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Nuclear geophysical assessment of aquifer groundwater quality in Okerenkoko community, Niger Delta: Implications for human health risk

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ABSTRACT

The evaluation of aquifer groundwater quality in Okerenkoko, an oil-producing community in southern Niger Delta, Nigeria was conveyed by exploiting the vertical electrical soundings (VES) method with the support (aid) of Terrameter (1000) The Assays, Borehole Electro-Magnetics (ABEM) signal (recording) averaging system, groundwater collection and samples analysis with the assistance of sodium iodide [Na(Tl)] detector. ABEM device is an easy-to-use, quick survey tool that can provide accurate resistivity models in the sounding field for environmental research, groundwater exploration, mapping, and tracking, as well as subsurface formations and mineral deposits studies. It takes only a few minutes to study depths of hundreds of meters, and the ABEM can complete the task. The geotechnical resistivity method of eight (8) VES units exposed the studied layers of the locations with poor/pathetic (<0.1 mho), weak/deficient (0.1–0.19 mho), and moderate/fair (0.2–0.69 mho) conductance identified by the longitudinal conductance map. It also revealed the depth of aquifer groundwater reservoirs to be 60–80 meters as shown from infinite vertical thickness via resistivity measurement of 562.0 to 7794.6 Ωm, in the fifth layer of the sand cluster. Therefore, thirty groundwater samples were collated and analyzed to establish the level and extent (amount) of hydrocarbon contamination, and pollution radiology of the aquifer groundwater quality within the reservoir depth. The mean results of radionuclide activity concentrations of aquifer groundwater are 264.85 ± 19.27Bql−1, 16.22 ± 4.18Bql−1, and 4.22 ± 1.11 Bql−1 for 40K, 238U, and 232Th respectively. The mean results exceeded world limits of 10 Bql−1 1.0 Bql−1 and 0.1 Bql−1 respectively. This may be attributed to petroleum hydrocarbon contamination waste released, oil spillage, the geological configuration of the area, and other anthropologic activities in the area. Nevertheless, the calculated radiological index health implications of aquifer groundwater mean results slightly exceeded world permissible limits. Therefore, there should be proper treatment of the aquifer groundwater before usage for domestic, agricultural, and industrial (purposes) works.

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Okerenkoko; groundwater pollution; geotechnical resistivity; health risk assessment; pollution radiology

Introduction

The Niger Delta metropolitan area is sufficient in gas and oil resources, which form the foundation of the Nigerian economy and account for 25% of GDP and 90% of the country's foreign exchange profits. The main environmental risk brought on by petroleum exploration in the blessed Niger Delta is oil spills, which are a huge societal issue in Nigeria, particularly in the oil-producing areas. According to Atakpo and Ayolabi (2009), there are many different reasons why oil spills happen, such as overpressure blowouts, equipment malfunctions, operator mistakes, corrosion, sabotage (pipeline vandalism), pigging functioning, flow-lines substitution, flow-stations improvement, tank reclamation, and natural events like lightning, flooding, heavy rain, and tree falling. Over 6,000 liquid runouts (spills) had been formally reported in Nigeria's 40-year oil development, with a mean of 150 each year, as stated by the Directorate of Petroleum Resources (DPR, 1997). 2/369,407.04 barrels (casks) of crude oil were wastefully spilled during 647 events from 1976 to 1996. 1,820,410.50 barrels were lost to the environment, with just 549,060.38 barrels recovered. A comparable study conducted by Petroleum Company (SPDC, 2004) found that the business had 457 oil mishaps between 2003 and 2004, resulting in the phenomenon of spillage of 18,219 barrels of oil. Meyer et al. (2015) investigated the primary organic pollutants in soil, such as methyl tert-butyl ether, benzene, total petroleum, and polycyclic aromatic hydrocarbons as well as their migration into the environment. Adeniji et al. (2017) reported the types and composition of oil pollutants. Borgman et al. (2019) noted that oil is a non-aqueous liquid that can contaminate nearby lands and groundwater when there is an oil spill. Groundwater

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contamination, soil erosion, and subsurface leaks can result from pipeline corrosion, oil well blowouts, and vandalism. These emissions can have a negative influence on the ecosystem. If the subterranean pollution seeps into the aquifer, a significant supply of drinkable water, without being observed on the surface, it might have a more immediate effect on humans. Because it can take decades or years for tainted water to be removed from a sourcing aquifer and replaced (exchanged) with clean water, soil pollution presents significant challenges (Nte et al., 2013; Pipkin, 1994). Oil-producing towns will uninterruptedly experience the negative environmental burdens and effects of extraction, production, and transportation, such as subsurface aquifer pollution. Over the years, scientists have researched on the radiological impact of petroleum hydrocarbon waste released into the environment and the human health implications (Agbalagba et al., 2019; Avwiri et al., 2011; Esi & Akpoyibo, 2024; Esi et al., 2023; Omeje et al., 2019). For this reason, it is necessary to assess the subsurface protective capacity using geophysical methods. Investigating the protective capability can be done with the help of geophysics, an efficient noninvasive technique. In aquifer safeguarding (control) studies and the assessment of aquifer physicochemical qualities, Henriet (1976) showed that the combination (integration) of stratum resistivity and thickness (depth) in the Dar Zarrouk variables; S (longitudinal conductance) and T (transverse resistance) could be directly useful. Additionally, a clayey aquifer overburden's ability to protect itself is correlated with its longitudinal unit (section) conductance S, which adds a temporal component to the aquifer (watershed) protection (e.g. infiltration time). According to this theory, the protective (preventive) capacity is proportionate to the longitudinal unit (division) conductance in mho (Oladapo et al., 2004); Atakpo and Ayolabi (2009). Numerous oil wells, flow stations, and pipelines with abundant petroleum hydrocarbon deposits can be found in the Okerenkoko study region, which is rich in gas and crude oil resources. Oilfield operations is a common trend in the Niger Delta, and the discharge or spilling of petroleum products can lead to environmental contamination. The hydrocarbon contaminants in the soil may eventually leak and flow downward into an aquifer (Hornero et al., 2016). The area (Niger Delta) has periodically experienced significant (substantial oil spills that have devastated aquatic (fish) organisms and vegetation (greenery), impacting the ecology and maybe the groundwater (Amaize, 2006; Vwavware et al., 2024). The release of petroleum hydrocarbon deposits may have polluted the aquifer groundwater of the studied area due to the migration of the contaminants from the surface through the soil profile to the aquifer groundwater. The residents of the area depend mostly on groundwater as their major source of drinking water, hence if polluted will negatively on them and the environment. Therefore, this research aims to determine the geoelectric parameters (soil-depth) index properties (resistivity, ρi, and thickness, hi), aquifer's depth and lateral extent, aquifer's protective capacity and the radionuclide concentration of groundwater and the radiological health risk indices. This research will serve as baseline data for the studied area.

