Geophysical assessment of aquifer vulnerability and management: a case study of University of Nigeria, Nsukka, Enugu State

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Abstract

Seventeen vertical electrical soundings and seven electrical resistivity tomography profiles were carried out at the University of Nigeria, Nsukka, Enugu State, Nigeria. The study involves the use of Schlumberger and Wenner electrodes configuration. The thrust of this work is on determining the vulnerability of the hydrogeological units by employing the aquifer vulnerability index (AVI) method. The resistivity data measured were interpreted manually and with computer software packages, which gave the resistivity, depth and thickness for each layer within the maximum current electrodes separation. The hydraulic conductivity (K) and hydraulic resistance (C) of the protective layers estimated from the primary parameters estimated have values ranging from 0.0434 to 0.4890 m day⁻¹ and 38.37 to 1005.84 day⁻¹, respectively. AVI of the study shows that the study area is characterised by low to high AVI with moderate AVI as dominant. This is to help in delineating aquifer protective zones and also possible locations, which further helps in groundwater resource exploration and management.

Keywords AVI · VES · ERT · Hydraulic conductivity · Hydraulic resistance

Introduction

Groundwater that exists below the water table in the zone of saturation moves slowly in the same direction the water table slopes and includes the moisture found in the pores between soil grains. Access to clean water is a human right and a basic requirement for human and economic development. The knowledge of the nature and identification of subsurface condition is important in groundwater study. For sustainable use of groundwater resources, there is a need for effective protection and management of buried aquifers covered by thick sediments (Bjerg et al. 1992; Hinsby et al. 2006; George et al. 2015a, b; Obiora et al. 2015). The quality of groundwater can be affected by the percolation of surface pollutants from dumpsites, sewage and run-off/flood. Once entered into the groundwater table, they affect the potability of groundwater (Hossain et al. 2014; Ibuot et al. 2017). The percolation of these pollutants is enhanced due to highly permeable covering

layers of subsurface and ease fluid flow through the subsurface since the flow is through a combination of intergranular pores, fissures and interconnected fractures. Quantitative description of aquifers has become vital in order to address several hydrological and hydrogeological problems (Ugwuanyi et al. 2015).

The information on groundwater vulnerability is required for groundwater protection and management. Vulnerability of aquifer reflects whether the subsurface characteristics can prevent or favour the transport of contaminants into the aquifer repositories, and vulnerability is greatly enhanced by the groundwater flow velocity, a factor that is dependent on hydraulic conductivity of the covering (protective) layers and the depth of the water table. The protective layers must have very high thickness and low hydraulic conductivity for effective groundwater protection and also a percolation time of more than ten years (Hölting et al. 1995), and the presence of sandy intrusions or fissures creates pathways within the protective layers for percolation, but these inhomogeneities are not taken into account (Hinsby et al. 2006; Weatherington-Rice et al. 2006). Groundwater quality once contaminated can lead to water-borne diseases, and its inaccessibility due to drawdown can affect human health. This may jeopardise the economic activities and other activities in a society.

The vertical electrical sounding (VES) and electrical resistivity tomography (ERT) methods have been used successfully

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by several researchers and authors in solving a wide range of hydrological and hydrogeophysical problems including mapping of saturated aquifer horizons from the adjoining formations, groundwater potential investigations, aquifer characterisation, assessment of infiltration rate of the vadose zone and groundwater contamination studies (Stempvoort et al. 1992; Samsudin et al. 2009; George et al. 2015b; Obiora et al. 2016; Lashkaripour and Nakhaei 2005; Ibuot et al. 2013; Aleke et al. 2018; Putranto et al. 2017, 2018).

The methods are preferable because of the resistivity contrast obtained when the groundwater zone is reached. VES and ERT display the conductivity/resistivity of the distributed arenaceous or argillaceous geological formations vertically and horizontally (Loke 2009). The need for water in many communities has led to an interest in the use of groundwater due to lack of surface water. Some of the drilled boreholes have been done without any preliminary geophysical investigations. This has resulted in failures of some boreholes and contamination of the water. In an attempt to manage these problems, the contribution to water scarcity and contamination by lithology and geology has to be assessed independently. The nature of the aquifer is a function of subsurface geological composition that plays an important role in determining the flow of water from the surface to subsurface through recharge processes (Bashir et al. 2014).

