament analysis was conducted to identify zones of localized weathering with high permeability and porosity, enhancing groundwater accumulation. Lineament analysis revealed zones of localized weathering with high permeability and porosity, enhancing groundwater accumulation. The study also highlighted the importance of geospatial techniques in narrowing down target areas for detailed hydrogeophysical exploration, leading to sustainable groundwater development.

Epuh et al (2022) delineated groundwater potential zones in Oyo state, Nigeria using GIS-based multi-criteria analysis techniques. Eight groundwater potential contributing factors were considered, including land cover, drainage density, lineament density, soil texture, geology, geomorphology, slope, and rainfall. Two multi-criteria analysis techniques, namely Multi Influencing Factor (MIF) and Analytic Hierarchy Process (AHP), were integrated to assess groundwater potential. Thematic layers representing eight groundwater potential contributing factors were processed and assigned weights using the AHP technique. The Bayes' integration approach was employed to recalculate criteria weights and generate an optimum groundwater potential map. The generated groundwater potential maps were validated using the Receiver Operating Characteristics (ROC) curve method. The study also evaluated the depths and yields from 1425 boreholes distributed across the study area to validate the groundwater potential zonation maps. The Bayes' approach showed groundwater percentage distributions of very low (36%), low (34%), moderate (14%), and high (16%) within the study area. The average borehole yields across the groundwater potential zones positively correlated, with high potential zones having the highest average borehole yield. The average borehole yields across the groundwater potential zones positively correlated, with high potential zones having the highest average borehole yield.

Fashae et al (2014) delineated groundwater potential zones in the crystalline basement terrain of SW-Nigeria using an integrated approach of multi-criteria decision analysis (MCDA), remote sensing (RS), and geographical information system (GIS) techniques. The study integrated nine different thematic layers, including geology, rainfall, geomorphology, soil, drainage density, lineament density, land use, slope, and drainage proximity, to generate an overall groundwater potential map for the study area. The analytic hierarchy process (AHP) was used as a decision-aiding method to assign weights to different thematic layers and their features. Weights were assigned to each thematic layer based on their relative contribution to groundwater occurrence. The thematic maps were integrated using ArcGIS software to generate the overall groundwater potential map for the study area. The result was validated with existing borehole/well yield data, which showed a good correlation with the observed groundwater potential zonation. The study area was categorized the study area into three groundwater potential zones: high, medium, and low. The high potential zone is characterized by weathered/fractured quartzite, quartz-schist, amphibolite schist, and phyllite bedrock settings. The medium potential zone is generally underlain by medium-porphyritic granite, biotite-hornblende granite, and granite gneiss bedrock settings. The low potential zone is mostly underlain by migmatite, banded, and augen gneiss bedrock settings. The integrated approach of MCDA, RS, and GIS methods used in this study is effective for groundwater resource evaluation and provides guidance for groundwater exploration and exploitation in crystalline basement settings.

Yusuf et al (2022) presented a study on groundwater prospectivity mapping in northeastern Nigeria using integrated GIS, remote sensing, and geophysical techniques. Thematic maps such as lithology, drainage density, slope, lineament density, and topography were integrated using the weighted sum tool of ArcGIS software to generate the groundwater prospectivity map. Data processing filters like horizontal derivatives, analytic signal processing, and 3D-Euler depth estimation were applied to magnetic data to map structures and lithologic contacts. Lineaments were manually mapped from the Digital Elevation Model (DEM) raster using Global Mapper software, and lineaments distribution contour maps were generated in ArcGIS. The integrated lineaments were mapped using the "Math Algebra" tool in the Spatial Analysts tool of ArcGIS software. The rock work software was used to produce a rose diagram of the integrated lineaments. The study identified regions with high prospects for groundwater occurrence, which were consistent with high transmissivity and yield values. The research demonstrates the effectiveness of GIS/remote sensing and geophysical techniques in generating groundwater prospectivity maps for planning groundwater exploration and exploitation.

