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ORIGINAL ARTICLE

Aquifer potentials and vulnerability studies in Northern parts of Anambra State, SE Nigeria

I. I. Obiadi[1] · N. E. Ajaegwu[2] · C. I. Meniru[1] · I. C. Nzeakor[1] · R. C. Ejike[1]

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Abstract
Geophysical and geologic field mapping data were used to model and estimate groundwater potentials and aquifer vulnerability in parts of Awka North Local Government Area of Anambra State, SE Nigeria. The Vertical Electrical Sounding VES technique of the Resistivity Method was employed to acquire field data used to estimate aquifer potentials, while the Aquifer Vulnerability Index AVI method was used to model and characterize aquifer vulnerability. Results from the interpretations of the VES data showed that the area is underlain by Topsoil, sandstone, clayey sandstone, and shale lithologies at various horizons and depths. The target aquifers are water-saturated sandstone units. The average depth to the aquifer (and overburden thickness) in the study area is 50.8 m. Depth to the aquifer increases southwards suggesting deeper aquiferous units towards the southern parts of the study area. Average aquifer thickness and transmissivity are 14.81 m and 396.85 m^2/day, respectively, and their values also increase towards the south. Aquifer potential classification based on aquifer transmissivity suggests moderate-high aquifer potentials in the study area. Estimated Aquifer Protective Capacity APC and Aquifer Vulnerability models gave moderate–good APC and moderate-high vulnerability, respectively. These models, which are a consequence of the overburden thickness and lithologies, have implications for groundwater quality and aquifer quality conservation. Groundwater conservation and exploitation are important elements in the sustainable development of groundwater resources in the study area. The results of the groundwater potentials, APC, and aquifer vulnerability analysis, therefore, suggest that groundwater exploitation schemes should target the southern parts of the study area where these parameters of interest are more favorable. Also, proper waste disposal management schemes designed with regard to the underlying geology/hydrogeology should be put in place in the study area since the aquifer is vulnerable to pollution.

Keywords Groundwater · Aquifer potentials · Aquifer vulnerability · Vertical electrical sounding · Nigeria

Introduction

Water is a vital natural resource needed by humans for sustenance and development, and the lack of access to potable water can have severe consequences (Mgbolu et al. 2019). Groundwater is a major source of water for humans, especially in developing nations and rural communities where the availability of the needed and necessary public infrastructure for surface water management, reticulation, and supply are lacking or inadequate to cater to the needs of the peoples (Okolo et al. 2017; Obiadi et al. 2016). Where this is the case, the inadequacy in public water supply results in the reliance of the people on groundwater resources which are mostly harnessed by way of drilling and development of boreholes and relatively shallow hand-dug wells. Groundwater potential in a given area depends on the presence and hydraulic properties (such as porosity, permeability, transmissivity, storage, etc.) of groundwater-bearing units also known as aquifers; while groundwater quality and potability depend on its hydrogeochemical properties and vulnerability to contamination/pollution (Mgbolu et al. 2019; Obiadi, et. al., 2012, 2013, 2016; Ozoemenam et. al., 2018; Okolo et. al., 2017). The vulnerability of groundwater qualitatively reflects the natural ability of the aquifer to be reached and affected by pollutants from surface sources such as landfill, industrial wastewater discharge, chemical fertilizers, pesticides, herbicides, waste dumps, etc. (Ekanem 2022; Gogu

✉ I. I. Obiadi
ii.obiadi@unizik.edu.ng

[1] Department of Applied Geophysics, Nnamdi Azikiwe University, Awka, Nigeria

[2] Department of Geology, Nnamdi Azikiwe University, Awka, Nigeria

and Dassargues 2000). Groundwater is largely protected from pollution by natural barriers such as impermeable overburden lithology like shale. However, in areas with thin/permeable overburden layers where aquifers are in hydraulic continuity with the ground surface, groundwater could be vulnerable to pollution from surface sources. Generally, aquifer vulnerability refers to the degree of protection against contamination offered by the overlying strata and the potential for the purification of contaminated water in the aquifer (Mundel et al. 2003). Sustainable management of groundwater resources such as exploration and exploitation, the prediction of vulnerability and pollution risk, and the protection of groundwater resources are very crucial and important in meeting water supply needs (Ducci and Sellerino 2022; Mgbolu et al., 2019). Groundwater contamination can be managed and minimized by delineating and monitoring vulnerable areas.

The study area (bounded by 06° 15′ 00″ N to 06° 18′ 00″ N and 07° 2′ 00″ E to 07° 5′ 00″ E.) is situated in Awka North Local Government Area of Anambra State, Southeast Nigeria, and covers semi-urban communities of Mgbakwu, Isu-Aniocha, and Urum, (Fig. 1). Geologically, the study area is within the Northern parts of the Niger Delta Basin, and it is underlain by the varied lithologies of the Paleocene Imo Formation and Eocene Ameki Group (Fig. 2). The lithologies of the formations are mainly shales, sandstones, siltstones, and occasional limestones. The Imo Formation is essentially an aquiclude, except for the small lenticular sandstone bands (Ebenebe sandstone and Amenyi sandstone), and fractured/weathered indurated shales which constitute good confined and unconfined aquifers that can sustain productive boreholes when encountered in some locations. The sandstones of the Ameki Group are known to be porous and generally very permeable, and are the main aquifer in areas where Ameki Group outcrops in the study area. These sandstone aquifers depend on primary porosity (pore spaces) and do not necessarily require secondary porosity (fractures) to be productive.

This research is aimed at identifying and characterizing the target aquifer(s) and aquifer vulnerability distributions for the sustainable exploitation and management of the groundwater resources in the study area for the benefit of the inhabitants. Since borehole durability and groundwater quality are two major factors mitigating groundwater exploitation and supply in the study area (Irumhe 2022; Ezim and Obiadi 2021; Okolo et al. 2020), the results from this research project will be very useful and important in the quest to increase access to potable water supply for locals.

