

Case Study

Geophysical and physicochemical assessment of groundwater and the implication on the public health in rural and semi-urban areas of Northern Nigeria

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Abstract

Groundwater resource plays a central role in every sector of life globally. Unfortunately, the roles of groundwater are often unappreciated in many parts of the world, especially in developing nations. The paper applied a combined geo-electrical method and hydrochemical analysis alongside physical surveys to investigate aquifer promising zones, the quality and the source of water supply in the selected regions. The geo-electric resistivity data were used to select the most aquifer-promising zone for groundwater development with a key interest in groundwater potential and aquifer overburden protective capacity overlying the water-bearing unit. Seventeen (17) vertical electrical sounding (VES) acquired in four regions reveals that the regional weathered/fractured unit which constitutes the aquifer unity extends from 13.4 m to 41.3 m in depth with the subsurface resistivity value varying between 53 Ωm –1013 Ωm in terms of resistivity values. The overburdened thickness (protective soil layers) stretches from 2.5 m to 13 m with a resistive layer of resistivity values ranging from 111 Ωm to 2877 Ωm , which could provide high aquifer protective cover for the regional groundwater systems. The computed aquifer transmissivity and hydraulic conductivity range from 0.54 m^2/h –15.85 m^2/h , and 0.95 m/day–9.19 m/day, respectively. The estimated average longitudinal conductance (0.2 moh) reveals that the regional groundwater systems are moderately protective against surface contaminants. In addition, the physicochemical water analysis was examined, which exposes the level of heavy metals (HMs) compositions in the regional groundwater systems and the possible public health risks compared to WHO permissible drinking water limits. The sample water from the Rivers had the highest concentration of HMs (0.089 mg/l–2.012 mg/l), followed by the hand-dug wells (HWDs) (0.033 mg/l–1.555 mg/l) and the lowest in the borehole (0.011 mg/l–0.511 mg/l). In contrast, the borehole water sample shows a moderation where the HMs presence falls within the WHO standard for drinking water. The outcomes of the study show that 63% of the investigated region consumed water with a high concentration of HMs above the WHO permissible standard allowance for drinking water, while only 37% took water that falls within the WHO permissible standard. In conclusion, the study showed significant impacts of anthropogenic activities on the regional water quality, which provides vital information about the regional groundwater systems and the quality of water supply for adequate groundwater development and sustainability.

Keywords Groundwater · Promising zone · Protective capacity · Boreholes · Water analysis · Heavy metals

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1 Introduction

Groundwater resource plays a central role in every sector of life and national building irrespective of national economic development, social conditions, political status, and technological advancement. Unfortunately, the roles of groundwater are often unappreciated in many parts of the world, especially in developing and underdeveloped nations [1]. Groundwater remains one of the most widely used natural resources on the planet Earth. Groundwater is found everywhere beneath the surface of the earth in pore space and fractures of soil [2]. However, the distribution of groundwater is largely unbalanced. Studies have shown that Nigeria has more than enough surface and groundwater resources to meet its current water demands [3–5]. Still, due to the growing demand for groundwater, the amount of water withdrawn from the ground can exceed the recharge from both rain and snow melt [6, 7]. However, the challenges of water systems have not always been scarcity but inadequate knowledge and capacity to effectively exploit groundwater resources at all scales and levels [1]. Though, continuous efforts have been put in place by various agencies, governmental and non-governmental organizations and institutes to enhance adequate access to potable and clean water for all Nigerians including those living in remote areas. Investigation and estimations indicate that only 58% of urban and semi-urban inhabitants and 39% of rural people have access to potable water supply [4, 8]. In 2011, the report showed that about 103 million Nigerians did not have access to sanitation facilities, while 69 million were reportedly estimated to have lacked access to a quality source of water in many rural and urban settlements, exposing the citizens to diseases [8].

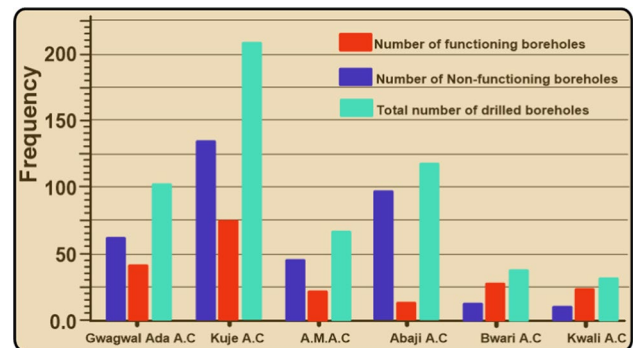
Groundwater systems remain one of the freshest and most reliable water due to their hidden nature, which is less susceptible to surface contamination [9, 10]. The shortage of fresh water is a global challenge due to the nexus of energy and the influence on global economics and the human environment. For instance, more than 30% of the world's freshwater is hidden and reserved as groundwater, while only 0.3% comes from surface water such as rivers, reservoirs, and lakes [11, 12]. Recent studies showed that rainwater remains the primary source of groundwater recharge that infiltrates the aquifer systems via the pores [13–15]. The shortage of freshwater may continue for a longer time in most of the metropolitan cities in Africa due to the large percentage of increase in urbanization, industries, and population, which is further complicated by climate change [16]. Urbanization has been identified as one of the major factors causing depletion and quality degradation of water resources, especially the groundwater resource, which is the world's largest freshwater [17]. In the last few decades, the quality of groundwater has been threatened by an ever-increasing in contaminants released by several points such as wastewater discharge from industries and non-points such as domestic wastewater sources [9, 10, 17, 18].

Unfortunately, urbanization is usually associated with high population density where most industrial activities placed more demand and stress on the groundwater resources. In Nigeria, groundwater pollution is one of the major consequences of poor waste management resulting from high population density [1]. According to some remarkable studies, the heavy contaminants from industries and human activities can easily break a weakly protective cover overlying the groundwater resources [19–23]. Estimation also showed that over 75% use pit latrines and 60% discharge wastewater to the environment directly exposing the groundwater systems vulnerable to pollution, while over 15% of semi-urban are without access to safe excreta disposal facilities [8]. However, there are several other visible problems of groundwater such as variation in groundwater level, climate impacts, poor maintenance of water supply facilities, and inadequate knowledge of groundwater systems [3, 5, 6] in the rural and semi-urban in Northern Nigeria. Groundwater pollution remains a giant factor affecting water supplies [9, 24]. For a well-protective aquifer, there exists a highly resistive overburdened thickness provided by the soil layer to resist the infiltration of contaminants from seeping into the soil down to the water table, thereby rendering the water unfit for consumption [7, 25–27]. Several studies have applied geophysical methods extensively in the last few decades for groundwater exploration in rural and semi-urban Northern Nigeria [5, 28–31], which is becoming a more promising approach for groundwater exploration. However, the minimum water security target of Sustainable Development Goals (SDGs) has not yet been reached [32, 33], especially in rural areas.