Omolaiye et al (2020) evaluated the groundwater potential of the Obafemi Owode local government area (LGA) in Ogun State, Nigeria, using remote sensing, GIS, and 2D resistivity techniques. The integration of remote sensing and GIS techniques helped narrow down target areas for detailed geophysical and hydrogeological surveys. The study used a modified DRASTIC model, considering factors like land use, lineament density, slope, drainage density, geology, and soil map, to assess groundwater potential. Lineament trended northeast-southwest and northwest-southeast directions, indicating potential permeable zones for groundwater storage and movement. The study also conducted 2D resistivity profiling, which suggested the occurrence of potential carbonate and silicate aquifers. The groundwater potential map was validated through the drilling and testing of wells, showing promising results for future drinking water and irrigation development.

Gravity Method

This method is not frequently used in groundwater exploration but in some cases, it has been integrated with other geophysical methods to determine the groundwater potential of an area.

Epuh et al (2020) mapped structural lineaments in the western sector of the Gongola Basin in northern Nigeria by integrating gravity data and Landsat 8 imagery. The gravity data analysis involved a convolution between the Fourier kernel obtained from the second horizontal derivative of the truncated horizontal plate and the gravity anomaly. The lineaments were extracted as sharp gradients in the second horizontal derivative map. In the Landsat imagery processing, a 5x5 directional filter was applied to the imagery in different directions (N-S, NE-SW, E-W, NW-SE). Edge detection, thresholding, and curve detection were then performed to extract the lineaments. The lineaments extracted from both methods were compared and showed a high correlation. The NW-SE and NE-SW lineaments delineated from the Landsat 8 correlated more with the lineaments from the gravity data. The lineaments extracted from both methods were found to be useful for groundwater mapping, with areas of high lineament density indicating high groundwater potential. The results demonstrated the advantage of remote sensing in lineament mapping for groundwater investigation and can aid more precise geophysical observation.

Magnetotelluric Method

The Magnetotelluric (MT) method is well-suited for studying complicated geological environments and can provide high-resolution shallow subsurface characterization for closely spaced stations. The method can establish whether the electromagnetic fields are responding to subsurface rock bodies of effectively one, two, or three dimensions.

Agyemang (2020) successfully used the magnetotelluric (MT) geophysical technique to identify zones of high groundwater potential in the Agona East District of Ghana. The technique helped in locating and determining the depth-to-aquifer zones with different resistivities. The MT technique involves the measurement of the earth's electrical conductivity and magnetic field over a range of frequency. Vertical resistivity variation with depth was measured at 7-15 MT sounding stations along six different 300-m long profiles. A V-5 system 2000 of Phoenix Geophysics was used for the measurements, following the procedures suggested by Gamble et al. (1979). The data used in the study included field coherencies greater than 0.7 and apparent resistivity with errors less than 10. The investigation depth ranges from 300 m below ground to 10,000 m or deeper with long-period soundings. The study identified two major geologic materials in the study area: the Eburnean Plutonic suite and the Tamnean Plutonic Suite. The Eburnean Plutonic suite showed relatively low resistivity, indicating the presence of weathered zones capable of holding water. The Tamnean Plutonic Suite, on the other hand, showed higher resistivity and depended on fracture zones for groundwater exploration. The study also revealed that the prevailing aquifer systems in the study area are controlled by fractures and weathered zones, rather than being regional. The magnetotelluric geophysical technique demonstrated its capability to delineate zones of high groundwater potential for borehole drilling purposes.

Hydrogeological Methods

The hydrogeological properties of the area can also be used to define the groundwater prospectivity.

Nsiah et al (2018) delineated groundwater potential zones in the Nabogo basin in Ghana to improve groundwater development for the local population's water supply needs. The basin is underlain by rocks of the Voltaian Sedimentary rocks, which have limited primary permeability, making secondary porosity crucial for groundwater availability. The success rate of boreholes in the basin is estimated to be no more than 60%, highlighting the need for improved groundwater exploration and reduced investment losses. The study combined spatial layers of aquifer transmissivity, borehole yields, regolith thickness, and static water level in a weighted overlay analysis to identify potential areas for groundwater development. The methodology involved acquiring data on well-distributed boreholes in the basin and using the weighted overlay technique in a GIS environment to integrate borehole yields, regolith thickness, static water level, and transmissivity. The study found that the northern and eastern parts of the basin, covering about 35% of the total area, were the most suitable areas for groundwater prospecting. The generated groundwater potential map categorized the basin into poor, moderate, and high zones, providing valuable information for groundwater development.

