Hydrogeological Characterization and Determination of Aquifer Hydraulic Properties Using Pumping Test at the College of Petroleum Resources and Energy Studies, Kaduna, Nigeria

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Abstract: The purpose of this study is to determine hydraulic properties of groundwater in college of petroleum and energy studies within Kaduna metropolis of North-western Nigeria using pumping test. Single well pumping tests were conducted for a period of 45 minutes to 5 hours at constant rate using 20 boreholes located in the study area to determine the aquifer parameters. The data obtained during pumping test sessions which lasted for a period of 20 to 120 minutes include; the static water level which varied from 3.8 to 9.0 m, the total depth of the existing boreholes vary from 14.9 to 66.3 m and the maximum drawdown observed was between 6.2 to 46.57 m. The obtained data were used to compute the hydraulic properties using the Cooper Jacob method. The results indicated that the yield capacity varied between 26.78 to 88.13 m^3/day with an average of 45.56 m^3/day, specific capacity values range from 0.934 - 7.956 m^2/day with an average of 3.152 m^2/day, aquifer transmissivity values varied from 0.494 to 4.982 m^2/day with an average of 1.747 m^2/day while hydraulic conductivity values varied from 0.016 to 0.255 m/day, with an average of 0.074 m/day. Transmissivity-based classification reveals a very low to low yield aquifer. According to the transmissivity and hydraulic coefficient, low horse power home pump size boreholes should be placed in the area for sustainable aquifer productivity. A strong correlation (correlation coefficient, R^2) of 0.8305 was obtained between transmissivity and specific capacity. The outcome thus points to a fair water-bearing unit that is able to supply a respectable volume of water for domestic needs. The findings of the research might provide baseline data for the study area's groundwater development and utilization.

***Keywords**: Groundwater, Boreholes, Pumping Test, Aquifer Parameters and Kaduna.*

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I. INTRODUCTION

Water is essential to human life and existence. The need for clean water is growing steadily along with the global population. In order for people to survive and thrive, more affordable and safe water sources are required in many parts of the world where access to clean, potable water is limited. Groundwater makes up the majority of drinking water in many regions; in Europe and Russia, it can reach 80%, and in North Africa and the Middle East, even higher percentages. In contrast to other raw commodities or natural resources, groundwater is found all around the world (Chatterjee, 2005). According to Bierkens and Wada (2019). Due to rainfall patterns and the distribution of aquifers—aquifers being rocks, sand layers, and other formations in which groundwater fills pore spaces—possibilities for its abstraction differ significantly from location to location. Although groundwater can be extracted all year round, it is typically only recharged during certain periods of the year. It is a limited yet replenishable resource (Walton, 1970). Groundwater may be extracted indefinitely as long as there is sufficient replenishment and the source is shielded from pollution (Freeze and Cherry, 1979). According to Todd and Mays (2004), excessive groundwater withdrawal may result in the depletion of groundwater storage, which could have detrimental effects on the environment, the economy, and

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society. An evaluation of groundwater availability and hydraulic properties is necessary for the sustainable development and management of groundwater resources (Falowo *et al*., 2020). Indirect observations of aquifer water levels are used to identify groundwater flow direction, which is important for measuring hydraulic parameters of the aquifer and comprehending its chemistry. It is important to recognize that the parameters and classifications of aquifers are a major simplification of the natural groundwater system. For the purposes of analysis, groundwater systems are generally defined in simplified terms and for most purposes this is sufficient, particularly at a regional or catchment size.

According to Anderson and Woessner (2002), the pumping test is a controlled field experiment used to evaluate an aquifer's hydraulic characteristics, including hydraulic conductivity, transmissivity, and storativity. The constant-rate test, which simultaneously serves as the control and observation well, is the most popular type of pumping test used to estimate these hydraulic properties. It involves pumping a control well at a constant rate and measuring the water-level response in terms of dynamic and residual drawdown in one or more nearby observation wells or in the pumping well itself (Jika and Tse, 2014). Pumping tests are the most widely used techniques to identify representative aquifer hydraulic characteristics sites with groundwater monitoring wells because they assess a significantly larger volume of the aquifer (Osei, 2001, Schwartz and Zhang 2003, Tse and Amadi 2008). Clayey sand and fractured shales make up subsurface of the study area. The drilled boreholes that receive groundwater from the cracked shales quickly run out of water due to over-abstraction brought on by a rising population and increased demand for water. In this investigation, boreholes within the study area were used for the authors' constant rate, single well pumping experiments. The data obtained from these tests offer information on the hydraulic parameters that describe the water-bearing units in the study area to various hydrogeological zones in order to effectively plan for and develop groundwater resources. Nevertheless, a number of writers have demonstrated that surface geoelectrical measurements can also be utilized to ascertain these parameters, including Sriniwas and Singhal, 1985; Onuoha and Mbazi, 1988; Mbonu et al., 1991; Kumar *et al*., 2001; and Okiongbo and Odubo, 2012.

