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Quantitative and Qualitative Appraisals of Aquifer Properties in Kachia Area of Kaduna State, Nigeria

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Authors' contributions

This work was jointly carried out by all the authors. Author IOO designed the study, coordinated primary data acquisition, wrote the protocol and the first draft of the manuscript and managed the literature searches. Author AOA prepared the piezometric surface map, the basement relief map and constructed the two lithologic profile sections. Authors AIA and OEA jointly participated in acquisition and organization of data and computation of the aquifer constants. All the authors read and approved the manuscript.

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ABSTRACT

Kachia Local Government Area (LGA) is located at the southern part of Kaduna State, Nigeria. Quantitative and qualitative appraisals were carried out in order to have proper understanding of the aquifer system and ensure sustainable development by using geophysical, geological and pumping test data obtained from 32 producing boreholes across the entire LGA. Hydraulic conductivity, transmissivity and storativity values were computed, piezometric surface map and the basement relief map were prepared, geoelectric layer characteristics were delineated and two geological profile sections were constructed. The hydraulic conductivity values were found to range from 0.021 m/day at Walijo to 1.391 m/day at Iddah-Hanya with an average of 0.42 m/day. The transmissivity values ranged between 0.90 m^2/day at Walijo to 25.37m^2/day at Iddah-Hanya, with average value of 6.31 m^2/day. Storativity values were lowest at Walijo with a value of 89.42 and highest at Iddah-Hanya having a value of 2877 with an average of 929.82. The lowest values of these three aquifer

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constants were observed to converge at Walijo at the extreme eastern part and they all peaked at Iddah Hanya on the western border of the study area. The piezometric surface contour map showed that static water level is generally deeper around the central part of the study area than at the southern and western parts. The basement relief map revealed that the depth to Basement rock is generally deeper at the central part than at the eastern, western and southern boundaries of the study area. Three-layer geoelectric horizons delineated agreed with the drilled sections. The two profile sections 1 and 2 suggested that the weathered layer constituted the major aquiferous unit, and it occurred within a depth of 1 m to as much as 35 m, except Kurmin-Sara with 80 m thickness. Groundwater prospecting can therefore be targeted to an approximately uniform regolith thickness across the entire study area.

Keywords: Aquifer properties; hydraulic conductivity; transmissivity; storativity; piezometric surface; Kachia.

1. INTRODUCTION

Groundwater is simply understood to mean water found within the saturated voids beneath the ground. Hydrogeologically, it is the water found in permeable geologic formations known as aquifers. Groundwater is nature's hidden treasure, and has become an important source of water supply throughout the world. It occurs more widely than surface water, cheaper to obtain [1] and has relatively excellent chemical and biological characteristics which makes it readily potable or requiring minimal or no treatment at all for most uses. Its use in industries, municipal water supply, rural homes, irrigation and other sectors continues to increase year in year out [1,2].

The increase in the standard of living of the inhabitants in the study area has led to increase in water demands. In response to these demands, the development of groundwater has soared over the past decades creating the concern for adequate water supplies in the area. A large part of the population still does not have access to water of good quality and adequate quantity. One of the factors responsible for this state of affairs is traceable to borehole failures resulting from poor geological and geophysical investigations prior to well construction. It is, therefore, pertinent to have a proper under-standing of the aquifer system of the area to ensure sustainable development. The determination of aquifer properties in the northern Nigeria dated back to 1946 when the first flowing artesian borehole in Chad Basin was drilled by the Geological Survey of Nigeria. Other early studies in this regard include [3,4,5].

This study presents an evaluation of the aquifer properties, namely Hydraulic conductivity, *K*, Transmissivity, *T* and Storativity, *S*, across Kachia Local Government Area (LGA) using geophysical, geological and pumping test data. The study also produced and appraised the piezometric surface map of the aquifer, the basement relief map, identified the geoelectric properties of layers, and profile sections across the study area were prepared and appraised.

