

Characterization of aquifers in Offa and environs, southwestern Nigeria, and implications on productivity

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Abstract: Borehole water is currently the most important source of water both for irrigation and domestic uses due to limitations such as inconsistency in availability and impaired quality associated with other sources of water. However, efficiency of boreholes is dependent on several factors that vary in space. 30 boreholes within Offa and environs have been evaluated with a view of determining their properties and relate them with borehole efficiency, establishing regional classification of boreholes and defining groundwater flow pattern(s). This was achieved through analysis of drilling and pumping test data of existing boreholes. 30 Vertical Electrical Soundings (VES) were conducted using Schlumberger array in order to determine geoelectric layers and fracture attributes. Geophysical investigation revealed three to four geoelectric layers which are inferred to be sand, laterite, weathered aquifer, and basement rocks. The frequency of curve types obtained are KH (50.00%), H (36.67%), QH (10.00%), and K (3.33%). Results of borehole aquifer characteristics showed that the depth of well varies from 23.86 - 46.17 m, static water level ranges from 2.04 - 11.22 m, discharge rate varies from 15.74 - 93.57 m³/day and drawdown varies from 3.5 - 19.98 m. Pumping test results revealed that transmissivity vary from 0.33 m²/day to 19.45 m²/day, with an average value of 2.84 m²/day, indicating aquifer of negligible to high potentials, hydraulic conductivity value vary from 1.13x10⁻² m/day to 1.0x10⁻¹ m/day, while the specific capacity value ranges from 1.07 m³/day/m to 21.89 m³/day/m which shows that the performance of boreholes in the study area varies from good to moderate. From the statistical evaluation, it was inferred that there are strong relationships between the following pairs of parameters; specific capacity and discharge, drawdown and depth of borehole, hydraulic conductivity and transmissivity. Pearson's correlation revealed that specific capacity against drawdown has a negative correlation which suggests an inverse relationship between the parameters.

Key words: Borehole; groundwater; Offa; geophysical; aquifer; hydraulic conductivity.

1. INTRODUCTION

Excessive abstractions of water from aquifers yield consequential reduction in the level of water in the well. The magnitude of the drawdown is related to aquifer properties (e.g. aquifer geometry, hydraulic properties and recharge) as well as borehole properties (e.g. abstraction rate, penetration depth and screen positioning). Therefore, aquifers are important component of hydrological cycle because they serve as receptor for percolating water (McDonald et al., 2005). Increase in human population and agricultural activities in rural and urban areas have led to a corresponding increase in the demand for fresh and potable water for human consumption and irrigation. About 97.2% of global water resource is salt water, mainly in oceans, while 2.8% is available as fresh water at any time on the earth. Out of this 2.8%, about 2.2% is available as groundwater (Raghunath, 2006). Natural groundwater storage provides a buffer against climatic variability and quality of the water is often good, but its occurrence depends primarily on geology, geomorphology, geometry of grains and structural attributes (Abdulrazzaq et al., 2020). Hence, borehole water has gained increased importance as it appears to represent the largest portion of water supply used for different applications (Gronwall and Danert, 2020).

However, decision to drill a privately owned borehole now sends fears that kill faster than virus because of the fear of failure. In addition, the most relevant borehole-related risks in the area are drying up of wells and deterioration of water quality as a result of unprofessional completion during

abstraction of water. Despite the policy of Federal government on provision of water in quantity and quality as contained in Sustainable Development Goal 6 (SDG 6) by 2020, inadequate information about basic aquifer parameters is inimical to practical implementation of the policy. In fact, lack of data and high uncertainty are typical features of many aquifers, particularly in basement complex terrains of Nigeria. Though these fractured aquifers are vital sources of quality water in the area, relatively little is known about the extent of the aquifers, their hydrogeological parameters and groundwater flow pattern.

Badmus and Olatinsu (2010) evaluated the aquifer characteristics and groundwater recharge pattern in a typical basement complex, southwestern Nigeria, geophysical survey involving 34 VES were carried out and the results revealed about 7 geoelectric layers which are top soil, sandy clay, clayey sand, shale/clay, sandstone, fractured basement and fresh basement, three probable aquifer units and one aquitard were delineated and the weathered and fractured basement constitutes the main aquiferous units in the area. Hydrogeological characteristics of groundwater yield in shallow wells of the Regolith aquifer was carried out by Ifabiyi et al. (2016), a total of 100 borehole points with their respective test data were collected. The mean yield (1.35 l/s) with a coefficient of variation (38.52%) indicates that well yield is less variable across the study area. The study also revealed that aquifer transmissivity and drawdown are the two most important hydrogeological characteristics that influence well yield in the study area and therefore should be given special attention when developing wells to achieve optimal yield and performance. Sule et al. (2013) determined the hydraulic characteristics of groundwater aquifer in Ilorin, north central Nigeria. A total of 35 borehole locations were used for the study and the determination of aquifer characteristics was based on the Theis Residual Recovery method. Results show the average depth of borehole to be 32.9 m, average well discharge, 0.89 l/s, average hydraulic conductivity, 1.97 m/day and average transmissivity, 49.12 m²/day. Maps showing the aquifer characteristics was developed, which can be used for the planning and drilling of wells in the area. Hassan et al. (2016) employed the use of pumping test data to evaluate groundwater potential of a basement terrain in Kaduna state. 18 pumping test data were used to evaluate the hydraulic parameters and results revealed that the values of specific capacity to range between 1.03×10^{-1} m²/s/m and 9.00×10^{-2} m²/s/m, and these values indicate that the aquifers in the area have low to moderate ground water potentials, the low yield range of between 0.45 l/s and 1.00 l/s recorded in the area shows the heterogeneous and anisotropy nature of the basement aquifer system in terms of groundwater discharge. The characterization of weathered basement aquifer and its implication for groundwater recharge was carried by Tijani et al. (2010). A total of 21 boreholes were analysed for this research. The study revealed varied weathered regolith thickness in banded gneiss, augen gneiss and quartz schist and the observed yield is low in all the bedrock setting. It was, therefore, concluded that not all parameters have noticeable impact on the recharge and productivity of regolith aquifers and it was also inferred that bedrock type and geologic structure influence regolith aquifer recharge and yield productivity. Eluwa et al. (2019) carried out a research on the determination of aquifer characteristics in Item Area of southeastern Nigeria using VES. A total number of 24 VES was conducted for the research. Study revealed that aquifer conductivity ranges from $2.57 \times 10^{-2} \Omega\text{m}$ – $1.176 \times 10^{-4} \Omega\text{m}$; transmissivity from 0.0976 m²/day – 78.65 m²/day. The downward continuation shows a progressive decrease in resistivity with depth, it was therefore concluded that the northern part of the study has serious underground water challenges.