Geomorphology and geology of the investigated area

The research domain, the Okerenkoko community is situated in Delta State's Warri South West local government area. Its average elevation measures roughly 7 m above sea level, and it stands between longitude 5.325° and 5.521° East and also latitude 5.562° and 5.722° North (Figure 1) of the equator. The research area is part of the blessed Niger Delta, which is distinguished by almost flat topography that slopes very little seaward and is covered with the Sombrero plain's quaternary sands (Anomohanran et al., 2023). It is situated inside the confirmed coastal creeks that connect both Warri and Escravos between the two Benin and Escravos rivers (Figure 1). Rainforests and mangrove forests define the vegetation. Mangrove swamps are typically located at low elevations, fewer than 5 m above the level of the ocean. The largest confirmed oil and gas reservations (reserves) in Delta State are claimed by this local government. Nigeria Maritime University has permanent campuses in Gbaramatu Kingdom and Okerenkoko. The community has at times witnessed major oil spills brought on by pipeline damage and other incidents that devastated aquatic life and vegetation, harming the ecology and maybe the groundwater (Okiotor et al., 2022). This region is surrounded by creeks, wetlands, and sedimentary basins. The region floods during the reoccurring rainy season and is comparatively dry during the changing dry season. The Atlantic and Pacific Oceans round the region. Except for the drainage stream, the vegetation in these places is typical of the rainforest belt in the Niger Delta domain. Three primary basic underlying lithostratigraphic units make up the Niger Delta's geologic pattern, and these units are covered in a variety of quaternary deposits (Akpoyibo & Vwavware, 2024; Akpoyibo et al., 2022; Atakpo & Ayolabi, 2009; Esi et al., 2023; Ofomola et al., 2017). The Akata formation, which forms the foundation of the unit, consists largely of marine shales with little amount of sand beds. The thickness (width) of the formation varies from roughly 550 to more than 6,000 m. The formation (unit) has been linked to very little hydrocarbons. The overlaying paralic series, known as the Agbada formation, which constitute of interbedded sands and also shale,

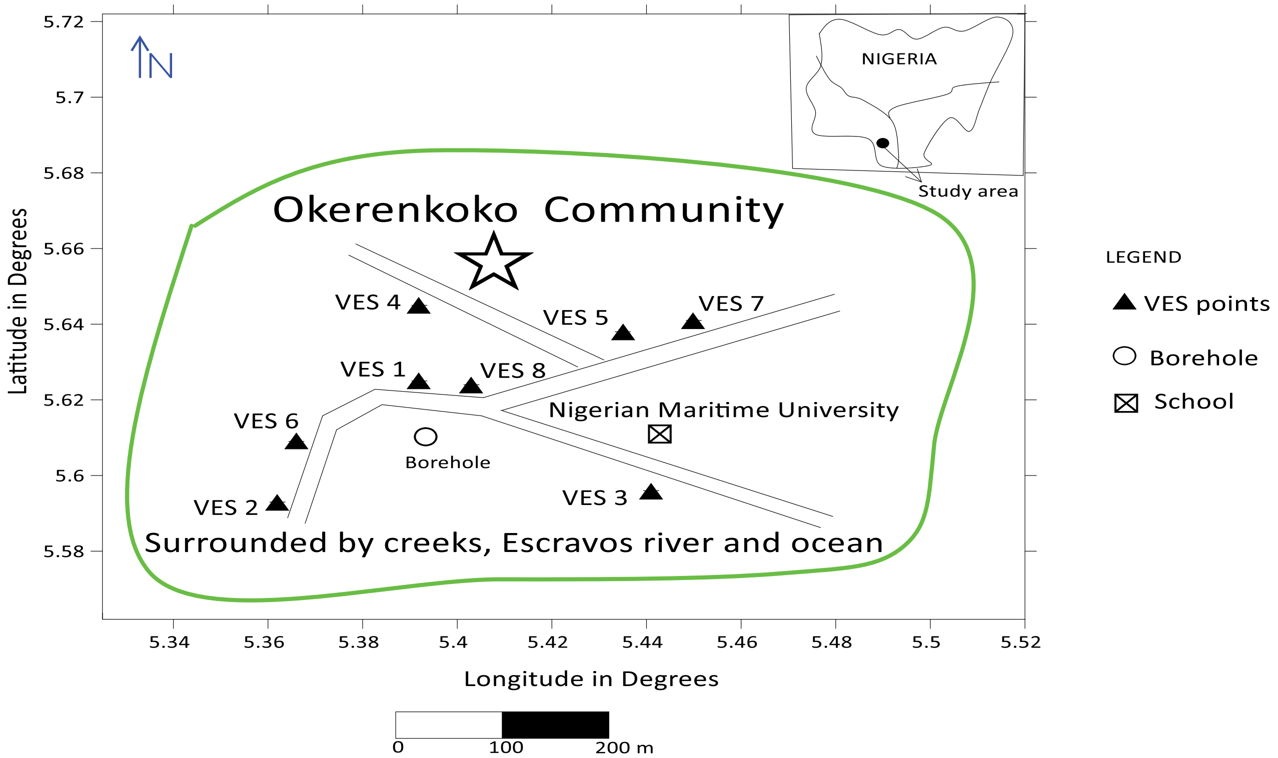

Figure 1. Okerenkoko base map displaying VES points.

that vary in thickness (height) from 300 to 4,500 m, thinning both toward the sea and the Delta margins. The thickest part of the unit is in the center of the Delta; the base of the sandstones explains the contact and linking with the beneath Agbada formation, which is clearly outlined by the base of the fresh water-bearing strata. The Benin unit is the highest strata; it has a composition of over ninety percent sandstone with shale intercalations, coarse-grained, gravely, sometimes fine-grained, poorly sorted, subangular to well rounded, and contains wood pieces and also lignite streaks (Akpoyibo et al., 2023; Anomohanran, 2014; Asseez, 1989; Esi & Akpoyibo, 2023).

Material and method

Geophysical material and method

The resistivity data was acquired using the Terrameter (1000) variant of the ABEM signal averaging system. With a good signal (alarm) – to-noise proportion and an integrated booster supporter for deeper penetration, it is incredibly portable. For this purpose of acquiring the data, the Schlumberger depth probing (sounding) method which is highly favored because of its predisposition and sensitivity to outermost surface inhomogeneities was used (Atakpo & Ayolabi, 2009; Esi & Akpoyibo, 2024; Okolie & Akpoyibo, 2012). This approach clearly defines groundwater-contaminated zones, has a sufficient penetration depth, can reveal subsurface structure, and requires minimal labor. The greatest electrode separation used in this study ranged from 500 m to 1,000 m to produce soundings that were shallow, deep, and very deep in Okerenkoko village, applying eight vertical electrical soundings (VES). The resistivity study's VES data is used to construct VES curves (Figures 2–9). Employing the Resist application (software), which was on the operation of Vander Velpen's 1988 work, the first (initial) order geo-electric values (the unit resistivity qi and the unit (layer) thickness hi, Table 1) for the ith layer (i = 1 for the surface stratum) were obtained by quantitatively interpreting the VES curves through computer iteration. These first (1st) order geoelectric characteristics were utilized to produce the longitudinal section conductance (Si), a second-order and rank geoelectric parameter also referred to as the Dar Zarrouk parameter (Atakpo & Ayolabi, 2009; Esi & Akpoyibo, 2023).

The total (sum) longitudinal section (unit) conductance

$$S = \sum_{i=1}^{n} \frac{h_i}{\rho_i} \tag{1}$$

Taking the overall longitudinal section conductance values of Equation 1, the overburden protection performance in the region was assessed (Oladapo et al., 2004). The research area's longitudinal conductance readings are displayed in Table 2.