1.1 The Study Area

1.1.1 Climate and physiography

Kachia Local Government Area (LGA), with its headquarter at Kachia, a semi-urban town, is located in the southern part of Kaduna State, Nigeria. The LGA covers a fairly large area and it lies approximately between latitudes 9°31.25'N and 10°10.00'N and longitudes 7°11.25'E and 8°06.25'E (Fig. 1). The climate consists of the characteristic wet and dry seasons commonly prevalent in Nigeria. The wet season occurs between April and October while the dry season occupies the remaining months of November to March, with December and January often being generally cold due to the influence of harmattan winds. The annual rainfall regime averages about 1400 mm, while the minimum and maximum temperatures average 12.8°C and 35°C respectively. The landforms in the area vary from ranges of hills and in selbergs to undulating plains, which run between 609m to 690m above sea level [6].

1.1.2 Geology and hydrogeology

The study area is situated on the reactivated Precambrian gneiss terrain. The four major rock units that characterized the area are the migmatite, granite-gneiss, undifferentiated schist and porphyritic biotite granite [7]. The dominant fracture trends include the NNE-SSW, N-S, NNW-SSE and marginally E-W. The fracture and

Fig. 1. Map of Kaduna state showing the local government areas

shear zones are interesting zones for groundwater prospecting [8]. Groundwater occurrence in the southern Kaduna area could be grouped into three, namely (a) The Weathered/Fractured Basement Complex (b) The Newer Basalts (c) The River Alluvium. The weathered granular sandy zone is composed of coarse-grained sands, which form a level below the loose clayey laterite. The granular sands may consist of sands or gravels derived from the disintegration of the crystalline rock. Good prospects for groundwater production exist in the horizon of the intermediate zones with an average thickness of about 6 m [9]. The majority of hand-dug wells in the study area terminate in this part of the zone. The Newer Basalts occur in the vicinity of Kafanchan and Manchok along the western edge of the Jos Plateau. The Basalts were erupted after the Plateau had achieved almost its present-day topography and are themselves little affected by erosion. Thus, they often overlie alluvial deposits. Zones of weathering and beds of alluvium also occur between individual basalt flows. The aquifer potential of the fluvio-volcanic sequence is good and yields of 370 to 500 m^3/day have been obtained [10].

2. MATERIALS AND METHODS

This study involved an appraisal of major aquifer properties with the aim of having a proper understanding of the aquifer system of the area and to ensure sustainable development. This is to be accomplished by determining quantitatively the hydraulic conductivity, *K*, transmissivity, *T,* and Storativity, *S*, of the aquifers in the Kachia Local Government Area (LGA) of Kaduna State using geophysical, geological and pumping test data obtained from the exploration and exploitation of 32 producing boreholes across the entire area. Qualitatively, the study produced the piezometric surface map and the basement relief map of the area, delineated the geoelectric layer characteristics from geophysical investigation data, and constructed two geological profile sections for further appraisal using Surfer 12.

3. RESULTS AND DISCUSSION

3.1 Quantitative Appraisal

The major functions of an aquifer is transmission and storage of water, and these important functions can be described quantitatively by the three major aquifer properties, also called aquifer constants, namely hydraulic conductivity K, transmissivity T, and Storativity S. These constants or coefficients are frequently used to evaluate the rate at which water moves into, through and out of subsurface materials, and how piezometric surfaces are affected. Hydraulic conductivity of an aquifer has been defined as the rate of flow of water in litres per day through a unit cross-sectional area of an aquifer under a temperature of 20°C [11,12]. Hydraulic conductivity measurements can be used, among other things, to quantify the volume of surface and ground water available, analyze or predict surface-subsurface water relations, design drainage system, estimate seepage from reservoirs or open channels and predict groundwater contamination from waste disposal sites.

Babuskin [13] evolved an approximate relationship for the determination of the hydraulic conductivity, *K*, which is written as:

$$K = \frac{0.366Q}{LS}\log\frac{1.32L}{r_w} \quad (1)$$

Where,

K is measured in $m.day^{-1}$, *Q* is borehole discharge in $m^3.day^{-1}$, *L* is the length of screen in metres, *S* is the drawdown in metres and r_w is the radius of the borehole in metres. Equation (1) was used to compute the hydraulic conductivity property of the Kachia aquifers. From the results obtained from the 32 boreholes located within the study area, the hydraulic conductivities of the aquiferous units range from 0.021 m/day at Walijo to 1.391 m/day at Iddah-Hanya with an average of 0.42 m/day.

