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Hydro-Geophysical Assessment of Groundwater Potential and Aquifer Vulnerability of the Turonian Makurdi Formation in North Bank area, Makurdi, Middle Benue Trough, Nigeria

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Abstract
Electrical resistivity investigation was carried out in North Bank and its environs in Makurdi, Benue State, with a view to determining the depth to aquifer, aquifer thickmess, groundwater potential of the area and aquifer vulnerability. Twenty−one (21) Vertical electrical sounding (VES) was carried out using the Schlumberger electrode array with the aid of ABEM Terrameter (SAS 3000C) with maximum electrode spacing of 200m. The VES data obtained were interpreted using partial curve matching approach and modelled using WinResist software. Modelled field curves reveal essentially three to four geo−elcetrical layers and two main aquiferous zones corresponding to the upper silty−sandstone and lower medium to coarse grained felspathic sandstones of the Makurdi Formation. The upper silty−sandstone aquifer is characterized by low to moderate resistivity value distribution (37 −2039 ohm−m) with layer thickness in the range of 3m to 15m. Computed hydraulic and geo−electric characteristics (Zarrouk parameters, hydraulic conductivity and transmissivity) depicts it as unconfined, vulnerable to infiltrating surface contaminants, with low groundwater potential ($0.63\ m^2\ day^{-1} < T \leq 199.65\ m^2\ day^{-1}$) and only suitable for small community water supply projects and private consumption. The lower felspathic sandstone aquifer is characterized by relatively thicker sequence of aquiferous materials (3m – 54m). The aquiferous zone is generally unconfined to semi−confined in nature, with groundwater potential ($30.96\ m^2\ day^{-1} < T \leq 542.73\ m^2\ day^{-1}$) seen to be largely moderate. The aquifer is deemed suitable for industrial, irrigational and municipal water supply purposes

Keywords: *Groundwater potential, Makurdi Formation, groundwater vulnerability, aquifer, Dar-Zarrouk parameters.*

Introduction

Groundwater remains an important source of fresh water for various purposes such as domestic, industrial, and agricultural purposes in areas where urban water supply infrastructures are gradually becoming non−functional. Many people around the world especially in sub−Saharan Africa (arid and semiarid areas) where surface water and seasonal rainfall are scarce or unevenly distributed are reliant on private and/or commercial boreholes for their vast water needs. Generally, groundwater sources hold the largest reserves of portable water on the planet and are considered safer as it is purified and protected by the vadose zone (Raghunath, 2010; Leap 2000). Nonetheless, these water sources are prone to contamination from anthropogenic activities associated with industrial development, rapid population growth, and extensive agricultural activities (Obrike *et. al.,* 2011). Also important are the treats groundwater abstraction hold to processes like surface subsidence, seawater intrusion, and contaminant transport (Abam *et. al.,*2008; Fatoba *et. al.,* 2014). Increasing industrialization and population growth in large urban centers such as Makurdi metropolis present periodic challenges of insufficient water supply especially during the dry season. Though sections of Makurdi town is densely drained by the Benue River and tributaries, the high silt content of the Benue River, surface water pollution arising from human activities, agriculture and waste disposal renders this water source increasingly unattractive. Thus, hand−dug wells, hand pumps and motorized boreholes are currently considered as viable alternative source of freshwater for drinking, personal hygiene and food processing within the metropolis. Situated within one of the sedimentary basins of Nigeria, extensive studies on the geology, structures, stratigraphy and economic mineral deposits of this section of the Benue Trough exist (Hoque and Nwajide 1984; Offodile 1989; Ofoegbu 1991; Obaje 2009; Nwajide 2013; Obrike *et al.,* 2019). In addition, a number of studies mostly of regional extents have shed light on the hydrogeological regimes of the Makurdi−Gboko axis of the Middle/Lower Benue Trough (Offodili, 1989; Najimi 2010) Furthermore, a few detailed studies on the assessment of the geo−electric properties of aquiferous zones, hydro−geochemistry, groundwater quality and contamination potential of surface water sources also exist (Akuh *et al.,* 2014; Obiora *et al.,* 2015). The foregoing notwithstanding, very little information is present on the groundwater potential of the Markurdi area in general and the North Bank – Wadata area of the metropolis in particular.

This paper assessed the groundwater potentials of the North Bank area of Makurdi town using electrical resistivity method. Groundwater potentials in the area was estimated using geo-electrical parameters to derive bedrock layer resistivity and thickness, and delineate potential aquifers (Zohdy *et al.* 1974). Based on the aforementioned, computed Dar-Zarrouk parameters, alongside pumping test data of some boreholes within the study area provided a viable means of evaluating the groundwater potential of the study area.

Regional Geological Setting and Hydrogeology of the Middle Benue Trough

The Benue Trough is a linear elongate intracratonic rift structure formed in the Late Jurassic to Early Cretaceous (Burke and Whiteman, 1973; Burke and Dewey, 1974; Olade, 1975; Wright, 1976, 1981; Fairhead and Binks, 1991; Guiraud and Maurin, 1991, 1992, 1993; Guiraud *et al.,* 2005; Nwajide, 2013). This mega-shear structure comprised of en-echelon arrangement of several NE-SW trending pull-apart sub-basins arbitrarily subdivided into lower, middle and upper segments is filled with Cretaceous to Tertiary sediments (Benkhelil *et al.,* 1988, 1989; Zaborski, 1998; Obaje, 2009; Nwajide, 2013). The entire Trough (at varying degrees) had undergone two episodes of compressional folding (Cenomanian and Santonian) culminating in the folding, faulting and upliftment of the pre-Santonian successions within the Trough (Zaborski, 1998; Nwajide, 2013). The middle segment of the Trough comprised of seven pull-apart sub-basins (depocentres), serves as a reservoir for upwards of 2500 – 3100 m of Cretaceous (Albian – Maastrichtian) sediments of both marine and continental origin. (Anudu, *et al.,* 2020; Benkhelil *et al*., 1988, 1989). The Albian Asu River group sediments made-up of the Arufu limestone, the Uomba Formation and the Gboko limestone are the oldest in the middle Benue Trough and directly overlies the basement unconformably (Offodile and Reyment, 1977). The Asu River group is overlain by the transitional marine to fluviatile, Late Albian to Early Cenomanian Awe Formation comprised of flaggy fine to medium grained sandstones with interbeds of salt-rich carbonaceous clays and shale (Offodile 1989; Zaborski, 1998; Obaje, 2009; Nwajide, 2013). The Late Cenomanian to Early Turonian Keana Formation overlies the Awe Formation unconformably with contact described as gradational (Nwajide 2013). The Turonian Eze-Aku Formation made-up of massive flaggy calcareous to non-calcareous shale, sandy or shaley limestone and calcareous sandstones overlies the Keana Formation with interfingering contact relationship established between the two in some locations (Offodile and Reyment, 1977; Nwajide 2013). Southwardly, the Keana Formation passes laterally into the Makurdi Formation which is a component of the Eze Aku Group (Nwajide 2013). The Makurdi Formation is seen to be the product of a local Turonian side-delta. Dominantly arenaceous, the Makurdi Formation consist of cross-bedded, coarse grained pebbly sandstones and ripple-bedded, fine grained micaceous sandstones. However, local marine influences are evident with occurrences of limestone interbedded with shales in places within the Makurdi Formation (Offodile and Reyment, 1977; Zaborski, 1998; Nwajide 2013). The Eze-Aku Formation is overlain by Late Turonian – Coniacian fissile shale dominated sediments of the Awgu Formation. The continental sediments of the post-folding Campano-Maastrichtian Lafia Formation essentially composed of sandstones of varied facies with intercalations of clays, are the youngest within the middle Benue Trough. The stratigraphic succession of the middle Benue Trough is presented in Fig. 1.

