



Georesistivity and physicochemical evaluation of hydrogeologic units in parts of Akwa Ibom State, Nigeria

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Abstract

In hydrogeologic unit, geohydraulic properties are very important parameters in the management and exploitation of groundwater resources. The present study integrated electrical resistivity and physicochemical methods to investigate the subsurface geohydraulic parameters and determine the degree of susceptibility to contamination via aquifer vulnerability index (AVI) and the physicochemical attributes. The subsurface lithological characteristics were characterized employing vertical electrical sounding technique in thirteen (13) locations within the study area to delineate the aquifer units. The results from the estimated parameters revealed the spatial variations of subsurface lithostratigraphy units as displayed in the contour maps. The values of these parameters vary widely across the study area (aquifer resistivity: 65.0 to 1867.7 Ωm ; hydraulic conductivity: 0.3431–7.8686 m/day; transmissivity: 19.6616–653.8802 m^2/day ; porosity: 20.69–33.60%; hydraulic resistance: 0.23–121.54). The AVI classified the vulnerability into extremely high, high and moderate. The various physicochemical analyses of the water samples obtained from six (6) boreholes gave their concentrations and the results were compared with the World Health Organization (WHO) allowable standard values for drinking water. Na^+ , Ca^+ , SO_4^{2-} , Fe^{2+} , Mn^{2+} , Mg^{2+} and Cl^- respectively have concentrations below the WHO standards. Integration of geoelectric and physicochemical facies showed the goodness of fit and demonstrates the efficacy of integrating the not direct geophysical method with physicochemical method.

Keywords Groundwater · AVI · Hydraulic parameters · Physicochemical · WHO

Introduction

The knowledge subsurface information is vital in groundwater exploration for proper management and protection of groundwater repositories. Groundwater is an essential natural asset that supports domestic, agricultural and industrial activities and its suitability is of great worry for its sustainability and efficient use (George et al., 2015a; Ibuot et al., 2019a; Martínez et al., 2008; Obiora et al., 2015). The availability of this natural resource is affected by its thickness, permeability, porosity, fractures and fissures.

The continuous deterioration of groundwater quality has become a growing concern to communities which may affect health, economic and social development of communities. Several boreholes/wells have been drilled and are under threat as a result of desecrations triggered by percolation of contaminants through the vulnerably porous layers of the earth subsurface (Akpan et al., 2013; George et al., 2014; Thomas et al., 2020). Groundwater quality is affected by pollutants emanating from dumpsites, sewage sites, leakage from surface and underground storage, oil spillage, mining activities, sewage from latrines, underlined petroleum pipes and septic tanks, and infiltrates into the aquifer units through the pores and crevices of rocks or soils after decomposition and become point source of groundwater pollution (Agrawal et al., 2011; Anosike et al., 2019; Aweto & Mamah, 2014; Eugene-Okorie et al., 2020; Ganiyu et al., 2015; Hossain et al., 2014; Umar & Igwe, 2019). It can also be attributed to geochemical reactions that occur in the subsurface geologic materials (George et al., 2014; Rawat et al., 2018). Groundwater

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quality is threatened and degraded by anthropogenic pollutants and are controlled by the geologic environment. The anthropogenic influences on groundwater repositories have become serious issues in many communities in the world (Kumar & Singh, 2018; Shil et al., 2019). Bulk electrical resistivity of soil depend on different factors such as soil type, water content, saturation, and pore fluid property.

The introduction of contaminants into groundwater repositories through rock fractures and pore spaces increases the concentration of organic and inorganic geofluids, thus changing the electrical properties of the subsurface rocks and groundwater. (Al-Tarazi et al., 2008). The geochemical processes, chemical and mineral composition of subsurface rocks and factors related to groundwater flow influence the quality of groundwater (Ibuot et al., 2019b; Inim et al., 2017; Thomas et al., 2020). According to literatures, porosity, permeability, and overburden thickness of geologic formation has great influence on groundwater susceptibility to contamination (Akakuru et al., 2022; Liu et al., 2018; Obiora et al., 2015). Subsurface sediments/rocks control groundwater chemistry since water from their sources flows through these sediments/rocks before their collection and storage in aquifer units (Pazand et al., 2011; Thomas et al., 2020). Many researchers have assessed groundwater quality/status for different purposes using hydrogeochemical data (Akakuru et al., 2022; Barzegar et al., 2017; Moussa et al., 2020; Papazotos et al., 2019), which results reveal the level of concentration of different ions.

The use of electrical resistivity technique can give information about the various geohydraulic parameters distributed across the subsurface, and provides a cost-effective and dependable means to identify the subsurface characteristics through the measurement of apparent resistivity (Aweto & Mamah, 2014; George et al., 2018; Ibuot et al., 2019a, 2017a; Olafisoye et al., 2013). The resistivity method could also be integrated with physicochemical method in studying groundwater quality (Akpan et al., 2013; Ehirim et al., 2010; Ibuot et al., 2017a; Lopes et al., 2012; Olofsson et al., 2006; Ugwu & Nwosu, 2009). The application of geoelectric and hydrogeological properties are effective and complementary characteristics which help in appraising groundwater repositories and the status of groundwater quality (George et al., 2014; Yahaya et al., 2021).

This study integrates both electrical resistivity and physicochemical methods in assessing the groundwater repositories to determine the nature of the aquifers, their distribution, and characteristics as it influences aquifer productivity and groundwater movement. Also, the study will ascertain the level of groundwater contamination in the study area. These will help in proper management and exploration strategies within the study area and areas having comparable geologic characteristics.

Materials and methods

Location, geology and hydrogeology of the study area

The study area falls between latitudes 5.07° N–5.28° N and longitudes 7.64° E–7.75° E (Fig. 1) and covers part of Ikot Ekpene Local Government Area of Akwa Ibom state. The study area is highly drained by the inland coastal water and is situated within the equatorial rain forest belt. The study area is of semi-temperate climate characterized by tropical climate having a mean annual temperature from 20.0 to 30.6 °C, while the maximum and minimum daily temperature ranges between 28 and 30 °C during March and 23 °C and 24 °C during July and August (Evans et al., 2010; George et al., 2010; Ibuot et al., 2013). The wet season is warm, oppressive, and overcast and the dry season is hot, muggy, and mostly cloudy. The study area consists of Coastal Plain sands weathered into lateritic layers located within the Benin Formation of the Niger Delta Basin where most of the aquifer units are found. The lithology shows mature, coarse and moderately sorted sandstone. The Miocene Akata Formation, Miocene-Pliocene Agbada Formation, and the Oligocene Benin Formation are geological Formations that characterized the study area from base to the top respectively. The major hydrogeologic units in the area is found in the middle and the upper sand units of the Benin Formation (Akpan et al., 2013; Edet & Worden, 2009).

Vertical electrical sounding

Vertical electrical sounding (VES) utilizing Schlumberger electrode configuration was used for this study involving thirteen vertical electrical soundings with ABEM SAS 4000 Terrameter to measure the resistive property of the subsurface in the course of current injection into the ground. The VES was completed with half current electrode spacing $\left(\frac{AB}{2}\right)$ ranging from 1.0 to 500 m and half potential electrode spacing $\left(\frac{MN}{2}\right)$ ranging from 0.25 to 20 m. The apparent resistivity for the Schlumberger electrode array used was estimated using:

$$\rho_a = K \cdot R_a \quad (1)$$

where K is the geometric factor which depends on the electrode configuration used, the geometric factor is given by:

$$K = \pi \cdot \left[\frac{\left(\frac{AB}{2}\right)^2 - \left(\frac{MN}{2}\right)^2}{MN} \right] \quad (2)$$

R_a is the apparent resistance that is measured.