Methodology

Geological and geophysical field surveys were conducted to obtain data that were analyzed and interpreted for this research. The topographic (base) map of the study area was obtained and studied, and landmarks and other important

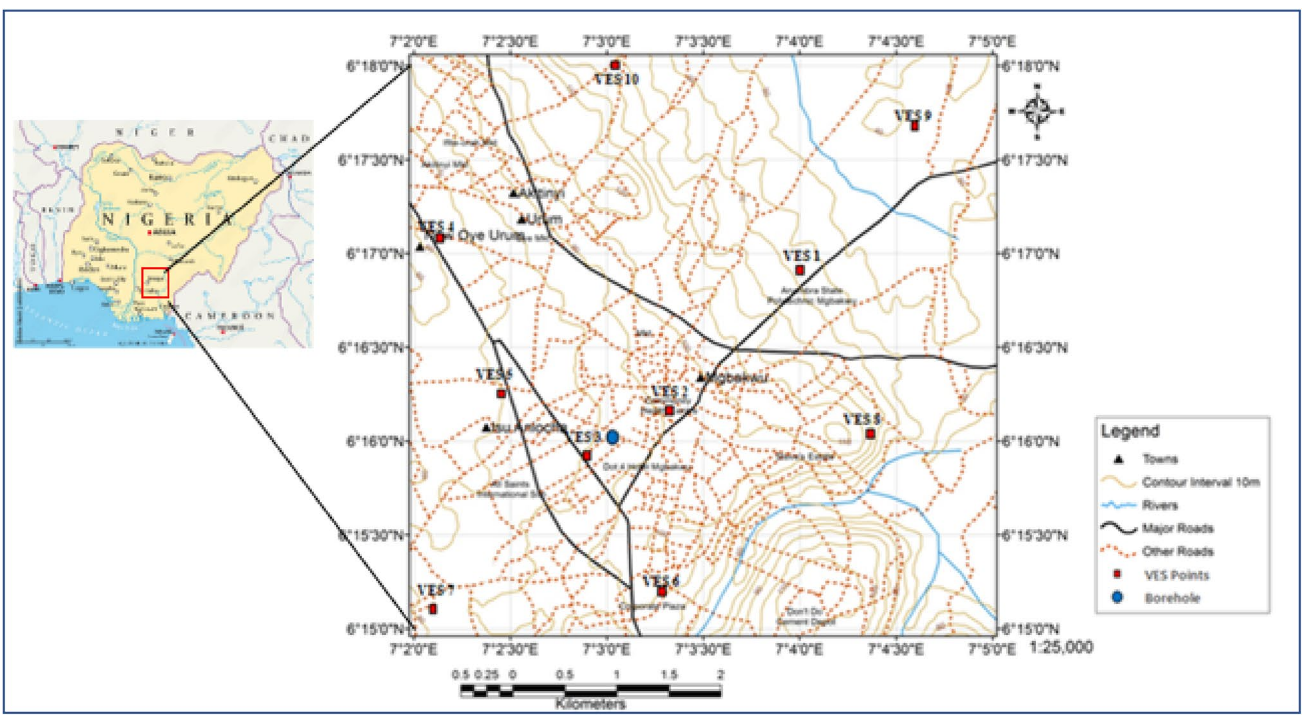

Fig. 1 Base map of the study area showing the target semi-urban communities and VES point