The porous and water yielding sandstone beds of the Awe Formation constitutes an important aquiferous zone for groundwater withdrawal within the middle Benue Trough. However, groundwater from these aquiferous sandstone beds are commonly contaminated by brine from the associated salt-rich inter-beds of carbonaceous clays and shale. These impervious intercalations are also known to produce artesian to sub-artesian groundwater conditions (Offodile and Reyment, 1977). Highly prolific yields have been reported for drilled wells within the formation (Offodile, 2002). The sandstone beds of the Keana and Markurdi Formations are largely indurated, with the aquiferous horizons associated with zones of fractured and/or less indurated sandstone beds. As such, borehole success in the Makurdi sandstones is somewhat erratic as groundwater potential is largely hinged on its secondary permeability derived from weathering and fracturing (Offodile, 2002). Hydraulic conductivity values in the range of 0.13 to 3.5 m/d have been reported for sandstones west of the Makurdi metropolis (Akuh et al., 2014). Offodile (2002) reported yields of 8.2ltr/sec, 2.5ltrs/sec, 3.9ltrs/sec and 8.7ltrs/sec for boreholes drilled into the Makurdi sandstones at locations in Makurdi town and neighboring Aliade, south of Makurdi town. The Makurdi sandstone aquifer receives direct recharge from precipitation, as well as infiltrating

Time Scale		Obaje 2000	Nwajide 2013			
		Lithostratigraphic units	Lithostratigraphic units		Sedimentary cycle	Paleoenvironment
Cretaceous	Maastrichtian	Lafia Fm	Lafia Fm Otobi Sst		Cycle 4	Continental to marginal marine (deltaic to estuarine)
	Campanian					
	Santonian	Awgu Fm	Awgu Fm		Cycle 3	Complete marine inundation in both Lower and Middle parts of the Trough, but paralic in the Upper parts of the Trough.
	Coniacian					
	Turonian				Cycle 2	Fluctuation from marginal marine, occasional full marine to fluvial.
		Eze-Aku Fm / Konshasha / Wadata	Eze-Aku Group	Makurdi Fm/Zurak Sst / Keana Fm		
		Awe – Keana Fms				Continental - fluvial
	Cenomanian	Awe – Keana Fms	Asu River Group	Awe Fm / Uomba Fm/ Arufu Lst/ Yandev Lst/ Muri Sst	Cycle 1	Marginal marine lagoonal / evaporitic to fully marine
	Albian	Asu River Group – Urufu – Uomba – Gboko Fms				Marine to continental –alluvial fan to fluvial
			Bima Sst			Continental –fluvial / alluvial fan and braided rivers
	Aptian		Pre-Bima			
Precambrian		Basement complex				

Fig. 1: Summary of the litho-stratigraphy and paleo-environment of deposition of Cretaceous rocks of the middle Benue Trough Compiled from Obaje 2000 and Nwajide 2013, (Erosional surfaces)

runoff and subsurface flow from the Benue River and tributaries. The poorly consolidated, commonly cross bedded, frequently ferruginized fine to coarse grained sandstones of the Lafia Formation constitutes a major aquifer in the middle Benue Trough. The poorly consolidated nature of the sandstones renders them most prolific of the aquifers in the middle Benue Trough. Average borehole yields of 4.2 ltrs/s have been reported for the wells drilled in the Lafia Formation (Offodile, 2002).

Location and Geological Setting of The Study Area

The study area lies within latitude 7^0 47' to N 7^0 44' and longitude E8^0 32' to 8^0 35' and is located in north-central Nigeria, within the Middle Benue Trough (Obaje 2009; Nwajidi, 2013). The area is generally undulating with sparse hills and valleys; the flood plains of the Benue River constitute the lowest elevation points within the area bounded by the southern and northern uplands. Makurdi town is essentially drained by the Benue River and its numerous seasonal tributaries. The section of the Benue River within the study area follows an east to west flow route. The drainage pattern of the area is essentially dendritic with medium drainage density. Vegetation-wise, Makurdi lies within the Guinea Savanna belt of Nigeria characterized by preponderance of short grasses dotted by few shrubs and medium sized trees, except along river/stream channels which support rain-forest vegetation characterized by deciduous trees (Nwajide, 1984). The average annual rainfall in the study area has been reported to be in the range of 1,500 to 2,000 mm with its peak rainfall in the month of July (Obiora *et al.,* 2015). The area is also characterized by moderate to high daily temperatures and mean annual humidity of about 60% with lowest monthly mean of 40% (Nwajide 2013). The study area is underlain by rock units of the Makurdi Formation (see Figure 1 and 2), deposited in the Turonian transgressive phase, in a shallow marine environment (Nwajide, 2013).

