*BAJOPAS Volume 15 Number 1, June, 2022* **http://dx.doi.org/10.4314/bajopas.v15i1.4**

***Bayero Journal of Pure and Applied Sciences, 15(1): 26 - 37***
*Received: May, 2022*
*Accepted: June, 2022*
**ISSN 2006 – 6996**

# AQUIFER CHARACTERISTICS AND GROUNDWATER FLOW SYSTEM IN A TYPICAL BASEMENT COMPLEX AND GUNDUMI FORMATION NORTHWEST, NIGERIA

**[1]Shuaibu, A.M., [2]Garba, M.L and [2]Abubakar, I.Y.**
[1]Geology Department Federal University Gusau, Zamfara, Nigeria
[2]Geology Department Ahmadu Bello University Zaria, Nigeria

***ABSTRACT***
***Aquifer performance was tested in 280 locations of the study area to assess the hydraulic characteristics of the various aquifers, potential yield from the flowing boreholes of both hard rocks and sedimentary formation underlain Zamfara State Northwestern, Nigeria. Pumping test result were subjected to standard methods of Jacob's and modified Theis equation for evaluation of aquifer parameters such as hydraulic conductivity (K), Transmissivity (T), Specific capacity and others. The results show that characteristic of areas underlain by crystalline rock units, especially migmatite, variably migmatized gneiss, schists and granites are characterized by thin/shallow overburden unit of usually less than 10m. In such settings the borehole depth varies from 38 to 78m while saturated thickness varies from 8 to 20m below ground level, with average yield of 44.1m$^3$/day. Hydrogeological parameters obtained from pumping test analysis within the basement rock units revealed aquifer transmissivity (T) values which range from 0.14 to 141.23m$^2$/day, with an average of 12.85m$^2$/day. This implies aquifers of negligible to high potentials. The hydraulic conductivity (K) values vary from 5.0 x 10$^{-2}$m/day and 8.8 x 10$^{-1}$m/day with an average of 2.2 x 10$^{-1}$m/day. The implication of these results is that the aquifers of the basement rock units cannot provide sufficient water for both domestic and agricultural needs of the area. However, Sixty-eight (68) analyzed borehole data set within Gundumi Formation, revealed the average discharge rate of 116.8m$^3$/day. This formation shows the highest water discharge within the study area. The average penetration depth of 65m was achieved. The hydraulic conductivity of this aquifer revealed average value of 5.7 × 10$^{-1}$m/day. This implies high permeability of aquifer system, which is typical of sedimentary formation of this nature. Transmissivity (T) revealed an average value of 38.89m$^2$/day, which indicate high rate of water flow through the entire aquifer medium of this formation. The geospatial analysis of yield from the wells indicate excellent groundwater potential around the western part of the study area.***
***Keywords: Pumping test, Aquifer parameters, Groundwater flow, Geospatial technique, Aquifer.***

## INTRODUCTION

The aquifer parameters like hydraulic conductivity and transmissivity are extremely important for the management and development of groundwater resources (Soupios *et al.,* 2007; Utom *et al.,* 2012). Due to a rapid increase in population and agriculture, the exploitation of groundwater resources is expanding worldwide (Dor *et al.,* 2011).

In many developing countries, groundwater plays a major life support to mankind, as it is the major source to support domestic needs and irrigation purposes. Because groundwater resources can be developed easily and with relatively low costs, they are used extensively for domestic, industrial and agricultural water supply throughout the world (Goni, 2006; Ramakrishnaiah *et al.,* 2009; Olasehinde, 2010).

Groundwater occurs in a range of rock types and usually requires little or no treatment; therefore, it is often the cheapest and simplest water supply option. However, the rising demand for water worldwide, mostly for irrigation, can lead to problems of over abstraction from the shallow aquifer, mainly because water-lifting devices were animal-powered earlier before now (Akujieze *et al.,* 2003; Adelana, 2006; Schoeneich, 2007).

However, since 1996 groundwater abstraction in Zamfara has increase substantially, both as consequence of the increase in the number of wells and use of energized pumps capable of lifting water from deeper aquifer up to a depth of 150m with much higher yields. This rapid development of groundwater resources had resulted in the declining of water table rapidly in many part of the study area and is one of the major cause of drying shallow well with a particular impact on those rural poor farmers unable to deepen their wells to chase the declining water level (Garba and Schoeneich, 2005).

These problem are very acute in those areas underlain by hard rocks, since the hard rock aquifers has limited storage capacity and stores only limited quantity. However, the climatic conditions of low and variable rainfall limit recharge and make the aquifers susceptible to drought (Tijani and Nton, 2009).

Classical analytical method of pumping test is expensive and depends on aquifers hydraulic boundaries and geometry, but remains the only suitable procedure for obtaining accurate transmitting properties in the hard rock aquifers (Kumar *et al.,* 2001; Sahu and Sahoo, 2006; Badmus and Olatinsu, 2010).

Groundwater demand is increasing gradually every year in Zamfara State. To provide information on aquifer characteristics needed for groundwater development, pumping tests were carried out in different locations. Parameters of the aquifer such as drawdown and recovery transmissivity, specific capacity, aquifer thickness, and storage coefficient derived from pumping tests were evaluated and described in this paper. This evaluation will provide the necessary hydrogeological information that will help understand the aquifer potential, for easy location of suitable groundwater zones for development.