However, the challenges of borehole failure are a general phenomenon in both rural and semi-urban Northern Nigeria, which has been identified as one of the forefront problems facing the rural regions. According to past studies, borehole failures are largely due to the lack of prior information about the hydrogeological condition of the area involved [1, 5, 34]. To mitigate against these challenges, Alao, et al., [1] recommended mapping a regional aquifer promising zone with a high aquifer overburdened protective capacity layer overlaying the regional groundwater resources via adequate geophysical survey and massive aquifer storage support facilities. According to Aweto [19] and

Table 1 Some selected studies on borehole functional condition and the possible causes in Nigeria

SN	Borehole installed	Number of unproductive	Failure rate (%)	Some of the possible causes of borehole failures	Source(s)
1	256	59	23%	Seasonal variations in water level and lack of geophysical investigation	[3]
2	50	31	62%	Poor design and construction, lack of geophysical survey & poor maintenance	[5]
3	69	16	23%	Poor/lack of geophysical investigation	[42]
4	60	12	20%	Aquifer depletion, equipment failure, poorly well design and construction	[34]

Fig. 1 Analysis of the functional status of boreholes in FCT (A case study)

Aboh, [31], aquifer-promising zones are best identified by delineating a weathered/fractured basement within the subsurface associated with high thickness and low resistivity values alongside the high aquifer protective capacity for groundwater development. Identifying the major factors responsible for borehole failure is a good approach towards strategic planning for water security and sustainability [1]. However, there are several other factors responsible for growing water challenges starting with the most critical ones, (i) groundwater contamination, (ii) borehole failures, (iii) inadequate knowledge of groundwater systems, and (iv) unpredicted climate change. The interaction between human activities and water quality in every settlement affects the factors aforementioned, which according to some studies, the assessment of groundwater protective capacity index against surface contamination is a function of both the hydraulic and longitudinal conductivity [35–39]. Therefore, modelling the regional groundwater potential zone is a good approach to improving regional water supplies [12, 40, 41]. This study seeks to delineate aquifer promising zones and protective capacity index based on the above trend of events to adequately provide subsurface information for groundwater development in response to frequent borehole failure alongside the regional water quality and groundwater pollution through physicochemical analysis of some water samples in the study area.

2 Borehole failures

Borehole failure is a popular phenomenon in Northern Nigeria [1, 3, 5]. Several studies have attributed the high rate of borehole failures to poor or no hydrogeological investigation because more than 90% of boreholes drilled in Northern Nigeria were sited based on the owner's choice of location rather than adequate hydro-geological/geophysical investigation [3, 5, 31, 42]. Several studies have also indicated that the water-bearing units (aquifers) within Northern Nigeria usually occur within the weathered residual overburden and the fractured bedrock [6, 43]. Therefore, viable aquifers wholly within the fractured bedrock are of rare occurrence because of the typically low storage of fracture systems, which is generally less than 1% [43]. Studies on groundwater development and frequent borehole failure have a long history in Nigeria and neighbouring African countries. Continuous and concerted efforts towards securing the water future in Northern Nigeria have not yet met the quest for quality water supply. Table 1 shows a brief history of borehole failures in Nigeria. Figure 1 presents a report of a case study of the functional status of boreholes in Federal Capital Territory (FCT) Abuja. The reports show that out of 556 boreholes drilled in FCT, only 358 boreholes are functioning, which represents 64% success, while 198 boreholes reportedly failed, which represents 36% failures [6].

3 Site geology and description

Figure 2 shows the relief of the terrane under study which lies within the geographical coordinates of latitude and longitude of 10.4326N to 10.429N and 7.4902E to 7.4965E respectively with an average height of 615 m above the sea level. The terrane is underlain by Precambrian rocks typical of the Northern basement complex of Nigeria [44]. However, the literature review for this work shows that the fractured basement and water-yielding capacities of wells drilled in the area and its environs always vary [1]. The area rocks are usually capped by consolidated laterites, quartzites, sandstones and silty sand, especially at the surface [4]. Still, the laterites have been weathered into lateritic nodules mixed with sandy clays and silty soil over time. The bioclimatic nature of the environment has affected the deep chemical weathering and fluvial erosion, which metamorphous the high undulating plains into subdued interfluves [43]. Like other places, the hydrogeology of Kaduna State is largely a function of the geologic setting [9]. On the other hand, climate variability is one of the fundamental factors that has affected the seasonal variation in the groundwater level. Northern Nigeria is one of the vulnerable regions to climate variability because it is located along latitude 8° – 12° N with dry and hot climate systems. The hot and dry climate can influence the groundwater [9]. The regional hydrogeology systems are usually influenced and controlled by climatic variability and drainage systems of the concerned region [9]. The geological formations underlying any region determine the aquifer type that would be developed and recharged in that region.

4 Materials and methodology

Geophysical investigations of the earth's interior involve the delineation of subsurface physical properties and providing information on underlying the earth's interior and subsurface characteristics [45]. Some of the materials used for this survey include the Ohmega resistivity meter and its accessories, range poles, global position system (GPS), a differential pulse anodic stripping voltammetry (DPASV), atomic absorption spectrometry (AAS), a portable computer for data processing, Flask, beakers, and clean plastic bottles (0.75-L), etc. to obtain water samples in two rivers, hand-dug wells, and boreholes for the hydrochemical analysis. After that, a total of seventeen (17) vertical electrical sounding (VES) stations were acquired using a Schlumberger array with a maximum spread of 200 m, which works on the principle of Ohm's law according to Eq. (1) [46].

$$\Delta V = IR \quad (1)$$

The apparent resistivity of the subsurface materials reacting to the current flow via the ground can be expressed by Eq. (2)

Fig. 2 Map describing the study areas showing the elevation and the VES stations

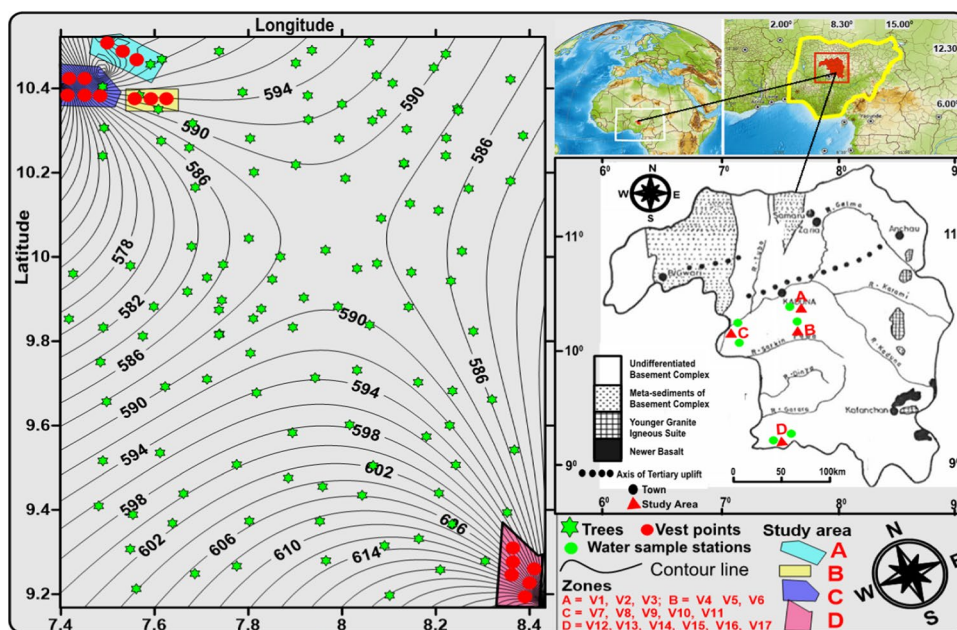
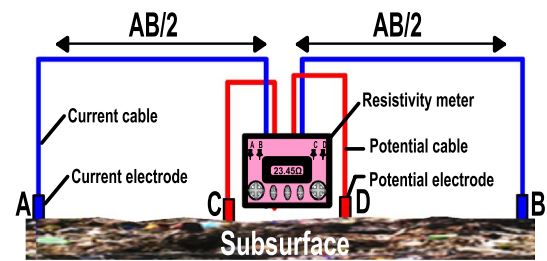


