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Characterization of Crystalline Aquifers in Ouaddaï Division (East of Chad) Using Electrical Resistivity Method: A Case Study of Waguiré and Anourchi

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ABSTRACT

This study aimed to locate suitable aquifers that can be exploited with their structural and hydraulic characteristics. So for this aim, combination of geoelectrical and drilling techniques was used. Eight electrical trailing and Vertical Electrical Soundings (VES) were carried out with Syscal R1 - Plus resistivimeter, using Schlumberger array. VES data were interpreted using the Ipi2win software, and geohydraulic parameters (conductivity, transmissivity, and porosity) were estimated based on geoelectric parameters computed. Results show four favorable shapes of electrical trailing (W, U, V, and H -shapes) and four types of VES curves (H, HA, QH and HKH). Three to five geoelectric layers were delineated from analysis of VES curves with aquifer resistivity influenced by clay content, varying from 6.09 to 33.84 Ω.m and thickness from 5.54 to 17.35 m. Computed hydraulic conductivity, transmissivity, and porosity vary from 14.19 to 70.93 m/day, 92.36 to 429.13 m²/day, and 37.44 to 44.68% respectively. The groundwater potential of the area ranges from moderate to high potential. Based on these geohydraulic parameters, two points (VES4 and VES7) were chosen to drill a hole. Drillings were a success and yield ranging from 2.72 m^3/h to 3.12 m^3/h. This study reveals that geohydraulic parameters could be an alternative to choose where to drill a positive borehole in the area with a similar geological context.

1. INTRODUCTION

Groundwater research in basement area made by granite require sometimes geophysical and hydrogeological investigation to locate the best place and make the best choice for drilling a borehole to satisfy water needs of population. The fact that this water does not require rigorous treatment before usage, make it suitable for many usage [1]. For this reason, many boreholes were drilled in rural area of Chad like Waguiré and Anourchi to satisfy water needs by groundwater. Despite these realization, population of these area faced to borehole failure and water needs in term of quantity and quality; then they return to alternative structures as wells with doubtful quality, to satisfy their needs (Figure 1). In typical basement complex as in Ouaddaï division, groundwater is usually contained within weathered and fractured zones [2-7]. But in this part of area of Chad, the difficulties to identify fractured aquifer by geophysical survey only by vertical electrical soundings (VES), remain high, due to weathered product made mainly by clayey material which reduce the resistivity and leads some misinterpretation [2]. Consequently, this situation shows the lack of serious knowledge about interpretation of data obtained during hydrogeophysical investigation [1, 2] in this area. To solve the problem and avoid unproductive boreholes, [2] suggest to drill a hole up to 60 m depth; but this solution is not a guarantee for success because aquifers can be identified up this value [6-9] at 120 m.

According to the study [2], borehole productivity in this Division depends on four factors: geomorphology, climatology, lithology and tectonics. In the same climatology and lithology conditions with a poor geomorphology contrast like in study area (Waguiré and Anourchi), its rest to focus on tectonics factors. But in these areas, it is difficult to observe at surface different outcrops of rocks, then tectonic structures that can help hydrogeologist in groundwater exploration. This context exposed the difficulties to choose a right place to drill a hole with high productivity despite geoelectric studies with only VES due to the lack of knowledge about aquifers characteristics. Few recent studies have proved that combination of geological and geophysical techniques (electrical trailing and vertical electrical sounding) are powerful tools to assess hydrogeological potential of aquifers and give opportunities to engineers to choose the right point where to drill and reduce the rate of boreholes failures in groundwater exploration in basement complex [3-7, 10-15]. Assessment of these aquifers characteristics by geoelectrical method could be an alternative by evaluating hydraulic parameters computed from Dar-Zarrouk parameter which is aquifer resistivity and thickness after 1D inversion [14-16]. This approach is rapid, produce high quality of results with a higher success rate and have a low-cost compare to Pumping test method, which require several boreholes, many operatives and a considerable amount of equipment [15, 16]. This paper aimed to contribute reducing borehole failure and improve the knowledge about structural, electrical and hydraulic characteristics of aquifers developed on granitic basement of Chad in general.

Figure 1. Wells used by population to satisfy their water needs at (A) Waguiré and (B) Anourchi

2. MATERIALS AND METHODS

2.1 Study area

Study areas (Figure 2) is located in Ouaddaï division, Eastern Chad at about 890 km from the capital N'Djamena. It covers an area of 29.940 km^2. Anourchi and Waguiré villages located there (prospected sites), are more precisely located in the township of Bourtail to the North-west of Abéché. They are respectively located within latitudes 13°53'28'' and 14°04'12'' North and longitudes 20°23'30'' and 20°38'35'' East. This study area is located in the Sahelian zone characterized by a hot and dry climate with low rainfall varying between 300 and 600 mm/year and temperatures ranging from 25 to 33°C. From a geomorphological point of view, the study areas present a contrasting relief made up of plains crossed in places by mountain ranges whose altitude varies between 480 and 820 m [17].