**STUDY AREA**

The study area is a component of Sokoto-Rima Hydrogeological Province of the northwestern Nigeria, lies between Longitude: $5^{0}1'27.638''$E to $7°18'13.709''$E, $13^{0}10'45.537''$N, to $10°49'4.152''$N (Figure 1). The area is located in the Sub-Saharan Sudan belt of West Africa in zone of Savannah-type vegetation. Rainfall, averaging about 30 inches annually in much of the basin, occurs chiefly in wet season, which lasts from May to October (Nigeria Meteorological Agency, 2019).

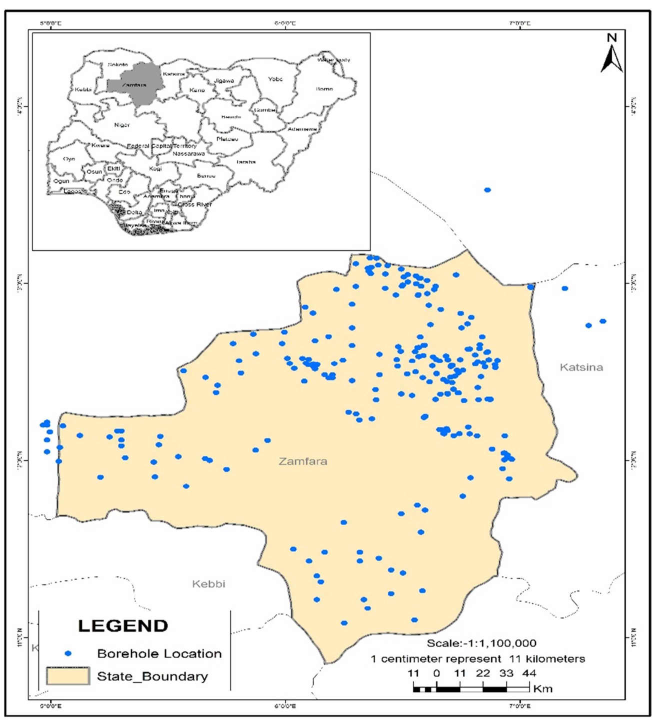


Fig. 1: The Study Area

**HYDROGEOLOGY OF THE STUDY AREA**

The study area is underlain largely by basement rock types (Figure 2). These include intrusive granites of igneous origin and metamorphic rocks, chiefly gneiss, schist, phyllite and quartzite. Groundwater in the upland areas of crystalline rocks is generally available in small quantities from fractures or other tabular partings and from the weathered rock (regolith) just beneath the land surface. The fractures are usually most open above a depth of 30ft but, even so, yields to boreholes are relatively low and high drawdown. Normally, Basement aquifers are developed within either the regolith (relatively high storativity but low permeability) or the fractured bedrock (low storage capacity with a relatively high permeability) according to (Ogilbee and Anderson, 1973; Yaya *et al.,* 2001).

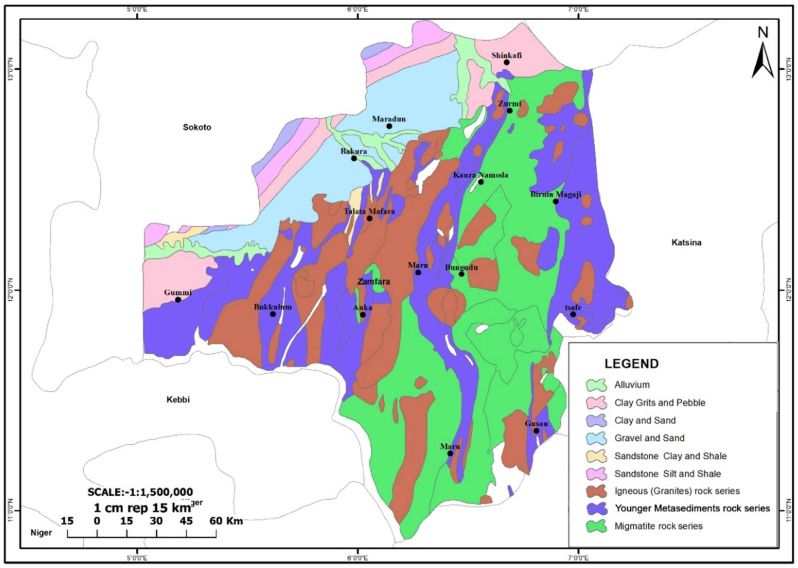


Fig. 2: Simplify Geological Map of the Study Area

Nonetheless, towards the base of the weathered zone at the interface with the fresh bedrock, the permeability is usually high, allowing water to move freely due to low proportion of clayey materials. However, in such situations, deep-seated fractures are important source of groundwater and can sometimes provide appreciable water supplies, especially when tectonically controlled (Mac-Donald *et al.,* 2005).

The water table in crystalline rock is partly phreatic and partly piezometric. In the rock mass, the joint planes act as water barrier. The water table is inclined and follows a general topography of ground. Inflow of water comes from infiltrated rainfall, while outflow of water takes place in springs or rivers. The hydraulic pressure of water in a rock depends on the depth below the water surface, and works on the face at both sides of the joint with a tendency to open the joint (Offodile, 2002).

However, about 20% of the study area is underlain by sedimentary rock series of Gundumi formation (Figure 2). These includes streams and lacustrine deposit, which comparatively coarser materials than any of the younger overlying formations of the Sokoto Basins. In the north near Isa and Sabon Birni, discontinuous lenses of quartz and feldspar pebble gravel are interbedded with more abundant clay and clayey sand. Farther south along the Gusau-Sokoto road, sandy beds prevail over gravel. However, the formation still contains a great deal of intermixed clay. The sandy beds decrease and clay beds increase with depth and to east toward the contact with the Pre-Cretaceous basement rocks but, near the base of Gundumi, a conglomerate of rounded quartz pebble up to 11/2 inches in diameter occurs in outcrop (Ogilbee and Anderson, 1973; Offodile, 2002).