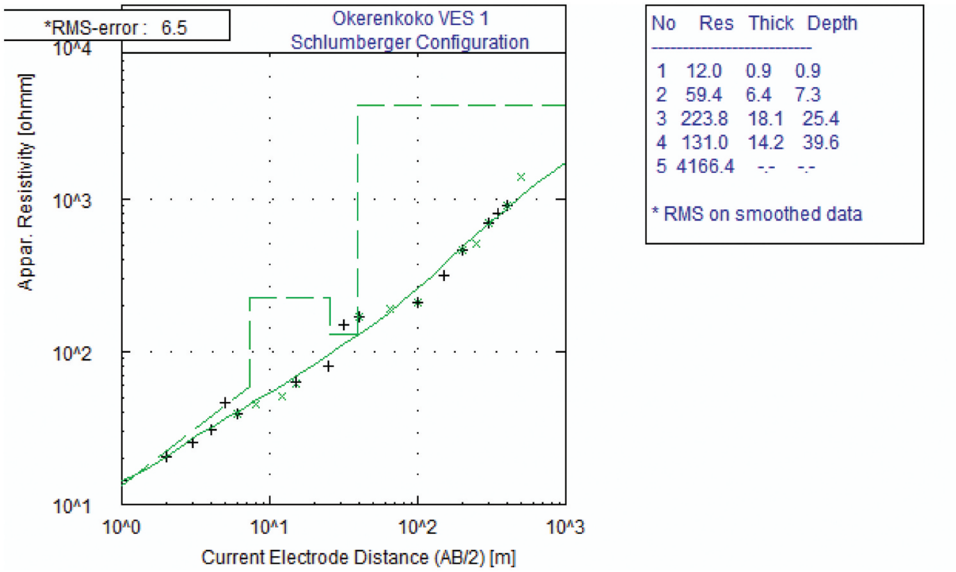

Figure 2. Normal AKH curve type (VES 1).

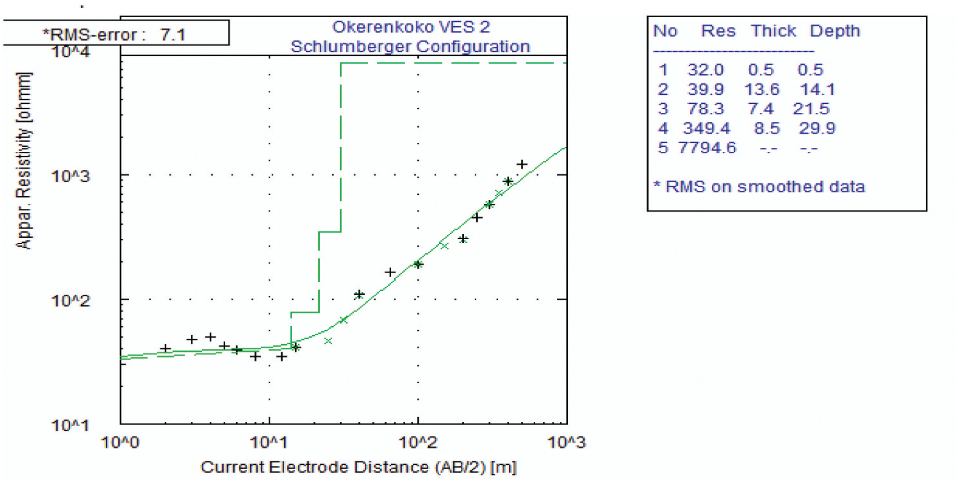

Figure 3. Typical AAA shape type (VES 2).

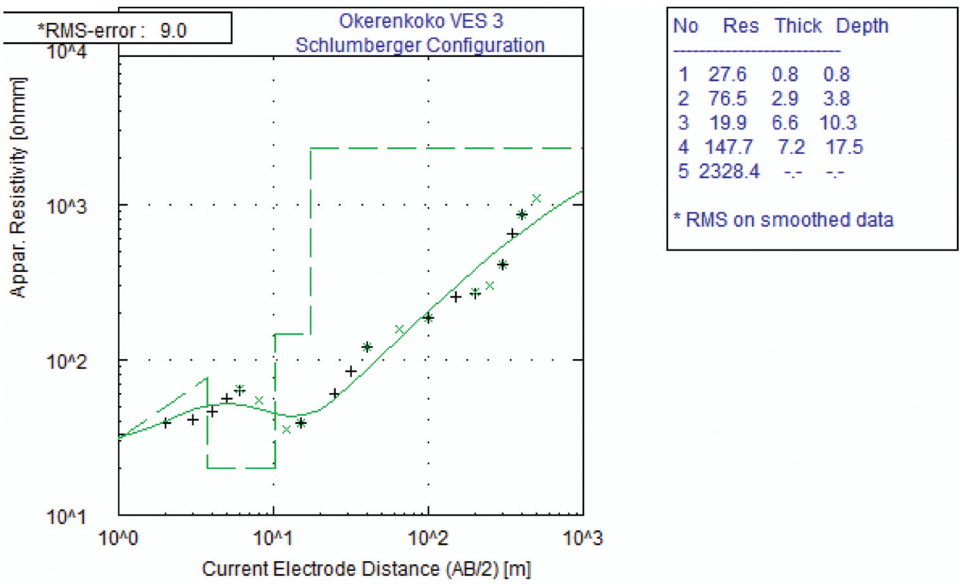

Figure 4. Typical KHA formation type (VES 3).

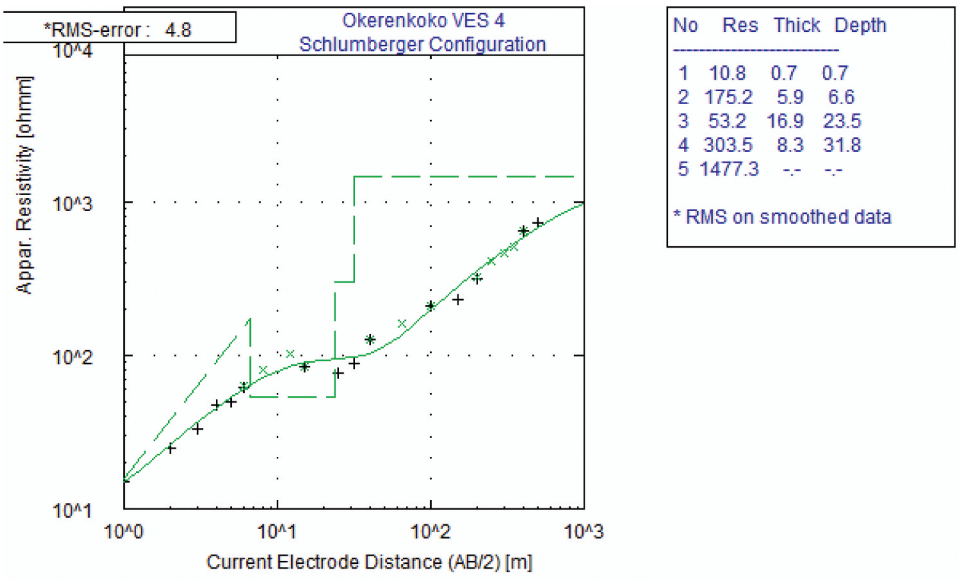

Figure 5. Typical KHA curve type (VES 4).

