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Evaluation of aquifer hydraulic characteristics using geoelectrical sounding, pumping and laboratory tests: A case study of Lokoja and Patti Formations, Southern Bida Basin, Nigeria

<https://doi.org/10.1515/geo-2018-0063>

Received July 23, 2017; accepted January 2, 2018

Abstract: The hydraulic characteristics of aquifers in Lokoja and Patti Formations were investigated using combination of vertical electrical sounding (VES), pumping and laboratory tests. A total of 20 VES (10 each in areas underlain by Lokoja and Patti Formations) were carried out at different locations with 5 pumping tests around VES stations in order to determine the geoelectric layers, thickness, depths to water table and groundwater potential of the area. 21 samples extracted from aquiferous units of surface outcrops were also subjected to laboratory constant head and falling head permeameter tests in order to determine hydraulic conductivity (K) values using the Darcy's law of liquid flow. The results of VES for areas underlain by Lokoja and Patti Formations revealed 4-5 geo-electrical layers. The depths to water table vary from 5.91-40.8 m. Thickness values are within the range of 7.37-27.3 m for aquiferous units of Lokoja Formation, and 10.8-20.1 m for the Patti Formation. The results of aquifer characteristics using Dar-Zarrouk Parameter gave hydraulic conductivity (K) values between 1.92-91.7 m/day and 2.15-31.8 m/day for aquifers of Lokoja and Patti Formations respectively. Transmissivity (T) values of the aquiferous units of Lokoja Formation fall within 24.97-2117 m²/day, while those of Patti Formation vary from 27.9-456.91 m²/day. There is a strong correlation between the values of measured and calculated hydraulic conductivity and transmissivity between measured and calculated transmissivity for the five wells ($R^2 = 0.99$ and 0.92 , respectively). Based on the results obtained and interpretations proffered, aquiferous units in both formations are capable of yielding optimum groundwater for private consumption and partly to small communities, and to some extent can supply water for great regional use. It is suggested that similar study should be carried out in other sedimentary basins where to aid

regional planning and management of groundwater resource.

Keywords: Aquifer, hydraulic characteristics, geoelectrical sounding, pumping test, groundwater

1 Introduction

The knowledge of aquifer parameters is essential for the management of groundwater resource. Determination of aquifer characteristics (hydraulic conductivity and transmissivity) is best made on the basis of data obtained from well pumping test. These properties are important in estimating the natural flow of water through an aquifer and its response to fluid extraction. However, few boreholes may be available and carrying out pumping tests at a number of sites may be costly and time consuming. Geophysicists have discovered that in such a situation, the integration of aquifer parameters calculated from the existing boreholes locations and surface resistivity parameters extracted from surface resistivity measurements can be cost

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effective and highly efficient. This is an alternative way of estimating aquifer parameters since a correlation between hydraulic and electrical aquifer properties can be possible, as both properties are related to the pore space structure and heterogeneity [1, 2]. The relationship established for the estimation of these aquifer properties in the case of limited pumping test data is known as Dar-Zarrouk Parameters from geophysical sounding. Furthermore, hydraulic conductivity can be determined in the laboratory using permeameters (falling head and constant head) through Darcy's formula.

Much geological and geophysical investigations in the southern Bida Basin, Nigeria have been carried by several researchers. [3–7] studied the geology and stratigraphy of the Middle Niger Basin. Also, Sedimentological characteristics were investigated by [3, 8–10]. Attempts to estimate aquifer parameters from geophysical sounding have been carried out by [11–24]. [25] used grain size distribution for the estimation of aquifer parameters in the northern part of the Bida Basin while [26] estimated aquifer parameters from grain size distribution in the southern part of the Bida Basin. However, till date, no published work on the use of Dar-Zarrouk parameter in order to determine the hydraulic characteristics of the Southern Bida Basin. The closest exception is the work of [26] that used empirical relationships of Hazen Breyer and Shepherd Formula's for the evaluation of the hydraulic characteristics of these Cretaceous sedimentary rocks. However, attempts with positive results from the use of Dar-Zarrouk parameter have been made by some authors in other basins within and outside Nigeria [27–29]. Despite the fact that the study area is located at the confluence of the Rivers Niger and Benue, a number of localities within this area still lack access to portable water (i.e. Felele, Odah, Okofi, Akpogu, etc.). In addition, there is little or shallow knowledge of aquifer parameters in the area resulting into poor management of groundwater resource. Thus, this study was undertaking to unravel aquifer characteristics and groundwater potential of this area.

2 General Background

The area is located between latitudes $N07^{\circ}45'$ and $N08^{\circ}30'$; longitudes $E006^{\circ}40'$ and $E006^{\circ}55'$ (Figure 1). It covers an area of about 2740 km^2 and falls within Kogi and Lokoja Local Government Areas of Kogi State. Twenty localities within the area were occupied which include Felele, Nat-aco, Okumi, Banda, Koton-karfi, Ozi, Agbaja, Akpayagbayi, Karara, Jamata, Edeha, Akpogu, Gegu Beki, Gegu

Figure 1: Map of Nigeria showing sedimentary basins where the Dar-Zarrouk parameter has been used and where it has not been used for aquifer characteristic studies [Modified from [9]].