**MATERIALS AND METHODS**

**Estimation of Aquifer Characteristics**

Detail pumping test results and lithologic logs of boreholes constructed across the study area were obtained from the Zamfara State Rural Water Development and Federal Ministry of Agriculture and Water Resources, Zamfara branch. These set of data cut across all the geologic terrain of the study area. The well logs data entailed the subsurface stratification, casing and screen diameter, static well levels and aquifer textural properties.

While the aquifer pumping test data comprised of drawdown, recovery and the discharge rate. Follow up field exercise was conducted to validate the pumping test from each borehole data collected, the ones that were not functioning any longer was rejected totally and global positioning system was used to record the coordinate of the respective active boreholes. Thus, these were used to determine aquifer hydraulic properties such as transmissivity (T), hydraulic conductivity (K), specific capacity (Cs), and well loss constant. Supplementary geological and hydrogeological information were obtained from available maps and measurements of static well level from hand dug wells.

**Hydraulic Characteristics:** The hydraulic properties of an aquifer were assessed by the values of its parameters such as coefficient of transmissivity, permeability or hydraulic conductivity, specific yield and storage coefficient. Both semi-equilibrium Jacob analysis and the Recovery method were used in the analysis of data obtained from pumping test within the sedimentary section (Gundumi Formation) of the study area.

Pumping test data analysis from crystalline basement complex within the study area was based on the Babuskin (1954) which developed a method for the determination of permeability of anisotropic rocks by pumping test (Chinin *et al.,* 2008). This method has been found suitable where the abstraction well itself serves as the observation well, as is the case in the present study. By this method, the Hydraulic conductivity (K) is given by:

$$K = \frac{0.366Q}{LS} log\ (1.32L)/rw \qquad (1)$$

Where K is the coefficient of hydraulic conductivity (m/day), Q is the discharge or yield ($m^3$/day), L is length of screen (m), s is drawdown (m) and rw is radius of borehole (m). This formula is useful because some of the boreholes are confined while others are semi-confined. The average drawdown for the twelve boreholes is about 20.41m. The transmissivity (T) was calculated from the following equation:

$$T = Kb \qquad (2)$$

Where T is the Transmissivity in ($m^2$/day), b is aquifer thickness (equivalent to the total screen length).

The specific capacity (Cs), are measure of well productivity, it was computed from:

$$Cs = Q \div Sw \qquad (3)$$

Where Cs is the specific capacity ($m^2$/day), $S_w$ is maximum drawdown (m).

Well loss constant {C}was estimated using the following equation:

$$C = S_w/Q^n \qquad (4)$$

Where C is the well loss constant in $s^2/m^5$

Experience has shown that in fractured rock aquifers **n** value may even exceed 3.5**,** but the **n** value equals 2 is widely accepted.

**Semi-Equilibrium Jacob Analysis:** Cooper and Jacob (1946) method is based on the Theis's formula with some restriction in its application.

The Theis's equation is expressed as in equation 5 and 6:

$$S = \frac{Q.W\ (u)}{4\pi KD} \qquad (5)$$

This reduce to:

$$S = \frac{2.30Q}{4\pi KD}\ log\ \frac{2.25KDt}{r2S} \qquad (6)$$

where Q = discharge in $m^3$/day; W(u) = well functions of u represent an exponential integral; K = hydraulic conductivity in m/day; D = is the aquifer thickness or saturated thickness of the aquifer in meters and, r = well radius in metres. Equation (6) is solved by plotting linear drawdown versus logarithm of time and reading off two parameters: s, the single log cycle drawdown increment, and to, the time when the straight line portion of the plot extrapolated backwards cuts the zero drawdown axis. Transmissivity KD can then be calculated by substituting the values for Q and S. Illustration of this is given in Figure 3.

Theis's recovery method can be used to calculate the hydraulic properties of an aquifer if the assumptions and conditions of Jacob's method are satisfied. A plot of t / t" (on the log axis) against S" yield a straight line whose slope is presented in equation 7:

$$T = \frac{2.3Q}{4\pi\Delta S}$$

Where t is the time since pumping started, t' is the time since pumping stopped, s" is the residual drawdown, T is transmissivity. An illustration of this method is presented in Figure 3.