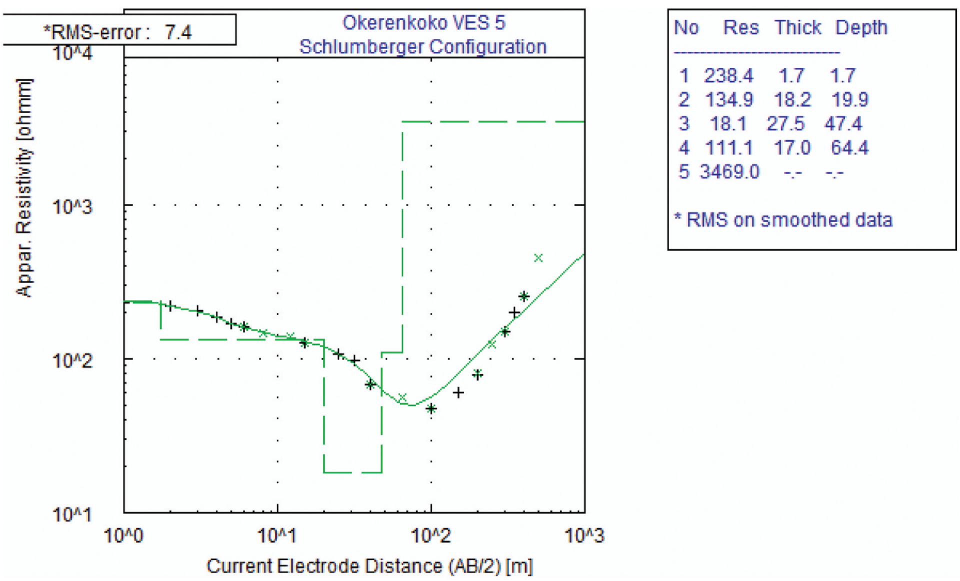

Figure 6. Typical QHA curve type (VES 5).

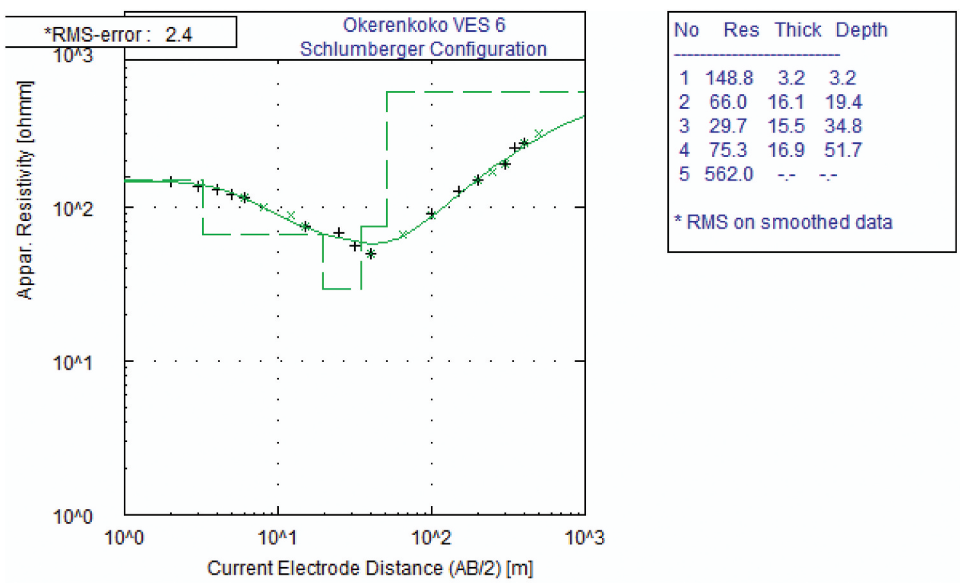

Figure 7. Typical QHA graph type (VES 6).

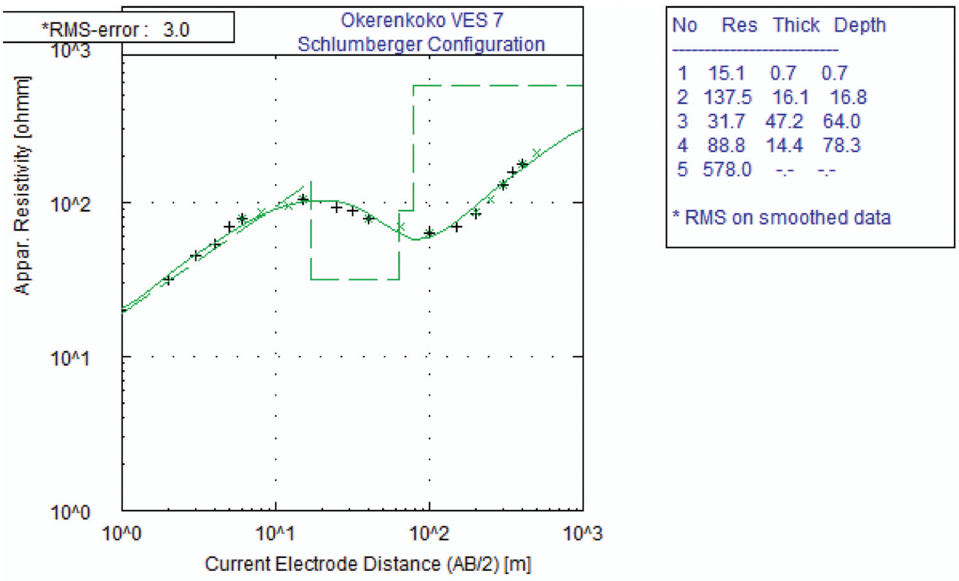

Figure 8. Typical KHA curve type (VES 7).

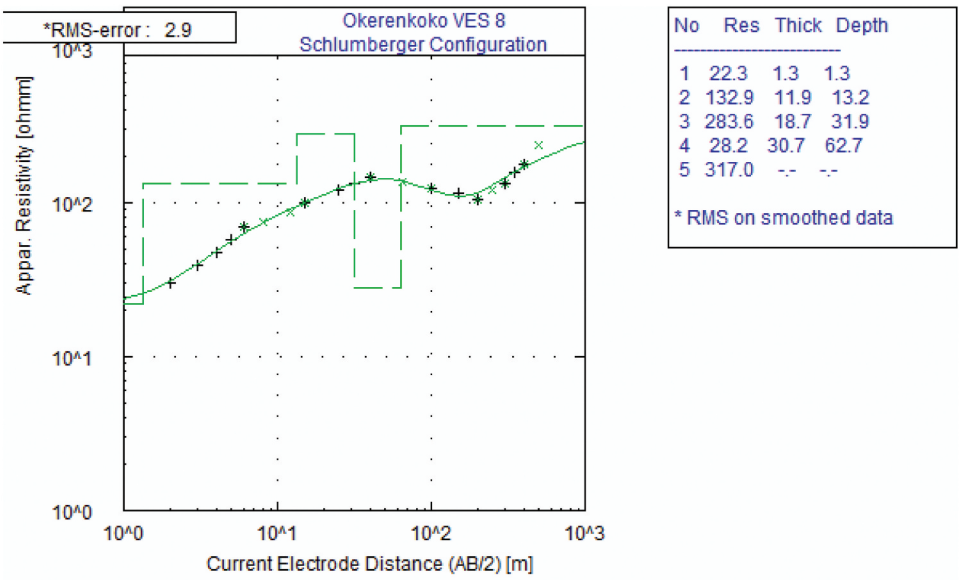

Figure 9. Typical AKH curve type (VES 8).