Reading of R_a for each electrode combination was made and the calculated apparent resistivity was inputted into

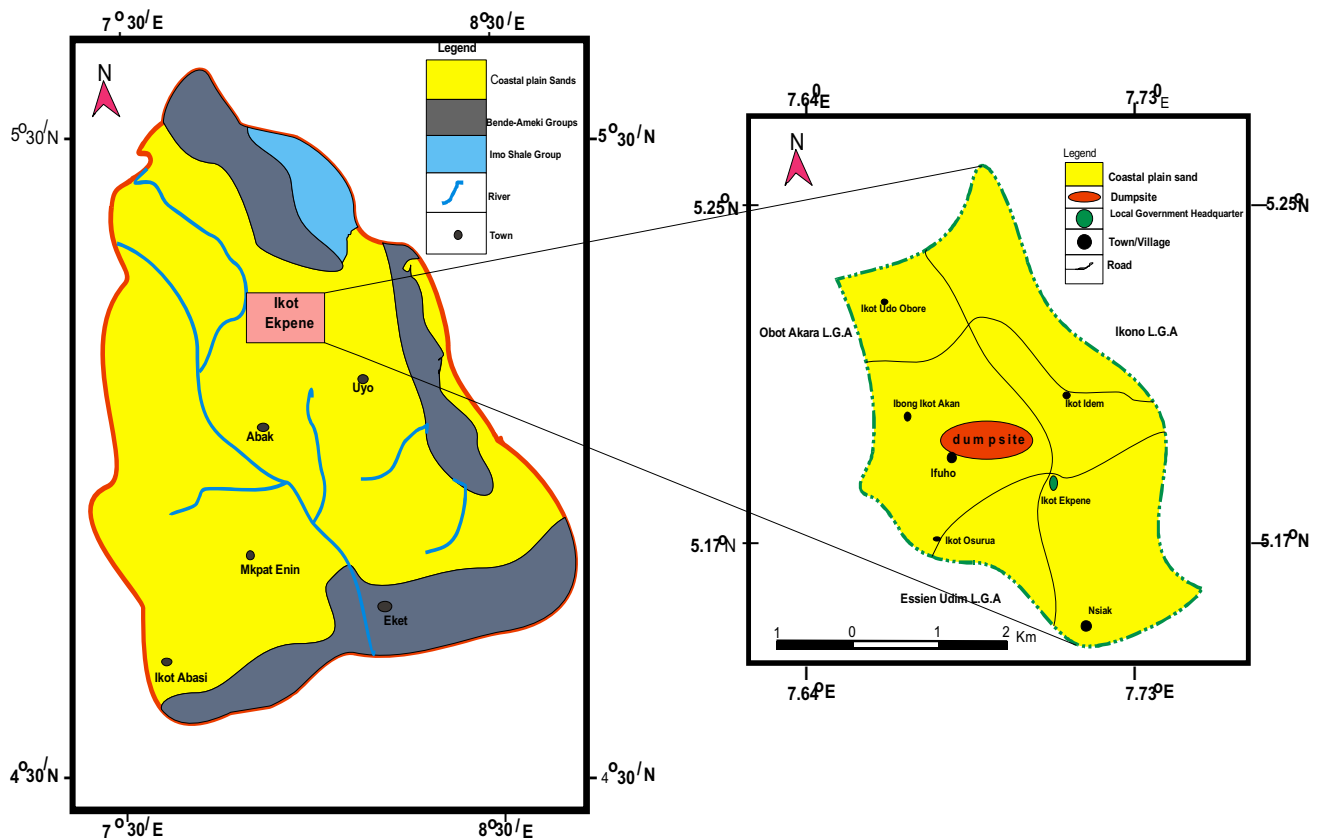


Fig. 1 Geologic map showing the location of the study area in Akwa Ibom state

the WINRESIST software for computer modeling. The values of resistivity, depth and thickness of each geoelectric layers were determined from the curves generated (Fig. 2). Using a bilogarithmic graph sheets, graphs of apparent resistivity (ρ_a) against current electrodes separation ($\frac{AB}{2}$) was first plotted and smoothed for curve matching by means of master curves charts. This aid the removal of the effect of lateral inhomogeneities and other noisy signatures such as outliers at crossover points that did not match with the dominant curve trend and were deleted. A number of the deleted data may have been the electrical signatures of the thin clay materials that may have suffered suppression from the overlying and underlying thick sandy aquifers.

The percolation of contaminants into the hydrogeologic units is affected by the hydrogeologic unit properties and the knowledge of water-transmitting properties (hydraulic conductivity, transmissivity, porosity, formation factor and tortuosity) which are important in this study. The sub-surface is characterized by pores and its connectivity, the knowledge of the pore properties give information about the movement of fluid in the subsurface (George et al., 2015a, b; Ibuot et al., 2019a).

The amount of pore spaces in a formation is porosity which is given by the relation;

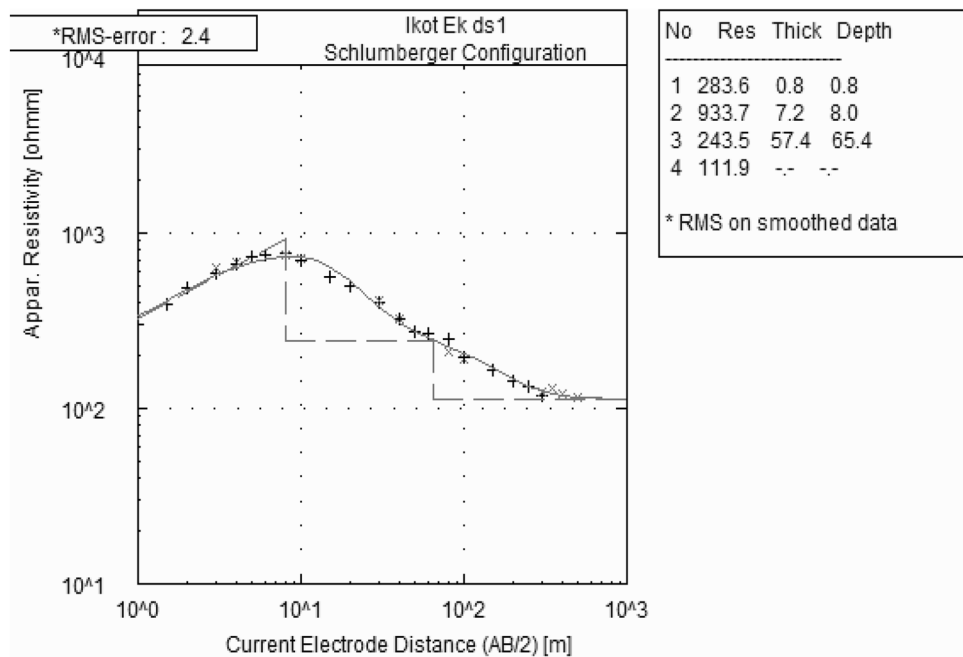
$$\text{Porosity } (\phi) = \frac{\text{Volume of pores}}{\text{Total rock volume}} \tag{3}$$

Factors as density, clay contents, tortuosity, hydraulic conductivity affects spatial variability of formation porosity (George et al., 2015a, 2015b). The relationship between porosity, bulk resistivity and water resistivity is given in Eq. (4);

$$\rho = a\rho_w\phi^{-m} \tag{4}$$

where ρ and ρ_w are the bulk resistivity and water resistivity respectively, while a and m represent the pore geometric factor and cementation factor respectively (Keller & Frishknecht, 2012). The variation of cementation factor is affected by the formation lithostratigraphy, permeability dependent factors and geologic age of geomaterials (Ekanem, 2020; Obianwu et al., 2011). The effective porosity (ϕ) was estimated using Eq. (5), According to Aleke et al., (2018), porosity is also dependent on the mode of formation of rocks and pressures to which rocks are exposed. Increase in porosity leads to decrease in electrical resistivity of a formation, and will

Fig. 2 Geoelectric curve at VES I and its parameter



also influence the values of the cementation factor of the propagating medium.

$$\phi = 25.5 + 4.5 \ln K \tag{5}$$

where K is hydraulic conductivity and ϕ is the porosity.