Thus, an integrated method of enhancing borehole efficiency has become an important tool in the optimization of borehole productivity (Chilton and Foster, 1995). This work then evaluates the characteristics of boreholes in Offa and environs with a view to determining factors that are responsible for their efficiency.

1.1 Description of the study area and VES locations

The study area is in the southern region of Kwara state and locally defined by latitudes 8° 4.97'N to 8° 15.14'N and longitudes 4° 34.34'E to 4° 44.23'E. The selected communities include Ijagbo,

Offa, Ilemona, Ira, Ojoku and Igbonna because of their records of industrialization, population increase and agricultural practices (Figure 1). This axis of southwestern Nigeria is connected to Federal road network (though in deplorable state) because it serves as direct link from northern Nigeria into southwestern part. The area of study is underlain mainly by metamorphic rocks and few granitic rocks. The prevailing high features are in the northeastern and southwestern parts of the study area. Most of the rainfall occurs in two rainy seasons, during October-November and February-March. The potential of evaporation in the area is slightly higher than precipitation, up to 2500 mm a year. Thus, subsurface retention water capacity will likely be limited. The drainage pattern is dendritic and has no major river system except tributaries of rivers Oyun and Asa towards the north which are suspected to be fracture controlled.

Hydrogeologically, apart from the seasonally high-pollution-prone surface water, the study area can be classified into two groundwater provinces; relatively shallow basement complex and deep fractured-basement complex units. These different hydrogeological units are spatially varied and defined by the distribution and degree of weathering of the dominant rock types. The rocks of the area (migmatite, granite, and granite gneisses) are known for their low potential for groundwater due to their limitation to primary porosity and permeability except where artificially fractured (Annor and Olasehinde, 1996). In this area, regolith (about tens of meters) which is produced from prolonged chemical weathering of fresh rock forms the top layer. This is followed by fissured and unfissured layers in the second and third units respectively. The density of fissuring decreases with depth and reduces the degree of interconnectivity (Dewandel et al., 2006). Thus, shallow water table will encourage wider aerial coverage by groundwater compare to deep water table which enhances compartmentalization of aquifer zones due to lateral heterogeneity.

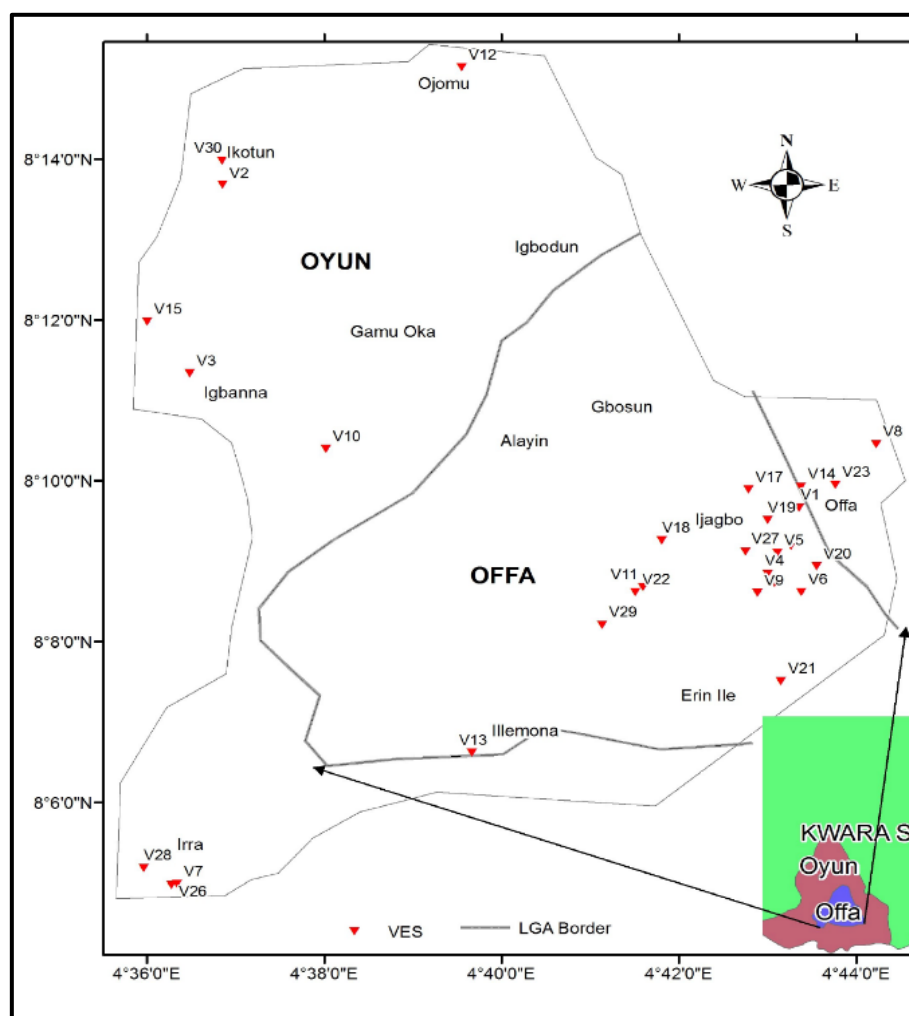


Figure1. Positions of the Vertical Electrical Sounding points.

