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Estimation of porosity and specific yield from vertical electrical sounding (VES) measurements in Anambra State, Southeastern Nigeria

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Estimation of porosity and specific yield was carried out from Vertical Electrical Sounding (VES) measurements in Anambra State, Southeastern Nigeria. The study area lies within longitudes 06° 38I 00IIE and 007° 15I 00IIE and latitudes 05° 42I 00IIN and 006° 45I 00IIN with an area extent of about 4844 km2 (1870 ml^2), underlain by formations within two geological basins. It falls within the Anambra River Basin. The dominant aquifer is the Nanka Sands with Ameki Formation, Ebenebe Sandstone and Amenyi Sands as sandy lenses. A total of four hundred and fifty-two (452) VES was carried out in over one hundred and seven towns (107) within the study area, employing the Schlumberger array configuration. Layer resistivities, thicknesses and depths were obtained using the computer program INTERPEX. Lithological inference from layer resistivity shows dominantly sand/sandstones with moderate shaley facies. The 2D regional maps for Iso-resistivity, Isopach, depth, formation resistivity factor (F), groundwater resistivity, porosity and specific yield were constructed. Iso-resistivity 2D map shows high layer resistivities within the central part of the study area, with corresponding appreciable thicknesses. These are possible potential groundwater zones. Based on the groundwater resistivity, values range from 350 to 800 Ωm for fresh water and 50 to 250 Ωm for non-fresh areas, possibly iron water. Formation resistivity factor F is variable and dimensionless. F ranges from 2 to 40. Porosity ranges from 10 to 30% within the sandy formations and 35 to about 60% within the shale/clay formations. Specific yield is varied in the study area with values ranging from 5 to 90%. The constructed 2D regional maps can serve as a useful guide for groundwater exploration, development and management.

Key words: Vertical Electrical Sounding (VES), porosity, groundwater resistivity, specific yield, regional map.

INTRODUCTION

Estimation of aquifer hydraulic properties is now well-advanced and dominant in most researches in the field of hydrogeophysics (Oborie and Udom, 2014; Utom et al., 2012; Sattar et al., 2014; Ezeh, 2011; Obiora et al., 2016;

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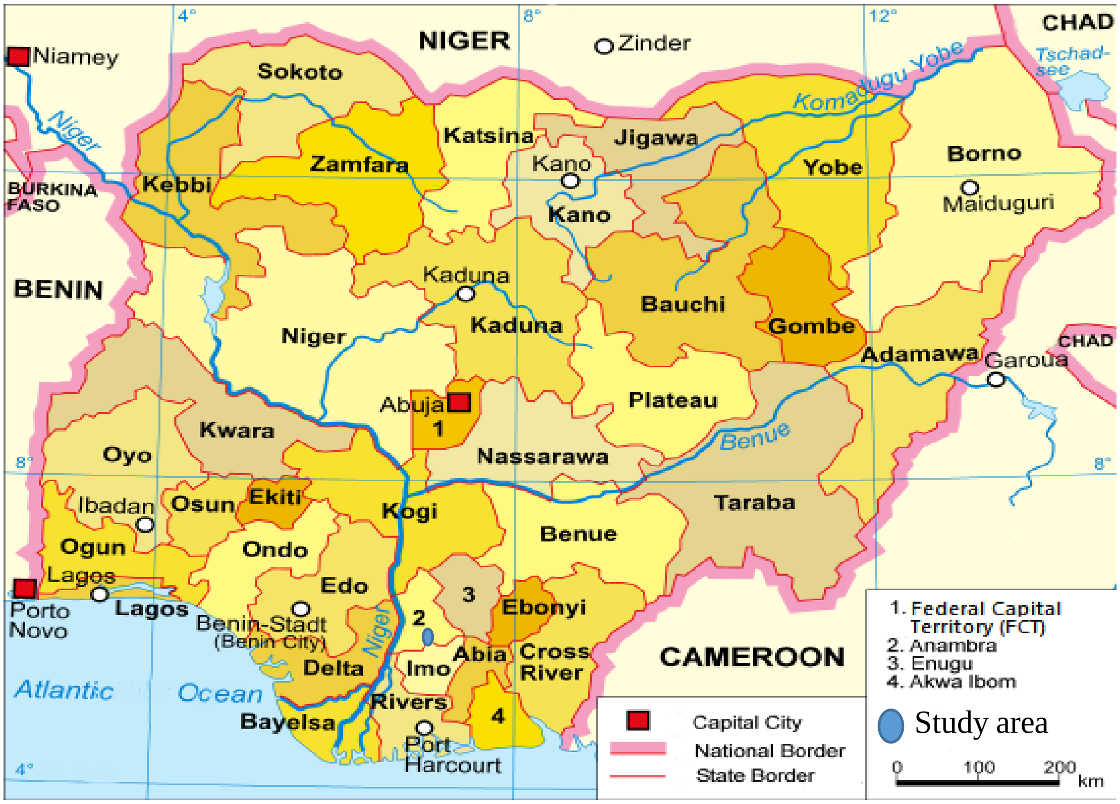

Figure 1. Map of Nigeria showing the study area.
Source: World Gazette (2011).

Tizro et al., 2012; Niwas and Celik, 2012). Aquifer hydraulic properties (transmissivity, hydraulic conductivity, porosity, specific yield, storativity) are physical parameters that characterize and rate aquifer performance. Knowledge of these parameters is the basis for exploration of groundwater resources and management. The only reliable means of computing hydraulic properties of aquifers is through pumping test (Ayers, 1989; Kruseman and de Ridder, 1994). However, geoelectrical sounding method, employing VES technique has provided an alternative approach for the estimation of some of the aquifer hydraulic parameters (Ahamed and de Marsily, 1987; Khan et al., 2002). In recent times, several researchers have made significant efforts by developing algorithms that relate aquifer hydraulic parameters and geoelectrical data. Sattar et al. (2014) developed functional analogous relations between geoelectrical data and aquifer parameters to compute transmissivity and hydraulic conductivity. Tizro et al. (2012) applied the geoelectrical method to estimate porosity and specific yield. Oborie and Udom (2014) determined aquifer transmissivity using geoelectrical sounding and pumping test data. Utom et al, (2012) estimated aquifer transmissivity using Dar-zarrouk parameters derived from surface resistivity measurements. Obiora et al. (2016) evaluated aquifer potential, geoelectric and hydraulic parameters using sounding. Niwas and Celik (2012) used VES technique to estimate porosity and the hydraulic conductivity of the Ruhrtal aquifer in Western Germany. Ezeh (2011) estimated aquifer hydraulic properties using geoelelctrical method in Enugu State, Nigeria. In the present study, attempts have been made to estimate porosity and specific yield from VES measurements, with derivations from formation resistivity factor (F).

Location, area extent and accessibility

The study area (Figure 1) is located south of the confluence of River Niger and River Benue, and directly east of River Niger. It is bordered to the north and northwest by Kogi State, to the south, southeast and northeast by Imo, Abia and Enugu states, respectively (Figure 2). The area extent is about 4844 km^2 (1870 ml^2) and lies within longitudes 06° 38^{l} E to 007° 15^{l} E and Latitudes 05° 42^{l} N to 006° 45^{l} N. The study area is accessible (Figure 3) through the major trunk A232 Road, which traverses the Enugu – Onitsha – Awka to Asaba in Delta State. Trunk A6 Road traverse Azia – Ihiala to Owerri in Imo State. Trunk A3 Road traverse through Aguleri – Omor to the north to Adani in Enugu State.