Ega, Etegi, Girinya, Abaji, Okofi, Odah and Ozahi (Figure 1). Also, the area consists of River Niger, its flood plain and tributaries, and is characterized by belt of mesas and plains. The River rises from Foutha-Djallon highlands in Guinea about 3,500 km to its confluence with River Benue in Lokoja, Kogi state, from where it continued to the Niger Delta. At the delta front, it deposits thick layers of marine sediments, which are highly petroliferous. Patti stream formed from a spring flows into the River Niger. These water bodies are annual and thus dry off at the peak of dry season due to decrease in water table as well as evaporation. Generally, the drainage pattern is simply dendritic, where many tributaries join the major river in a tree-like manner.

2.1 Geology of the area

The study area lies within the Mid-Niger or Nupe Basin. The stratigraphic succession of the Mid-Niger Basin, collectively referred to as the Nupe Group [30] comprises of Northern Bida Basin (Sub-Basin) and Southern Bida Basin or Lokoja Sub-basin (Figure 2).

Stratigraphically, in the Southern Bida Basin, the Campanian – Maastrichtian Lokoja Formation non-conformably overlies the Pre-Cambrian to Lower Paleozoic Basement gneisses and schists. This is overlain by the Maastrichtian Patti Formation and succeeded by the

Bida Area (Sub-basin)					Lokoja Area (Sub-basin)				
MAASTRICHTIAN	Batati Ironstones			— — —	Agbaja Ironstones				
	Enagi Siltstones				Patti Formation				
	Sakpe Ironstone								
CAMBRIAN-MAASTRICHTIAN	Bida Sandstone	Jima member	— — —	Lokoja Sandstone	Claystone (member) Sandstone (member)				
		Doko member			Basal Conglomerate (member)				
PRE-CAMBRIAN – LOWER PALAEOZOIC	+	+	+	+	+	+	+	+	
	+	+	+	+	+	+	+	+	
	+	+	+	+	+	+	+	+	
	+	+	+	+	+	+	+	+	

Figure 2: Stratigraphic successions in the Mid-Niger Basin [Redrawn from [6].

Maastrichtian Agbaja Ironstone Formation. The Lokoja and Patti Formations constitute the focus of this study.

2.1.1 The Lokoja Formation

The lithologic units within Lokoja Formation include conglomerates, coarse to fine grained sandstones, siltstones and claystones [7, 31]. The rocks are generally poorly sorted and comprise quartz and feldspar, and are therefore texturally and mineralogically immature [32]. The water-bearing bodies or aquiferous units of interest in this Formation are conglomerate, coarse, medium and fine grained sandstone. While siltstones and claystones are not good aquiferous bodies, they can be of importance when they are associated with major amount of sand e.g. clayey sand or silty sand but when with minor amount of sand (sandy silt or sandy clay) they can only be fair. Field study by [6] shows that the basal Lokoja Formation is exposed within Lokoja and Koton-karfe area which is largely the southern part of the study area (Figure 1). Study localities (Felele, Nataco, Okumi, Banda, Karara, Jamata, Edeha, Okofi, Odah, Akpaya-gbayi) are underlain by Lokoja Formation and have similar geology (sedimentological and stratigraphic characteristics) generally consist of lithologic units with a generally finning upward (coarsening downward) sequence [7].

2.2 Patti Formation

The lithologic units within Patti Formation include sandstones, siltstones, claystones and shales interbedded with bioturbated ironstones [7]. The sandstone unit of this formation is more mineralogically mature compared to the Lokoja Formation in the southern Bida Basin [31]. There is predominance of argillaceous units especially siltstone, shales and claystones in this Formation [32]. The water-bearing bodies of interest are therefore the sandstone units and where the clays or siltstone are with a major amount of sand (i.e. clayey sand). However, where shale or clay is the only geo-material or has minor amount of sand (e.g. sandy clay), it is not of primary interest. The outcrops of this Formation are exposed within Koton-Karfe and Abaji [6] which are largely the northern part of the study area (Figure 1). Thus study localities (Akpogu, Gegu Beki, Gegu Ega, Etegi, Girinya, Abaji, Koton-karfi, Ozi, Ozahi) are underlain by Patti Formation and also have similar geology. [33] noted that the coarser Lokoja Formation becomes more and more buried and the finer members of the Patti Formation becomes more exposed as one moves into the basin. Also, the work of [7] shows that argillaceous (fine grained) sediments predominate in the central parts of the basin. Thus it is logical to say there is a general finning upward and coarsening downward of the rock units. Generally, the rock units of Patti and Lokoja Formations have different grain sizes, porosity and permeability [26]. Hence, making it possible to unravel the hydraulic characteristics by the use of geophysical, pumping test and laboratory methods.

3 Materials and Methods

The methodology adopted include the integration of pumping tests data with geophysical data (Dar - Zarrouk Parameter) and the use of laboratory method (Constant and Falling head permeability test) for extracted samples of aquiferous units from surface outcrops. While the Former was used to determine the transmissivity and hydraulic conductivities of the aquifers, the later was used to determine the coefficient of permeability (hydraulic conductivity) only.