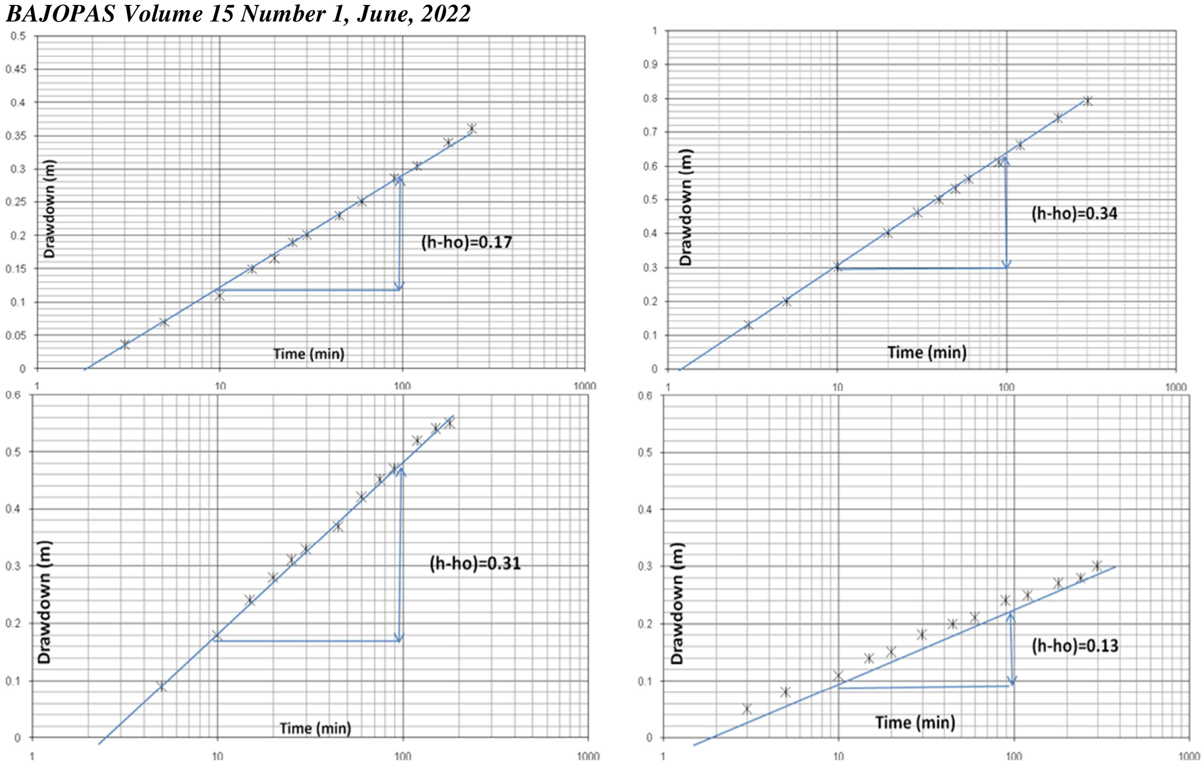


Fig. 3: Selected Plot of Drawdown Against Time

The results obtained from the evaluation of pumping test was subjected to basic statistical analysis for easy interpretation and assessment as the data involved were very large.

Geospatial analysis was carried out on the borehole data set and the estimated data sets of aquifer characteristic in order to revealed the extent of variation of each parameter within the study area using ArcGis 10.4 software.

**Static Well Level Measurement:** In order to define groundwater flow directions and rates through aquifer systems, basic measurements of static well level were carried out to come up with hydraulic head which were used to generate contour maps of water levels. Data of static water level measurement was used for the construction of groundwater configuration map for the study area. These maps define the equi-potentiometric contour surface, which is like a topographical map but define potential energy in the groundwater system.

## RESULTS AND DISCUSSION

### General Assessment of Aquifer Characteristics of the Study Area

Aquifer characteristic were calculated from borehole pumping test data as shown in Table 1. Aquifer properties such as borehole depth, screen interval (assumed aquifer thickness), static well level, drawdown and yield (discharge rate) were established in the field while aquifer hydraulic conductivity (K), transmissivity (T), specific conductivity (Cs), were calculated. Table 1 presented the geologic units of various borehole with their average discharge rate and penetration depth. The aquifer parameters were subjected to descriptive statistical analysis, only drawdown shows negative skewness the rest parameters were positively skewed as presented in Tables 3,4 and 5.

**Table 1: Aquifer Properties of the Study Area**

| S/No | Lithology | Average Discharge ($m^3$/day) | Average Borehole Depth (m) | Hydraulic Conductivity (m/day) | Transmissivity ($m^2$/day) | Specific Yield |
|---|---|---|---|---|---|---|
| 1 | Undifferentiated basement rocks with pebble beds (Granite-gneiss, Migmatite, Schistose rock types). | 44.1 | 48 | 0.48 | 13.74 | 2.94 |
| 2 | Undifferentiated Meta-sediments | 45.12 | 54 | 0.22 | 12.85 | 2.99 |
| 3 | Pan-African Older Granites | 51 | 52 | 0.3 | 12.5 | 2.7 |
| 4 | Clay grits and pebble beds/ Unconsolidated Alluvial Sands. | 116.8 | 65 | 0.57 | 38.89 | 8.71 |

Generally, the study area revealed an average discharge rate that range between 44.1 to 51$m^3$/day within the basement environment, while the average discharge value is 116.8$m^3$/day in sedimentary terrain (Table 1). The basement aquifer properties of the study area evaluated revealed transmissivity (T) values ranging from 0.14$m^2$/day to 141.23$m^2$/day with an average of 12.85$m^2$/day. According to Offodile (2002), a transmissivity (T) ranges of 5 to 50$m^2$/day could be regarded as high potential in crystalline rock situations. By the above standard, the basement aquifers in the area are classified as aquifers of negligible to high potentials. The hydraulic conductivity (K) values vary from $5.0 \times 10^{-2}$ m/day and $8.8 \times 10^{-1}$m/day with an average of $2.2 \times 10^{-1}$m/day. The range of values reveals moderate hydraulic conductivity. The specific capacity values for the boreholes do not show correspondence with transmissivity, hydraulic conductivity and borehole yields. This could be attributed to differences in the degree of weathering, presence or absence of fractures in some places and method of construction of the wells. Based on specific capacity values, most of the boreholes have moderate performance which corresponds to moderate hydraulic conductivity and negligible to high transmissivity values.