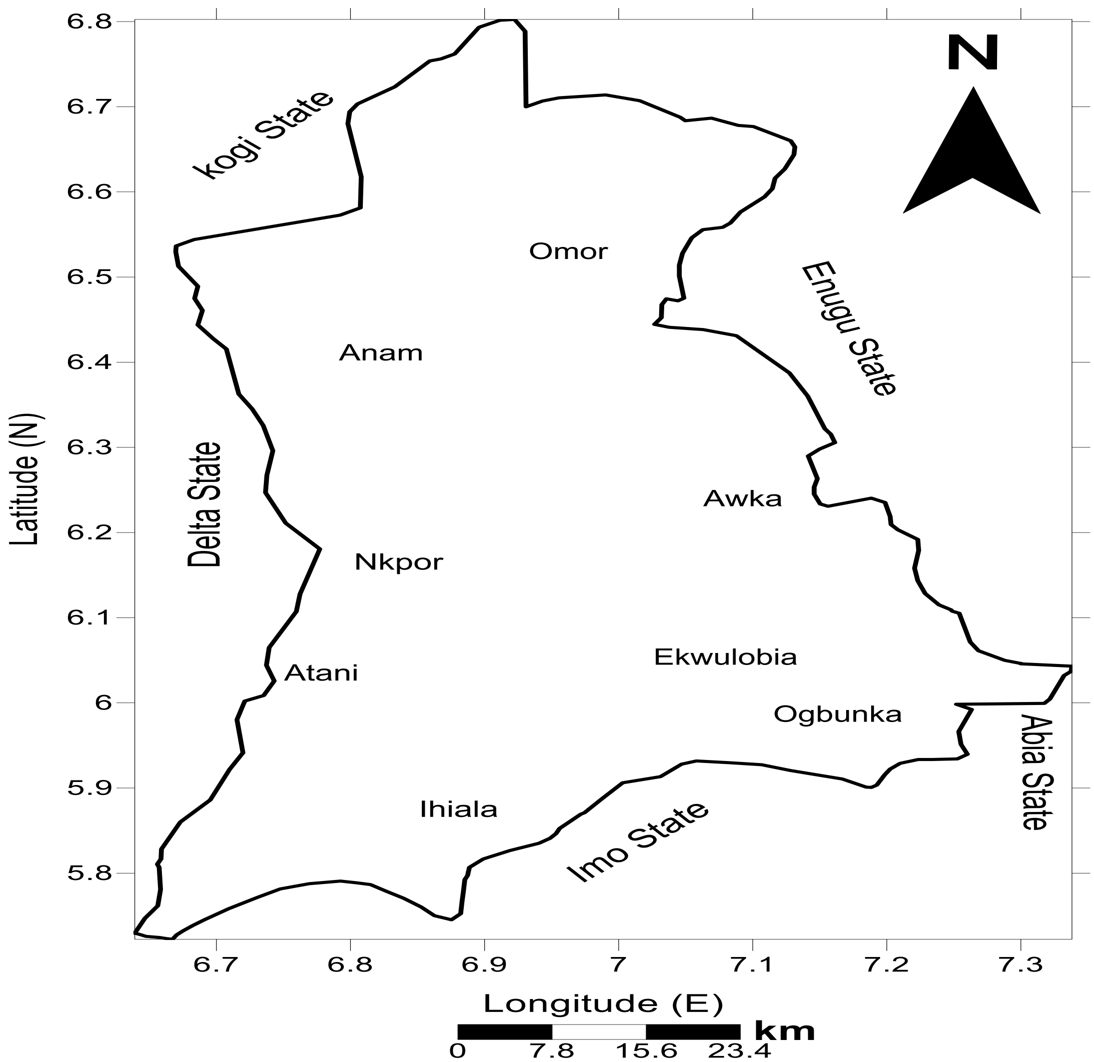

Figure 2. Boundary map of the study area.
Source: Authors.

Geology and hydrogeology

The study area falls within the Tertiary Niger Delta Basin (Nwajide, 2013) and the Anambra Basin. The age range is from Paleocene to Recent and Campanian to Maastrichtian, respectively. Two main geological basins underlie the study area (Figure 4); the Imo Formation, Ameki Group (Ameki Formation, Nanka Formation and Nsugbe Formation), Ogwashi-Asaba Formation and Alluvial Sands. The lithostratigraphic units have a thickness of up to 2500 ms (Reyment, 1965). Hydrogeologically, the study area falls within (Figure 5) the Mamu River Basin (Offodile, 2002). It is a sub-basin of the Anambra River Basin. The River Mamu is a very important tributary of the Anambra River. The most important aquifers in the Mamu River Basin are the Ajali Formation, the Ebenebe, Amenyi and the Nanka Sands. The Ajali Formation exhibit confined condition towards the center of the basin. It is estimated that in Awka area, this aquifer could be encountered at much deeper levels of about 360 to 800 m depth. Nanka sands around Nanka, Idemili, Oko, Agulu, Nnobi and Ekwulobia, the water table is generally very low, ranging from 30 to 300 m in depth. Apart from Ajali Formation, shallow aquifers exist within the Mamu River Basin. They are the Ugwuoba Sandstone, also described as Ebenebe Sandstone and Amenyi sands. These aquiferous sand bodies are members of Imo Shale. Higher water table conditions are obtained in boreholes located in the lowland areas or valleys usually interspersing the predominantly hilly country.

MATERIALS AND METHODS

Theoretical basis

Vertical Electrical Sounding (VES) is a technique in Electrical Resistivity (ER) method. The ER method is utilized in diverse ways

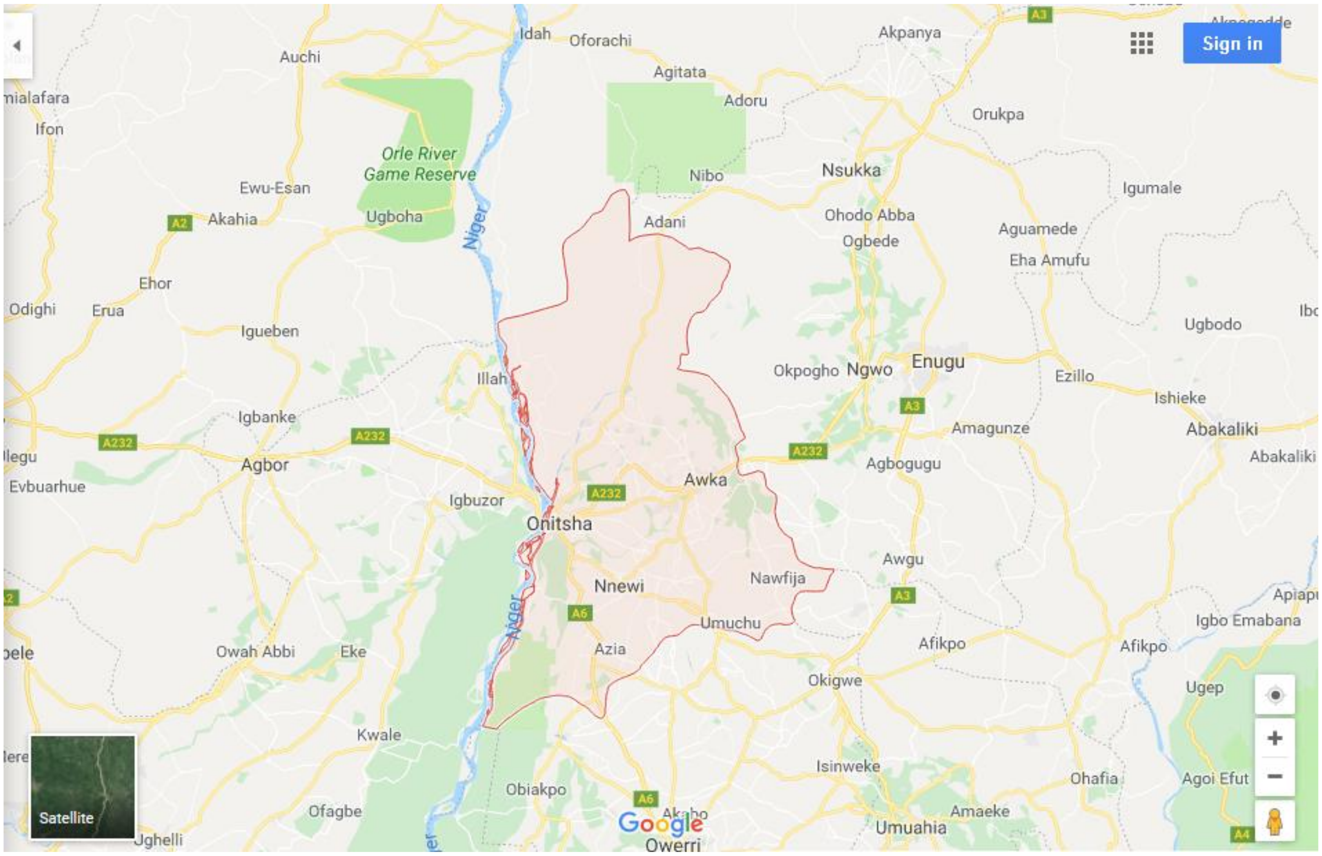

Figure 3. Satellite imagery map showing the accessibility roads within the study area.
Source: Map Data (2019).

