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Research Paper

Transmissivity Distribution in the Sandstone Aquifer around Lafia, Nigeria using the Dar Zarrouk Transmissivity Technique

Aisha Abubakar Kana[1]* and Ahmad Abubakar Kana[2]

Corresponding Author:* ***Aisha Abubakar Kana* *abubakara@nsuk.edu.ng*

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Transmissivity of aquifers is a very useful parameter in assessment and management of groundwater resources. The most reliable means of obtaining transmissivity is through pumping tests, a tedious and expensive exercise which requires that many tests be done to obtain spatial distribution. Geophysical methods provide a means of rapidly obtaining data over large areas and if carefully processed and interpreted, can provide useful information on the areas being investigated. Electrical methods measure electrical resistivity distribution in the subsurface, a parameter that has been linked to and used to characterise hydraulic properties of aquifers. Direct and inverse relationships between Dar Zarrouk parameters obtained from resistivity sounding have been explored with the sole aim of characterizing aquifer properties. This paper presents one of such applications in determining the spatial distribution of transmissivity of a sandstone aquifer in Nigeria. The study area, Lafia is underlain by the Lafia Sandstone; the aquiferous zone is the sandstone unit of the formation consisting entirely of clean sandstone. The method here involved exploring the inverse relationship between the Dar Zarrouk parameter: longitudinal conductance and aquifer transmissivity obtained from pumping tests for a few points to obtain a constant. This constant was then used to translate resistivity measurements from 19 VES points to transmissivity and in so doing, obtaining the distribution of transmissivity over the study area.

Keywords: Aquifer, Sandstone, Transmissivity, Electrical Resistivity, Dar Zarrouk

Introduction

Effective exploitation and management of groundwater resources requires adequate knowledge of the quantity and quality of available resources; these in turn are determined by the yield capacity of aquifers. This in turn depends on transmissivity of the aquifer. Traditionally, aquifer transmissivity is determined through

[1] Department of Geology and Mining, Nasarawa State University, Keffi, PMB 1022, Nigeria.
[2] Nasarawa State Water Board Headquarters, Lafia, PMB 15, Nigeria.

pumping tests in boreholes, a process which is expensive, tedious and provides aquifer information in a limited area, close to the point of the tests. Furthermore, the need to have spatial coverage of determined aquifer properties requires interpolation of properties between boreholes. This is a difficult task as the effectiveness of the interpolation requires a reasonable dense network of boreholes from which the yield can be extrapolated. Geophysical methods provide a non destructive *in-situ* means of obtaining information on aquifer properties in areas where pumping test data are scarce. Electrical resistivity survey techniques form excellent tools for groundwater exploration due to the sensitivity of electrical resistivity to the presence of water in the subsurface. Vertical electrical sounding technique yields subsurface layering on the basis of differences in electrical resistivity values and thus assists in subdivisions of the subsurface into geoelectric layers, with each layer characterized by its bulk resistivity and thickness. The area chosen for this survey is characterized by sparse pumping test data.

Surface resistivity surveys have been successfully applied to solve a variety of problems relating to groundwater ranging from the search for (Carruthers and Smith, 1992; Amadi and Olasehinde, 2010; Mohammaden and Ehab, 2017) and quality assessment (McCann, 1994; Hussain *et al*., 2017). Direct and inverse relationships between aquifer permeability and electrical resistivity have been developed (Frohlich and Kelly, 1985; Mazac *et al*., 1990). Inverse relationship exists between the porosity and resistivity where the aquifer is sandy and generally clay free; conversely, where clay content is significant, direct relationships exist (Archie, 1942).

Aquifer transmissivity describes the ease with which water moves from one point to another within an aquifer and is a product of aquifer hydraulic conductivity and thickness. Dar Zarrouk parameters (Maillet 1947) i.e.: transverse resistance R_t (Ωm^2) (eqn 1) and longitudinal conductance L_c (eqn 2) describe the relationship between electrical resistivity and hydraulic conductivity of an aquifer.