The chosen methods, apart from being available and easily accessible, are capable of distinctively showing the geology of unconsolidated overburden areas that are permeable, therefore allowing infiltration of surface contaminants into the subsurface. The VES is a depth sounding galvanic method which has proved very useful in groundwater studies, and ERT is widely used in studies involving overburden layers because of its sensitivity to lithologic unit contrasts. Both methods are very reliable in groundwater studies and availability of interpretation software programs for analysis of acquired data.

This non-invasive study to determine the aquifer characteristics involves the analysis and interpretation of the subsurface, so as to evaluate aquifer potential, geoelectric and geohydraulic parameters. Also, the use of the aquifer vulnerability index (AVI) as a tool of determining whether the overburden layer is protected against the percolation of contaminants will demonstrate the effectiveness of the method. The aim of this work was achieved through the following objectives: to determine the depth and thickness of the geoelectric layers to estimate geohydraulic parameters in order to assess the vulnerability index of the aquifer protective layers and to propose the efficient and economic groundwater management strategy.

Fig. 1 a Google Earth map of the area showing the VES points in the study area within the University of Nigeria, Nsukka. b Geologic map of the area showing the location of the study area within the Univer-

sity of Nigeria, Nsukka, and the geological cross section along the line trending SW–NE

Location and geologic setting

The study was carried out within the University of Nigeria, Nsukka Campus, Enugu State (Fig. 1a). Geologically, the Ajali and Nsukka Formations are the two geologic

formations outcropping in the study area (Fig. 1b) and lie within the Anambra sedimentary basin whose rocks are upper cretaceous in age. The Ajali Formation is underlain by shaley impermeable units of Mamu Formation that trapped the Ajali aquifers. According to Agagu et al. (1985), the

Fig. 1 (continued)

Ajali Sandstone (upper Maastrichtian) is about 451 m thick. Lithologically, Ajali formation has poorly consolidated sandstone typically cross-bedded with minor clay layers (Reyment 1965). Nsukka Formation (upper coal measures) conformably overlies the Ajali Sandstone Formation. The lithology of Nsukka is mainly sandstones intercalating with clay, interbedded shales, siltstones, sands and thin coal seams (Reyment 1965), but have become lateritised in many places where they characteristically form resistant capping on mesas and buttes. Nsukka Formation is described as cap rock previously known as upper coal measures (Simpson 1954; Reyment 1965). Nsukka Formation is physiographically dotted by numerous cone-shaped hills which are separated by low lands and broad valleys and are laterite capped (Ogbukagu 1976). Nsukka Formation with Imo Shale marks the onset of another transgression in Anambra Basin during the Palaeocene (Obaje 2009). The most prominent topographical features in the study area are the North–South trending cuesta over Ajali sandstone.

Materials and methods

The materials used to carry out the VES and ERT resistivity surveying include the IGIS (Integrated Geo and Instrument Services), Model: SSR-MP-ATS; GPS for coordinate and elevation measurements; WINRESIST least square iterative inversion software programs for 1-D resistivity inversion; RES2DINV.EXE version 3.57.37 iterative software program for 2-D resistivity inversion; and Surfer Software program for contouring.

Vertical electrical sounding employing Schlumberger electrode configuration was used in the survey. Direct current was sent into the ground through a pair of current electrodes (A and B), and another pair of potential electrodes (M and N) measured the potential difference created. During this process, the apparent resistance R_a of the penetrated geologic materials was read from the crystal display of the resistivity meter.

The apparent resistivity was calculated by multiplying the apparent resistance (R_a) by the geometric factor G , given by the expression in Eq. (1):

$$\rho_a = \pi \frac{\left[\left(\frac{AB}{2} \right)^2 - \left(\frac{MN}{2} \right)^2 \right]}{MN} R_a, \quad (1)$$

where the geometric factor G is

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

The calculated apparent resistivity was plotted on a bilogarithmic graph, characterised by a dynamic range for smoothing and correction of outliers that were viewed as noise. The smoothed resistivity curve was electronically inverted to true resistivity using WINRESIST software program. The software program generates VES curves, which, in addition, gives the primary parameters (which are true resistivity, thickness and depth). Layer resistivity (ρ) and depth (h) are the two parameters that characterised a geologic unit and are fundamentally important both in the interpretation and in the understanding of the geoelectrical models. These parameters helped in deriving other parameters (hydraulic conductivity and hydraulic resistance) for the horizontal, homogenous and isotropic layers (Gemail et al. 2011; Stempvoort et al. 1993). The hydraulic conductivity (K) according to Heigold et al. (1979) is given as in Eq. (3). The hydraulic conductivity of the aquifer protective layers is a key parameter in assessing aquifer vulnerability.

$$K = 386.40 R_{rw}^{-0.93283}, \quad (3)$$

where K is the hydraulic conductivity and R_{rw} is the aquifer resistivity

The rocks of the subsurface are porous and fractured, and the hydraulic conductivity describes the ease with which groundwater moves through the porous spaces.