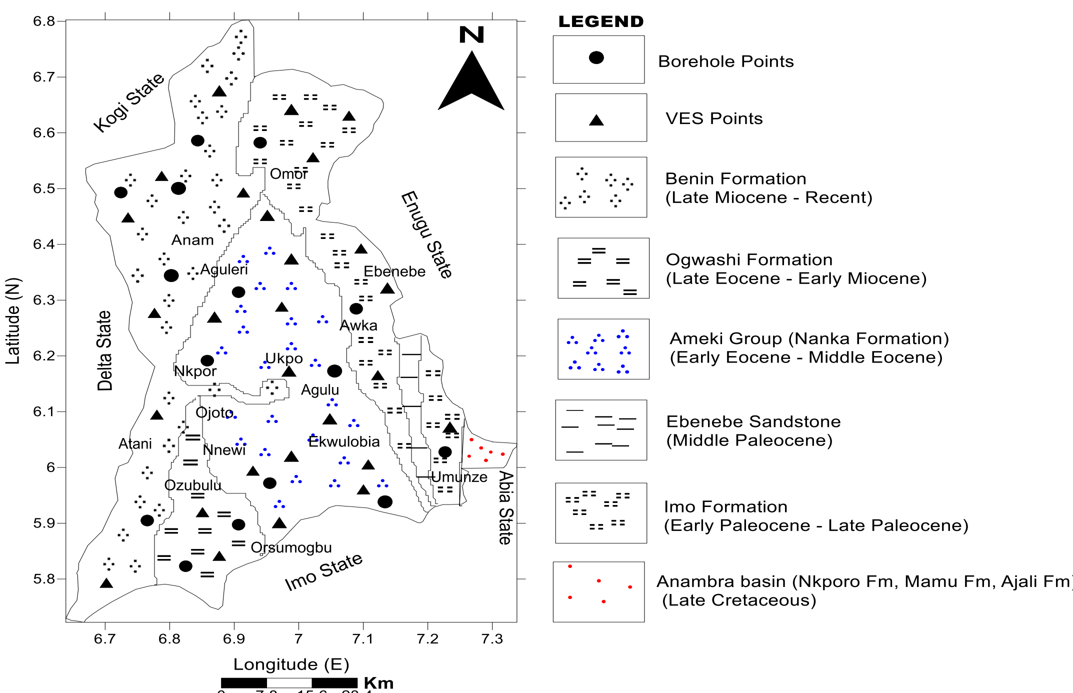

Figure 4. Geologic map of the study area showing VES and Borehole points.
Source: Authors.

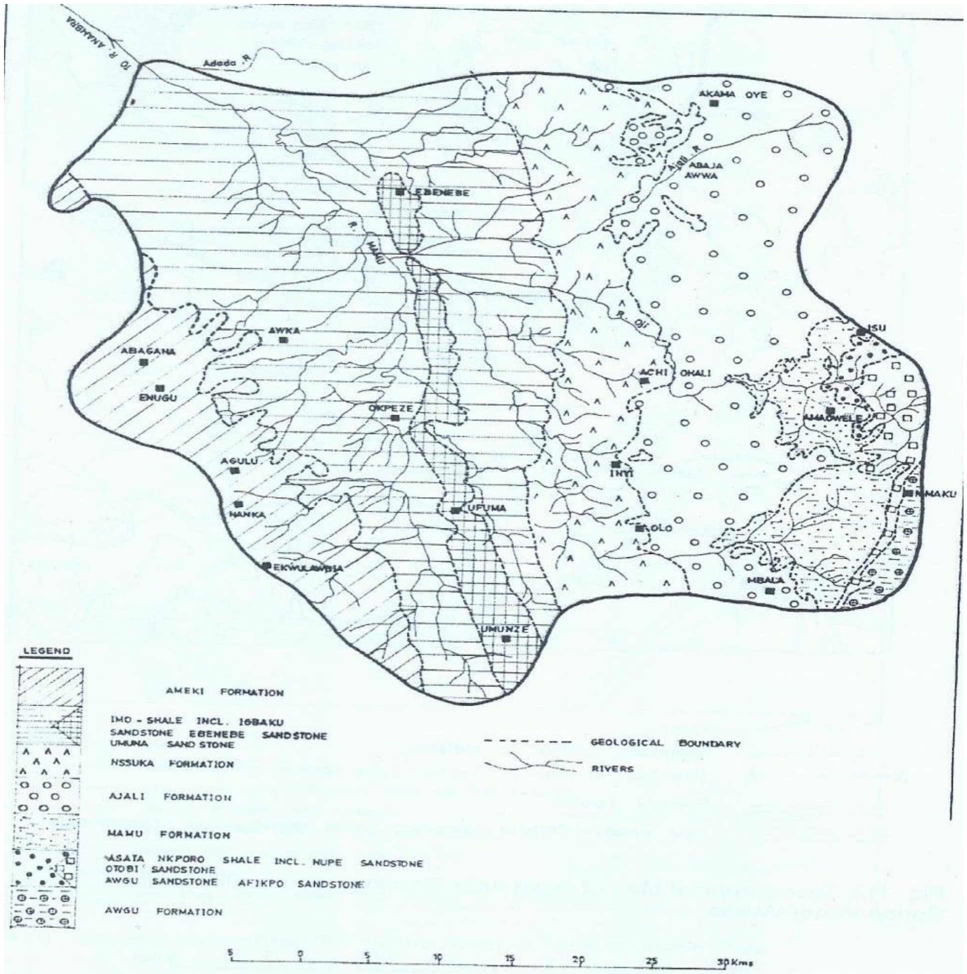

Figure 5. Geological map of the Mamu River sub-basin.
Source: Offodile (2002).

for groundwater water exploration (Zohdy, 1976; Choudhury et al., 2001; Frohlich and Urish, 2002) and subsurface features/structural mapping (Chávez et al., 2014; Al-Zubedi, 2016; Ezeh et al., 2022; Amini and Ramazi, 2017). Electrical surveys are usually designed to measure the ER of subsurface materials by making measurements at the earth surface. Currents are introduced into the ground by a pair of electrodes, while measuring the subsurface expression of the resulting potential fields with an additional pair of electrodes at appropriate spacing.

Data acquisition and interpretation

A total of four hundred and fifty-two (452) vertical electrical sounding (VES) were carried out in over one hundred and seven towns (107) within the study area (Figure 4). Some VES stations were very close to existing boreholes for correlation purposes. The Schlumberger electrode configuration (Figure 6) was used, with a maximum current and potential electrodes separation of AB=800 m and MN=40 m, respectively. The equipment used for the fieldwork was the versatile ABEM terrameter SAS 1000 resistivity meter. A high-resolution resistivity meters. After acquiring the data, measured field resistance (R) in Ohms was converted to apparent resistivity (ρ_a) in Ohm-meter by multiplying resistance (R) by the geometric factor (k). A log-log graph plot of apparent resistivity (ρ_a) against current electrode distance (AB/2) was plotted for each VES station to generate a sounding curve. Using the conventional partial curve matching technique, in conjunction with auxiliary point diagrams (Orellana and Mooney, 1966; Koefoed, 1979; Kellar and Frischknecht, 1966), layer resistivities, thickness and depth were obtained, which served as a starting point for computer-assisted interpretation. The computer program INTERPEX was used to interpret all the datasets obtained. From the interpretation of the resistivity data, it has been possible to compute for every VES station, the Transverse resistance (T):

$$T = h \times \rho_a \tag{1}$$

And longitudinal conductance (S)

$$S = h/\rho_a \tag{2}$$

where h and ρ_a are thickness and apparent resistivity of the aquiferous layer. These parameters T and S are known as the Dar-Zarrouk variable and Dar-Zarrouk function respectively (Maillet, 1947). Both parameters T and S and the derived concept of Dar-Zarrouk curves (Maillet, 1947) are of prime significance in the development of interpretation theory for VES data. T and S did not

