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ORIGINAL PAPER

Vulnerability studies of aquifer potential within Auchi Polytechnic Campuses

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Abstract

The increase in anthropogenic activities resulting from an increase in population in Auchi and environs has made groundwater within the study area vulnerable to contamination through infiltration. This research is necessary to ascertain the vulnerability status of aquifer potential within Auchi. The vulnerability of the aquifer potential in the study area was studied with the application of the Dar Zarrouk model. The field data were collected with an Omega 48 resistivity meter using the electrical resistivity method. The Schlumberger arrangement was used to obtain ten (10) vertical electrical soundings (VES) with current electrodes at a maximum spacing of 350m. Seven to ten geo-electric layers were discovered from the analyzed field data. The lithology of the subsoil was found to be predominantly sandstone, with some clay and shale thrown in for good measure. The aquifer has a thickness of 34.995m and 98.557m as the lowest and highest figures, respectively, with an average figure of 59.717m. The aquifer depth was estimated to have a minimum figure of 105.11m and a maximum figure of 140.38m, with an average figure of 123.423m. The aquifer resistivity in the study area was found to have the lowest figure of 404.76Ωm and the highest figure of 4094.5Ωm, with an average figure of 1442.957Ωm. The longitudinal conductance across the region ranges from 0.0162 to 0.2093mhos with an average value of 0.0651mhos, whereas the transverse resistance has a minimum and maximum values of 21661.2144Ωm^2 to 272317.006Ωm^2 respectively with an average figure of 85393.0926Ωm^2. Transmissivity figures of 578.3125m^2/day as a minimum and 675.5673m^2/day as a maximum with an average of 621.7676m^2/day were obtained. The entire study area is generally characterized by low and weak aquifer protective capacity, indicating that the aquifer within the research area is prone to contamination via infiltration. This study would be beneficial in groundwater development and management across the study area and it would also help educate the residents of Auchi on the proper ways of waste disposal.

Keywords Hydraulic parameters · Lithology · Groundwater · Vulnerability · Contamination

Introduction

Accessibility to potable water is very vital in the day-to-day activities of a man. The global demand for water increases with an increase in the population of people and urbanization. Groundwater is widely needed for domestic, agricultural, and industrial purposes (Khosravi et al. 2018). Groundwater vulnerability and contamination can result from increased anthropogenic activities (Obiora and Ibuot 2020). Humans are exposed to severe sicknesses through contaminated groundwater (Popoola and Adenuga 2019). The aquifer is primarily recharged by water bodies and precipitating atmospheric moisture that has permeated the Earth's subsoil (Kwami et al. 2018). The porosity and permeability of the underlying rocks determine

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groundwater occurrence and development. The volume ratio of pore spaces to the overall volume of soil, rock, or sediment is known as porosity (Obiora et al. 2015). Electrical resistivity methods can be utilized to offer useful information on aquifer potential (Senthilkumar et al. 2017). The correlation between transverse resistance and hydraulic transmissivity is required for using the resistivity method to examine water-bearing geologic formations (Kelly and Reiter 1984). Maillet (1947) devised the method of using resistivity and thickness of rocks to estimate aquifer characteristics. Hydraulic conductivity is one of the most important components to consider while evaluating aquifer characteristics (Gemail et al. 2011). The transverse resistance and longitudinal conductance are very crucial for estimating groundwater flow within a permeable geologic formation (Chang et al. 2011). Assessing aquifer potential and susceptibility to contamination is significant in long-term groundwater resource management. Groundwater vulnerability has been studied widely by several researchers using varieties of methods such as overburden protective capacity (Duarte et al. 2019). The increased population in Auchi and the gradual industrialization of its surrounding Okpella community where Dangote Cement and other factories are located have led to the increase in anthropogenic activities within the study area. Groundwater is susceptible to contamination, especially in areas where an unconfined aquifer is dominant; the presence of contaminants in groundwater would make it unfit for a variety of purposes. The predominance of unconfined aquifer within Auchi and environs necessitated this research to assess the vulnerability of the aquifer to contamination for proper groundwater development and management.

The geological setting of the research area

The entire study area lies within Anambra Basin. This basin is almost trapezoidal, covering about 3000km^2 and containing an estimated 9km^3 of sediments (Olubayo 2016; Iheanacho 2016). The basin is part of the Lower Benue Trough, which comprises sediments from the Campanian–Maastrichtian through the Eocene epochs (Obaje, 2009). In the study area, three lithofacies from two different lithostratigraphic units have been identified to be a shale unit overlain by cross-bedded sandstone, burrowed sandstone, and ferruginized sandstone (Adekoya et al. 2011). The shale unit is thought to be from the Mamu Formation and the sandstone units are most likely from the Ajali Formation (Geologic Map of Nigeria, GSN 1994). The shale units are thought to be formed in a shallow marine environment, whereas the sandstone units are believed to be formed in a fluvio-deltaic environment (Nwajide 1990). Fine to coarse-grained and weakly to somewhat sorted sediments were discovered across the research region by Ilegieuno et al. (2020).