2. MATERIALS AND METHODS

2.1 Geoelectric inversion result and qualitative interpretation

Thirty (30) vertical electrical sounding measurements were carried out in the study area using an ABEM SAS 2000 Terrameter. The electrical resistivity method is excellent for locating suitable underground position for groundwater accumulation from the surface by using contrasting values between fresh/hard rock and aquifer zones. The fresh hard rock areas have higher value than the water bearing unit, depending upon the degree of weathering and concentration of dissolved ions. For each VES point, the distance between potential electrodes MN was gradually increased in steps starting from 0.5 m to a suitable distance according to the geometrical factor (K) for the Schlumberger configuration to obtain a measurable potential difference. The half current electrodes separation ($AB/2$) was usually increased in steps up to maximum of 150 m depending on the required depth of penetration. The apparent resistivity (ρ_a) was determined using the equation:

$$\rho = \pi \left\{ \frac{\left(\frac{AB}{2}\right)^2 - \left(\frac{MN}{2}\right)^2}{MN} \right\} \Delta \frac{V}{I} \quad (1)$$

where, AB = distance between the current electrodes (metres), MN = distance between the potential electrodes (metres), ΔV = potential difference measured between the potential electrodes (volts), I = applied current strength.

2.2 Hydraulic conductivity and transmissivity

Singh (2005) postulated an empirical relation to compute the hydraulic conductivity (K) and by extension, transmissivity (T) from resistivity values of aquifers sandwiched between resistive overburden layer and intact basement granitic rocks. This equation was used to compute the hydraulic conductivity and transmissivity of the weathered aquifer found in the study area.

$$K = 8 * 10^{-6} * e^{-0.0013\rho} \quad (2)$$

$$T = Kh = (8 * 10^{-6} * e^{-0.0013\rho})h \quad (3)$$

3. RESULTS AND DISCUSSION

3.1 Well parameters and aquifer characteristics

Table 1 shows locations and properties of the 30 boreholes including their coordinates. Total depth drilled at each borehole point was controlled by the positions of aquifers but vary considerably across the whole area. Total depth is shallowest at Gaa Odosun (23.96 m) and deepest beside Palace in Ikotun (46.17 m). Thus, the positions of the fractures can be classified as near surface ≤ 30 m). Table 2 shows the summary of results of pumping test and pre-drilling geophysical survey data. Static water level ranges from 2.04 - 11.22 m, discharge rate varies from 15.74 - 93.57 m³/day and drawdown varies from 3.5 – 19.98 m. Pumping test results revealed that transmissivity vary from 0.33 m²/day to 19.45 m²/day, with an average value of 2.84 m²/day, indicating aquifer of negligible to high potentials, hydraulic conductivity value vary from 1.13x10⁻² m/day to 1.0x10⁻¹ m/day, while the specific capacity value ranges from 1.07 m³/day/m to 21.89 m³/day/m, which shows that the performance of boreholes in the study area varies from good to moderate.

Table 3 shows the Pearson correlation matrix, from the statistical evaluation, it was inferred that there are strong relationships between the following pairs of parameters: specific capacity and discharge, drawdown and depth of borehole, hydraulic conductivity and transmissivity. It also revealed that specific capacity against drawdown has a negative correlation, which suggests an inverse relationship between the parameters.

Table 4 shows the classification of borehole performance based on specific capacity (after Ishaku et al., 2009), result shows that 90% of the boreholes sampled falls in the “moderate performance” group, 6.7% falls in the “good performance” group, while 3.3% of the boreholes have a poor performance.

Table 1. Borehole parameters in Offa and environ, southwestern Nigeria.

BH No.	Borehole Location	GPS reading			SWL (bgl) (m)	SWL (asl) (m)	Total Depth (m)	Estimated Yield (l/sec)
		N (Deg., Min., sec.)	E (Deg., Min., sec.)	Elevation (m)				
1	Gudugba, Ikotun	8°11'58.6"	4°36'00.3"	380.8	4.22	385.02	44.71	0.24
2	Beside palace Igbonna	8°11'20.1"	4°36'29"	430.7	2.35	433.05	40.77	0.55
3	GaaAjele, Igbonna	8°10'23.4"	4°38'11.3"	427.1	11.22	438.32	29.15	0.29
4	Ansarul Islam school, Ikotun	8°13'58.9"	4°36'51.2"	419.5	7.6	427.1	24.20	0.31
5	Beside palace, Ikotun	8°13'40.7"	4°36'51.4"	419.5	15.32	434.82	46.17	0.64
6	Beside palace, Ojoku	8°15'8.4"	4°39'33.2"	399.7	2.04	401.74	37.77	0.47
7	Muu road, Offa	8°9'30.5"	4°43'0.1"	426.1	5.11	431.21	34.20	0.61
8	OGS, Offa	8°9'7.3"	4°42'45"	429.1	5.83	434.93	27.28	1.37
9	Gaalomifufu I, Offa	8°8'37"	4°41'30.3"	448.5	8.61	439.89	29.36	0.39
10	Shawo central, Offa	8°8'36.1"	4°42'53.3"	430.9	3.72	430.32	24.20	0.61
11	GaaOdoosun, Offa	8°7'30.4"	4°43'9.2"	427.5	8.46	435.96	23.96	0.275
12	Essa B, Offa	8°8'36.9"	4°43'22.8"	426.5	5.33	431.83	29.96	0.55
13	Film house, Offa	8°8'43.7"	4°43'4.9"	429.6	3.45	433.05	26.55	0.44
14	BoludeShawo central, Offa	8°8'50.2"	4°43'00.2"	429.9	2.23	432.13	28.00	0.38
15	Ojomu central A, Offa	8°9'6.03"	4°43'6.6"	430.8	6.15	436.95	29.21	0.314
16	Ojomu central B, Offa	8°9'11.5"	4°43'16"	434.5	5.8	440.3	27.52	0.78
17	Owode market, Offa	8°9'40.11"	4°43'21.2"	420.6	3.98	424.58	28.42	0.62
18	Bintinlaye, Offa	8°9'55.4"	4°43'22.6"	422.5	4.11	426.61	28.75	0.23
19	Rodoojomu NNW, Offa	8°9'53.1"	4°42'47.3"	428.7	6.65	435.35	29.05	0.64
20	ShawoSakun area, Offa	8°9'15.5"	4°41'48.3"	426.6	6.80	433.4	26.21	0.596
21	Gaalomifufu II, Offa	8°8'40.6"	4°41'36"	444.3	4.62	448.92	28.38	0.19
22	Chief Imam's comp, Irra	8°4'59"	4°36'20.6"	408.5	3.41	411.91	24.89	0.51
23	Shehu's comp, Irra	8°5'11"	4°35'58.1"	395.6	2.41	398.01	26.22	0.478
24	Ataka's comp, Irra	8°4'59.6"	4°36'12.8"	386.5	5.00	391.5	27.56	0.31
25	Ile obada, Irra	8°4'58.5"	4°36'16.9"	407.3	5.20	412.5	40.00	0.95
26	Aiyegbamimo, Ilemona	8°6'37.1"	4°39'39.8"	417.3	9.24	416.54	30.04	0.75
27	Navy school area, Irra road	8°8'12.6"	4°41'8"	423.5	2.76	426.26	34.50	1.33
28	Ojomudoyin, Offa	8°8'56.1"	4°43'33.1"	410.9	2.24	413.14	27.30	0.391
29	Ijagbo	8°10'27.2"	4°44'13.4"	403.2	5.78	408.98	39.71	0.50
30	Ijagbo Park	8°9'56.8"	4°43'45.8"	397.5	3.20	400.7	33.70	0.44