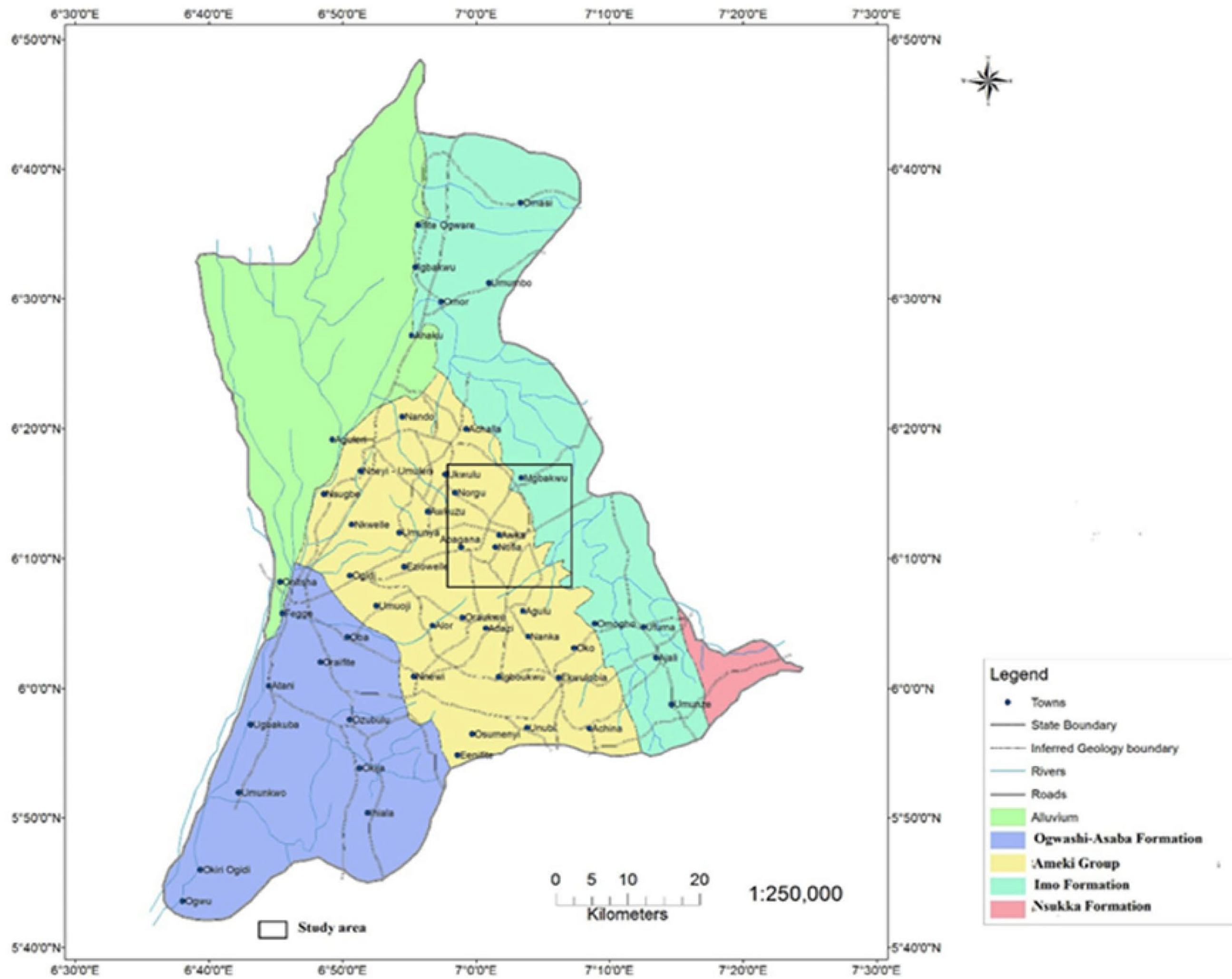

Fig. 2 Geologic map of Anambra State showing the major lithostratigraphic units outcropping in the study area (enclosed in the square) (not drawn to scale)

features were identified before the field exercises. Geological field mapping, by surface traversing, contact identification, and detailed outcrop studies, were done to identify the lithologies outcropping in the study area and their spatial distribution, which formed input parameters for aquifer vulnerability assessment.

The geophysical field survey was done using the Electrical Resistivity Method (Vertical Electrical Sounding VES) of geophysical investigation. Ten (10) VES locations on representative grid points (determined and identified on the base map; Fig. 1) were conducted to investigate the vertical and lateral distribution of lithologies; presence, nature, and depth to aquifer unit(s); and the nature of overburden. The Schlumberger array configuration was used in the VES data acquisition, with a maximum half-current electrode spacing (AB/2) of 115 m. The resistivity meter (Petrozenith™) was used to acquire the resistivity distribution data, and the data were recorded and stored on a laptop computer. The apparent resistivity distribution data was then analyzed, modeled, and interpreted using the Interpex 1D inversion and RES1DIV inversion software to produce the geo-electric sections of the surveyed points with the respective layer thicknesses and depths. Geo-electric models and interpretations were constrained by borehole logs and data obtained within the study area especially those close to the VES points. The geo-electric sections were then correlated to determine the depth and horizontal distributions, and lateral continuity of lithologic units (aquifer and overburden) of interest. The results/data obtained from the modeling and interpretation of the VES field data were used to plot maps of depth to aquifer and aquifer thickness of the study area.

Aquifer hydraulic property (transmissivity) was modeled and estimated from the electrical resistivity field data using the equation (Niwas and Singhal, 1981):

$$T = K\sigma R = \frac{KS}{\sigma} = Kh, \quad (1)$$

where T is the transmissivity, K is the hydraulic conductivity (an average of 26.8 m/day was obtained from pumping tests within the area (Offordile, 2002)), R is the transverse resistance of the aquifer, S is the longitudinal conductance, σ is the aquifer electrical conductivity (inverse of resistivity) and h is aquifer thickness. R and S are commonly called the Dar Zarrouk parameters, and are estimated using the following relations:

$$R = \sum_{i=1}^{n} h_i \rho_i \quad (2)$$

and

$$S = \sum_{i=1}^{n} \frac{h_i}{\rho_i}, \quad (3)$$

where h_i and ρ_i are the thickness and resistivity of the i^{th} layer in the section, respectively.

The Aquifer Protective Capacity APC was estimated from the distribution of the longitudinal conductance values, and the overburden protective capacity of the study area was analyzed and rated (Golam et al. 2014). Excellent and good APC are characterized by relatively high longitudinal conductance while weak and poor APC are characterized by relatively low longitudinal conductance. A map of the APC distribution was produced.

Aquifer Vulnerability Index AVI method (Stempvoort et al. 1993) was used to model and characterize aquifer vulnerability in the study area. AVI method has been widely used in analyzing different aquifer types and settings, and the choice of the method in this research is informed by the scale of the project, the hydrogeological/lithological characteristics, and data availability in the study area (Ducci and Sellerino 2022; Ekanem 2022; Gogu and Dassargues 2000; Novinpour and Khezri 2019). AVI method quantifies vulnerability by hydraulic resistance to vertical flow of water through the protective layers. Hydraulic resistance C is defined by

$$C = \sum_{i} \frac{d_i}{k_i}, \quad (4)$$

where d_i, K_i are the thickness and hydraulic conductivity of each protective (overburden) layer. The dimension of C is time. Typical values for K, based on Freeze and Cherry (1979) as used by Stempvoort et al. (1993), are sand: 10 m/day, silt: 10^{-1} m/day, and massive till (mixed sand–silt–clay): 10^{-5} m/day. Expressing C in years, the log C can be used for aquifer vulnerability classification like: log $C < 1$, extremely high vulnerability; log c = 1–2, high vulnerability; log C = 2–3, moderate vulnerability; log C = 3–4, low vulnerability; and log C > 4, extremely low vulnerability. The aquifer vulnerability map of the study area was produced from the results of the AVI model. The workflow of the research methodology is presented in Fig. 3.