According to Stempvoort et al. (1993), aquifer vulnerability index (AVI) is a method that quantifies vulnerability by hydraulic resistance to vertical flow of water through the covering layers. The estimation of AVI makes use of two parameters: the thickness (h) of the protective layers and the estimated hydraulic conductivity (K). The hydraulic resistance (C) was computed using the two parameters and is expressed as

$$C = \sum_{i=1}^n \frac{h_i}{K_i}, \quad (4)$$

Table 1 Relationship between aquifer vulnerability index (AVI) and hydraulic resistance (Stempvoort et al. 1993)

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

where K_i is the hydraulic conductivity, while h_i is the thickness of the vadose zone materials. Table 1 gives the relationship between the hydraulic resistance (C) and aquifer vulnerability index (AVI) and helps in determining the vulnerability level.

The spread of the conductivity/resistivity was achieved using the Surfer software program, which displayed the resistivity contrasts in contour segments. In the case of 2-D electrical resistivity measurement for ERT, the pairs of current and potential electrodes were, respectively, increased at 5 m constant separations throughout the entire measurement until the maximum separation is exhausted. This implies that measurement was taken in steps of 5 m, 10 m, 15 m, 20 m, etc., until the maximum length of 200 m was exhausted. The measured resistance for different intervals was converted to apparent resistivity using the expression as follows:

$$\rho_a = 2\pi a R_a, \quad (5)$$

where a is the electrode separations.

The resulting resistivity values were used to generate the ERT using the RES2DINV.EXE software program.

Results and discussion

The analysis and interpretation of the VES data give results for the three primary geoelectric parameters which are the formation resistivities, formation thicknesses and formation depths, and the summary of the computer-aided model for the study area is displayed in Table 2. Figure 2a, b shows some of the geoelectric curves. The resistivity of layer 1 ranges from 213.7 to 4884.9 Ωm with depth and thickness ranging from 0.5 to 5.6 m, respectively, which may be delineated as lateritic sand. The second layer with a resistivity range of 42.3–7208.6 Ωm is a medium-coarse brownish sand intercalation with clay. This layer has thickness and depth ranging from 2.0 to 97.5 m and 3.0 to 99.5 m, respectively.

The third layer has resistivity values varying from 61.1 to 16,724.1 Ωm with thickness and depth ranging from 7.1 to 79.2 and 14.1 to 137.2 m whose lithology can be described as coarse sand and coarse pebbly blackish sand. The fourth layer with relatively high resistivity values (11.3–23,398.0 Ωm) with its high thickness values is the aquifer layer in most of the VES points except at VES 10. The aquifer layer has resistivity ranging from 198.2 to 2398.0 Ωm ; this layer is relatively thick with thickness ranging from 37.7 to 184.3 m and depth ranging from 105.5 to 198.5 m. The hydrogeological (aquifer) layers are overlain by these top layers. The high resistivity values observed in these layers may be attributed to high compact nature of the earth materials and lithification.

The geohydraulic parameters (hydraulic conductivity and hydraulic resistance) were estimated using the combination of the primary geoelectric parameters (resistivity and depth) of the layers overlying the aquifers by employing Eqs. (3) and (4), respectively (Table 3). The hydraulic conductivity (K) ranges from 0.0434 to 0.4890 m day^{-1} , while the hydraulic resistance which quantifies groundwater vulnerability ranges from 38.37 to 1005.84 day^{-1} . The bulk resistivity of the layers overlying the aquifer was contoured (Fig. 3); as shown in the figure, the resistivity is high in the north-western part of the study area. The high resistivity observed across the top layers indicates the compact nature of the geomaterials. Figure 4 shows a contour map displaying the distribution of the sum of the overlying thicknesses. It shows high thickness in the north-eastern, and it decreases towards the southern part. The region of high thickness corresponds to region of low resistivity. The hydraulic conductivity (K) estimated from Eq. (3) was contoured (Fig. 5), and its variation shows a decrease in K from the south towards the eastern and western parts. The variation of this parameter indicates the presence of argillaceous materials in the subsurface and characterises the dynamic behaviour of an aquifer to allow for groundwater flow through the protective layers/unsaturated layers.