Fig. 3 Schlumberger Configuration



$$\Rightarrow \rho_a = RK \quad (2)$$

where R is resistivity and K is a geometrical factor which depends on the four electrode's geometry (Fig. 3) and can be expressed in Eq. (3):

$$K = 2\pi \left[\left(\frac{1}{r_A} - \frac{1}{r_B} \right) - \left(\frac{1}{R_A} - \frac{1}{R_B} \right) \right]^{-1} \quad (3)$$

Further derivatives like Dar Zarrouk [DZ] parameters can be used to estimate the aquifer protective capacity [47]. The basic parameters DZ parameters (longitudinal conductance, S_L and transverse resistance, R_T) can express by Eqs. (4) and (5) respectively from apparent resistivity (ρ_a) and thickness (h_a) of the geoelectric layer [47]. High S_L and R_T values usually indicate relatively thick succession and should be a focus in terms of groundwater potential.

$$S_L = h_a / \rho_a \quad (4)$$

$$R_T = h_a \cdot \rho_a \quad (5)$$

The earth's interior has since been described as a natural medium that filters the contaminated fluids seeping into the ground. This may be difficult if there are soil pores in the earth's interior. However, hydraulic conductivity has been identified as one of the most important and variable parameters for estimating the contaminant travel time [48, 49], it was noted that hydraulic conductivity is most reliably estimated via aquifer pumping, but if the aquifer's yield is very low, slug tests are conducted [50]. However, where these data are difficult to obtain or not available, they could be estimated by Eq. (6) [1]:

$$K = \frac{86400}{9750000} \rho_a^{1.195} (\text{m/day}) \quad (6)$$

5 Data processing

The resistivity data acquired in the field were converted to subsurface apparent resistivity (ρ_a) using Eq. (2). The apparent resistivity data were fed into a computer software *Res ID version 1.00.07 Beta* and its model parameters [51], which transformed the data to reveal the lithological sequence of the study area. The water sample obtained was tested for four heavy metals (Chromium (Cr), iron (Fe), cadmium (Cd), and lead (Pb)) and the electrical conductivity (EC), for physicochemical water analysis in the laboratory presented in Table 2 and Fig. 7. According to a remarkable study. The water samples obtained from boreholes should be allowed to flow for at least 5 min before collection to stabilize variation in EC and temperature [10]. The samples were transferred and stored in a plastic reagent bottle for AAS analysis after being acidified to 1% with nitric acid to keep the metals in solution. The AAS lamp was on for 5 min warm and calibrated to determine the unknown concentration of an element such as electrical conductivity (EC), chromium (Cr), chloride (Cl), cadmium (Cd), and lead (Pb) by several solutions of known concentrations. A set-up system of 2 m wavelength was selected to improve the quality of the analysis. The AAS was allowed to warm up for 5–10 min to stabilize the energy source, which was constantly rescaled for various concentrated solutions used. The different heavy metals (EC, Pb, Cd, Fe, and Cr) are analyzed in Sects. 4.3, Table 2, and Fig. 7.

6 Results and discussion

Table 3 indicates the summary of the interpreted VES results and the estimated second aquifer parameters such as longitudinal conductance, transverse resistance, hydraulic conductivity, subsurface apparent resistivity, layer thickness and aquifer transmissivity in the study area using Eqs. (2, 3–6). These parameters were used to evaluate aquifer promising zones and aquifer protective capacity. The aquifer hydraulic parameter values also show that the regional aquifer can supply continuous water if the wells or boreholes are sited based on the geophysical prediction. The computed values of the regional aquifer transmissivity and hydraulic characteristics have an average value of $3.2 \text{ m}^2/\text{hour}$ and $3.4 \text{ m}/\text{day}$ (Table 3). These can enhance the regional aquifer recharge process and productivity. However, the pockets of clay contrast encountered beneath the topsoil are relatively impermeable, which implies high aquifer protective capacity. The regional transverse resistance varies between $673 \Omega\text{m}^2$ – $13,828 \Omega\text{m}^2$, which that the aquifer systems of the study area are promising with a quantifiable groundwater potential.

6.1 Geoelectric/geology section

Figure 4 presents borehole data acquired by the National Water Resources Institute (NWRI), which is about 800 m away from the study area. The information provided by the vertical cylindrical borehole data of six-inch diameter provides this study with a good geological insight for critical analysis. The subsurface layers revealed by the borehole data indicate four distinctive layers including the top layer consisting of sandy clay, clayed sand and brownish-red lateritic soil with an average overburden thickness of 20 m [8]. The geoelectric/geologic section obtained from this study presents a section of the subsoil formation and the sequence of layered rocks. The interpreted field data of the seventeen (17) VES stations in four different locations depicted A, B C and D, were employed to prepare the subsoil section displayed in Fig. 5a, b. The geo-electric section shows that the study areas are underlain by four to five geological layers. The first (topsoil) and second (laterite/dry clay/sand) layers constitute the overburdened thickness layer overlying the aquifer units of the study areas, which spreads from 2.5 m to 13 m (Fig. 5a, b). The third (weathered) and fourth (fractured) layers constitute the aquifer units of the area, which vary between 14.3 m and 41.4 m. However, the fourth layer interpreted to be a fractured region was not encountered in some VST stations (A1, B1, B2, C4, C5 and D4). That is, the weathered and fractured basement is the main regional aquifer unit within the study area with high aquifer promising zones. While the resistivity and thickness values of the weathered layer vary between $53 \Omega\text{m}$ and $334 \Omega\text{m}$ and 14.3–41.4 m respectively, the fractured basement varies between $335 \Omega\text{m}$ – $1013 \Omega\text{m}$ and 9.3–18.4 m respectively. The last layer is characterized by high resistivity values ranging from $1533 \Omega\text{m}$ to $66,153 \Omega\text{m}$, which suggests an unfractured fresh basement (Fig. 5a-b).

