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Scrutinate proclivity of regional aquifer hydraulic parameters: apriorisms for borehole failures within parts of the middle Benue Trough, Nigeria

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ABSTRACT

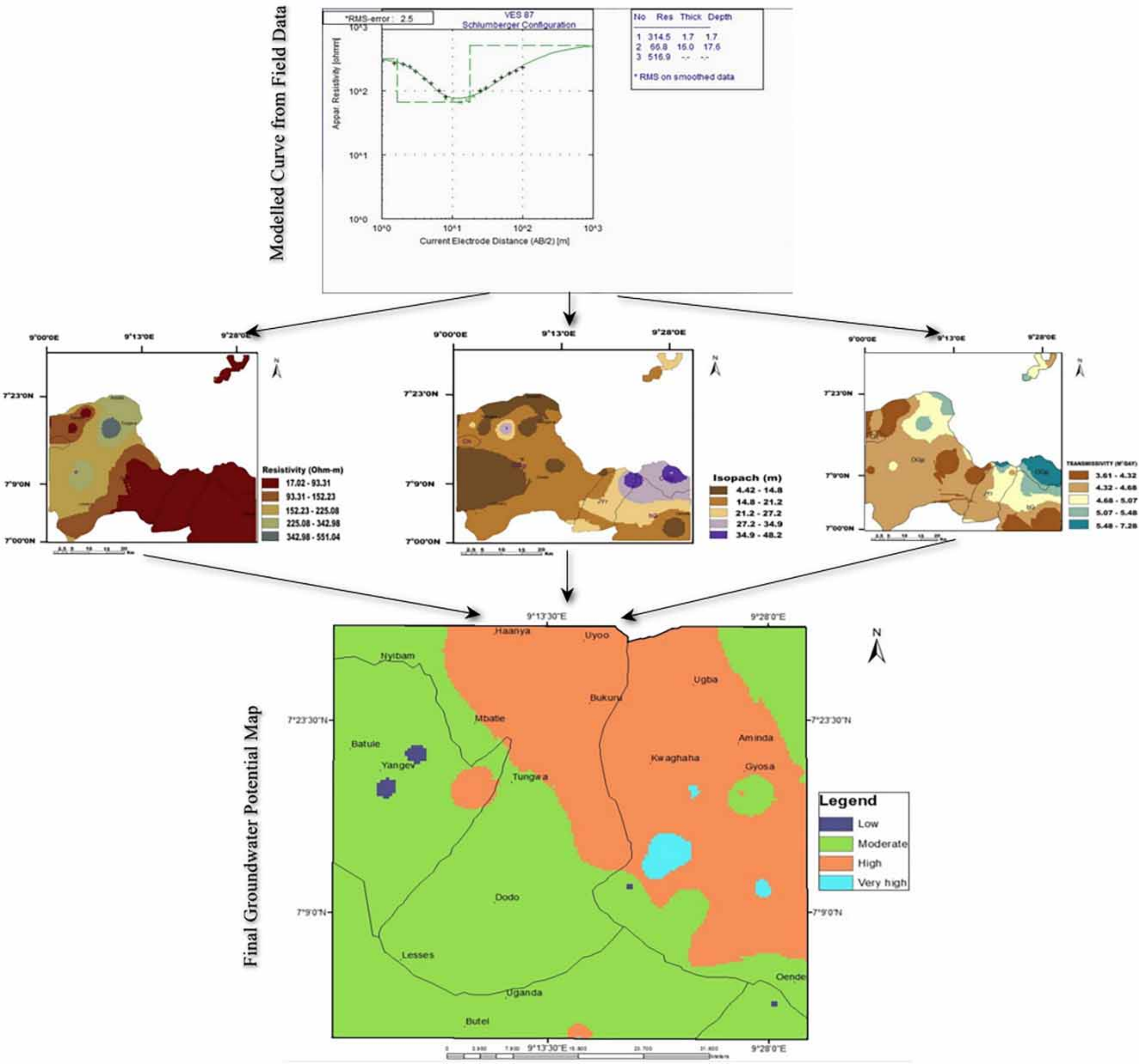
Water borehole failures in Nigeria's middle Benue Trough are caused by imprecise aquifer features. This study employed empirical data to understand hydraulic parameters, anticipate regional groundwater potential, and explain borehole failures in difficult geological locations. 89 VES stations and quantitative data interpretation were required to determine the geoelectric properties beneath each station. Aquifer layers were delineated and their resistivity and thickness combined using geo-environment specific relations to yield transmissivity, hydraulic conductivity for both basement complex and sedimentary environments variously. Results show that aquifer resistivity ranges from 4.5 – 984.4 ohm-m; aquifer layer thickness varies from 4.4 m – 96.7 m with average thicknesses in sedimentary environment considerably greater; hydraulic conductivities range from 0.056 – 30.15 m/day, Transmissivity values range from 0.31 – 1281.36 m^2/day. Log transformed transmissivity values range from 3.51 – 7.1 m^2/day. Approximately 60.34% of the entire study area falls within transmissivity magnitude III and IV and can only support withdrawals for local water supply adequate for small communities and private consumption only and this may be the inferred cause for the low yield and high borehole failure rates. Understanding hydraulic characteristics is critical for 6controlling groundwater; research advances knowledge of transmissivity and conductivity in complex terrain.

Key words: basement complex, borehole failure, geoelectric, groundwater, transmissivity

HIGHLIGHTS

- The Benue Trough in Nigeria is experiencing a concerning trend of water borehole failures.
- The researchers collected data from 89 VES stations.
- 60.34% of the study area falls within the limits of limited groundwater availability.
- Aquifers in the study area can only support water withdrawals for local water supplies in small communities.

GRAPHICAL ABSTRACT



INTRODUCTION

The constant increase in water demand caused by the growing human population and industrial development impedes the supply of potable water (Abiola *et al.* 2009; Mogaji *et al.* 2016). Furthermore, as indicated by Akaamaa *et al.* (2014), the challenging portion is made much more difficult by the unpredictable temporal and spatial dispersion of traditional water sources. Despite geological and financial barriers to groundwater exploration (Akoachere *et al.* 2019), a lack of drinkable surface and rainfall water has necessitated the investigation, development, and management of groundwater reserves to meet the needs of communities lacking surface water (Oteze & David 2002; Ifeanyichukwu *et al.* 2021). The research site is in Nigeria's Benue State, which is noted for its scarcity of potable water. Furthermore, there is a severe problem with surface water contamination in the area. The study's findings revealed that a substantial proportion of persons living in Katsina-Ala, a well-known town in the study region, suffered from the negative effects of urinary schistosomiasis, specifically 48% of the population. Previous studies by Galadima *et al.* (2011) and Falebita & Ayua (2022) found a robust link between this specific health condition and acute pollution levels in surface water.

Drilling operations for around 638 boreholes were implemented as a result of state government activities to address water scarcity between 2015 and 2017 (Falebita & Ayua 2022). Following that, in 2022, this figure was expanded to around 2,000 boreholes. However, a number of incidents of diminishing productivity and outright inefficiency, resulting to borehole abandonment, have been reported (Akpen *et al.* 2019). Between 2015 and 2017, 450 boreholes were restored around the state as a result of the need to address the frequent occurrence of borehole failure. According to Egu and Ilozobhie's documentation, approximately half of the boreholes claimed to have been drilled during that time period were part of this rehabilitation project (2020). However, it should be noted that borehole rehabilitation on its own is not a viable alternative. To discover the root causes of failures, a full understanding of the geological and hydraulic features of the local aquifers is required. This information is critical for developing a comprehensive regional water project that maximizes the utilization of available water resources while ensuring long-term sustainability. As a result, before initiating any drilling initiatives, a thorough assessment must be performed. Akpen *et al.* (2019) acknowledge the scarcity of research on the aquifer properties of the study area. However, just a few investigations have been conducted in the scientific sector.

Olutoyin *et al.* (2014) used a number of geophysical techniques, including very low frequency electromagnetic (VLF-EM) and vertical electrical sounding (VES), to examine the potential of groundwater in the Katsina-Ala region. The results of their investigation revealed that the study region could be categorized into zones with high, moderate, and low groundwater potential utilizing geoelectric parameter analysis. Jika and Mamah conducted a study in 2014 in which they explored the Vandeikya region of central Nigeria using electrical resistivity and electromagnetic listening techniques. Obiora *et al.*'s (2015a, 2015b) study geophysically examined the hydrological units in Makurdi and investigated the probability of groundwater flow. The researchers used the surficial electrical resistivity approach for their investigation. Ehirim & Nwakwo (2016) conducted a thorough analysis and assessment of the potential of groundwater resources in selected areas of Buruku and Gboko. The study's findings revealed two distinct zones of groundwater with variable quality levels.

Terhemba *et al.* used galvanic and electromagnetic resistivity methods to statistically locate and describe aquifers in the Katsina-Ala basement complex in a 2016 study. Their study sought to create a map of subsurface water productivity. The researchers classified the estimated transmissivity values into three categories: extremely low, low, and intermediate. These three classes – very low, low, and intermediate – were found to correlate with varied levels of groundwater potentiality.