The Makurdi Formation is made up of series of sandstone beds separated by intercalations of shales and limestone beds. It is highly indurated and cemented mainly by quartz and iron oxide. Facies changes in the sandstones (silty and felspathic) and sandy shales are common. The thickness of the Makurdi Formation varies, with some locations estimated to be more than 300m thick (Offodili 1989; Nwajidi 2013; Obiora *et al.,* 2015). Largely the sandstones of the Makurdi Formation are essentially coarse to fine grained and vary in hardness from place to place (Offodili 1989; Nwajide 2013). Generally, the silty sandstone facies is light yellow to brown in colour, fine grained and moderately sorted. It is tabular, fine-medium grained, with shaley intercalations at its basal portions and is faintly current bedded and has ripple mark (Shell 1957; Nwajide, 1982; Nwajide 2013). The felspathic sandstone variety is essentially non-tabular in character and forming occasional massive outcrops. The felspathic sandstones are poorly to moderately sorted, fine to very coarse and sometimes conglomeritic indurated and arkosic (Shell 1957; Offodile 1989). The felspathic sandstone facies forms the basal parts of the Makurdi Formation and is thought to be a time equivalent of the Keana Formation (Offodile 1989). In addition to the Makurdi Formation, parts of the study area are underlain by recent alluvium occurring along river and stream channels which are commonly liable to seasonal flooding.

Materials and Methods

For this study, twenty-one (21) Vertical Electrical Sounding (VES) using Schlumberger array were carried out in North Bank and its environs. However, fewer VES probes were conducted in the northern part of the study area as a result of access restrictions in-place in the forestry reserve areas (see Figure 2). The largest current electrode spacing used was 200m. The resistances of the subsurface were measured and recorded against the appropriate potential and current electrodes separation. The depth of investigation in resistivity sounding using the Schlumberger electrode array is approximately 0.33 to 0.25 of AB/2 (Bernard 2003: Anudu *et al* 2014), as gradual varying of the electrodes separation provides deeper probes of the stratification at depth of the point of interest (Dahlin, 2001; Bernard 2003). The VES technique is widely used in groundwater exploration to determine depth from surface, thickness and boundary of an aquifer (Anudu *et al*., 2014; Fatoba et al 2014). Using the conventional partial curve matching technique with two-layer master curves in conjunction with auxiliary point diagrams (Orellana and Mooney, 1966), the initial estimates of VES data was achieved. From this, estimates of layer resistivities and thicknesses were obtained which served as start points for computer-assisted interpretation. A computer software program WinResist 1.0 was used and the data sets obtained from the manual interpretation stage were keyed in as inputs into the computer modeling software to generate data for the estimated model. The delineated depth to aquifer and aquifer thickness were estimated from the developed VES models.

The Dar-Zarrouk parameters (longitudinal conductance and transverse resistance) derivable from VES models allowed for the computation of intrinsic hydraulic properties and aquifer parameters such as hydraulic conductivity and transmissivity, which provided insight with regards the groundwater potentials of existing aquifers in the study area. The term "groundwater potential" is used here conservatively as this would require information on a number of aquifer properties such as porosity, permeability, specific yield, specific retention, total head, hydraulic conductivity, transmissivity and storage coefficient of the various aquiferous zones. However, studies have shown that qualitative estimate of groundwater potential is achievable using transmissivity data of the aquiferous zones (Gheorghe, 1978; Niwas and Singhal, 1981; Krasny 1993; Ekwe et al., 2006).

Commonly, a unit square cross-sectional area cut out of a group of *n* layers of infinite lateral extent is considered to derive the hydrogeophysical model parameters. The sum of transverse unit resistance *TR* is represented by;

$$\boldsymbol{TR = \sum_{i=1}^{n} h_i \rho_i} \quad \text{......(1)}$$

where hi and ρi are the layer thickness and resistivity, respectively, of the ith layer in the section. The sum of longitudinal conductance S can be shown as:

$$\boldsymbol{S = \sum_{i=1}^{n} \frac{h_i}{\rho_i}} \quad \text{......(2)}$$

The longitudinal layer conductance Si can be presented as:

$$\boldsymbol{S_i = \sigma_i h_i} \quad \text{......(3)}$$

where σi is the layer conductivity. Conductivity in this case is analogous to the layer hydraulic conductivity K used in groundwater hydrology on a regional scale (Asfahani, 2013). On less coarse scale, the layer hydraulic conductivity $K,$ can be obtained from pumping test data of existing boreholes and in conjunction with σ values extracted from VES interpretation for the aquifer at borehole locations, extrapolations for proximate areas of similar geology and water quality of layer hydraulic conductivity and transmissivity is rendered possible (Niwas and Singhal, 1981; Ekwe et al., 2006). Furthermore, after Heigold et al (1979) hydraulic conductivity of aquifers can also be derived for areas with no existing data obtained from boreholes using the following relationship:

$$K = Ae^{B_\rho} \quad (4)$$

where A is a constant equal to 386.40 and B are site dependants for particular aquifers, for this study, B value of − 0.93283 was used after Obiora et al., (2015)

Transmissivity computation is given by:

$$T_i = K_i h_i \quad (5)$$

where *Ki* is the hydraulic conductivity of the *i*th layer of thickness *hi*.

Equations (1) and (2) are referred to the Dar-Zarrouk parameters (Maillet 1947), and the relationship between the transmissivity, T_c, and total transverse unit resistance, *TR*, is given as:

$$Tc = K\sigma TR = Kh \quad (6)$$

According to Niwas and Singhal (1981), areas where the geological setting and water quality do not vary greatly, the product *Kσ* remains fairly constant. As such, a similar relationship can be derived between the transmissivity T_c and aquifer longitudinal conductance *S*:

$$Tc = \frac{KS}{\sigma} = Kh \quad (7)$$

Results and Discussion

Geo-Electric Characteristics and Correlation with Geology

Interpreted VES curves obtained from the study area revealed three to four geo-electric layers. Typical VES curve types identified in the study area are the H (ρ1>ρ2<ρ3), HA (ρ1>ρ2<ρ3<ρ4), HK (ρ1>ρ2<ρ3>ρ4) and QH (ρ1>ρ2>ρ3<ρ4) types. Representative examples of the VES curves in the study area are shown in Figure 3. The predominant curve types are the H and QH types that constitute 48% and 29% respectively of all the VES curves in the study area. The HA and HK curve types make up the remaining 29% (see Table 1). Three to four geo-electric layers were revealed in the modeled VES curves. The first layer having resistivity values in the range of 894 to 2666 ohm-m and a layer

Table 4: Reactivation window and potential for induced seismicity and fault leakage

VES curve type	Curve characteristics	Frequency	Percentage
H	(ρ1>ρ2<ρ3)	10	48
HA	(ρ1>ρ2<ρ3<ρ4)	4	19
HK	(ρ1>ρ2<ρ3>ρ4)	2	10
QH	(ρ1>ρ2>ρ3<ρ4)	5	29
Total		21	100

thickness that varied from 0.3 to 4.6 m. The resistivity values of second layer varied from 37 to 2031 ohm-m with a mean of 660 ohm-m and the layer thickness varied from 1.8 to 15.2 m. The resistivity values of the third layer varied from 34 to 133 ohm-m with a mean value of 61 ohm-m and layer thickness of 5.4 to 54.5 m. The fourth layer exhibited resistivity values in the range of 159 to 1085 ohm-m, however the overall layer thickness was not attained due the shallow depth of penetration adopted during sounding.