II. GEOLOGY AND HYDROGEOLOGY

The area has a mean monthly minimum and maximum temperatures of 15.9°C and 35.35°C with the annual mean of roughly 19.45°C, the greatest temperatures are being recorded in December and January. The research region is located in a tropical Savanna environment with distinct dry and wet seasons. The dry season lasts from October to April, with an annual rainfall of approximately 1530 mm. The months of December and January have extreme harmattan. This is when the Sahara belt's northeast trade winds start to sweep into the nation from the south. This time of year is often colder and less humid than usual, with occasional periods of limited visibility due to dust in the air. The area has typical Sudan Savannah vegetation, which is divided by enormous, isolated trees and sparse shrubs. The grass cover is more consistent. The region experiences between 1110 and 1280 mm of mean annual evaporation. A basement complex of primarily Jurassic to Pre-Cambrian igneous and metamorphic rocks covers the research region. Granite, gneisses, migmatites, schists, and quartzites make up the majority of the rocks in the basement complex. The region's geology is primarily composed of metamorphic rocks, specifically migmatite and biotite gneiss. The presence of groundwater in the study region and basement complex is contingent upon the extent to which fractures and weathered overburden have developed. Regolith and fractured basements generally occur in a typical basement terrain (Odusanya and Amadi 1990; Mogaji *et al*., 2011). Studies have shown that the unconsolidated overburden could constitute reliable aquifer if significantly thick (Satpathy and Kanungo, 1976; Bala and Ike, 2001). The location of the study area is shown in Fig 1.

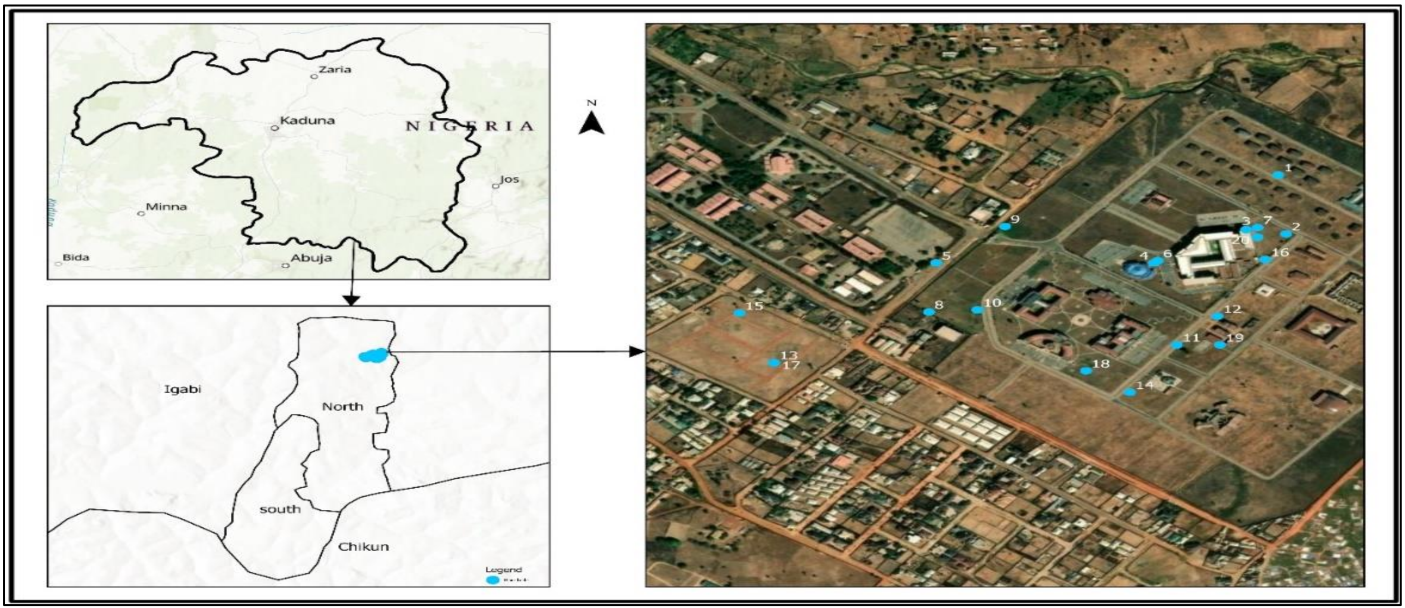

Fig 1 Map of the Study Area Showing the Borehole Locations

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III. MATERIALS AND METHODS

- *Materials*

The specific capacity, transmissivity, and hydraulic conductivity of the overburden aquifers were estimated by pumping tests conducted in the twenty (20) borehole/wells in the research region (Brassington, 1988). In a single well pumping test, water levels are measured during pumping and recovery at a constant or variable rate. Utilizing a one-horsepower Grundfos submersible pump with a check valve and a 19-mm discharge pipe, the continuous pumping test was performed for each borehole. The test well was 30 meters away from the pumped water. Borehole depth, static water level, dynamic drawdown data, aquifer thickness and pumping rate were among the information acquired at each location during the pumping test. Depending on when the individual borehole that was pumped reached equilibrium, the pumping test may last anywhere from 20 to 120 minutes. According to Assaad *et al.,* (2004), the pumping rate varies from 0.31 to 1.39 L/s in response to water abstraction in the borehole and the yield of the pumping well/aquifer unit. In pumping and observation wells, data loggers were employed to track water levels. This test was selected due to its simplicity in field operations, logistics, and economic factors. It enables a quick and cost-effective determination of aquifer properties, such as K and T of the zone of interest, at a single location.