The previous study was limited in its spatial breadth and data coverage, resulting in an insufficient characterization of surrounding aquifers. As a result, the models that are created may not be resilient. Furthermore, this has resulted in regional knowledge gaps about groundwater potential, which must be filled in order to develop a comprehensive and effective plan for managing and utilizing groundwater resources. Furthermore, it should be noted that current interpretation models have not taken into consideration the presence of native geological variability, which is present even in places dominated by basement complexes, such as Katsina-Ala. As a result, the hydraulic characteristic models that were developed may have contained mistakes.

The Middle Benue Trough is a geologically varied region with foundational and sedimentary rock formations. This region, however, has significant water scarcity challenges, owing mostly to a lack of surface water reservoirs and severe river and stream contamination (Eyankware *et al.* 2020; Eyankware & Aleke 2021; Falebita & Ayua 2022). Borehole failures have also been observed while groundwater studies are ongoing. The shortcomings discovered can be attributed in part to a lack of understanding of the geological features that influence groundwater accessibility, one of which is the presence of lineaments.

This research consequently carried out an in-depth study of the geoelectric earth-layer models of the entire area and utilized empirically derived relations to develop hydraulic parameters from a dense coverage of VES data. This was necessary for the description of regional aquifer architecture and groundwater flow within regional aquifers; projection of the regional groundwater potential and making inferences on causes of high rate of borehole failures in a hydrological challenged geo-environment, comprising basement complex and sedimentary terrains.

GEOLOGY AND HYDROGEOLOGY OF THE STUDY AREA

The study area is bounded by latitudes 7° 00′ to 7° 30′ N and longitudes 9° 00′ to 9° 30′ E covering a total land area of about 3,278.5 km^2 (Figure 1).

The geology of the study area comprises both sedimentary and basement rocks (Jika and Mamah 2014) as can be seen in Figure 2. Part of the study area falls within the sedimentary middle Benue Trough (King 1950; Farrington 1952; Murat 1970; Odusanya & Amadi 1990). The Benue Trough occupies an intracontinental position and has a thick compression-folded supracrustal fill of varied composition whose age ranges from Albian to Maastrichtian (Obaje 2004). The sedimentary succession in the middle Benue Trough consists of the Asu River Group, the Awe, Keana, Eze-Aku, Awgu, and Lafia Formations.

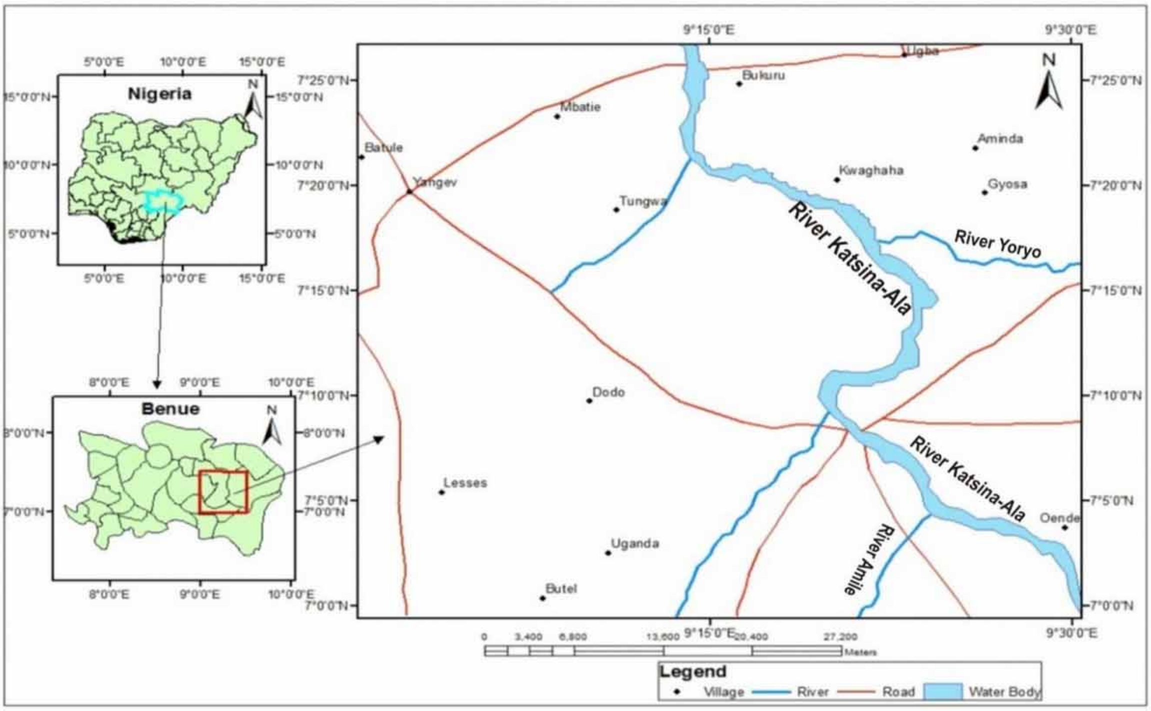


Figure 1 | Administrative map of the study location.

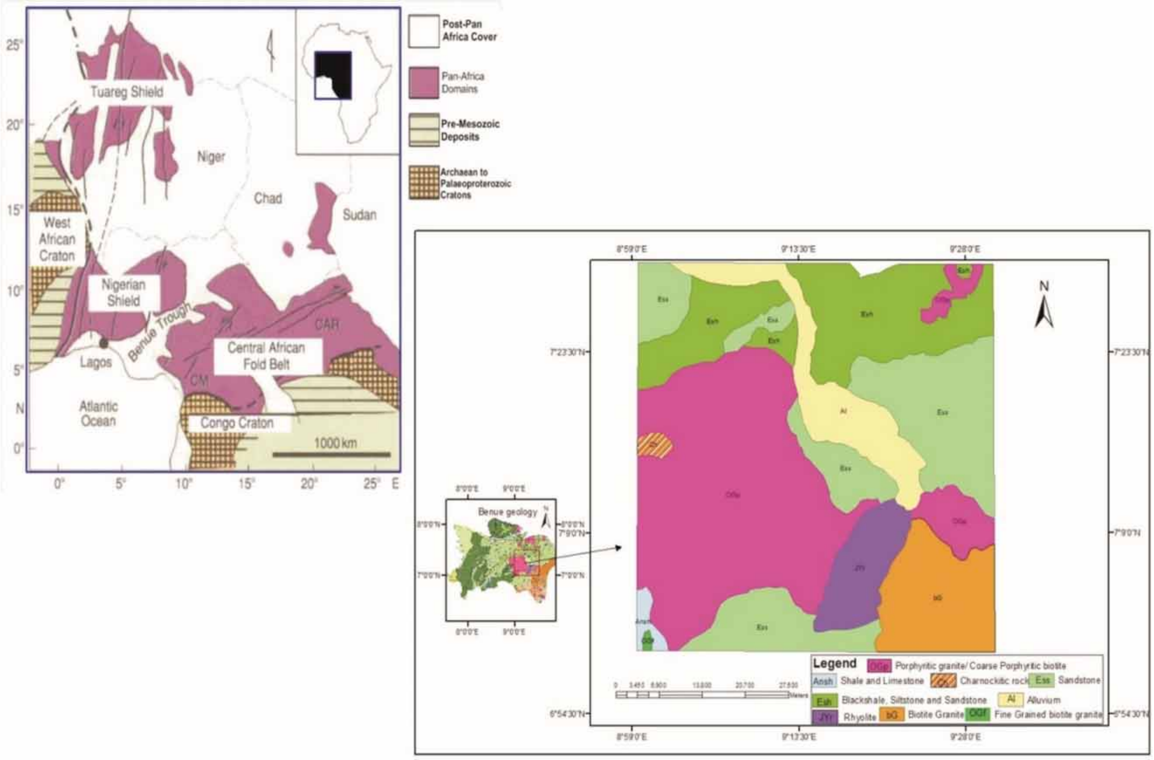


Figure 2 | Location of the study area within a framework of the geology of West Africa (geology of Benue State).

The crystalline basement outcrops in some places in the Middle Benue Trough are characterized by major and minor intrusives (Cratchley & Jones 1965; McCurry 1976), which were formed during the Pan African orogeny (Kogbe 1989; Mogaji & Lim 2017). The crystalline basement in these areas is part of the Eastern Nigerian

Basement Complex and comprises quartzite, siliciferous rocks, migmatite gneiss, older granites, and other undifferentiated basement rocks (Offodile 2002; Terhemba *et al.* 2016).

