



## AQUIFER CHARACTERISTICS OF SOME LOCAL GOVERNMENT AREAS OF BENUE STATE, NIGERIA

G. D. Akpen<sup>1,\*</sup>, M. I. Aho<sup>2</sup> and M. G. Adejo<sup>3</sup>

<sup>1, 2, 3</sup>, DEPARTMENT OF CIVIL ENGINEERING, UNIVERSITY OF AGRICULTURE, MAKURDI, BENUE STATE, NIGERIA

*E-mail addresses:* <sup>1</sup>[deliakpen@yahoo.com](mailto:deliakpen@yahoo.com), <sup>2</sup>[aho\\_ped@yahoo.com](mailto:aho_ped@yahoo.com), <sup>3</sup>[musacogy@gmail.com](mailto:musacogy@gmail.com)

### ABSTRACT

*Well pumping test results from 74 boreholes within twelve LGAs of Benue State were collated and analysed to determine the aquifer hydraulic characteristics. Cooper-Jacob's non-uniform flow equation was used to determine the transmissivity,  $T$ , storativity,  $S$ , hydraulic conductivity,  $K$  and specific capacity,  $S_c$  of the aquifers of the study areas. The Geographical Information System (GIS) was used to generate colour coded maps of the determined hydraulics characteristics of the aquifers. The static water level (SWL) ranged from 2 to 8 m in Katsina-Ala, Ado, parts of Vandeikya and Gboko, while the rest of the study areas had SWL of 8 to 20 m with isolated areas of Konshisha and Gboko having SWL up to 38 m. Hydraulic conductivity values fall between 0.01 to 1.0 m/day in most of the study areas except Gboko and Buruku LGAs where  $K$  ranged between 1.0 to 5.0 m/day. The specific capacity of major parts of the study areas ranged from 0.01 to 10 m<sup>2</sup>/day except Konshisha, Gboko and Ushongo LGAs where the values ranged from 10.0 to 50.0 m<sup>2</sup>/day with the highest value of 83 m<sup>2</sup>/day obtained at Tse-Filla in Konshisha LGA. Transmissivity values ranged from 0.01 to 8 m<sup>2</sup>/day except, parts of Konshisha and Gboko where the value went up to 16 m<sup>2</sup>/day and 49 m<sup>2</sup>/day respectively. The highest value of storativity was 2.4 in Ado LGA with a range of 0.4 to 1.0 in parts of Katsina-Ala, Ukum, Konshisha, Ushongo and Gboko LGAs. The remaining parts of the study area had storativity values of 0.01 to 0.4. The results show that the aquifers of the study areas are of moderate to low or limited yield. The generated hydraulic characteristics are useful tools for planning and development of ground water in the study area.*

**Keywords:** *Aquifer characteristics, non-uniform equation, pumping test, ground water.*

### 1. INTRODUCTION

The worth of an aquifer as a source of water depends largely on two inherent characteristics: its ability to store and to transmit water. It is recognized that these two characteristics, referred to as the coefficients of storage and transmissibility, generally provide the very foundation on which quantitative studies are constructed. Ground water hydraulics methods are applied to determine these constants from field data [1]. Tube wells and boreholes are fast becoming the most dependable sources of potable water for domestic and agricultural uses particularly in rural areas of Nigeria. Investigations have shown that most of the existing boreholes drilled by individuals, state and the federal

government of Nigeria to curb the scarcity of potable water in the rural and semi urban areas of Benue State go dry after few months of being put to use. This is because of inadequate knowledge of the geology and hence characteristics of the aquifers and/or inadequate geophysical investigations before the drilling and operation of the boreholes.

A survey of literature revealed little information on the aquifer characteristics of the study area. The Cooper-Jacob method was adopted by [2] and they reported hydraulic conductivity, transmissivity and specific capacity values of some parts of Konshisha Local Government area as  $6.1 \times 10^{-2}$ - $6.45 \times 10^{-1}$  m/day, 0.49-4.52 m<sup>2</sup>/day and 18.41-117.92 m<sup>2</sup>/day

\* Corresponding author tel +234 – 703 – 904 – 9051

respectively. Elsewhere, estimates of aquifer transmissivity were made from specific capacity data using simulation [3, 4]. Pumping test data from twelve boreholes in Azare area were analysed by [5] to determine the hydraulic properties of the aquifers. Generally, low values of the aquifer constants were reported. The transmissivity, fell between  $7.39 \times 10^{-6}$  and  $3.55 \times 10^{-4}$  m<sup>2</sup>/sec and hydraulic conductivity ranged from  $5.62 \times 10^{-7}$  to  $42.54 \times 10^{-5}$  m/sec, while the average specific capacity was  $2.10 \times 10^{-4}$  m<sup>3</sup>/sec/m. It was concluded that, the available boreholes cannot provide sufficient water for domestic and agricultural needs of the area because of the poor hydraulic characteristics of the aquifers. The aquifer parameters of Erho, Nigeria were estimated by [6] using the Cooper-Jacob evaluation method. Mean values of transmissivity, storage coefficient and specific capacity of the aquifers were obtained as  $6.15 \times 10^{-2}$  m<sup>2</sup>/min,  $9.3 \times 10^{-4}$  and  $0.33$  m<sup>2</sup>/min respectively.