$$R_t = hp \qquad ...(1)$$

$$L_c\left(\frac{h}{\rho}\right) \qquad ...(2)$$

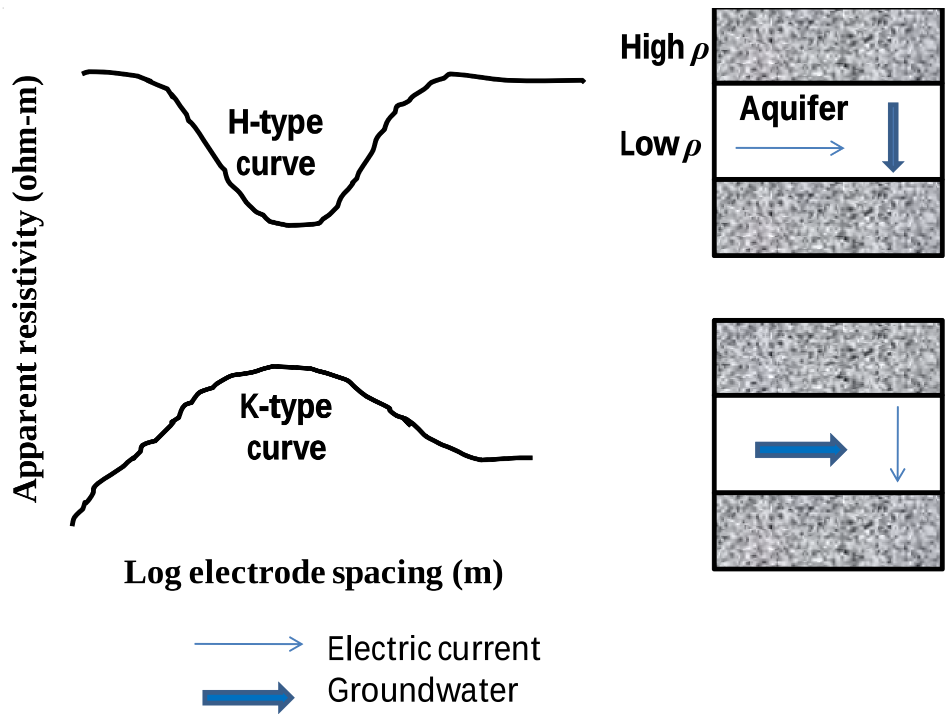
Thickness of the aquifer is expressed as h in meters and ρ is electrical resistivity in ohm-meters. For a layer where electric current flows perpendicular to the general bedding, the parameter R_t dominates; conversely, where current flow is parallel to bedding, L_c dominates (Figure 1), (Frohlich and Kelly, 1985). In the first case, a K-shaped curve will be produced from resistivity sounding data while a in the latter, an H-type curve will be produced (MacDonald *et al*., 1990). When the thickness and resistivity of an aquifer are known, the Dar Zarrouk parameters can be calculated easily. Dar Zarrouk parameters have since been used in the estimation of the hydraulic characteristics of aquifers (Onuoha and Ezeh, 1988; Ekwe *et al.,* 2006; Bawallah *et al*., (2018).

Using the expression for transmissivity: $T = Kh$, the following equations can be derived for transmissivity using the Dar Zarrouk parameters (Niwas and Singhal, 1981).

$$T = R_t\left(\frac{K}{\rho}\right) \qquad ...(3)$$

$$T = R_t C_1 \qquad ...(4)$$

Figure 1: H And K Type Curves
With Corresponding Electrical Resistivity Distribution With Depth



$$T = L_c(K_\rho) \quad ...(5)$$

$$T = L_c C_2 \quad ...(6)$$

It then follows that depending on the lithology of the aquifer under investigation, transmissivity can be directly related to transverse resistance (when clay content controls hydraulic conductivity) and longitudinal conductance (when effective porosity is the dominant control on hydraulic conductivity).

In the present study, aquifer transmissivity of a sandstone aquifer in Nigeria is determined from resistivity sounding data. The approach here is that described in MacDonald *et al.,* (1990) which requires that the following assumptions be made about the aquifer under investigation. That permeability is exclusively controlled by either clay content or effective porosity of the aquifer. Secondly, electrical conductivity of the groundwater must remain fairly constant throughout the aquifer. Lastly, for a K-shaped curve, the aquifer resistivity must be isotropic since current flow is vertical and groundwater flow is horizontal.