Transmissivity is an aquifer property that is of significant importance whenever the flow through the entire thickness of the aquifer is being considered. It is defined as the rate of flow per unit width through the entire thickness of an aquifer per unit hydraulic gradient. The transmissivity is sometimes used as a convenient quantity in the calculation of groundwater flow instead of the hydraulic conductivity. In Basement rocks, aquifer performance can be related to transmissivity according to the scale provided by [14] in Table 1.

The relationship between transmissivity, *T*, and hydraulic conductivity, *K*, is given by the equation:

$$T = Kt \quad (2)$$

Where,

t is the saturated thickness of the aquifer [15], [11]. From equation (2), the transmissivity property of Kachia aquifers were calculated for the 32 wells and the values were found to range between 0.90 m^2/day at Walijo and 25.37 m^2/day at Iddah-Hanya, with an average value of 6.31 m^2/day From Table 1, it can be deduced that the aquifers in Kachia area generally belong to the class of Very-Low-Potential to Low-Potential aquifers.

The storativity of an aquifer*, S*, can be defined as the volume of water released from or taken into storage, ΔU_w, per unit surface area of the aquifer, *A*, and per unit decline (or rise) of piezometric head, $\Delta\emptyset$*,* normal to that surface. Mathematically, storativity can be expressed as:

$$S = \frac{\Delta U_W}{A\Delta\phi} \quad (3)$$

S is an aquifer property, and is dimensionless. In an unconfined aquifer, changes in storage represent the product of the volume of the aquifer between the water table before and after a given period of time, and the specific yield. This storativity invariably corresponds to the specific yield as more or less all the water is released from storage by gravity drainage, except only very small part resulting from compression of the aquifer and expansion of water. In the confined aquifer, on the other hand, water is not yielded simply by gravity drainage from the pore spaces because there is no falling water table, and the material remains saturated. Yield, therefore, is affected by other factors such as consolidation of the aquifer, and expansion of water consequent upon lowering of piezometric surface. The values of the storage coefficient in most confined aquifers fall within the range 10^{-5} to 10^{-3}, indicating that significant changes of pressure are required over extensive areas to produce substantial water yields. This explains why unconfined aquifers yield much more water than confined aquifers [16,17,11]. Storativity in a confined aquifer is the outcome of water and matrix compressibility, while in a phreatic aquifer water is mostly drained from the volume of pore space between the two positions of the phreatic surface. The storativity of a phreatic aquifer is, therefore, sometimes referred to as specific yield, S_y, which gives the yield of an aquifer per unit drop of the water table.

From equation (3) above, the dimensionless values of storativity for the Kachia aquifers were computed for the 32 well locations and were found to range between 89.42 at Walijo and 2877 at Iddah-Hanya with a mean value of 929.82. It can be inferred that the lowest values of these three aquifer constants for Kachia area converged at Walijo at the extreme eastern part, while they all peaked at Iddah Hanya on the western border of the study area.

Fig. 2 shows the graphical representation of the relationship between the hydraulic conductivity *K*, transmissivity *T*, and storativity *S,* of the aquifers in the study area. The three aquifer properties show a near-parallel lateral relationship as the values vary from one location to the other. This implies that there is a direct linear relationship between these aquifer properties.

Other aquifer properties obtained for the study area include the discharge from the wells, which ranges from 21.6 to 246.24 m³/day with an average value of 72.72 m³/day, and drawdown, which occurs from 6.5m to 36m with 11.55m as mean value.

3.2 Qualitative Appraisal

3.2.1 Piezometric surface contour map

The depths to the water table at the well locations were used to prepare the piezometric surface contour map of the study area. The contour map (Fig. 3) was plotted using Surfer 12 software. The depth to groundwater is shallowest at Kushe where static water level stands at a depth of 2.8m, and deepest at Maraban Mazuga in which static water level stands at a depth of 11.8m. The average depth to water table across the LGA is found to be 8.75m. From this figure, it can be further deduced that static water level is generally deeper across the central part of the study area in the NE – SW direction than at the southern and western parts.