Well loss constant (Cs) value range between $2.0 \times 10^{-2}$ to $39.2 \times 10^{-1} s^2/m^5$ with mean value of $82.6 \times 10^{-1} s^2/m^5$. However, the static well level generally revealed value that range between 2.1 to 43.2m with average water level of 8.9 m. The maximum drawdown ranges between 1.37 to 32.5m with average value of 16.7m. This implies that all the studied wells are not deteriorated, as the values are below the standards for well deterioration.

A relationship was established between transmissivity and hydraulic conductivity using linear regression method as shown in Figure 4. However, all parameters show positive correlation which implies that they are directly proportional to each other. Suggesting that the rate at which groundwater passes a unit width of saturated thickness of aquifers underlying the study area is directly proportional to the coefficient of permeability of the aquifer and its degree of porosity.

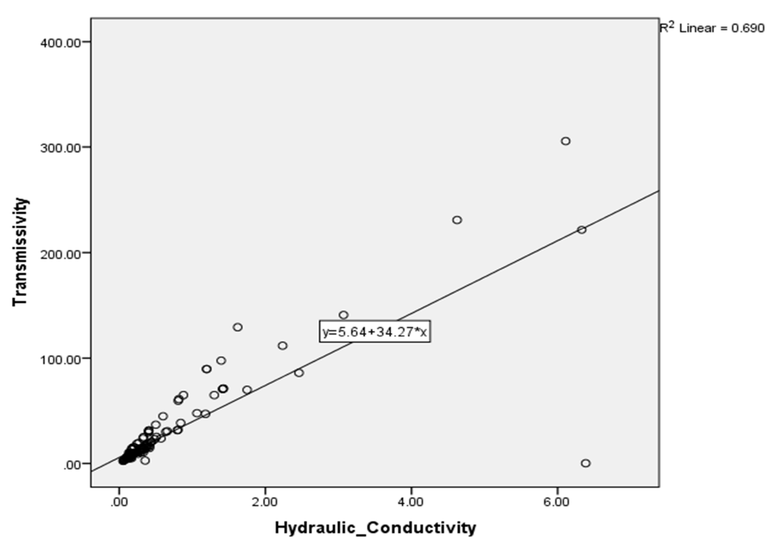


Fig. 4: Regression plot of Transmissivity against Hydraulic Conductivity

Based on the Table 2 entire study area revealed the average transmissivity value which shows low potential to moderate transmissivity, though it varies seriously among different rock units.

**Table 2: Transmissivity potential of aquifer system**

| Transmissivity (T) Range in $m^2/hr$ | Class |
|---|---|
| ➢ 500 | High Potential |
| 50 – 500 | Moderate Potential |
| 5 – 50 | Low Potential |
| 0.5 – 5 | Very Low Potential |
| < 0.5 | Negligible Potential |

Source: (Gheorghe, 1978)

**Aquifer Characteristics of the Older Metasediments Rock Units**

Eighty (80) borehole data were analyzed within this rock unit as presented in Table 3. Static well level shows value ranging between 3.8 to 16.6m, with average value of 8.8m, this is a typical characteristics of the water table aquifers of the crystalline rock unit. While water discharge range between 22.9 to 82.94$m^3$/day with average value of 44.1$m^3$/day which implies low to moderate yield. Transmissivity (T) range between $1.4 \times 10^{-1}$ to $1.41 \times 10^2 m^2$/day with mean value of 13.47$m^2$/day, from Table 2 it implies that the rock formation has negligible to moderate potential. The hydraulic conductivity ranges between $8.0 \times 10^{-2}$ to 6.38m/day with average value of $4.8 \times 10^{-1}$m/day respectively, this is evident of fractured aquifer. The borehole depth revealed a value that range between 38 to 78m with mean value of 48m accordingly.

**Table 3: Aquifer Properties of Older Metasediments Rock Units**

| Parameter | Minimum | Maximum | Mean | ± Deviation |
|---|---|---|---|---|
| Static Well Level (M) | 3.8 | 16.6 | 8.8 | 2.81503 |
| Hydraulic Head (M) | 294.7 | 571.4 | 409 | 56.22473 |
| Yield M/day | 22.9 | 82.94 | 44.1 | 18.2752 |
| Max. Drawdown (Sw) | 6.19 | 29.9 | 17.7 | 4.81237 |
| Specific Capacity | 1.06 | 11.47 | 2.94 | 2.36709 |
| Well head constant | 0.59 | 25.22 | 9.1 | 5.65963 |
| Hydraulic Conductivity (K) | 0.08 | 6.38 | 0.48 | 1.14839 |
| Transmissivity (T) | 0.14 | 141.23 | 13.74 | 23.48079 |
| Aquifer Thickness (B) M | 38 | 78 | 48 | 7.7914 |

**Aquifer Properties of Younger Meta-Sediments Rock Units**

Seventy (70) borehole data were analyzed within this rock unit as presented in Table 4. The aquifers of this lithology has Transmissivity value that range between 3.18 to 65.1$m^2$/day with average value of 12.85$m^2$/day. Comparing the average value with table 2 above, it implies that it has low transmissivity potential, which is typical of crystalline rocks of this nature. The hydraulic conductivity value range between $7.0 \times 10^{-2}$ to $8.8 \times 10^{-1}$m/day with mean value of $21.8 \times 10^{-2}$m/day, this signifies low water flow capacity through a porous media of the aquifer in question. Though it revealed maximum value that depicted moderate potential in terms of fluid transmissivity which might be in locations where the overburden saturated thickness (porosity and permeability) or the fracture interconnectivity is moderate enough to permit ease of water flow. The aquifer specific capacity range between 1.09 to 11.99m/day with average value of 2.9m/day though this might vary as aquifer abstraction increases.