6.2 Evaluation protective capacity index

The protective capacity index was evaluated from the geoelectric top layer resistivity employing the service Dar-Zarrouk and hydrological parameters in Table 3. The computed longitudinal Conductance (S) presented in Table 3 was used to prepare Fig. 6 to evaluate the regional aquifer protective capacity in comparison with the aquifer protective capacity rating presented in Table 4. The overburdened topsoil layers overlying the regional aquifer vary between 2.5 and 13 m indicating a high protective capacity index. The high impervious clayey overburden encountered beneath the topsoil can endure the infiltration of any contaminant plumes since the interior can as a filtering medium. Some considerable studies on aquifer susceptibility indicate that the aquifer protective capacity index hinges on the degree of impermeability/permeability of the overburden thickness overlying media to the transmission of pollutants into groundwater systems [9,

Table 2. Physio-chemical water analysis of the two Hand-Dug Wells, two rivers and two boreholes

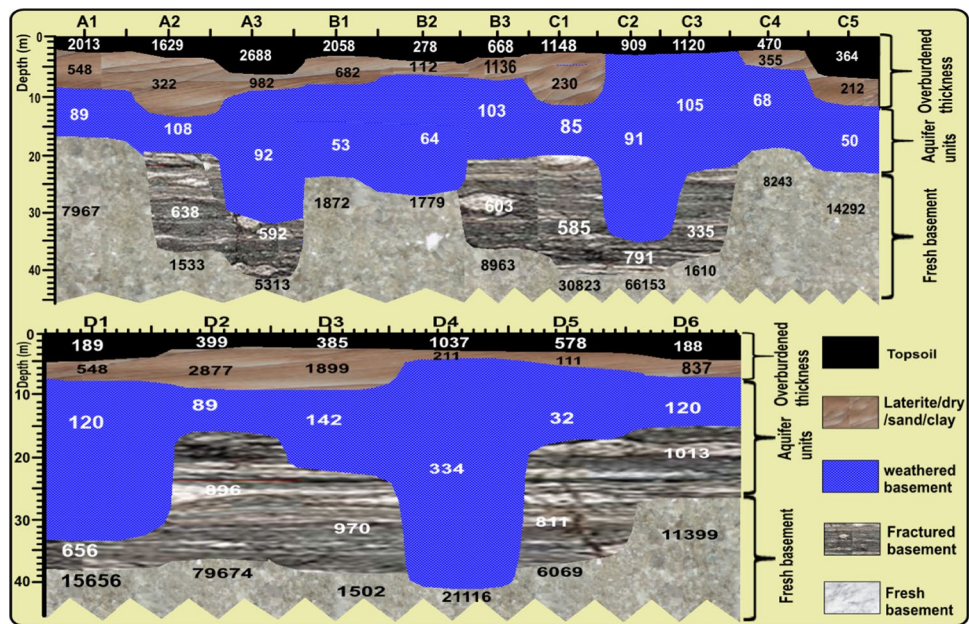
Parameter	Unit	HDW 1	HDW 2	River 1	River 2	BH 1	BH 2	[57]
EC	ms/cm	0.909	0.971	1.024	1.211	0.329	0.418	0.100 – 1.000
Cr	mg/l	0.512	0.497	0.712	0.801	0.371	0.299	0.030 – 0.050
Cd	mg/l	0.042	0.033	0.091	0.089	0.011	0.013	0.003 – 0.005
Pb	mg/l	0.791	1.555	1.871	1.312	0.499	0.511	0.010 – 0.030
Fe	mg/l	1.003	1.012	2.012	1.919	0.397	0.311	0.300 – 1.000

■ Below WHO Standard
 ■ Satisfies WHO Standard
 ■ Above WHO Standard

Regional geological borehole data around the study area by (NWRI, 2002)				Previous regional studies		Current study data	
Depth (m)	Lithology	Driller Description	Geology Interpretation	Infer subsoil lithologies	Reistivity values/ Ω m	Reistivity values/ Ω m	Thickness values/m
0 - 25		Topsoil, Laterite, Lateritic clay	Uper/overburdened layer (unsaturated)	Lateritic topsoil, wet/dry clay, sand	200 - 2800	188 - 2688	2.2 - 10.2
25 - 35		Granite, gravel, Brownish fine sand, Quartz	Weathered fresh basement	Fine sand/silty/clay, Weathered basement	50 - 400	32 - 334	81 - 36.2
35 - 40		Gap	Fractured basement	Fractured basement	500 - 1000	335 - 1013	11.2 - 28.3
40 - 50		Granite	Fresh basement	Fresh basement	> 1000	1502 - 79674	—

Fig. 4 Geological well-logs (borehole data) around the study area

Fig. 5 Geoelectric/geologic section across all the Profiles of the study area



19, 24]. The study area is characterized by relatively high longitudinal conductance that can reduce infiltration of surface contaminant into the underlying aquifer (Fig. 6). The aquifer protective capacity of the study area groundwater systems is weakly protective against surface contaminants except in the VES stations A2, A3, B2, C1 and C2 (Fig. 6), where the groundwater systems are moderately protective against surface pollutants. Only one VES station indicates poor aquifer protective capacity. Comparing Table 4 and Fig. 6, the regional aquifer systems are relatively protective against surface infiltrations with an average value of 0.2 mhos approximately. While the regional aquifer occurs at deep zones indicating a high capacity for groundwater development, the high hydraulic conductivity within the aquifer unit shows high groundwater productivity. In addition, the results from the VESs were applied to model the longitudinal conductance, transmissivity and hydraulic conductivity values for the study area. The computed values indicated that the aquifer transmissivity and hydraulic conductivity vary between $0.54 \text{ m}^2/h$ – $15.85 \text{ m}^2/h$, and 0.95 m/day – 9.19 m/day , respectively, while the estimated average longitudinal conductance (0.2 moh) reflect the nature of the regional groundwater systems. The results revealed close approximations, which reflect the dependability of the VES's results. The obtained results also suggest a prolific and highly permeable aquifer with a high degree of rechargeability within the study area.

Table 3 The Summary of Computed Dar-Zarrouk Parameters and the Hydraulic Characteristics Estimated from the Geoelectric Parameters across all the seventeen VES stations of the study area

SN	VES Pts	Aquifer resistivity $\rho(\Omega m)$	Aquifer thickness d(m)	Transverse resist- ance $R(\Omega m^2)$	Longitudinal con- ductivity $S(\Omega^{-1})$	Hydraulic conduc- tivity $K(m/day)$	Transmissiv- ity $T(m^2/h)$
1	A1	89	15.0	1335	0.1685	1.892	1.183
2	A2	53	12.7	673	0.2396	1.019	0.539
3	A3	63	13.9	876	0.2206	1.252	0.726
4	B1	103	18.2	1875	0.1767	2.253	1.709
5	B2	84	17.9	1504	0.2131	1.766	1.317
6	B3	290	31.6	9164	0.1090	7.764	10.22
7	C1	63	16.5	1040	0.2619	1.252	0.861
8	C2	50	19.9	995	0.3980	0.950	0.788
9	C3	89	15.0	1335	0.1686	1.893	1.183
10	C4	141	22.5	3173	0.1596	3.280	3.075
11	C5	334	41.4	13,828	0.1240	9.191	15.85
12	D1	90	16.6	1494	0.1844	1.918	1.326
13	D2	120	14.3	1716	0.1192	2.705	1.611
14	D3	162	23.0	3726	0.1420	3.872	3.710
15	D4	211	27.0	5697	0.1280	5.309	5.972
16	D5	260	21.4	5564	0.0823	6.814	6.075
17	D6	86	17.0	1462	0.1977	1.817	1.287
Average		135	20.2	3266	0.1800	3.200	3.400