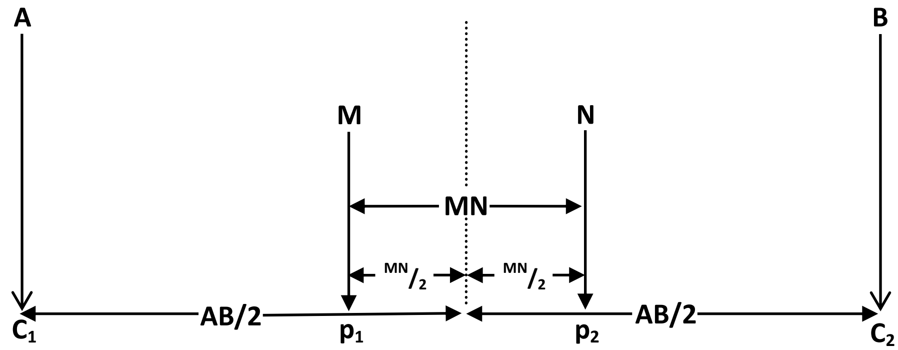

Figure 6. Schlumberger electrode configuration.
Source: Okonkwo et al. (2017).

form part of the discussion for obvious reasons.

Formation resistivity factor

This is the expression of the passive behavior of a rock in the presence of an electric field. This is usually denoted as F. It is expressed as a ration of ρ_{rock} and ρ_w as follows:

$$F = \frac{\rho_{rock}}{\rho_w} \tag{3}$$

where ρ_{rock} is the saturated aquifer resistivity estimated from surface geoelectrical sounding data interpretation and ρ_w is the water resistivity. ρ_w was obtained by converting water conductivity σ_w to resistivity (Ωm) using the relation (Ezeh, 2011).

$$\rho_w(\Omega m) = \frac{10^4}{\sigma_w}\ (\mu mhos\ cm^{-1}) \tag{4}$$

According to Archie (1942), F is related to porosity (ф) by

$$F = a\phi^{-m} \tag{5}$$

where *a* and *m* are constants related to rock type. Frohlich and Kelly (1998) expressed specific yield (S_y) as:

$$S_y = \left(\frac{\rho_w}{\rho_{sat}}\right)^{\frac{1}{m}} \left(1 - \left(\left(\frac{\rho_{sat}}{\rho_{unsat}}\right)^{\frac{1}{n}}\right)\right) \tag{6}$$

where ρ_{sat} and ρ_{unsat} are obtained from VES measurements, while ρ_w is the water resistivity. In the present study, m was assigned values between 1 and 1.2 for shale (Ezeh, 2011) and 1.3 for unconsolidated sand (Doveton, 1986); n is assumed to be 2 (Keller and Frischknecht, 1966). ρ_w was obtained using Equation 4. Thus, based on Equations 5 and 6, porosity and specific yield were estimated.

RESULTS AND DISCUSSION

Lithological inference from the VES layer resistivity model (Figure 7) shows dominantly sand/sandstone around the country Ekwulobia, Agulu-Nanka. While shale facies occur around the country Mgbakwu, Amansea and Achalla (Figure 8). The sand looks somewhat progradational to the SW of the study area. 2D Iso-resistivity, Isopach (thickness) and depth map were constructed from VES interpreted layer model. The iso-resistivity 2D map (Figure 9) shows high layer resistivities within the central part of the study area comprising Nanka, Agulu, Ekwulobia, etc. with moderate layer resistivities around the country Awka, Ogbunka, Ihiala, etc. and low layer resistivities around the country Anam, Omor, etc. The high and the moderate layer resistivity areas are possible potential aquiferous zones. These areas show corresponding thicknesses (Figure 10) and depth (Figure 11). High depths were observed around the potential aquiferous zones. Groundwater resistivity ρ_w (Figure 12) computed from water conductivity using Equation 4 shows fresh water in most part of the study area. Possible fresh zones were observed at the central part of the study area and down south. Values range from 350 to about 800 Ωm. Possible non-fresh water areas range from 50 to about 250 Ωm. This could be iron water. This falls around Awka-Anam-Omor axis. Formation resistivity factor (F) is variable (Figure 13) and dimensionless. Maximum values (14 to 40) are less dominant. While values (2-10) are most dominant, increase in F will result in corresponding decrease in porosity (Salem, 1999). Porosity (Figure 14) ranges from 10 to 30% at Ogbunka-Ekwulobia-Nkpor axis and 35% to about 60% at Atani-Ozubulu-Ihiala axis. Specific yield is variable (Figure 15), with high values (60 to 90%) at the NW, around Anam and Omor. Spotted marginal occurrences (30 to 55%) are observed around the country the Ogbunka. Specific yield values of 5 to 25% occur around the country Ekwulobia-Nkpor-Awka and Ihiala-Atani axis.

Conclusion

Analytical algorithms may now proffer solutions in the

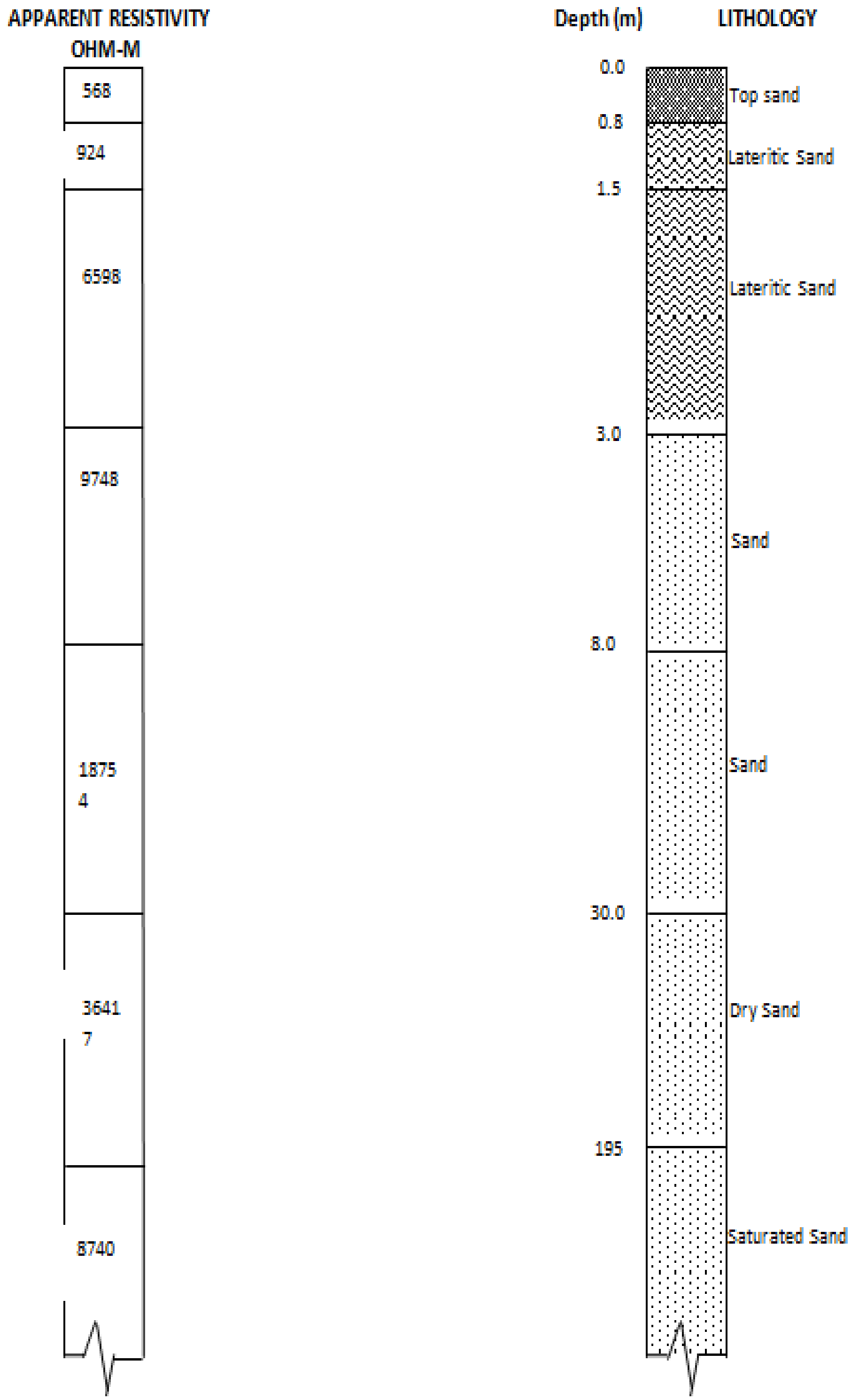

Figure 7. Nanka geoelectric layer in the study area.
Source: Authors.