Hydrogeologically, the basement complex rocks are largely meagre aquifers characterized by low porosity and permeability, resulting from their crystalline nature (Ilozobhie *et al.* 2023). Accessibility of groundwater resources in such areas is possible only with the development of secondary porosity and permeability resulting from weathering and fracturing (Ogundana & Talabi 2014). The lithostratigraphic units of the sedimentary portion include shales, sandstones, and limestones of the Asu River Group; gray to black shales and siltstones of the Eze-aku formation with facie changes to sandstones and sandy shales (Adelana *et al.* 2008), with only the Eze-Aku formation possessing good aquifers (Okonkwo & Ujam 2013).

The aquifer units in the study area are derived essentially from the weathered and or fractured rocks (Offodile 2002; Ojo & Olorunfemi 2013; Terhemba *et al.* 2016); unconsolidated overburden, if significantly thick (Satpathy & Kanungo 1976; Dan-Hassan & Olorunfemi 1999; Bala & Ike 2001); and permeable sedimentary lithology with high matrix porosity. Highly indurated sedimentary rocks may also require interconnected fractured systems for groundwater flow, so exploration is dependent on the location of zones with brittle structures like faults or fractures. The combination of all these factors makes the study area a hydrologically challenged environment.

MATERIALS AND METHODS

Eighty-nine VES stations were occupied using the Schlumberger array with half current electrode separation (AB/2) ranging from a minimum value of 65 m to a maximum of 130 m. The VES data were plotted on bi-logarithmic papers and interpreted quantitatively using the partial curve matching technique. This involved segment-based matching of field and standard theoretical curves on the master curve, and appropriate auxiliary curves to obtain the resistivity and depth ratios from which apparent resistivity and thickness were calculated (Umoren *et al.* 2017). This was repeated sequentially until the entire curve segment was interpreted. The choice of starting model was constrained by a priori geologic information obtained from the geologic map of the study area (Obaje 2004), borehole log data (Okafor & Mamah 2012; Terhemba *et al.* 2016), and literature in order to ensure best fit and limit iteration cycles. The results obtained from the partial curve matching were further refined by 1-D computer-assisted forward modeling using WinResist® software (Vander Velpen 2004) to obtain the true resistivity and thickness of the subsurface geologic sequence underlying the station and thus delineate the aquifer layer(s).

Maximum iterations for the forward modeling were set to 30 and the resulting output with an RMS error of less than 5% was accepted for the study. For data points with RMS error greater than 5%, the interpretation was repeated to obtain better-starting models and forward modeling was reiterated. However, where the RMS error of the new output was within acceptable limit, results were accepted but where the RMS error still exceeded the RMS error limit, the data point was excluded as non-reliable. On this basis, 89 VES data used for the study were selected.

Aquifer transmissivity and hydraulic conductivity

Using non-linear relations presented in Equations (1) and (2) for basement and sedimentary terrains, respectively, transmissivity (T) was evaluated from the aquifer resistivity and thickness (Heigold *et al.* 1979; Singh 2005; Mogaji *et al.* 2011; Obiora *et al.* 2015b; Ehirim & Nwakwo 2016; Agbasi *et al.* 2019; Abdulrazzaq *et al.* 2020; Adegoke Ige *et al.* 2020).

$$T = (0.0538)e^{0.0072\rho} \times h(\text{Basement terrain}) \tag{1}$$

$$T = (386.40)\rho^{-0.93283} \times h(\text{Sedimentary terrain}) \tag{2}$$

where T is the transmissivity (m^2/day); ρ is the aquifer resistivity (Ωm); h is the aquifer thickness (m).

Transmissivity values in both basement and sedimentary terrains were converted into logarithmic transmissivity index X (m^2/day) for easier representation, characterization on maps and comparison across dissimilar geo-environments (Terhemba *et al.* 2016). Transmissivity transformation was achieved using the following equation after Krasny (1993).

$$X = \log\left(\frac{T}{86,400}\right) + 8.96 \tag{3}$$

Ehirim & Nwakwo (2016) defined Hydraulic conductivity to be the ratio of the bulk aquifer transmissivity to the aquifer thickness. The hydraulic conductivity can therefore be obtained using Equations (1) and (2) for the appropriate geo-environment;

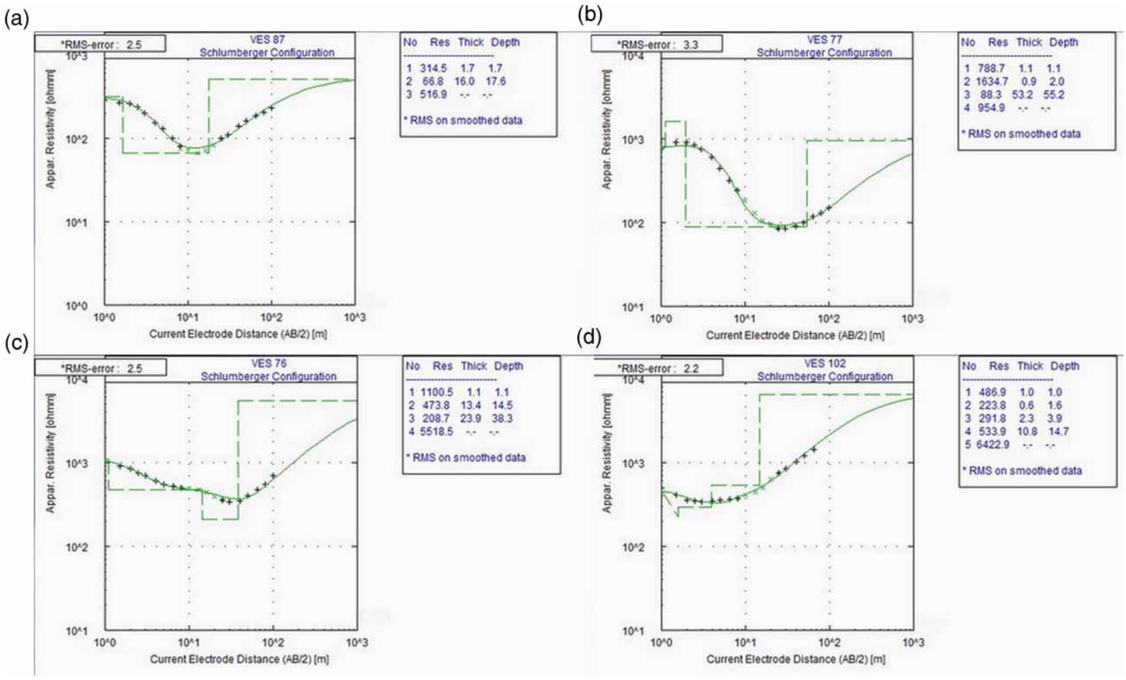
$$\text{Hydraulic conductivity} = \frac{T}{h} \tag{4}$$

where T is the transmissivity; h is the aquifer thickness.

RESULTS AND DISCUSSIONS

VES interpretation and aquifer delineation

The study area exhibits high variability of resistivity sounding curves indicative of the heterogeneity emblematic of a multipart geologic setting (Akinlalu *et al.* 2017). The curves shown in Figures 3 and 4 show that the field data have a high degree of precision because the root mean square (RMS) error for the curves is less than 4%. The H-type curve, which occurred roughly 36% of the time, and the KH-type curve, which occurred approximately 33.3% of the time, were the two most common curve types in the area. Other categories in the data set were QH, which made up 16% of the total; HA, which made up 10.6%; and the A-type curves, HKH, and AKH, which made up 1.3% apiece (Figures 3 and 4).



(a)

No	Res	Thick	Depth
1	314.5	1.7	1.7
2	66.8	16.0	17.6
3	516.9	-.-	-.-

* RMS on smoothed data

(b)

No	Res	Thick	Depth
1	788.7	1.1	1.1
2	1634.7	0.9	2.0
3	88.3	53.2	55.2
4	954.9	-.-	-.-

* RMS on smoothed data

(c)

No	Res	Thick	Depth
1	1100.5	1.1	1.1
2	473.8	13.4	14.5
3	208.7	23.9	38.3
4	5518.5	-.-	-.-

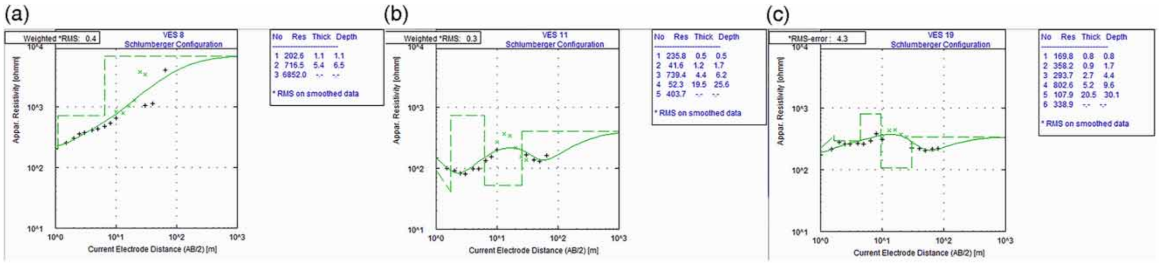
* RMS on smoothed data

(d)

No	Res	Thick	Depth
1	486.9	1.0	1.0
2	223.8	0.6	1.6
3	291.8	2.3	3.9
4	533.9	10.8	14.7
5	6422.9	-.-	-.-

* RMS on smoothed data

Figure 3 | Characteristic curve types encountered within the study area: (a) H-type curve; (b) KH-type curve; (c) QH-type curve; (d) HA-type curve.