An evaluation of the aquifer characteristics of Nanka sands was conducted by [7], who reported transmissivity and hydraulic conductivity values of 0.48 to 19.50 m<sup>2</sup>/day and 0.06 to 3.75 m/day respectively. Transmissivity values of  $4.84 \times 10^{-4}$ – $1.63 \times 10^{-3}$  m<sup>2</sup>/s were reported for parts of Bayelsa state, Nigeria [8]. The aquifer hydraulic characteristics of Akpabuyo coastal plain, in Cross Rivers State, Nigeria were estimated by [9]. They reported that, transmissivity, hydraulic conductivity, and specific capacity, ranged from 485.0 m<sup>2</sup>/d to 1346.0 m<sup>2</sup>/d, 9.7 m/d to 27.9 m/d, 0.02 m<sup>3</sup>/d/m to 346 m<sup>3</sup>/d/m respectively.

A method developed by [10] which is based on an approximation of the equation developed by [11] for transient radial flow to a well was used by [12] to estimate the hydraulic conductivity and transmissivity from specific capacity data from Utah county, Utah. The groundwater resources potentials of Khanewal District, Pakistan, were determined using a geophysical method in combination with pumping test data [13]. Results obtained revealed transmissivity values obtained from pumping test data and the VES method range between 954 to 4263 m<sup>2</sup>/day and 200 to 5600 m<sup>2</sup>/day respectively. Hydraulic conductivity values range between 15.9 to 60.9 m/day and 29.76 to 72.3 m/day from pumping test data and geoelectrical technique respectively.

The aim of this study is to determine the aquifer characteristics of the study area and produce the GIS

(Geographical Information System) map of the various aquifer characteristics. This will provide information regarding the availability and quantity of water in storage, the depth at which the water can be abstracted which will be useful for proper management of ground water resources in the study area.

## 2. MATERIALS AND METHOD

### 2.1 Study of Area

Benue State is situated between Latitudes 6° 30'N and 8° 15'N and Longitudes 7°30'E and 10°00'E with land area of about 34,059 km<sup>2</sup> and a population of 2,780,398 by 1991 Census and 4,253,541 by 2006 estimate. The study area covers 12 out of the 23 Local Government Areas (LGAs) of Benue State, namely: Ado, Obi, Oju, Konshisha, Gboko, Ushongo, Vandeikya, Tarka, Buruku, Logo, Katsina-Ala and Ukum.

Benue State experiences two distinct seasons, the wet season and the dry season. The rainy season lasts from April to October with annual rainfall in the range of 1120 to 1500 mm. The dry season begins in November and ends in March. The climate is characterized by high temperature regime, ranging from 27-38°C as mean annual. Relative humidity is between 60-80%. It has a vegetation cover of the guinea savannah type. The main river systems include the River Benue and the River Katsina Ala which together with their tributaries, traverse the area. The drainage system of the Cross River basin bordering the lower Benue basin to the south rises from the area, through the River Konshisha and its tributary rivulets and streams, flowing southwards into the main basin of the Cross River to the south. The region is well drained and presents good potential for water resources development. The stream flow over the impermeable geological environments indicates low ground water component and very high runoff.

Knowledge of the general geology of Benue State is obtained from the works of [14] and [15]. The State is underlain by both basement and sedimentary rocks which vary in character across the State (Figure 1). Basement complex rocks comprising ancient igneous and metamorphic rocks, occur mainly in Kwande, Ushongo, Guma, Vandeikya and the eastern part of Oju LGAs.