3.1 Pumping Test

A total of five (5) pumping test data were used in this study. The Pumping tests data used in this study were carried out by self and some were obtained from Lower Niger River Basin Authority, Ilorin, Kwara State and Kogi

State Water Board, Lokoja Nigeria. Three (3) of the pumping tests were carried out in Felele, Odah and Okofi penetrating the Lokoja Formation while the remaining two (2) were carried out at Akpogu town and Ozahi, penetrating the Patti Formation (Figure 1). The pumping test data were evaluated using constant pumping rate discharge method. The pumping rates were within 0.2 l/sec – 2 l/sec, and the time of pumping varies from 1 – 6 hrs. The principle of a pumping test involves the application of a stress to an aquifer by extracting groundwater from a pumping well and measuring the aquifer response to that stress by monitoring drawdown as a function of time. The obtained pumping test data were incorporated into an appropriate well flow equation (i.e. Theis recovery formula, Jacobs-Cooper drawdown-time formula) to determine in-situ aquifer characteristics. The transmissivity of the aquifers from pumping tests were determined by the Theis recovery method and Jacob Cooper's drawdown method [34, 35].

For Jacob Cooper's method,

$$T = \frac{2.3 Q}{4\pi \times \text{drawdown}} \quad (1)$$

While for Theis recovery method,

$$T = \frac{2.3 Q}{4\pi \times \Delta S} \quad (2)$$

Where Q is discharge rate in m^3/day , $\Delta S'$ = change in the residual drawdown in metre per log cycle of t/t' (t is time since pumping started and t' is time since pumping stopped). Change in residual draw down is actually the difference between the drawdown component due to continuous pumping and the recovery component due to recharge. The S' is plotted on the arithmetic scale of the y-axis, the t/t' is plotted on the logarithmic scale of the x-axis.

3.2 Geophysical investigation

A total of twenty (20) Vertical Electrical Soundings using Schlumberger configuration were carried out at nineteen (19) different localities within the area. The AB/2 (half-current spacing) was between 40 m to 80 m, because of the knowledge of borehole depths within the area. The ABEM Terrameter Geo-Pulse was used which performs automatic recording of both voltage and current, stacks the results, computes the resistance in real time and digitally displays it. Apparent resistivity values were obtained by multiplying resistance with appropriate geometric factor. The values were plotted against half electrode spacing on

logarithmic coordinate to obtain the sounding curves from which, geo-electric layers, resistivities and thicknesses and depths of the layers were determined using IPI2WIN software. The resulting curves generated from the software produced a low Root Mean Square Error of not more than an approximate 1%. From the curve, resistivity and thickness and depth to water table were obtained.

3.3 Dar-Zarrouk Parameters

The term Dar-Zarrouk parameters (Transverse resistance (R) and the longitudinal conductance (S)) were first used by [36]. These parameters are derived from layer resistivity and thickness obtained during VES survey. [37] derived the analytical relationship between aquifer transmissivity and transverse resistance, as well as the relationship between transmissivity and longitudinal conductance. The estimation of aquifer parameters – transmissivity and hydraulic conductivity from a pumping test is time consuming and expensive especially when it involves performing a number of them in an area. The geophysical method (VES) has been proven by many authors to be an efficient, cost effective and less time consuming alternative. In this study, attempt has been made to estimate aquifer parameters (transmissivity and hydraulic conductivity) using Dar-Zarrouk parameter (Transverse Resistance) from VES. The relationship between transmissivity values from five (5) pumping test (at Felele, Odah, Okofi, Akpogu and Ozahi) and transverse unit resistance was derived by performing a regression analysis between both parameters (Table 1 and Figure 3). The method used is called “grand mean centering”. This was used because it helps to avoid negative constant term when the negativity does not make interpretable sense. When this method is used, it does not alter the estimates of the other independent variables. The relationship derived between transmissivity from pumping test and transverse resistance is given as: $T = 13.39 + 0.06R$. Where R is transverse unit resistance measured in ohm-m^2 and T is transmissivity measured in m^2/day .

Using this relationship, transmissivity is calculated for the 20 VES points in the area of study. Values of hydraulic conductivity (K_p) and transmissivity (T_p) gotten from locations where pumping test results were correlated with the values of hydraulic conductivity (K_c) and T_c (Transmissivity) from Dar-Zarrouk parameter to see whether they are in strong agreement (strongly correlated) or weak agreement (weakly correlated).

Table 1: Data of Transmissivity (TM) from pumping test, Transverse Resistance (TR) and Transformed values of TR (Mean Centering).

TM (Transmissivity – m ² /day)	TR) (Transverse Resistance – Ohm-m ²)	Transformed values of Transverse Resistivity (based on 'grand mean centering' method)
0.27	193.7	-263.964
0.54	210.04	-247.624
1.11	241.8	-215.864
15.01	655.2	197.536
	987.58	530
50	457.664 is the mean of the data. Then select subtract each value from its mean.

Figure 3: Relationship between pumping test transmissivity (TM) and Transverse Resistance (TR) (from mean centering).