Table 1. Aquifer performance in relation to transmissivity

Transmissivity, T (m²/day)	Aquifer performance classification
Greater than 500	High Potential
50 – 500	Moderate Potential
5 – 50	Low Potential
0.5 – 5	Very Low Potential
Less than 0.5	Negligible Potential

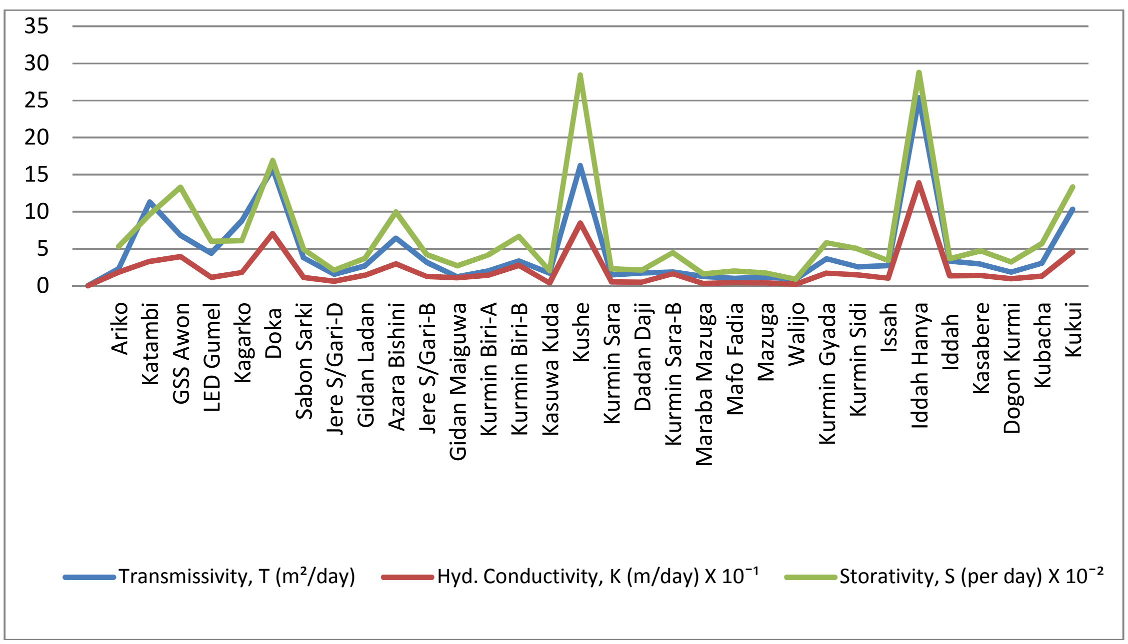

Fig. 2. Comparative plot of well locations Vs hydraulic flow parameters

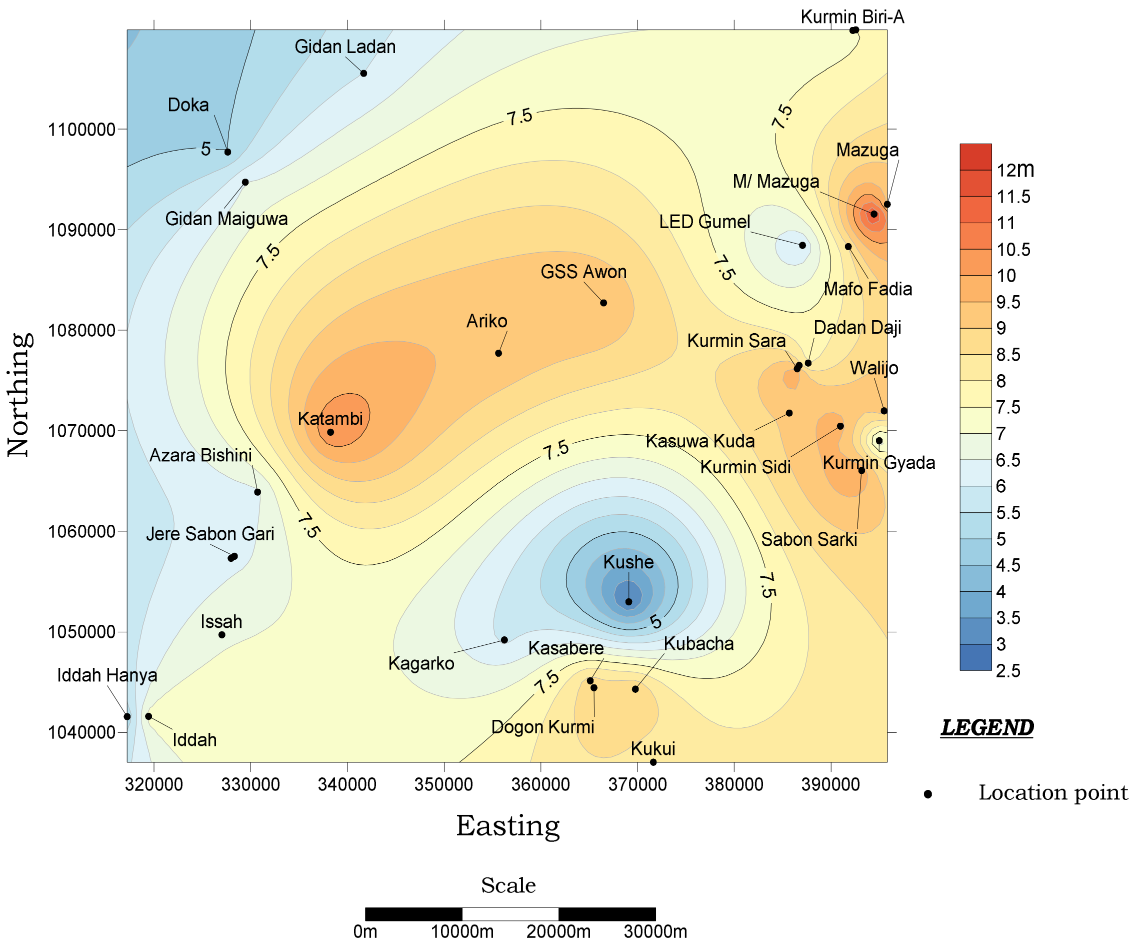

Fig. 3. Piezometric Surface Contour Map of Kachia LGA

3.2.2 Basement relief map

The basement relief map of the study area is presented as Fig. 4. From the data obtained from the 32 borehole locations, the depth to basement rocks vary from the shallowest points of 6 m depth at Kushe, 12 m each at LED Gumel and Kukui to average depths of 19 m at Mazuga and 25 m each at Doka and Walijo, then to greater depths of about 31 m at Dogon-Kurmi/ Kasabere and 36 m at Kurmin-Sara. In other words, the depth to Basement rock is generally deeper at the central part of the study area than at the eastern, western and southern boundaries of the study area. The basement rock has a thick weathered upper layer overlying the fractured and fresh basement.

3.2.3 Geologic layer resistivities

The field resistivity data obtained from the study area revealed essentially three layer horizons which agreed with the geologic sections observed after drilling. The uppermost layers generally consist of dark-to-light orange brown laterite grading gradually to light grey clayey-to-gravelly silt with a resistivity range of 170 Ωm to more than 3000 Ωm and thicknesses from 0.3 – 4 m. This layer is underlain by a second layer comprising of light grey-brown sandy silt to grey-brown kaolinitic sandy gravel layer that grades progressively into the weathered basement layer with resistivity range of 200 – 2800 Ωm and thickness range of 25 – 70 m. The third layer is the partly fractured basement lying on the fresh basement rock. The resistivity values range from 500Ω m at the uppermost fractured parts to as high as 5000Ωm or more in the deeper unfractured parts whose bottom was not reached during the geophysical investigation. All the wells drilled in this area are productive, especially because the geophysical investigation provided sufficient and reliable information about the aquiferous units with regards to the precise depth to drill at each location.