(a)

No	Res	Thick	Depth
1	202.6	1.1	1.1
2	716.5	5.4	6.5
3	6852.0	-.-	-.-

* RMS on smoothed data

(b)

No	Res	Thick	Depth
1	235.8	0.5	0.5
2	41.6	1.2	1.7
3	739.4	4.4	6.2
4	52.3	19.5	25.6
5	403.7	-.-	-.-

* RMS on smoothed data

(c)

No	Res	Thick	Depth
1	169.8	0.8	0.8
2	358.2	0.9	1.7
3	293.7	2.7	4.4
4	802.6	5.2	9.6
5	107.9	20.5	30.1
6	338.9	-.-	-.-

* RMS on smoothed data

Figure 4 | Characteristic curve types encountered within the study area; (a) A-type curve; (b) HKH-type curve; (c) AKH-type curve.

Conceptual model of aquifer

The aquifer zones in the basement complex areas are predominantly made up of the weathered/fractured basement complex rocks. The aquifers tend to be localized and vary greatly in thickness. They are predominantly unconfined with thicknesses ranging from 4.4 to 74.8 m. Generally, in the sedimentary portion of the study area, aquifers are the sands and shaly sand layers of the Eze-Aku formation and the sands, clayey sands and sandy clay layers of the alluvium deposits with thicknesses ranging from 4.9 to 96.7 m.

Geoelectric sequence characterization and lithology description

From the interpreted VES Sections, three- to five-layer earth models were predominant within the study area.

The three-layer models

Three geoelectric layers were encountered. The topsoil is relatively thin, composed of predominantly laterite, lateritic clays and clay and is characterized by resistivity values ranging from 18.3 to 2,656 ohm-meter with thicknesses of 0.4–6.1 m. The second layer has resistivity values that vary from 5.9 to 391.2 ohm-m and thicknesses ranging from 4.4 to 56.20 m. This layer is the weathered basement and is the main aquifer unit. The last layer has a resistivity range of 24.3–6,852 ohm-m, infinite thickness and is the fresh/fractured basement.

The four-layer earth models

Four geoelectric layers were encountered. The topsoil is predominantly composed of laterite, lateritic clays and clays; it is relatively thin and has resistivity ranging from 40.1 to 4,476.9 ohm-m with thicknesses of 0.4–2.4 m. The second layer has resistivity values that vary from 9.0 to 2,235.9 ohm-m and thicknesses 0.4–34.1 m. Its lithologic composition is sand and sandy clay and it is predominantly wet. It may form part of the aquifer unit, especially in the sedimentary regions. The third layer is the weathered basement rock identified as the main aquifer unit and has resistivity values ranging from 4.5 to 1,343 ohm-m, with a thickness of 5.7–53.2 m. In the sedimentary environment, this layer is composed of clays intercalated with thin sand lenses that may form perched aquifers. The final layer with a resistivity range of 52.2–5,518.5 ohm-m and infinite thickness is the fresh/fractured basement.

The five-layer earth models

Five geoelectric layers were encountered. The topsoil is relatively thin; composed of laterite and lateritic clays; and characterized by resistivity ranging from 116.5 to 951.7 ohm-m with thicknesses that vary from 0.5 to 1.6 m. The second layer is highly localized with extensive deviations in characteristics. Its lithologic composition includes sands, clays, lateritic sands, and lateritic clay; its resistivity varies from 41.6 to 1,466.9 ohm-m; it is relatively thin with thicknesses ranging from 0.6 to 7.9 m. This layer sometimes forms a seal confining the aquifers below where their composition is more clayey. The third layer has resistivity ranging from 28 to 1,570.1 ohm-m and a thickness of 1.7–88.8 m; it is composed of sands, sandy clay, and clays. It is predominantly wet and may form good aquifers that are sufficiently porous and thick. The fourth layer is lithologically weathered basement rock. It has resistivity values ranging from 29.3 to 902.6 ohm-m; it is relatively more conductive and is identified as the main aquifer unit in this model. The thicknesses range from 5.0 to 96.7 m. In sedimentary regions, the layer is composed of sand intercalated with clay. The final layer with a resistivity range of 138–21,294.3 ohm-m and infinite thickness is the fresh/fractured basement. The above geo-electrical lithologies compared satisfactorily with borehole log information (Okafor & Mamah 2012; Terhemba *et al.* 2016) and published literature (Jika & Mamah 2014). Anomalously low resistivity recorded within the basement complex in the four and five earth-layer models is suspected to be as a result of infiltration of connate water of marine origin stored during the formation and deposition of the basin, a phenomenon that is reported in some parts of the Benue Complex terrain. It may also result from fracturing, shearing, and saturation of fresh basement rocks with fluid (Terhemba *et al.* 2016).

Aquifer resistivity

Basement complex resistivity ranges from 17.0 to 551.0 ohm-m. The resistivity is relatively low around the Katsina-Ala and Ushongo areas. The highest resistivities occur around the Tungwa and Mbatie areas (Figure 5). In the Sedimentary regions, the Resistivity values are higher compared to basement complex resistivities. Regions around Nyibam and Batule, North-West of the map have the highest resistivity with a resistivity of up to 340.0–900.0 ohm-m. Areas around Kwaghaha, Aminda, and Gyosa to the northeast of the map show the

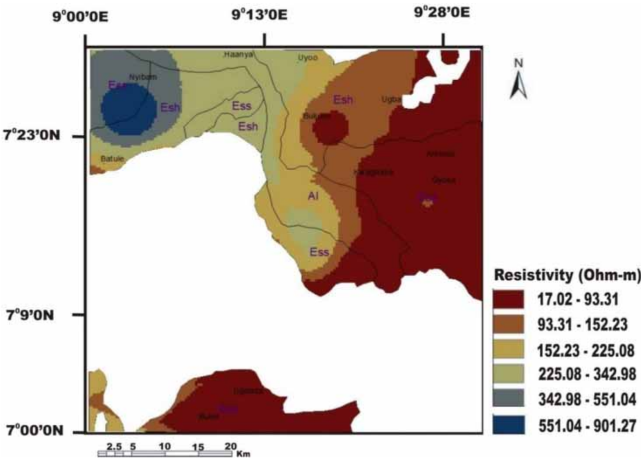


Figure 5 | Iso-resistivity map of the study area (basement complex portion).

lowest resistivity within the area ranging from about 17.0 to 150.0 ohm-m (Figure 6). Resistivity is a factor twice removed from groundwater potential and is thus used to indirectly measure aquifer performance. Resistivity is inversely associated with the clay content of the aquifer, which in turn controls permeability. Low resistivity implies high clay content and thus low permeability (Okiongbo & Akpofure 2012); the converse also holds true. Aquifers with relatively high resistivity (low clay content) will have a correspondingly high groundwater potential due to high permeability.

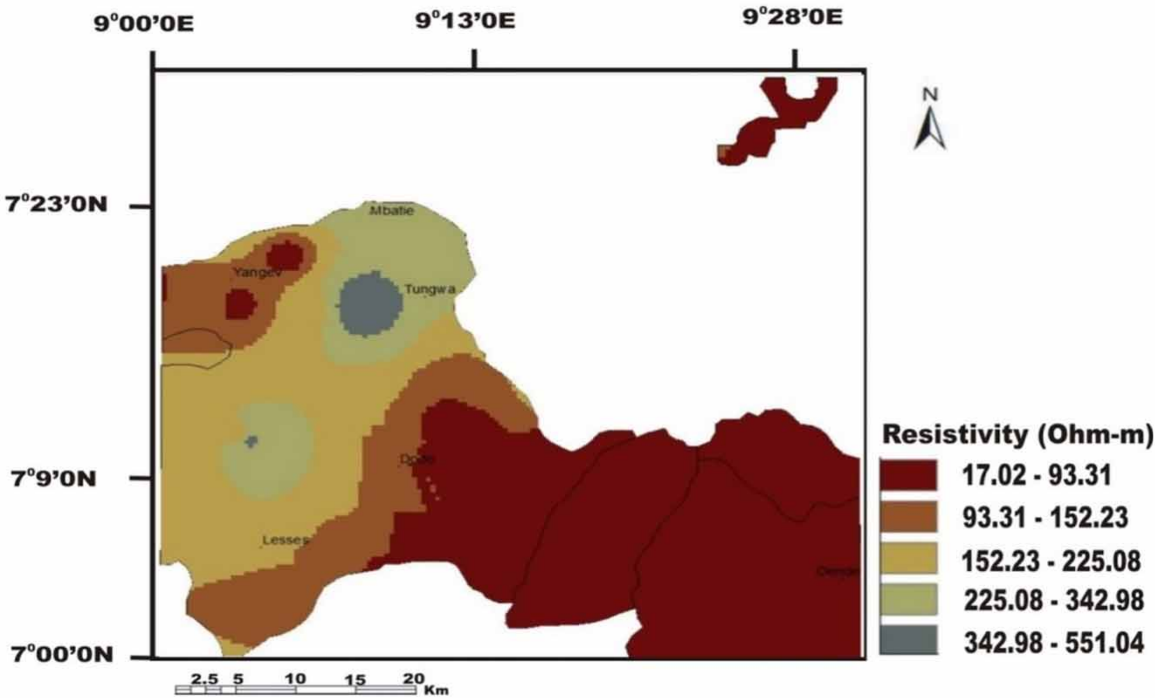


Figure 6 | Iso-resistivity map of the study area (sedimentary portion).