Results

VES analysis and aquifer hydraulic properties characterization

Resistivity data (resistance measured in ohms) acquired from the field surveys and stored in a laptop computer were converted to apparent resistivity data (in ohm-meter) by multiplying the measured resistance values with the appropriate geometric factor corresponding to the array configuration and electrode spacing. The apparent resistivity data obtained for the various sounding event at each sounding location were plotted against the current electrode spacing (AB/2) and interpreted using the iterative modules of Interpex 1D™ and RES1DIV™ inversion software (Fig. 4). The interpretation was constrained by data obtained through partial curve matching of master curves and auxiliary point charts (Obiadi et al. 2013). The results of the interpreted VES plots and geo-electric sections gave six (6) to seven (7) layers with their respective thickness, depths, and apparent resistivities.

Geologic (lithology) inferences were made from the apparent resistivity distribution style of the geo-electric section and the knowledge of the local geology and constrained by lithologic logs obtained from boreholes drilled close to VES points in the study area. The inferred lithologies include Topsoil, dry sandstone, clayey sandstone, shale, and water-saturated sandstone, of variable thicknesses and occurring at variable depths. The water-saturated sandstones are the target aquifers. The depth to the aquifer (and overburden thickness) varies from

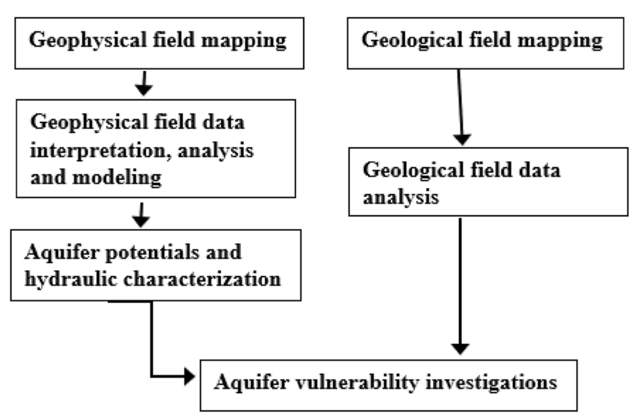

Fig. 3 Research methodology workflow

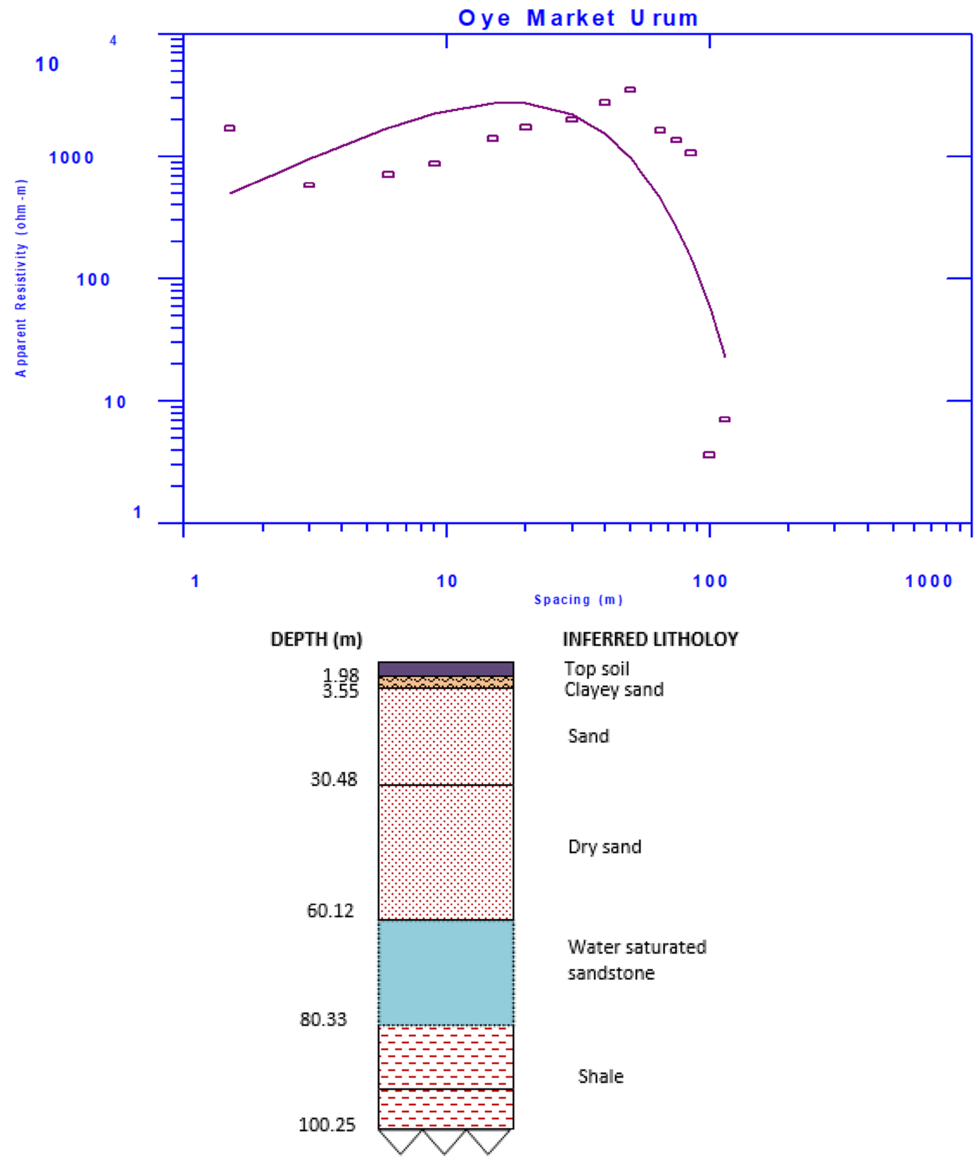

Fig. 4 Representative plot of VES data and the geologic section inferred from the analysis of the VES geo-electric section

22 to 80 m (with an average of 50.8 m; Fig. 5), while aquifer thickness varies from 8 to 21 m (with an average of 14.81 m; Fig. 6), and the aquifer apparent resistivity varies from 1600 to 5850 Ωm (with an average of 2678.5 Ωm). The overburden lithologies include Topsoil, sandstone, clayey sandstone, and shale. These overburden rock types have variable hydraulic properties (porosity and permeability) and these have implications for Aquifer Protective Capacity APC and aquifer vulnerability.