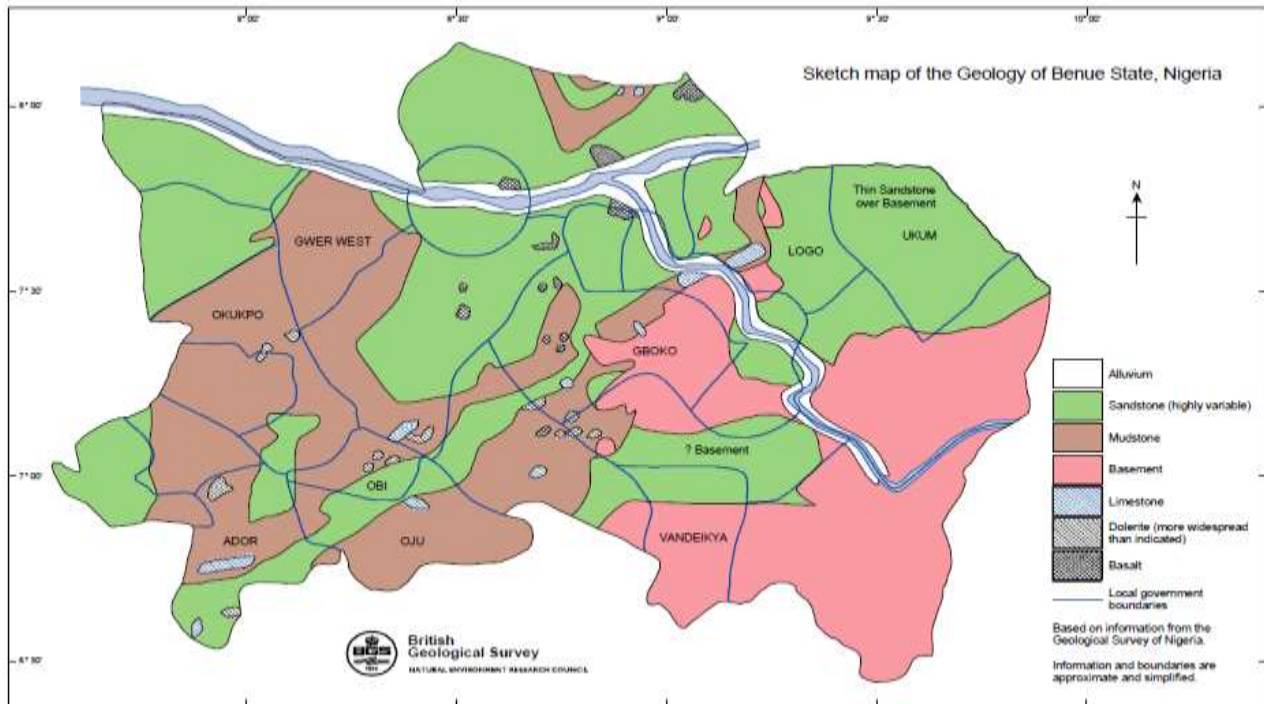


Figure 1: Geology of Benue State

The basement rocks are dominated by porphyritic granites, migmatites, diorites, pegmatites and gneisses. The sedimentary rocks are dominantly sandstones and mudstone, but also contain shale, siltstone, limestone and quartzite. In some places, the sandstone can be soft and porous, and contain much groundwater. In other places, it is hard and fine grained and contains little groundwater. Mudstone is generally poor in terms of the quantity and quality of groundwater, particularly in the northwest where it is soft and sticky. On the flood plains of the Benue are Katsina Ala Rivers and other smaller rivers, alluvial deposits, comprising of assortment clays, sand, gravels and pebbles, overlie the meta- sediments and form the superficial geology

**2.2 Data Collection and Collation**

The pumping test data for each of the 74 boreholes in the study area were obtained from secondly sources/commissioned reports of government organizations. The data for the boreholes of Obi, Oju, Vandeikya, Ushongo, Ukum and part of Katsina-Ala Local Government Areas were provided by the Lower Benue River Basin Development Authority (LBRBDA). While data for the boreholes of the Ado, Konshisha, Tarka, Gboko, Buruku and Logo LGAs were provided by the Benue State Ministry of Water Resources

(BSMWR). The geographical co-ordinates of 36 borehole sites were given in the reports submitted to the LBRBDA and BSMWR by their respective well drillers. The co-ordinates of the remaining 38 borehole sites were determined at the various borehole locations using the site descriptions given in the pumping test reports. The co-ordinates were determined by reading from decimetre accuracy hand held GPS (Global Positioning System) equipment placed by the borehole cap. The co-ordinates were used for the mapping of the aquifer characteristics determined.

**2.3 Data Analysis**

The Theis', Cooper-Jacob's and Chow's methods are commonly used for the determination of the aquifer constants; transmissivity, T and storativity S, from pumping test data. In this study, the [16] straight-line method, which is a modification of the [11] non-equilibrium well equation was used to produce the semi-log graphs of the drawdown, s versus time, t for determination of log-cycle gradients, Δs. The non-equilibrium equation is expressed as:

$$s = \frac{Q}{4\pi T} [W(u)] \tag{1}$$

where W (u) is the well function, expressed in a convergent series as:

$$W(u) = -0.5772 - \log_e(u) + u - \frac{u^2}{2 \times 2!} + \frac{u^3}{3 \times 3!} - \frac{u^4}{4 \times 4!} + \dots \quad (2)$$

s is the drawdown and u is defined as in Equation 3 thus:

$$u = \left(\frac{r^2 S}{4Tt}\right) \quad (3)$$

For small values of r (radial distance of the observation well from the pumped well) and large values of t (time since pumping started); [16] noted that the value of u is relatively small, Equation 1 can be simplified to:

$$\begin{aligned} s &= \frac{Q}{4\pi T} [-0.57720 - \log_e(u)] \\ &= \frac{Q}{4\pi T} \left[-0.57720 - \log_e\left(\frac{r^2 S}{4Tt}\right)\right] \\ &= \frac{2.30Q}{4\pi T} \log_{10}\left(\frac{2.25Tt}{r^2 S}\right) \end{aligned} \quad (4)$$

Equation 4 indicates that the drawdown (s) varies linearly with logarithm of time t because all other terms are constant for an observation well.

For the determination of the aquifer constants, storativity, S and transmissivity, T, the following procedure was used:

- (i) The observed values of the drawdown, s in the observation well were plotted on the arithmetic scale against the values of t on the logarithmic scale. A best-fit straight line was then drawn through the plotted points.
- (ii) The value of change in the drawdown ( $\Delta s$ ) over one log cycle was determined from the best-fit straight line.
- (iii) The value of T was determined from drawdown per log cycle in meters (m),  $\Delta s$  as:

$$T = \frac{2.30 Q}{4\pi(\Delta s)} \quad (5)$$

- (iv) For the determination of S, the best-fit straight line was extended to intersect the abscissa at  $t = t_0$ . It may be noted that  $t_0$  is the time up to which the drawdown remains zero.