- *Methods*

The hydraulic properties were estimated using the data obtained. The Cooper and Jacob (1946) straight-line solution to time-drawdown data collected in the observation well, which is a modification of the Theis (1935) non-equilibrium well equation, was used to estimate the aquifer properties. The yield of a well is the amount of water discharged through it in a given amount of time. Each well will only produce a certain amount of water in a given amount of time, depending on the aquifer's properties and the well's design features. One of the key factors influencing an aquifer's unique yield or water-bearing characteristics is its porosity. Aquifers can only be made of porous materials, such as soil, although great porosity by itself does not guarantee the ability to produce water (Schwartz and Zhang, 2003). The specific capacity of the well is known as the pumping rate divided by the change in well water level. It normally has the units of m^2/day. The productivity of a well is often expressed in terms of its specific capacity (Freeze and Cherry, 1979). Therefore by implication, aquifer with a higher figure equates to a higher producing well. It is useful to develop a relationship between specific capacity and transmissivity. In areas where no pumping test results exist, transmissivity can be derived from the more abundant specific capacity information.

Transmissivity is a measure of the capability of the aquifer to transmit groundwater through a one metre wide band over its full depth, under a one metre or unit gradient. It is the ease with which water can be extracted from the aquifer. If there is considerable resistance to groundwater flow through the host sediments the transmissivity will be low. Transmissivity is equivalent to hydraulic conductivity multiplied by the aquifer thickness. The units of transmissivity are m^3/day/metre, which simplifies to m^2/day. The hydraulic conductivity is considered as a measure of the resistance to flow, where the greater the hydraulic conductivity, the lower the resistance to flow. Hydraulic conductivity is usually higher in the horizontal plane for local alluvial sediments. This reflects the way they were deposited in nature by rivers. The higher the hydraulic conductivity and the larger the hydraulic gradient, the greater the rate of groundwater flow through an aquifer. Hydraulic conductivity has the units of metres/second (m/s) or metres/day (m/day), and is related to permeability. While hydraulic conductivity reflects the characteristics of both the water and the geology, the fluid characteristics such as density, temperature or salinity are less important.

Thus, Yield capacity, Q = volume/time (m^3/day) (1)

$$\text{Specific Capacity, } C_s = \frac{Q}{s} \ (\text{m}^2/\text{day}) \quad (2)$$

$$\text{Transmissivity, } T = \frac{2.303Q}{4\pi\Delta s} \ (\text{m}^2/\text{day}) \quad (3)$$

$$\text{Hydraulic conductivity, } K = \frac{T}{B} \ (\text{m/day}) \quad (4)$$

Where:

S = Drawdown

ΔS = Change in draw-down over one log cycle

B = Aquifer thickness

IV. RESULTS AND DISCUSION

- *Results of Hydraulic parameters*

The data obtained during pumping test sessions which lasted for a period of 20 to 120 minutes include; the static water level which varied from 3.8 to 9.0 meters with an average depth of 5.4 meters, the total depth of the existing boreholes vary from 14.9 to 66.3 m with an average depth of 37.1 meters. The boreholes range in installation depth from 11.04 to 62.10 meters, with a mean depth of 34.16 meters. The test yielded drawdown values from the visible wells ranging from 6.20 to 46.57 meters, with an average of 18.17 meters. The yield capacity varied between 26.78 to 88.13 m^3/day and the maximum drawdown observed was between 6.2 to 46.57 m. The high yielding boreholes are those with thicker and sandy aquifer material and less drawdown as the lowest drawdown value was obtained from BH 1. The Kaduna River and its tributaries replenish the wells in this area. Every well's yield, the precise amount of water released via the well in a given amount of time, was measured. The area's average yield value was 4.15 L/s, with variations between 0.31 and 1.39 L/s. BH 15 and 17 had relatively high yield values exceeding 1.0 L/s. This points to a fair water-bearing unit that can supply a suitable volume of water for household use. Data analysis revealed that the specific capacity ranges from 0.052 to 0.331 m^2/day, Transmissivity values fell between 0.494 to 4.982 m^2/day, and the Hydraulic Conductivity ranges from 0.016 to 0.255 m/day. Table 1 and 2 displays the results of the hydraulic properties of the aquifer

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while Figure 2 to 5 present summary of the measured hydrogeological parameters.

Table 1 Pumping Test Data Obtained from the Boreholes

NO	Co-ordinates	T.D (m)	I.D (m)	SWL (m)	B (m)	S (m)	Yield (m^3/d)	P.C (Hp)
1	N10°36'24.9"E07°28'31.85"	14.90	11.00	4.80	10.1	6.20	26.78	1.0
2	N10°36'19.4"E07°28’32.3"	50.18	19.20	3.80	46.38	13.75	32.83	1.0
3	N10°36'19.8" E07°28’30.0"	22.80	39.20	4.57	18.23	9.08	38.88	1.0
4	N10°36'16.7" E07°28'24.69"	36.70	18.20	5.60	31.1	26.20	39.74	1.0
5	N10°36'16.7" E07°28'12.12"	22.90	13.65	5.15	17.75	15.05	32.83	1.0
6	N10°36'16.9" E07°28’24.9"	33.20	31.80	4.93	28.27	18.77	36.29	1.0
7	N10°36'20.0" E07°28'30.66"	21.12	17.55	4.37	16.75	15.46	33.70	1.0
8	N10°36'12.1" E07°28'11.7"	21.00	14.90	6.04	14.96	7.71	61.34	1.0
9	N10°36'20.1" E07°28'16.10"	16.37	51.86	6.16	10.21	8.74	55.30	1.0
10	N10°36'12.3" E07°28’14.5"	24.83	21.93	5.80	19.03	8.90	31.84	1.0
11	N10°36'9.03" E07°28’26.0"	39.02	18.00	5.42	33.60	18.78	53.57	1.0
12	N10036'11.7" E07°28'28.35"	61.00	33.65	3.88	57.12	35.32	44.06	1.0
13	N10°36'7.38" E07°28’2.77"	61.80	23.70	5.16	56.64	13.04	43.51	1.0
14	N10°36'4.6" E07°28’23.3"	58.10	20.20	9.00	49.10	18.00	62.21	1.0
15	N10°36'12.0" E07°27'0.78"	66.30	24.20	5.29	61.01	46.57	43.51	1.0
16	N10°36'17.0" E07°28'31.1"	46.02	14.70	4.68	41.34	25.22	55.30	1.0
17	N10°36'7.35" E07°28'2.77"	63.20	13.75	6.83	56.37	18.60	88.13	1.0
18	N10°36'6.6" E07°28'20.75"	24.83	26.40	5.77	19.06	16.16	56.16	1.0
19	N10°36'9.03" E07°28’28.5"	22.00	27.00	5.05	16.95	12.95	36.29	1.0
20	N10°36'19.1" E07°28'30.65"	35.55	29.90	4.80	30.75	28.85	38.88	1.0