Fig. 6 Computed longitudinal conductance of the study areas

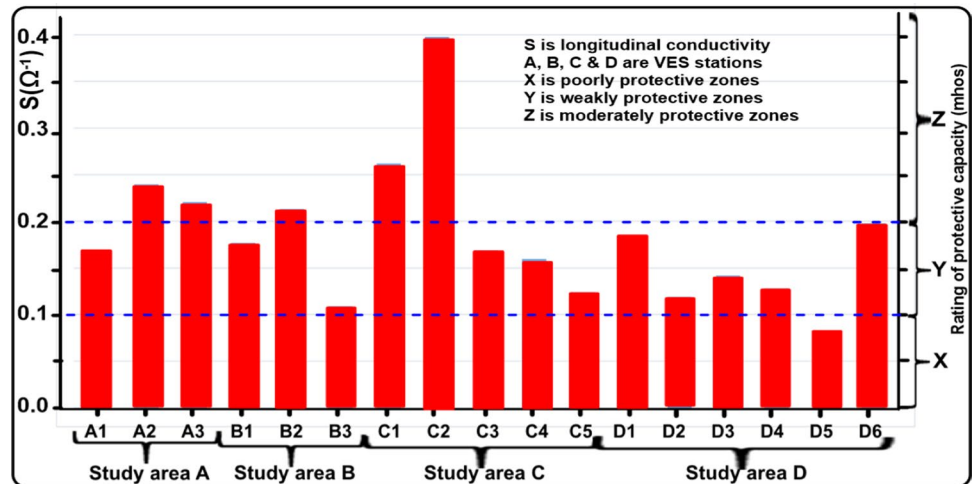
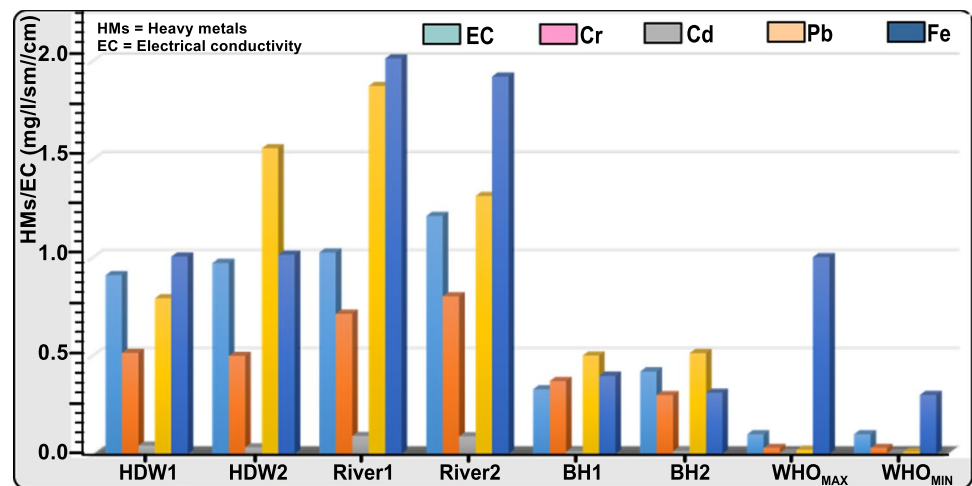


Table 4 Protective capacity rating [50, 52]

Protective Capacity (mhos)	Rating
< 0.1	Poor
0.1–0.19	Weak
0.2–0.69	Moderate
0.7–4.9	Good
0.5–10	Very good
> 10	Excellent

Fig. 7 The degree of heavy metal compositions and the electrical conductivity present in the water samples taken from the regional hand-dug well, rivers, and boreholes



6.3 Physicochemical analysis of the water sample

Figure 7 presents the levels of HM composition in the sample water obtained from different sources (rivers, hand-dug wells and boreholes) and the EC alongside the WHO permissible limits for drinking water. The surface water samples contain the highest content of HMs (0.089 mg/l–2.012 mg/l), followed by the HDWs (0.033 mg/l–1.555 mg/l) and the lowest in the borehole (0.011 mg/l–0.511 mg/l). The borehole water samples show a moderate concentration of HMs, which falls within the WHO permissible standard for drinking water. The high concentrations of HMs encountered in the surface water and well-water reflection of the degree of the exposures of the regional water supply, while the moderate HMs present in the borehole water sample okays the regional borehole water. However, the river water indicates the highest contents of HMs and conductivity (Fig. 7), which could expose the health of the villagers vulnerable to attack. This may have been attributed to the fact that the rivers are open to all kinds of contaminants since they are not protected by any cover [10]. Reliable sources indicate that the villagers sometimes use the river water for drinking, especially during the dry periods when most of the HDWs dry off and the boreholes yield very low [1, 3]. The remarkable contents of HMs displayed by the HDWs sample water may not be unconnected to the open and shallow nature of the wells because virtually all the dug wells were either without cover or perforated cover. The borehole sample water shows some level of moderation (Fig. 7). However, the depth of the boreholes is not available in this study to further express the relation between the HM's presence and the borehole depth. However, the contaminated surface water (rivers) remains one of the major sources of regional aquifer recharge. According to some remarkable studies, landfill leachate plumes remain one of the major threats to regional groundwater systems, which is relatively dependent on the HDW's depth and contaminant source distance [10].

However, the sample water from the RVs had the highest EC (2.024 mg/l–2.211 mg/l), followed by the HDWs (0.909 mg/l–0.971 mg/l) and the lowest in the BH (0.329 mg/l–0.418 mg/l). While the WHO-allowed standard indicates that the sample from BH is mild, the samples from HDWs are comparatively above the WHO-permissible standard. As a result, it is assumed that the dumpsite leachate plumes, which are suspected to be the major cause of regional groundwater pollution [10] must have migrated outward to the regional groundwater and the surrounding environment. The presence of heavy metals (HMs) in drinking water is considered harmful to human health, especially when consumed in excess, as per the WHO guideline and other noteworthy research [10, 53, 54]. Another outstanding study found that heavy metals (HMs) are not readily apparent to the naked eye and that their effects are rarely acknowledged until they cause major harm to human health systems. The regional surface and groundwater from the rivers, streams, and HDWs are deemed toxic and unsafe for human consumption based on the evidence gathered for this study. Constant exposure to heavy metal levels in drinking water is very harmful to human health [10, 54–56].

In addition, the outcomes of the study show that 63% of the investigated region consumed water with a high concentration of HMs above the WHO permissible standard allowance for drinking water, while only 37% took water that falls within the WHO permissible standard. No water sample station fell below WHO permissible standards. Thus, the health implications of HMs in drinking water vary proportionally to the degree of its concentration with device advise effect on public health such as heart and kidney-related issues, which could trigger cancer and related health crises. In

developing countries like Nigeria, especially in the remote or semi-remote regions, where contaminated drinking water or agricultural wastewater are rarely treated or partially treated, which leads to excess consumption of water/foods polluted with HMs poses the highest risk to human health. These toxic substances can disrupt biological and biochemical processes within the body, leading to adverse health outcomes. Therefore, it is important to study and regulate heavy metal levels in the regional drinking water to safeguard public health.