The ease with which pore fluids passes through a permeable medium is the hydraulic conductivity. The hydraulic conductivity (K) was estimated using Eq. (6), this parameter (K) measures the resistance to movement of water flowing through a porous medium and is a function of the liquid as well as the medium (Omeje et al., 2021).

$$K = 386.40 \rho^{-0.93283} \tag{6}$$

where ρ is the layer resistivity.

Transmissivity of the hydrogeologic unit was estimated using Eq. (7). This property connects the bulk of areal flow through a porous medium and it is controlled primarily by the nature of geological formations (George et al., 2018).

$$T_r = Kh \tag{7}$$

where h is the aquifer thickness.

A pore geometry factor of 0.62 and cementation factor of 2.15 from their experiment on compacted sandstones as express in the Humble equation (Eq. 8);

$$F = \frac{0.62}{\phi^{2.15}} \tag{8}$$

where F is the formation factor. The geometric patterns of grains and the resulting porosity affect the cementation factor of the propagating media considerably (George et al.,

2018). The presence of dead-end pores or impermeable geologic materials of cementation or induration in formations can obstruct effective pore fluid transmission within and across the aquifer units. The flow of fluid in the subsurface may be control by these parameters which are dependent on the pore geometry, nature of grain size, non-uniformity of pore grain orientations and type of pore grains and channels and hydraulic pressure.

The fundamental parameters (layer resistivity and thickness) that characterized the subsurface geologic helped in deriving the aquifer vulnerability index (AVI) using Eq. (9), this will help in quantifying the vulnerability of the hydrogeologic units by hydraulic resistance to vertical flow of water through the covering layers.

$$C = \sum_{i=1}^n \frac{h_i}{\kappa_i} \tag{9}$$

where C is the hydraulic resistance, κ_i is the hydraulic conductivity while h_i is the thickness of the protective layers. The relationship between hydraulic resistance (C), log C and AVI is shown in Table 1.

Physicochemical methods

A total of six water samples (BH A, BH B, BH C, BH C, BH D, BH E and control BH) were collected from six different boreholes sited within the study area and analyzed for physical and chemical parameters and results given in Table 3. The bottles containing the water samples were covered tightly and during the analysis, the refrigerated water

Table 1 Hydraulic resistance/aquifer vulnerability index rating (Thomas & Yusrizal, 2018)

Hydraulic resistance (C)	Log C	Vulnerability (AVI)
0–10	< 1	Very high
10–100	1–2	High
100–1000	2–3	Moderate
1000–10,000	3–4	Low
> 10,000	> 4	Extremely low

samples were allowed to attain room/ambient temperature. The water conductivity and pH were measured using water conductivity and 09 Kion pH meters. The cations (K^+ , Na^{2+} , Ca^{2+} , Mg^{2+} , Cu^{2+} , Mn^{2+} and Fe^{2+}) were determined using an atomic absorption spectrophotometer (Unicam 969 AAS) at 455 nm. To determine the anions, the water samples were acidified with nitric acid (HNO_3) to prevent the metallic ions from adhering to the walls of the container. The anions (SO_4^{2-} , Cl^- and F^-) were determined using a DR 2000 spectrophotometer at 450 nm. The results obtained were compared with the World Health Organization (WHO) standard (WHO, 2017), to assess the contamination status of the groundwater in the area.

Results and discussion

VES

The VES results give information about the subsurface hydrolitho-facies (Table 2) with the respectively values of resistivity, depth and thickness of each layer and define the lithology of the study area with a stratigraphic succession. The values in Table 2 were obtained from the modeled VES curves, 3–5 geoelectric layers were obtained across the study area. VES 4 has resistivity values for 5 layers with corresponding values of thickness and depth while the fifth layer which is defined only by resistivity is undefined within the maximum current electrode separation. VES 1, 2, 3, 5, 6, 9 and 12 have 4 geoelectric layers each, while VES 7, 8, 10, 11 and 13 has 3 geoelectric layers each with the last layers undefined. The variation in resistivity at depths may be attributed to geology, topography, lithology, water quality and degree of saturation. In layer 1, the resistivity values ranged from 58.2 Ωm at VES 12 to 1405.2 Ωm at VES 9, while both the thickness and depth ranged from 0.8 to 3.3 m. The second layer has resistivity values ranging from 178.7 Ωm at VES 5 to 1867.7 Ωm at VES 10, it thicknesses and depths ranged from 7.2 to 94.5 m and from 8.0 to 95.6 m respectively. The third layer which harbors most of the aquifer has resistivity values ranging from 42.3 Ωm at VES 5 to 2099.9 Ωm at VES 8, while the thickness and depth ranged from 38.7 m

Table 2 Summary of results from geoelectric survey

VES stations	Longitude (°E)	Latitude (°N)	Resistivity (Ωm)					Thickness (m)				Depth (m)					
			P1	P2	P3	P4	P5	h1	h2	h3	h4	d1	d2	d3	d4		
VES 1	7.6824	5.1942	283.6	933.7	243.5	111.9	-	0.8	7.2	57.4	-	0.8	8.0	65.4	-	-	-
VES 2	7.6881	5.1776	732.4	1375.8	272.1	133.9	-	1.4	6.8	43.3	-	1.4	8.2	51.5	-	-	-
VES 3	7.7058	5.1795	324.1	950.3	267.0	135.8	-	0.8	7.3	54.7	-	0.8	8.1	62.8	-	-	-
VES 4	7.6940	5.1860	368.1	995.5	298.4	183.3	151.4	1.0	6.8	38.7	76.8	1.0	7.8	46.4	123.2	-	-
VES 5	7.7092	5.1807	619.2	178.7	356.0	264.3	-	3.3	34.9	80.0	-	3.3	38.2	118.2	-	-	-
VES 6	7.6868	5.1968	363.9	969.2	293.2	177.3	-	0.8	8.3	87.3	-	0.8	9.1	96.5	-	-	-
VES 7	7.6953	5.1824	187.9	193.9	42.3	-	-	1.8	54.8	-	-	1.8	56.6	-	-	-	-
VES 8	7.6801	5.1895	904.7	400.4	2099.9	-	-	2.2	28.1	-	-	2.2	30.4	-	-	-	-
VES 9	7.6916	5.1746	1405.2	352.5	86.2	1825.0	-	2.0	7.3	77.1	-	2.0	9.2	86.3	-	-	-
VES 10	7.6955	5.1819	214.7	1867.7	649.7	-	-	2.1	57.3	-	-	2.1	59.4	-	-	-	-
VES 11	7.6846	5.1753	245.2	1463.4	348.6	-	-	1.1	94.5	-	-	1.1	95.6	-	-	-	-
VES 12	7.7006	5.1874	58.2	577.0	65.0	21.5	-	2.8	8.6	83.1	-	2.8	11.4	94.4	-	-	-
VES 13	7.6972	5.1856	75.2	430.0	50.8	-	-	1.5	47.4	-	-	1.5	58.9	-	-	-	-

Table 3 Calculated aquifer geohydraulic parameters from resistivity and thickness of aquifer layer