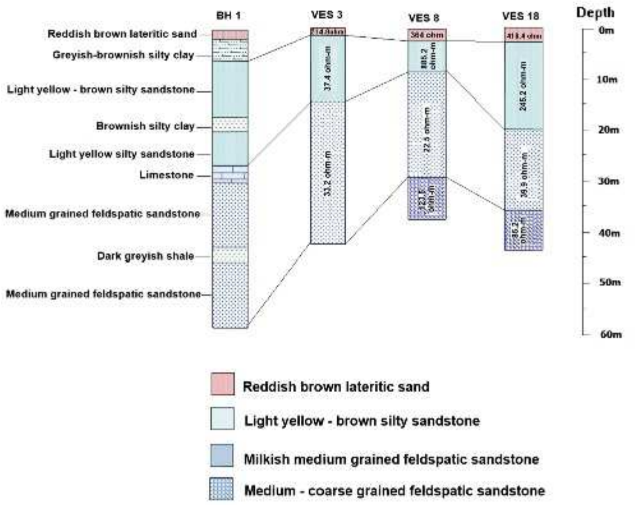

Fig. 4: Correlation of sounding (VES) data interpretation results with borehole/well lithological logs

Correlation with borehole logs obtained from a number of drilled wells during the follow-up drilling stage (Figure 4 & 5) revealed the geo-electric layers as follows; The first layer is seen to correlate with the lateritic sandy clay and/or greyey shale layer in some locations. This reddish − brown (sometimes lateritic) sand to greyish shale layer is seen to directly overlie the weathered silty sandstone. In sections of close proximity to the River Benue, this layer corresponds to the alluvium cover and is characterized by relatively lower resistivity values. The second layer corresponds

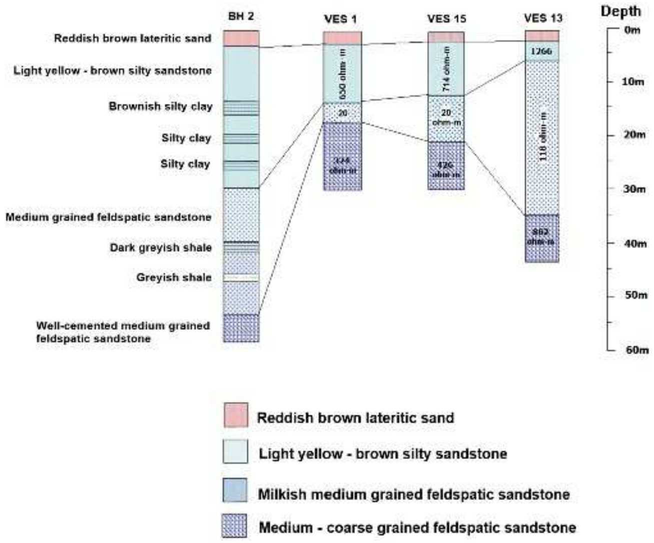

Fig. 5: Correlation of sounding (VES) data interpretation results with borehole/well lithological logs

to the silty sandstone facies, typically light yellow to brown in colour, fine grained, silty and in most cases moderately sorted. This lithology is characteristically silty and its near surface character may explain the high silt content associated with the River Benue flow. This fine–medium grained silty sandstones also contains shaley intercalations, with geoeletrical logs obtained suggesting a variable layer thickness of between 2 to 30 m. The third and fourth layers are seen to correlate with the felspathic sandstone facies separated by varied thickness of intercalations of shales and limestone beds. Litho–log descriptions of sample cuttings obtained show these fractured sandstones to be poorly to moderately sorted, fine to very coarse and sometimes lightly conglomeritic and arkosic in nature.

Low resistivity values in sandstones is often a function of porosity, clay type and content, temperature, salinity, dissolved heavy metal content and to a large extent the degree of saturation (Ebong et al., 2014) with average resistivity values for saturated sandstones commonly within the range of 10 – 850 ohm–m (Olhoeft, 1989). The relatively low resistivity values that characterize these layers (3rd and 4th layers) suggests considerable presence of clayey intercalations and zones of high water saturation with regards groundwater exploration (Ebong et al., 2014). Studies by Choudhury and Saha (2004) have also shown that the presence of salt water intrusion into fresh water bearing strata can significantly reduce resistivity values in the aquiferous zone. Nwajide (1984) alludes the presence of salt bearing silty–clayey intercalations at depth within the Makurdi Formations as possible source of saline water at depths greater than 200m. Generally, the layer thickness and depths interpreted from the VES data were to a very large extent seen to be consistent with field observations during borehole drilling.

Aquifer Hydraulic Characteristics

Computer modelled VES curves of the study area revealed two main aquiferous zones – the upper silty–sandstone and lower felspathic sandstones of the Makurdi Formation. The presence of intercalations of argillaceous materials notwithstanding both aquiferous zones exhibited unconfined and semi–unconfined conditions. The lithologic logs of drilled wells put the boundary between the two sandstone facies at 25 – 30m. Table 1 highlights the geophysical and hydrogeological parameters computed for the upper silty–sandstone aquifer.

Figure 6(a) shows the low to moderate resistivity distribution of the upper silty–sandstone aquifer ranging from a minimum of 37 ohm–m to a maximum of 2039 ohm–m, with a mean value of 660 ohm–m. The resistivity distribution of the silty–sandstone aquifer is lowest southwards towards the recharge zones of the Benue River and northwards in the direction of the watershed of forest reserves. The aquifer thickness map (Figure 6–b) shows increased aquifer thickness in the range of 10m to 15m, southwards in the direction of the River Benue flow route and towards the northern part of the study area. The upper silty–sandstone aquifer has hydraulic conductivity values in the range of 0.32 m/day to 8.89 m/day with an average value of 2.93 m/day (Figure 6–c). The average value of 2.93 m/day is lower than the theoretical average of 8.64 m/day obtained by Niwas and Singhal (1981) for a porous media – sand and gravel mixes. The presence of intercalation of shales, clay lenses and high silt content may explain the lower hydraulic conductivity values recorded for the silty–sandstone aquifer in the study area. Transmissivity values for the upper aquiferous zone (Figure 6–d) are in the range of 0.63 m^2/day to 199.65 m^2/day and an average value of 23.83 m^2/day, with higher values associated with regions of close proximity along the route of the Benue River and major tributaries. This near surface silty–sandstone aquifer is of immense importance as it serves as the main source of water to all lined and unlined hand–dug wells, shallow to medium depth hand pumps and boreholes in the area. Similar trends are seen to exist in the spatial distribution of Transverse resistance and transmissivity and also that of hydraulic conductivity and aquifer thickness (see Figure 6a–6f).