T.D = Total Depth (m), I.D = Installation Depth, SWL = Static Water Level, B = Aquifer Thickness, S = Drawdown, P.C = Pumping Capacity

Table 2 Calculated Hydraulic Properties of the Aquifer in the Study Area

NO	Co-ordinates	Yield (m^3/d)	Specific Capacity C_s (m^2/d)	Transmissivity, T (m^2/d)	Hydraulic Conductivity, K (m/d)
1	N10°36'24.9"E07°28'31.85"	26.78	4.319	1.226	0.121
2	N10°36'19.4"E07°28’32.3"	32.83	2.388	0.859	0.019
3	N10°36'19.8"E07°28’30.0"	38.88	4.282	1.424	0.078
4	N10°36'16.7" 07°28'24.69"	39.74	1.517	0.728	0.023
5	N10°36'16.7" 07°28'12.12"	32.83	2.181	1.367	0.077
6	N10°36'16.9"E07°28’24.9"	36.29	1.933	0.739	0.026
7	N10°36'20.0" 07°28'30.66"	33.70	2.17	0.494	0.029
8	N10°36'12.1" E07°28'11.7"	61.34	7.956	3.512	0.235
9	N10°36'20.1"E07°28'16.10"	55.30	6.327	1.583	0.156
10	N10°36'12.3"E07°28’14.5"	31.84	3.578	4.861	0.255
11	N10°36'9.03" E07°28’26.0"	53.57	2.853	0.755	0.022
12	N10036'11.7"E07°28'28.35"	44.06	1.247	1.345	0.024
13	N10°36'7.38"E07°28’2.77"	43.51	3.337	4.982	0.088
14	N10°36'4.6" E07°28’23.3"	62.21	3.456	1.140	0.023
15	N10°36'12.0"E07°27'0.78"	43.51	0.934	0.957	0.016
16	N10°36'17.0" E07°28'31.1"	55.30	2.193	3.377	0.082
17	N10°36'7.35"E07°28'2.77"	88.13	4.738	1.794	0.032
18	N10°36'6.6" E07°28'20.75"	56.16	3.475	1.715	0.090
19	N10°36'9.03"E07°28’28.5"	36.29	2.802	0.665	0.039
20	N10°36'19.1"E07°28'30.65"	38.88	1.347	1.424	0.046

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➢ *Discussion*

- *Yield Capacity*

Fig 2 shows the distribution of the yield values for different aquiferous units in the study area. The yield capacity of the aquifer unit from the area varying between 26.78 to 88.13 m^3/day shows predominant range of 1 – 100 m^3/day as shown on the map. A non-prolific aquifer is typically indicated by this range of values. The groundwater usage survey conducted in the research region indicates that an average yield value of 45.56 m3/day achieved is less than the 200 m3/day necessary for domestic usage. This points to a fair water-bearing unit that can supply a quantifiable and acceptable amount of water for residential use. However, high yield aquifer is observed in BH 2. An index for evaluating the area's groundwater potential can be found in the groundwater yield of boreholes.