VES Stations	Longitude (°E)	Latitude (°N)	Aquifer resistivity ρ_a (Ωm)	Aquifer thickness h_a (m)	K (m/day)	T_r (m^2/day)	Porosity ϕ (%)	Formation factor F	Hydraulic resistance (C)	Log. C	AVI
VES 1	7.6824	5.1942	243.5	57.4	2.2953	131.7502	29.24	0.00044	15.64	1.1942	High
VES 2	7.6881	5.1776	272.1	43.3	2.0694	89.6060	28.77	0.00045	26.76	1.4274	High
VES 3	7.7058	5.1795	267.0	54.7	2.1063	115.2131	28.85	0.00045	16.53	1.2182	High
VES 4	7.6940	5.1860	183.3	76.8	2.9915	229.7484	30.43	0.00040	121.54	2.0847	Moderate
VES 5	7.7092	5.1807	356.0	80.0	1.6105	128.8422	27.65	0.00049	50.36	1.7021	High
VES 6	7.6868	5.1968	293.2	87.3	1.9302	168.5027	28.46	0.00046	19.36	1.2870	High
VES 7	7.6953	5.1824	193.9	54.8	2.8387	155.5595	30.20	0.00041	0.62	- 0.2106	Extremely high
VES 8	7.6801	5.1895	400.4	28.1	1.4433	40.5564	27.15	0.00051	3.26	0.5133	Extremely high
VES 9	7.6916	5.1746	86.2	77.1	6.0470	466.2215	33.60	0.00032	25.61	1.4084	High
VES10	7.6955	5.1819	1867.7	57.3	0.3431	19.6616	20.69	0.00092	0.81	- 0.0896	Extremely high
VES 11	7.6846	5.1753	1463.4	94.5	0.4308	40.7121	21.71	0.00083	0.48	- 0.3166	Extremely high
VES 12	7.7006	5.1874	65.0	83.1	7.8686	653.8802	34.79	0.00030	12.15	1.0845	High
VES 13	7.6972	5.1856	430.0	47.4	1.3504	23.4968	26.85	0.00053	0.23	- 0.6608	Extremely high
Mean			470.9	62.45	2.5635	174.1346	28.34	0.00050	22.56	1.3534	

to 87.3 m and from 46.4 m to 1182.2 m, respectively, but undefined in VES 7, 8, 10, 11 and 13. The geohydraulic parameters were estimated from the values of the resistivity and thickness using Eqs. (4) to (9) (Table 3). The parameters (hydraulic conductivity K , transmissivity T_r , porosity ϕ , formation factor F and hydraulic resistance C), the AVI was determined in terms of Log C to determine the vulnerability status of the area. The aquifer resistivity and thickness ranged from 65.0 to 1867.7 Ωm and from 17.4 to 94.5 m respectively, this low resistivity suggests the presence of sand intercalated with clay. The spatial distribution (Fig. 3) showed that greater part of the study area has low resistivity suggesting the presence of fractured zones and conductive geologic materials which may be attributed to permeation and accumulation of leachate ensuing from dumpsite situated close to some VES points. This suggests that infiltrated contaminants are concentrated more in the deeper layers.

The hydraulic conductivity affects the dynamic behavior of fluids flow in aquifer layers, the estimated values vary from 0.3431 to 7.8686 m/day with an average value of 2.5635 m/day. The distribution of hydraulic conductivity (Fig. 4) shows that the northeastern part has highest values of this parameter. It indicates the effect of resistivity on hydraulic conductivity, as increase in resistivity lowers hydraulic conductivity. This distribution of hydraulic conductivity may affect the productivity of wells and the speed of pollutant spread.

In Fig. 5 shows the variation of aquifer transmissivity and the region with high transmissivity corresponds to the area with high hydraulic conductivity which shows that both parameters are directly proportional to each other. The values of transmissivity estimated from K and h range from 19.6616 to 653.8802 m^2/day , which indicates a moderate to high aquifer potential. The high aquifer potential may be due to the porous nature of the hydrologic unit and the interconnectivity of the pore spaces (Ekanem et al., 2019; George et al., 2018). The values of effective porosity ranges from 20.69 to 33.60%, based on these values it could be inferred that the aquifer layers are more of unconsolidated sediments such as coarse sand intercalated with clay (George et al., 2015a, b; Ibuot et al., 2019a, b).

In Fig. 6 shows high porosity in the northeastern part of the study area which reflects the same trend as transmissivity and hydraulic conductivity. Areas in the southwest and southeast have low porosity indicating the presence of poorly sorted materials compare to the northeast with high porosity, and areas with high porosities are associated with low resistivity areas. The variations in porosity values may be due to the presence of clay and shaly materials within the aquifer units (George et al., 2017).

Formation factor is lowest in the northeast and corresponds to regions having lowest aquifer resistivity (Fig. 7). The low values of formation factor indicate that the aquifer

Fig. 3 Distribution of aquifer resistivity

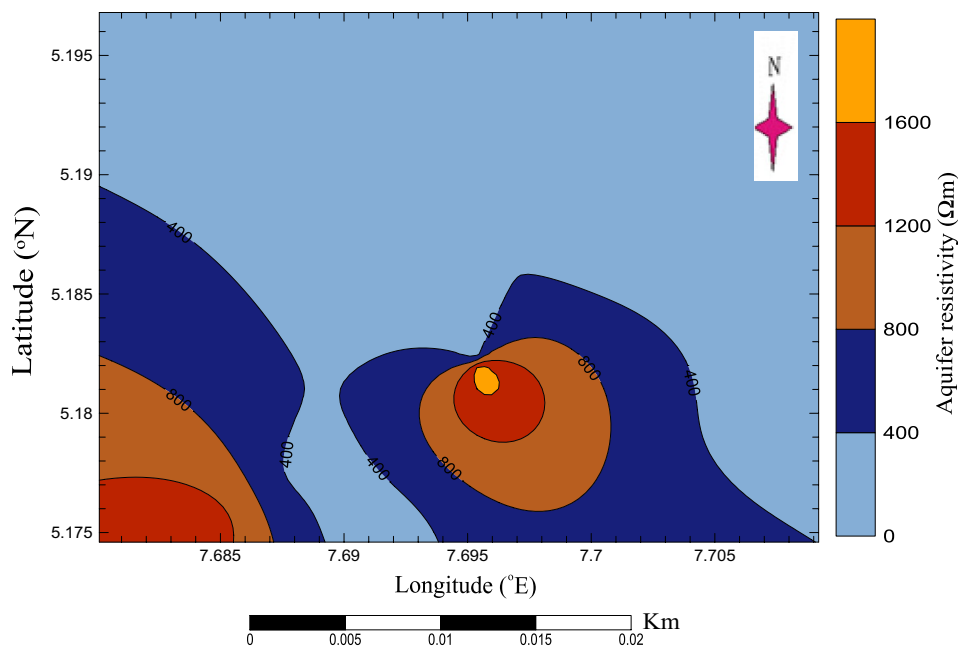
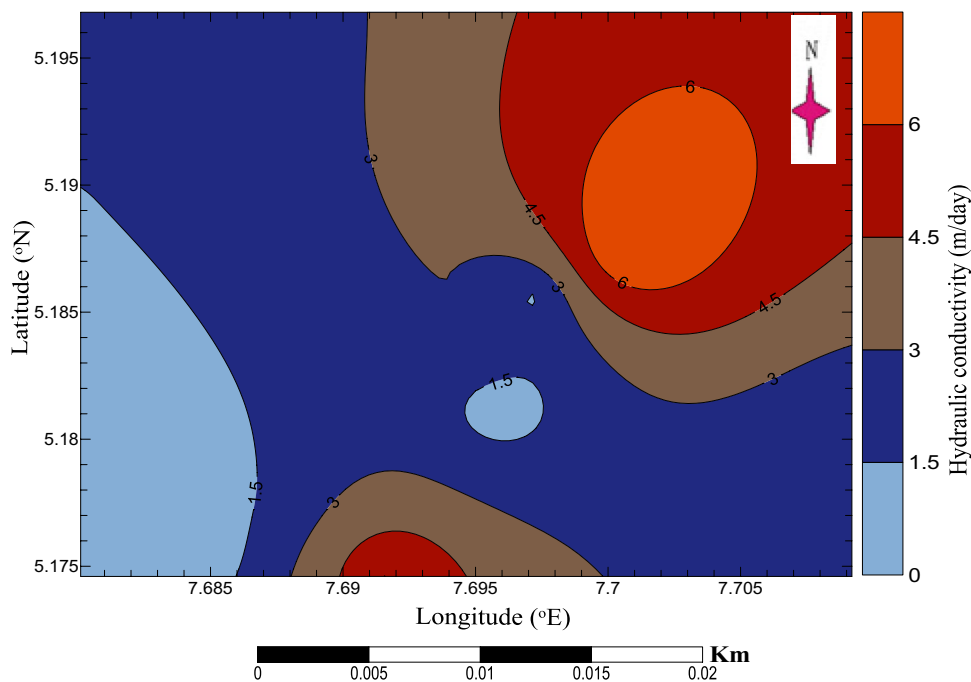