3.2 Geoelectric inversion result and qualitative interpretation

Table 5 shows the result of geophysical inversions of the resistivity data collected from Offa and environs. The model recovered from inversion of the VES resistivity data shows that Offa and environs are characterized by three to four geoelectric layers of varying thickness and resistivity values, with four type curves; KH (50.00%), H (36.67%), QH (10.00%), and K (3.33%) (Figure 2). The inferred lithologies of the three layer geoelectric model from top to bottom are, laterite or clayey horizon 0.408 - 6.57 m thick and resistivity of 65 - 2513 Ω m, weathered aquifer layer occurs at a depth range of 4.6 - 23.5 m and resistivity values between 10.6 - 354 Ω m, and intact basement rock/aquifer layer having resistivity range 121 - 13000 Ω m. Top to bottom inferred lithologies of the four layer geoelectric model are sand/top soil 0.54 - 3.8 m thick and resistivity of 25-4000 Ω m, lateritic clay horizon occurs at depths between 1.31-12 m and has resistivity range values of 124-

3200 Ωm , weathered aquifer layer depths range is 5.2-49.8 m and having resistivity values of 15-1250 Ωm , intact basement aquifer has resistivity values that ranges from 200-100000 Ωm . Weathered aquifer layer is assumed to directly overly the intact basement rock/aquifer in both 3 and 4 layer geoelectric models.

Table 2. Summary of results of pumping test and pre-drilling geophysical survey data.

BH S/N	Depth (m)	Static Water Level, SWL (m)	Time of Pumping Test (min)	Discharge, Q (m^3/day)	Draw-down, s (m)	Specific Capacity, Q/s ($\text{m}^3/\text{day/m}$)	Aquifer Thickness, b (m)	Transmissivity, T (m^2/day)	Hydraulic Conductivity, K (m/day)
1	44.71	4.22	360	20.81	19.40	1.07274	29.30	0.33111	0.01130
2	40.77	2.35	360	49.87	11.99	4.15833	28.30	2.76647	0.09776
3	29.15	11.22	360	39.07	8.59	4.54631	23.00	1.35893	0.05908
4	24.20	7.60	360	42.01	13.30	3.15913	19.30	1.30007	0.06736
5	46.17	6.33	360	57.82	10.52	5.49594	33.10	4.50221	0.13602
6	37.77	2.04	360	93.57	19.30	4.84802	28.50	1.35821	0.04766
7	34.20	5.11	360	44.35	11.63	3.81280	21.80	1.25504	0.05757
8	27.28	5.83	360	74.44	7.79	9.56142	24.30	2.86801	0.11803
9	29.36	8.61	600	50.44	7.63	6.61449	23.20	2.12099	0.09142
10	24.20	3.72	290	46.22	8.51	5.42944	19.50	19.48595	0.99928
11	23.86	8.46	360	33.06	8.59	3.84991	22.20	1.80745	0.08142
12	29.96	5.33	400	76.68	3.50	21.88627	15.00	4.64635	0.30976
13	26.55	3.45	242	62.15	6.95	8.94114	23.50	2.89833	0.12333
14	28.00	2.23	252	32.09	6.07	5.28387	19.40	1.60895	0.08294
15	29.21	6.15	360	20.24	5.74	3.52829	19.20	7.82089	0.40734
16	27.52	5.80	360	67.20	10.53	6.38424	20.20	1.47066	0.07281
17	28.42	3.98	252	59.84	4.63	12.92557	13.50	4.95166	0.36679
18	28.05	4.11	360	31.03	12.57	2.46859	16.90	0.78994	0.04674
19	29.05	6.65	450	64.80	7.56	8.57523	25.70	2.65883	0.10346
20	26.21	6.80	242	15.74	7.76	2.02828	25.30	0.92738	0.03666
21	28.38	4.62	360	24.60	9.17	2.68279	26.30	1.49180	0.05672
22	24.89	3.41	410	45.82	6.08	7.53791	22.90	2.52720	0.110360
23	26.22	2.41	360	34.07	7.43	4.58808	23.50	1.35534	0.05767
24	27.56	5.00	360	20.51	7.18	2.85666	21.50	0.82802	0.03851
25	40.00	5.20	520	60.91	19.98	3.04936	14.50	0.88680	0.06116
26	30.04	9.24	410	78.16	7.58	10.31177	22.60	4.30976	0.19070
27	34.50	2.76	360	23.76	10.25	2.31767	14.70	1.70795	0.11619
28	30.30	2.24	85	41.20	10.07	4.09026	14.50	1.13983	0.07861
29	39.71	5.11	400	49.02	10.90	4.49654	34.50	2.09208	0.06064
30	33.70	3.20	360	30.13	11.49	2.62214	25.40	2.07184	0.08157

Table 3. Pearson correlation.