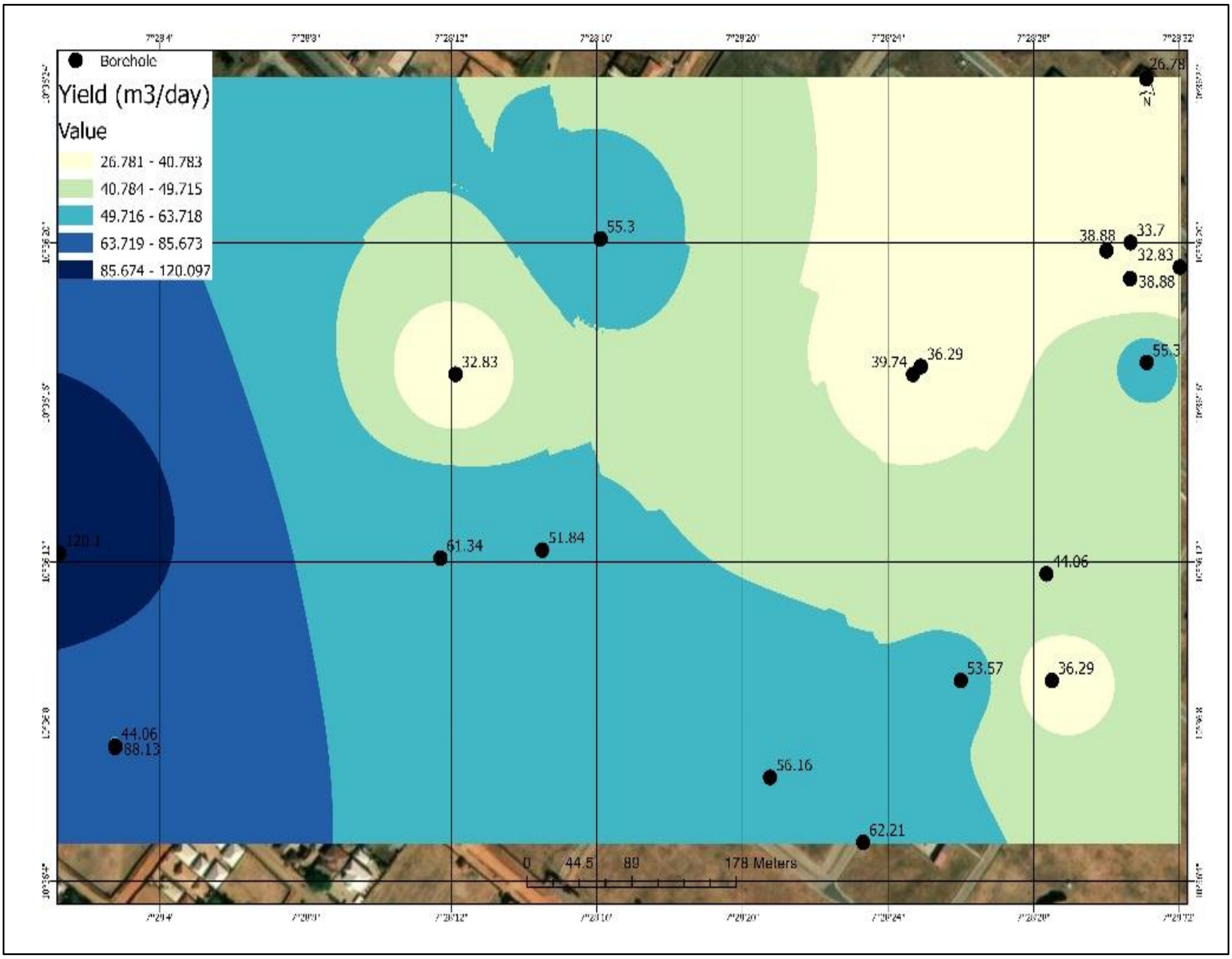

Fig 2 Distribution of Yield Values in The Study Area

- *Specific Capacity (C_s)*

Specific capacity is the discharge rate per drawdown. The calculated specific capacity of wells ranged from 9.02 to 346m^3/d/m with a mean of 82.40m^3d/m. The specific capacity of the well, with a higher figure equates to a higher producing well, and therefore by implication, aquifer. Specific capacities of wells in a certain aquifer system are used to determine the transmissivity distribution of the aquifer. In general, there is a strong relationship between aquifer yield and well performance, unless the well is inefficient and a larger drawdown than would otherwise reflect the aquifer properties. It is helpful to establish a relationship between specific capacity and transmissivity; in areas lacking pumping test results, transmissivity can be determined from the more abundant specific capacity data. Several authors have also developed empirical or observed relationships between specific capacity and transmissivity (Logan 1964, Razack and Huntley 1991, Bal 1996).

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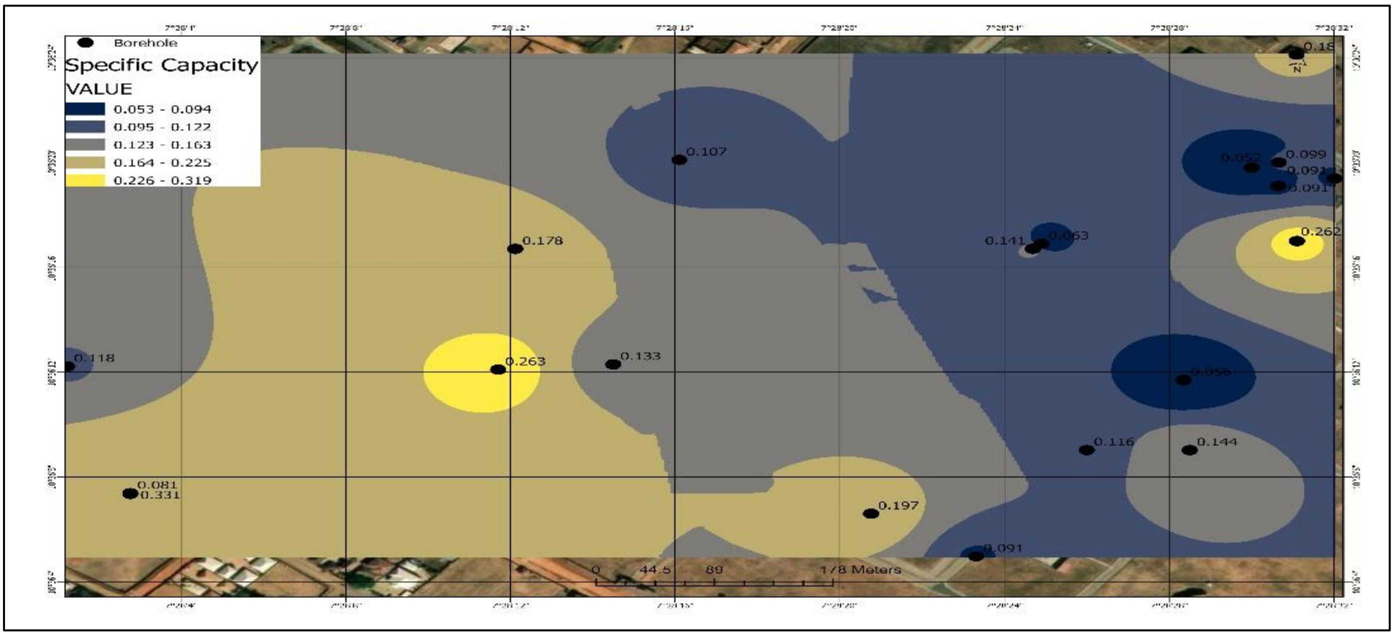