The hydraulic resistance was contoured (Fig. 6), and the variation shows the highest value at the north-eastern part of the study area and the lowest concentration in the southern part of the study area. The hydraulic resistance varies inversely with hydraulic conductivity; this implies that both parameters are interdependent on each other. Hydraulic resistance is an essential geological formation parameter that is used in quantifying the resistance of an aquifer to vertical flow of fluid through the protective layers, and the relationship between the aquifer vulnerability index (AVI) and C and $\log C$ (Table 2) shows that AVI in most of the locations was moderate according to the rating of Stempvoort et al. (1993), while VES 6, 7, 8 and 12 were high.

The electrical resistivity tomography (ERT) profiles (Figs. 7, 8 and 9) show the vertical and horizontal spread of resistivity across the subsurface in areas close to the sewage and dumpsite locations. Figure 7 shows the spread of low resistivity across the topmost layers of the subsurface which extends to depth below 10.0 m with high resistivity observed at deeper depths. Figure 8, which was taken 30.0 m away from the sewage site, is characterised by relatively high resistivity across the top layers. This indicates that away from the sewage site (pollutant source) the less the effects of the pollutant (leachate) on the subsurface. Figure 9 shows the effect of pollutants from the top to deeper depths. It could be inferred from this study that regions close to the pollution source will likely have low resistivity values which vary vertically and horizontally across the subsurface. This could be attributed to percolation of contaminant fluids into

Table 2 Summary of measured electrical resistivity data in the study area

VES	Longitude (°E)	Latitude (°N)	Layer resistivity (Ωm)					Thickness (m)					Depth (m)					Elevation (m)
			ρ ₁	ρ ₂	ρ ₃	ρ ₄	ρ ₅	h ₁	h ₂	h ₃	h ₄	h ₅	d ₁	d ₂	d ₃	d ₄		
1	7.4065	6.8585	398.9	874.7	2855.5	4554.0	6809.9	1.3	6.4	53.1	83.1	–	1.3	7.7	60.8	143.9	442	
2	7.4127	6.8693	422.3	2553.3	2455.6	5713.9	7118.9	1.5	9.0	35.7	104.6	–	1.5	10.5	46.2	150.8	418	
3	7.4231	6.8613	1714.9	866.1	4284.2	4089.3	7661.0	1.4	2.9	35.0	108.4	–	1.4	4.3	39.3	147.7	458	
4	7.4267	6.8613	3108.3	756.2	2714.2	7211.7	33,327.2	0.9	3.2	46.1	109.8	–	0.9	4.0	50.2	160.0	468	
5	7.4079	6.8691	626.1	185.7	14,163.8	6799.0	2086.4	1.4	2.9	28.3	114.9	–	1.4	4.4	32.7	147.6	416	
6	7.4222	6.8525	331.6	103.5	2212.0	2398.0	4332.0	2.8	4.6	7.1	137.3	–	2.8	7.4	14.5	151.8	475	
7	7.4098	6.8596	196.6	760.9	320.2	11,463.1	3617.1	0.7	7.1	14.2	98.2	–	0.7	7.8	22.1	120.3	454	
8	7.4089	6.8698	547.4	570.6	1125.9	6261.6	1322.4	3.2	7.4	15.8	117.2	–	2.2	10.6	26.4	143.6	414	
9	7.4056	6.8681	4884.9	7208.6	3993.5	15,235.9	1094.3	5.0	8.3	25.8	86.9	–	5.0	13.3	39.1	126.0	419	
10	7.4123	6.8716	346.2	2403.9	232.0	11.3	–	2.0	97.5	37.7	–	–	2.0	99.5	137.2	–	419	
11	7.4038	6.8719	314.7	1532.9	5083.7	198.2	9.0	1.3	21.9	40.9	41.3	–	1.3	23.2	64.1	105.5	402	
12	7.4105	6.8651	408.3	1266.1	61.1	6191.5	2598.5	1.0	2.0	11.1	184.3	–	1.0	3.0	14.1	198.5	425	
13	7.4016	6.8589	798.9	258.8	3847.1	20,428.3	3901.3	1.8	9.2	12.8	138.7	–	1.8	11.0	23.5	162.2	432	
14	7.4091	6.8625	393.4	42.3	16,724.1	1246.8	821.5	1.8	2.3	39.5	116.1	–	1.8	4.1	43.6	159.8	436	
15	7.4132	6.8639	1758.8	1196.7	1445.2	1270.8	781.7	5.4	13.1	79.2	71.9	–	5.4	18.6	97.7	169.6	430	
16	7.3980	6.8617	2151.0	4350.2	2446.5	9774.9	2455.5	5.6	10.3	29.6	114.0	–	5.6	15.9	45.4	159.4	409	
17	7.4067	6.8696	213.7	493.1	15,855.9	2517.0	3785.6	0.5	4.9	28.4	160.3	–	0.6	5.5	34.0	194.3	412	

Fig. 2 Geoelectric curve at **a** VES 2 and **b** VES 8

the subsurface, which affects the groundwater quality and is hazardous to human health.