Table 2 lists the computed geophysical and aquifer hydraulic parameters of the lower felspathic sandstones aquifer. The relatively low resistivity values in the range of 10 – 132 ohm–m with a mean of 64 ohm–m, associated with these aquiferous layers suggest zones of saturation (Figure 7a). The thematic map of aquifer thickness of the lower felspathic sandstones is presented in Figure 7(b). The aquifer thickness ranges from 3m – 54m with a mean of 20.4m and the spatial thematic distribution reveals thicker sequence of aquiferous beds are located towards the southern, western and north–eastern parts of the study area. The aquifer hydraulic conductivity values are in the range of 4.06 m/day to 23.62 m/day with a mean of 12.95 m/day (Figure 7c). These values suggest relatively coarser grain mix and/or less significant content of fines in the lower aquiferous

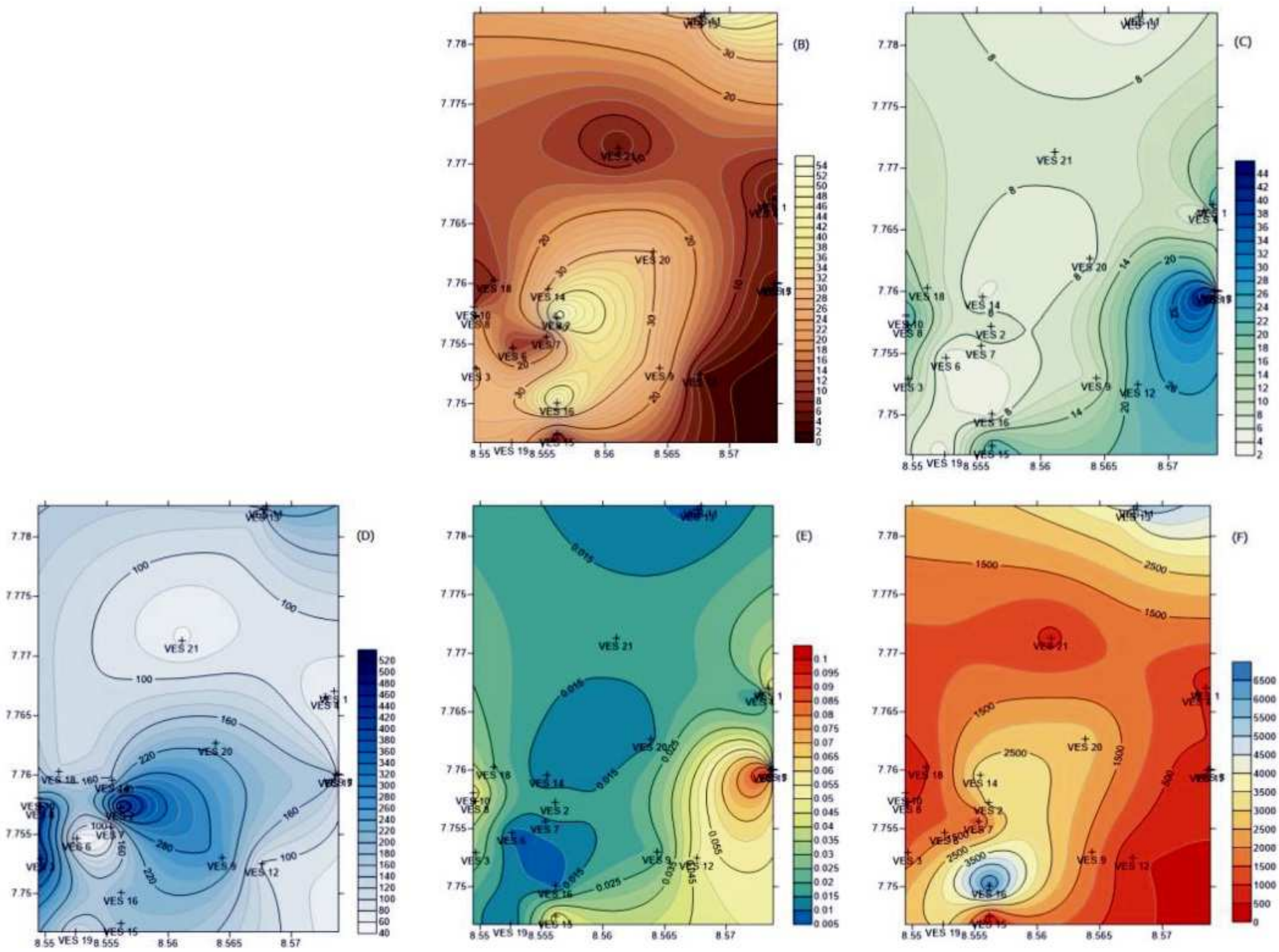

Fig. 6: Maps of (a) resistivity, (b) thickness, (c) hydraulic conductivity, (d) transmissivity, (e) Longitudunal conductance and (f) Transverse Resistivity for the upper silty–sandstone aquifer of the Makurdi Formation in North Bank area deduced by the use of 21 VES points.

zone in relation to the upper silty–sandstone aquifer. The lower felspathic sandstone aquifer transmissivity values vary from 30.96 m^2/day to 542.72 m^2/day with higher values associated with saturated zones of thicker sequence of relatively more permeable strata (Figure 7d). The spatial variation in Longitudinal Conductance and Transverse Resistance values for the lower felspathic sandstones aquifer are presented in Figures 7(e) & 4(f). The distributions of the thickness, transmissivity and transverse resistance of the lower felspathic sandstone aquifer visibly suggests different hydrogeological characteristics within this aquiferous zone. Two distinct, relatively transmissive structures can be observed (north–east and south–western parts) from the spatial distributions of the thematic maps (see Figures 7b, 7d &7f). These structures are of prime influence in the distribution of groundwater potentials within this aquiferous zone.