Meanwhile the yield of this aquifer revealed value that range between 19.86 to 259.2$m^3$/day with average value of 50.52$m^3$/day, this implies moderate aquifer discharge, which is typical of the Meta-sediment crystalline environment. It equally reveals a static well level of value that range between 5.46 to 19m with average value of 9.9m. The penetration depth within these rock units as revealed from borehole well-logs range between 40 to 80m with mean value of 54m.

**Table 4: Aquifer Properties of Younger Meta-Sedimentary Rock Units**

| Parameter | Minimum | Maximum | Mean | ± Deviation |
|---|---|---|---|---|
| Static Well Level (M) | 5.46 | 19 | 9.9 | 4.73 |
| Hydraulic Head (M) | 234.14 | 581.53 | 387.6 | 94.23 |
| Yield ($m^3$/day) | 17.28 | 138.24 | 45.12 | 27.53 |
| Max. Drawdown (Sw) | 8.88 | 25.82 | 16.95 | 3.34 |
| Specific Capacity | 1.09 | 11.99 | 2.99 | 2.71 |
| Well head constant | 0.96 | 14.61 | 8.27 | 3.65 |
| Hydraulic Conductivity (K) | 0.07 | 0.88 | 0.22 | 0.10 |
| Transmissivity (T) | 3.18 | 65.05 | 12.85 | 14.28 |
| Aquifer Thickness (B) M | 40 | 80 | 54 | 13.06 |

**Aquifer Characteristics of Pan-African Older Granites**

Granites being a crystalline rock, its porosity and permeability will depend on the degree of fracturing and the extent of weathering that has taken place. These will enhance pore spaces and the thickness of overlying regolith. However, the data of sixty-two (62) borehole situated within this rock unit were analyzed as presented in Table 5. The aquifer yield from this rock unit range between 19.86 to 259.2$m^3$/day with mean value of 50.5$m^3$/day. Static well level of the aquifer ranges between 3.8 to 17.6m with average value of 8.6m. This depict the water table of the aquifer system under discussion, the aquifer depth ranges between 40 to 78m with average depth of 52m, this information revealed the saturated thickness of the aquifer system of this rock unit. The hydraulic conductivity ranges between $5.0 \times 10^{-1}$ to $8.1 \times 10^{-1}$m/day with mean value of $2.2 \times 10^{-1}$m/day, while transmissivity range between 2.4 to 59.69$m^2$/day with mean value of 12.52$m^2$/day. This implies low transmissivity potential according to Gheorge (1978).

**Table 5: Aquifer Properties of Pan-African Granite Rock Types**

| Parameter | Minimum | Maximum | Mean | ± Deviation |
|---|---|---|---|---|
| Static Well Level (M) | 3.8 | 17.6 | 8.6 | 3.83 |
| Hydraulic Head (M) | 322.34 | 543.6 | 432.2 | 68.76 |
| Yield ($m^3$/day) | 19.86 | 259.2 | 50.5 | 54.69 |
| Max. Drawdown (Sw) | 9.65 | 27.9 | 18.3 | 4.40 |
| Specific Capacity | 0.71 | 11 | 2.7 | 2.29 |
| Well head constant | 2.14 | 39.19 | 10.0 | 8.20 |
| Hydraulic Conductivity (K) | 0.05 | 0.81 | 0.3 | 0.19 |
| Transmissivity (T) | 2.4 | 59.69 | 12.5 | 13.16 |
| Aquifer Thickness (B) | 40 | 78 | 52 | 11.72 |

**Aquifer Characteristics of Clay, Grits and Pebble beds/Sandstone**

Table 6 shows statistical summary of the sixty-eight (68) analyze borehole data set within Gundumi Formation, the static well level range between 4.14 to 9.12m with value of 12.5m. The aquifer of this formation occurs under water table condition in the outcrop area. Whereas the discharge rate range between 34.7 to 345.6$m^3$/day with mean value of 116.8$m^3$/day. This formation shows the highest water discharge within the study area. The thickness of aquifer of this formation varies from one location to another, which range from 40 to 78m with average depth of 65m. The hydraulic conductivity of this aquifer range between $1.1 \times 10^{-1}$ to 1.62m/day with average value of $5.7 \times 10^{-1}$m/day. This implies high permeability of aquifer system, which is typical of sedimentary environment of this nature. Transmissivity range between 5.55 to 129.7$m^2$/day with average value of 38.89$m^2$/day, which indicate moderate rate of water flow through the entire aquifer medium of this formation. From field observations and analysis this formation is recharged, essentially on its outcrop area directly from infiltration, precipitations and also by effluent seepage from streams during the wet season. This particular lithological unit is a segment of the Gundumi formation which underlain about 20% of the study area. This research goes in accordance to the findings of (Ogilbee and Anderson, 1973; Yaya *et al.,* 2001; Garba and Schoneich, 2005).