Fig. 4 Distribution of hydraulic conductivity



repositories have high conductivity hence are not affected by higher concentration of contaminants. The closed range observe in these parameters suggest a fairly homogeneous to moderately anisotropic medium which can aid the transport of particles in aquifer layers.

The hydraulic resistance (C) ranged from 0.23 to 121.54 with an average value of 22.56, the AVI was determined from the log of C . The contour map (Fig. 8) shows the variation of C with lowest values of C in the western

and southern parts of the study area. The ability of earth medium to impede fluid flow determines of its protective capacity since the earth medium act as a natural filter to the infiltrating fluids (Mogaji et al., 2007; Obiora et al., 2015). AVI was rated and classified into extremely high, high and moderate, the highly vulnerable zone reveals the ease of percolation of contaminants through the protective layers. These zones depict high permeability and low clay content and thus vulnerable to contamination.

Fig. 5 Distribution of aquifer transmissivity

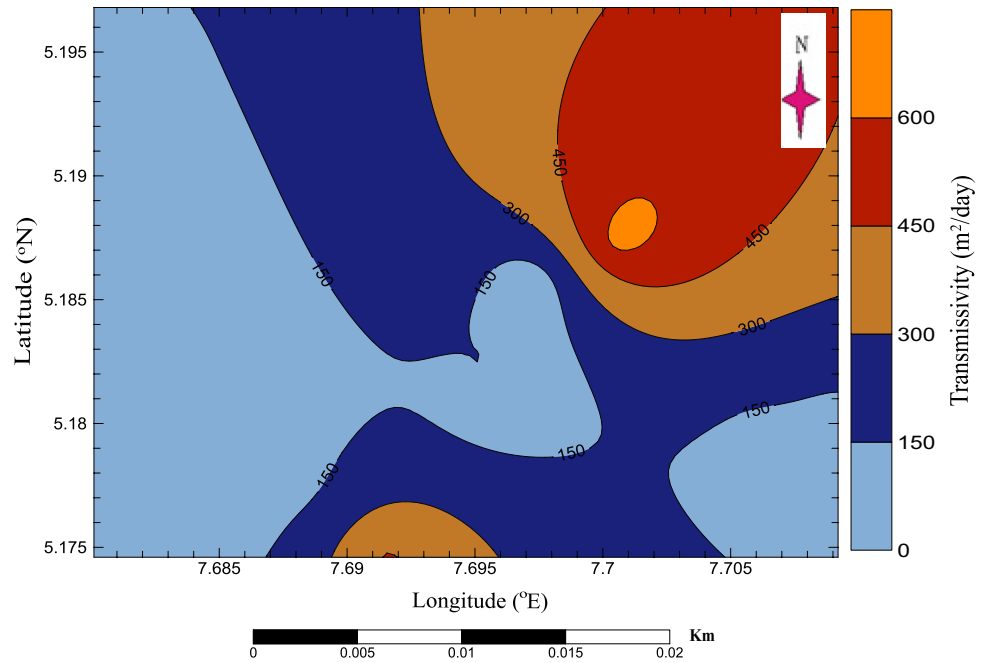
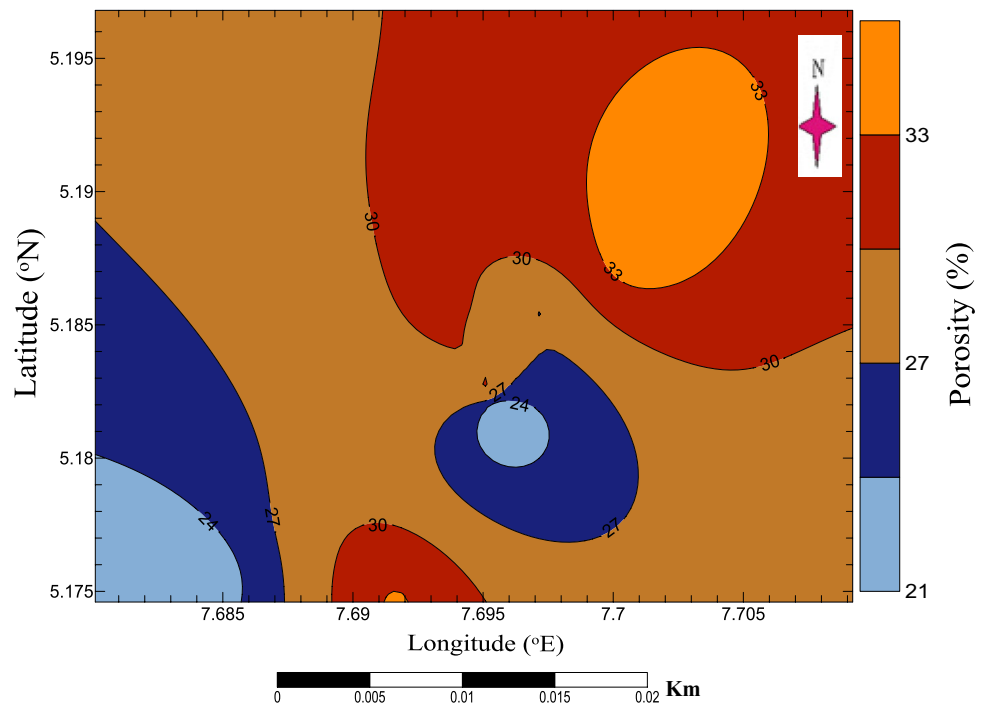


Fig. 6 Distribution of aquifer effective porosity



Physicochemical

The analysis of the water samples gives the results for physical and chemical parameters (Table 4). The pH values which ranged from 6.7 to 8.5 fell within the range of WHO standard from 6.5 to 8.5 for drinking water. Boreholes with pH values lower than 7 indicates that

water in those boreholes are slightly acidic, while above 7 are slightly basic, these may be due to the dissolution, draining, decomposition of vegetative materials and also dissolution of minerals by the atmospheric carbon dioxide (CO₂) from the industries situated within the study area (George et al., 2014; Ibut, et al., 2017b, 2019b). The electrical conductivity with range of 28.3–1183 μS/cm is below the WHO standard suggesting less amount