Groundwater Potentials

Groundwater potential is generally influenced by

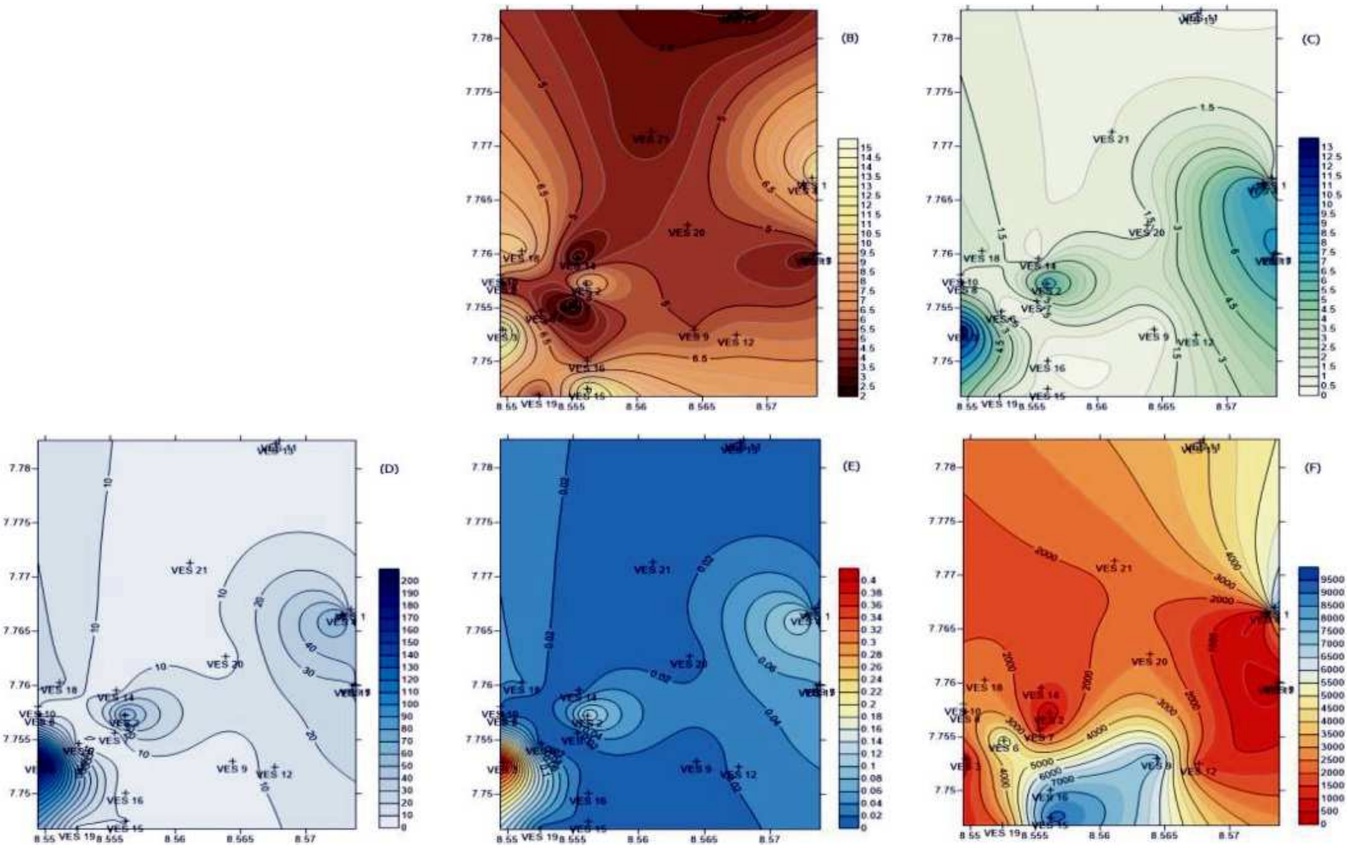

Fig. 7: Maps of (a) resistivity, (b) thickness, (c) hydraulic conductivity, (d) transmissivity, (e) Longitudunal conductance and (f) Transverse Resistivity for the lower felspartic-sandstone aquifer of the Makurdi Formation in North Bank area deduced by the use of 21 VES points.

surface and subsurface factors such as geomorphology. drainage density, soil-type, precipitation intensity, land-use, lithology and lineament density. However, intrinsically within a localized subsurface environment, groundwater potential is chiefly influenced by soil texture (hydraulic conductivity), permeability characteristics (transmissivity and lineament density) and its relative potential to recharge (Kruseman and De Ridder, 1994; Todd and Mays, 2005; Rao, 2016).

The groundwater potential of the study area was assessed after Gheorghe (1978) and Krasny (1993) standards for transmissivity (Tables 4&5). Using Gheorghe (1978) standards for transmissivity, groundwater potential in the upper silty-sandstone aquifer ($0.63\ m^2\ day^{-1} < T \leq 199.65\ m^2\ day^{-1}$) is generally "Low to Very low" with only areas around Rano station, Jiddah and Ichwa 2 exhibiting "Moderate" potentials (see Table 2, Figure 8). The Krasny (1993) standards for transmissivity depicts the aquifer as primarily zoned into areas suitable for withdrawal of local water supply (small communities, plants etc.) and areas suitable for smaller withdrawal for local water supply (private consumption), while the Federal Low Cost area is categorized as suitable for local water supply with limited consumption. This categorization of groundwater potentials will prove useful to the Benue State Rural Water Supply and Sanitation Agency (BERWASSA) a UNICEF assisted agency of government responsible for rural water supply and sanitation in the study area. The agency had drilled over 50 shallow – medium depth wells installed with hand or motorized pumps for domestic water supply in various communities within the North Bank area and environs. Reported yield from wells for these areas currently categorized as suitable for local water supply with limited consumption is generally low ($2.24 – 5.26\ m^3hr^{-1}$). Results from this study suggests the inappropriateness of shallow wells for some of these locations but predicts better yield for deeper motorized well tapping from the lower aquaferous zone for the same locations. The values of total longitudinal conductance provide a measure of the overburden's protective capacity for the subsurface aquifers. Using the Henriet, (1976) and Oladapo et. al., (2004) aquifer protective capacity rating (Table 5), the longitudinal conductance values of the upper silty-sandstone aquifer (0.001 mho $< S \leq 0.405$ mho) depicts the aquifer protective capacity rating as generally "Weak to Poor" with only sections around Jiddah shown to be "Moderate" in protective rating. These low values suggest relatively thin lenses or presence of significant gaps between horizontal intercalation streaks, this may explain the aquifer's unconfined character irrespective of its numerous argillaceous intercalations (Nwajide, 1984). The values also portrayed an aquifer prone to ingress of surface contaminants (Oladapo *et. al.*, 2004).