Aquifer thickness

The aquifer layer thickness in the study area varies from 4.4 to 96.7 m. Figure 7 shows the distribution of the main aquifer unit (weathered/fractured basement) for the basement complex aquifers. Thicknesses range from about 4.4 to 50.0 m. Very low thicknesses are observed around Mbatile and to the north and east of Lesse ranging from 4.4 to 14.0 m. Areas north of Oende have the highest thickness of up to 40.0–50.0 m. On average,

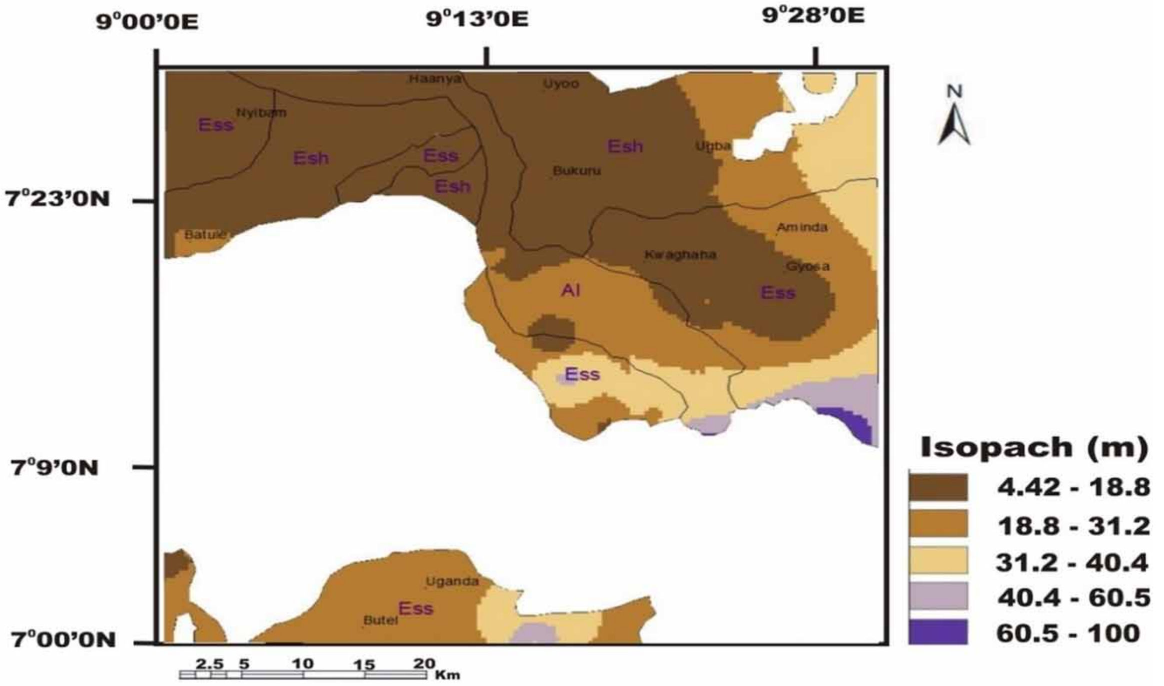


Figure 7 | Aquifer isopach map of the study area (basement complex terrain).

thicknesses within this area fall between 14.9 and 21.2 m. Aquifer thickness within the Sedimentary portion falls between 4.4 and 90.6 m. Aquifers with considerable thicknesses of up to 90 m are found within a small portion of the sedimentary terrain toward the south of Gyosa. Areas to the north-west of the map (Figure 8) around Nyibam, and Haanya and extending toward the north and east to areas such as Aminda and Gyosa have relatively low aquifer thicknesses ranging from 4.4 to 18.8 m. Generally, regional aquifers are hypothesized to have lengths much greater than their thicknesses; therefore, the thickness of the aquifer is of more importance to the calibration of aquifer volume at the borehole than other dimensions. This implies that thicker aquifers would be more desirable for consideration of aquifer fluid capacity and groundwater potential in general.

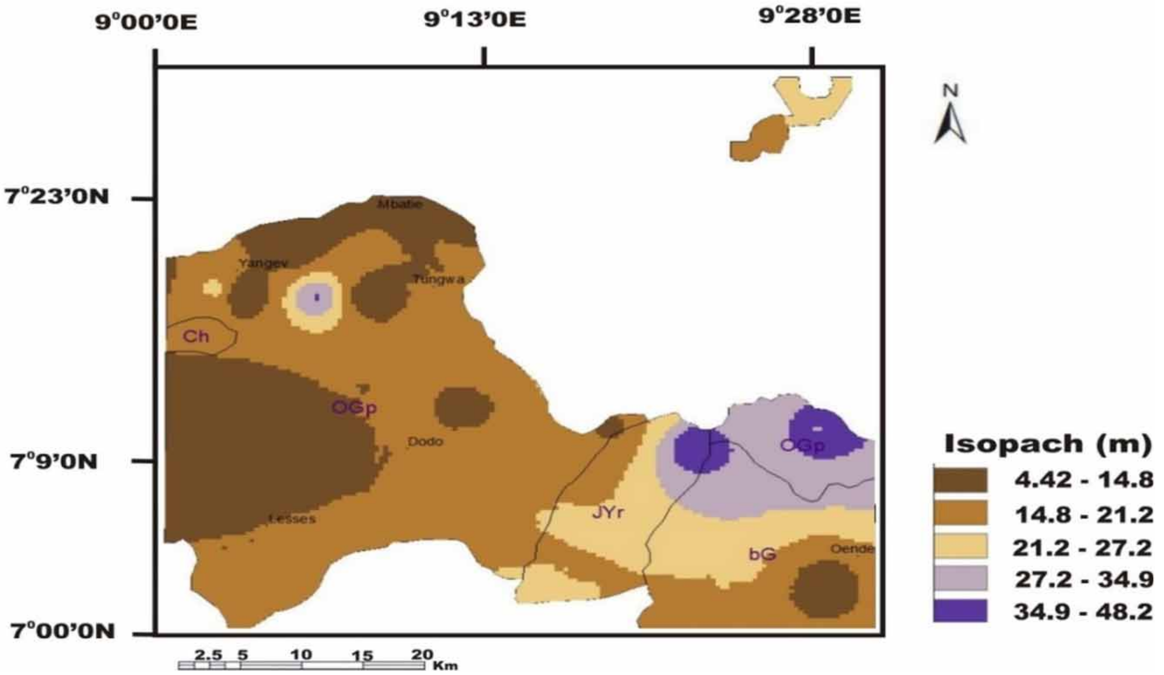


Figure 8 | Aquifer isopach map of the study area (sedimentary terrain).

Transmissivity and log transmissivity

Transmissivity values before transformation ranged from 0.31 to 50.53 m^2/day for the basement complex and 3.37–1,281.36 m^2/day for the sedimentary regions (Figures 9 and 10). This represents more than the order-three difference in magnitude. The log-transformed values of transmissivity in the basement complex range between 3.52 and 5.73 m^2/day. Two zones of low transmissivity located at the north-west of the study, east of