Materials and procedures

In this research, the Schlumberger arrangement was employed to acquire the field data. The approach involves the placement of four (4) electrodes at predetermined intervals, which are used to deploy current and calculate the potential posed by current flow within the subsurface. The electrode spacing is raised to acquire more information from deeper depths at a specific place (Egbai, 2011). This is based on the fact that the wider the gap between the current electrodes, the deeper the current can penetrate the subsurface. The resistivity values were measured with the help of a resistivity meter. The field practice entails the conveyance of current via the current electrodes down to the various layers of the Earth's subsurface by spreading out the current electrodes (AB) at equal distances from the midpoint at the same time as the potential electrodes (MN) were fixed at equal distances from the midpoint, and the resulting resistivity values of the various layers were recorded by the resistivity meter. As the resistivity values gained became inconsequential, the technique was continued and the potential electrodes were extended further at a similar distance. A straight line was maintained between

Table 1 Henriet (1976), Oladapo et al. (2004), and Ogungbemi et al. (2004) all rated longitudinal conductance/aquifer protective capacity (2013)

Longitudinal conductance (mhos)	Protective capacity rating
>10	Excellent protective capacity
5–10	Very good protective capacity
0.7–4.9	Good protective capacity
0.2–0.69	Moderate protective capacity
0.1–0.19	Weak protective capacity
˂0.1	Poor protective capacity

Table 2 Transmissivity and aquifer potential scale (Gheorghe 1978)

Value range	Potential
> 500 m^{2}day^{-1}	High aquifer potential
50–500 m^{2}day^{-1}	Moderate aquifer potential
5–50 m^{2}day^{-1}	Low aquifer potential
0.5–5 m^{2}day^{-1}	Very low aquifer potential
˂0.5 m^{2}day^{-1}	Negligible aquifer potential