3.4 Laboratory method (Constant and Falling head permeameters)

Twenty-One (21) samples extracted from aquiferous units of surface outcrops belonging to Lokoja and Patti Formations were subjected to Constant Head and Falling Head Permeameter test in order to determine the coefficient of permeability (hydraulic conductivity). The samples were named after the localities from which they have been taken. For twelve samples extracted from aquiferous units belonging to Lokoja Formation, the samples are labeled Ohono (1, 2 and 3), Agbaja Hill (1, 2 and 3), Jamata, Before Niger Bridge, Felele (1 and 2), Okumi and Mount Patti 1. While for nine samples extracted from aquiferous units belonging to Patti Formation, the samples are labeled Agbaja Hill (4, 5 and 6), Mount Patti (2 and 3), Ozi, Gegu Beki, Girinya and Gegu Ega. Five (5) coarse grained sandy samples belonging to the Lokoja Formation were analyzed using the Constant head, while sixteen (16) samples which are the fine grained sandy fractions from Lokoja Forma-

tion and the Patti Formations were analyzed using Falling head permeameter. The hydraulic conductivity values (coefficient of permeability) were obtained using the Darcy's law of liquid flow.

3.4.1 Procedure for the Constant Head Permeameter

The samples were placed in between porous stone in a cylindrical jar (Figure 4). The water supply at the inlet was adjusted such that the difference of head between the inlet and outlet remains steady. The setting was left in this condition for minimum of 24 hours to establish a constant rate of flow. The water which flowed through the sample during a known duration was collected in a graduated flask.

Figure 4: Set-up for Constant head permeability test.

The procedure was repeated for other samples and the coefficient of permeability for each of the sample was calculated using the relationship given below.

Coefficient of Permeability,

$$K = \frac{QL}{Aht} \quad (3)$$

Where, Q = Total quantity of water flowing through in elapsed time (cm^3), L = Length of sample in the Permeameter (cm), A = Area of cross- section of the sample (cm^2), h = Hydraulic head (cm).

$$K = \frac{\frac{\text{cm}}{\text{sec}}}{100} = 1 \text{ cm} \times 1 \text{ sec} \times 86400 = \text{m/day} \quad (4)$$

3.4.2 Procedure for the Falling Head Permeameter

For the fine sands and clays, the constant head permeability test shown in Figure 5 is not suitable, because only very small quantity of fluid flows through the soil, and it would take very long time to collect an appreciable volume of water. For such soils a test set up as illustrated in Figure 6 is more suitable.

Figure 5: Falling head Permeability test.

In the apparatus, a sample is enclosed by a small circular ring, placed in a container filled with water. The lower end of the sample is in open connection with the water in the container, through a porous stone below the sample. At the top of the sample it is connected to a thin glass tube, in which the water level is higher than the constant water level in the container. Because of this difference in water level, water will flow through the sample, in very small quantities, but sufficient to be observed by the lowering of the water level in the thin tube. In this case the head difference h is not constant, because no water is added to the system, and the level h is gradually reduced. This wa-

ter level is observed as a function of time. The procedure for calculation of hydraulic conductivity is given by:

$$K = \frac{2.3026aL}{A} \times \frac{\frac{\text{Log}_{10}H_1}{\text{Log}_{10}H_2}}{t_2 - t_1} \quad (5)$$

Where a , is the area of stand pipe tube.

$$a = \frac{\pi d^2}{4} = \frac{\pi(3)^2}{4} = \quad (6)$$

L = Length of sample = 130 mm

A = Cross Sectional Area of the sample = $\frac{\pi d^2}{4} = \frac{3.142(100)^2}{4} = 7857.143 \text{ mm}^2$

$$k = \frac{K_1 + K_2}{2}; \text{mm/sec}$$

$$K = \frac{1\text{mm}}{1000} \times 1 \text{ sec} \times 86400 = \text{m/day}$$

4 Results and Discussion

4.1 Vertical Electrical Sounding (VES)

The results of VES for areas underlain by Lokoja and Patti Formations revealed 4-5 geo-electrical layers (Table 1-5). The resistivity and thickness values of the first layer varies from 9.5-2303 ohm-m and 0.82-529 m, respectively, which is diagnostic of the top soil of variable composition. The resistivity values of the second layer are within 2.5-637 ohm-m with thickness values between 0.19-8.38 m. The resistivity and thickness values of the third layer are within 5.27-3110 ohm-m and 2.59-15.7 m, respectively. The fourth layer has resistivity and thickness values varying from 3.86-1677 ohm-m and 8.19-32.3 m, respectively. The fifth layer has resistivity value of 14.9-513 ohm-m and thickness values from 7.37-13.4 m. Each geo-electrical layer has geological and hydrogeological significance. The first is the top soil, the second is clay or shale in the case of Patti Formation, and this is an aquiclude (impermeable layer). The third layer is sandy clay which is not desirable for optimum groundwater yield. The fourth layer is clayey sand which in many places has significant groundwater yield depending on the thickness. The fifth layer is the sand which is significant for optimum groundwater yield. The fourth or the fifth layer constitute the target layer for groundwater potential evaluation. The interpretation generally agrees with the sedimentological characteristics of the rocks in the basin with finning upward or coarsening downward sequence.

Table 2: Summary of the VES results for Lokoja Formation.

Layer	Felele			Nataco			Okumi			Jamata			Odah		
	h	p	d	h	p	d	h	p	d	h	p	d	h	p	d
1	1.02	348	1.02	1.49	310	1.49	1.43	52.7	1.43	2.93	1317	2.93	2.01	775	2.01
2	6.53	11	7.55	4.64	38.9	6.12	4.1	79.2	5.53	0.48	377	3.41	0.46	90.3	2.47
3	9.55	59.8	17.1	9.31	72.6	15.4	10.7	5.27	16.3	6.34	606	9.71	8.51	426	11
4	22.3	46.8	39.4	18.1	316	33.5	17.4	112	33.7	16.9	75.9	26.6	29.5	723	40.5
5	7.37	134	46.8										13	14.9	53.5

Table 3: Summary of the VES results for Lokoja Formation.