7 Implications of the results on the public health risk

The results from the physicochemical analysis show high concentrations of HMs such as Chromium (Cr), Cadmium (Cd), Lead (Pb), and Iron (Fe) in the regional drinking water, which has significant implications for regional public health. This data was crucial in evaluating the potential public health risks of these substances. According to remarkable studies, the degree of impact of HM-contaminated drinking water depends on the level of consumption of affected water [9, 10, 24]. For instance, excess consumption of HM-contaminated water can cause several health issues associated with lung cancer, kidney and liver damage, and skin irritation, especially the water with a heavy content of chromium and cadmium. Exposure of human beings to lead and iron can result in increased blood pressure for adults and developmental delays in children's brains. However, these substances are not always detrimental to human health when taken in small amounts or within the dose standard. The relationship between the amount of exposure (dose) and the severity of the effect (response) is interconnected. Therefore, assessing the level how much metal a person has been exposed to, through water intake is quite essential in every settlement, in which this has been exposed. Combining both geophysical data and physicochemical data provides society with enormous information and awareness, which eventually metamorphose into great cautions for individuals or populations. Based on the information gathered from the geophysical data and physicochemical data, it is important to note that groundwater vulnerability of HM contaminants is individual and public susceptibility to high health risks [10, 55, 58], especially the pregnant women, children, and the elderly, which are often more vulnerable to the toxic effects of heavy metals. Individuals drinking the polluted water may be at risk of exposure to toxic substances. Therefore, it is important to address and mitigate the potential health risks associated with contaminated regional groundwater through effective monitoring, which may involve implementing measures to prevent excess exposure for the protection of public health and the environment.

8 Conclusion and recommendation

The combined geophysical investigation, physicochemical water analysis and physical survey approaches have shown high capacity in addressing the rural and semi-urban water challenges. A geo-electrical investigation carried out in seventeen (17) VES stations across four areas reveals four to five geological layers characterized by topsoil, clays/laterite/sandy soil, weathered layer, fractured basement and fresh bedrock. The computed second aquifer parameters reveal that the regional groundwater systems are moderately protective against surface contaminants. Based on the results of the geophysical investigation findings and the physicochemical properties of the regional water samples, match with the physical surveys.

- a. The 17 VES acquired in four regions reveals that the regional weathered/fractured unit which constitutes the aquifer unit has an electrical layer of resistivity values ranging from 53 Ωm –1013 Ωm and extends from 13.4 m–41.3 m in depth, while the overburdened thickness or upper unsaturated layers (protective soil layers) stretches from 2.5 m to 13 m with layer resistivity values of 111 Ωm to 2877 Ωm , which could provide high aquifer protective cover for the regional groundwater systems.
- b. Only a few stations (A1, B1, B2, C4, & C5) in the three zones sited are directly in regions of high predicted aquifer low potential and the regions should take advantage of alternative water storage facilities to reduce pressure on boreholes and take control of water scarcity, especially in during dry periods.
- c. The physical surveys show that 63% of the boreholes found in the villages were not productive. In comparison, only 67% were recorded productive in the semi-urban area, while the geophysical investigation conducted in the regions shows the challenges of borehole failure may be largely attributed to poor pre-investigation about the condition of

the regional groundwater potential. Thus, geophysical recommendations for groundwater development should be strictly adhered to when selecting a site for groundwater exploration.

- d. The geophysical investigation shows that only two stations (A3 and C2) of seventeen stations indicate poor regional aquifer transmissivity and hydraulic conductivity, which may have a direct impact on the regional aquifer recharge process. Thus, alternative high water storage facilities to cushion the effect of unfavourable climate phenomena
- e. The physicochemical tests on the sample water show a high content of HMs (0.011 mg/l–2.012 mg/l), which vary significantly across the three water sources with the rivers showing the highest, followed by HDW and least in the BH water. The high-content HMs are presumed to have significantly influenced regional public health, especially that of children.
- f. More than 50% of sources of water supply rely on surface water (rivers) and hand-dug wells in rural and semi-urban regions of Northern Nigeria, which have been compromised by the presence of HMs causing water pollution and exposing the villagers to health hazards. The results of the physicochemical analysis show that the river water supplies left a huge question mark on the quality of water available for the villagers because the river source is highly interconnected with the regional groundwater systems.
- g. Identifying aquifer-promising zones with a high protective capacity index shows high capacity is critical to groundwater development. However, this may not be enough to secure the future of regional water resource management in the face of the growing scarcity of quality water, which has significantly impacted the socio-economic development of rural and semi-urban inhabitants.
- h. Regions with flow paths, where the rock formations are fractured (fractured aquifers) within a depth of 30 m and above are considered good for groundwater development, but if the flow paths occur at overburdened layers overlying the water-bearing units, the region may be avoided for groundwater exploration due to high susceptibility to surface contaminants.
- i. The modeled longitudinal conductance, transmissivity and hydraulic conductivity values for the study area vary between 0.1 moh–0.4 moh, $0.54\text{ m}^2/h$ – $15.85\text{ m}^2/h$, and 0.95 m/day–9.19 m/day, respectively, reflect the nature of the regional aquifer, which suggest a prolific and highly permeable aquifer with a high degree of rechargeability.
- j. Regardless of the high aquifer potential, regional groundwater systems will be much more successful in areas with proper waste management systems. This study identifies areas where the protective capacity index is high and should be expected to fight against regional water scarcity and municipality challenges.
- k. Based on the information gathered from the geophysical data and physicochemical data, more than 50% of the people living within a 200 m radius of dumpsite are vulnerable to HM exposure, which often has more toxic effects on pregnant women, children, and the elderly.
- l. All the stakeholders and decision-makers in waste and water resource management must look beyond providing water, and focus on effective water treatment/resource management and environmental education with a concerted effort to improve adequate knowledge of regional groundwater systems and capacity development. To secure the water future in Northern Nigeria, especially in rural and semi-urban areas, ultimate attention should be paid to the hydrological investigation to ascertain the potential of regional groundwater before sitting boreholes.

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Declarations

Competing interests The authors declare no conflicting interest.