Resistivity material and method

Collection, preparation, and analysis of radioactivity samples

In order to establish the aquifer groundwater radiological concentrations level at the depth of 60 to 80 meters as shown from infinite vertical thickness via resistivity measurement of 562.0 to 7794.6 Ωm, in the fifth layer of the sand cluster, 30 groundwater samples were collected across Okerenkoko community. The samples were scientifically prepared and analyzed according to radioactivity methods using a Sodium iodide NaI(Tl) detector (Agbalagba et al., 2012; Esi & Akpoyibo, 2024; Tchokossa et al., 2011). The detector has thickened 10 centimeters of shielded lead. The detector Multichannel Analyzer (MCA) was attached to ORTEC 456 amplifier and GENIE 2000 software to detect activity concentration levels due to gamma-ray spectrum. Before the samples were analyzed, the detector was calibration both for energy and efficiency standard point sources of ^{241}Am, ^{137}C, and ^{60}Co. This is to establish the quality activity concentration photo peaks. The background spectra band was built for 480 m at 600 V to create great peaks at gamma giving up energies of 1332.5 kev for ^{40}K gamma energies peak; 834.8 kev for ^{214}Bi gamma energies peak; 1274.5 kev, 1173.2 kev for ^{228}Ac to evaluate activity concentrations in the groundwater using Equation 1 below:

$$A = \frac{NPC}{Tff * I(CLT) * \in (DEP) * M}$$

where NPC is the number of peak counts, I(CLT) is the counting lifetime, ε(DEP) is the detection energy performance and M is the mass in kg.

Table 1. VES (soundings) interpreted outcomes and longitudinal conductance values.

VES	Strata	Resistivity	Thickness	Lithology	$S = \sum_{i=1}^{n} \frac{h_i}{\rho_i}$	Protecting Strata Longitudinal Conductivity
VES 1	1	12.0	0.9	Topsoil	0.075	
	2	59.4	6.4	Clay	0.107744	
	3	223.8	18.1	Sand	0.080876	0.093004
	4	131.0	14.2	Sandy clay	0.108397	
	5	4166.4	—-	Sand		
VES 2	1	32.0	0.5	Topsoil	0.015625	
	2	39.9	13.6	Clay	0.340852	0.118828
	3	78.3	7.4	Clayey sand	0.094508	
	4	349.4	8.5	Sand	0.024327	
	5	7794.6	—-	Sand		
VES 3	1	27.6	0.8	Topsoil	0.028986	
	2	76.5	2.9	Clay	0.037909	0.111825
	3	19.9	6.6	Clay	0.331658	
	4	147.7	7.2	Sand	0.048748	
	5	2328.4	—-	Sand		
VES 4	1	10.8	0.7	Topsoil	0.064815	
	2	175.2	5.9	Laterite	0.033676	
	3	53.2	16.9	Clay	0.317669	0.110877
	4	303.5	8.3	Sand	0.027348	
	5	1477.3	—-	Sand		
VES 5	1	238.4	1.7	Topsoil	0.007131	
	2	134.9	18.2	Laterite	0.134915	
	3	18.1	27.5	Clay	1.519337	0.453599
	4	111.1	17.0	Clayey sand	0.153015	
	5	3469.0	—-	Sand		
VES 6	1	148.8	3.2	Topsoil	0.021505	
	2	66.0	16.1	Clay	0.243939	
	3	29.7	15.5	Clay	0.521886	0.252942
	4	75.3	16.9	Clay	0.224436	
	5	562.0	—-	Sand		
VES 7	1	15.1	0.7	Topsoil	0.046358	
	2	137.5	16.1	Lateritic clay	0.117091	
	3	31.7	47.2	Clay	1.488959	0.453643
	4	88.8	14.4	Clayey sand	0.162162	
	5	578.0	—-	Sand		
VES 8	1	22.3	1.3	Topsoil	0.058296	
	2	132.9	11.9	Laterite	0.089541	
	3	283.6	18.7	Sandy clay	0.065938	0.325607
	4	28.2	30.7	Clay	1.088653	
	5	317.0	—-	Sand		

Table 2. Improved longitudinal conductance/protective capacity ranking (Ajayi & Achuka, 2009; Oladapo et al., 2004.).

Longitudinal conductance (mho)	Protective capacity (capableness) Grading (rating).
(>10)	Excellent (Highest quality)
Range 5 to 10	Very good
From 0.7 to 4.9	Good
Within 0.2 and 0.69	Moderate
Between 0.1 and 0.19	Weak (Imperfect)
Less than 0.1	Poor

Radiological index health implication (RIHI)

The RIHI were calculated using the scientific world permissible standard Formulas as shown in Table 3 below. The calculation was done given ascertaining and evaluating radiological potential risk implications and the quality of drinking water being consumed by residents of the studied community (Esi & Akpoyibo,

Table 3. Formulas used in calculating radiological index health implications of aquifer groundwater.

S/No	Hazard Index	Formulas
1	Radium Equivalent Index	$Ra_{eq} = Z_{Ra} + 1.43Z_{Th} + 0.077Z_k$ (3)
2	Representation Level Index (I_{yr})	$I_{yr} = \frac{Z_{Ra}}{150} + \frac{Z_{Th}}{100} + \frac{Z_k}{1500}$ (4)
3	External Hazard Index (HI_{ex})	$H_{ex} = \frac{Z_{Ra}}{370} + \frac{Z_{Th}}{259} + \frac{Z_k}{4810}$ (5)
4	Internal Hazard Index (HI_{in})	$H_{in} = \frac{Z_{Ra}}{185} + \frac{Z_{Th}}{259} + \frac{Z_k}{4810}$ (6)
5	Absorbed Does Rate (D)	$D = 0.461Z_{Ra} + 0.623Z_{Th} + 0.04144Z_k$ *(7)*
6	Annual Effective Dose Rate (Outdoor)	$AEDRO(mSvyr^{-1}) = D(nGrh^{-1}) \times 8760hryr - 1 \times 0.7 \times (10^3 mSv/10^9)nGy \times 0.2$ *(8)*
7	Annual Effective Dose Rate (Indoor)	$AEDRI(mSvyr^{-1}) = D(nGrh^{-1}) \times 8760hryr - 1 \times 0.7 \times (10^3 mSv/10^9)nGy \times 0.8$ *(9)*
8	Excess Lifetime cancer risk (ELCR)	$ELCR = AEDE \times LD \times RF$ *(10)*

* All radiological indexes retain their scientific connotation. LD is life time 55.75 years and RF is risk factor (Sv^{-1}), fatal cancer risk. For stochastic impacts, ICRP 60 adopts public values of 0.05 ((Avwiri & Esi, 2015; Mokobia et al., 2020; Ramasamy et al., 2009).

2024; Ohwoghere-Asuma & Esi, 2021; Ohwoghere-Asuma et al., 2021; UNSCEAR, 2000).

Results and discussion

The findings of the VES analysis: the curve types of AKH, AAA, KHA, QHA, and AKH in the research region (Figures 2–9), and the overburden aquifer unit of the longitudinal conductance computed for VES 1–8 are summarized in Table 1. The contour lines are visible and filled with diagnostic colors in the SURFER-13 program's advanced contour level option. These colors are utilized to differentiate between the various protective capacity ratings as shown by Atakpo and Ayolabi (2009), as indicated in Table 2.