Results of the hydraulic characterization of the aquifer using the VES data and the Dar Zarrouk model showed that the aquifer transmissivity ranges from 218 to 563 m^2/day, with an average of 396.85 m^2/day (Table 1, Fig. 7).

Aquifer protective capacity and aquifer vulnerability characterization

Aquifer Protective Capacity (APC) distribution in the study area was modeled from the longitudinal conductance (S)—a Dar Zarrouk parameter estimated from the product of hydraulic conductivity and aquifer thickness (Golam et al., 2016; Henriet, 1976; Oladapo et al., 2004; Ogungbemi et al., 2013; Table 2). Referencing the computed longitudinal conductance values distributions across the VES point locations against standards, it was inferred that the study area is characterized by moderate to (fairly)

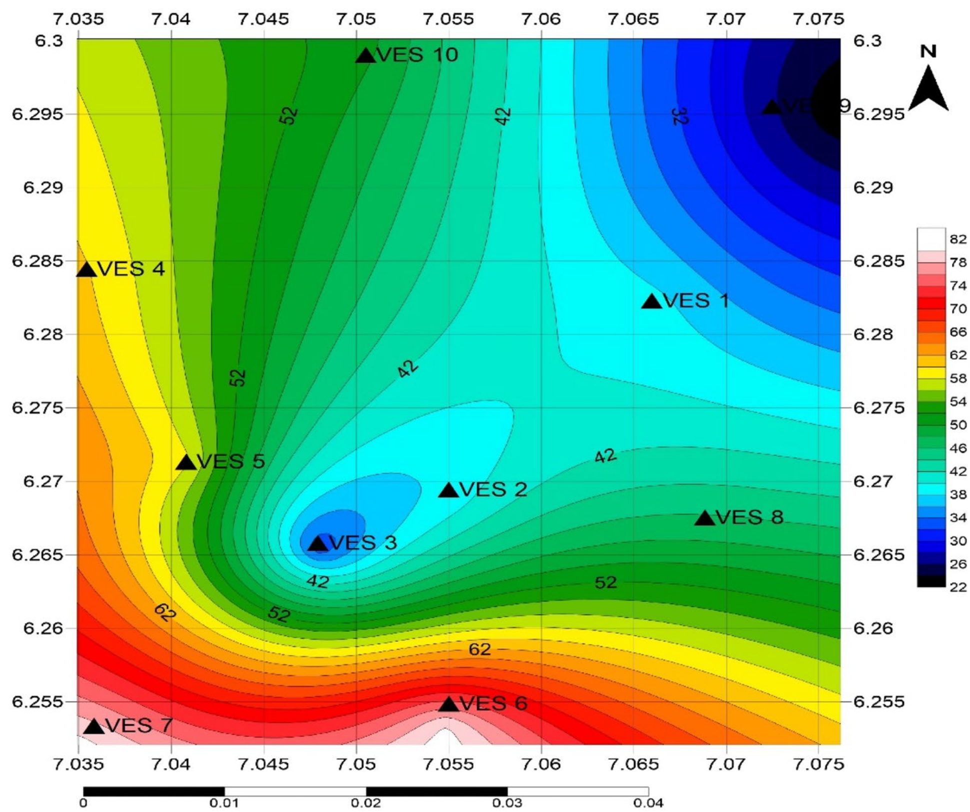

Fig. 5 Depth to water table (aquifer) map of the study area (in meters). The x- and y-axes represent longitude (E) and latitude (N), respectively