Layer	Okofi			Banda			Akpaya-gbayi			Karara			Edeha		
	h	p	d	h	p	D	h	p	d	h	p	d	h	p	d
1	1.23	144	1.23	0.82	100	0.82	0.82	332	0.82	1.23	144	1.23	1.09	319	1.09
2	1.94	45.7	3.17	2.51	4.16	3.32	8.38	162	9.2	5.81	46.4	7.04	3.71	637	4.8
3	4.85	59.8	8.02	2.59	72.2	5.91	14.7	33.8	14.7	7.63	60.6	14.7	5.37	951	10.2
4	32.3	3.86	40.8	27.3	135	33.2	18.6	50.5	33.3	18.6	81.9	33.2	23.1	1518	33.2
5	12.5	16.8	53.3												

Table 4: Summary of Geo-electric Layer Inferred Interpretation for Lokoja Formation.

Layer	Felele	Nataco	Okumi	Jamata	Odah	Okofi	Banda	Akpaya-gbayi	Karara	Edeha
1	Top Soil	Top Soil	Top soil	Top soil	Top Soil	Top soil	Top soil	Top soil	Top soil	Topsoil
2	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay
3	Sandy Clay	Sandy Clay	Sandy Clay	Sandy Clay	Sandy Clay	Sandy Clay	Sandy Clay	Sandy Clay	Sandy Clay	Sandy Clay
4	Clayey Sand	Clayey Sand	Clayey Sand	Clayey Sand	Clayey Sand	Clayey Sand	Clayey Sand	Clayey Sand	Clayey Sand	Clayey Sand
5	Sand				Sand	Sand				

Table 5: Summary of the VES results for Patti Formation.

Layers	Koton-karfe LGEA			Kotonkarfe (Mkt.)			Ozi			Akpogu			Ozahi		
	h	p	d	h	p	d	h	p	d	h	p	d	h	p	d
1	1.47	9.5	1.47	2.55	893	2.55	2.34	113	2.34	5.29	1050	5.29	1.47	118	1.47
2	2.46	2.5	3.93	1.07	350	3.61	2.59	3.72	6.06	0.19	49.1	5.49	1.7	25.5	3.17
3	9.8	16.5	13.7	7.08	935	10.7	15.7	83.9	21.7	13.7	693	19.19	4.86	59.8	8.03
4	20.1	33.8	33.8	11.2	805	21.9	11.5	149	33.2	8.19	44.6	27.38	32.3	230	40.3
5	-	-	-	10.8	98.3	32.7	-	-	-	13	50.4	40.38	13	18.6	53.3

Table 6: Summary of the VES results for Patti Formation.

Layers	Gegu			Girinya			Adabo			Etegi			Abaji		
	h	p	d	h	p	d	h	p	d	h	p	d	h	p	d
1	1.57	1839	1.57	1.07	855	1.07	2.43	322	2.43	2.86	2303	2.86	1.68	548	1.68
2	1.02	480	2.59	5.98	176	7.04	6.92	472	9.34	0.45	350	3.32	1.88	753	3.55
3	14.2	3110	16.8	8.65	76.6	15.7	11	258	20.3	15.5	2154	18.9	4.63	1087	8.19
4	16.5	149	33.2	17.6	420	33.2	13	142	33.3	14.4	316	33.2	11.6	1677	19.8
5													13.4	513	33.2

Table 7: Summary of geo-electric Layer Inferred Interpretation for Patti Formation.

Layer	Koton-karfe LGEA	Koton-karfe (Mkt.)	Ozi	Akpogu	Ozahi	Girinya	Adabo	Etegi	Gegu	Abaji
1	Top soil	Top soil	Top soil	Top soil	Top soil	Top soil	Top soil	Top soil	Top soil	Top soil
2	Clay/Shale	Clay/Shale	Clay/Shale	Clay/Shale	Clay/Shale	Clay/Shale	Clay/Shale	Clay/Shale	Clay/Shale	Clay/Shale
3	Sandy Clay	Sandy Clay	Sandy Clay	Sandy Clay	Sandy Clay	Sandy Clay	Sandy Clay	Sandy Clay	Sandy Clay	Sandy Clay
4	Clayey Sand	Clayey Sand	Clayey Sand	Clayey Sand	Clayey Sand	Clayey Sand	Clayey Sand	Clayey Sand	Clayey Sand	Clayey Sand
5		Sand		Sand	Sand					Sand

Figure 6: Pumping Test Graph for Felele (Pumping rate (Q) is 2 l/s = 172.8 m³/day).