Location and Geological Setting of the Study Area

The study area forms part of Lafia the capital of Nasarawa State, Central Nigeria**.** It is centred on the Coordinates: N08°33'13" and 008°31'58". The state itself was created in 1996 and due to its proximity to the state capital the study area has had its fair share of rapid population growth and development over the years. Geologically, it forms part of the Lafia Sub basin of the Middle Benue Trough (Offodile, 2014) and consists of a succession of sedimentary strata laid down mainly in the Cretaceous. The oldest sediments belong to the Asu River Group and consist of shales and siltstones of marine origin. These sediments represent the Middle Albian transgression into the Benue Valley. This was followed by a regressive phase that led to the deposition of the transitional beds of the Awe Formation which are essentially flaggy, whitish, and medium to coarse-grained sandstones interbedded with carbonaceous shales or clays. Awe Formation is overlain by continental fluviatile sands belonging to Keana Formation in Late Cenomanian-Early Turonian. The regressive Awe and Keana Formation are overlain by the marine Facies of the Ezeaku Group in the mid-Santonian period. Ezeaku Formation consists essentially of calcareous shales, micaceous fine to medium – grained friable sandstones, and occasional beds of limestones. The Coniacian Awgu Formation consists mainly of black shales, sandstones and local seams of coal, and overlies the Ezeaku Formation. Lafia Formation is the youngest formation reported in the Middle Benue Trough (Maastrichtian) and consists of coarse-grained ferruginous sandstones, red loose sand, flaggy mudstones and clays (Offodile, 2014).

The main rock type in the study area is the Lafia sandstone which forms the major aquifer. It has been exploited for domestic water supply; however there still remains insufficient data on the transmissivity of the aquifer. In the study area, the aquifer has a thickness of about 70 to 100m (Offodile, 1976). A lot of boreholes have been sunk into the aquifer, however pumping test data remain a challenge. Electrical resistivity sounding is the main geophysical technique used to explore for groundwater and to choose most promising point to sink a borehole. By implication, resistivity sounding data remains abundant while pumping test data is scarce. The area is well drained with two main streams flowing from the eastern part of the area, towards the north and south western parts. The streams are perennial and are fed by groundwater especially in the dry season.

Research Methodology

The aim of the present study is to determine transmissivity distribution in the sandstone unit of Lafia Formation around Lafia town. To achieve this, electrical resistivity sounding surveys were carried out to obtain aquifer resistivity and thickness of the aquiferous units in the area. Transmissivity was then determined from the sounding data using the methodology described in MacDonald *et al*., (1990). Determination of aquifer transmissivity using this approach requires the use of the constants: C_1 and C_2 (eqn 4 and 6). To determine the constants, a linear regression between transmissivity (determined from e.g. pumping tests for a few points within the study area) and either transverse resistance or longitudinal conductance as the case may be needs to be taken. In the present study, Dar Zarrouk parameters were calculated using equations 1 and 2 for all sounding points, using predetermined aquifer resistivity and thickness at all points. Transmissivity data derived previously from pumping test close to five VES points in the study area were used for the regression analyses.

For the present study, 19 vertical electrical soundings were undertaken using the full Schlumberger electrode configuration. Maximum spread (AB) was 200m which allowed a penetration of 100m below ground surface. VES data collection points are shown in Figure 3. This was followed by groundwater sampling to measure water level distribution in already drilled water wells in the study area. *In-situ* tests of groundwater temperature, electrical conductivity and pH were also done to assess the distribution in particular, of electrical conductivity in the aquifer.

Results and Discussion

Electrical resistivity sounding data were plotted on a semi log graph sheet, after which the curve shapes were interpreted to separate H – type and K- type curves. In each case, aquifer resistivity and thickness was determined then the Dar Zarrouk parameters estimated from aquifer resistivity and thickness. All 19 VES points showed H-type curves (Figure 3) meaning the longitudinal conductance is the dominant Dar Zarrouk parameter. Lithologically, the aquifer unit consists of clean sandstone with negligible amount of clay particles, indicating that permeability in the aquifer is controlled by effective porosity. This is reflected in the shape of the VES curve produced and satisfies one of the assumptions of the Dar Zarrouk Transmissivity method. The second assumption is that groundwater conductivity must be fairly constant. *In – situ* measurements of electrical conductivity of water samples from water wells, boreholes and stream channels showed that the conductivity was fairly constant within the study area (180 to 269 μS/cm).

