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The Shallow Aquifers Vulnerability Investigations using Dar-Zarrouk Parameter at Nnewichi Landslide Site, Nnewi, Anambra State, Nigeria

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Abstract

Dar-Zarrouk parameter estimated from vertical electrical sounding (VES) was executed at the Nnewichi landslide site, aimed at investigating shallow aquifer vulnerability. The Schlumberger electrode array, involving twenty soundings, was deployed. The field data were interpreted qualitatively and quantitatively using WinResist software. The interpreted geoelectric resistivity and thickness were used to estimate the Dar-Zarrouk longitudinal conductance. The results reveal three to four geoelectric units as loose counteraction material of resistivity 604.8 to 2084.1 Ωm, regolith/colluvia of resistivity 48.0 to 820.4 Ωm and weathered sandstone of resistivity 35.2 to 1930.2 Ωm characterized by Q (60%), QH (35%), and KQ (5%) curve types. The estimated longitudinal conductance has values ranging from 0.006 to 0.236 Ω^{-1} with an average value of 0.07375 Ω^{-1}. 70% of the VES points have poor protective rating (<0.1 Ω^{-1}), 10% have weak protective rating (0.1 – 0.19Ω-1) and 20% have moderate protective rating (0.2 – 0.69 Ω^{-1}). This implies a poor protective layer rating. Hence, the overlying counteraction materials and regolith/colluvia units are permeable to the surface contaminants, thereby making the shallow weathered sandstone aquifer unit vulnerable to contamination. The geophysical investigation provides a cost-effective means of probing aquifer vulnerability in the absence of geochemical analysis.

1. Introduction

Groundwater is the most important source of drinking water for 70% of the Nigerian population because it is relatively free from contamination and requires less intensive purification, making it more desirable than surface water [1, 2, 3]. This has resulted in its extraction and development even within delicate and complex environments to satisfy some industrial and domestic needs, consequently leading to reduced water quality. Groundwater has unique chemistry due to several processes like soil/rock-water interaction during recharge, and groundwater flow, prolonged storage in the aquifer, dissolution of mineral species, and many more; nonetheless, hydrogeochemical processes that are responsible for altering the chemical composition of groundwater vary with respect to space and time [4, 2]. Groundwater contamination is one of the major dangers on the subsurface, resulting in huge stress on the environment and leading to problems like ill-health in humanity [5, 6]. More and more, concern about groundwater systems arises from the fact that the repository layers are not visible; therefore, some extensive and intensive measures are required for protective investigations of the repository layers. Rapid growth in population and increasing urbanization activities in Nnewi communities in Anambra State, Nigeria, are accompanied by increasingly challenging demands for clean water supplies. However, this is more challenging in the landslide-affected geologic environment of the Nnewichi community in Nnewi, Anambra State. The landslide site has become a dumpsite for various domestic, industrial, and medical garbage whose effluents are conveyed down the subsurface through runoff and infiltration. Nnewi metropolis is fairly surrounded by numerous surface water bodies and has aquifer zones ranging from deep to shallow groundwater systems [7]. These aquifer zones are recharged through surface water percolation from heavy rainfall. Therefore, there is a need for guaranteed protective measures in the aquifer systems. Most often, traditional geotechnical methods, which are costly, time-consuming, and relate to discrete points information are being deployed. However, geophysics, being a non-invasive and cost-effective method, has proven successful in hydrogeological investigations. [8, 9, 10]. Studies have shown that vertical electrical sounding (VES) is ideal for determining aquifer depth, boundary, protectivity, thickness, and water content [10]. Eugene-Okorie [3] investigated the groundwater potential and vulnerability of Oraifite, Anambra, using geoelectrical methods. The results reveal zones with layer characteristics and serve as a reference for decision-making in groundwater abstraction and management. Ewusi [10] researched the estimation of aquifer transmissivity in some northern Ghana districts using Dar-Zarrouk parameters. The results provided geophysical means of improving the success rate of groundwater management. Oladapo [11] reported on their use of VES in a hydrogeological study of Ogbese town in Ondo State, Nigeria. They demonstrated the application of the characteristic longitudinal conductance of the area in rating the overburden protective capacity into three categories: moderate (0.2 to 0.69 Ω^{-1}), weak (0.1 to 0.19 Ω^{-1}), and poor (< 0.1 Ω^{-1}). Also, Abiola [12] deployed VES in the study of the groundwater potential and aquifer protective capacity of overburden units in Ado-Ekiti, Nigeria. The results enabled the overburden protective capacity to be rated as good, moderate, and weak. More and more, successful groundwater exploitation and management are dependent on vast knowledge of the transverse resistance, longitudinal conductance, and other aquifer hydraulic parameters [13, 3]. As a means of mitigating groundwater contamination from surface contaminants from different sources around the polluted Nnewichi landslide, this study is aimed at investigating shallow aquifer vulnerability using the Dar-Zarrouk parameter estimated from vertical electrical sounding (VES).