4.2 Depths to water table and aquifer thickness

The depths to water table for Lokoja Formation are within 5.91 – 40.8 m, while those of Patti Formation fall within 13.7 – 40.3 m (Table 8). The variation in depths to water table can be attributed to various factors, one of such is differences in elevation. The increase in depths to water table towards the Lokoja area may be due to higher concentration of groundwater exploitation because of higher population as being the capital of the Kogi state. The thicknesses of aquiferous units of Lokoja Formation range from 7.37 – 27.3 m, while those of Patti Formation range between 10.8 – 20.1 m (Table 7). The higher values of aquiferous units of Lokoja Formation over Patti Formation support the findings of [7, 31, 33] that there is the predominance of argillaceous rocks (siltstones, shales and claystones) in the Patti Formation.

4.3 Aquifer characteristics from VES

The pumping test result (Figures 6-10), calculated hydraulic conductivity and transmissivity results are presented in Tables 9 and 10, for Lokoja and Patti Formations. The hydraulic conductivity (K) values of aquiferous units of Lokoja Formation using Dar-Zarrouk parameter range from 1.92-91.7 m/day, whereas those of the Patti Formation varies between 2.15-31.8 m/day. Transmissivity values for Lokoja Formation from Dar-Zarrouk parameter range from 24.97-2117 m²/day, while those of Patti Formation range from 27.9-456.91 m²/day.

Figure 7: Pumping Test Graph for Odah (Pumping rate (Q) is 0.2 l/s = 17.28 m³/day).

Figure 8: Pumping Test Graph for Okofi (Pumping rate (Q) is 0.48 l/sec. = 41.47 m³/day).

Figure 9: Pumping Test Graph of Akpogu (Pumping rate (Q) is 0.38 l/s = 32.382 m³/day).

4.3.1 Hydraulic conductivity-K and Transmissivity-T from VES

Based on the hydraulic conductivity classification scheme of [26], the hydraulic conductivities obtained for the aquifers in both formations are in the range of Permeable to High (Figure 11a). These results are slightly different from that obtained by [26] for the same formations within

Table 8: Depths to water table and thickness of aquiferous units of Lokoja and Patti Formations from VES.

Lokoja Formation			Patti Formation		
Locality (VES Station)	Water Table (m)	Thickness of Aquifer (m)	Locality (VES Station)	Water Table (m)	Thickness of Aquifer (m)
Felele	39.4	7.37	Kotonkarfe LGEA	13.7	20.1
Nataco	15.4	18.1	Kotonkarfe Mkt.	21.9	10.8
Okumi	16.3	17.4	Ozi	21.7	11.5
Jamata	9.71	16.9	Akpogu	27.38	13
Odah	40.5	13	Ozahi	40.3	13
Okofi	40.8	12.5	Girinya	15.7	17.6
Banda	5.91	27.3	Adabo	20.3	13
Akpaya-gbayi	14.7	18.6	Gegu	16.8	16.5
Karara	14.7	18.6	Etegi	18.9	14.4
Edeha	10.2	23.1	Abaji	19.8	13.4

Table 9: Pumping Test Result of different locations within Lokoja and Patti Formations.

Lokoja Formation						Patti Formation			
Felele		Odah		Okofi		Akpogu		Ozahi	
Time ratio t/t' (mins)	Residual Drawdown s' (m)	Time (mins)	Drawdown, s (m)	Time (mins)	Drawdown, s (m)	Time ratio t/t' (mins)	Residual Drawdown s' (m)	Time (mins)	Drawdown, s (m)
1.5	0	4	7	5	6	2	0	4	1
2.5	0.05	10	12	10	10.9	2.3	0.08	10	1.5
6	0.1	20	15	20	13.9	2.86	0.08	20	4.8
12	0.2	40	17	40	16.9	3.6	0.12	40	7.8
30	0.2	60	19.2	60	18	5.3	0.15	60	8
40	0.2	75	20.5	75	19	7.5	0.25	75	19.8
50	0.2	90	21.2	90	21.4	14	0.12	90	20.4
60	0.4	120	21.5	120	21.8	17.25	0.19	120	20.4
80	0.4	125	22	125	23.8	33.5	0.53	150	21
110	0.8	150	22.2	150	25	66	0.77	180	21
140	1.25	180	22.8	180	25.4	2	0	210	21
160	1.9	210	22.8	210	25.4	2.3	0.08	250	21
180	2.8	225	22.8	250	25.4	2.86	0.08	260	21
		250	22.8	260	25.4			300	21
		300	22.8	300	25.4			360	
		320	22.8	320	25.4				
		350	22.8	350	25.4

Figure 10: Pumping Test Graph of Ozahi (Pumping rate (Q) is 0.9 l/sec = 78.6 m³/day).

the Southern Bida Basin because of differences in methodology adopted. While this study adopts the use of Dar-Zarrouk Parameter, their study adopted the use of empirical relationship of Shepherd from grain size distribution. Their results gave permeable to high range for Lokoja Formation and within permeable range for Patti Formation (Figure 11b). However, because of higher thickness values of the aquifers of Lokoja Formation, they have higher transmissivity than those of Patti Formation, since it is the product of hydraulic conductivity (K) and thickness (h), thus, making the aquifers of Lokoja Formation more prolific for groundwater exploration than those of Patti Formation (Table 11). Based on the transmissivity classification scheme of [38], the transmissivity values of the aquifers of Lokoja Formation are within Low to High, while

Table 10: Hydraulic conductivity and Transmissivity from Dar-Zarrouk parameter.