Topsoil, laterite, clay, and sand formations make up the five strata that make up the subsurface, according to the results of well logging that were connected with sounding data (depth probing). The topsoil comprises the foremost layer, which changes in thickness from 0.5 to 3.2 m and resistivity from 10.8 to 238.4 m. The second stratum is made up of laterite and clay, and its vertical thickness varies from 2.9 to 18.2 m, while its resistivity ranges from 39.9 to 175.2 m. In VES 1, only fine sand is present in the third layer; however, in VES 3, 4, 5, 6, and 7, and clayey sand in VES 2, clay is present. This stratum's resistivity ranges from 18.1 to 223.8 m, although its significant depth (thickness) is found to be between 6.6 and 47.2 m. In VES 1, sandy clay was the fourth geo-electric substratum; in VES 2, 3, and 4, sand was present. Clay makes up VES 6, whereas clayey sand makes up VES 5 and 7. The thickness significantly varies from 7.2 to 14.4 m, while the resistivity goes from 75.3 to 349.4 m. The aquiferous unit, which has an infinite vertical thickness via resistivity measuring from 562.0 to 7794.6 Ωm, is the fifth layer that is associated with the sand cluster and these lithologic formations correlate with the geophysical logs data of two drilled boreholes in Okerenkoko vicinity (Figure 10). In the event of an oil spill or pipeline vandalism, groundwater should be drawn from 60 to 80 m below the surface to obtain clean subsurface water that is devoid of pollutants and hydrocarbon pollution. SURFER 8 software (2002), was utilized to create a protective potential (capacity) map based on the determined values of longitudinal conductance. The protective capacity (PC) was evaluated using the modified PC evaluation in Table 1 (Atakpo & Ayolabi, 2009; Oladapo et al., 2004). To differentiate between areas with good (strong) PC (0.1–4.9 Mho), weak (fragile) PC (0.1–0.19 Mho), and poor PC (<0.1 Mho) for the different soundings, the longitudinal conductance maps displaying the overburden PC of eight soundings in the community were color-coded in Figure 11. The regions in magenta are those with longitudinal conductance less than 0.1 mhos and between 0.1 and 0.19 mhos, indicating inadequate and weak protective capacity. The colors chartreuse, icy blue, and deep yellow represent VES points with moderate PC having longitudinal conductance of 0.2–0.69 mho. Figure 11 displays the longitudinal conductance curve (map) illustrating Okerenkoko's potential to defend against overburden. VES 2, 3, and 4 are located in areas (domains) with weak protective capacity. The aquifer in this residential neighborhood lacks protection and is vulnerable to hydrocarbon pollution since VES 1 location is located in an area with low protective capacity. Hence,

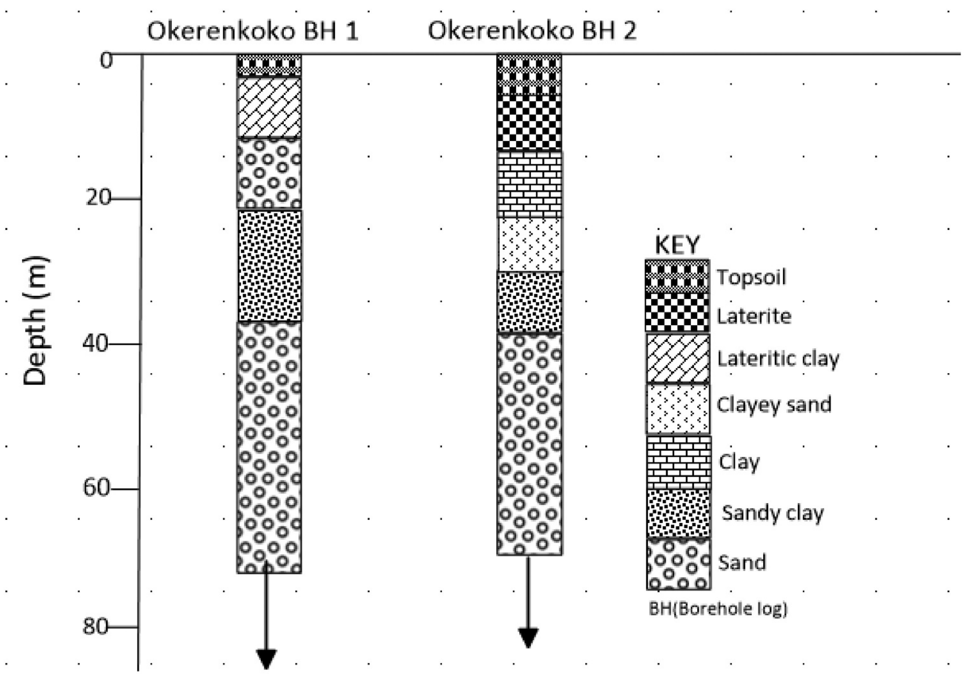

Figure 10. Geophysical logs from boreholes of Okerenkoko in correlation with the Soundings (VES) interpretations of the researched area.

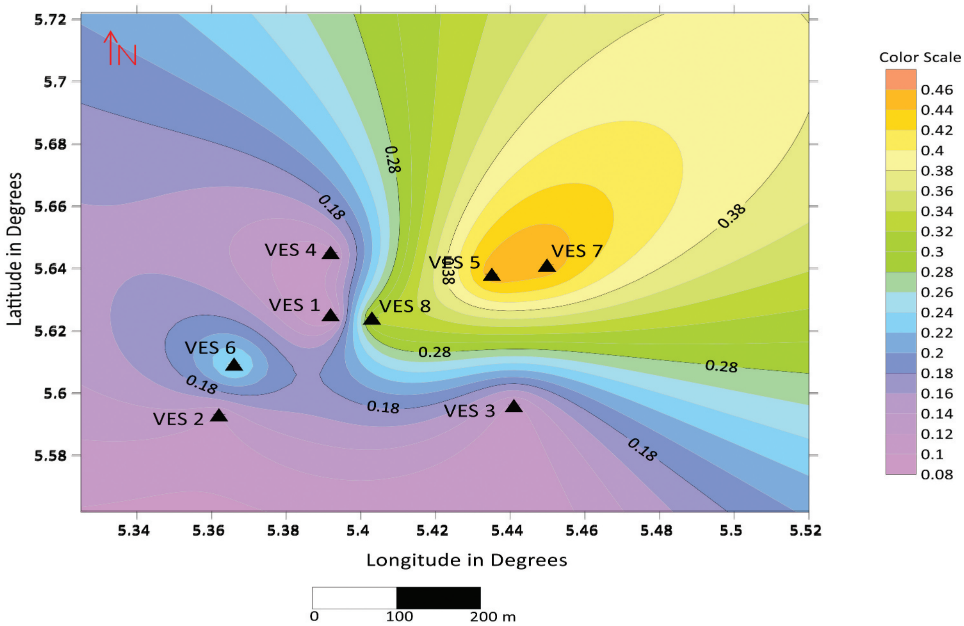

Figure 11. Protective capacity (PC) map of the study area.

hydrocarbon contamination is more likely to occur in the weak (imperfect) and poor (pitiable) protective zones. This is due to the possibility that deposits containing radioactive minerals may seep into the groundwater system as groundwater passes through the sedimentary layers of the rock (Tchokossa et al., 2011). The aquifer in VES 5, 6, 7, and 8 is shielded from percolating (seeping) fluid since they are classified as moderately protected zones. Therefore, in the case of hydrocarbon and petrochemical pollution, the aquifer in the Okerenkoko village is susceptible to infiltration. The presence of oil reservoirs (wells) and pipelines in this community raises and enhances the potential groundwater contamination. The aquifer in the vicinity is shielded by very little to no lateritic clay. Groundwater taint (contamination) from oil spills could leak into the aquifer and threaten the health of the residence in Okerenkoko.