Fig 3 Specific Capacity Distribution in the Study Area

- *Transmissivity (T)*

Transmissivity is a significant hydraulic property of aquifers and is typically correlated with well production (Kruseman and De Ridder, 1970). A well's output capacity increases with its transmissivity (Osei, 2001). The area as depicted in Figure 4 provided the transmissivity values. The northwestern portion of the study area exhibits rising transmissivity, according to the transmissivity distribution of the region. The transmissivity in the range of 0 to 50 m²/d dominates seventy-five percent (75%) of the research area, while the remaining twenty-five percent (25%) reported high transmissivity values above 50 m²/d with substantial water output. Additionally, high transmissivity closing pockets are occasionally observed in various locations as shown in Figure 3 which also reveals increasing transmissivity in north eastern part of the study area. An aquifer can only supply enough water for home use if its transmissivity value is less than 12.4 m^2/day, according to Driscoll (1986), but with higher values can supply sufficient water even for industrial and irrigation purposes. At higher values, the aquifer can supply enough water for agriculture, industry, and domestic use. Hence from the results, the area's aquifers can only supply water for residential usage. Table 3 indicates that the aquifer in the region may be categorized as very low to low in terms of transmissivity magnitude based on the Krasny (1970) transmissivity classification method. The aquifers' very low to low yield suggests that the only way to maintain well productivity is to install low horse power pumps, ideally manual pumps.

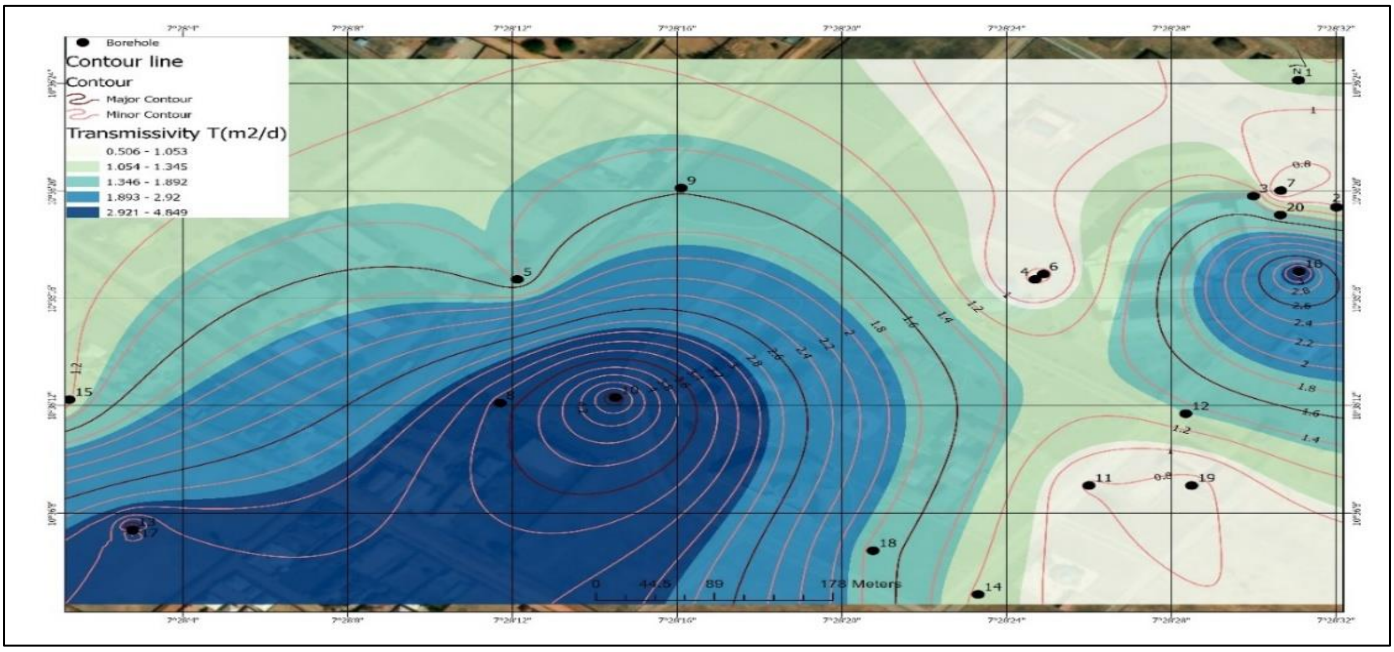

Fig 4 Transmissivity Distribution in the Study Area

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Table 3 Transmissivity Magnitude Classification (After Krasny 1970)