**Table 6: Aquifer Properties of the Sedimentary Hydrogeologic Province**

| Parameter | Minimum | Maximum | Mean | ± Deviation |
|---|---|---|---|---|
| Static Well Level (M) | 4.14 | 19.12 | 12.5 | 5.81 |
| Hydraulic Head (M) | 276.58 | 385.55 | 315.6 | 26.04 |
| Yield ($m^3$/day) | 34.56 | 345.6 | 116.8 | 95.51 |
| Max. Drawdown (Sw) | 3.06 | 23.96 | 15.13 | 5.17 |
| Specific Capacity | 1.51 | 21.75 | 8.71 | 6.32 |
| Well head constant | 0.19 | 15.82 | 3.66 | 4.30 |
| Hydraulic Conductivity (K) | 0.11 | 1.62 | 0.57 | 0.47 |
| Transmissivity (T) | 5.55 | 129.7 | 38.89 | 35.03 |
| Aquifer Thickness (B) | 40 | 78 | 65 | 14.45 |

**Groundwater Potential**

Area such as Bakura, Bukkuyum, Shinkafi, part of Kaura Namoda which fall within the NW-W part of the study area shows moderate to high yield (Figure 5). This area is underlain by unconsolidated sediment of different varieties, which is typical of Gundumi-Illo formation. However, area such as Gusau, Tsafe, Zurmi, Birnin Magaji (NE-SE part of the study area) depict low to moderate yield.

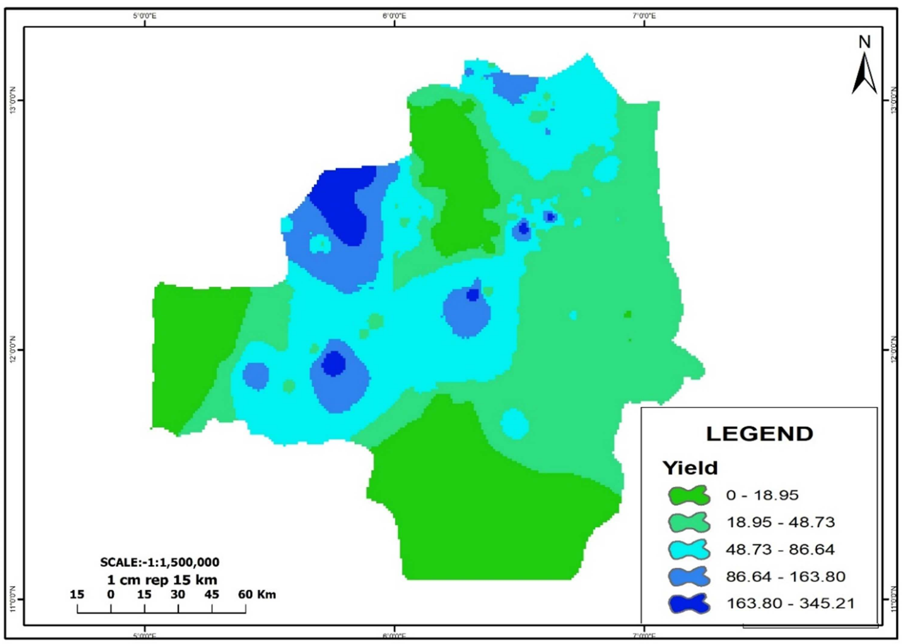


**Fig. 5: Distributions of Aquifer Yield**

Spatial distribution of hydraulic conductivity as shown in Figure 6 revealed moderate to high aquifer conductivity around area such as Shinkafi, Bakura, Bukkuyum, Talata Mafara, part of K/Namoda which falls within NE-W part of the study area. Comparison between Figure 5 and Figure 6 revealed that hydraulic conductivity of an aquifer is one of the key major factor that influence recharge rate, as aquifer yield of most locations tends to coincide with the conductivity potential of the lithologic framework of the study area. However, area such as Gusau, Birnin Magaji, Zurmi, large part of Maru, Anka, Tsafe, Maradun (NE-SE part of the study area) are virtually within low hydraulic conductivity settings, this is typical of crystalline aquifer formation.

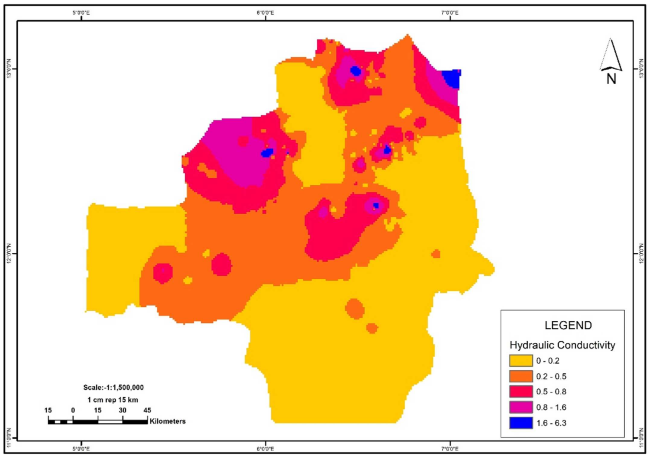


**Fig. 6: Aquifer Hydraulic Distributions**

Transmissivity which is the product of hydraulic conductivity and aquifer thickness were interpreted as shown in Figure 7. The aquifer characteristics play a major role in the identification of groundwater potential zones, because they reflect the rock structures through which the water flows. In general, transmissivity values greater than $100m^2$/day are considered good in hard rock terrains (Sridharan *et al.,* 1995). In this study, the low drawdown, high recovery transmissivity, and high specific capacity represent locations that are considered to delineate the potential groundwater zones for development. The southwestern sides, and a part of northeastern side, had low drawdown values that were less than $50m^2$/day and recovery transmissivity values that were higher than $100m^2$/day (Figure 7). Sensitivity analysis also showed a similar trend in drawdown transmissivity for most of the locations. The optimum yield was higher, and the aquifer was thicker, in the western part of the study area. Analysis of aquifer parameters indicates that the western and south-central parts of the study area are suitable for groundwater development.