Fig. 7 Distribution of formation factor

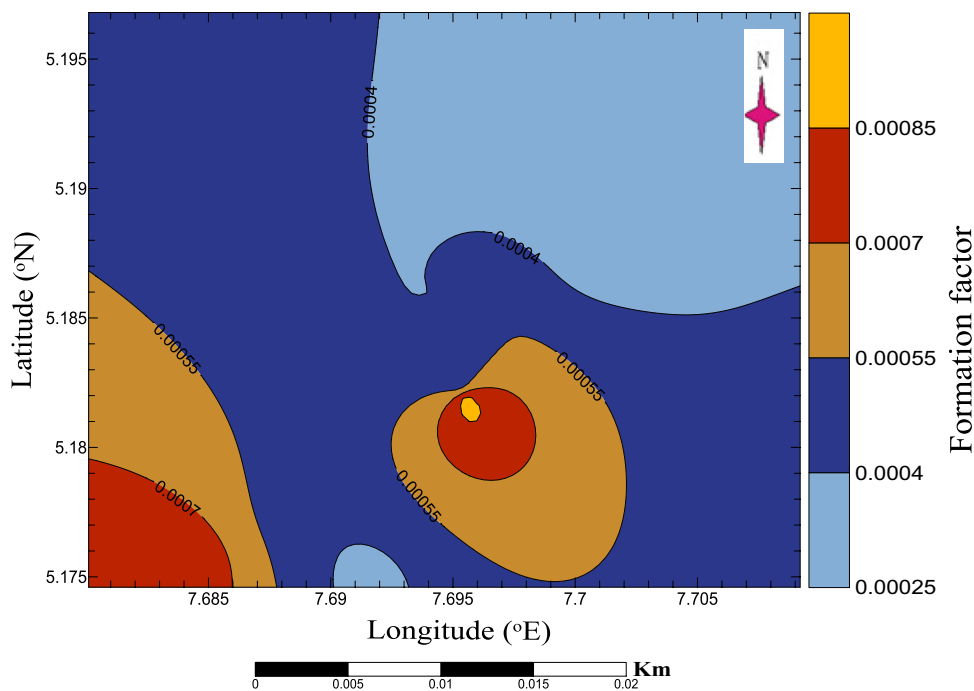
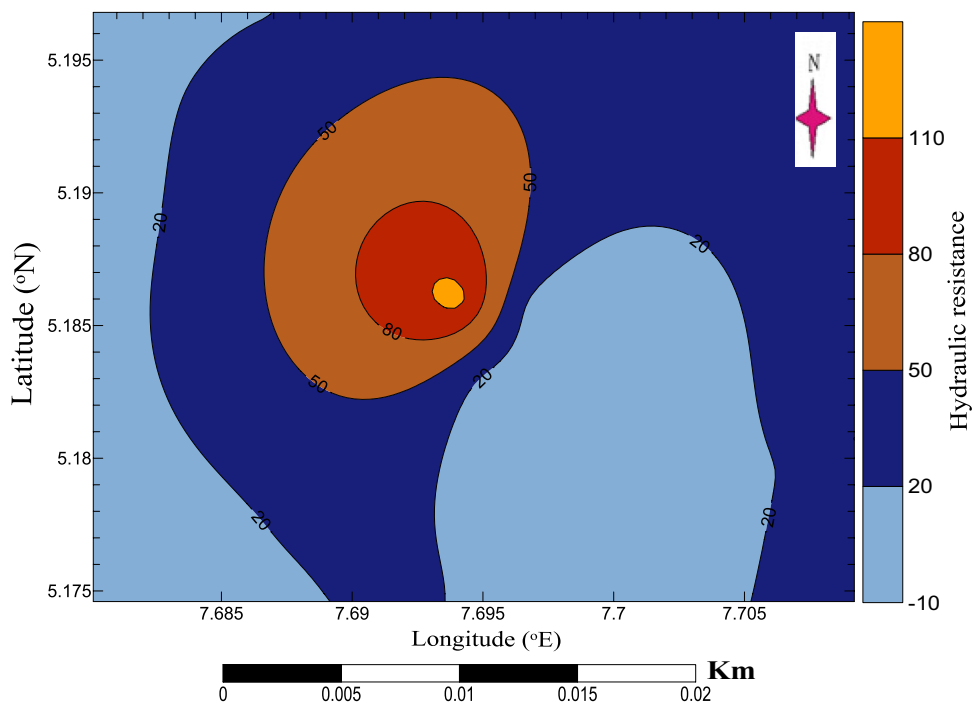


Fig. 8 Distribution of hydraulic resistance



of dissolved ions/solid in the water samples (George et al., 2014) The concentrations of Na^+ (2.9–11.9 mg/L), Ca^{2+} (0.9–15.9 mg/L), SO_4^{2-} (0.6–7.0 mg/L), Fe^{2+} (0.004–0.11 mg/L) and Cl^- (5.8–76.9 mg/L) are below the WHO standard, also K^+ (0.6–18.5 mg/L), F^- (0.003–1.9 mg/L) and Cu^{2+} (0.004–0.11) have high concentrations in some boreholes that exceed the WHO standard. The high concentration of K^+ in may be due

to the consequence of fertilizer and industrial activities. The variations in the physicochemical parameters across the study area may be a function of the geologic layer in which groundwater is stored. The presence of these ions in groundwater repositories affects the bulk electrical properties through the vadose zones to the aquifer units (Akpan et al., 2013; Thomas et al., 2020). The low concentration of Na^+ may be due to the low rate of

Table 4 Result of physicochemical analysis

	Parameters	Bh A (mg/L)	Bh B (mg/L)	Bh C (mg/L)	Bh D (mg/L)	Bh E (mg/L)	Control Bh (mg/L)	WHO
1	pH	6.9	6.7	7.8	8.2	8.5	7.1	6.5–8.5
2	Electrical conductivity (μ S/cm)	1183	129	34	509	65	28.3	1400
3	SO ₄ ²⁻	1.0	6.0	3.2	7.0	3.6	0.6	400
4	Cl ⁻	17.9	76.9	43.8	55.6	17.9	5.8	600
5	F ⁻	0.6	0.3	0.7	0.4	1.9	0.003	0.01
6	K ⁺	18.5	2.1	0.6	1.7	3.6	0.7	2.0
7	Na ²⁺	8.9	11.9	4.3	4.9	7.8	2.9	200
8	Ca ²⁺	5.4	7.3	0.9	15.9	11.6	1.4	250
9	Mg ²⁺	2.3	0.4	5.1	5.9	1.8	0.35	150
10	Cu ²⁺	2.01	2.08	1.20	0.06	0.12	0.41	1.5
11	Fe ²⁺	0.07	0.11	0.05	0.03	0.01	0.004	1.0
12	Mn ²⁺	0.007	1.002	0.008	0.001	0.004	0.002	1.05

soil reaction, ion exchange, oxidation and or reduction (George, Ibanga, et al., 2015). The control borehole which is located far from the dumpsite shows values less than the investigated boreholes, this indicates that away from the pollutants source the more suitable the groundwater for human consumption.

VES and physicochemical

The results of the surface resistivity (VES) technique have reveal the lithological variation of the subsurface layers. The technique allows the extrapolation of geoelectric and geohydraulic parameters estimated from already established equations. It can be inferred from this study that the lithologic characters such as grain size distribution, permeability, porosity and the geometry of the pore space affects the aquifer units. The contour maps are relevant in showing how these parameters are distributed in the subsurface. Some ions were below the WHO standards, while some were above the acceptable standard. These variations may be due to the unequal draining of the subsurface by contaminant-loaded plume (Anosike et al., 2019). The relatively high concentrations of K⁺, F⁻ and Cu²⁺ in the groundwater samples may be attributed to tectonically induced secondary structures like, divides, fault lineaments, and folds of the sedimentary facies and thus leads to leaching, precipitation, and dissolution in the groundwater repositories (George et al., 2014; Thomas et al., 2020). The rate of infiltration of contaminants into the aquifer units is influence by the high permeability of the top geologic layers and communicating pore channels linking the pore-aquifer geologic formation (Ibuot & Obiora, 2021).