estimation of most aquifer hydraulic properties. The insight from the analytical algorithms can be applied to other study areas with similar geologic setting. Formation resistivity factor F was the basis for these estimations with the parameters extracted from VES data. From the estimation studies, high resistivity areas are possible potential groundwater zones with good porosities and specific yields. Groundwater explorations should target

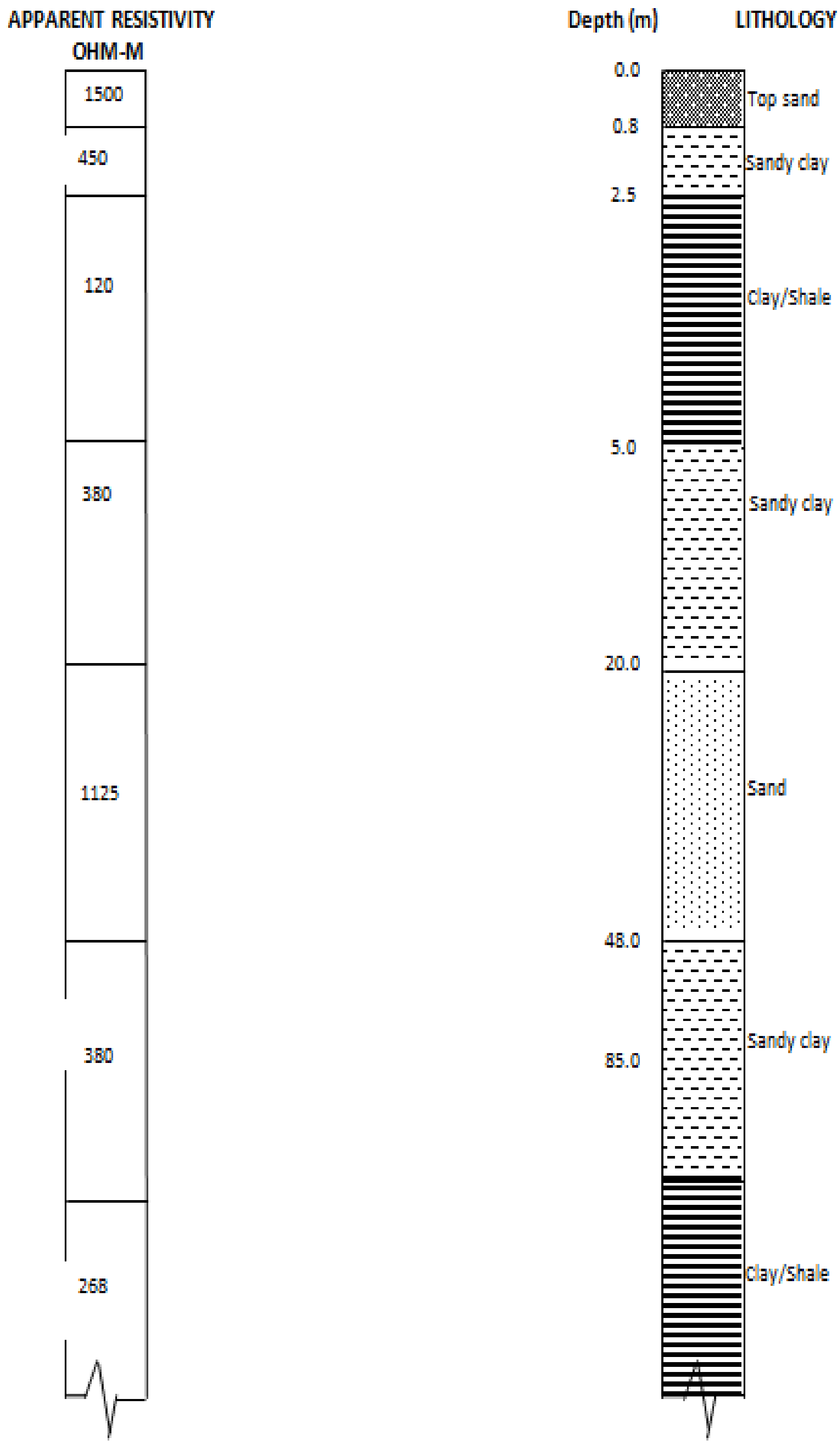

Figure 8. Achalla geoelectric layer in the study area.
Source: Authors.

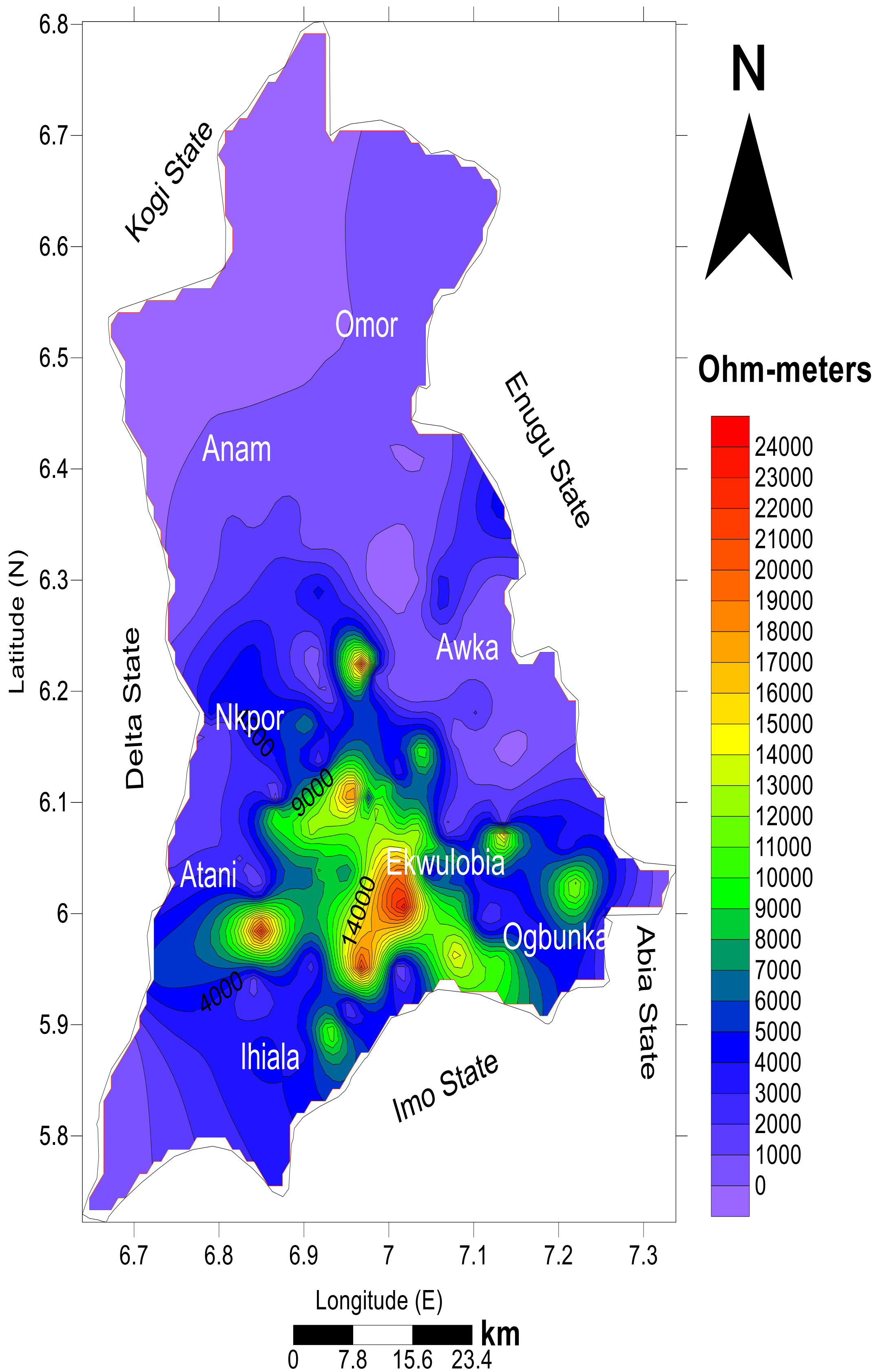

Figure 9. 2D Iso-resistivity map of the study area.
Source: Authors.