The mean aquifer groundwater radionuclide concentration results of depth of 60 to 80 meters are presented in Table 4. The activity concentration of ^{40}K ranged from BDL to 709.9 ± 53.25 Bql^{-1} with mean value of 264.85 ± 19.27 Bql^{-1}, ^{238}U ranged from BDL to 45.01 ± 10.77 Bql^{-1} with mean value of 16.22 ± 4.18 Bql^{-1} and ^{232}Th ranged from BDL Bql^{-1} to 11.34 ± 1.20 Bql^{-1} with mean value of 4.22 ± 1.11 Bql^{-1}. The activities due to ^{232}Th are low when compared to ^{40}K and ^{238}U. This is consistent with previous report (Tchokossa et al., 2011). The mean values for ^{40}K, ^{238}U, and ^{232}Th of aquifer groundwater measured exceeded world permissible limits of 10 Bql^{-1} 1.0 Bql^{-1}and 0.1 Bql^{-1} respectively (UNSCEAR, 2000). Oil and gas operations could be the cause of the high activity concentration that was observed. It should be mentioned, nonetheless, that naturally occurring radioactive elements are dissolved in groundwater and do not just exist in oil reserves (Paschoa, 1997). As a result, radionuclides may build during extraction and separation procedures. Groundwater becomes contaminated as a result of the produced water being carried to the surface with oil and then leaching into the surrounding ecosystem.

The statistical pie chart representations are shown in Figures 12,13 and 14. The results obtained from

Table 4. Measured Mean concentration values of ^{40}K, ^{238}U and ^{232}Th in aquifer groundwater.

			ACTITIVY			
S/N	SAMPLE	CODE	^{40}K (Bq/L)	^{238}U (Bq/L)	^{232}Th (Bq/L)	Ra_{eq} (Bq/L)
1	Okenrenkoko Well Water A	OWWA	195.56 ± 14.10	BDL	10.69 ± 1.08	196.38
2	Okenrenkoko Well Water B	OWWB	BDL	8.08 ± 2.13	6.16 ± 0.64	12.378
3	Okenrenkoko Well Water C	OWWC	68.60 ± 4.95	6.35 ± 1.70	BDL	78.50
4	Okenrenkoko Well Water D	OWWD	647.54 ± 44.83	27.56 ± 7.47	BDL	687.77
5	Okenrenkoko Well Water E	OWWE	BDL	15.29 ± 4.17	11.34 ± 1.20	22.69
6	Okenrenkoko Well Water F	OWWF	608.04 ± 43.54	45.01 ± 10.77	BDL	673.23
7	Okenrenkoko Well Water G	OWWG	BDL	10.39 ± 2.79	6.42 ± 3.61	15.68
8	Okenrenkoko Well Water H	OWWH	BDL	32.17 ± 8.40	7.62 ± 4.61	46.83
9	Okenrenkoko Well Water I	OWWI	709.9 ± 53.25	16.16 ± 4.08	BDL	733.83
10	Okenrenkoko Well Water J	OWWJ	418.87 ± 32.05	1.15 ± 0.31	BDL	421.34
Mean			264.85 ± 19.27	16.22 ± 4.18	4.22 ± 1.11	288.86

aquifer groundwater measured were found to be higher compared to scientific reported published works (Agbalagba et al., 2012; Almayahi et al., 2012; Avwiri et al., 2007; Khalid et al., 2003; Salih, 2022; Suleiman et al., 2024; Tchokossa et al., 1999, 2011). These aquifer groundwater values may be accredited to the release of hydrocarbon waste, oil spillage, geological configuration of the area, and other anthropologic activities in the area. The calculated radium equivalent (Raeq) values ranged between 15.69 Bql^{-1} and 733.83 Bql^{-1} with an average value of 288.86 Bql^{-1}, which is less than the world permissible limit of 730 Bql^{-1} as shown in Figure 15. From Table 5 the mean aquifer groundwater calculated radiological health implication values of (Iyr), external hazard index, and internal hazard index are 1.931 $mSvy^{-1}$ and 1.486 $mSvy^{-1}$ respectively. These mean values slightly exceed word unity except external hazard index of 0.779 $mSvy^{-1}$ which is below word unity (UNSCEAR, 2000). This study was also compared with other reported research works and observed that it slightly exceeds them (Ajayi & Achuka, 2009;

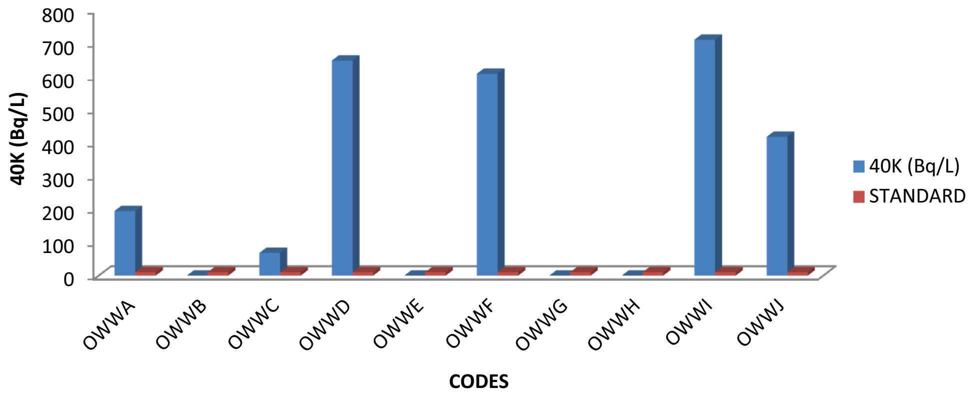

Figure 12. Comparison between ^{40}K measured values (Bql^{-1}) of aquifer groundwater and world average.

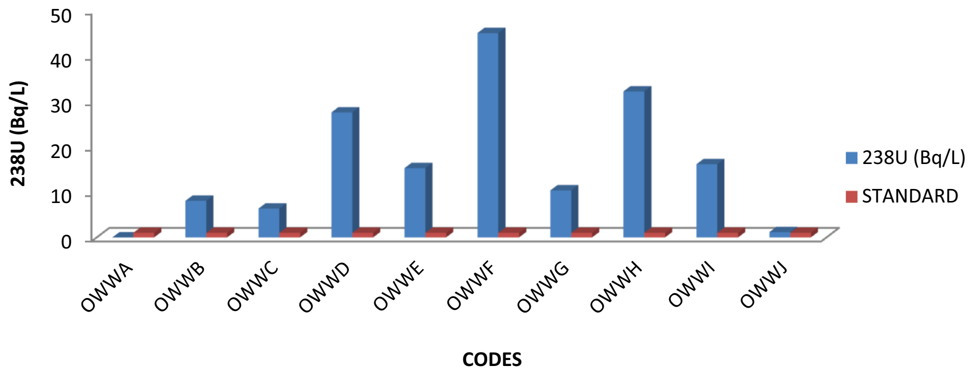

Figure 13. Comparison between ^{238}U measured values (Bql^{-1}) of aquifer groundwater and world average.