Conclusion

The surface resistivity and physicochemical methods were successfully employed to assess the hydrogeologic units of the study area. This study delineated three to five geoelectric layers with values of their resistivity, depth and thickness. The geohydraulic parameters estimated from the electrical parameters show wide variations of the parameters, which indicate the variations in grain sizes and the pore geometry. The hydraulic resistance was used to predict the AVI, where the study area was classified into extremely high, high and moderate vulnerability zones. It could be inferred from this study that the aquifer protective layers are highly permeable thus easy percolation of contaminant fluids into the aquifer units. The contaminants that percolate into the subsurface on reaching the aquifer layer affect the groundwater chemistry by either increasing or decreasing the concentrations of ions. The physicochemical method was performed for cations (K⁺, Na²⁺, Ca²⁺, Mg²⁺ Cu²⁺, Mn²⁺ and Fe²⁺), anions (SO₄²⁻, Cl⁻ and F⁻), pH and electrical conductivity. The water samples analyzed revealed low concentrations of Na⁺, Ca⁺, Mg²⁺, SO₄²⁻, Fe²⁺, Mn²⁺ and Cl⁻ which are below the WHO standard while the concentrations of K⁺, F⁻ and Cu²⁺ were high and above the WHO standard in some boreholes. The results could help in assessing the groundwater quality of the area, improve the groundwater management plan of the area and demonstrate the economic feasibility of the integrated methods.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

References

- Agrawal, A., Pandey, R., & Agrawal, M. L. (2011). Impact of solid waste leachate on groundwater sources—a case study. *International Journal of Chemical and Environmental Engineering*, 2(2), 113–118.
- Akakuru, O. C., Eze, C. U., Okeke, O. C., Opara, A. I., Usman, A. U., Iheme, O., Ibeneme, S. I., & Iwuoha, P. O. (2022). Hydro-geochemical evolution, water quality indices, irrigation suitability and pollution index of groundwater (PIG) around eastern Niger Delta, Nigeria. *International Journal of Energy and Water Resources*, 1, 1. <https://doi.org/10.1007/s42108-021-00162-0>
- Akpan, A. E., Ugbaja, A. N., & George, N. J. (2013). Integrated Geophysical, Geochemical, and Hydrogeological investigation of shallow Groundwater resources in parts of the Ikom-mamfe Embayment and the adjoining areas in Cross River State, Nigeria. *Environmental Earth Sciences*, 70(3), 1435–1456.
- Aleke, C. G., Ibuot, J. C., & Obiora, D. N. (2018). Application of electrical resistivity method in Estimating geohydraulic properties of a sandy hydrolithofacies: a case study of Ajali Sandstone in Ninth Mile, Enugu State, Nigeria. *Arabian Journal of Geosciences*, 11, 322. <https://doi.org/10.1007/s12517-018-3638-8>
- Al-Tarazi, E., Abu Rajab, J., Al-Naqa, A., & El-Waheidi, M. (2008). Detecting leachate plume and Groundwater pollution at Ruseifa Municipal landfill Utilizing VLF-EM method. *Journal of Applied Geophysics*, 65, 121–131.
- Anosike, S., Ibuot, J. C., Obiora, D. N., & Ugbor, D. O. (2019). Geophysical and physicochemical investigation of groundwater repositories in Njaba LGA of Imo State, eastern Nigeria. *International Journal of Environmental Science and Technology*, 16(12), 8129–8146.
- Aweto, K. E., & Mamah, L. I. (2014). Application of resistivity methods to groundwater protection studies in Niger Delta. *International Journal of Environmental Protection*, 4(3), 27–35.
- Barzegar, R., Asghari Moghaddam, A., & Tziritis, E. (2017). Hydro-geochemical features of groundwater resources in Tabriz plain, northwest of Iran. *Applied Water Science*, 7, 3997–4011.
- Edet, A., & Worden, R. H. (2009). Monitoring of the physical parameters and evaluation of the chemical composition of river and Groundwater in Calabar (Southeastern Nigeria). *Environmental Monitoring and Assessment*, 213(1–3), 209–217.
- Ehirim, C. N., Ebeniro, J. O., & Ogwu, D. A. (2010). A geophysical and hydrogeophysical study of the contaminant impact of solid waste landfill (SWL) in Port Harcourt Municipality, Nigeria. *The Pacific Journal of Science and Technology*, 10(2), 269–285.
- Ekanem, A. M. (2020). Georesistivity modeling and appraisal of soil water retention capacity in Akwa Ibom State University main campus and its environs, Southern Nigeria. *Modeling Earth Systems and Environment*, 1, 1. <https://doi.org/10.1007/s40808-020-00850-6>
- Ekanem, A. M., George, N. J., Thomas, J. E., & Nathaniel, E. U. (2019). Empirical relations between aquifer geohydraulic-geoelectric properties derived from surficial resistivity measurements in parts of Akwa Ibom State, Southern Nigeria. *Natural Resources Research*, 1, 1. <https://doi.org/10.1007/s11053-019-09606-1>
- Eugene-Okorie, J. O., Obiora, D. N., Ibuot, J. C., & Ugbor, D. O. (2020). Geoelectrical investigation of groundwater potential and vulnerability of Oraifite, Anambra State, Nigeria. *Applied Water Science*, 10(10), 1–14.
- Evans, U. F., George, N. J., Akpan, A. E., Obot, I. B., & Ikot, A. N. (2010). A study of superficial sediments and aquifers in parts of Uyo Local Government Area, Akwa Ibom State, Southern Nigeria, using electrical sounding method. *E-Journal of Chemistry*, 7(3), 1018–1022.
- Ganiyu, S. A., Badmus, B. S., Oladunjoye, M. A., Aizebeokhai, A. P., & Olurin, O. T. (2015). Delineation of leachate plume migration using electrical resistivity imaging on Lapite dumpsite in Ibadan, Southwestern Nigeria. *Geosciences*, 5(2), 70–80.
- George, N. J., Akpan, A. E., & Obot, I. B. (2010). Resistivity study of shallow aquifers in the parts of southern Ukanafun Local Government Area, Akwa Ibom State, Nigeria. *E-Journal of Chemistry*, 7, 693–700.
- George, N. J., Ekong, U. N., & Etuk, S. E. (2014). Assessment of economically accessible groundwater reserve and its protective capacity in eastern Obolo local government area of Akwa Ibom state, Nigeria, using electrical resistivity method. *Geophysical Journal International*, 2014, 1–10.
- George, N. J., Ibanga, J. I., & Ubom, A. I. (2015a). Geoelectrohydrogeological indices of evidence of ingress of saline water into freshwater in parts of coastal aquifers of Ikot Abasi, southern Nigeria. *Journal of African Earth Sciences*, 109, 37–46.
- George, N. J., Ibuot, J. C., & Obiora, D. N. (2015b). Geoelectrohydraulic of shallow sandy in Itu, Akwa Ibom State (Nigeria) using geoelectric and hydrogeological measurements. *Journal of African Earth Science*, 110, 52–63.
- George, N. J., Akpan, A. E., & Akpan, F. S. (2017). Assessment of spatial distribution of porosity and aquifer geohydraulic parameters in parts of the Tertiary-Quaternary hydrogeoresource of South-eastern Nigeria. *NRIAG Journal of Astronomy and Geophysics*, 6(2017), 422–433.
- George, N. J., Ibuot, J. C., Ekanem, A. M., & George, A. M. (2018). Estimating the indices of inter-transmissibility magnitude of active surficial hydrogeologic units in Itu, Akwa Ibom State, Southern Nigeria. *Arabian Journal of Geosciences*, 11(6), 1–16.
- Hossain, M. L., Das, S. R., & Hossain, M. K. (2014). Impact of landfill leachate on surface and groundwater quality. *Journal of Environmental Science and Technology*, 7, 337–346.
- Ibuot, J. C., & Obiora, D. N. (2021). Estimating geohydrodynamic parameters and their implications on aquifer repositories: A case study of University of Nigeria, Nsukka, Enugu State. *Water Practice and Technology*, 16(1), 162–181.
- Ibuot, J. C., Akpabio, G. T., & George, N. J. (2013). A survey of the repositories of groundwater potential and distribution using geoelectrical resistivity method in Itu Local Government Area (LGA), Akwa-Ibom State, Southern Nigeria. *Central European Journal of Geosciences*, 5(4), 538–547.
- Ibuot, J. C., Obiora, D. N., Ekpa, M. M., & Okoroh, D. O. (2017a). Geoelectrohydraulic investigation of the surficial aquifer units and corrosivity in parts of Uyo L. G. A., Akwa Ibom, Southern Nigeria. *Applied Water Science*, 7, 4705–4713.
- Ibuot, J. C., Okeke, F. N., George, N. J., & Obiora, D. N. (2017b). Geophysical and physicochemical characterization of organic waste contamination of hydrolithofacies in the coastal dumpsite of Akwa Ibom State, Southern Nigeria. *Water Science and Technology: Water Supply*, 17(6), 1626–1637.
- Ibuot, J. C., George, N. J., Okwesili, A. N., & Obiora, D. N. (2019a). Investigation of litho-textural characteristics of aquifer in Nkanu West Local Government Area of Enugu state, southeastern Nigeria. *Journal of African Earth Sciences*, 157, 197–2017.
- Ibuot, J. C., Okeke, F. N., Obiora, D. N., & George, N. J. (2019b). Assessment of impact leachate on hydrogeological repositories in Uyo, Southern Nigeria. *Journal of Environmental Engineering and Science*, 14(2), 97–107.