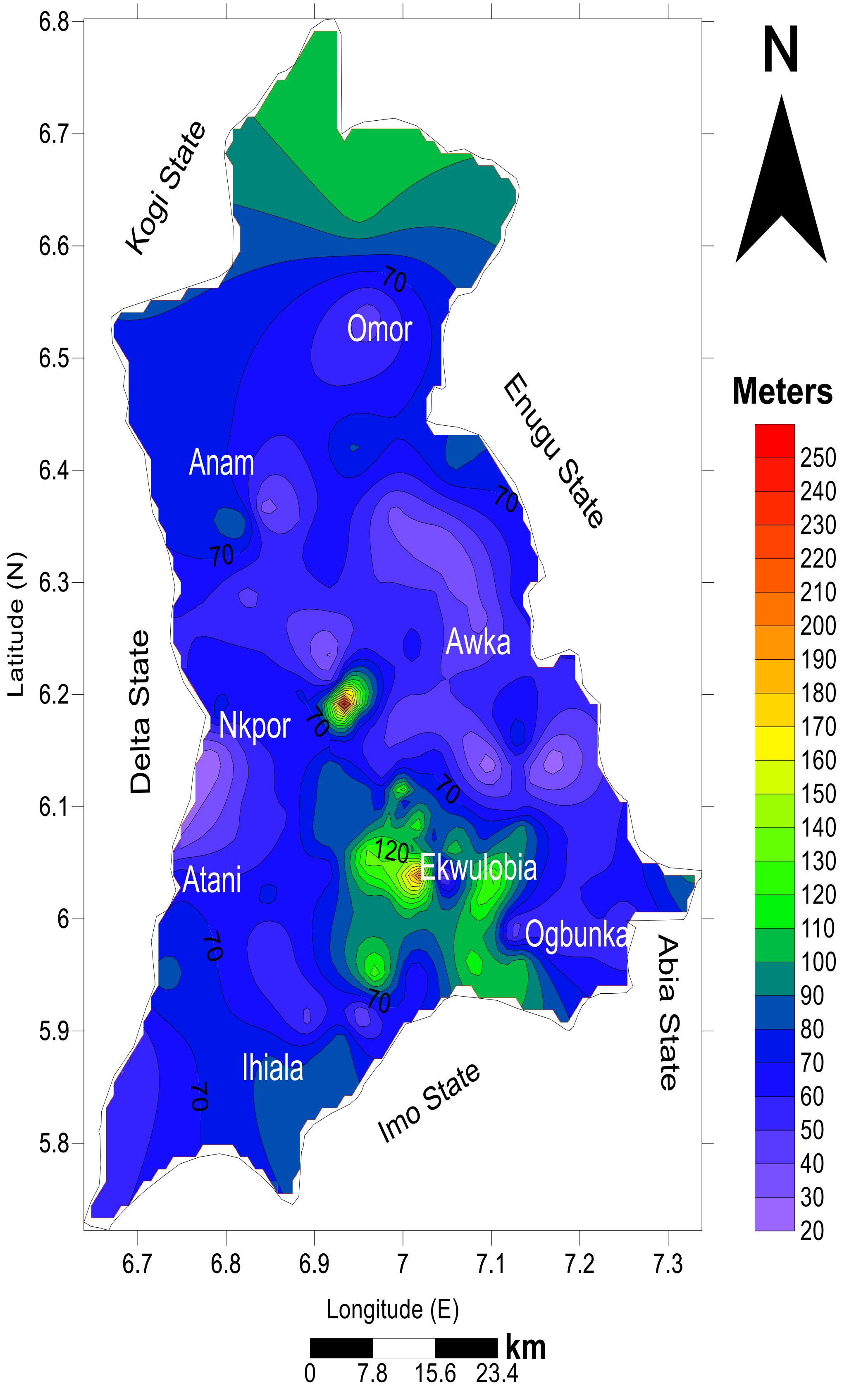

Figure 10. 2D Isopach (thickness) map of the study area.
Source: Authors.

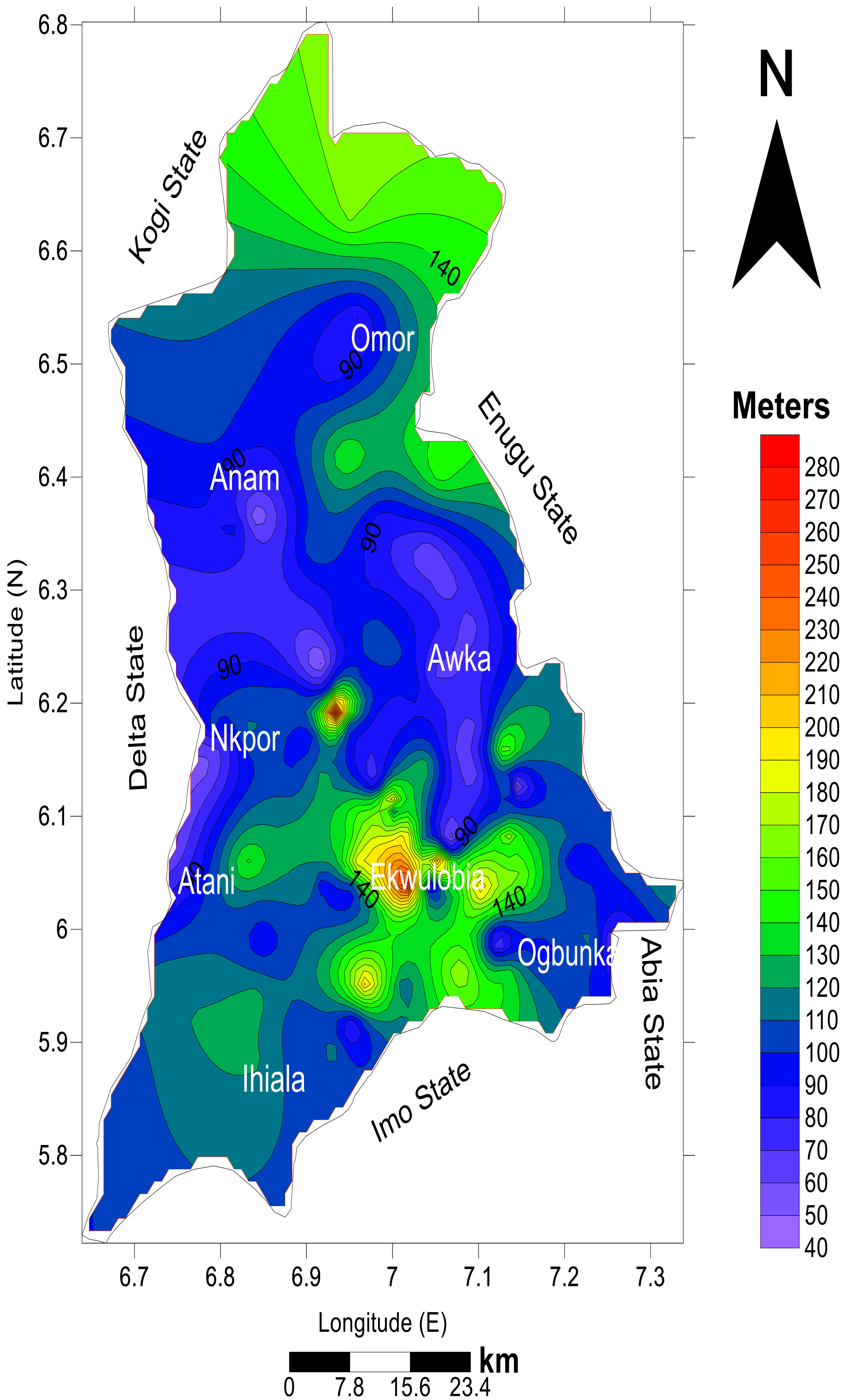

Figure 11. 2D depth map of the study area.
Source: Authors.