1.1 Location, Geology and Hydrogeology of the Study Area

The Nnewichi landslide site (Figure 1) is geographically located between latitudes N6°.00' and N6°.04' and longitudes E6°.54' and E6°.57' in Nnewi North in Anambra State, southeastern Nigeria. Nnewichi is a hub of commercial, entrepreneurial, and residential activities. The site is an active landslide site, measuring about 7.08724 km in perimeter and 367.39927 km^2 in area, with most of its surficial soils eroded to a varying great depth. However, some remediation and counteraction work has been done on the concave dips.

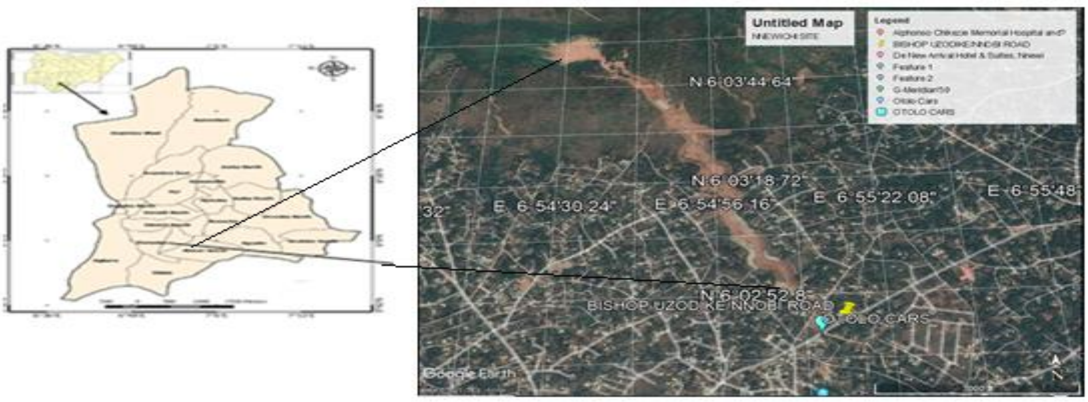

Figure 1: Location of the Study Area

The study area is in the tropical wet climate zone with two distinct seasons: the rainy season (March/April to October/November) and the dry season (October/November till March/April). The annual distribution of rainfall is between 1500 mm and 2500 mm [14, 15, 16], with average monthly temperatures between 22°C and 28°C in the rainy season. The topography is steeply sloppy concave terrain with elevations ranging from 68 m to 116 m (Figure 2). The geology of Anambra State is derived from the Anambra Basin, which is of the cretaceous age; the basin is a northeast-southwest trending syncline, a part of the Central African Rift System, formed as a result of the extending and subsidence of major crustal blocks during the lower cretaceous separation stage of the Gwanwana supercontinent [17, 18]. The sedimentary formations within the basin are the Mamu, Ajali, and Nsukka formations, which conformably overrun each other, with the Nsukka formation being the youngest Cretaceous series [19, 20, 21]. The tertiary formations include the Palaeocene Imo Shale, overlain by the Eocene Ameki Formation/Nanka Sands, the Ogwashi-Asaba Formation, and the Quaternary Alluvium [22, 23]. The study area local geology, falls within the tertiary Ogwashi-Asaba Formation (Oligocene–Miocene), which consists of loose and poorly consolidated fine-grained sand materials with low clay content and little or no coarse-grained aggregates [19, 20, 21, 24]. The Ogwashi-Asaba Formation has an approximate thickness of 300 m [25]. The hydrogeological environment is derived from the Ogwashi-Asaba Formation, [24, 25]. However, the Nnewichi community has a little distance surrounding surface water bodies like the Iyi-Ukwu, Oraukwu River, Iyiogu (Nanka) River, and others, with aquifer zones ranging from deep to shallow groundwater systems [7]. These water bodies have a westward flow direction, from areas of high elevations on the Nanka Formation to areas of low elevations on the Ogwashi Formation [7] This implies that the study area's shallow aquifer zones recharge sources are surface water bodies' percolation and surface infiltration from the annual heavy rainfall.