Substituting  $s = 0$  and  $t = t_0$  in Equation 4, we had:

$$S = \left(\frac{2.25 T t_0}{r^2}\right) \quad (6)$$

Specific capacity,  $S_c$  ( $m^2/day$ ) and hydraulic conductivity, K ( $m/day$ ) were computed using Equations 7 and 8 respectively. While the screen lengths, B were obtained from the well drillers' reports which contained the lithology loggings and the well design.

$$S_c = \frac{Q}{s} \quad (7)$$

$$K = \frac{T}{B} \quad (8)$$

where, Q = Constant pumping rate ( $m^3/day$ ), s = drawdown (m) and B = aquifer thickness taken as equivalent to screen length (m).

### 2.4 Mapping of Aquifer Parameters

The computed values of the static water Level (SWL), transmissivity (T), hydraulic conductivity (K), specific capacity ( $S_c$ ) and storativity (S) were brought to geographical information system (GIS) environment, gridded, contoured and colour-coded into ranges to produce the respective maps. Surfer 10 software was used in plotting the aquifer parameters. The latitude and longitude of the borehole stations were converted to northings and eastings respectively while, the parameter of interest was the third dimension. The data were arranged in x, y, z format in notepad and the file saved with an extension recognized by Surfer. The saved files were exported to Surfer for gridding. The gridded files were used to plot the contour lines and the contour lines filled with colour separation.

## 3. RESULTS AND DISCUSSION

### 3.1 Hydraulic Conductivity (K)

The hydraulic conductivity, K is presented in Figure 2. Most parts of the study area had K values of 0.01 to 1.0 m/day while the values of 1.0 to 5.0 m/day were obtained for Buruku, northern parts of Gboko, southern parts of Tarka, and western parts of Logo LGAs. Higher k values (9.7m/d to 27.9m/d) were reported by [9] for Akpabuyo Coastal Plain, Cross River State.

### 3.2 Transmissivity (T)

The map of the transmissivity from drawdown data, T, is given as Figure 3. Transmissivity ranged from 0.01 - 8  $m^2/day$  in most of the study area except parts of Konshisha where it was up to 16  $m^2/day$  and Gboko where it went up to 49  $m^2/day$ . The value of transmissivity obtained in this study for the Konshisha LGA of 0.63 to 11.26  $m^2/day$  is in line with the range of 0.49 to 4.52  $m^2/day$  obtained by [2]. The transmissivity for Vandeikya range from 0.55 to 1.5 is within the range of 0.49 to 13.99  $m^2/day$  reported by [17] for the area. From the results obtained the aquifers of the study area falls within

low to intermediate transmissivity based on [18] classification.

**3.3 Storativity (S)**

The map of the storativity, *S*, is given as Figure 4. Storativity values of most LGAs of the study area fall within a range of 0.01 to 0.4, 0.4 to 1.0. The highest storativity value of 2.4 was obtained in Ado LGA. The computed values of storativity were considered valid approximation of Theis solution because the values of  $u = r^2S/4Tt < 0.03$  showed that the approximation error was less than 1% [19].

**3.4 Specific Capacity (*S<sub>c</sub>*)**

The map of the specific capacity, *S<sub>c</sub>*, as given in Figure 5 shows that the specific capacity of major parts of the study area ranged from 0.01 to 10 m<sup>2</sup>/day with the exception of Konshisha, parts of Ushongo, Vandeikya and Oju with a range of 10 to 40 m<sup>2</sup>/day. Tse-Fila in Konshisha LGA had the highest *S<sub>c</sub>* value of 83 m<sup>2</sup>/day. The value of specific capacity obtained in this study for Konshisha LGA ranged from 9.88 to 82.77 m<sup>2</sup>/day. Specific capacity values of 78.62 - 86.40 m<sup>2</sup>/day were reported by [2] in some parts of Konshisha LGA.

**3.5 Static Water Level (SWL)**

The colour coded map of the static water level (SWL) of the study area is shown in Figure 6. The SWL ranged from 2 to 8 m in major parts of Oju, Southern parts of Vandeikya, Northern half of Katsina Ala, whole of Tarka, Northern parts of Gboko and Logo LGAs. SWL ranged from 8 m to 20 m in other parts of the study area except little spots in Konshisha and southern parts of Gboko LGA where it rose to a range of 28 to 38 m.

**3.6 Yield of aquifers of the various LGAs of study area**

The estimated yields of the aquifers of the study area based on the determined hydraulic characteristics are presented in Table 1. The table indicates that the aquifers are generally of low to moderate yield based on [20] classification. According to [18] classification, the aquifers of the study area fall within the intermediate to very low class. The moderate category is good for withdrawals for local water supply and small scale irrigation farming while the low category gives smaller withdrawals good for local water supply through hand pump and private consumption using low energy submersible pumps.