The groundwater potential of the lower felspathic sandstones aquifer ($30.96\ m^2 day^{-1} < T \leq 542.73\ m^2 day^{-1}$) is seen to be largely moderate (Gheorghe, 1978) as shown in Figure 9 and suitable for withdrawal of lesser regional purposes and local water supply for small communities, plants etc. (Krasny, 1993). The lower felspathic sandstones aquifer is characterized by longitudinal conductance values in the range of 0.10 mho < S ≤1.08 mho with mean value of 0.38 mho. The values depict an aquifer protective capacity rating in the range of "Good to Weak". Nwajide (1984) using borehole log records of drilled wells and stratigraphic studies, described the aquifer system of the Makurdi Formation as essentially sandstones with intercalations of clays, limestone and shales (sometimes about 2m thick), the bands are discontinuous and rarely exceed 200m horizontally. However, the longitudinal conductance values from this study suggest that the sandy‑silty‑clayey‑limestone bands may form localized semi‑confined aquiferous zones in areas characterized as "Good" (Kruseman and de Ridder, 1989).

Generally, groundwater potential in the study area is chiefly influenced by soil texture (variation in grain sizes and the presence of argillaceous intercalations), permeability characteristics (degree of induration within the sandstone beds ‑visible from well cuttings) and its relative potential to recharge (close proximity to drainage flow paths), as seen in Figures 8 and 9.

Table 2: Geophysical and computed hydrogeological parameters for the upper silty‑sandstone aquifer across the study area.

VES Station	Location Name	Latitude (N^o)	Longitude (E^0)	Aquifer Resistivity (ρ)	Aquifer Thickness (m)	Longitudinal Conductance (S)	Transverse Resistance (*TR*)	Hydraulic Conductivity (Kc = m/day)	Transmissivity ($T=m^2/day$)	Groundwater Potential
1	Ichwa 1	$7^0$46’1.39”	$8^0$34’24.50”	658	11	0.017	7238	0.908054	9.988589	Low
2	Rano station	$7^0$45’26”	$8^0$33’22”	70	9	0.129	630	7.343013	66.08712	Moderate
3	Jiddah Str	$7^0$45’10.58”	$8^0$32’58.74”	37	15	0.405	555	13.3098	199.647	Moderate
4	Ichwa 2	$7^0$45’59.604	$8^0$34’21.99	63.5	8	0.126	508	8.041845	64.33476	Moderate
5	FHA	$7^0$45’36.276”	$8^0$34’25.788”	57	5	0.088	285	8.894148	44.47074	Low
6	Army housing	$7^0$45’16.728”	$8^0$33’9.306”	1414	4	0.003	5656	0.44484	1.779358	Very Low
7	Conoil	$7^0$45’20.202”	$8^0$33’19.164”	444	2	0.005	888	1.310626	2.621252	Very Low
8	Mkar Str	$7^0$45’26.40”	$8^0$32’58.61”	885	3	0.003	2655	0.688716	2.066147	Very Low
9	Court 5	$7^0$45’10.80”	$8^0$33’51.75”	1482	5	0.003	7410	0.42577	2.128849	Very Low
10	Mission Ward1	$7^0$45’29”	$8^0$32’58”	369	7	0.019	2583	1.557535	10.90275	Low
11	Fed Low Cost	$7^0$46’57.42”	$8^0$34’4.70”	2039	2	0.001	4078	0.316165	0.632329	Very Low
12	Fed Housing1	$7^0$45’8.95”	$8^0$34’3.42”	216	6	0.028	1296	2.56678	15.40068	Low
13	Asase	$7^0$46’56.4’’	$8^0$34’’3.7	1266	3	0.002	3798	0.493167	1.479501	Very Low
14	Old Lafia Rd.	$7^0$45’34.45”	$8^0$33’19.62”	724	2	0.003	1448	0.830591	1.661182	Very Low
15	HUDCO Qtrs.	$7^0$44’50.97”	$8^0$33’22.212”	714	13	0.018	9282	0.841437	10.93869	Low
16	Court 5_1	$7^0$45’0.29”	$8^0$33’22.21”	1524	5	0.003	7620	0.414814	2.074069	Very Low
17	Fed Housing2	$7^0$45’36”	$8^0$34’25”	68.6	3.5	0.051	240.1	7.48271	26.18948	Low
18	Mission Ward2	$7^0$45’37”	$8^0$33’04”	245	10.3	0.042	2523.5	2.282187	23.50653	Low
19	Old Customs	$7^0$44’48.378”	$8^0$33’8.946”	467	4.5	0.010	2101.5	1.250312	5.626402	Low
20	Mnyim	$7^0$45’45.59”	$8^0$33’49.88”	518	4.8	0.009	2486.4	1.135086	5.448414	Low
21	Kwenbeh Str	7^0 46’16.788”	8^0 33’ 40.002”	601	3.5	0.006	2103.5	0.988143	3.458499	Very Low

Conclusions

Results of vertical electrical soundings carried out in the North Bank area of Makurdi metropolis, north‑central Nigeria, revealed three to four geo‑electric layers and two main aquiferous zones corresponding to the upper silty‑sandstone and lower felspathic sandstones of the Makurdi Formation. Spatially, the upper silty‑sandstone aquifer appears more prolific southwards towards the recharge zones of the Benue River and northwards in the direction of the watershed of the forest reserves. With relatively moderate aquifer thickness, groundwater potential of the upper silty‑sandstone aquifer ($0.63\ m^2 day^{-1} < T \leq 199.65\ m^2 day^{-1}$) is generally "Low" and deemed adequate for small community water supply projects and private consumption. The longitudinal conductance and transmissivity values describe the aquiferous zone as delicate, unconfined and vulnerable to the admittance of contaminants from surface anthropogenic processes. The lower felspathic

Table 4: Reactivation window and potential for induced seismicity and fault leakage