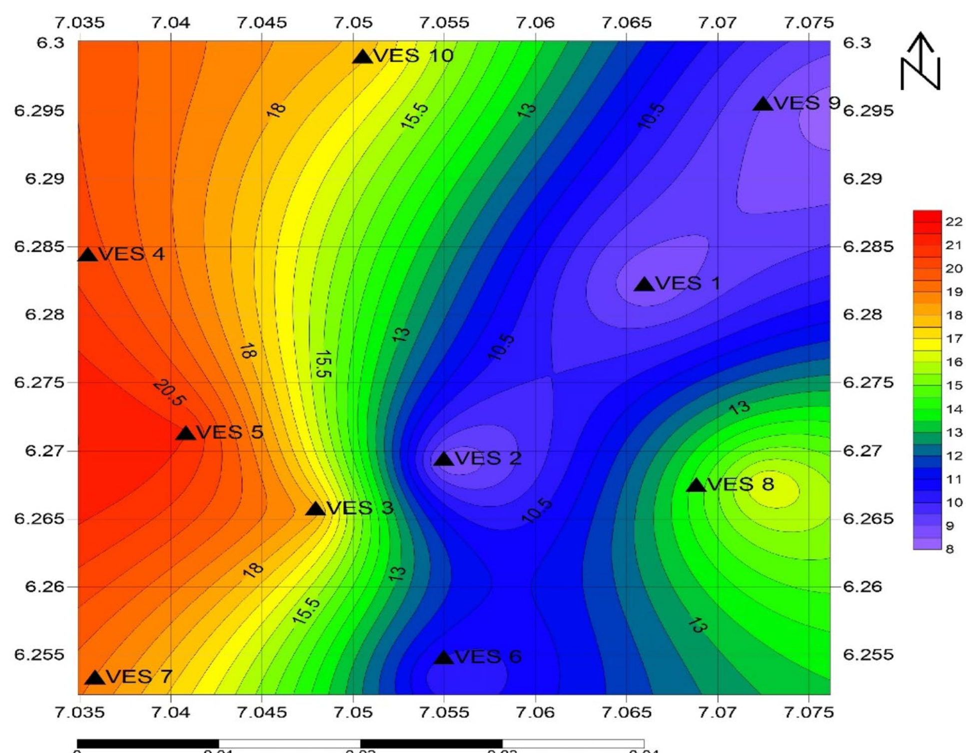

Fig. 6 Aquifer thickness map of the study area. The *x*- and *y*-axes represent longitude (E) and latitude (N), respectively

Table 1 Aquifer parameters and hydraulic property estimated from VES data conducted in the study area

VES number	Aquifer apparent resistivity (ρ)	Depth to aquifer (m)	Aquifer thickness (m)	Overburden thickness (m)	Aquifer transmissivity (m^2/day)
1	3017.2	38.71	8.51	38.71	228.068
2	5833.23	38.71	8.51	38.71	228.068
3	3250.44	32.45	18.17	32.45	486.956
4	2945.17	60.12	20.21	60.12	541.628
5	2015.11	58.31	21.01	58.31	563.068
6	1955.28	80.19	10.02	80.19	268.536
7	2220.36	80.98	19.07	80.98	511.076
8	2252.27	45.72	16.59	45.72	444.612
9	1625.15	22.2	8.15	22.2	218.42
10	1670.55	50.65	17.84	50.65	478.112

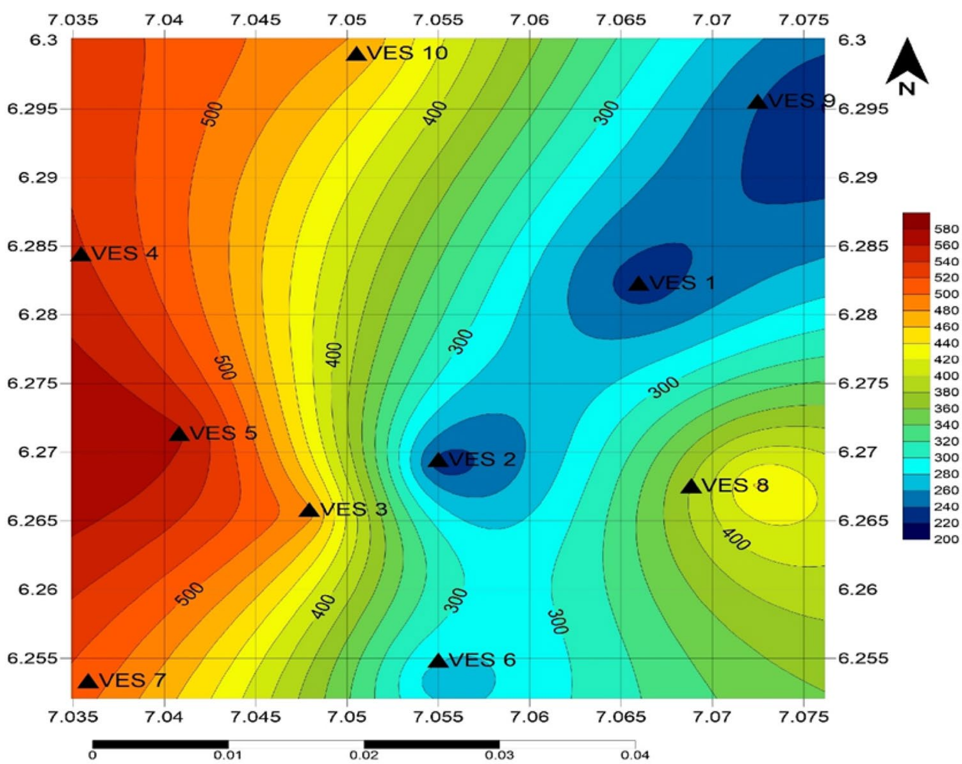

Fig. 7 Aquifer transmissivity map of the study area. The *x*- and *y*-axes represent longitude (E) and latitude (N), respectively

Table 2 Longitudinal conductance/aquifer protective capacity rating (after Henriet 1976; Oladpo et al. 2004; Ogungbemi et al. 2013)

Longitudinal conductance (mhos)	Protective capacity 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

good APC (Table 3). This has implications for aquifer vulnerability and groundwater quality conservation. An APC distribution map of the study area is presented in Fig. 8.

Aquifer vulnerability distribution over the study area was modeled using the Aquifer Vulnerability Index AVI. This model quantifies vulnerability by hydraulic resistance to the vertical flow of water through the protective (overburden) layers. The results of the Log of the AVI {i.e. Log (c)}, when compared against the standard (Stempvoort

Table 3 Aquifer potentials, APC and aquifer vulnerability distribution in the study area

VES Number	Aquifer transmissivity (m^2/day)	Aquifer potentials	S (mhos)	APC	Log (C)	Aquifer vulnerability
1	228.068	Moderate potentials	0.267	Moderate	2.6	Moderate
2	228.068	Moderate potentials	1.708	Good	1.4	High
3	486.956	Moderate potentials	1.946	Good	2.2	Moderate
4	541.628	High potentials	1.513	Good	2.4	Moderate
5	563.068	High potentials	0.986	Good	2.3	Moderate
6	268.536	Moderate potentials	3.922	Good	2	High
7	511.076	High potentials	0.888	Good	2.6	Moderate
8	444.612	Moderate potentials	0.656	Moderate	2.2	Moderate
9	218.42	Moderate potentials	0.778	Good	1.8	High
10	478.112	Moderate potentials	1.107	Good	1.6	High