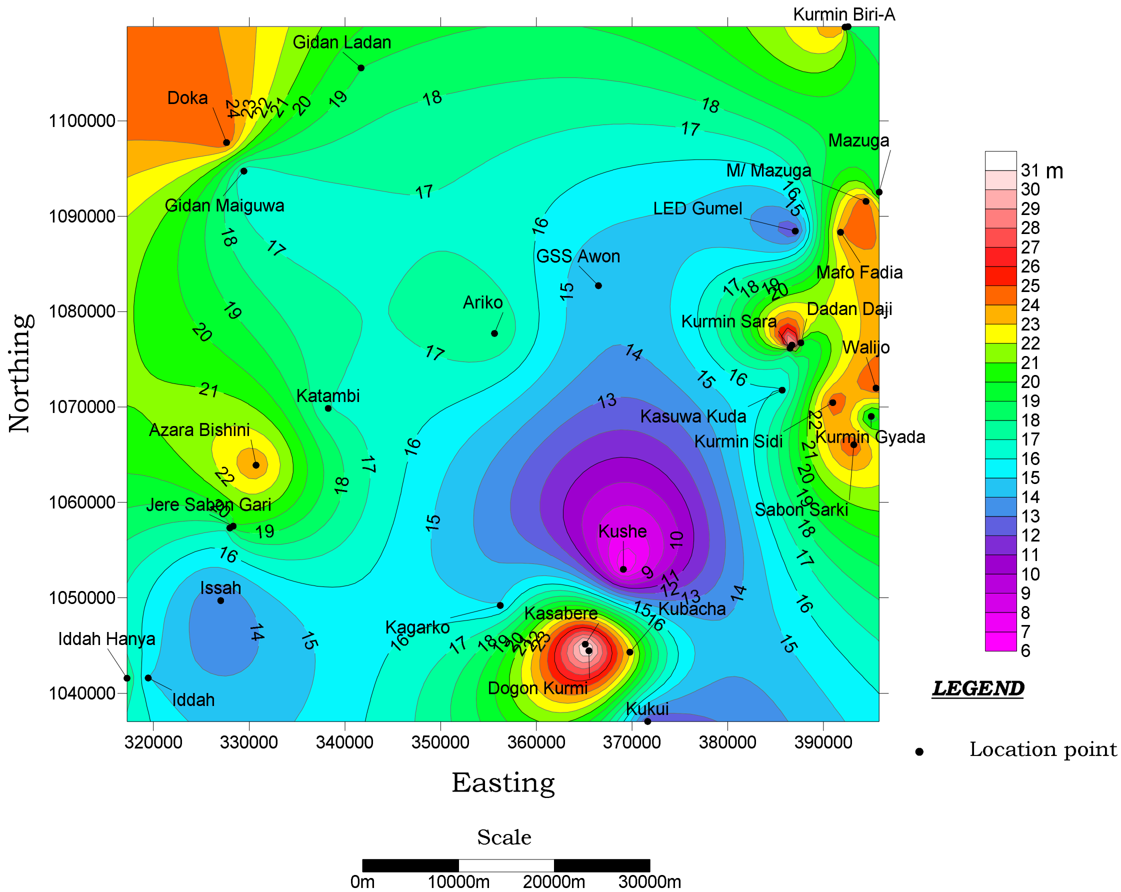

Fig. 4. Basement relief map of the study area

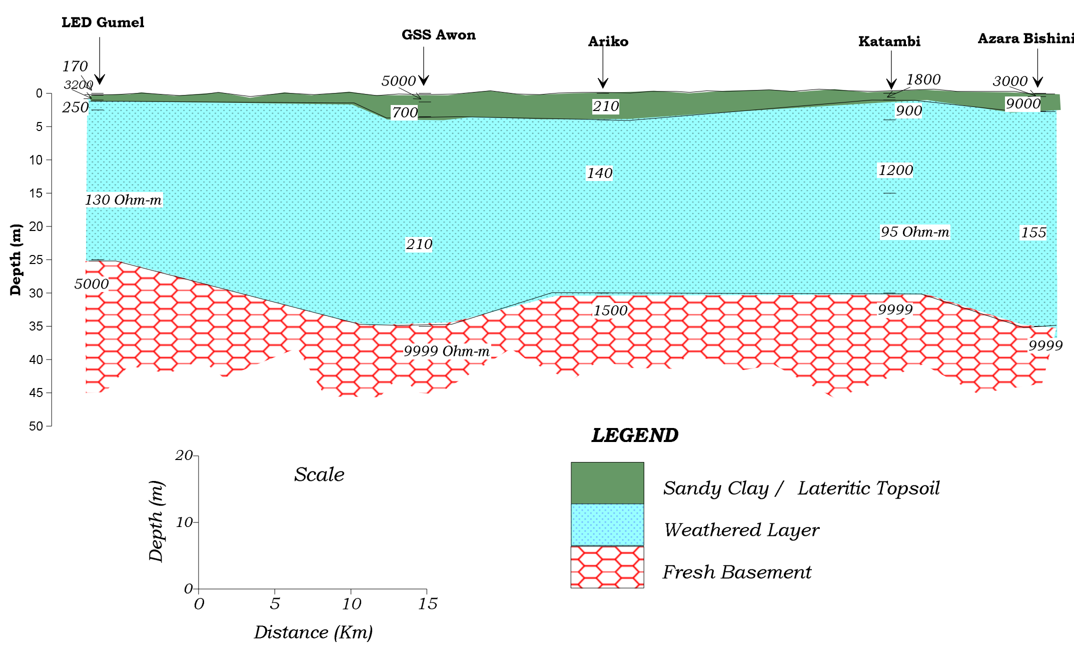

Fig. 5. Geological profile section 1 of the study area

3.2.4 Geological profile sections from well data

Two geological profile sections of subsurface geology were constructed by using the well data from the study area. These lithological profiles are model sections depicting the lateral relationship and continuity in rock units across the area. Profile 1 cuts across the middle section of the study area from LED Gumel through GSS Awon, Ariko, Katambi to Azara-Bishini in the NE – SW direction, as shown in Fig. 5. In this profile, the weathered layer constituted the major aquiferous unit with somewhat uniform thickness ranging from a depth of 1m to as much as 35m at most locations along the profile section. Groundwater prospecting can therefore be targeted to an approximately uniform depth along the area covered by the profile.

The second profile (Profile 2) reveals the subsurface lithology from Maraba-Mazuga through Dadan-Daji, Kurmin-Sara, Kasuwa-Kuda to Kushe in the southern part of the study area (Fig. 6). This profile shows a similar range in the thickness of the weathered horizon as in Profile 1, except for Kurmin-Sara where the weathered layer is revealed to be as thick as 80 m. It can, therefore, be deduced that the underlying geology in the study area did not vary significantly as revealed from the two profile sections, and likewise the groundwater aquifer occurs within a similar range of depth across the entire study area.

3.3 Summary of Findings

The range of values obtained for hydraulic conductivity, transmissivity and storativity are within the typical ranges for most Basement complex rock formations. With reference to Table 1, the transmissivity of Kachia aquifers range from 0.90 m²/day to 25.37 m²/day with average value of 6.31 m²/day. This shows that the aquifers in Kachia area can generally be classified as having low potential. The piezometric surface contour map showed that static water level is generally deeper around the central part of the study area than at the southern and western parts, and this coincided with the outcome of the basement relief map which also shows that the depth to Basement rock is generally deeper at the central part than at the eastern, western and southern boundaries of the study area. The three