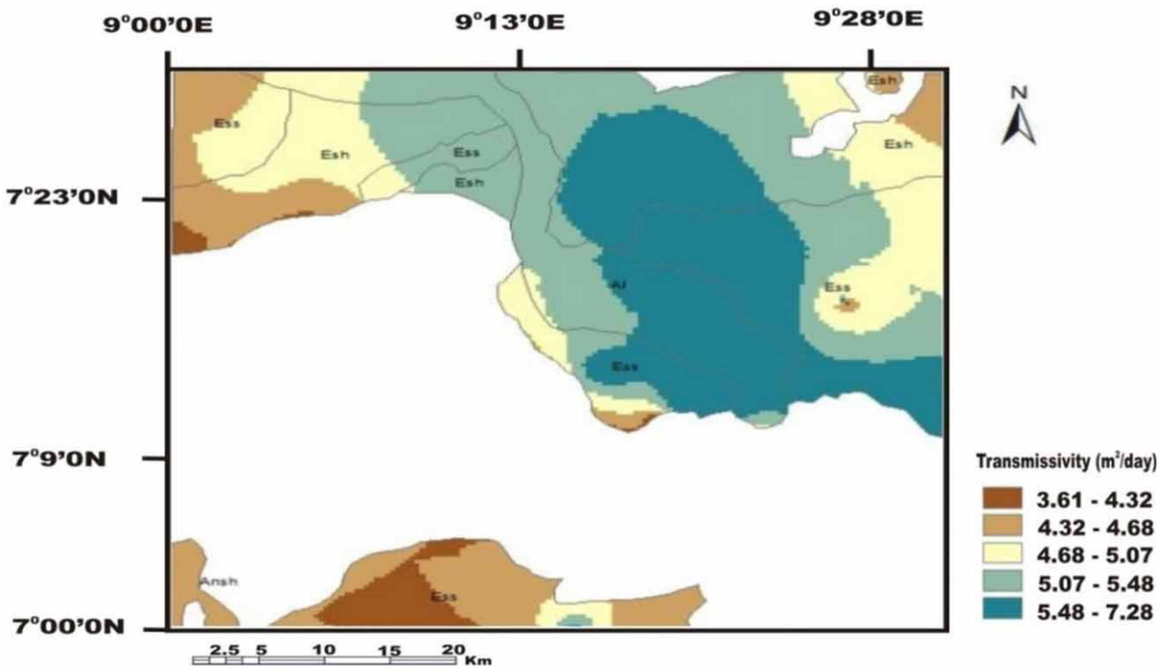


Figure 9 | Transmissivity map of the study area (basement complex terrain).

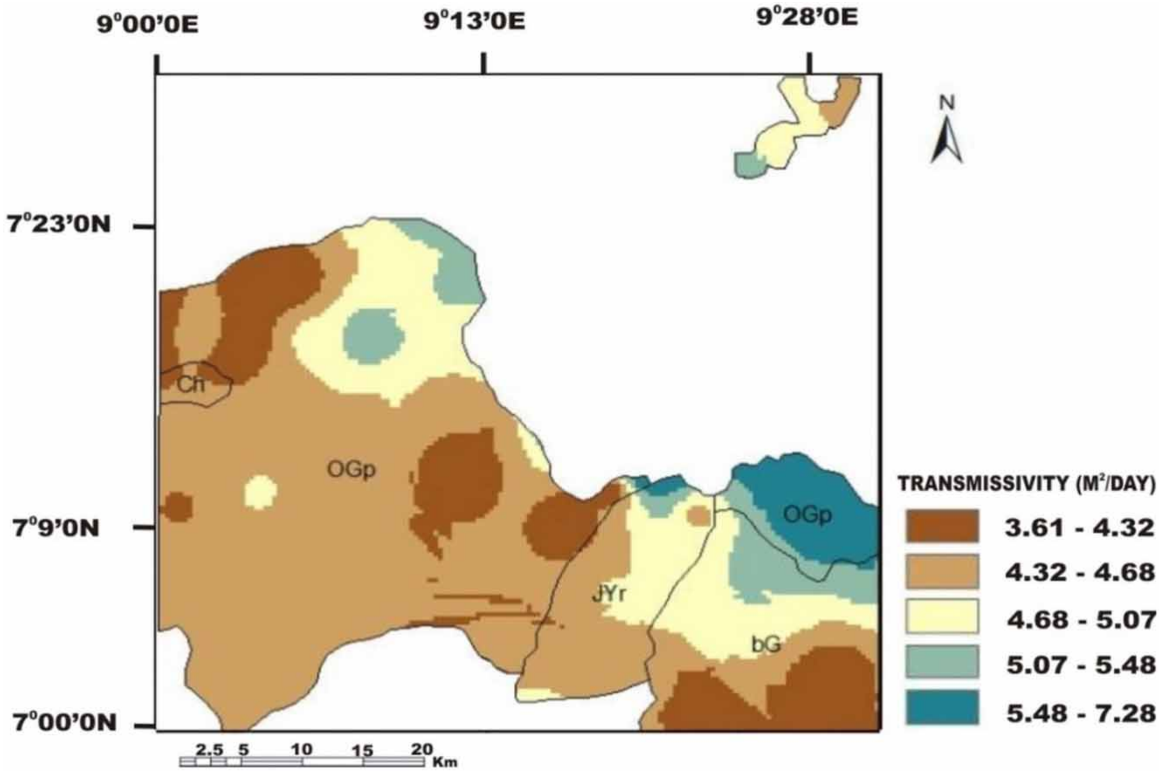


Figure 10 | Transmissivity map of the study area (sedimentary terrain).

the Nyibam area; and south of the study area in the Ushongo region were delineated. About half the areas within the sedimentary terrain have moderate to high transmissivity ranging from 5.0 to 7.0 m^2/day as is evident around Kwaghasa and Gyosa areas. However, 60% of the entire study area including most of the basement complex

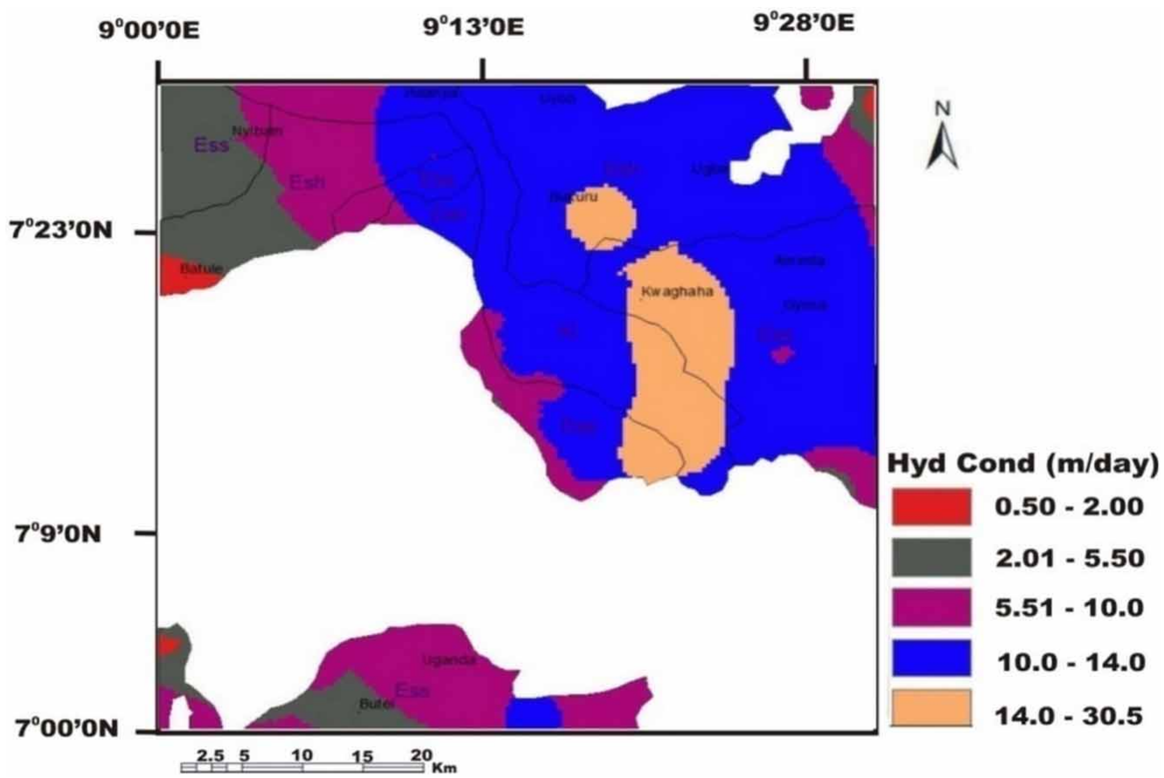


Figure 11 | Hydraulic conductivity map of the study area (basement complex terrain).