	Time of Pumping (min)	Depth (m)	Discharge (m^3/day)	Static water level (m)	Draw-down (m)	Specific capacity ($\text{m}^3/\text{day/m}$)	Aquifer thickness (m)	Transmissivity (m^2/day)	Hydraulic conductivity (m/day)
Time of Pumping (min)	1								
Depth (m)	0.131	1							
Discharge (m^3/day)	0.70	0.124	1						
Static water level (m)	0.486	-0.188	0.61	1					
Drawdown (m)	0.34	0.630**	0.69	-0.171	1				
Specific capacity ($\text{m}^3/\text{day/m}$)	0.81	-0.208	0.65*	0.099	-0.536**	1			
Aquifer thickness (m)	0.124	0.460*	0.048	0.086	0.225	-0.253	1		
Transmissivity (m^2/day)	-0.71	-0.195	0.115	-0.036	-0.285	0.231	-0.124	1	
Hydraulic conductivity (m/day)	-0.107	-0.249	0.106	-0.064	-0.317	0.299	-0.276	0.982**	1

** Correlation is significant at 0.01 level

* Correlation is significant at 0.05 level

Table 4. Classification of borehole performance based on specific capacity (Ishaku et al., 2009)

Group	Specific Capacity (m ³ /day/m)	Borehole Performance
1	>31.30	Excellent
2	11.95 – 31.30	Good BH12, BH17
3	1.16 – 11.95	Moderate BH2, BH3, BH4, BH5, BH6 BH7, BH8, BH9, BH10, BH11, BH13, BH14, BH15, BH16, BH18, BH19, BH20, BH21, BH22, BH23, BH24, BH25, BH26, BH27, BH28, BH29, BH30.
4	0.60 – 1.16	Poor BH1

Table 5. Results of inverting resistivity sounding data.

ID	N	E	ρ_1	h1(m)	ρ_2	h2(m)	ρ_3	h3(m)	ρ_4	TC	ρ_{Aq}	h _{Aq}
V1	8.1611	4.7226	120	1	1300	2	90	15.7	1010	KH	90	15.7
V2	8.2280	4.6143	2100	1.7	270	15.3	1250	∞	NA	H	270	15.3
V3	8.1889	4.6081	399	0.807	124	4.403	37.5	11.09	1618	QH	37.5	11.09
V4	8.1532	4.7211	157	1	800	1	20	3.2	270	KH	20	3.2
V5	8.1517	4.7185	480	2.29	1432	2.33	202	9.68	2656	KH	202	9.68
V6	8.1436	4.7230	80.8	2.77	10.6	9.73	10000	∞	NA	H	10.6	9.73
V7	8.0831	4.6057	81.4	0.884	24.5	19.21	4200	∞	NA	H	24.5	19.21
V8	8.1742	4.7371	209	0.73	57.7	6.27	13000	∞	NA	H	57.7	6.27
V9	8.1434	4.7148	122.62	0.408	26.071	5.939	3200	∞	NA	H	26.071	5.939
V10	8.1732	4.6337	85.5	2.51	23.6	3.43	7000	∞	NA	H	23.6	3.43
V11	8.1446	4.6933	48.6	1.28	597	5.81	26.2	∞	634	KH	26.2	5.81
V12	8.2523	4.6592	175	3.8	520	4	140	20	850	KH	140	20
V13	8.1103	4.6611	65	2.2	13	2.4	1700	∞	NA	H	13	2.4
V14	8.1654	4.7229	4000	1.8	550	10.2	220	37.8	7000	QH	220	37.8
V15	8.1996	4.6001	2513	1.18	307	18.12	1327	∞	NA	H	307	18.12
V16	8.1473	4.7167	141	2.8	400	1.3	45	15.3	7000	KH	45	15.3
V17	8.1648	4.7131	42.3	0.61	172	0.7	35	11.13	230	KH	35	11.13
V18	8.1543	4.6968	163	0.54	2500	1.3	24	9.64	7500	KH	24	9.64
V19	8.1585	4.7167	201	1.02	56.3	11.48	236	∞	NA	H	56.3	11.48
V20	8.1489	4.7259	127	2.1	45.1	6.13	450	∞	NA	H	45.1	6.13
V21	8.1251	4.7192	400	0.7	1100	1.4	170	21.6	1000	KH	170	21.6
V22	8.1436	4.6918	196	0.72	354	9.09	121	∞	NA	K	354	9.09
V23	8.1658	4.7294	25	0.75	140	1.3	15	5.06	200	KH	15	5.06
V24	8.1455	4.7180	850	1.27	3200	2.01	1250	30.3	5500	KH	1250	30.3
V25	8.1455	4.7180	230	0.6	2800	1.3	90	31.8	775	KH	90	31.8
V26	8.0829	4.6047	227	1.07	1187	1.23	17.4	9.8	384	KH	17.4	9.8
V27	8.1520	4.7125	624	6.57	61.9	16.93	2050	∞	NA	H	61.9	16.93
V28	8.0864	4.5995	423	0.785	1532	1.785	80.8	19.63	979	KH	80.8	19.63
V29	8.1368	4.6856	2040	1.6	540	6.82	60.6	5	100000	QH	60.6	5
V30	8.2330	4.6142	147	0.711	218	9.889	61.5	13.7	5214	KH	61.5	13.7

N and E are VES northings and eastings in decimal degrees, ρ_1 , ρ_2 , etc. are resistivity (in Ohm-m) of layer 1, 2, etc.; ρ_{Aq} is the weathered aquifer resistivity which is assumed to be the second to the last geoelectric layer from the bottom and h_{Aq} is its corresponding thickness; h_1 , h_2 , etc. are thickness of layer 1, 2, etc; TC is the model type curve.