Longitudinal conductance was calculated for the VES points close to the points where transmissivity data from pumping tests were available (Table 1). The regression analysis on the longitudinal conductance and transmissivity, setting the intercept to zero, returned a value of C_2 = 714.6 Ùm (Figure 4). The transmissivity

Figure 2: The Study Area, Inset is a Map of Nigeria Showing the Location of Nasarawa State

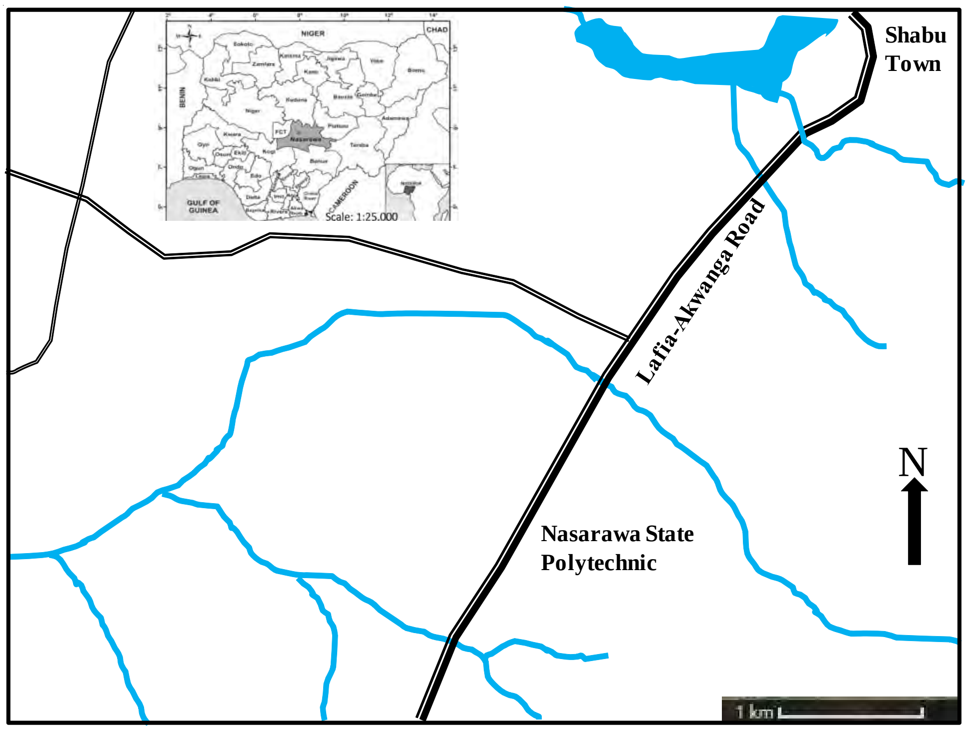


Table 1: Aquifer Transmissivity at Five Points Close to VES Points In The Present Study, Used in the Regression Analysis to Obtain The Coefficient C_2

Borehole	VES	Measured T (m^2/day)	Longitudinal Conductance (Ωm)	Regression Derived T (m^2/day)
1	09	79	0.20	144.62
2	13	176	0.29	210.64
3	14	87	0.20	143.46
4	16	155	0.23	162.41
5	19	355	0.35	251.03

Figure 3: Layout of VES Data Collection Point within the Study Area

values calculated for the same points using the constant, gave values within the order of magnitude as the measured values but slightly higher.

Transmissivity for the remaining 14 VES points was then calculated using the constant. Figure 6 shows the distribution of transmissivity in the study area. The values range between: 67.5 and 302.99m²/day with an average value of 155.55m²/day. The spatial distribution is such that there are isolated pockets of relatively higher transmissivity, labelled A and B in Figure 6. These isolated pockets are areas where the aquifer is relatively thick. Variations in transmissivity values are likely

Figure 4: Resistivity Sounding Curves For Some Ves Points Within the Study Area Showing a Dominant H-type Shape.