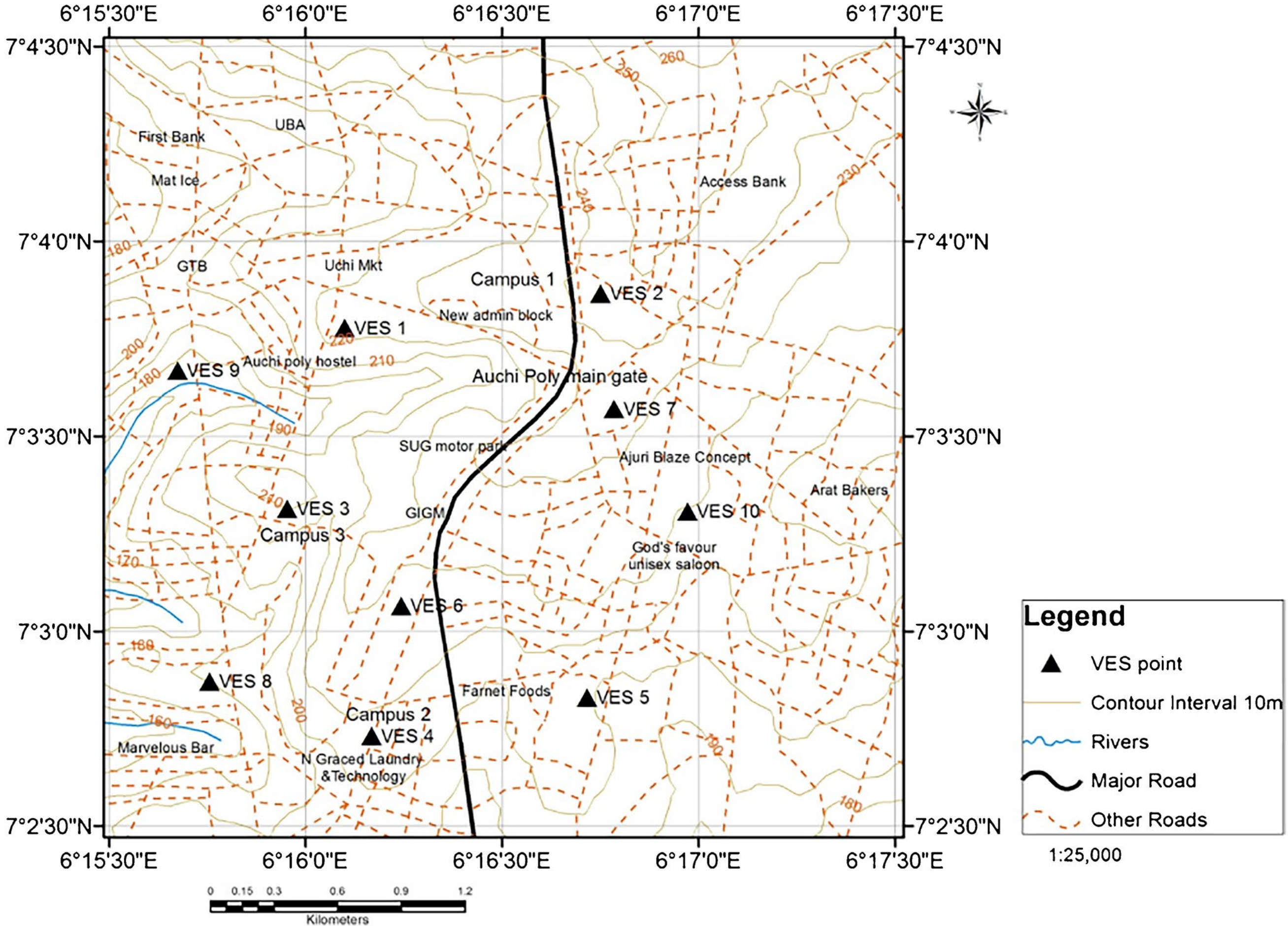


Fig. 1 Locations of vertical electrical sounding (VES) on a base map

the potential and current electrodes during the survey. The apparent resistivity of the various layers was estimated from the obtained resistance values. The apparent resistivity and current electrode spacing AB/2 were plotted on a log-log graph. Master curves and supplementary point charts were combined to partially curve match the resulting curves (Koefoed 1979; Orellana and Mooney 1972). Maillet (1947) used Dar Zarrouk to explain the connection between transverse resistance and longitudinal conductance. Equations 1 and 2 were used to compute longitudinal conductance (S) and transverse resistance (R) for each point within the study region.

$$\boldsymbol{R} = \sum_{i=1}^{n} \boldsymbol{h}_i \boldsymbol{\rho}_i \tag{1}$$

where ρ_i is the resistivity and h_i is the thickness of the layers. R denotes the transverse resistance.

$$\boldsymbol{S} = \sum_{i=1}^{n} \frac{\boldsymbol{h}_i}{\boldsymbol{\rho}_i} \tag{2}$$

The longitudinal conductance and transverse resistance are known as the Dar Zarrouk parameters and they are very useful in understanding aquifer potential (Zohdy et al. 1974). The aquifer protective capacity (APC) was rated across the study area using Table 1.

Equations 3 and 4 were used to calculate the transmissivity and hydraulic conductivity of the aquifer

$$T = K\,\sigma R = \frac{KS}{\sigma} = Kh \tag{3}$$

where R is referred to as the aquifer's transverse resistance, σ is the conductivity, T denotes transmissivity, S represents the longitudinal conductance, and K stands for the hydraulic conductivity. Heigold et al. (1979) proposed Eq. 4 for estimating an aquifer's hydraulic conductivity,

$$K = 386.40{R_{rw}}^{(-0.93283)} \tag{4}$$

where R_{rw} stands for aquifer resistance and K symbolizes hydraulic conductivity.

Table 3 Vertical electrical sounding data yielded aquifer and hydraulic parameters