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References

1. Alao JO, Yusuf MA, Nur MS, Nuruddeen AM, Ahmad MS, Jaiyeoba E. Delineation of aquifer promising zones and protective capacity for regional groundwater development and sustainability. *SN Appl Sci.* 2023;5:149. <https://doi.org/10.1007/s42452-023-05371-2>.
2. V. V. Patil and A. B. Toradmal, "Identification of Groundwater Potential Prospect Zones in Semi-Arid Region- A Case Study of Karjat Tehsil, Ahmednagar District, Maharashtra," *Journal of Xidian University* 10 14:5. <https://doi.org/10.37896/jxu.14.5/085>, 2020.
3. Ajayi O, Abegunrin OO. Borehole failures in crystalline rocks of South-Western Nigeria. *GeoJournal.* 1994;34:397–405. <https://doi.org/10.1007/BF00813135>.
4. M. O. Eduvie, "Borehole Failures and Groundwater Development in Nigeria - Paper presented at a National Seminar: National Water Resources Institute Kaduna Nigeria," 2006.
5. Afuwal GC, Lawal KM, Sule P, Ikpokonte AE. Geophysical investigation of the causes of borehole failure in the crystalline basement complex: a case study of Kaura Area of Kaduna State, Nigeria. *J Environ Earth Sci.* 2015;5(17):122–31.
6. M. A. Dan-Hassan, "Review of borehole Failure: Causes and Remedies," National Convention of Association of Water Well Drilling Rig Owners and Practitioners: <https://www.researchgate.net/publication/334376977>; DOI: <https://doi.org/10.13140/RG.2.2.13702.93768>, 2017.
7. Abdulrazzaq ZT, Agbasi EO, Aziz NA, Etuk SE. Identification of potential groundwater locations using geophysical data and fuzzy gamma operator model in Imo, Southeastern Nigeria. *Appl Water Sci.* 2020;10:188. <https://doi.org/10.1007/s13201-020-01264-6>.
8. NWRI, "National Assessment of Drinking Water Quality Project Report," National Water Resource Institute (NWRI), Kaduna, Federal Ministry of Water Resource, Nigeria, 2011.
9. Alao JO. Impacts of open dumpsite leachates on soil and groundwater quality. *Groundw Sustain Dev.* 2023;20:100877. <https://doi.org/10.1016/j.gsd.2022.100877>.
10. Alao JO, Fahad A, Abdo GH, Ayejoto DA, Almohamad H, Ahmad MS, Nur MS, Danjuma TT, Yusuf MA, Francis OT, Joy AO. Effects of dumpsite leachate plumes on surface and groundwater and the possible public health risks. *Sci Total Environ.* 2023;1:165469. <https://doi.org/10.1016/j.scitotenv.2023.165469>.
11. Senanayake IP, Dissanayake D, Mayadunna BB, Weerasekera WL. An approach to delineate groundwater recharge potential sites in Ambalantota, Sri Lanka Using GIS Techniques. *Geosci Front.* 2016. <https://doi.org/10.1016/j.gsf.2015.03.002>.
12. Mallick J, Khan RA, Ahmed M, Alqadhi SD, Alsubih M, Falqi I, Hasan MA. Modeling groundwater potential zone in a semi-arid region of aseer using fuzzy-AHP and geoinformation techniques. *Water.* 2019;11:2656. <https://doi.org/10.3390/w11122656>.
13. FAO, "Water Harvesting and Storage," Food and Agriculture Organization (FAO) of the United Nations, 2021.
14. Mahato S, Mishra AK, Debnath S. Impact of rainwater harvesting structures on groundwater recharge potential in India. *Int J Curr Microbiol App Sci.* 2020;9(06):66–74. <https://doi.org/10.20546/ijcmas.2020.906.008>.
15. Paolo T, Elena C, Maurizio R. Rainwater harvesting techniques to face water scarcity in African drylands: hydrological efficiency assessment. *Water.* 2020;12:2646. <https://doi.org/10.3390/w12092646>.
16. Owolabi ST, Madi K, Kalumba AM, Orimoloye IP. A groundwater potential zone mapping approach for semi-arid environments using remote sensing (RS), geographic information system (GIS), and analytical hierarchical process (AHP) techniques: a case study of Buffalo catchment, Eastern Cape, South Africa. *Arab J Geosci.* 2020;13:1184. <https://doi.org/10.1007/s12517-020-06166-0>.
17. Ferreira C, Adama-Ajonye O, Ikenna AE, Kalantari Z. Groundwater quality in the vicinity of a dumpsite in Lagos metropolis, Nigeria. *Geogr Sustain.* 2023. <https://doi.org/10.1016/j.geosus.2023.09.005>.
18. Yusuf MA, Abiye TA. Risks of groundwater pollution in the coastal areas of Lagos, southwestern Nigeria. *Groundw Sustain Dev.* 2019;9:100222. <https://doi.org/10.1016/j.gsd.2019.100222>.
19. Aweto K. Aquifer vulnerability assessment at Oke-Ila area, Southwestern Nigeria. *Intl J Phys Sci.* 2011;6(33):7574–83. <https://doi.org/10.5897/IJPS11.933>.
20. Aneesh TD, Archana MN, Krishna RP, Arun TJ, Reji S. Groundwater vulnerability assessment of an urban coastal phreatic aquifer in India using GIS-based DRASTIC model. *Groundw Sustain Dev.* 2022;19:100810. <https://doi.org/10.1016/j.gsd.2022.100810>.
21. Aziz FF, Hussain EK. Spatiotemporal variation of heavy metals and pollution indices in groundwater around Al-Diwaniyah Open Dump. *J Ecol Eng.* 2023;24(8):106–17. <https://doi.org/10.12911/22998993/166063>.
22. Omali AO, Arogundade JT, Snow D. Assessment of health risks associated with contaminants in groundwater in the catchment area of selected dumpsites in Abuja north central Nigeria. *Discover Environ.* 2023;1:7. <https://doi.org/10.1007/s44274-023-00001-5>.
23. Gogoi N, Sarma A, Choudhury M. Soil heavy metal pollution and ecological risk assessment in disturbed and undisturbed soil of Morigaon, Assam. *Discover Environment.* 2024;2:13. <https://doi.org/10.1007/s44274-024-00039-z>.
24. Adiat K, Adegoroye AA, Adebisi AD, Akeredolu BE, Akinlalu AA. Comparative assessment of aquifer susceptibilities to contaminant from dumpsites in different geological locations. *Heliyon.* 2019;5:e01499. <https://doi.org/10.1016/j.heliyon.2019.e01499>.
25. Nugrah GU, Gao KI, Hartanto P, Bakti H. Aquifer Vulnerability: Its Protection and Management—A Case Study in Pangkalpinang City, Indonesia. *Int J Geophys.* 2020; 23:1. Doi: <https://doi.org/10.1155/2020/8887914>.
26. Babika ZM, Tukur AI. Spatial correlation of groundwater pollutants with the vulnerability index in Kano Metropolis, North-western Nigeria. *Water Pract Technol.* 2022;00:1. <https://doi.org/10.2166/wpt.2022.141>.
27. Gonçalves V, Albuquerque A, Carvalho P, Almeida P, Cavaleiro V. Groundwater vulnerability assessment to cemeteries pollution through GIS-based DRASTIC index. *Water.* 2023;15:812. <https://doi.org/10.3390/w15040812>.
28. Bahammou YA, Benamara A, Ammar A, Hritta D, Dakir I, Bouikbane H. Application of vertical electrical sounding resistivity technique to explore groundwater in the Errachidia basin, Morocco. *Groundw Sustain Dev.* 2021;15:100648. <https://doi.org/10.1016/j.gsd.2021.100648>.
29. K. I. Arowoogun and O. O. Osinowo, "3D resistivity model of 1D vertical electrical sounding (VES) data for groundwater potential and aquifer protective capacity assessment: a case study. *Model Earth Syst. Environ.* 8, 2615–2626 (2022). <https://doi.org/10.1007/s40808-021-0125-w>, 2022.