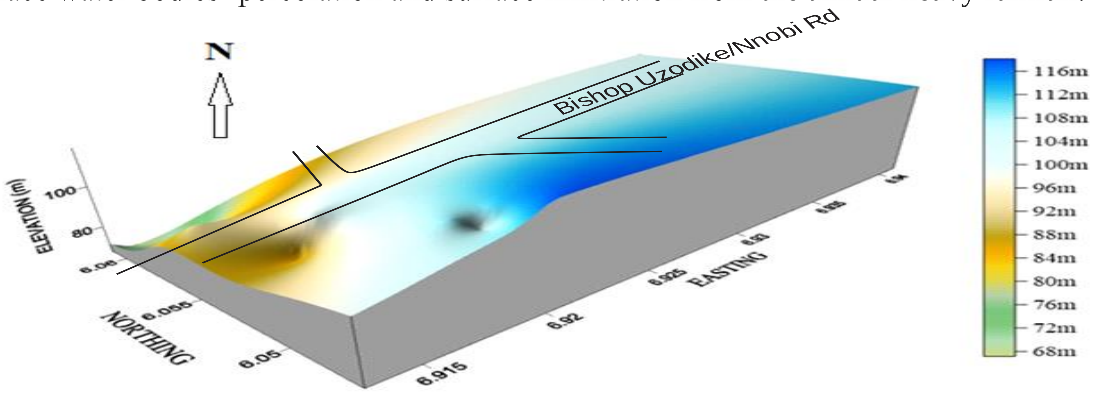

Figure 2: Nnewichi Site Topography

Figure 3: Geological Map of Anambra State [26]

2.0 Materials and Method

The VES was executed using a PASI 16-GL resistivity meter. The Schlumberger array was deployed. Owing to some barricade restrictions within the site, a total of twenty VES points, labeled V1 to V20, were acquired (Figure 4), at inter station spacing of 20 m along some profile. The maximum current electrode separation (AB) was 130m. The response of the ground was estimated as apparent resistivity (ρa) by multiplying the recorded resistance (R) with the geometric factor (G) of the Schlumberger array given in Equations 1 and 2.

$$\rho a = (0.5\pi(AB^2 - MN^2)R)/MN \quad (1)$$

$$G = (0.5\pi(AB^2 - MN^2))/MN \quad (2)$$

where AB and MN are the current electrodes and potential electrodes spacing respectively.

Figure 4: Site Study Map with the VES locations

The VES apparent resistivity data were first plotted on a log-log graph against half-current electrode separation and then curved matched using standard theoretical curves. True lithological unit resistivity and their corresponding thicknesses were estimated. The estimated parameters were then used as initial models in the WinResist 1.0 software. The software iteratively correlated the field curve and the theoretical curve and determined the true resistivities and thicknesses of the interpreted lithological units at a very acceptable root mean square value. The Dar Zarrouk parameter: longitudinal conductance (SL), which explains the problem of non-uniqueness [27, 3], was calculated from the interpreted model parameters using Equation 3.

$$S_L = \sum_{i=1}^{n-1}\left(\frac{hi}{\rho i}\right) = \frac{h_1}{\rho_1} + \frac{h_2}{\rho_2} + \frac{h_3}{\rho_3} + \frac{h(n-_1)}{\rho(n-_1)} \quad (3)$$

The Dar-Zarrouk parameter of the overlying units was then used to estimate the vulnerability of the underlying weathered sandstone layer.

3.0 Results and Discussion

3.1 Results

The results of the study are presented as VES inverted models (Figure 4), the interpreted layer parameters (Table 1), the curve types graph (Figure 5) and longitudinal conductance (Figure 6).