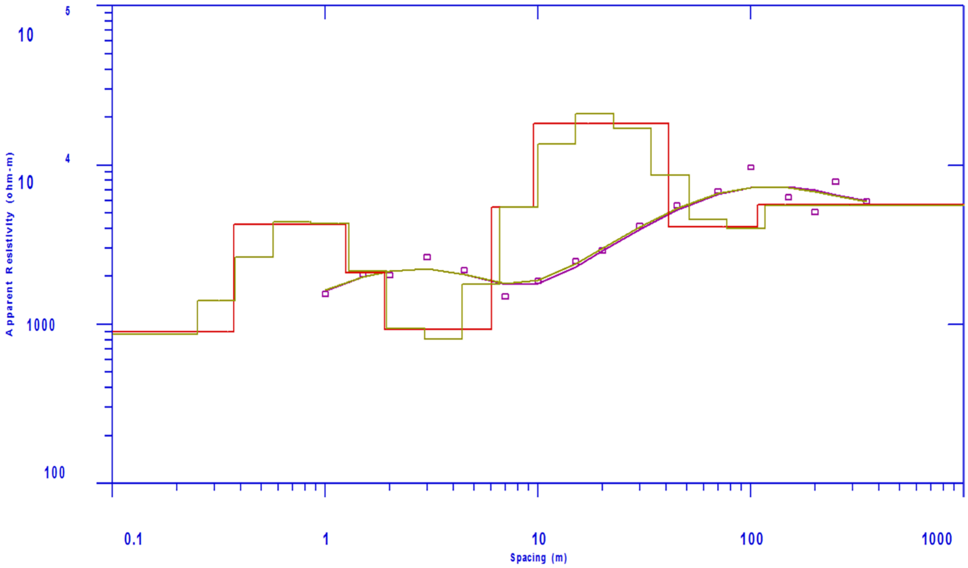
VES	Easting	Northing	Apparent resistivity, ρ (Ωm)	Thickness, h (m)	Depth (m)	Longitudinal conductance, S (mhos)	Transverse resistance, R (Ωm^2)	Aquifer conductivity (Ωm^{-1})	Hydraulic conductivity, K (m/day)	Transmissivity, T (m^2/day)
1	6.268282	7.063008	4094.5	66.508	107.5	0.016243	272317	0.000244	0.164994	675.5673
2	6.279131	7.064485	1505.7	34.995	130.55	0.023242	52691.97	0.000664	0.419515	631.6635
3	6.265839	7.055226	545.76	39.69	129.7	0.072724	21661.21	0.001832	1.081135	590.0401
4	6.269418	7.045512	404.76	84.734	140.38	0.209344	34296.93	0.002471	1.428779	578.3125
5	6.278563	7.047159	1529.9	40.913	116.85	0.026742	62592.8	0.000654	0.413321	632.3404
6	6.270611	7.051136	866.56	90.513	126.8	0.104451	78434.95	0.001154	0.702377	608.652
7	6.279642	7.059543	721.99	61.677	105.11	0.085426	44530.18	0.001385	0.832748	601.2356
8	6.262487	7.047898	1866.4	39.704	124.97	0.021273	74103.55	0.000536	0.343357	640.8413
9	6.261181	7.061133	1225.7	39.879	118.24	0.032536	48879.69	0.000816	0.508276	622.994
10	6.282824	7.055169	1668.3	98.557	134.13	0.059076	164422.6	0.000599	0.381244	636.0295

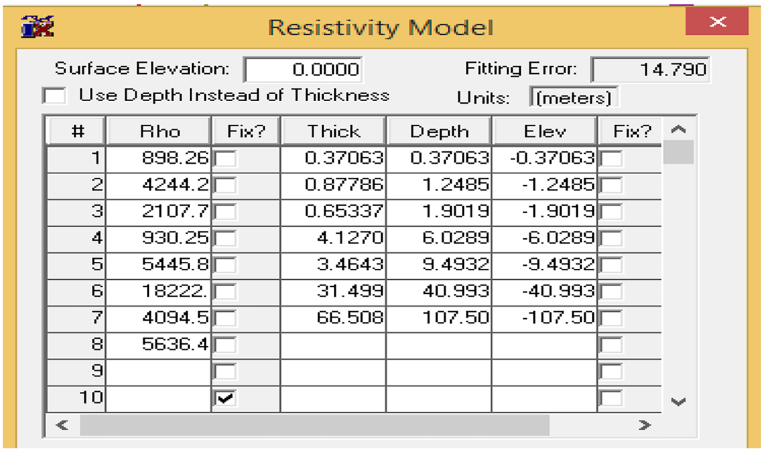
The result of $K\sigma$ is rather steady in places with comparable geologic background. As a result, an understanding of K gleaned from present boreholes and $\boldsymbol{\sigma}$ from VES sounding may be utilized to determine $\boldsymbol{K\sigma}$ for a similar geologic region, allowing for the projection of transmissivity and aquifer hydraulic conductivity for the entire area (Niwas and Singhal 1981). The transmissivity and aquifer potential scale are shown in Table 2.