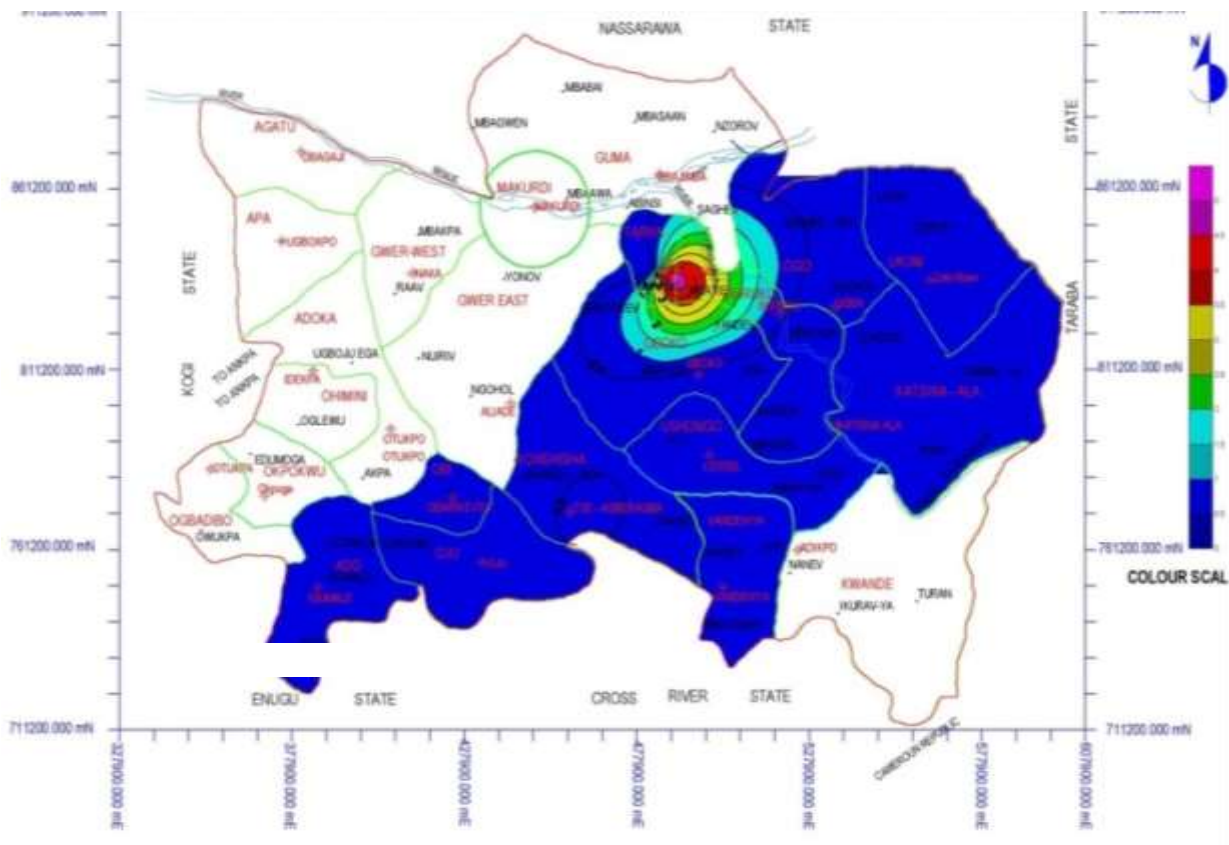


Figure 2: Hydraulic Conductivity, *K* (m/day)

Table 1: Yield of the Aquifers Based on Determined Hydraulic Characteristics of Study Area

LGAs	Well Discharge		Specific Capacity (m <sup>2</sup> /day)	Hydraulic Conductivity (m/day)	Transmissivity (m <sup>2</sup> /day)	Yield (Based on [17] classification)
	(m <sup>3</sup> /day)	L/s				
Ado	55-95	0.06-0.11	2.10-9.30	0.111-0.316	1.01-2.85	B, D - Moderate
Obi	25-173	0.03-0.20	1.04-9.61	0.040-0.540	0.38-4.86	B, D - Moderate
Oju	34-173	0.04-0.20	1.11-11.73	0.050-0.620	0.61-5.64	E – B, D – Limited to Moderate
Konshisha	82-78	0.10-0.09	4.89-82.77	0.060-0.930	0.63-11.26	B, D - Moderate
Vandeikya	31-78	0.04-0.09	1.41-3.14	0.030-0.100	0.55-1.51	E – B, D – Limited to Moderate
Ushongo	39-157	0.05-0.18	2.27-8.45	0.050-0.298	0.90-3.35	E – B, D – Limited to Moderate
Gboko	130-160	0.15-0.19	3.50-4.38	0.110-0.170	1.40-2.02	E – B, D – Limited to Moderate
Buruku	137-137	0.16	3.33-3.33	0.070-0.070	0.90-0.90	E - Limited
Tarka	43-60	0.05-0.07	1.74-5.33	0.070-5.400	0.88-43.91	E – B, D – Limited to Moderate
Logo	9-24	0.01-0.03	0.45-1.13	0.010-0.050	0.19-0.58	E – Limited
Katsina-Ala	34-172	0.04-0.02	1.16-7.15	0.040-0.220	0.53-3.01	E – B, D – Limited to Moderate
Ukum	16-157	0.02-0.18	1.08-9.78	0.030-0.240	0.48-3.60	E – B, D – Limited to Moderate

Key: B, D = Moderate – Withdrawals for local water supply (smaller communities, small-scale irrigation etc.)  
 E = Smaller withdrawals for local water supply (supply through hand pump, private consumption)