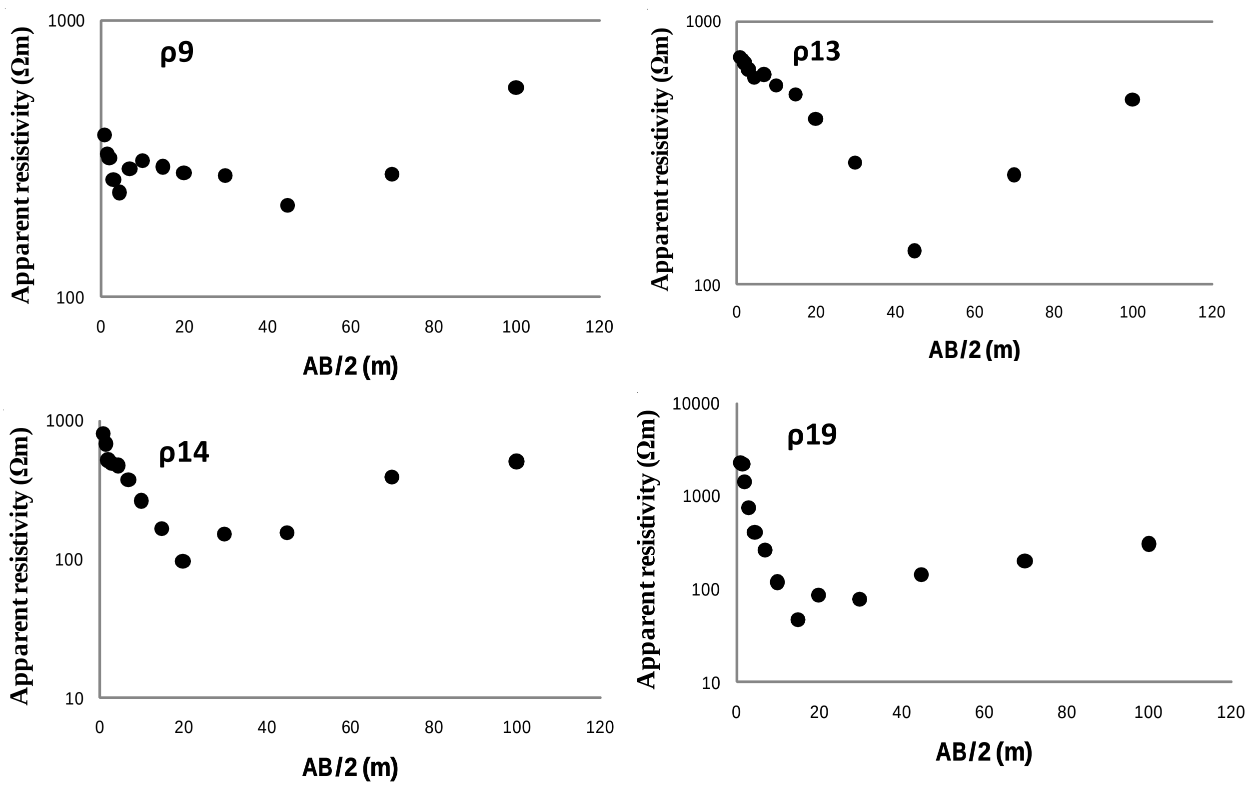


Figure 5: C2 Determination From Data at Five Sites Within the Study Area

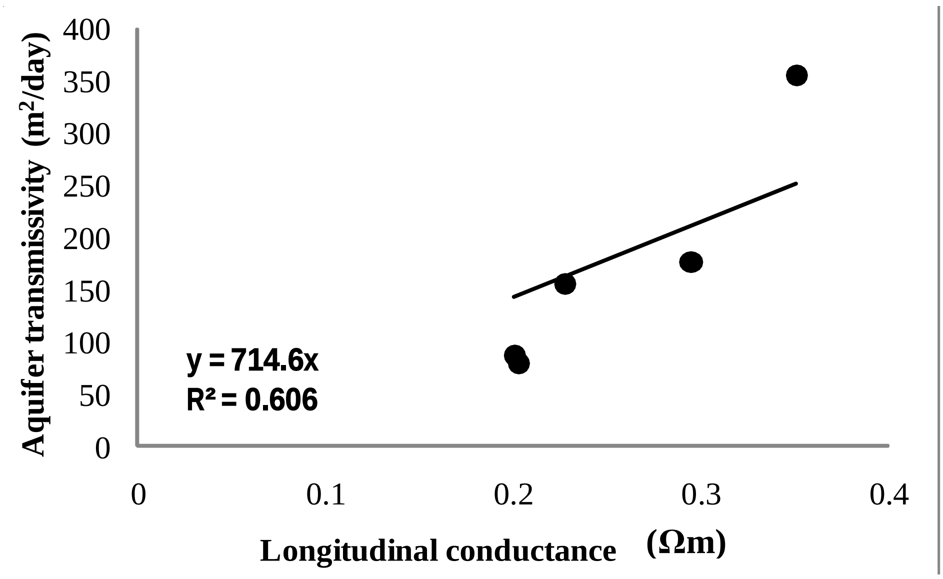
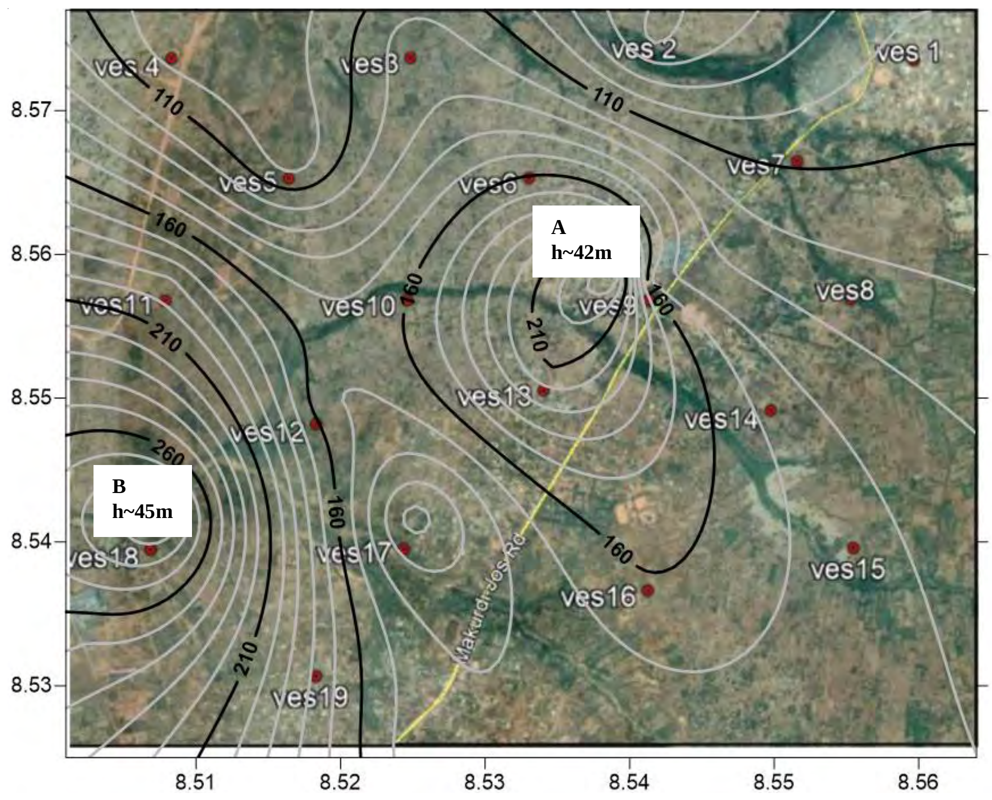


Figure 6: Spatial Distribution of Calculated Transmissivity in the Study Area



a reflection of variation in thicknesses of aquifer units within the study area, since the thicknesses were used to calculate the Dar Zarrouk parameter.

Conclusion

The preceding analysis provided a quick means of obtaining spatial distribution of aquifer transmissivity for a relatively uniform aquifer unit with little variation in groundwater conductivity. The determined values however require validation to ascertain their reliability and that of the methodology employed here through e.g. pumping tests in boreholes within the study area. As an initial approximation, the method is useful in determining the overall potential of aquifers and where best to exploit such aquifers. It is ideal for the assessment and predictive modelling of groundwater occurrence and movement, where aquifers have simple and uniform geometry, and where the geologic and hydrogeologic conditions are considerably well understood.

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