Machine Learning

Technological advancements have further propelled the application of artificial neural networks, boosted regression trees, classification, and regression trees, as well as random forest models in machine learning and deep learning to address engineering challenges *(Naghibi & Pourghasemi, 2015)* and *(Fugara et al., 2020).*

Siabi et al (2022) utilized machine learning techniques, specifically artificial neural networks (ANN), to predict groundwater recharge in selected locations in Ghana. Two ANN models, Feedforward Neural Network with Multilayer Perceptron (FNN-MLP) and Extreme Learning Machine (FNN-ELM), were used. The prediction of groundwater recharge was based on 58 years of Groundwater data. Model evaluation showed that FNN-MLP performed better in predicting groundwater recharge, with R2 values ranging from 0.97 to 0.99, compared to FNN-ELM with R2 values between 0.42 to 0.68. The selection of the optimal number of neurons in the hidden layer of the ANN models was done using a trial-and-error approach, with Mean Squared Error (MSE) as the measure of selection. The study employed the modified Chaturvedi method to estimate groundwater recharge, which formed the input variable for the ML algorithms. Overall, both models showed acceptable performance, indicating that ANN is a useful forecasting tool for groundwater assessment. The outcomes of this study contribute to the current methods of groundwater assessment and development, aligning with the sustainable development goals (SDG 6).

5.0 Discussion

Nigeria, Ghana and Burkina Faso were the main authoring countries for this research. These three countries were the primary contributors because the literature search was conducted in English.

In West Africa, various techniques have been employed in the exploration and exploitation of groundwater, with geophysical methods proving highly valuable in this context. Among these, the electrical resistivity method stands out as the most widely utilized due to its numerous advantages. This method demonstrates the greatest variation among the physical properties of rock, particularly in distinguishing between fresh rocks and those weathered or fractured, especially when water is present. It effectively delineates geoelectric layers or hydro-lithostratigraphic units, aiding in the identification of suitable drilling sites and recommending borehole depths. The electrical resistivity method is known for its relative ease of use and cost-effectiveness compared to alternative geophysical methods. However, it does have limitations, such as its restricted coverage and provision of point source data, making it challenging for regional surveys. Additionally, it can be time-consuming, and data interpretation may face ambiguity, especially when factors like the presence of metals cause sharp contrasts in resistivity in rocks. While a thorough geological review can mitigate this issue, the method may not provide a definitive geological solution. In his studies, *Olayinka (1992)* emphasized resistivity as the most frequently used method in groundwater exploration. This preference is attributed to the close relationship between electrical conductivity and certain hydrogeological properties of the aquifer, such as porosity, clay content, mineralization of the groundwater, and the degree of water saturation. It has been observed that from that time until the present, there hasn't been any significant change or advancement in the methods employed for groundwater exploration in West Africa.

An intriguing observation from the research is that lots of the studies employed multiple geophysical methods. This trend arises from the inherent nature of geophysical interpretations, which often involve inferences, and there could be several plausible explanations for a given geophysical anomaly. Each of these explanations may be geophysically accurate but could lead to geological inconsistencies. To enhance the value and accuracy of interpreted results, researchers frequently integrate two or more geophysical methods. For instance, *(Adelusi et al., (2014)* integrated electromagnetic and vertical electrical sounding. *Ndikilar et al (2019),* and *Okpoli & Akinbulejo, (2022)* also in their research integrated aeromagnetic and resistivity data and their results proved that integrating these two methods gives a more solid and reliable interpretation of the work. Other researchers such as *Omolaiye et al (2020)* integrated resistivity and remote sensing data while *Dailey et al (2015), Ejepu et al (2017), Ogungbade et al (2021),* *Yusuf et al (2022)* amongst others integrated aeromagnetic and GIS in their exploration for groundwater. Acquiring several of these data for integration can be quite problematic and time-consuming. Researchers are embracing the integration of Machine Learning in groundwater exploration. However, in West Africa, the research findings indicate that relatively little work has been undertaken in utilizing machine learning for groundwater exploration**.**