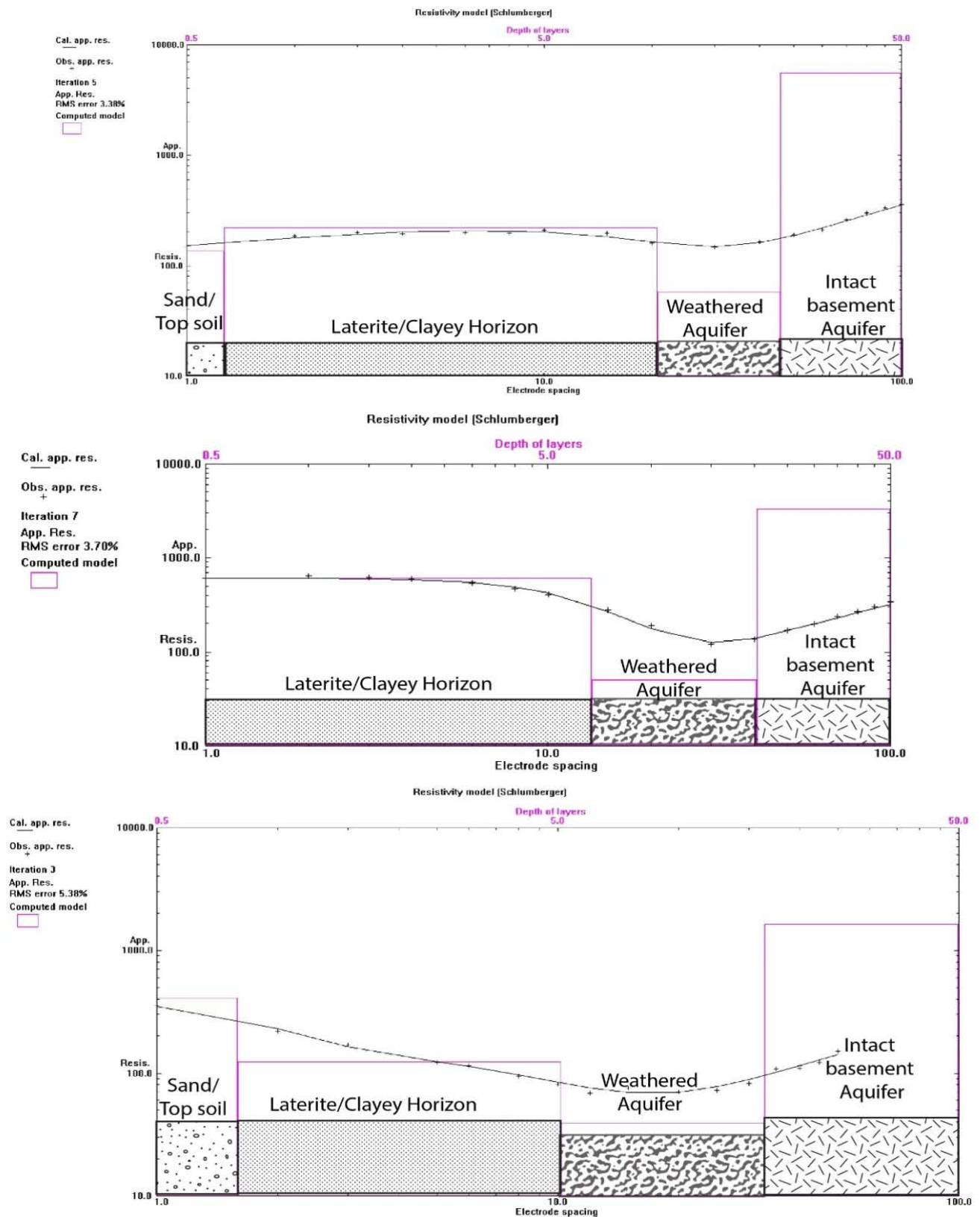


Figure 2. Typical vertical electrical sounding curves of the study area and inferred lithological units. Top panel model was recovered from V30 and consist of four layers with KH-type curve. Middle panel model was recovered from V27 and consist of three geoelectric layers, and bottom panel model recovered from V3 consist of four geoelectric layers with QH-type curve.

3.3 Thickness and depth

The thickness of weathered aquifer layer within the study area varies between 2.40 - 37.80 m (mean = 13.34 m, median = 11.11 m, third quartile = 17.82 m), with depth to bottom of values that ranges between 4.60 and 49.80 m (mean = 16.65 m, median = 13.86 m, third quartile = 21.67 m), and hence it can be classified as a shallow to mid depth aquifer and will only sustain year round water supply, if the underlying fractured basement aquifer is also tapped. The spatial interpolation map of aquifer thickness (Figure 3A) and depth (Figure 3B) shows that lower values are found in the central areas and the higher values around the flanks.