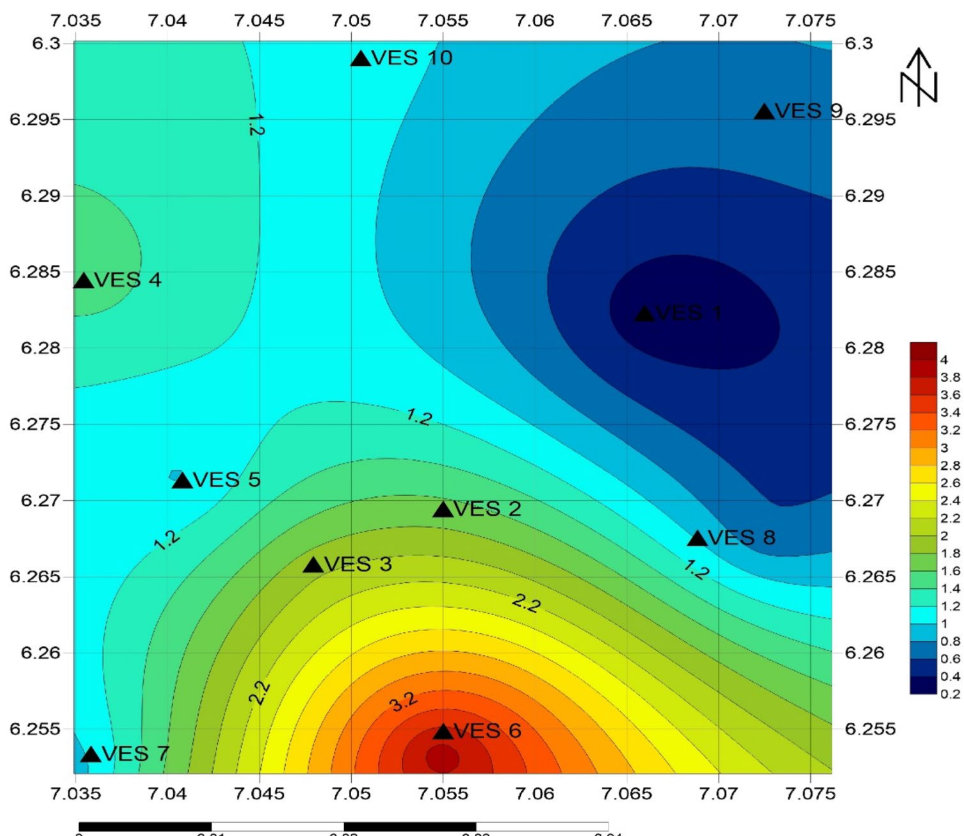

Fig. 8 APC distribution map of the study area. The *x*- and *y*-axes represent longitude (E) and latitude (N), respectively

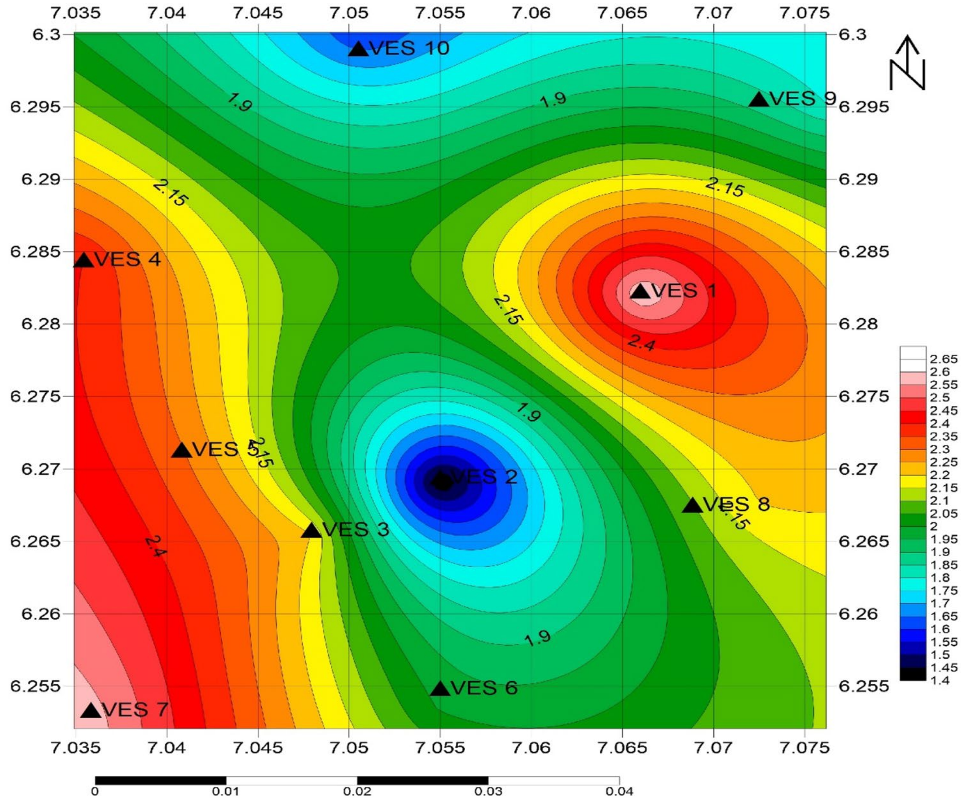

Fig. 9 Aquifer vulnerability map of the study area. The *x*- and *y*-axes represent longitude (E) and latitude (N), respectively

Table 4 Transmissivity/aquifer potential Scale (after Gheorghe 1978)

Range ($m^2 day^{-1}$)	Potential
> 500	High potential
50–500	Moderate potential
5–50	Low potential
0.5–5	Very low potential
< 0.5	Negligible

et al. 1993) showed that the study area is characterized by high to moderate aquifer vulnerability (Table 3). The aquifer vulnerability map of the study area is presented in Fig. 9.