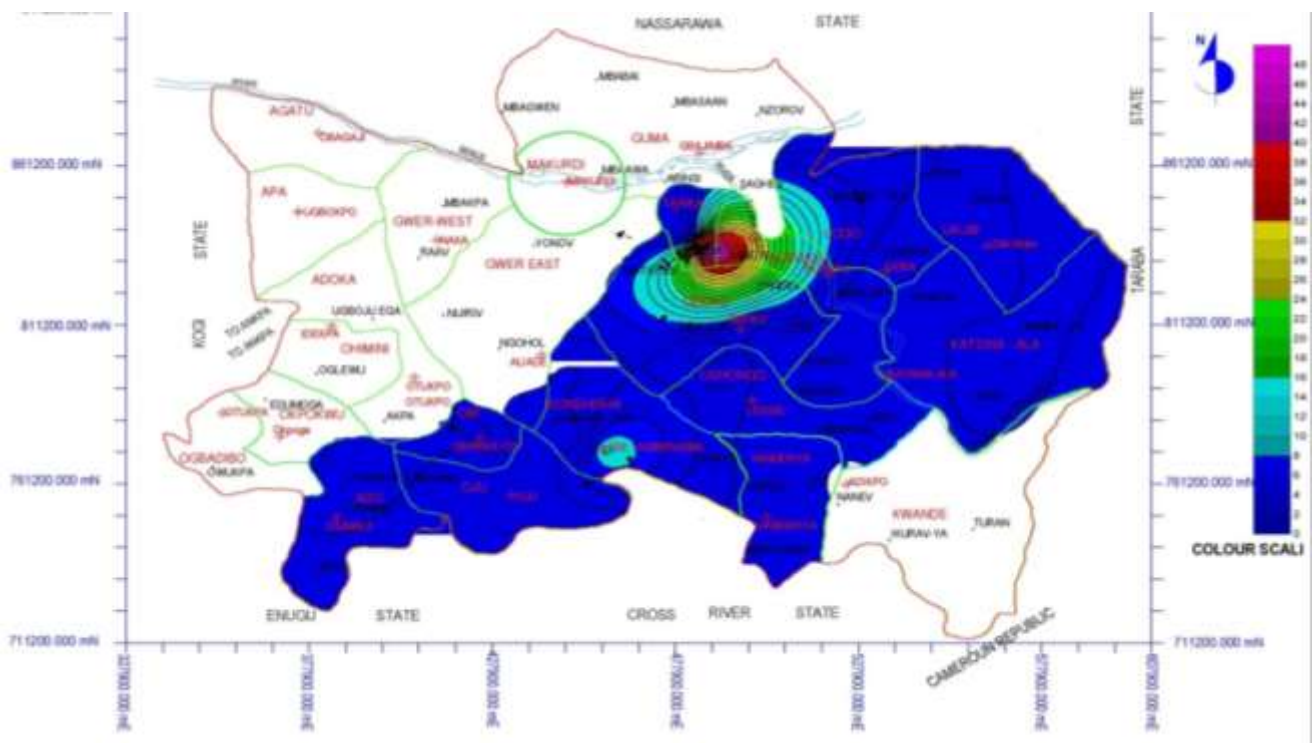


Figure 3: Transmissivity, T (m<sup>2</sup>/day)