VES Station	Location Name	Latitude (N^0)	Longitude (E^0)	Aquifer Resistivity (ρ)	Aquifer Thickness (m)	Longitudinal Conductance (S)	Transverse Resistance (*TR*)	Hydraulic Conductivity (Kc = m/day)	Transmissivity (T=m^2/day)	Groundwater Potential
1	Ichwa 1	7^{0}46’1.39”	8^{0}34’24.50”	20	3	0.15	60	23.62639	70.87916	Moderate
2	Rano station	7^{0}45’26”	8^{0}33’22”	50	54	1.08	2700	10.05048	542.7261	High
3	Jiddah Str	7^{0}45’10.58”	8^{0}32’58.74”	33	31	0.939	1023	14.80886	459.0748	Moderate
4	Ichwa 2	7^{0}45’59.604	8^{0}34’21.99	78	8	0.103	624	6.637958	53.10367	Moderate
5	FHA	7^{0}45’36.276”	8^{0}34’25.788”	104	6.1	0.059	634.4	5.075606	30.9612	Low
6	Army housing	7^{0}45’16.728”	8^{0}33’9.306”	122	10	0.082	1220	4.373389	43.73389	Low
7	Conoil	7^{0}45’20.202”	8^{0}33’19.164”	70	10	0.143	700	7.343013	73.43013	Moderate
8	Mkar Str	7^{0}45’26.40”	8^{0}32’58.61”	22.5	21	0.933	472.5	21.16804	444.5289	Moderate
9	Court 5	7^{0}45’10.80”	8^{0}33’51.75”	48	26	0.542	1248	10.44059	271.4552	Moderate
10	Mission Ward1	7^{0}45’29”	8^{0}32’58”	20	10	0.5	200	23.62639	236.2639	Moderate
11	Fed Low Cost	7^{0}46’57.42”	8^{0}34’4.70”	100	53	0.53	5300	5.264742	279.0313	Moderate
12	Fed Housing1	7^{0}45’8.95”	8^{0}34’3.42”	20	4	0.2	80	23.62639	94.50555	Moderate
13	Asase	7^{0}46’56.4’’	8^{0}34’’3.7	118	30	0.254	3540	4.511526	135.3458	Moderate
14	Old Lafia Rd.	7^{0}45’34.45”	8^{0}33’19.62”	96	30	0.313	2880	5.46909	164.0727	Moderate
15	HUDCO Qtrs.	7^{0}44’50.97”	8^{0}33’22.212”	20	8	0.4	160	23.62639	189.0111	Moderate
16	Court 5_1	7^{0}45’0.29”	8^{0}33’22.21”	132	49	0.371	6468	4.063518	199.1124	Moderate
17	Fed Housing2	7^{0}45’36”	8^{0}34’25”	10	4	0.4	40	45.10318	180.4127	Moderate
18	Mission Ward2	7^{0}45’37”	8^{0}33’04”	40	10	0.25	400	12.37621	123.7621	Moderate
19	Old Customs	7^{0}44’48.378”	8^{0}33’8.946”	111	24.5	0.221	2719.5	4.776376	117.0212	Moderate
20	Mnyim	7^{0}45’45.59”	8^{0}33’49.88”	75.3	30	0.399	2259	6.859721	205.7916	Moderate
21	Kwenbeh Str.	7^{0}46’16.788”	8^0 33’ 40.002”	55	6	0.109	330	9.195484	55.1729	Moderate

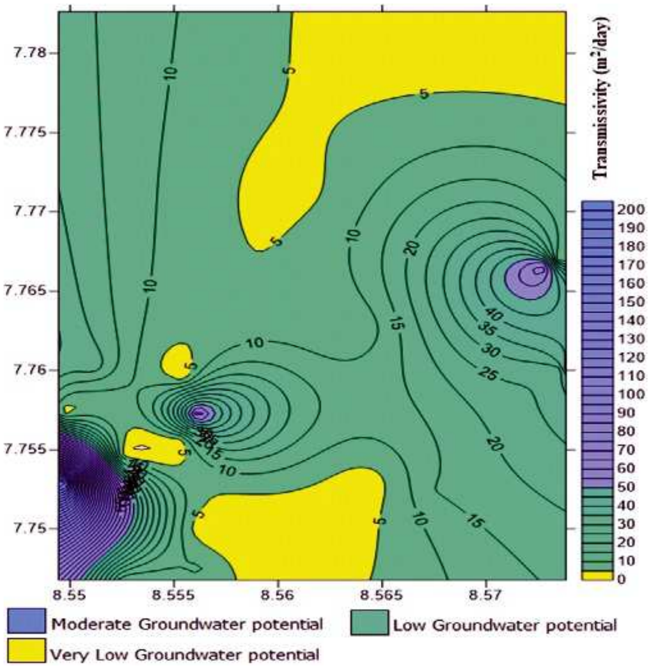

Fig. 8: Groundwater potential map for the upper silty-sandstone aquifer of the Makurdi Formation in North Bank area

Table 4: Standards for transmissivity (Gheorghe, 1978)

Transmissivity range (m^2/day)	Transmissivity potentials
>500	High potential
50 – 500	Medium potential
5 – 50	Low potential
0.5 - 5	Very Low potential
< 0.5	Negligible potential

Table 5: Standard for transmissivity (Krasny, 1993)

Transmissivity (m^2/day)	Designation	Groundwater supply potential
>1000	Very high	Withdrawal of great regional importance
100 - 1000	High	Withdrawal of lesser regional importance
10 – 100	Intermediate	Withdrawal of local water supply (small communities, plants etc.)
1 -10	Low	Smaller withdrawal for local water supply (private consumption)
0.1 - 1	Very low	Withdrawal for local water supply with limited consumption.
< 0.1	impermeable	Source for local water supply are difficult, if possible, to ensure.

Table 6: Aquifer protective capacity rating after Henriet, (1976) and Oladapo *et al.*, (2004)

Longitudinal Conductance (mho)	Protective rating
>10	Excellent
5 – 10	Very good
0.7 – 4.9	Good
0.2 – 0.69	Moderate
0.1 – 0.19	Weak
< 0.1	Poor

sandstone aquifer is typically medium to coarse grained sometimes conglomeritic at depth and characterized by relatively thicker sequence of aquiferous materials. It's groundwater potential (30.96 m^2 day^{-1} < T ≤ 542.73 m^2 day^{-1}) is largely moderate and suitable for withdrawal of lesser regional purposes and local water supply for small communities. Longitudinal conductance results at VES probe depth of 60 – 80m suggests the lower aquiferous zone is generally unconfined to semi–unconfined in nature.

Largely, the results for both aquifers at the current depth of probe may not favour withdrawal for massive industrial, irrigational and municipal purposes. However, It's believed that at greater depths far higher groundwater potentials may be encountered. Nwajide (1984) reported high yields (32 – 35 m^3hr^{-1}.) for deep well (150 – 200m) drilled at other locations within the Makurdi Formation. Nonetheless, caution is required as some wells deeper than 200m have been reported to be abandoned as a result of saline water (Nwajide, 1984).

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