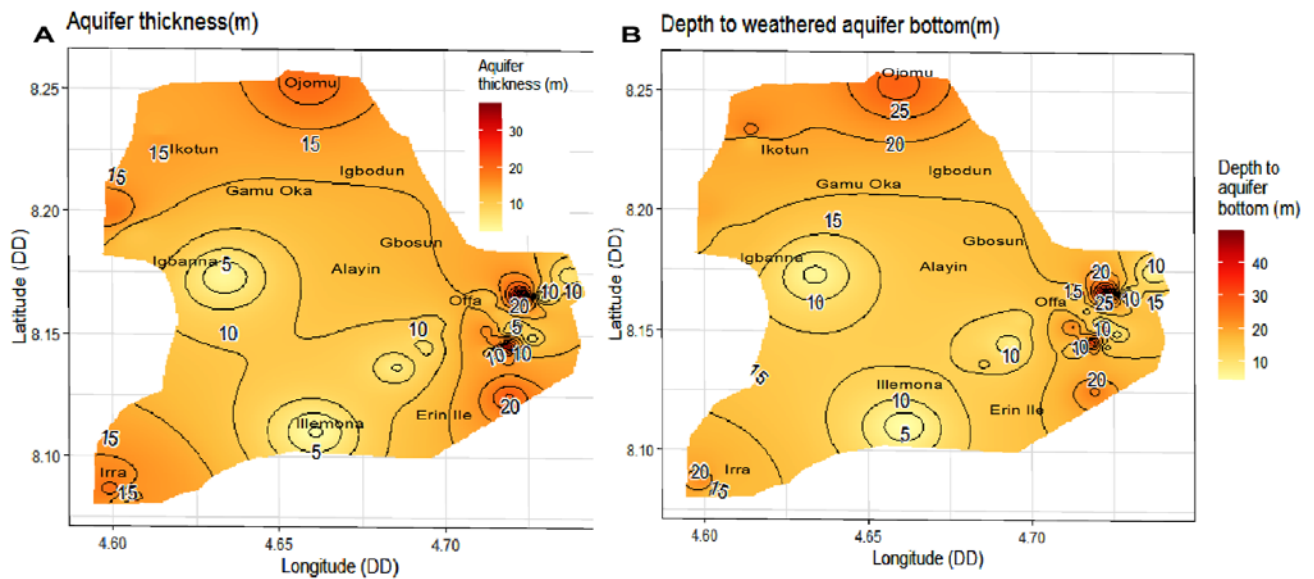


Figure 3. Spatial distribution of thickness (A), and depth to bottom (B) of weathered aquifer layer in Offa and environs.

3.4 Resistivity, longitudinal unit conductance and transverse unit resistance

Offa weathered aquifer has resistivity values between 10.6-1250 Ωm (mean = 127.83 Ωm , median = 57.00 Ωm , third quartile = 127.50 Ωm). The spatial distribution of resistivity values (Figure 4A) shows that areas in the northwest and southeast of the study have higher resistivity values, which may be attributed to lesser clay content in their mineral grain matrix and hence have higher groundwater potential.

Longitudinal unit conductance (S) and Transverse unit resistance (T) also called Dar-Zarrouk parameters (Maillet, 1947) are derived from geoelectric layer resistivity (ρ) and thickness (h) values and mathematically calculated by equations 4 and 5:

$$S = h/\rho \quad (4)$$

$$T = h\rho \quad (5)$$

Longitudinal unit conductance (S) of weathered aquifer layer of study area ranges from 0.024 to 0.918 Ω^{-1} (mean = 0.245 Ω^{-1}), and hence are considered to be low indicating a freshwater aquifer with low clay content. The spatial distribution of longitudinal unit conductance (Figure 4B) shows that the highest values are found in the southwest and may be attributed to clay enrichment in that area. Transverse unit resistance ranges from 31.2 to 37875.0 Ωm^2 (mean = 2663.3 Ωm^2 ,

median = $558.5 \Omega\text{m}^2$, third quartile = $2588.8 \Omega\text{m}^2$), and has spatial distribution (Figure 4C) that is the inverse of longitudinal unit conductance with high values found in the northwest and southwest of the study area and thus corresponding with areas of higher groundwater potentials due to their lower inter-granular clay content.