Discussion

Geological mapping results showed that the area is covered by sandy–clayey sand topsoil; however, visible fractures were not mapped at the ground surface. The topsoil lithology has negative implications for APC and aquifer vulnerability in the study area as they are permeable to semi-permeable units (Ducci and Sellerino 2022; Ekanem 2022). Leachate and pollutants easily percolate through permeable/semi-permeable rock types, invade and pollute aquifers, and degrade groundwater quality rendering it unfit for many domestic and industrial uses (Mgbolu et al. 2019).

Results from the interpretations of the VES data suggest the presence of potential aquifer at variable depths ranging from 22 to 81 m, across the study area. The estimated depths to the aquifer correlate very well with values obtained by Offordile (2002). The correlation of the aquifer at different point locations and the overburden layer thicknesses showed that the depth to the aquiferous unit and the overburden layer thicknesses increases towards the southern parts of the study area (Table 1). Aquifer layer thickness also follows the same trend with a general increase towards the south (Table 1); however, highest aquifer layer thickness was recorded in the central region. This observation may be a result of depositional processes and accommodation space prevalent during the deposition period (Obiadi and Obiadi 2016).

According to Gheorghe (1978) (Table 5) aquifer potentials can be classified based on aquifer transmissivity. Results of aquifer transmissivity estimated from the geophysical field data showed that the study area is characterized by aquifer of high-moderate potentials (Table 4, Fig. 7). The aquifer potential distribution also followed the North–South trend already established for other aquifer parameters, collaborating the inference that aquifer potentials increase towards the south. This suggests better porosity and permeability towards the southern parts of the study area (Mgbolu et al. 2019) and hence better prospects for productive and durable groundwater exploitation schemes in the southern region.

Ogungbemi et al. (2013) and Oladapo et al. (2004) calibrated and classified Aquifer Protective capacity APC of an area from values of computed longitudinal conductance. Values of longitudinal conductance estimated from the field resistivity survey data in the study area showed that the study area is characterized by good-moderate Aquifer Protective Capacity (Table 3, Fig. 8). The APC classification improves southwards, following the same trend of other modeled aquifer parameters. The result of the APC model for the study area (good-moderate) collaborates and correlates well with the results of the aquifer vulnerability model which indicated moderate-high aquifer vulnerability distributions across the study area (Table 3; Fig. 9). Aquifer vulnerability improves southwards of the study area, similar to the trend established for APC. Areas with good APC and moderated aquifer vulnerability are characterized by greater overburden thickness and less permeable overburden lithologies (shale and clayey sandstone) which tends to protect the underlying aquifer from contaminants/pollutants through dispersion and surface infiltration.

The success and durability of water boreholes depend on the presence of prolific aquifer with the capacity to store and yield water in good quantities (Offordile 2002). Also, groundwater quality conservation depends to a large extent on the vulnerability of the aquifer to pollution. The presence of aquifer with good hydraulic properties has been established in the study area from the interpretation and modeling of VES data. The aquifer vulnerability model produced from geophysical and geological field data has shown that the aquifer is characterized by variable vulnerability at different spatial locations. Generally, aquifer potentials and protective capacity increase towards the southern parts of the study area.

Conclusions

Geophysical and geologic field mapping data were used to model and estimate groundwater potentials and aquifer vulnerability in parts of Awka North Local Government Area of Anambra State, SE Nigeria. Results of the geologic mapping showed that the area is covered by sandy and clayey sand top soils of the Imo Formation and Ameki Group lithostratigraphic units. Results from the interpretations of the VES data showed that the area is underlain by sandstone, clayey sandstone, and shale lithologies at various horizons and depths. The target aquifers are water-saturated sandstone units. The average depth to the aquifer (and overburden thickness) in the study area is 50.8 m. Depth to the aquifer increases southwards suggesting deeper aquiferous units towards the southern parts of the study area. The average aquifer thickness is 14.81 m, and also increases towards the south. This same southward trend (increase) was also observed for estimated aquifer transmissivity which gave an average of 396.85 m^2/day. Aquifer potential classification based on aquifer transmissivity suggests moderate-high aquifer potentials in the study area.

Estimated Aquifer Protective Capacity APC and Aquifer Vulnerability models gave moderate–good APC, and moderate-high vulnerability, respectively. These models, which are a consequence of the overburden thickness and lithologies, have implications for groundwater quality and aquifer conservation. Groundwater conservation and exploitation are important elements in the sustainable development of groundwater resources in the study area. The results of the groundwater potentials, APC, and aquifer vulnerability analysis suggest that prospects for productive boreholes exist more towards the south, and therefore, groundwater exploitation schemes should target the southern parts of the study area where these parameters of interest are more favorable. Water exploited from the southern parts where more favorable aquifers exist can be reticulated to other parts of the study area to improve water supply and water quality. Also, proper waste disposal management schemes should be put in place in the study area since the aquifer is variably vulnerable to pollution with spatial location (Mgbolu et al. 2019; Obiadi et al. 2016). The nature and characteristics of the underlying geology/hydrogeology must be taken into consideration in the choice, design, and location of waste disposal sites to conserve groundwater quality. It is recommended that municipal waste be disposed of in landfills sited within areas with thick overburden and high APC since the aquifers in these areas are better protected from the impact of pollutants leaching out of the waste. This recommendation is also applicable to other parts of Anambra State and beyond with similar geologic/hydrogeologic characteristics.

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Declarations

Conflict of interest The authors hereby state that this research has no conflict of interest.

Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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