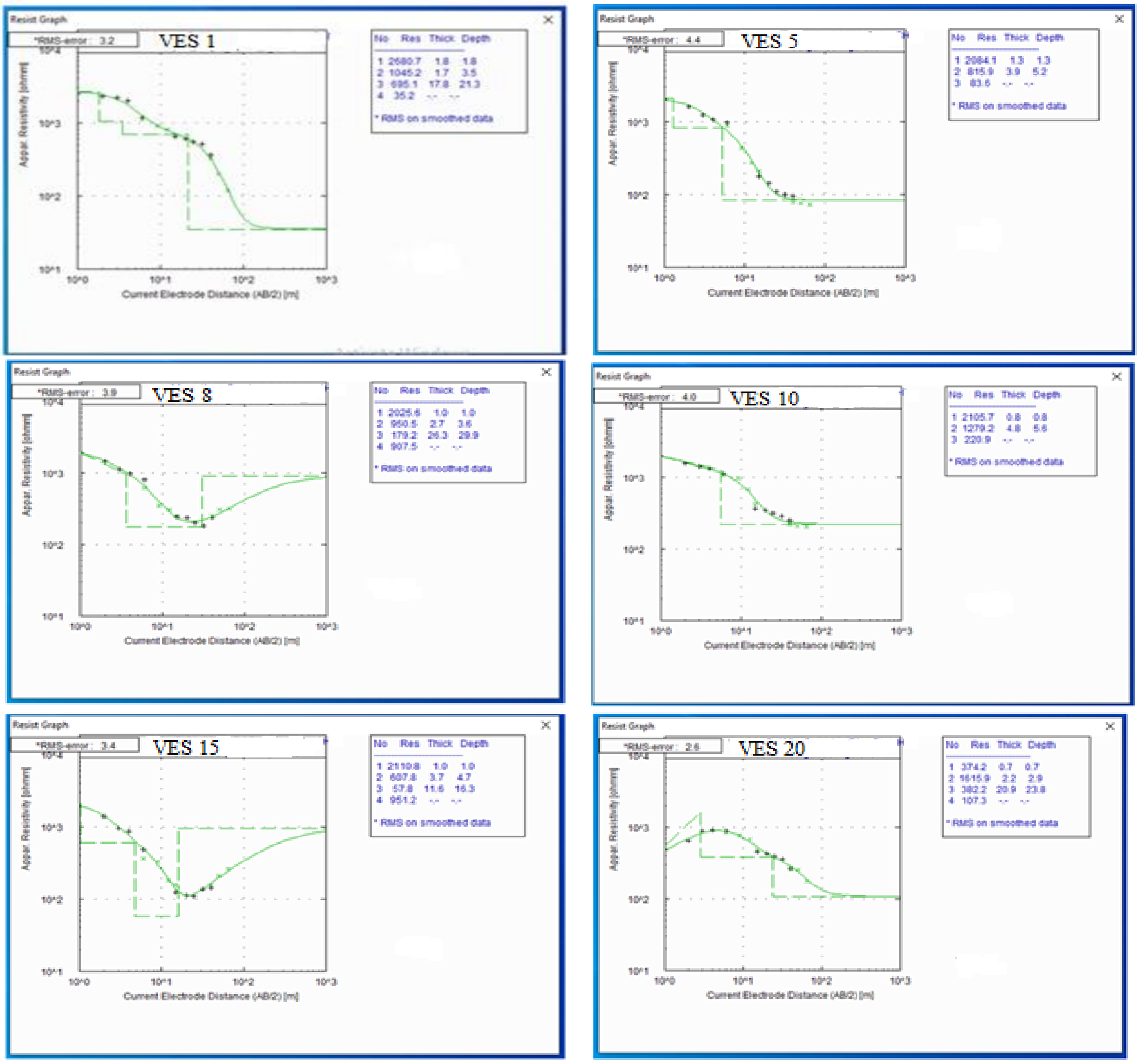

Figure 4: Some VES inverted models

Table 1: Interpreted layer parameters

VES	Layer	Resistivity(Ωm)	Thickness(m)	Curve Type	RMS %	S_L (Ω^{-1})	Geoelectric unit
V1	1	2680.7	1.8	Q	3.2	0.028	LCM
	2	1045.2	1.7				CM
	3	695.1	17.8				R/C
	4	35.2	---				WS
V2	1	2669.6	1.0	Q	2.5	0.031	LCM
	2	1197.2	2.5				CM
	3	657.5	19.0				R/C
	4	53.1	---				WWS
V3	1	2290.8	1.4	Q	3.2	0.034	LCM
	2	1100.9	3.1				CM
	3	519.0	16.1				R/C
	4	53.1	---				WS