Results

The result from the qualitative and quantitative interpretation of the field data was used to describe the aquifer's potential and vulnerability in the research area. Ten (10) vertical electrical soundings (VES) were collected from the research area (Fig. 1; Table 3) and analyzed using computer software (interpex). The acquired VES curves were curve matched with the master curves for correctness. VES 1, 2, 3, 4, 5, 6, 7, 8, 9, and 10 presented KAK, A, AKH, KH, KH, AKH, AKH, A, KH, and A curve types, correspondingly. The data were analyzed qualitatively, and seven (7) to ten (10) geo-electric strata were discovered across the research area. Figure 2 depicts a representative plot of the interpreted profile and VES point resistivity models. Topsoil, clay, clayey sand, shale, water-saturated sand, and dry sand are some of the lithologies found in the research area. The minimum and maximum aquifer thickness figures are 34.995m and 98.557m with an average figure of 59.717m, the lowest and highest estimated aquifer depth values are 105.11m and 140.38m with an average depth figure of 123.423m, and a minimum and maximum aquifer resistivity value of 404.76Ωm and 4094.5Ωm were obtained with an average value of 1442.957Ωm. The longitudinal conductance has the lowest figure of 0.0162mhos and the highest figure of 0.2093mhos, with an average figure of 0.0651mhos. The transverse resistance in the research area gave the lowest figure of 21661.2144Ωm^2 and the highest figure of 272317.006Ωm^2, with an average of 85393.0926Ωm^2 which is an indication that there is an adequate thickness of aquifer in the research area. The aquifer conductivity has a minimum and maximum figures of 0.00024423Ωm^{-1} and 0.0024706Ωm^{-1}, respectively, with a mean figure of 0.001035503Ωm^{-1}. The hydraulic conductivity is estimated to have the lowest figure of 0.164993857m/day and a maximum figure of 1.428778783m/day, with a mean figure of 0.627574572m/day. Transmissivity figures of 578.3125m^2/day as a minimum and 675.5673m^2/day as a maximum with an average of 621.7676m^2/day were obtained.

Fig. 2 A typical interpreted profile as well as the VES point resistivity models




Resistivity Model

Surface Elevation: 0.0000

Fitting Error: 14.790

☐ Use Depth Instead of Thickness

Units: [meters]

#	Rho	Fix?	Thick	Depth	Elev	Fix?
1	898.26	☐	0.37063	0.37063	-0.37063	☐
2	4244.2	☐	0.87786	1.2485	-1.2485	☐
3	2107.7	☐	0.65337	1.9019	-1.9019	☐
4	930.25	☐	4.1270	6.0289	-6.0289	☐
5	5445.8	☐	3.4643	9.4932	-9.4932	☐
6	18222.	☐	31.499	40.993	-40.993	☐
7	4094.5	☐	66.508	107.50	-107.50	☐
8	5636.4	☐				☐
9		☐				☐
10		☑				☐

Discussion of the findings

The longitudinal conductance was used to model and estimate the overburden protective capacity. It was discovered that the research area has a poor to weak aquifer protective capacity, indicating that the aquifer is highly sensitive to contamination. Figure 3 shows a map of the aquifer's protective capacity, and areas with poor and weak protective capacity can be seen on the map. The aquifer protective capacity across the research area was rated (Table 4) with the help of the Longitudinal Conductance/Aquifer Protective Capacity Rating (Henriet 1976; Oladapo et al. 2004; Ogungbemi et al. 2013). Aquifer vulnerability to contamination may be increased in areas where the vadose zone is very porous and permeable (Usman 2009). Transmissivity is high in porous and permeable geologic materials while vulnerability to contamination is equally high in porous geologic materials. An aquifer is vulnerable to contamination in regions where the overlying geologic formation above the aquifer is very permeable and when the water table tends to be recharged within a short time due to the lack of a confined geologic layer. Unconfined aquifers are recharged faster than confined aquifers (Thomas and Walker 2001; Oke et al. 2018). As noted by Golam et al. (2014) and Anomohanran (2013), impermeable geologic materials such as clay and shale usually have high longitudinal conductance values as a result of their low resistivity values, hence implying significant protection to the underlying aquifer, whereas permeable materials such as sand and gravels have low longitudinal conductance values resulting from their high resistivity values and do not have significant protection of the underlying aquifer. The overburden lithologies within the research area are primarily permeable sandstones with little or no impermeable geologic layers; hence, the aquifer is very vulnerable