30. Ebong CD, Emeka CN, Melouah O, Ullaha R, Ita A, Asfahani J. Delineation of groundwater potential zones using electrical resistivity technique in Obudu basement terrain of Cross River State, Southeastern Nigeria. *Water Prac Technol.* 2023;18:3. <https://doi.org/10.2166/wpt.2023.174>.
31. Aboh HO. Assessment of the aquifers in some selected villages in Chikun local government area, Kaduna state, Nigeria. *Sci World J* 4: 2 www.scienceworldjournal.org, pp. 37–42, 2009.
32. IGRAC. "Groundwater, key to the Sustainable Development Goals (SDGs)," <https://www.un-igrac.org/stories/groundwater-key-sustainable-development-goals-sdgs>, 2022.
33. Saqr AM, Ibrahim MG, Fujii M, Nasr M. Sustainable development goals (SDGs) associated with groundwater over-exploitation vulnerability: geographic information system-based multi-criteria decision analysis. *Nat Resourc Res.* 2021;30(6):4255–76. <https://doi.org/10.1007/s11053-021-09945-y>.
34. Ezeamaka C. Assessment of the Causes of Borehole Failure in Chikun Local Government Area of Kaduna State, Nigeria. *Int J Water Res Environ Eng.* 2019;1:1.
35. M. Mohammed, N. P. Szabó and P. Szűcs, "Prediction of the Protective Capacity of The Nubian Aquifer in Bahri City, Sudan, Using Electrical Resistivity Method," *Geosciences and Engineering*, Vol. 11, No. 1, <https://doi.org/10.33030/geosciences.2023.01.xxx>, 2023.
36. H. A. Ibrahim, M. A. Abd-Elmegeed and A. e. a. Ghanem, "Assessment of groundwater development potential in Upper Cretaceous aquifer in Sinai, Egypt," *Arab J Geosci* 14, 2058. <https://doi.org/10.1007/s12517-021-08409-0>, 2021.
37. Dielman SA. Hydraulic Conductivity/Transmissibility. *Ground Water Hydrol.* 2005. <https://doi.org/10.1002/047147844X.gw481>.
38. Nowinski JD, Cardenas MB, Lightbody AF. Evolution of hydraulic conductivity in the floodplain of a meandering river due to hyporheic transport of fine materials. *Geophys Res Lett.* 2011. <https://doi.org/10.1029/2010GL045819>.
39. Iserhien-Emekeme ER, Ofomola OM, Ohwohere-Asuma O, Chinyem FL, Anomohanran O. Modelling aquifer parameters using surficial geophysical techniques: a case study of Ovwian Southern Nigeria. *Model Earth Syst Environ.* 2020. <https://doi.org/10.1007/s40808-020-01030-2>.
40. Chiedu S, Chiedu SO, Edet A. An integrated approach for aquifer characterization and evaluation in a complex geologic terrain (Cross River State, Nigeria): a contribution to support sustainable development and management of groundwater. *J Afr Earth Sc.* 2023;201:104894. <https://doi.org/10.1016/j.jafrearsci.2023.104894>.
41. Mohamed A, Alarifi SS, Musaab M. Geophysical monitoring of the groundwater resources in the Southern Arabian Peninsula using satellite gravity data. *Alex Eng J.* 2024;86:311–26. <https://doi.org/10.1016/j.aej.2023.11.060>.
42. Adefila SF. Decline in pressure head of the 'Middle Zone' aquifer of the Chad basin in parts of south-eastern Niger and north-east Nigeria. *J Min Geol.* 1975;12(1 & 2):23.
43. Isaac OO, Jonah CA, Joel AO. Assessment of aquifer characteristics in relation to rural water supply in part of Northern Nigeria. *Researcher.* 2010;2(3):22–7.
44. Oyawoye MO. The Basement Complex of Nigeria, In Dessauvage, TFJ and Whiteman, A. J (Eds) *African Geology*. Ibadan of University Press, Ibadan Nigeria, 1970.
45. Osumeje JO, Eshimiakhe D, Kudanmya EA, Ojo I, Lawal KM. Geophysical Investigation of Part of Ahmadu Bello University Farm, Nigeria. *Afr Sci Rep.* 2023;2:49. <https://doi.org/10.46481/asr.2022.2.1.49>.
46. Telford WM, Geldart LP, Sheriff ER. *Applied Geophysics*, Cambridge University Press, 1990.
47. Singh UK, Das RK, Hodlur GK. Significance of Dar-Zarrouk parameters in the exploration of quality affected coastal aquifer system. *Environ Geol.* 2004;45:696–702. <https://doi.org/10.1007/s00254-003-0925-8>.
48. Austin and Gabriel. Determination of Dar-zarrouk parameters for prediction of Aquifer protective capacity: a case of Agbani Sandstone Aquifer, Enugu State, Southeastern Nigeria. *Int Res J Geol Min.* 2015;5(1):12–9.
49. Okonkwo AC, Ugwu GZ. Determination of Dar-zarrouk parameters for prediction of Aquifer protective capacity: a case of Agbani Sandstone Aquifer, Enugu State, Southeastern Nigeria. *Int Res J Geol Min.* 2015;5(1):12–9.
50. Fatoba JO, Omolayo SD, Adigun EO. Using geoelectric soundings for estimation of hydraulic characteristics of aquifers in the Coastal Area of Lagos, Southwestern Nigeria. *Int Lett Nat Sci.* 2014;11:30–9.
51. Loke MH. *Electrical Imaging Surveys for Environmental and Engineering Studies. A Practical Guide to 2-D and 3-D Surveys*, 61, 2000.
52. Oladapo MI, Akintorinwa OJ. Hydro-geophysical study of Ogbese South western, Nigeria. *Global J Pure Appl Sci.* 2007;13(1):55–61.
53. Chowdhury S, Mazumder M, Al-Attas O, Husain T. Heavy metals in drinking water: occurrences, implications, and future needs in developing countries. *Sci Total Environ.* 2016;569(570):476–88. <https://doi.org/10.1016/j.scitotenv.2016.06.166>.
54. Alao JO, Lawal HA, Nur M. Investigation of groundwater vulnerability to open dumpsites and its potential risk using electrical resistivity and water analysis. *Heliyon.* 2023;8: e13265. <https://doi.org/10.1016/j.heliyon.2023.e13265>.
55. Wang M, Li M, Duan P. Occurrence, Controlling Factors and Health Risks of Cr6+ in Groundwater in the Guanzhong Basin of China. *Expo Health* 14, 239–251. <https://doi.org/10.1007/s12403-021-00410-y>, 2022.
56. Meng Y, Wu J, Li P, Wang Y. Distribution characteristics, source identification and health risk assessment of trace metals in the coastal groundwater of Taizhou City, China. *Environ Res.* 2023;238: 117085. <https://doi.org/10.1016/j.envres.2023.117085>.
57. WHO, "Guidelines for drinking-water quality: fourth edition incorporating the first addendum," World Health Organization (WHO). Geneva: Licence: CC BY-NC-SA 3.0 IGO. <https://apps.who.int/iris/bitstream/handle/10665/254637/9789241549950-eng.pdf?sequence=1>, 2017.
58. Ayejoto DA, Agbasi JC, Egbueri JC, Echefu KI. "Assessment of oral and dermal health risk exposures associated with contaminated water resources: an update in Ojoto area, southeast Nigeria. *Int J Environ Anal Chem.* 2022;1:1–21.