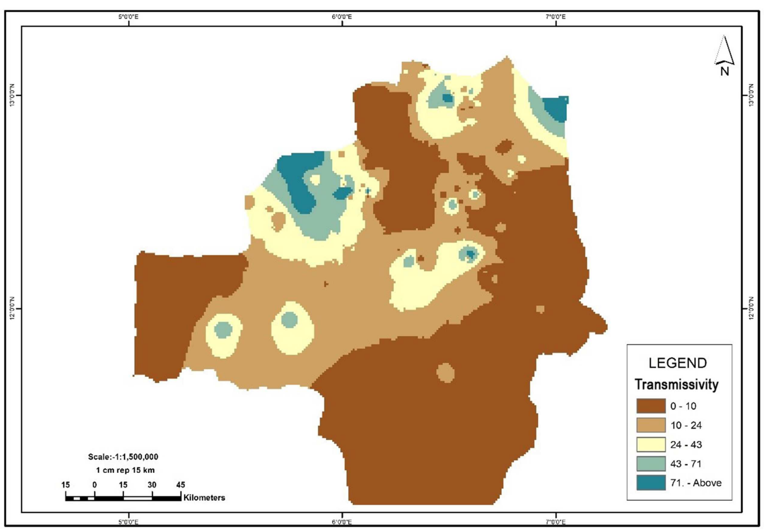


**Fig. 7: Aquifer Transmissivity Distribution**

**Groundwater Flow System**

Analysis of the piezometric surface map of the aquifer in the study area shows a general flow pattern towards western part of the study area (Figure 8). This map defines the equi-potentiometric contour surface, which is like a topographical map but define potential energy in the groundwater system. However, water table configuration was depicted by thick contours of water table elevation above mean sea level, as indicated by arrow.

Groundwater flow down gradient, which implies that the water flows in the direction of the steepest gradient, meaning that it flows perpendicular to the equipotential. The groundwater that results from recharge flows towards stream and river channels, this indicated by arrows drawn perpendicular to equipotential lines and tends to diverge from the recharge areas (watershed) and converge towards the drainage channels. Though if the hydraulic conductivity of the aquifer is much higher in one direction than another or dominated by fractures with particular orientations, then this can redirect groundwater flow askew to the maximum gradient.

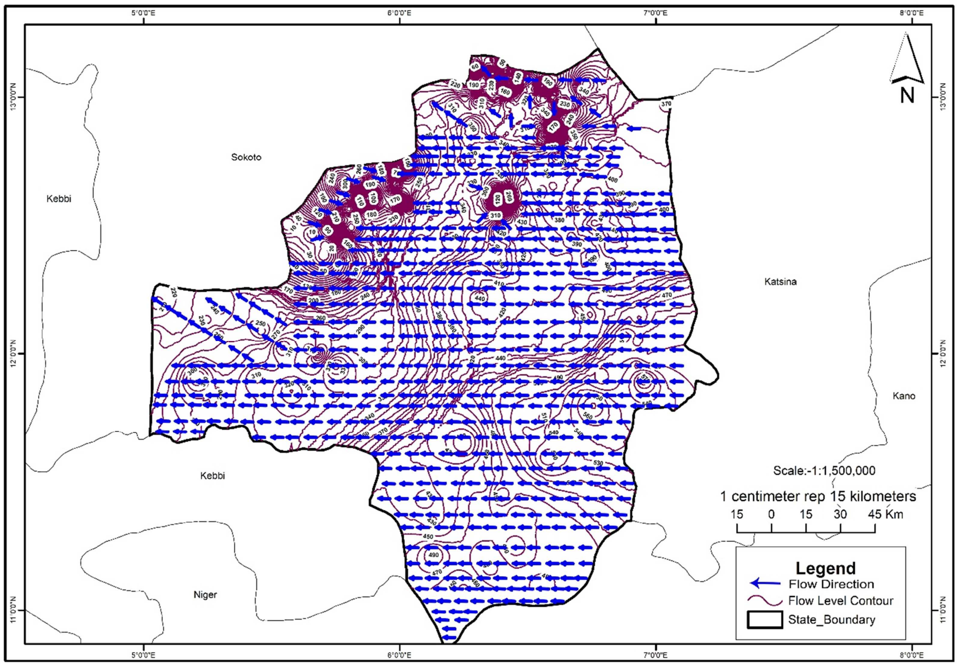


**Fig. 8: Groundwater Configuration Map**

## CONCLUSION

Aquifer parameters, such as transmissivity, hydraulic conductivity, specific yield, optimum yield and time required for full recovery, have been analyzed to evaluate the groundwater potential of the study area. Results show that the saturated thickness is high in the western part, where the optimum yield is also high. The recovery transmissivity and optimum yield and hydraulic conductivity are also relatively high in this area. In contrast, in the central and eastern zones of the study area, the saturated thickness and optimum yields were low. The high recovery transmissivity and high optimum yield found in the western part, and at some locations in the eastern part, are mainly because of the primary and high secondary porosity, the geomorphological setting and the high weathered thickness. The high drawdown and recovery are because of the lineaments or the structural displacements. The low recovery, saturated thickness and optimum yield may reflect a lack of secondary porosity, compaction of litho units and a shallower weathered layer, this is more peculiar in those area underlain by basement rock units. Groundwater flow system favors the western part of the area of study.

However, this attempt at assessing the aquifer parameters of the hard rock and sedimentary formation has shown the groundwater potential of the area. The evaluation of the aquifer performance test will no doubt aid in borehole programs and provide additional database for groundwater development and utilization in the study area.

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