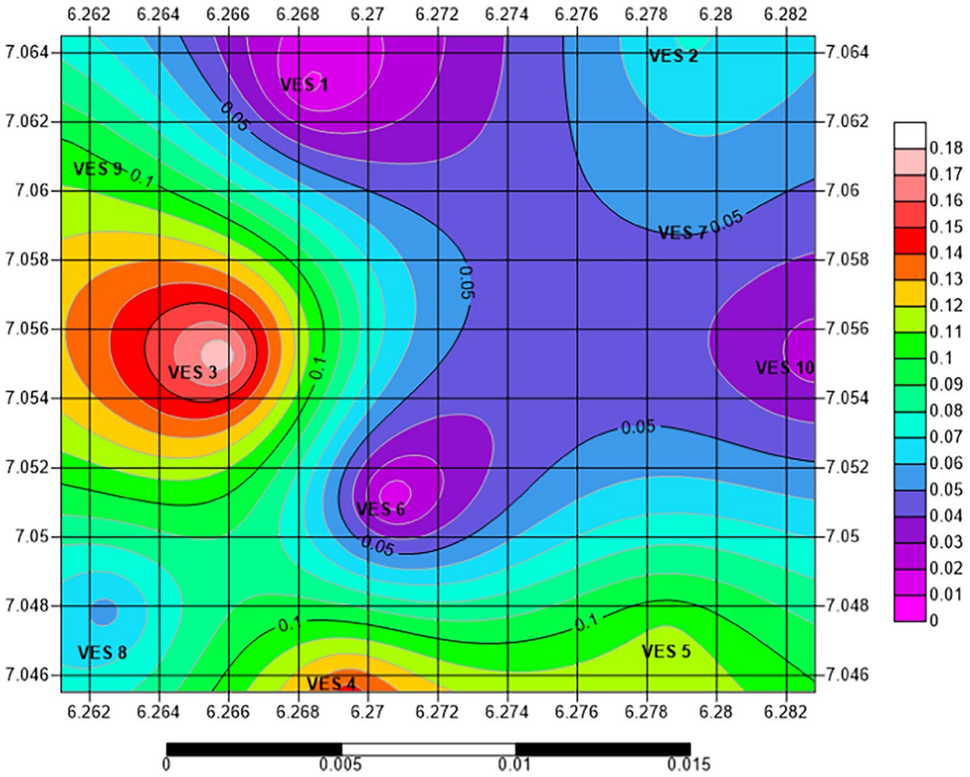


Fig. 3 The study area's aquifer overburden protective capacity map

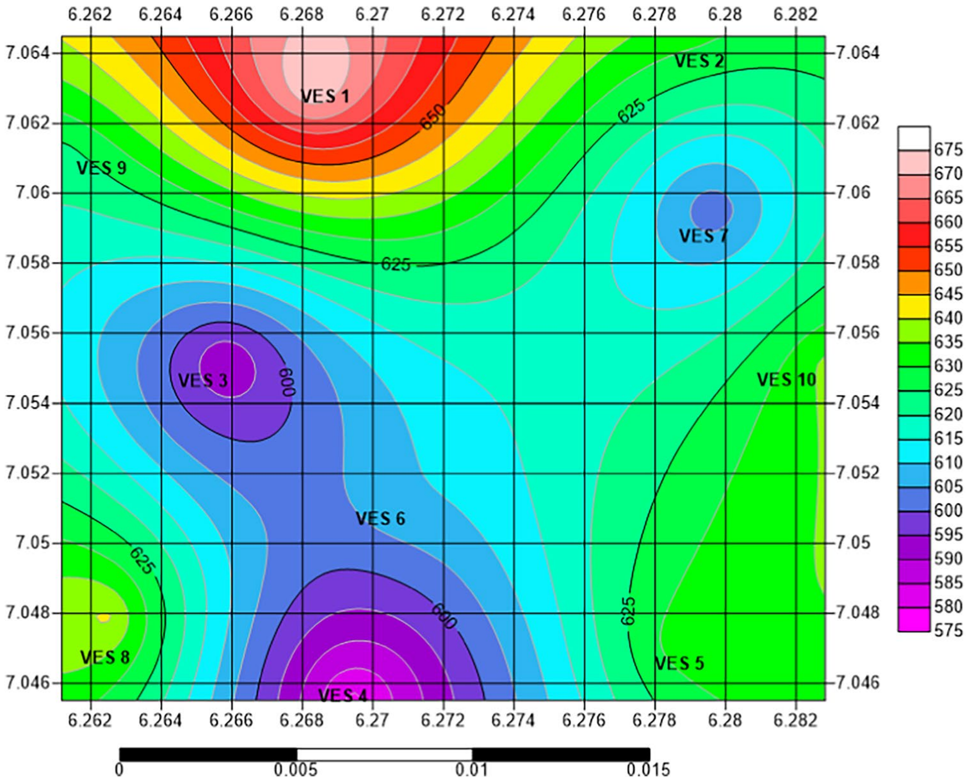
to contamination through infiltration. The values of the transverse resistance across the study area show that the area is generally characterized by low to high aquifer thickness. Transverse resistance below 200,000m^2 does not signify a lack of an aquifer, but it probably means the insufficient thickness of an aquifer or strongly mixed aquifer formation with finer sediments (Ezeh, 2012). The study area typically has high groundwater flow rate which is indicated by the values of hydraulic conductivity. Hydraulic conductivity suggests a smooth flow of water beneath the surface of the Earth (Ezema et al., 2020). High values of hydraulic conductivity indicate a high groundwater flow rate. Aquifer regions with high values of hydraulic conductivity will have high permeability (Niwas & Singhal, 1985).