V4	1	2161.4	0.8	QH	3.6	0.236	LCM
	2	1432.0	2.1				CM
	3	107.7	25.2				R/C
	4	433.6	---				WS
V5	1	2084.1	1.3	Q	4.4	0.005	CM
	2	815.9	3.9				R/C
	3	83.6	---				WS
V6	1	1951.5	1.7	Q	3.1	0.008	CM
	2	643.2	4.6				R/C
	3	79.6	---				WS
V7	1	1959.6	0.9	QH	4.2	0.083	LCM
	2	1061.4	2.3				CM
	3	175.7	14.2				R/C
	4	973.9	---				WS
V8	1	2025.6	1.0	QH	3.9	0.150	LCM
	2	950.5	2.7				CM
	3	179.2	26.3				R/C
	4	907.5	---				WS
V9	1	2056.9	1.0	QH	4.2	0.154	LCM
	2	909.9	2.8				CM
	3	181.4	27.2				R/C
	4	951.3	---				WS
V10	1	2105.7	0.8	Q	4.0	0.004	LCM
	2	1279.2	4.8				CM
	3	220.9					R/C
V11	1	2149.0	0.7	Q	3.4	0.004	LCM
	2	1352.3	4.4				CM
	3	251.7	---				R/C
V12	1	2051.4	0.9	Q	3.2	0.004	LCM
	2	1291.0	4.4				CM
	3	223.4	---				R/C
V13	1	2177.1	0.8	QH	3.9	0.196	LCM
	2	810.1	3.3				CM
	3	48.0	9.2				R/C
	4	1930.2	---				WS
V14	1	2140.5	1.0	QH	3.7	0.220	LCM
	2	604.8	3.7				CM
	3	57.2	12.2				R/C
	4	956.0	---				WS
V15	1	2110.8	1.0	QH	3.4	0.207	LCM
	2	607.8	3.7				CM
	3	57.8	11.6				R/C
	4	951.2	---				WS
V16	1	1689.0	0.9	Q	2.8	0.004	LCM
	2	1396.6	5.4				CM

	3	99.1	---				WS
V17	1	1739.5	0.9	Q	2.4	0.006	LCM
	2	1188.3	6.0				CM
	3	86.3	---				WS
V18	1	1505.9	1.0	Q	2.6	0.012	CM
	2	820.4	9.1				R/C
	3	295.8	---				WS
V19	1	1482.6	0.8	Q	3.4	0.031	CM
	2	401.1	12.3				R/C
	3	91.3	---				WS
V20	1	374.2	0.7	KQ	2.6	0.058	LCM
	2	1615.9	2.2				CM
	3	382.2	20.9				R/C
	4	107.3					WS

S_L Longitudinal conductance, LCM Loose counteraction material, CM Counteraction material, R/C Regoliths/colluvia, WS Weathered sandstone