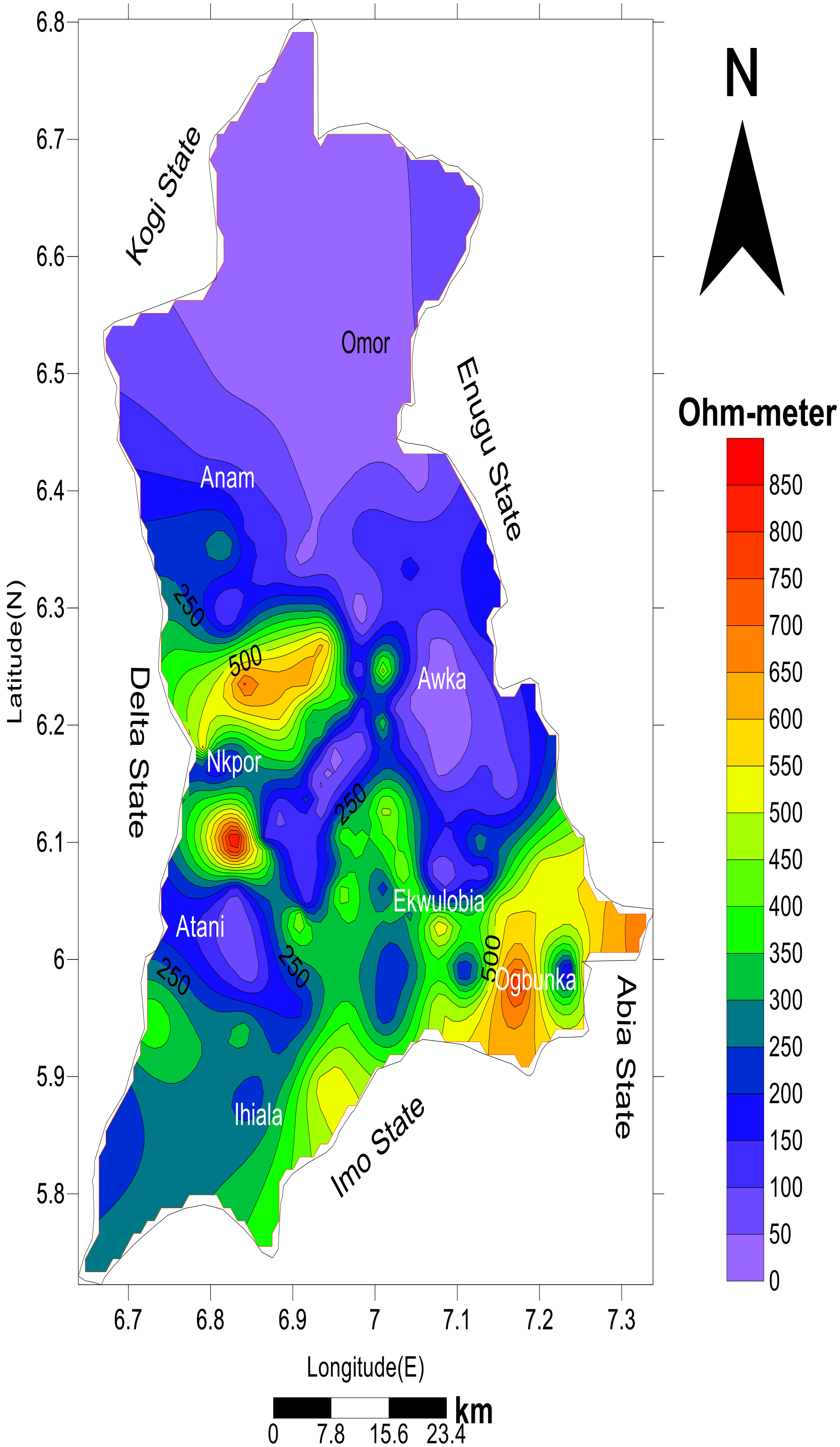

Figure 12. 2D Groundwater resistivity ρ_w map of the study area.
Source: Authors.

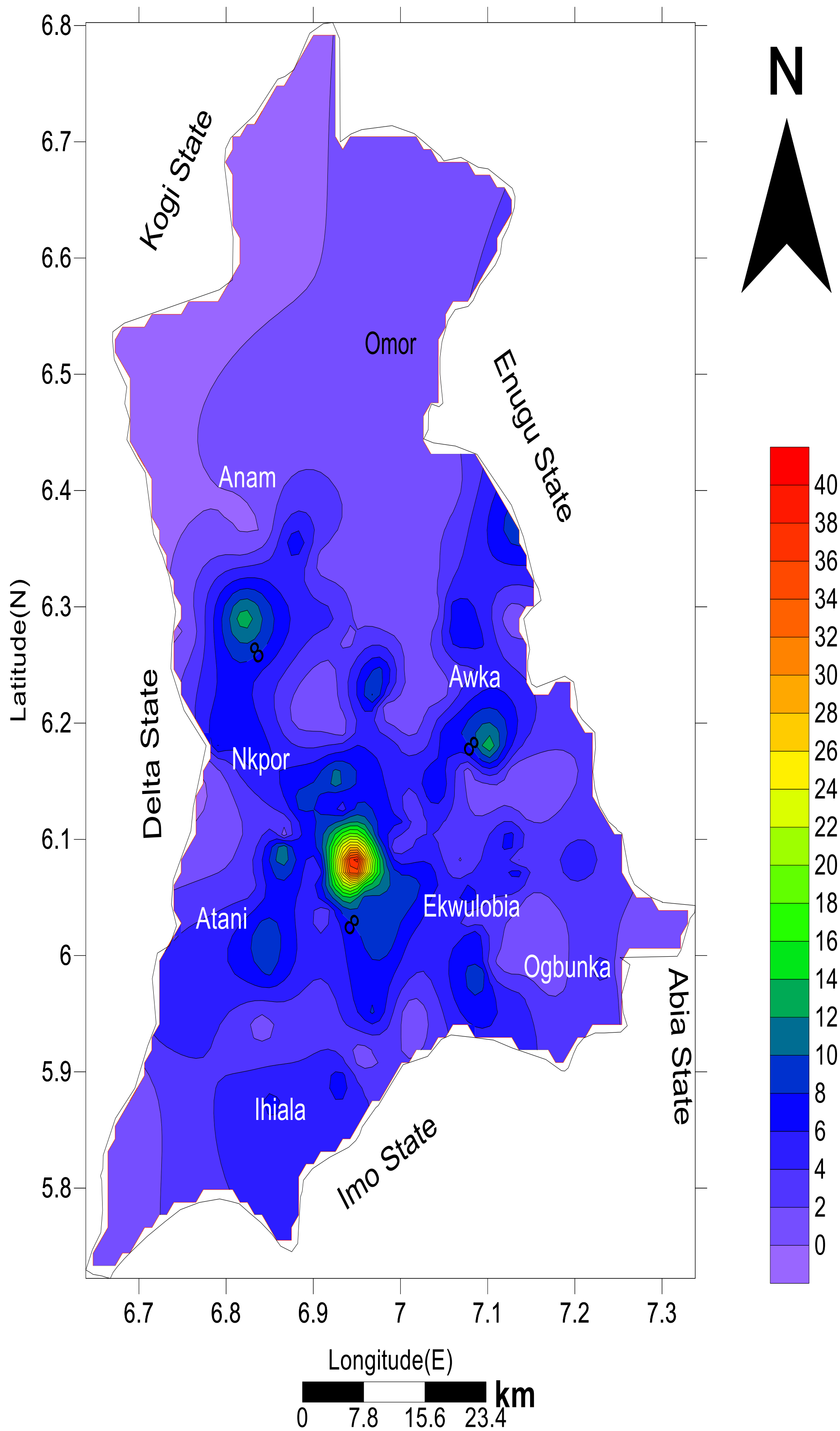

Figure 13. 2D Formation resistivity factor (F) map of the study area.
Source: Authors.