Table 3 shows that the transmissivity has a minimum and maximum figures of 578.3125002m^2/day and 675.5673476m^2/day, respectively, with an average figure of 621.7676308m^2/day. The transmissivity map of the research area is shown in Fig. 4. High aquifer potential is

Table 4 Summary of the study area's aquifer potential and protective capacity rating

VES	Longitude	Latitude	Transmissivity (m^2/day)	Aquifer potential	Longitudinal conductance	Aquifer protective capacity rating
1	6.268282	7.063008	675.5673476	High potential	0.007730646	Poor
2	6.279131	7.064485	631.6635394	High potential	0.072147876	Poor
3	6.265839	7.055226	590.040092	High potential	0.072724274	Weak
4	6.269418	7.045512	578.3125002	High potential	0.145613678	Weak
5	6.278563	7.047159	632.340407	High potential	0.1138851104	Weak
6	6.270611	7.051136	608.6519984	High potential	0.011740088	Poor
7	6.279642	7.059543	601.2355576	High potential	0.054201786	Poor
8	6.262487	7.047898	640.8413183	High potential	0.055778155	Poor
9	6.261181	7.061133	622.994028	High potential	0.103801103	Weak
10	6.282824	7.055169	636.0295191	High potential	0.024075943	Poor

Fig. 4 The study area's transmissivity map



matched by high transmissivity figures. Significant transmissivity values of more than 500m^2/day are widespread in the research area, indicating high aquifer potential.

Conclusion

The qualitative and quantitative data processing and interpretation of VES data across the research area revealed seven (7) to ten (10) geo-electric layers. The VES plots gave KAK, A, AKH, KH, KH, AKH, AKH, A, KH, and A types. The research area has a significant depth to the aquifer. The predominance of sandstones with little or no shale/clay across the research area makes the aquifer to be vulnerable to contamination through infiltration. The transverse resistance figures show that the thickness of the aquifer in the research area is appropriate and transmissivity figures of more than 500m^2/day are common in the research area, signifying a high aquifer potential. The preponderance of sandstone lithology is responsible for the high aquifer yield seen throughout the research area. It is therefore concluded that the research area has high aquifer potential but it is prone to contamination via infiltration and this will pose a serious health implication to the inhabitants of the study area since groundwater is their major source of drinking water. This study will be helpful in the effective and sustainable management of the groundwater resources within the study area.

Declarations

Conflict of interest The authors declare that they have no competing interests.

References

Adekoya JA, Aluko AF, Opeloye SA (2011) Sedimentological characteristics of Ajali Sandstone in the Benin flank of Anambra Basin. Nigeria Ife J Sci 13(2):327–337

Anomohanran O (2013) Hydrogeophysical and hydrogeological investigations of groundwater resources in Delta Central, Nigeria. J Taibah Univ Sci 9:57–68

Chang SW, Clement TP, Simpson MJ, Lee K (2011) Does sea – level have an impact on saltwater intrusion? Adv Water Resour 34:1283–1291

Duarte L, Espinha MJ, Teodoro AC (2019) An open source GIS-based application for the assessment of groundwater vulnerability to pollution. Environments 6(7):86

Gemail KS, El-Shishtawy AM, El-Alfy M, Ghoneim MF, Abd El-Bary M (2011) Assessment of aquifer vulnerability of industrial wastewater using resistivity measurements. A case study, along El-Gharbyia main drain, Nile Delta, Egypt. J Appl Geophys 75:140–150

Geological map of Nigeria, GSN (1994)

Gheorghe A (1978) Processing and synthesis of hydrological data. Abacus Press June Bridge Wells, Kent. pp. 122–136

Golam SS, Keramat M, Shahid M (2014) Deciphering transmissivity and hydraulic conductivity of the aquifer by vertical electrical sounding (VES) experiments in Northwest Bangladesh. J Appl Phys. pp. 4-6

Heigold PC, Gilkeson RH, Cartwright K, Reed PC (1979) Aquifer transmissivity from surficial electrical methods. Groundwater 17(4):338–345