Coefficient of Transmissivity (m^2/day)	Magnitude Classification	Magnitude Designation
Above 1000	I	Very high
100-1000	II	High
10-100	III	Intermediate
1-10	IV	Low
0.1-1	V	Very low
0-0.1	VI	Imperceptible

- *Hydraulic Conductivity (K)*

The ease with which a substance on Earth may transfer fluids is known as its hydraulic conductivity. The higher the hydraulic conductivity, the greater the rate of groundwater flow through an aquifer. The area's estimated hydraulic conductivity is 4.5487 m/day on average, with a range of 6.1 x 10^{-2} to 6.45 x 10^{-1} m^3/day. The K-values are almost consistent throughout the region, with the exception of BH 17, which has a large water yield and a comparatively high value of 88.13 m^3/day (Figure 5). The aquifer units in the region, according to Tables 3, are classified as semi-permeable with a K-value of 10 – 0.1 m/day. The aquifer is primarily composed of fine sand consolidated material as revealed in Table 4. According to Bisson and Lehr (2004), a material's permeability is determined by its hydraulic conductivity (K), also known as its coefficient of permeability. Permeability is the capacity of a given material (rock or soil) to permit the passage of fluids into or through it without compromising its structure.

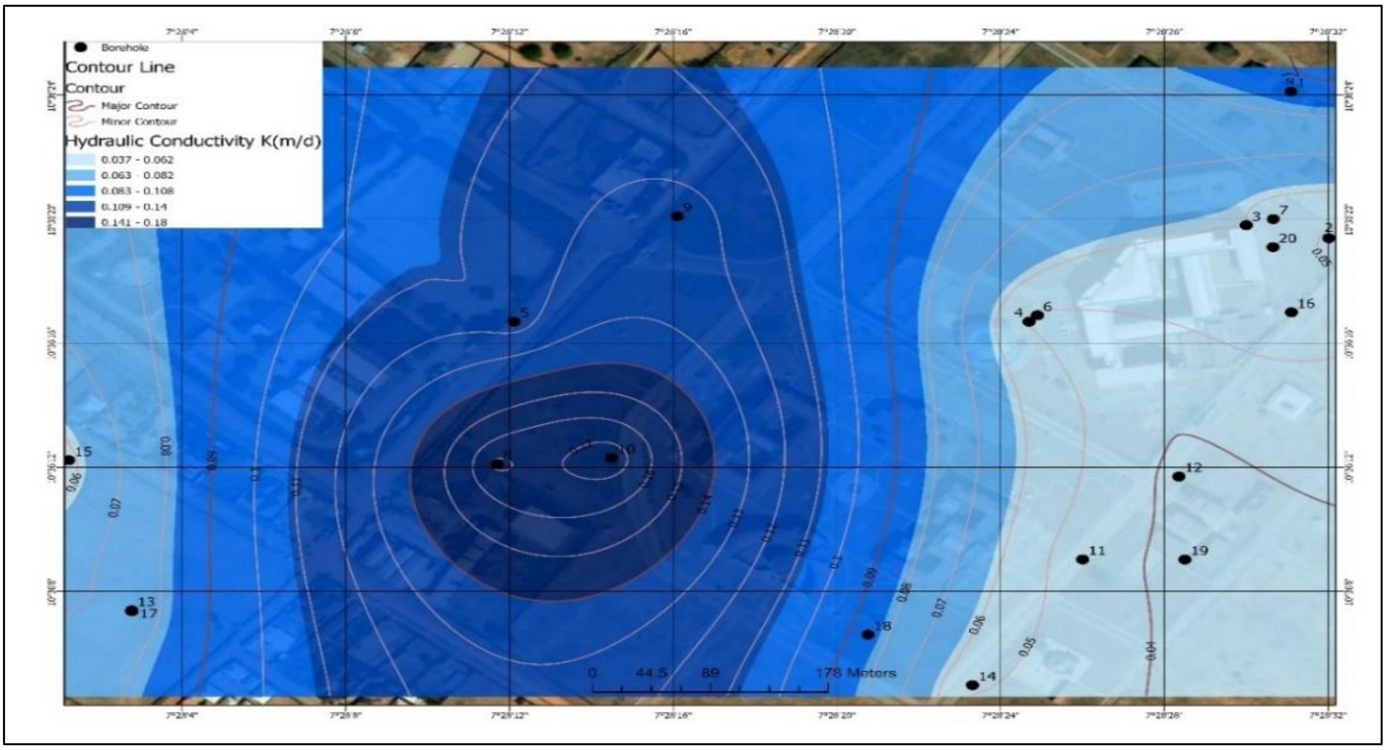

Fig 5 Hydraulic Conductivity's Spatial Variation in the Study Area

Table 4 Classification of Water Bearing Geological Units Based on Coefficient of Permeability (Singh, 2008).