VES Location	$\rho(\Omega m)$	$h(m)$	$R=hp$ (Ωm^2)	$T_c = 13.39 +$ $0.06R$ (m^2/d)	$K_c = T_c/h$ (m/d)	* T_p	* K_p
Lokoja Formation							
*Felele	134	7.37	987.58	72.64	9.86	50.18	6.7
Karara	81.9	18.6	1523.34	104.79	5.6		
Okumi	112	17.4	1948.8	130.32	7.5		
Nataco	316	18.1	5719.6	356.57	19.7		
Banda	135	27.5	3712.5	236.14	8.6		
Edeha	1518	23.1	35065.8	2117.34	91.7		
Akpaya- Gbayi	50.5	18.6	939.3	69.75	3.8		
*Odah	14.9	13	193.7	24.97	1.92	0.27	0.023
Jamata	75.9	16.9	1282.71	90.35	5.3		
*Okofi	16.8	12.5	210	25.99	2.08	0.54	0.045
Patti Formation							
*Akpogu	50.4	13	655.2	52.70	4.1	15.0	1.51
Girinya	420	17.6	7392	456.91	26.0		
Abaji-Naharati	513	13.4	6874.2	425.84	31.8		
Ozi	149	11.5	1713.5	116.2	10.1		
Koton-karfe Market Sq.	98.3	10.8	1061.64	77.09	7.1		
Koton-karfe LGEA	149	16.5	2458.5	160.9	9.8		
*Ozahi	18.6	13	241.8	27.90	2.15	1.11	0.09
Adabo	142	13	1846	124.15	9.6		
Gegu	149	11.5	1713.5	116.2	10.1		
Etegi	316	14.4	4550.4	286.4	19.9		

* T_p and K_p , T_c and K_c are transmissivity and hydraulic conductivity values derived from pumping test and Dar-Zarrouk Parameter respectively.

those of Patti Formation fall within Low to Moderate potential (Table 12).

Figure 11: Evaluation of hydraulic conductivity of aquiferous units of: (a) Lokoja Formation and Patti Formation (current study). (b) Lokoja and Patti Formation [26].

Based on the classification and potentiality scheme proposed by [39], it can be deduced that areas of low, moderate and aquifer potential can be targets for groundwa-

ter exploration depending on the scale/magnitude of intended purpose (Tables 12, 13 and 14).

There is a strong correlation between the hydraulic conductivity calculated from Dar-Zarrouk parameter (r -squared = 0.99) and Pumping test and between the calculated Transmissivity derived from Dar-Zarrouk Parameter and Pumping test (R -square = 0.92) in Figures 12 and 13, respectively. [28] study of the complex porous aquifer system in Anthemountas Basin, Northern Greece derived a strong correlation ($r = 0.708$) between hydraulic conductivity values from Dar-Zarrouk parameter and pumping tests. Also, [29] in Khanewal District derived a strong correlation coefficient of 0.9 between modelled and measured hydraulic conductivities. [27] study in Northwest Bangladesh found an error or differences of 26% between calculated transmissivity and pumping tests for 15 sites. Due to higher hydraulic conductivities and transmissivity values of the Aquifers of Lokoja Formation over the Patti, they are more prolific for ground water exploration than those of Patti Formation, corroborating [26] study.

Table 11: Comparison of the findings of [26] study of the hydraulic characteristics of the Lokoja and Patti Formations with this present study.

Results from [26]	This study
The hydraulic conductivity of Lokoja Formation is within permeable to high range	The hydraulic conductivity of Lokoja Formation is within Permeable to High range
The hydraulic conductivity of Patti Formation is within permeable range	The hydraulic conductivity of Patti Formation is within Permeable to High range
Lokoja Formation is more prolific for groundwater exploration than Patti Formation	Lokoja Formation is more prolific for groundwater exploration than Patti Formation because of higher aquifer thickness
Deeper Lokoja Formation should be concentrated upon for Groundwater exploration	Lokoja and Patti Formations may be concentrated upon for Groundwater exploration depending on the scale of intended purpose.

Table 12: Aquifer Transmissivity Potential for Lokoja and Patti Formations [After, [38]].

VES Location	Lokoja Formation			Patti Formation	
	Transmissivity values (m ² /day)	Potential	Locality	Transmissivity values (m ² /day)	Potential
Felele	72.64	Moderate	Akpogu	52.70	Moderate
Karara	104.79	Moderate	Girinya	456.91	Moderate
Okumi	130.32	Moderate	Abaji-Naharati	425.84	Moderate
Nataco	356.57	Moderate	Ozi	116.2	Moderate
Banda	236.14	Moderate	Kotonkarfe	77.09	Moderate
Edeha	2117.34	High	Market Sqr. Kotonkarfe	160.9	Moderate
Odah	24.97	Low	LGEA	27.9	Low
Jamata	90.35	Moderate	Ozahi	124.15	Moderate
Okofi	25.99	Low	Adabo	116.2	Moderate
Akpaya-Gbayi	69.75	Moderate	Gegu	286.4	Moderate
			Etegi		

4.4 Coefficient of Permeability (Hydraulic conductivity) from Laboratory test

The results of coefficient of permeability tests using Falling head and Constant head permeameters for 21 extracted aquiferous units from surface outcrops belonging to Lokoja and Patti Formations are presented in Table 16, and are interpreted using [26] hydraulic conductivity classification. The hydraulic conductivity values for aquiferous units of Lokoja Formation are in the range of 10^{-2} - 10^2 m/day, while those of Patti Formation range from 10^{-2} - 10^0 m/day. Aquifers of Lokoja Formation thus have K values ranging from low to high range, whereas those of Patti Formation are within low to permeable range. It should be noted however that these results are for extracted aquif-

erous units of surface outcrops and not from subsurface. Whereas the VES results was used to estimate the result of coefficient of permeability (hydraulic conductivity) of subsurface shallow aquifers, the Constant head and Falling head permeability tests were carried out to estimate the coefficient of permeability of extracted aquiferous units from surface outcrops. Hence it is expected that there may be differences in the range of results of coefficient of permeability.