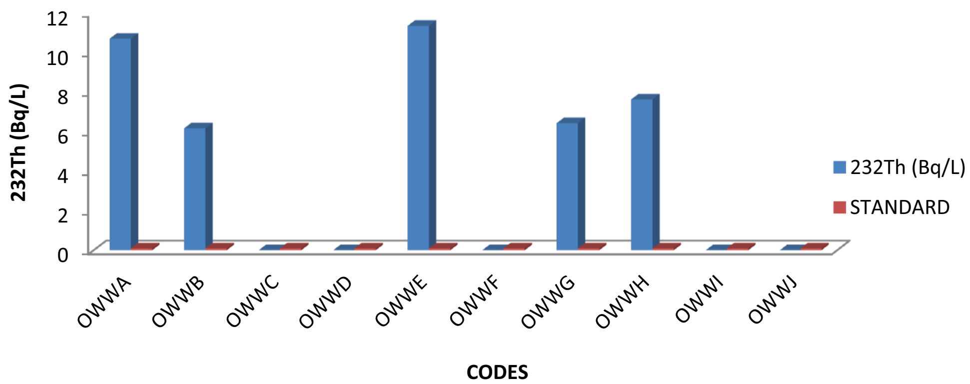

Figure 14. Comparison between ^{232}Th measured values (Bql^{-1}) of aquifer groundwater and world average.

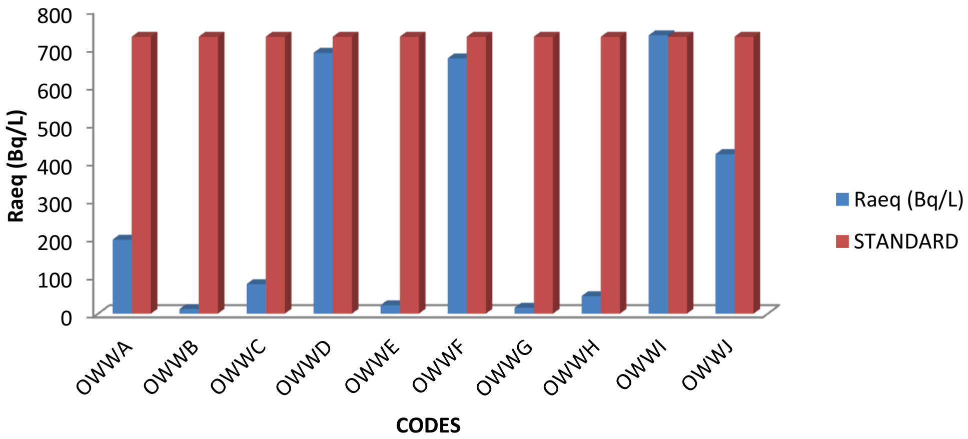

Figure 15. Comparison between computed Raeq values (Bql^{-1}) and world average.

Table 5. Calculation of radiological index health implications of aquifer groundwater.

S/No	CODES	Iyr	Hex	Hin	D	AEDE (Outdoor)	AEDE (Indoor)	ELCR × 10^{-3} (Outdoor)	ELCR × 10^{-3} (Indoor)	ELCR × 10^{-3} (Outdoor+ Indoor)
1	OWWA	1.311	0.531	1.059	90.596	111.107	44.443	0.310	1.239	1.549
2	OWWB	0.085	0.033	0.033	5.289	6.486	2.595	0.018	0.072	0.09
3	OWWC	0.521	0.210	0.395	35.580	43.635	17.454	0.122	0.487	0.609
4	OWWD	4.593	1.856	3.607	315.686	387.157	154.863	1.079	4.317	5.396
5	OWWE	0.161	0.061	0.061	9.996	12.259	4.904	0.034	0.137	0.171
6	OWWF	4.504	1.817	3.460	308.348	378.158	151.263	1.054	4.216	5.27
7	OWWG	0.108	0.042	0.042	6.739	8.265	3.306	0.023	0.092	0.115
8	OWWH	0.327	0.126	0.126	20.358	24.967	9.987	0.070	0.278	0.348
9	OWWI	4.894	1.981	3.810	337.332	413.704	165.482	1.153	4.613	5.766
10	OWWJ	2.804	1.137	2.269	193.815	237.695	95.078	0.663	2.650	3.313
Mean		1.931	0.779	1.486	132.374	162.343	64.938	0.456	1.810	2.263

Ajayi & Owolabi, 2007; Ayodele et al., 2020). The aquifer groundwater absorbed dose rate (D) values are between 5.289 ηGyh^{-1} and 337.332 ηGyh^{-1} with an average value of 132.374 ηGyh^{-1}. The calculated average AEDE for outdoor and indoor are 162.343 μSvy^{-1} and 64.938 μSvy^{-1} respectively and ELCR outdoor, indoor, and addition of outdoor and indoor are 0.456, 1.810, and 2.263, respectively, slightly exceeded world average (Avwiri et al., 2007; UNSCEAR, 2000). Nevertheless, the radionuclides concentration results and the calculated radiological index health implications of aquifer groundwater studied area may not cause significant radiological health hazard implications on residents' groundwater drinking water when utilized for industrial and domestic use.

Conclusion

Eight Schlumberger, electrical resistivity sounding (VES), and sodium iodide [Na(TI)] detector analyses were used in the inspection of the quality of oil-rich Okerenkoko community aquifer groundwater. The maximum (highest) electrode separation was adjusted between 750 m and 1000 m and the VES signals were displayed as curves, which were quantitatively evaluated using Resist Software after partial curve (shape) matching before computer modeling and iteration to calculate the layer depth or thickness (h) and resistivity (q), the first basic order geoelectric quantities. The longitudinal sounded unit conductance was calculated using first or initial-order geoelectric factors to determine the protective capability area of the layers to the aquifer groundwater. Areas with poor protective capability have values of less than 0.1mho (<0.1 mho), weak (varying from 0.1 to 0.19 mho), moderate (between 0.2 and 0.69 mho), and strong protective capability (changing from 0.7 to 4.9 mho), these were identified using the longitudinal contoured conductance maps. Okerenkoko community aquifer groundwater of depth 60–80 meters with moderate protective capacities, imply not effectively shielded from hydrocarbons contamination pollution. Hence, 30 groundwater samples were collected for radiological analysis using a sodium iodide [Na(TI)] detector to ascertain the extent of hydrocarbon contamination pollution radiologically. The mean results of radionuclide activity concentrations of aquifer groundwater are ^{40}K is 264.85 ± 19.27Bql^{-1}, ^{238}U is 16.22 ± 4.18Bql^{-1} and ^{232}Th is 4.22 ± 1.11Bql^{-1}. The mean results from the analysis revealed that the values exceeded world limits. This may indicate hydrocarbon contamination pollution in the aquifer groundwater due to to released of hydrocarbon waste, oil spillage, the geological configuration of the area, and other anthropologic activities in the area. Nevertheless, the calculated radiological index health implications of aquifer groundwater mean results slightly exceeded world permissible limits. These research findings ascertained the migrations of petroleum hydrocarbon waste released from the surface to the contaminated groundwater, the radiological contamination level, and the human health implications. Therefore, there may be proper treatment of the aquifer groundwater before usage for domestic, agricultural, and industrial (purposes) works. Additionally, this community should have groundwater monitoring (tracking) wells and regularly (periodically) analyze the water cleanliness and quality. Due to the limitations of not applying isotope methods, analyzing biological parameters, heavy metals, and physiochemical parameters of the groundwater, It is therefore imperative to recommend that further research work should be carried out on the above parameters.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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