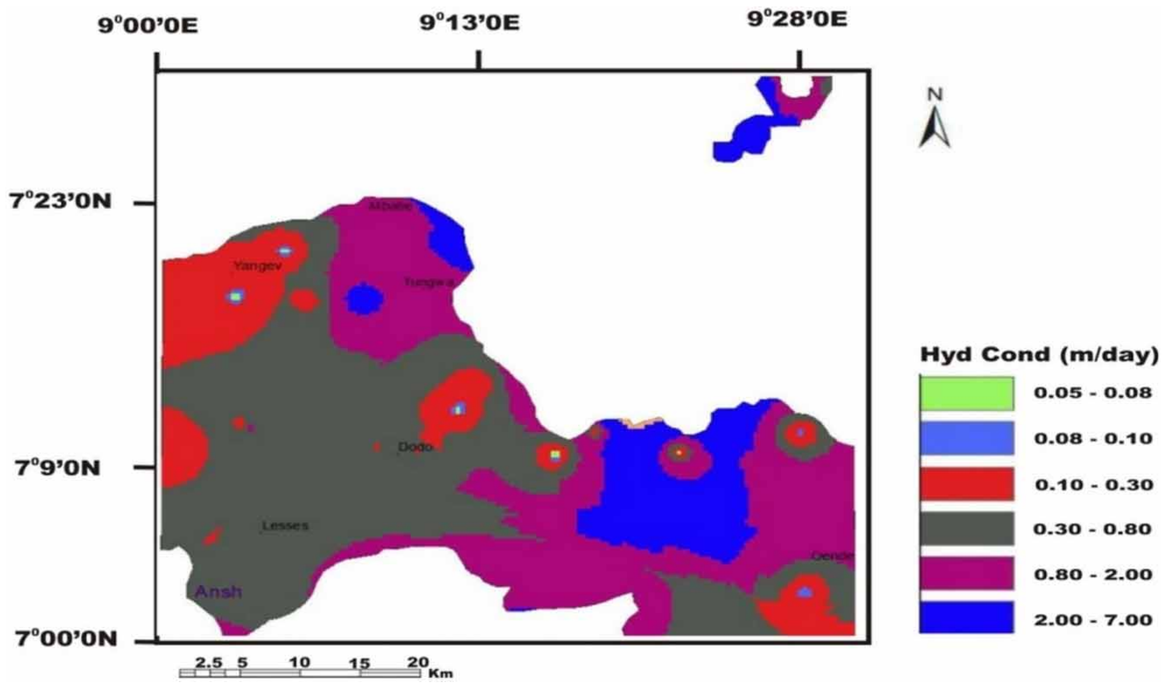


Figure 12 | Hydraulic conductivity map of the study area (sedimentary terrain).

Table 1 | Summary of aquifer hydraulic parameters for Basement complex rocks

VES	AQ R (Ωm)	AQ Th (m)	Hyd Cond (m/day)	Trans (T mag) (m^2/day)	Log Trans (X) (m^2/day)
1	119.30	35.80	0.13	4.55	4.68
2	88.10	21.10	0.10	2.14	4.35
6	67.90	30.20	0.09	2.65	4.45
7	70.90	31.00	0.09	2.78	4.47
8	716.50	5.40	9.36	50.54	5.73
9	143.00	43.90	0.15	6.61	4.84
11	52.30	19.50	0.08	1.53	4.21
14	275.50	74.80	0.39	29.25	5.49
15	228.60	46.20	0.28	12.89	5.13
16	51.90	12.00	0.08	0.94	4.00
18	68.10	20.90	0.09	1.84	4.29
19	107.90	20.50	0.12	2.40	4.40
21	40.90	4.60	0.07	0.33	3.54
23	29.10	8.50	0.07	0.56	3.77
24	267.10	22.50	0.37	8.28	4.94
25	74.30	10.40	0.09	0.96	4.00
26	69.90	6.90	0.09	0.61	3.81
27	21.50	7.90	0.06	0.50	3.72
32	109.90	35.60	0.12	4.23	4.65
34	29.30	10.30	0.07	0.68	3.86
35	124.80	15.60	0.13	2.06	4.34
36	87.80	8.60	0.10	0.87	3.96
37	95.80	10.40	0.11	1.12	4.07
38	25.10	4.80	0.06	0.31	3.51
39	29.90	6.00	0.07	0.40	3.63
40	32.90	8.80	0.07	0.60	3.80
41	58.80	9.40	0.08	0.77	3.91
44	32.50	15.80	0.07	1.07	4.05
46	98.90	56.20	0.11	6.16	4.81
54	64.10	10.50	0.09	0.90	3.98
55	35.70	16.60	0.07	1.15	4.09
59	120.10	13.20	0.13	1.69	4.25
60	115.10	17.60	0.12	2.17	4.36
63	5.90	20.90	0.06	1.17	4.09
64	4.50	20.90	0.06	1.16	4.09
65	49.80	16.50	0.08	1.27	4.13
66	52.50	9.70	0.08	0.76	3.91
69	55.80	18.70	0.08	1.50	4.20
73	69.90	38.20	0.09	3.40	4.55
74	125.30	41.20	0.13	5.46	4.76
77	88.30	53.20	0.10	5.41	4.76
78	39.80	23.00	0.07	1.65	4.24
79	38.30	26.80	0.07	1.90	4.30
89	38.10	6.40	0.07	0.45	3.68
97	40.70	45.30	0.07	3.27	4.54

(*Continued.*)

Table 1 | Continued

VES	AQ R (Ωm)	AQ Th (m)	Hyd Cond (m/day)	Trans (T mag) (m^2/day)	Log Trans (X) (m^2/day)
98	158.10	4.40	0.17	0.74	3.89
99	151.70	13.20	0.16	2.12	4.35
100	24.40	5.70	0.06	0.37	3.59
102	533.90	10.80	2.51	27.14	5.46
104	163.80	10.50	0.17	1.84	4.29
105	268.00	7.90	0.37	2.93	4.49
106	391.20	8.90	0.90	8.01	4.93
110	10.60	9.70	0.06	0.56	3.77
111	18.90	9.50	0.06	0.59	3.79
112	30.60	26.60	0.07	1.78	4.27
113	56.20	22.70	0.08	1.83	4.29
114	133.10	22.60	0.14	3.17	4.52
115	161.20	22.20	0.17	3.81	4.60
116	27.30	10.50	0.07	0.69	3.86
117	174.60	35.30	0.19	6.68	4.85
118	41.80	9.20	0.07	0.67	3.85

terrain falls within the low to intermediate designation. Transmissivity is comparable to permeability and thus gives a direct measure of groundwater flow and transport model.

Hydraulic conductivity

Hydraulic conductivities in the basement complex range from 0.05 to 7.00 m/day. The lowest hydraulic conductivity regions have values ranging from 0.05 to 2.00 m/day, covering substantial portions of the basement complex terrain (Figure 11). Low hydraulic conductivity is an indication of high clay content (Ehirim & Nwakoro 2010) and thus low permeability (Obiora *et al.* 2015a) and as such its observation across the study area reveals low groundwater potential. In the sedimentary terrain (Figure 12), areas around Kwaghaha in Katsina-Ala have the highest recorded hydraulic conductivities within the study area reaching values of about 14.00–30.00 m/day. Tables 1 and 2 show a summary of aquifer hydraulic parameters of the basement complex and sedimentary terrains. Interestingly, the groundwater potential of the study area is quite prolific and has a range from low, moderate, and high to very high-water capacity as shown in Figure 13; with the very high potential patch located in the east-central region. The largely moderate and high gave approximately 60.34% water capacity potential.

DISCUSSION

Significant fluctuations in resistivity sounding curves can be considered a trustworthy indicator of the complicated geological conditions encountered in the study area. Because of the nature of the rock formations, this occurrence is complex due to the existence of a broad range of geological features and rock formations at the same time (Wisén *et al.* 2008). However, it is critical that the data's accuracy and dependability be prioritized. The fact that the RMS error is less than 4% shows that the data are correct and reliable. This result demonstrates the data's accuracy and trustworthiness. Accuracy is a critical prerequisite for successfully performing geological and hydrogeological investigations because it ensures the dependability of interpretations and assessments obtained from data and allows them to be used efficiently in decision-making processes (Burakov 2019).

The frequency of H-type and KH-type curves in resistivity data has significant relevance, it serves as indicators of unique aquifer features. These curve types suggest aquifers with distinct characteristics. Because they display unique hydrogeological characteristics, such as increased transmissivity, these aquifers are typically rated as the primary priorities for groundwater research. Understanding the existence and features of these aquifers is crucial to better the management of groundwater resources in the area. This tool makes it easy to discover places with the

Table 2 | Summary of aquifer hydraulic parameters for the Sedimentary terrain

VES	AQ R (Ωm)	AQ Th (m)	Hyd Cond (m/day)	Trans (T mag) (m^2/day)	Log Trans (X) (m^2/day)
47	70.80	25.90	7.27	188.19	6.30
50	852.50	14.70	0.71	10.48	5.04
56	377.10	19.20	1.53	29.31	5.49
57	217.70	8.30	2.55	21.15	5.35
58	220.40	8.40	2.52	21.16	5.35
61	15.40	42.50	30.15	1,281.36	7.13
67	96.90	5.80	5.42	31.45	5.52
68	50.50	9.30	9.96	92.61	5.99
70	33.20	22.50	14.73	331.34	6.54
71	41.00	4.90	12.09	59.26	5.80
72	66.50	22.00	7.70	169.47	6.25
75	259.60	33.40	2.16	72.22	5.88
76	208.70	23.90	2.65	352.35	6.83
80	76.30	7.80	6.78	52.85	5.75
81	556.60	15.70	1.06	16.67	5.25
82	224.40	96.70	7.88	48.07	5.71
83	984.40	5.40	0.62	3.37	4.55
84	65.60	6.20	7.80	48.37	5.71
85	27.00	30.90	17.86	551.79	6.77
87	66.80	16.00	7.67	122.74	6.11
88	44.60	27.50	11.11	305.58	6.51
90	138.00	14.60	3.90	56.92	5.78
91	173.10	10.40	3.16	32.82	5.54
93	375.90	24.70	1.53	37.81	5.60
94	42.30	5.50	11.75	64.61	5.83
95	333.20	8.90	1.71	15.25	5.21
96	37.60	7.10	13.11	93.09	5.99
101	902.60	10.10	0.68	6.83	4.86

Key: VES: Aquifer VES station number; AQ R: aquifer resistivity; AQ Th: aquifer thickness; Hyd Cond: hydraulic conductivity; Trans (T mag): magnitude of transmissivity; log trans (*Y*): logarithmic transmissivity.

greatest potential for groundwater extraction and provides useful information to aid in well placement and drilling technique selection.