Table 13: Aquifer Transmissivity Range and Potentiality [39].

Coefficient of Transmissivity (m^2/day)	Groundwater Supply Potential
>1000	Withdrawals of great regional importance
100-1000	Withdrawals of lesser regional importance
10-100	Withdrawals for local water supply (small communities etc.)
1-10	Smaller withdrawals for local water supply (private consumption)
0.1-1	Withdrawals for local water supply with limited consumption
<0.1	Sources for local water supply are difficult

Table 14: Potentiality of Aquiferous Units of Lokoja Formation.

Coefficient of Transmissivity (m^2/day)	Aquifers of Lokoja Formation	Potentiality
10-100	Moderate potential	Can supply water to small communities
100-1000	High potential	Can supply water for great regional use

Table 15: Potentiality of Aquiferous Units of Patti Formation.

Coefficient of Transmissivity (m^2/day)	Aquifers of Patti Formation	Potentiality
10-100	Moderate potential	Can supply water to small communities
1-10	Low	Can supply water for private consumption and partly to small communities

Table 16: Interpretation of coefficient of permeability data for extracted samples of aquiferous units from surface outcrops of Lokoja and Patti Formations [26].

Lokoja Formation			Patti Formation		
Location	K(m/d)	Interpretation	Location	K(m/d)	Interpretation
Ohono 1	1.50×10^{-1}	Permeable	Agbaja Hill 4	2.90×10^{-1}	Permeable
Ohono 2	2.20×10^{-1}	Permeable	Agbaja Hill 5	1.80×10^0	Permeable
Ohono 3	7.00×10^{-2}	Low	Agbaja hill 6	1.60×10^{-1}	Permeable
Agbaja Hill	0.95×10^{-2}	Low	Mount Patti 2	6.20×10^{-2}	Low
Jamata	7.60×10^{-2}	Low	Mount Patti 3	8.20×10^{-2}	Low
Before Niger bridge	5.47×10^{-2}	Low	Ozi	4.00×10^{-2}	Low
- Spring	5.47×10^{-2}	Low			
Agbaja Hill 2	1.25×10^{-1}	Permeable	Gegu Beki	2.20×10^{-1}	Permeable
Agbaja Hill 3	2.33×10^2	High	Girinya	3.00×10^{-2}	Low
Felele 1	2.09×10^2	High	Gegu Ega	2.50×10^{-2}	Low
Felele 2	1.20×10^2	High			
Okumi	8.98×10^1	High			
Mount Patti 1	2.67×10^2	High			

5 Conclusion

Based on the results presented in this paper, the following can be inferred:

1. The geoelectric layers for both aquifers are between four (4) and five (5) within AB/2 of 80 m.
2. The depths to water table in the study area range from 5.91-40.8 m
3. Aquiferous units of Lokoja Formation vary between 7.37-27.3 m in thickness, whereas those of Patti Formation are within 10.8-20.1 m.

Figure 12: Correlation between hydraulic conductivity from pumping test (Kp) and hydraulic conductivity from Dar-Zarrouk Parameter (Kc).

Figure 13: Correlation between transmissivity from pumping test (Tp) and transmissivity from Dar-Zarrouk Parameter (Tc).

4. Hydraulic conductivity (K) values obtained for Lokoja and Patti Formations using Dar-Zarrouk parameter fall within 1.92-91.7 m/day and 2.15-31.8 m/day respectively, while transmissivity (T) values are within 24.97-2117 m²/day and 27.9-456.9 m²/day respectively.
5. Coefficient of Permeability for extracted aquiferous unit from surface outcrops belonging to Lokoja Formation is in the range of 10⁻²-10⁻² m/day, whereas those of Patti are within 10⁻²-10⁰ m/day.
6. The aquiferous units in both formations are capable of yielding optimum groundwater for private consumption and partly to small communities, and to some extent can supply water for great regional use.

Based on the above results, it is recommended that areas of moderate and high aquifer potential should be the target for groundwater exploration depending on the scale/magnitude of designated purpose. It is also suggested that further field hydrogeological surveys should be to better infer the hydraulic features of these aquifers. Finally, similar study should be carried out in other sedimentary basins to aid regional planning and management of groundwater resource.

Acknowledgement: This paper is part of the M.Sc Thesis of Mr Obasaju Daniel Opemipo. The authors thank Mr Rahman and Mr Ayuba for field assistance, Mr Femi for laboratory assistance and Mr Job for accommodation. We thank the editors and anonymous reviewers for their invaluable

comments that helped to greatly improve the quality of the paper.

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