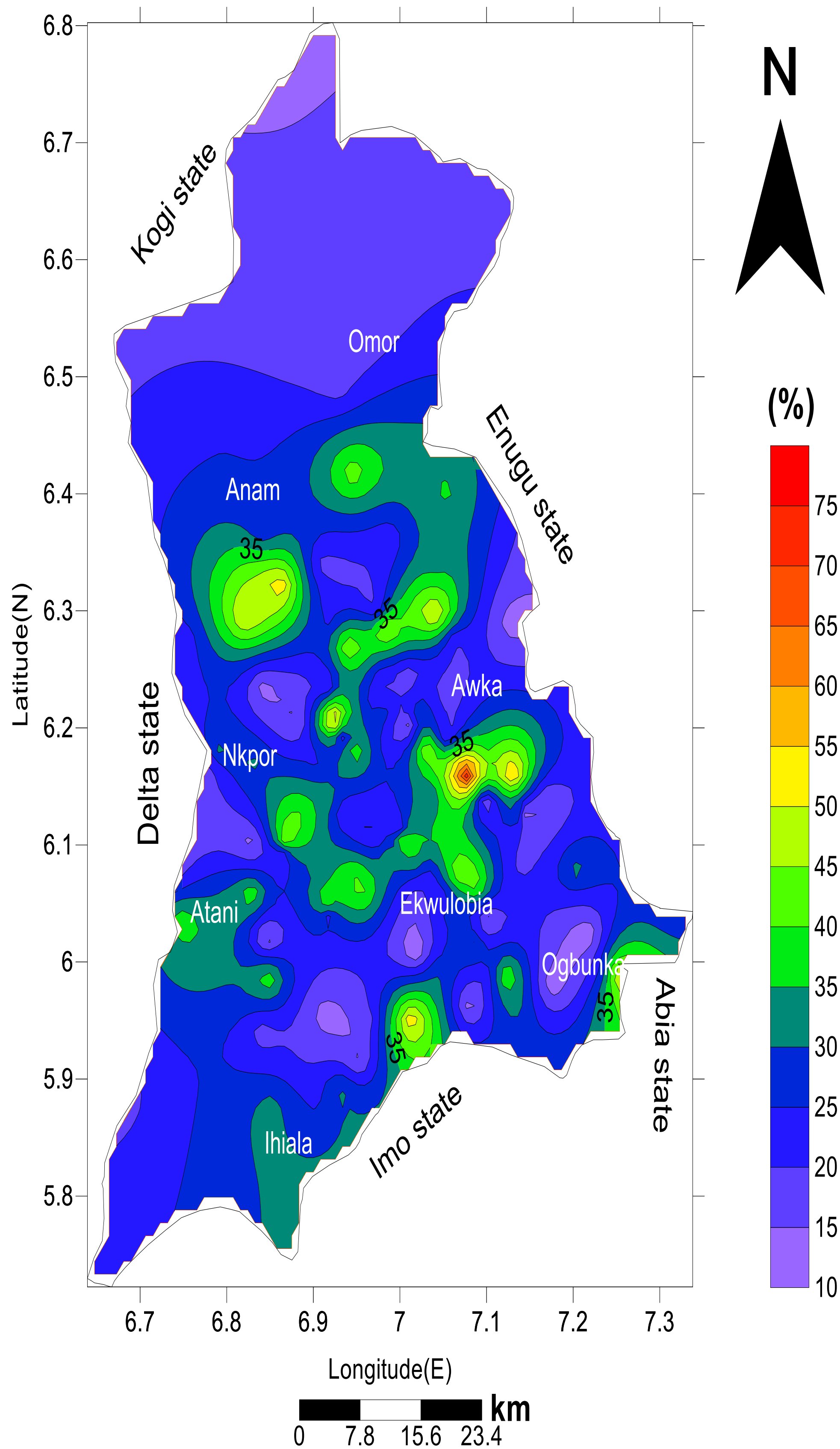

Figure 14. 2D Porosity map of the study area.
Source: Authors.

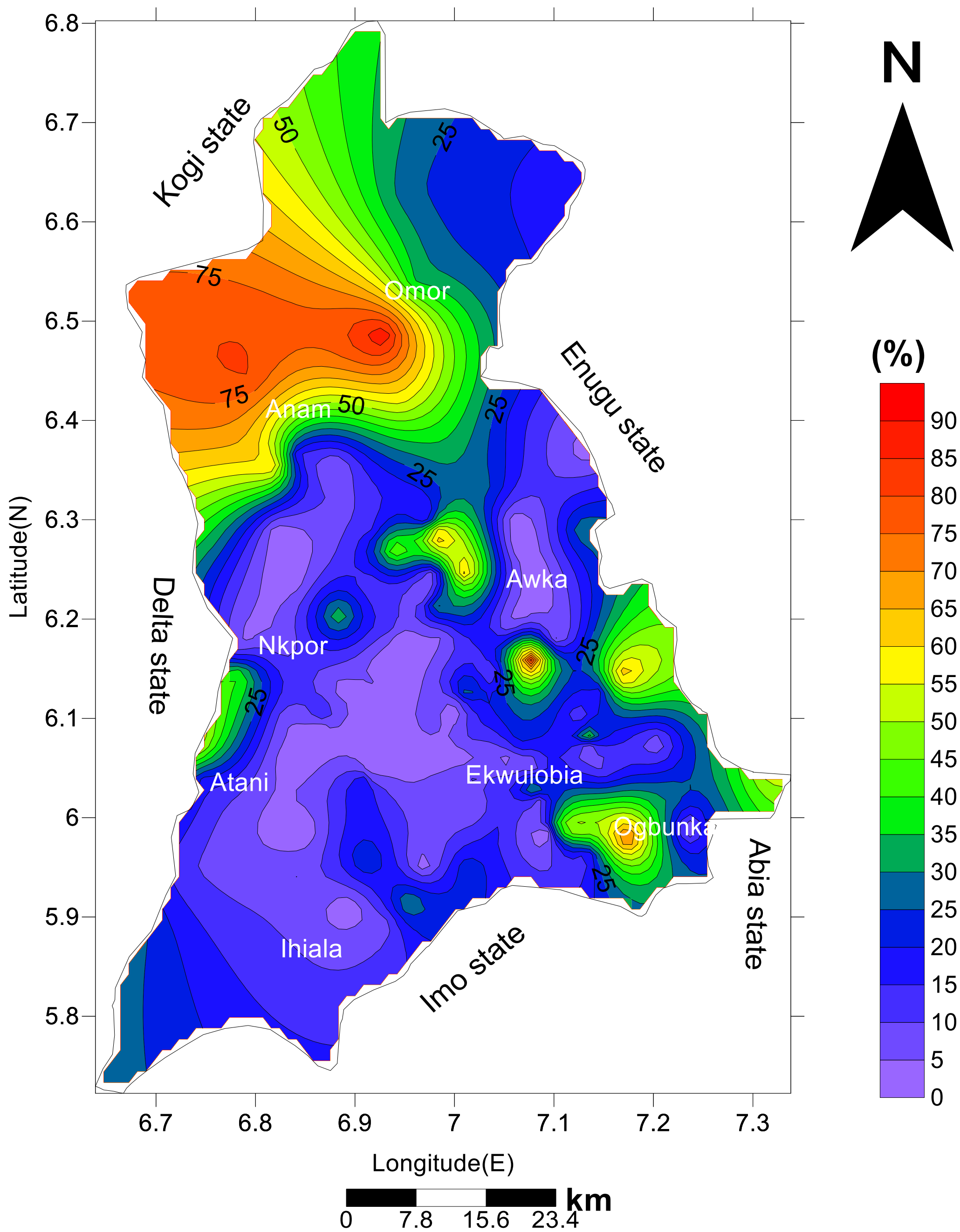

Figure 15. 2D Specific yield map of the study area.
Source: Authors.

these areas with high groundwater characterization. The constructed 2D regional maps can serve as a useful guide for groundwater exploration, development and management.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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