The observed disparities in localization (complex and sedimentary terrain) and thickness necessitate the establishment of these zones. The aquifers within the basement complex are spatially limited and have varied thicknesses ranging from 4.4 to 74.8 m. Sedimentary terrain, on the other hand, has a diverse range of aquifers.

The analysis and interpretation of VES profiles can provide significant information on the underlying geological layers in the chosen research region. Numerous layer models (three, four, and five), make it easier to understand the underlying lithology and how it impacts groundwater flow. Layer models are required to appropriately detect aquifer zones, comprehend their geographic distribution, and assess their inherent properties. Geological models that anticipate groundwater dynamics and provide guidance for optimal resource management can be constructed using this technique (Mogaji *et al.* 2021).

Aquifer resistivity values vary across the study area, with noticeable differences between the basement complex and sedimentary terrain. A low resistivity value implies that there is a higher percentage of clay material present, which results in reduced permeability. A high resistivity, on the other hand, shows that groundwater flow should be enhanced (Ohwoghere-Asuma *et al.* 2020; Obasi *et al.* 2021). In terms of groundwater resource availability and potential, the discrepancies discovered were quite significant. High resistivity areas provide more favorable

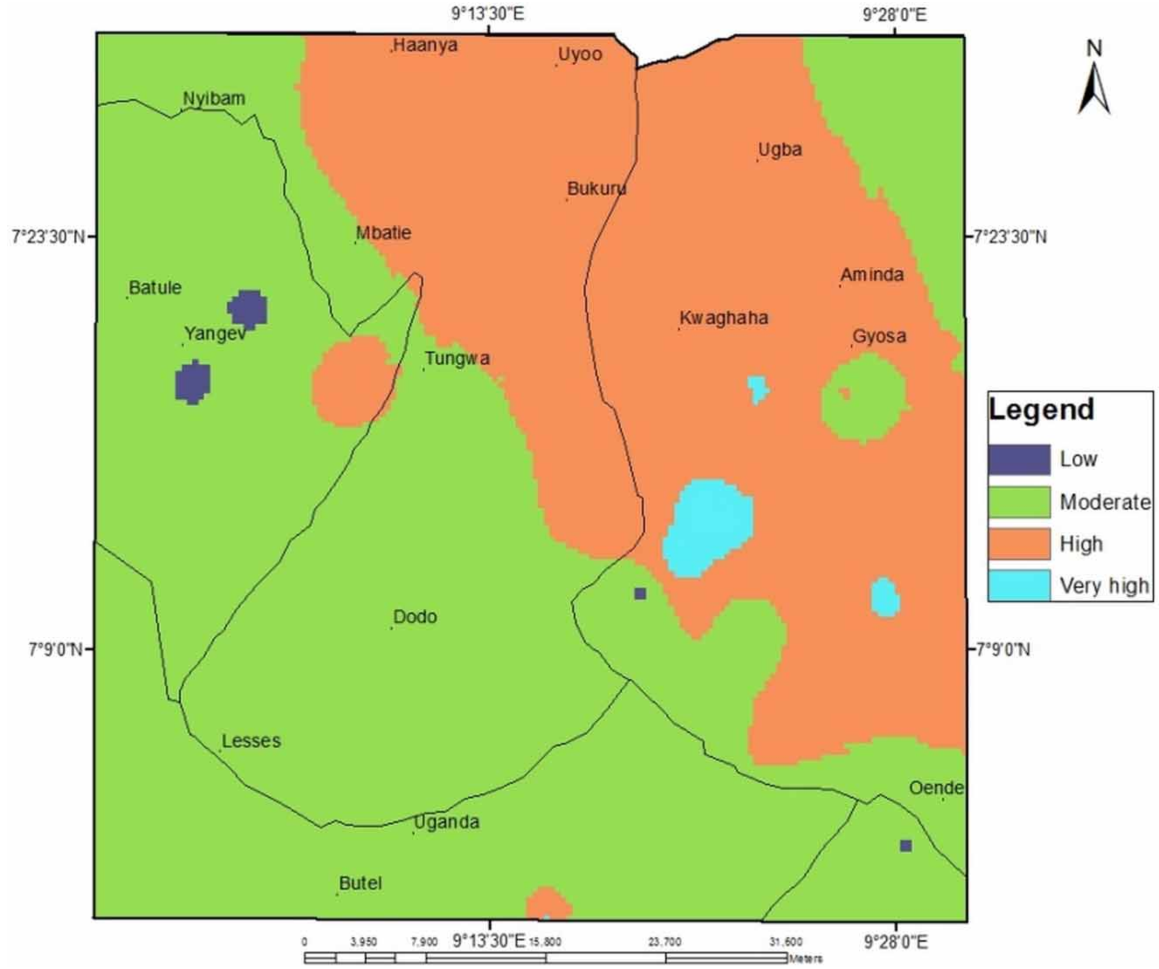


Figure 13 | Groundwater potential map of the study area.

circumstances for groundwater resource exploitation, whereas low resistivity areas may have limited groundwater availability. The information provided is critical in determining which locations should be prioritized for well drilling and how to establish sustainable groundwater resources.

Groundwater capacity is affected by aquifer thickness. Groundwater sources with better storage and supply capacity are more helpful (Akaolisa *et al.* 2022; George *et al.* 2022). To calculate groundwater availability and quantity, it is necessary to first establish the regional variation of aquifer thickness in the research area. This understanding makes it simple to locate readily available and valuable groundwater.

Transmissivity measurements provide essential information on groundwater flow dynamics and material distribution inside an aquifer. Better comparison and representation are made feasible by converting these numbers to logarithmic transmissivity (Utom *et al.* 2012). This observation emphasizes substantial differences in the likelihood of groundwater movement between sedimentary geology and basement complex geology. Furthermore, determining groundwater potential is heavily reliant on measuring hydraulic conductivity, a vital metric that differs across a variety of distinct geographic regions (Ekwok *et al.* 2020; Osinowo & Arowoogun 2020). The low hydraulic conductivity in foundation complex areas suggests a low permeability due to a high clay content. Sedimentary environments, on the other hand, have higher hydraulic conductivity ratings, implying that there may be more groundwater potential in specific places. This knowledge is essential for supporting efficient water resource management and determining the optimal areas for groundwater extraction.

The overall findings indicate that there is a wide variety of groundwater potential in the study's geographic area. Notably, the east-central area has a high potential for water storage. Decision-makers can use this information to identify areas with the greatest potential for groundwater extraction and then prioritize subsequent resource management initiatives. The detailed examination of the lithological makeup and geoelectric characteristics of the aquifer, as well as its thickness, transmissivity, hydraulic conductivity, and resistivity, provides critical information for understanding and managing groundwater resources in the designated research area. The findings of this study provide a solid platform for thoughtful decision-making in the fields of groundwater exploration, extraction, and promotion of sustainable consumption.

CONCLUSION

High-quality integrity analysis of the subsurface aquifer is tremendously linked to the hydraulic conductivity and transmissivity as portrayed in this erudition. Interestingly, confirmed results largely showed this technical synonym with higher properties with sedimentary terrain than the basement complex. This is perhaps due to the existence of an abundance of subsurface porous and permeable conduit matrixes. The existence of lower hydraulic conductivity only confirms the availability of low porous and permeable sediments. Comparative analysis of both cases improved the choice of location for water exploitation purposes. The presence of other viable VES points with improved hydraulic conductivity and aquifer transmissivity would aid appreciable data volume for water resources management and planning.

The major findings from this study are perhaps the hydraulic property development of both quantitative and qualitative basement complex and sedimentary terrain data analytics for the basis of detailed comprehensive and effective study, which is a viable innovation for the dynamic improvement of the quality of present and future water exploration and exploitation survey activities. This is carefully showcased in the quality of water potential capacity delineation of the study area.

In contribution to knowledge, the introduction and development of percentage evaluation analytics is perhaps critical to aquifer properties evaluation for different geologic environments with complex heterogeneous constraints ranging from non-porous, non-permeable hard rocks to non-porous and non-permeable sediments. This is believed to be a valuable technically aided geophysical tool for improved water exploration and re-evaluation. This research will also boost existing data banks and literature on water exploration in the middle Benue trough, Nigeria.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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