Henriet JP (1976) Direct applications of the Dar Zarrouk parameters in groundwater survey. Geophys Prospect 24:344–353

Iheanacho PU (2016) Subsurface evaluation of source rock and hydrocarbon potential of the Anambra Basin, South Eastern Nigeria. Dissertation.com Boca Raton, Florida, USA. Www.Bookpump.com. ISBN 978-1-59942-339-5

Ilegieuno OA, Ighodaro EJ, Sunny RO (2020) Sedimentology and paleogeography synthesis of cretaceous sediments in Auchi area of Anambra Basin. J Appl Sci Environ Manag. https://doi.org/10.4314/jasem.v24i5.32

Kelly WE, Reiter PF (1984) Influence of anisotropy on relations between electrical and hydraulic properties of aquifers. J Hydrol 74:311–321

Khosravi K, Sartaj M, Tsai FTC, Singh VP, Kazakis N, Melesse AM, Prakash I, Bui DT, Pham BT (2018) A comparison study of DRASTIC methods with various objective methods for groundwater vulnerability assessment. Sci Total Environ 642:1032e1049

Koefoed O (1979) Geosounding Principles I. Resistivity sounding measurements, Elsevier Scientific Publishing Company, Amsterdam, p. 275

Kwami IA, Ishaku JM, Bello AM, Yusuf A, Mukkafa S (2018) Assessment of water quality index for the groundwater in Gombe and environs, North-east Nigeria. IOSR J. Appl. Geol. Geophys. (IOSR-JAGG) 6.5 29–37

Maillet R (1947) The fundamental equations of electrical prospecting. Geophysics 12(4):529–556

Niwas S, Singhal DC (1981) Estimation of aquifer transmissivity from Dar-Zarrouk parameters in porous media. J Hydrol 50:393–399

Nwajide CS (1990) Cretaceous sedimentation and paleogeography of the Central Benue Trough. In: Ofoegbu CO (ed) The Benue Trough structure and evolution. International Monograph Series, Braunschweig, pp 19–38

Obiora DN, Ajala AE, Ibuot JC (2015) Evaluation of aquifer protective capacity of overburden unit and soil corrosivity in Makurdi, Benue State, Nigeria, using electrical resistivity method. J Earth Sys Sci 124:125–135

Obiora DN, Ibuot JC (2020) Geophysical assessment of aquifer vulnerability and management: a case study of University of Nigeria, Nsukka, Enugu State, Applied Water Science, vol. 10, no. 1

Ogungbemi OS, Badmus GO, Ayeni OG, Ologe O (2013) Geo-electric investigation of aquifer vulnerability within Afe Babalola University, Ado–Ekiti, Southwestern Nigeria. J Appl Geol Geophys 1:28–34

Oke SA, Vermeulen D, Gomo M (2018) Intrinsic vulnerability assessment of shallow aquifers of sedimentary basin of southwestern, Nigeria. Jamba: J Disas Risk Stud 10(1):a333

Oladapo MI, Mohammed MZ, Adeoye OO, Adetola OO (2004) Geoelectric investigation of the Ondo-State Housing Corporation Estate Ijapo, Akure southwestern Nigeria. J Min Geol 40:41–48

Olubayo LB (2016) The main oil source formations of the Anambra Basin, Southeastern Nigeria. Geology Department, University of Ibadan, Nigeria. www. Search and discovery. Com

Orellana E, Mooney HM (1972) Two and three layer master curve and auxiliary point diagrams for VES, Interciencia. Madrid, Spain. P. 43

Popoola OI, Adenuga OA (2019) Determination of leachate curtailment capacity of selected dumpsites in Ogun State southwestern Nigeria using integrated geophysical methods, Scientific African, vol. 6, article e00208

Senthilkumar S, Gowtham B, Vinodh K, Arulprakasam V, Sundararajan M (2017) Delineation of subsurface layers using resistivity imaging techniques in coastal blocks of Thiruvallur District, Tamil Nadu, India, 46, 986–994

Thomas H, Walker LG (2001) Assessing vulnerability of groundwater; California Department of Health Services Report 1–11: Sacramento, CA, USA

Usman DK (2009) Evaluation of models for assessing groundwater vulnerability to pollution in Nigeria. Bayero Pure Appl Sci 2(2):138–142

Zohdy AAR, Eathon CP, Mabey DR (1974) Application of surface geophysics to groundwater investigation. Tech. Water Resources Investigation. Techniques of water resources investigation of the United States Geological Survey, United States Department of Interior Geological Survey Washington DC. I19, 13