Class 1	K (m/d)	Examples
Extremely permeable	> 10	Coarse sandstone, limestone and fissured crystalline rocks, pebbles, gravels
Semi-permeable	10 – 0.1	Fine grained sands, loams, slightly jointed crystalline rocks
Impermeable	< 0.1	Clays, marls, compact igneous rocks

- *Correlation*

Transmissivity data was also plotted with specific capacity data to further check the accuracy of the calculations. This is done in an attempt to highlight the connection between transmissivity and specific capacity. This was accomplished utilizing the spatial analyst toolbox's Ordinary Least Square statistical method. The result of this was the best-fit linear regression. The strength of the association between the two variables was indicated by the R^2 and modified R^2 values. A strong correlation (correlation coefficient, R^2) of 0.8753 was obtained between transmissivity and specific capacity (Fig 6). In summary, the greater the well's production, the higher the value of the link between transmissivity and specific capacity.

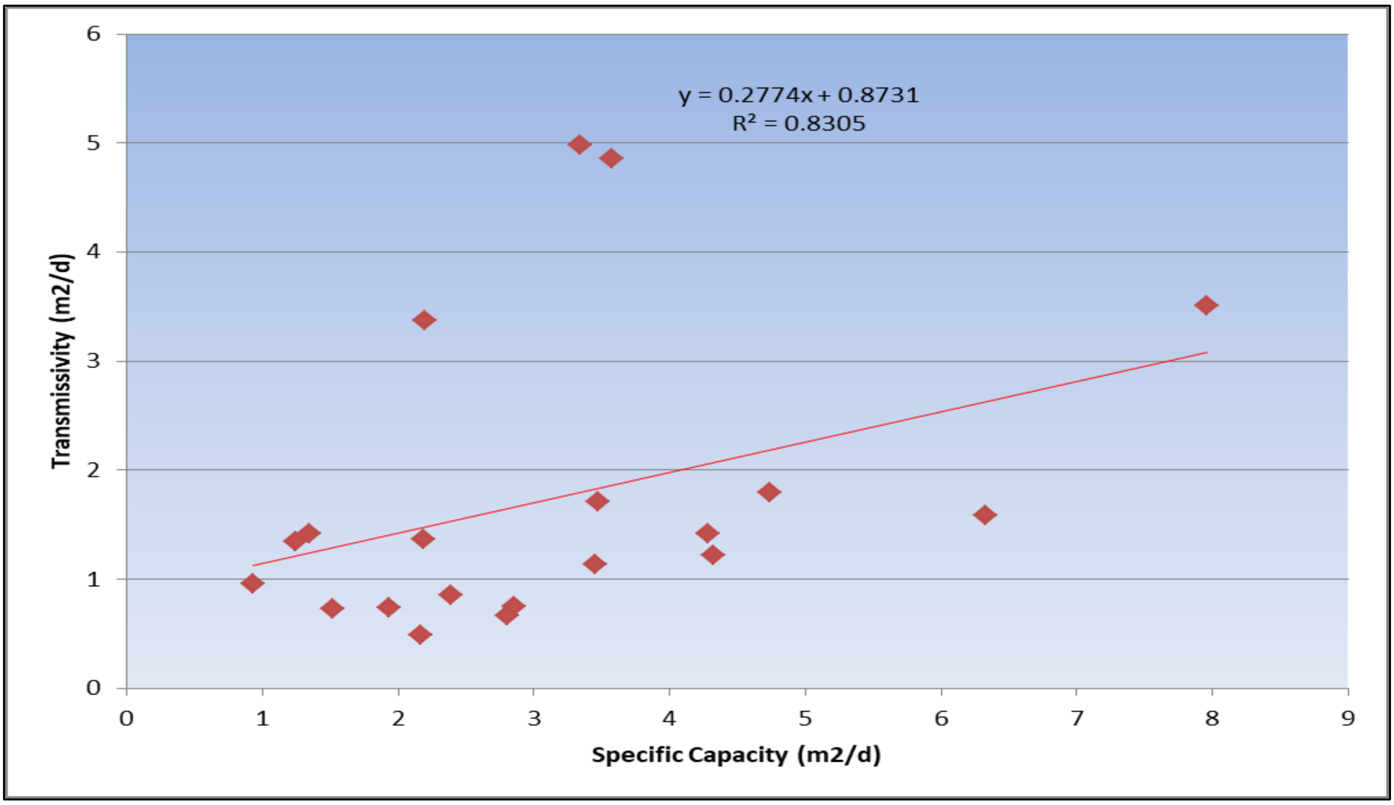

Fig 6 Correlation Coefficient between Transmissivity and Specific Capacity

Comparative studies in Kaduna metropolis (e.g., Bala *et al*., 2021) reported similar hydraulic properties, confirming the general groundwater potential of the basement complex environment.

V. CONCLUSION

One of the best methods for identifying and describing the aquifer units in a given area is to use Pumping tests to obtain accurate estimates of the hydraulic parameters of the geological formations. This study has aided to provide data on the aquifer hydraulic conductivity, transmissivity, specific yield, and yield capacity. The findings indicate that a fair proportion (60%) of the research region is composed of aquiferous units, which are generally considered to have favorable hydraulic qualities and would be highly suitable for groundwater development and exploitation. To validate and support the results of this study, particularly in remote locations, other geophysical techniques and remote sensing approaches should be employed. These findings might be the consequence of inadequate fracturing of the aquifer materials. It is advised to install low horse power pumps, preferably low pressure hand pumps, in order to assure sustainable groundwater withdrawal and continued availability, given the low transmissivity of the borehole yields.

➢ *Conflict of Interest*

The authors have not declared any conflict of interests.

➢ *Acknowledgement*

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