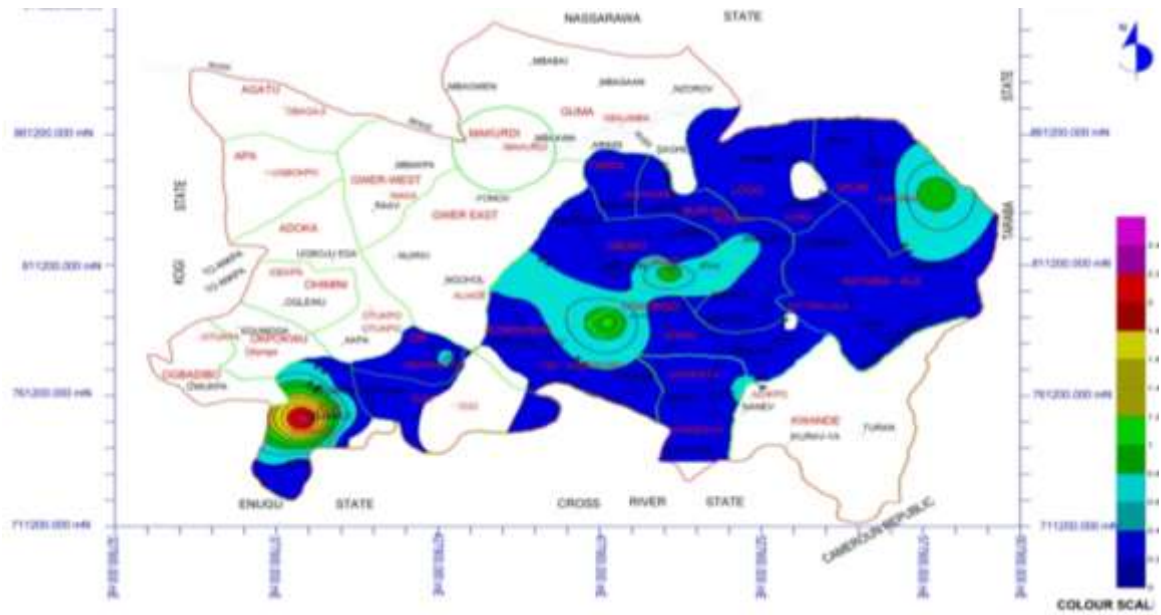


Figure 4: Sorativity,  $S$

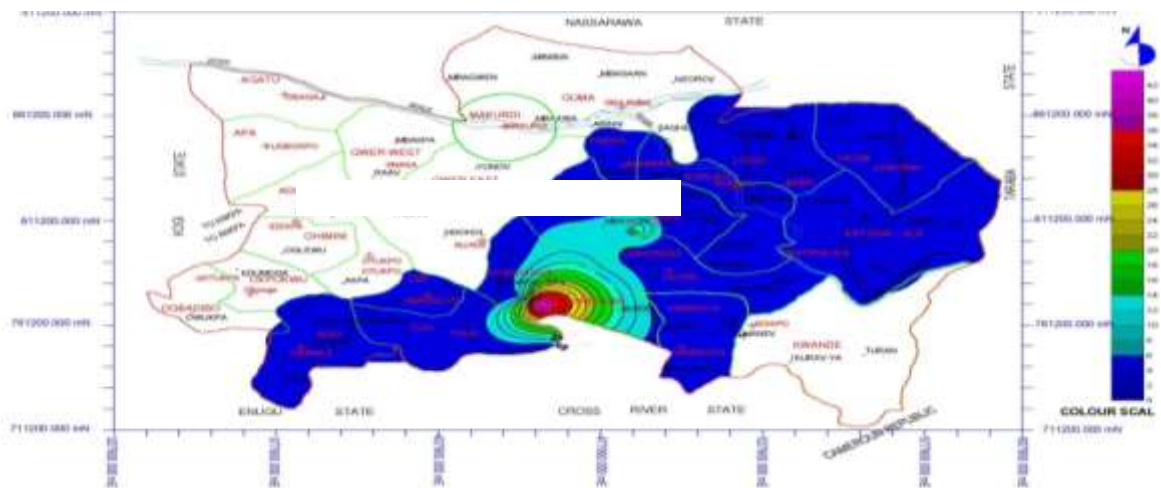


Figure 5: Specific capacity,  $S_c$  ( $m^2/day$ )

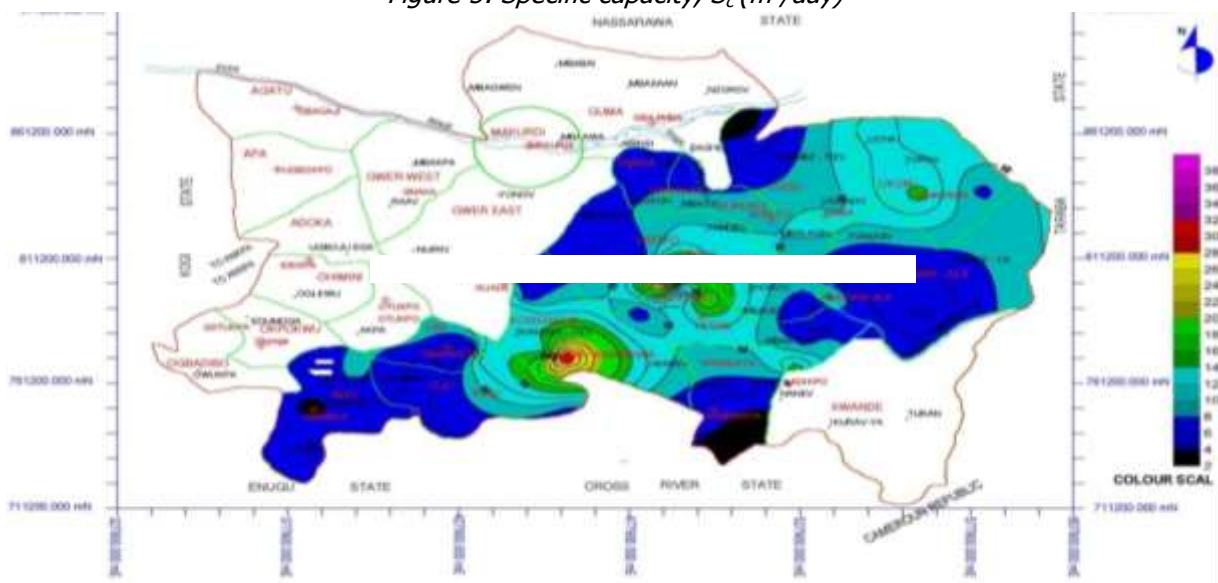


Figure 6: Static Water level (m)

#### 4. CONCLUSION AND RECOMMENDATIONS

The study on the determination of hydraulic characteristic of the aquifers of some local Government Areas of Benue State was carried out using the pumping test results of seventy-four boreholes in various communities of twelve Local Government Areas of Benue State. The aquifer hydraulic characteristics namely: static water level, specific capacity, hydraulic conductivity, Transmissivity and storativity have been determined and plotted on a geographical information system map of the study area.

The results show that the aquifers of the study area are of moderate to low or limited yield. Such aquifers will not yield enough water for municipal supply but can be used for rural supply where the demand is not usually high. It is recommended that the determined hydraulic characteristics can be utilised by any underground water prospector for a well-informed prediction of the expected yield of the groundwater in storage in any of the aquifers within the study area.