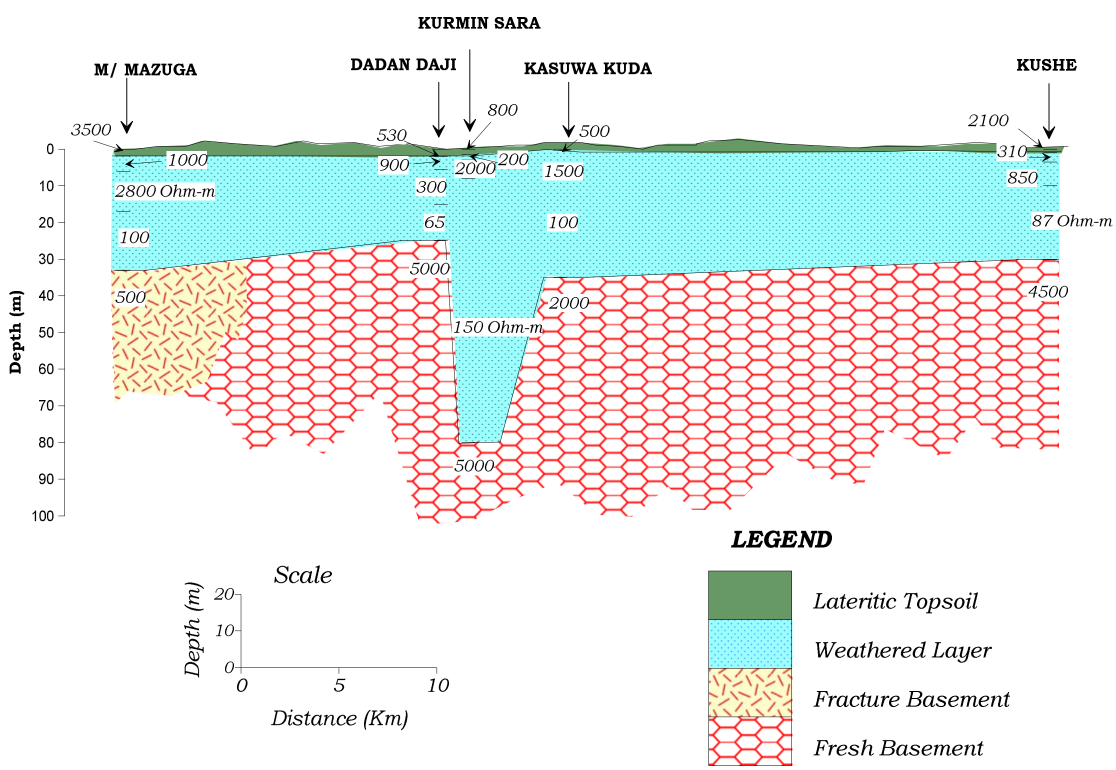

Fig. 6. Geological profile section 2 of the study area

layer horizons delineated from the electrical resistivity data agreed with the geologic sections observed after drilling. Water wells used for study were successful and productive because drilling was preceded with geophysical investigation. The weathered layer constituted the major aquiferous unit with somewhat uniform thickness ranging from a depth of 1m to as much as 35m at most locations along the profile sections. The underlying geology did not vary significantly and groundwater prospecting can be targeted to almost uniform depths across the study area.

4. CONCLUSION

Quantitative and qualitative appraisals have been carried out on the groundwater aquifer properties of the Kachia Local Government Area of Kaduna State, Nigeria. Geophysical, geological and pumping test data were used to appraise the hydraulic conductivity, the transmissivity and the storativity properties of the aquifers in the area. The lowest values of the three aquifer constants were found to have converged at Walijo at the extreme eastern part, while they all peaked at Iddah Hanya on the western border of the study area. The piezometric surface contour map showed that static water level is generally deeper around the central part of the study area than at the southern and western parts. The basement relief map revealed that the depth to Basement rock is generally deeper at the central part than at the eastern, western and southern boundaries of the study area. From the field resistivity data, the three-layer horizons which were delineated agreed with the geologic sections observed after drilling. The two lithological profile sections of the subsurface geology showed that the major aquiferous unit, which is the weathered layer, occurs within a depth of 1m to as much as 35m, except at Kurmin-Sara where it is found to be much thicker. Therefore, it can be concluded that aquifer properties are generally favourable for groundwater development, and an approximately uniform thickness of the weathered layer remains the main target across the entire study area. However, it is recommended that groundwater prospecting should be preceded with geophysical investigation for more successful outcomes.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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