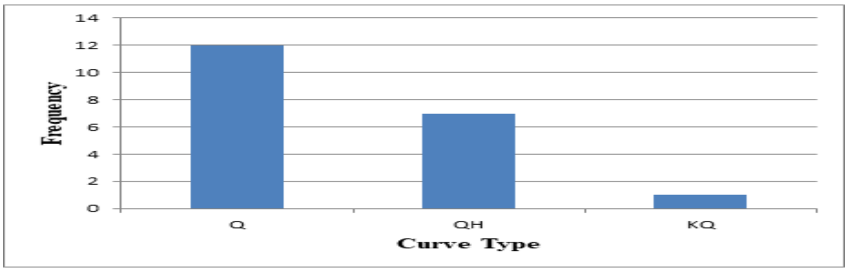

Figure 5: Curve type graph

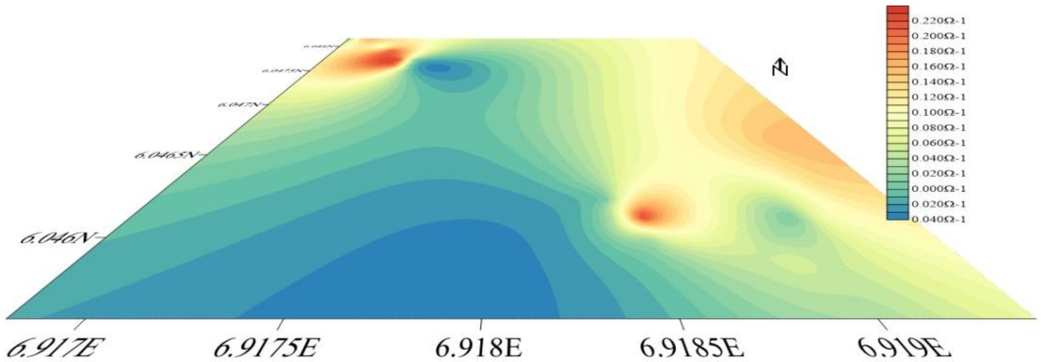

Figure 6: Longitudinal Conductance Contour Map

3.2 Discussion

The analyzed VES inverted models (Figure 4) and the interpreted layer parameters (Table 1) reveal that the site is characterized by three to four geoelectric units. Generally, the first two units are loose counteraction and counteraction materials of variable resistivity and thickness. This material is composed of lateritic soils and gravel. The resistivity of the loose counteraction unit has values ranging from 374.2 to 2680.7 Ωm, with a thickness range of 0.7 to 1.8 m. The counteraction material unit has a resistivity value range of 604.8 to 2084.1 Ωm and a thickness range of 1.3 to 6.0 m. The regoliths/colluvia is the third unit, with a resistivity range from 48.0 to 820.4 Ωm and a thickness range from 3.9 to 27.2 m. The weathered sandstone is the fourth unit, with a resistivity range of 35.2 to 1930.2 Ωm. This is the shallow aquifer unit. The curve type analysis (Figure 5) shows that twelve (60%) of the VES curves are of curve type Q, while seven

(35%) are hybrid QH-curves. The Q-curve implies a resistivity decrease down the depths, indicating water infiltration down the subsurface. The QH-curve indicates an intermediate groundwater repository unit after some resistivity decreases down the depths. Generally, the infiltration of fluids into an aquifer unit is a function of the overlying layers thickness and the presence of clays and silts [28, 3]. The longitudinal conductance distribution (Figure 6) has values ranging from 0.006 to 0.236 Ω^{-1} with an average value of 0.07375 Ω^{-1}. According to Oladapo [11, 27] rating (Table 2), 70% of the VES points have poor protective rating (<0.1 Ω^{-1}), 10% imply weak protective rating (0.1 – 0.19Ω^{-}1) and 20% moderate protective rating (0.2 – 0.69 Ω^{-1}). This indicates that the mapped area is characterized by poor protective layers rating less than 0.1 Ω^{-1}.The study site generally has the underlying sandstone units exposed in the barricaded area, hence, possible overlying protective layers eroded. However, lateral heterogeneity such as presence of clay layers and varying hydraulic transmissivity not evaluated in this study is a parameter on contaminated groundwater migration. Hence, there may be need for calibration with shallow borehole data of close areas to establish possible contamination migration directions.

Table 2: Longitudinal Conductance Rating [11, 27]

Longitudinal Conductance (Ω^{-1})	Rating
>10	Excellent
5 - 10	Very good
0.7 – 4.9	Good
0.2 - 0.69	Moderate
0.1 – 0.19	Weak
<0.1	Poor

4.0 Conclusion

In this study, twenty VES were deployed in the geologically distorted Nnewichi landslide site aimed at investigating shallow aquifers vulnerability using the Dar-Zarrouk parameter estimated from the VES subsurface layer parameters. The findings from this study reveal three to four geoelectric units as loose counteraction material of resistivity 374.2 to 2680.7 Ωm, counteraction material of resistivity 604.8 to 2084.1 Ωm, regolith/colluvia of resistivity 48.0 to 820.4 Ωm and weathered sandstone of resistivity 35.2 to 1930.2 Ωm. The interpreted VES curves are characterized by curve types of Q (60%), QH (35%), and KQ (5%). The Q and hybrid QH-type curves imply decreasing resistivity with depth. Also, the estimated longitudinal conductance has values ranging from 0.006 to 0.236 Ω^{-1} with an average value of 0.07375 Ω^{-1}. 70% of the VES points have poor protective rating (<0.1 Ω^{-1}), 10% have weak protective rating (0.1 – 0.19Ω^{-}1) and 20% have moderate protective rating (0.2 – 0.69 Ω^{-1}). This generally implies a poor protective layer rating. Hence, the overlying counteraction materials and regolith/colluvia units are permeable to the surface contaminants, thereby making the shallow weathered sandstone aquifer unit vulnerable to contamination. The geophysical investigation provides a cost-effective means of probing aquifer vulnerability in the absence of geochemical analysis. It is recommended that monitoring boreholes for geochemical analysis of contaminant migration tracking be dug at specific locations around the study site to mitigate contamination risks.

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Data availability

The authors declare that the data supporting the findings of this research are available within this paper.

Declarations

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