#### 5. REFERENCES

- [1] Ferris, J. G., Knowles, D. B. Brown, R. N. and Stallman, R.W. (1962). *Theory of Aquifer Test*. U.S. Geological Survey Water Supply Paper 1536-E, US Government Printing office, Washington, pp 69-174, 1962.
- [2] Jika, H.T. and Tse, A. C. "Determination of Hydraulic Characteristics of an Aquifer Capacity from Pumping Test: A case study of Konshisha Area, Central Nigeria", *Scientia Africana*, Vol.13, Number 2, pp 136-145, 2014.
- [3] Razack, M. and Huntley, D. "Assessing Transmissivity from Specific Capacity Data in a Large and Heterogeneous Alluvial Aquifer". *Groundwater*, Vol. 29, Number 6, pp 56 – 861, 1991.
- [4] Okonkwo, C. A., Ezeh, C. C., Opara, A. I. "Estimates of Aquifer Transmissivity from Specific Capacity Data in Sandstone Aquifers in Enugu state, Southeastern Nigeria", *Int. Res. J. Geo. Min.* Vol.3, Number 8, pp 291-297, 2013.
- [5] Tse, A. C; Amadi, P. A. "Hydraulic Properties from Pumping Tests Data of Aquifers in Azare Area, North Eastern Nigeria." *Journal Applied Science Environmental Management*, Vol. 12, Number 4, pp 67- 72, 2008.
- [6] Anomohanran, O. and EIserrhien-Emekeme, R. "Estimation of Aquifer Parameters of Erho, Nigeria using the Cooper-Jacob Evaluation Method", *American Journal of Environmental Sciences*, Vol.10, Number 5, pp 500-508, 2014.
- [7] Okoro, E I., Egboka, B. C. E., Onwuemesi, A. G. "Evaluation of the Aquifer Characteristic of Nanka Sands using Hydrogeological Method in Combination with Vertical Electrical Sounding (VES)", *J. Appl. Sci. Environ. Manage.* Vol. 14, Number 2, pp 5 – 9, 2010.
- [8] Oborie, E. and Udom, G. J. "Determination of Aquifer Transmissivity using Geoelectrical Sounding and Pumping test in Parts of Bayelsa State, Nigeria", *Peak Journal of Physical and Environmental Science Research*, Vol. 2, Number 2, pp 32-40, 2014.
- [9] Amah, E. A, Anam G. S. "Determination of Aquifer Hydraulic Parameters from Pumping Test Data Analysis: A Case Study of Akpabuyo Coastal Plain Sand Aquifers, Cross River State, S-E Nigeria." *IOSR Journal of Applied Geology and Geophysics*, Vol. 4, Number 1, pp 1-8, 2016.
- [10] Bradbury, K. B. and Rothschild, E. R. "A Computerized Technique for Estimating the Hydraulic Conductivity of Aquifers from Specific Capacity Data", *Ground Water*. Vol. 23, Number 2, pp 240– 246, 1985.
- [11] Theis, C. V. "The Relation between the Lowering of the Piezometric Surface and the Rate and Duration of Discharge of well using Groundwater Storage", *Am. Geophys. Union Trans.*, Vol.16, pp 519-524, 1935.
- [12] Jordan, J. L. *Aquifer Parameter Estimation from Aquifer Tests and Specific-Capacity Data in Cedar Pass Area, Utah County, Utah*. Utah Geological Survey, Special Study 146, 68p, 2014.
- [13] Akhter, G. and Hasan, M. "Determination of Aquifer Parameters using Geoelectrical Sounding and Pumping Test Data in Khanewal District, Pakistan" *Geosciences*, Vol. 8, pp 630–638, 2016.
- [14] Reyment, R. A. *Aspect of Geology of Nigeria*. Ibadan University press, 122p, 1965.
- [15] Grant, N. "The South Atlantic, Benue Trough and Gulf of Guinea Cretaceous Triple Junction", *Geol. Soc. Am. Bulletin*, Vol.82, pp 2295-2298, 1971.
- [16] Cooper, H. H. and Jacob, C. E. "A Generalized Graphical Method for Evaluating Formation Constants and summarising Well-Field History", *Transactions, American*



- Geophysical Union*, Vol.27, Number 4, pp 524-534, 1946.
- [17] Jika, H. T and Mamah, L. I. "Application of Electromagnetic Method and Electrical Resistivity Sounding in Hydrogeological Studies, A Case Study of Vandeikya Area, Central Nigeria", *International Journal of Scientific & Technology Research*, Vol.3, Number 2, pp 179-190 2014.
- [18] Krásny, J. "Classification of Transmissivity Magnitude and Variation", *Groundwater*, Vol. 31, Number 2, pp 230–236, 1993.
- [19] Meier, P. M., Jesus, C. and Sanchez-Vita, X. "An Evaluation of Jacob's Method for the Interpretation of Pumping Tests in Heterogeneous Formations". *Water Resources Research*, Vol.34, Number 5, pp 1011-1025, 1998.
- [20] Bäumle, R., Neukum C. H., Nkhoma J. and Silembo, O. *The Ground Water Resources of Southern Province, Zambia (Phase 1)*. Ministry of Energy and Water Development Department of Water Affairs, Zambia & BGR Federal Institute for Geosciences and Natural Resources, Germany; *Technical Report, Lusak*, Vol. 1, 132p, 2007.