The limited work in machine learning within the context of West Africa's groundwater exploration can be attributed to various factors that collectively contribute to this shortfall. Some key reasons include the lack of institutional support, that is, inadequate institutional support and funding for research and limited financial resources within academic institutions and research organizations have restricted the capacity to invest in cutting-edge technologies. Also, insufficient technological infrastructure in some West African regions have posed challenges for implementing machine learning techniques. The absence of robust computational resources and data storage facilities have also impeded the application of advanced algorithms. Thirdly, limited technological know-how, that is the shortage of expertise and specialized training in machine learning within the region has been a significant barrier. The lack of professionals with the requisite skills to implement and interpret machine learning models has hindered its widespread adoption. The scarcity of data has also been a major factor since machine learning heavily relies on large and diverse datasets for effective training and model development. The scarcity of comprehensive and high-quality groundwater data in West Africa has limited the application of machine learning, as models require substantial datasets for accurate predictions. Research priorities and preference for traditional methods due to familiarity on the part of researchers have also played a role in limited work in machine learning. The limited collaboration between academia, government institutions, and industry has also hindered the exchange of knowledge and expertise. Lastly, Limited awareness and understanding of the capabilities of machine learning within the broader community may result in a reluctance to adopt these technologies. Public acceptance and willingness to embrace innovative methods are crucial for the successful implementation of machine learning in groundwater exploration**.**

Addressing these challenges will require concerted efforts from various stakeholders, including governments, academic institutions, and industry partners. Initiatives aimed at capacity building, promoting research collaboration, and raising awareness about the benefit of machine learning can contribute to overcoming these barriers fostering a more technologically advanced approach to groundwater exploration in West Africa.

This review not only provides a retrospective understanding but also serves as a critical compass for the future of groundwater exploration in West Africa. For researchers, this review serves as a knowledge foundation, informing their work with a nuanced understanding of past methodologies and their outcomes. It encourages a shift towards innovative approaches, fostering a culture of continuous improvement and adaptability within the research community. Government institutions, entrusted with the responsibility of water resource management, can benefit immensely from this review. It provides them with evidence-based insights to shape policies, allocate resources judiciously, and implement sustainable practices for groundwater exploration. The review can aid in the development of strategic plans that align with the region's water needs, population growth, and environmental considerations. Looking ahead, future work in groundwater exploration for West Africa should focus on the integration of cutting-edge technologies, such as machine learning and artificial intelligence, to enhance predictive modeling and decision-making processes. Collaboration between researchers, government bodies, and industry stakeholders is pivotal in fostering a holistic and forward-thinking approach to groundwater exploration, ensuring the sustainable utilization of this vital resource for generations to come.

Highlighting the pressing need for West Africa to embrace the use of machine learning in groundwater exploration, it becomes imperative to leverage advanced technologies to address existing challenges and propel the region toward more efficient and effective groundwater resource management. The integration of machine learning techniques can revolutionize data analysis, enhance predictive modeling, and contribute to a more sustainable and comprehensive understanding of groundwater dynamics in the region. Embracing this technological shift is not just a step forward but a crucial leap toward advancing the field of groundwater exploration in West Africa.

6.0 **Conclusions**

This paper presents a systematic review of groundwater exploration methods in West Africa spanning from 2013 to 2023. The review underscores a notable over-concentration on Vertical Electrical Sounding (VES) methods in groundwater exploration studies within the examined period. The preeminence of VES, while providing valuable insights, may have contributed to a limited exploration of alternative and potentially more advanced techniques. Furthermore, a striking gap exists in the incorporation of machine learning methodologies, signalling a significant area for future research development in the context of West Africa's groundwater exploration. Several factors contribute to these patterns, including the familiarity and historical precedence of VES methods, the need for specialized knowledge and infrastructure for machine learning, and the potential constraints posed by limited resources and research priorities in specific countries. Bridging these gaps requires collective efforts, emphasizing the importance of diversifying methodological approaches, fostering interdisciplinary collaboration, and enhancing awareness and capacity for the adoption of innovative technologies, particularly in the realm of machine learning. Addressing these challenges will not only contribute to a more holistic understanding of groundwater resources but also pave the way for sustainable and technologically advanced groundwater exploration practices in West Africa

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