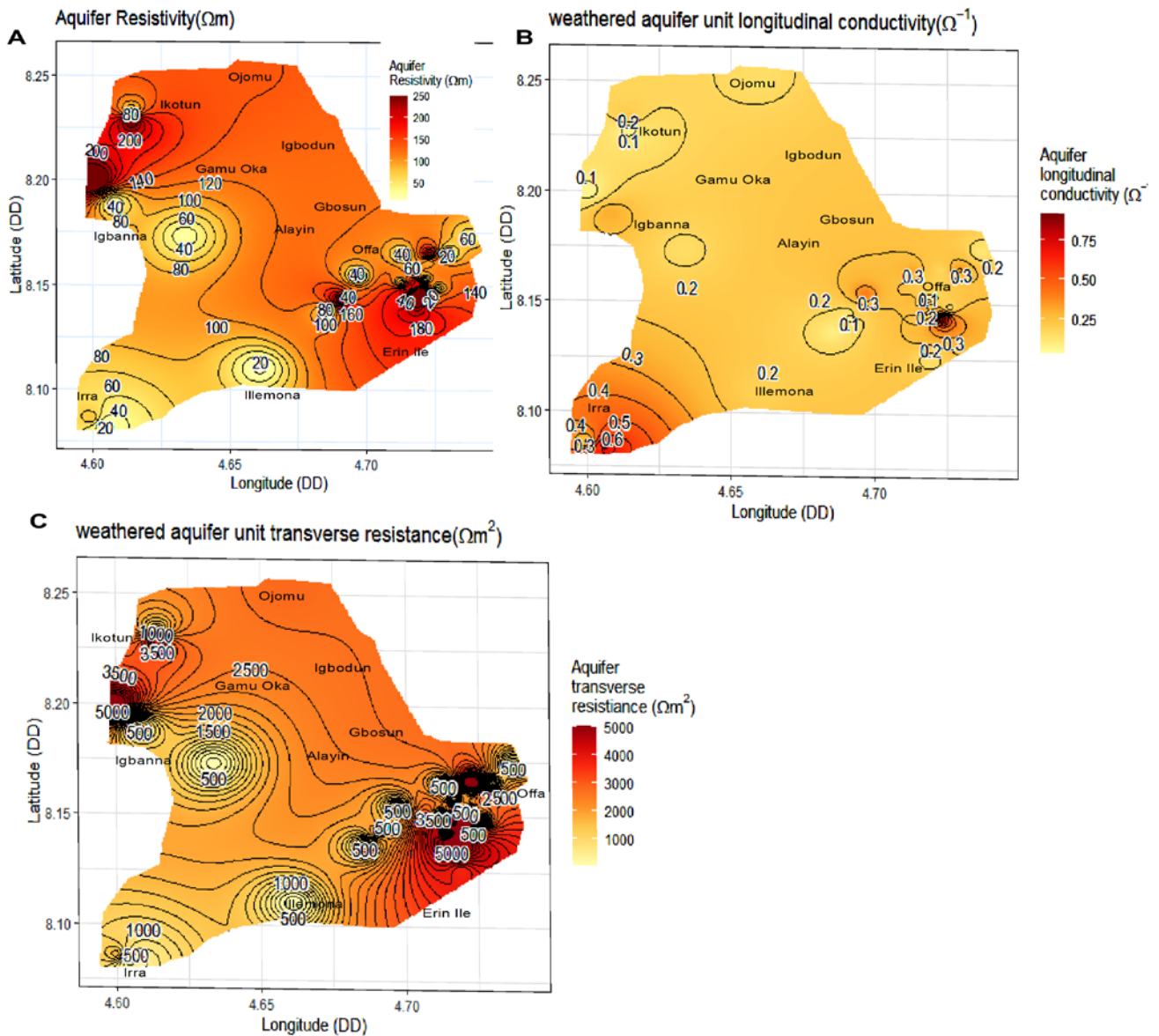


Figure 4. Spatial distribution of resistivity (A), longitudinal unit conductance (B), and transverse unit resistance (C) of weathered aquifer layer in Offa and environs.

3.5 Hydraulic conductivity and transmissivity

Estimated hydraulic conductivity values at VES points varies between 0.136 to 0.682 m/day (mean = 0.604 m/day), and its interpolated spatial map (Figure 5A) indicates a fairly uniform distribution of this property throughout the study area. Transmissivity ranges between 1.631 - 19.629 m^2/day (mean = 7.544 m^2/day , median = 6.967 m^2/day , third quartile = 9.894 m^2/day), and the spatial interpolation map (Figure 5B) shows that areas in the central have lower transmissivity values and corresponds to areas have lower aquifer thickness.

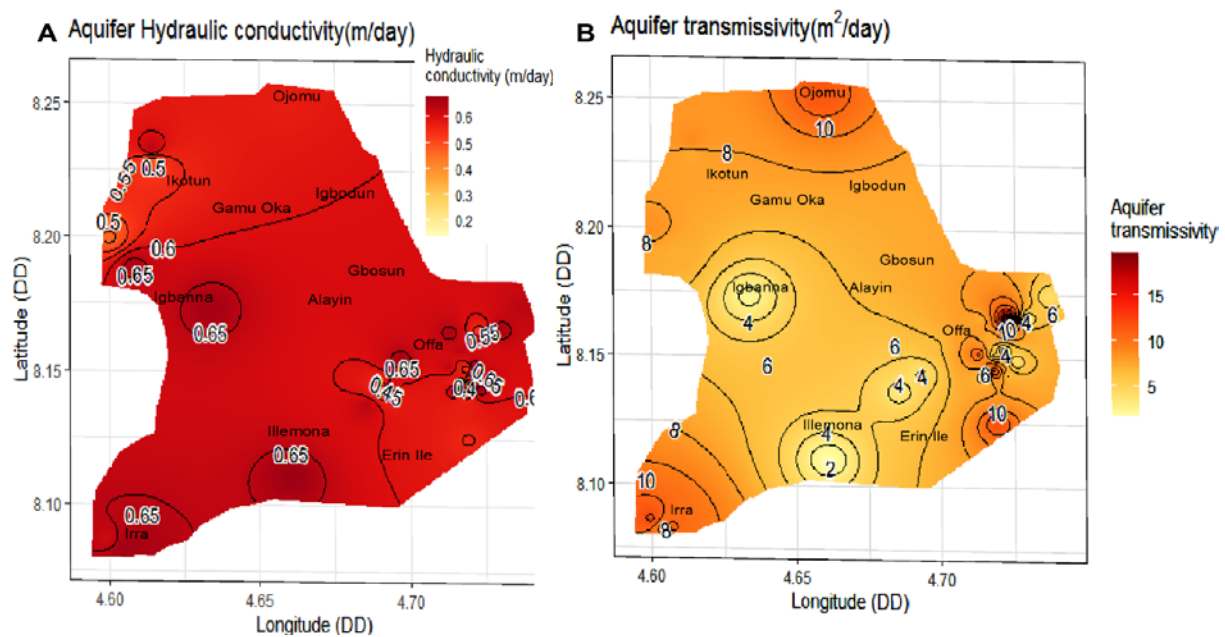


Figure 5. Spatial distribution of hydraulic conductivity (A) and transmissivity (B) of weathered aquifer layer in Offa and environs.

4. CONCLUSION

Evaluation of the aquifer properties from 30 boreholes and geophysical investigation in Offa and environs has shown that the presence of overburden materials, their thicknesses and amount of clayey materials determine the first order aquifer units in the area while water-bearing fractured basement rocks constitute second order. Geophysical investigation revealed three to four geoelectric layers of varying thickness and resistivity values with four type curves; KH (50.00%), H (36.67%), QH (10.00%), and K (3.33%). Sustainability of water supply for all year round by the overburden material is not realistic except drilling is extended to fractured underlying hard rock to an average depth of 30 m. Longitudinal unit conductance showed that the water is fresh and typical of water from basement rock. An evaluation transmissivity and hydraulic conductivity revealed that Offa town has the highest aquifer productivity potential while Ikotun axis has the least potential. Pearson correlation analysis established direct and positive dependency between hydraulic conductivity and transmissivity while indirect and negative relationship exists between specific capacity and drawdown.

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