In general, from the spread of resistivity we can infer that the percolation of contaminants (leachate) is only surficial, indicating that the aquifer layers are not affected. This may be attributed to the compact nature of the study area. This result (ERT) agrees with the results from VES sounding, where we observed high resistivity values at the aquifer layers.

Conclusion

The VES and ERT results were used in assessing the aquifer vulnerability of the study area. The use of the resistivity method allows the extrapolation of geoelectric and geohydraulic parameters. The variation of the geoelectric parameters showed high resistivity values across subsurface. The

primary parameters (resistivity and thickness) of the protective layers were used in estimating the hydraulic conductivity and hydraulic resistance, in order to evaluate the aquifer vulnerability index (AVI). The ERT profiles showed the lateral and horizontal heterogeneities of the subsurface, and the profiles reflect high resistivity across the subsurface both laterally and horizontally. The geohydraulic parameters provide information about aquifer protective layers which aided the description of the vulnerability of the aquifer layers. The wide variations of the estimated parameters as shown in the contour maps indicate the change in the inhomogeneity of arenaceous sediments. The use of AVI and ERT in this study gives an overview of the groundwater protection of the study area showing the distribution of protected areas. These parameters provide information that is essential in groundwater resource management as well as acts as a guide to assess the vulnerability of hydrogeological units.

Table 3 Estimated geohydraulic parameters

VES	Longitude (°E)	Latitude (°E)	ρ_a (Ω m)	ρ (Ω m)	h (m)	K (m day ⁻¹)	C	log C	AVI
1	7.4065	6.8585	4554.0	4129.1	60.8	0.1637	371.40	2.5699	Moderate
2	7.4127	6.8693	5713.9	5431.2	46.2	0.1268	364.44	2.5616	Moderate
3	7.4231	6.8613	4089.3	6865.2	39.3	0.1019	385.75	2.5863	Moderate
4	7.4267	6.8613	7211.7	6578.7	50.2	0.1060	473.52	2.6753	Moderate
5	7.4079	6.8691	6799.0	14,975.6	32.6	0.0492	662.38	2.8211	Moderate
6	7.4222	6.8525	2398.0	2647.1	14.5	0.2478	58.51	1.7672	High
7	7.4098	6.8596	11,463.1	1277.7	22.0	0.4890	44.99	1.6532	High
8	7.4089	6.8698	6261.6	2243.9	26.4	0.2892	91.30	1.9605	High
9	7.4056	6.8681	15,235.9	16,087	39.1	0.0460	849.31	2.9291	Moderate
10	7.4123	6.8716	232.0	2750.1	99.5	0.2392	416.02	2.6191	Moderate
11	7.4038	6.8719	198.2	6616.6	64.1	0.1055	607.89	2.7838	Moderate
12	7.4105	6.8651	6191.5	1735.5	14.1	0.3675	38.37	1.5840	High
13	7.4016	6.8589	20,428.3	4904.8	23.8	0.1394	170.71	2.2323	Moderate
14	7.4091	6.8625	1246.8	17,159.8	43.6	0.0434	1005.84	3.0025	Low
15	7.4132	6.8639	1270.8	4400.7	97.7	0.1543	633.35	2.8016	Moderate
16	7.3980	6.8617	9774.9	8947.7	45.5	0.0796	571.81	2.7572	Moderate
17	7.4067	6.8696	2517.0	16,562.7	33.8	0.0448	754.42	2.8776	Moderate

Fig. 3 Contour map showing the distribution of bulk resistivity of the overlying layers **Fig. 5** Contour map showing the variation of hydraulic conductivity **Fig. 4** Contour map showing the distribution of thickness of the overlying layers **Fig. 6** Contour map showing the variation of hydraulic resistance

Fig. 7 ERT profile close to dumpsite location

Fig. 8 ERT profile near sewage site

Fig. 9 ERT profile near dumpsite 2

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Compliance with ethical standards

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

Human and animal rights This article does not contain studies with human or animal subjects.

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