- Inim, I. J., Affiah, U. E., Asuaiko, E. R., Abia, U. B., & Tom, A. A. (2017). Hydrogeochemical evaluation of groundwater in coastal alluvial aquifer of Akwa Ibom, southeastern Nigeria. *Journal of Coastal Sciences*, 4(2), 1–8.
- Kumar, B., & Singh, U. K. (2018). Source apportionment of heavy metals and their ecological risk in a tropical river basin system. *Environmental Science and Pollution Research*. <https://doi.org/10.1007/s11356-018-2480-6>
- Liu, J. T., Gao, Z. J., Wang, M., Li, Y., Ma, Y., Shi, M., & Zhang, H. (2018). Study on the dynamic characteristics of groundwater in the valley plain of Lhasa City. *Environment and Earth Science*, 77(18), 646.
- Lopes, D. D., Silva, S. M. C. P., Fernandes, F., Teixeira, R. S., Celligoi, A., & Dall'Antonia, L. H. (2012). Geophysical technique and groundwater monitoring to detect leachate contamination in the surrounding area of landfill–Londrina (PR-Brazil). *Journal of Environmental Management*, 113, 481–487.
- Martínez, A. G., Takahashi, K., Núñez, E., Silva, Y., Trasmonte, G., Mosquera, K., & Lagos, P. (2008). A multi-institutional and interdisciplinary approach to the assessment of vulnerability and adaptation to climate change in the Peruvian Central Andes: Problems and prospects. *Advances in Geosciences Journal*, 14, 257–260.
- Mogaji, K. A., Adiat, K. A. N., & Oladapo, M. I. (2007). Geoelectric investigation of the DapePhase III housing Estate, F.C.T Abuja, North central Nigeria. *Journal of Earth Science*, 1(2), 76–84.
- Moussa, B. A., Chandoul, S., Mzali, H., Salem, S. B. H., Elmejri, H., Zouari, K., Hafane, A., & Mrabet, H. (2020). Hydrogeochemistry and evaluation of groundwater suitability for irrigation purpose in the Mornag region, northeastern Tunisia. *Environment, Development and Sustainability*, 2020, 1–21.
- Obianwu, V. I., George, N. J., & Udofia, K. M. (2011). Estimation of aquifer hydraulic conductivity and effective porosity distributions using laboratory measurements on core sample in the Niger Delta, southern Nigeria. *International Review Physics Praise Worthy Prize, Italy*, 5(1), 19–24.
- Obiora, D. N., Ajala, A. E., & Ibuot, J. C. (2015). Evaluation of aquifer protective capacity of overburden unit and soil corrosivity in Makurdi, Benue State, Nigeria, using electrical resistivity method. *Journal of Earth System Science*, 124(1), 125–135.
- Olafisoye, E. R., Sunmonu, L. A., Adagunodo, T. A., & Oladejo, O. P. (2013). Groundwater contaminants investigation at aarada waste disposal site using geophysical and hydro-physicochemical approach. *Journal of Environmental Science Toxicology and Food Technology*, 2(4), 1–10.
- Olofsson, B., Jernberg, H., & Rosengvist, A. (2006). Tracing leachates at waste sites using geophysical and geochemical modelling. *Environmental Geology*, 49, 720–732.
- Omeje, E. T., Ugbor, D. O., Ibuot, J. C., & Obiora, D. N. (2021). Assessment groundwater repositories in Edem, Southern Nigeria, using vertical electrical sounding. *Arabian Journal of Geosciences*, 14, 42.
- Papazotos, P., Koumantakis, I., & Vasileiou, E. (2019). Hydrogeochemical assessment and suitability of groundwater in a typical Mediterranean coastal area: A case study of the Marathon basin NE Attica, Greece. *Hydro Research*, 2, 49–59.
- Pazand, K., Gbanbari, Y., Hezarkhani, A., & Aghavali, N. (2011). Groundwater geochemistry in the middle Meshkinshahr basin of Ardabil province in Iran. *Environment and Earth Science*, 65, 871–879.
- Rawat, K. S., Singh, S. K., & Gautamo, S. K. (2018). Assessment of groundwater quality for irrigation use: A peninsular case study. *Applied Water Science*, 2018, 8. <https://doi.org/10.1007/s13201-018-0866-8>
- Shil, S., Singh, U. K., & Mehta, P. (2019). Water quality assessment of a tropical river using water quality index (WQI), multivariate statistical techniques and GIS. *Applied Water Science*, 2019, 9. <https://doi.org/10.1007/s13201-019-1045-2>
- Thomas, P. T., & Yusrizal, M. B. S. (2018). Determining the groundwater vulnerability using the aquifer vulnerability index (AVI) in the salatiga groundwater Basin in Indonesia. *AIP Conference Proceedings*, 2021(1), 030016. <https://doi.org/10.1063/1.5062740>
- Thomas, J. E., George, N. J., Ekanem, A. M., & Nsikak, E. E. (2020). Electrostratigraphy and hydrogeochemistry of hyporheic zone and water-bearing caches in the littoral shorefront of Akwa Ibom State University. *Southern Nigeria. Environmental Monitoring and Assessment*, 192, 505. <https://doi.org/10.1007/s10661-020-08436-6>
- Ugwu, S. A., & Nwosu, J. I. (2009). Effect of waste dumps on groundwater using geophysical method. *Journal of Applied Science and Management*, 13(1), 85–89.
- Umar, N. D., & Igwe, O. (2019). Geo-electric method applied to groundwater protection of a granular sandstone aquifer. *Applied Water Science*, 2019, 9. <https://doi.org/10.1007/s13201-019-0980-2>
- WHO (2017) Drinking water standards, monitoring and reporting, vol. 1 of recommendations, WHO, Geneva, Switzerland, 2nd edition.
- Yahaya, S. M., Abubakar, F., & Abdu, N. (2021). Ecological risk assessment of heavy metal-contaminated soils of selected villages in Zamfara State, Nigeria. *SN Applied Sciences*, 3, 168. <https://doi.org/10.1007/s42452-021-04175-6>