2.2 Geological and hydrogeological setting

The study area belongs to the basement complex of Ouaddaï in eastern part of Chad with Precambrian crystalline rocks consisting mainly of calcoalcaline granitic and granodioritic batholith known as regional granite [2, 18, 19] with similar characteristics with granitoids from Adamawa-Yade domain in Cameroon [18, 19]. These rocks are poorly appeared at the surface, but are influenced structurally by Pan - African tectonics structures [17-19] that play an important hydrogeological role in crystalline basement area [4, 7, 10-13]. In fact, these structures influence groundwater storage and circulation. According to the study [2], two aquifers are identified in Ouaddaï division: weathered and fractured aquifers. Weathered aquifer is unsaturated due to weak recharge by rainfall, and main permanent aquifer exploited is fractured aquifer.

2.3 Sampling and analytical methods

The approach used for this study to determine where to drill a positive borehole is a combination of geophysical techniques after taking into account, geomorphology and hydrolographic network. Geophysical techniques uses consisted of Electrical trailing (ET) and Vertical Electrical Sounding (VES). These geoelectrical techniques was performed according to the Schlumberger approach by using Syscal R1 - Plus resistivimeter from Iris Instrument. Structure and resistivity of aquifers was determined by calibration of geoelectrical sections with cuttings obtained during borehole drilling.

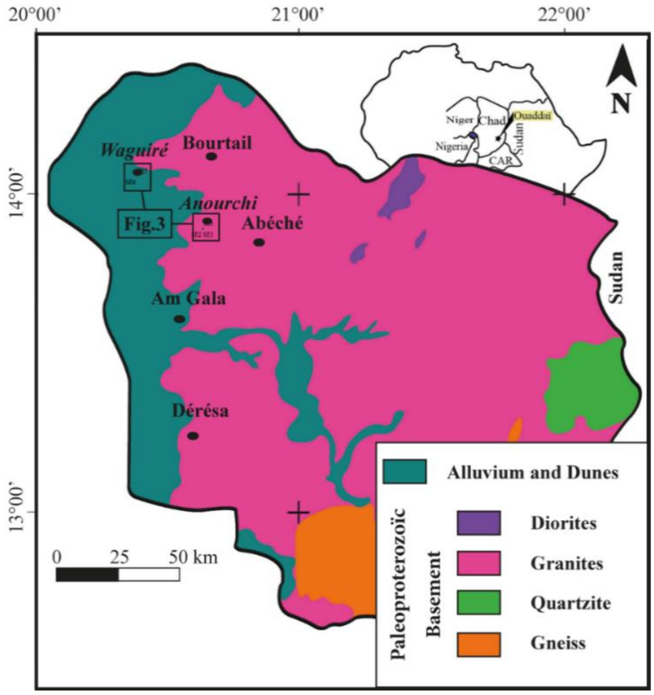

Figure 2. Location map of study areas in geological map of Ouaddaï Division (after [2] and [19])

For ET, four trailing profiles were chosen at each site. Profile of ET subjected to realization of VES were represented on sample map (Figure 3). Method consisted to determine lateral resistivity of field by moving laterally the electrodes (Figure 4A) AMNB through a given direction N150° (for ET1 to ET6), N175° (for ET7) and N220° (for ET8) to detect anomalies which could be a fault and where to put in place VES. This was done with constant spacing for MN (10 m) and spacing between AB varying from 130 m to 280 m with constant spacing between two points of measure which is 10 m. Resistivity profiles are made by using the Excel spreadsheet (Figure 4B). On these profiles, different contrasts of resistivity's corresponding to anomalies detected was mentioned. These anomalies can be conductive or resistive; and it is a conductive anomaly which is chosen for VES realization (e.g. Case of VES5 on Figure 4B). Thus, discontinuities are detected through identical conducting anomalies on several profiles. The implementation of the VES on the field (Figure 4C) was carried out with the spacing between the AB/2 electrodes vary from 1.5 to 100 m (at Waguiré) and 150 m (at Anourchi) with 18 measurement stations. This was made by successive and gradual measurements that leads to vertical exploration of subsoil where conductive anomalies were identify on ET (Figure 4B). At the end, eight VES points were sounded. Results of apparent resistivity obtained, was represent in function of distance (AB) in a bilogarithmic diagram (Figure 4D).

Initial interpretation of VES data is carried out using curve matching techniques with Ipi2win software [5] to obtained resistivity values and thickness of different layers. Based on lithological structure of field and VES curves, depth location of aquifer was chosen at place where anomalies observed in conformity with litho-logs obtained after boreholes drilling [20].

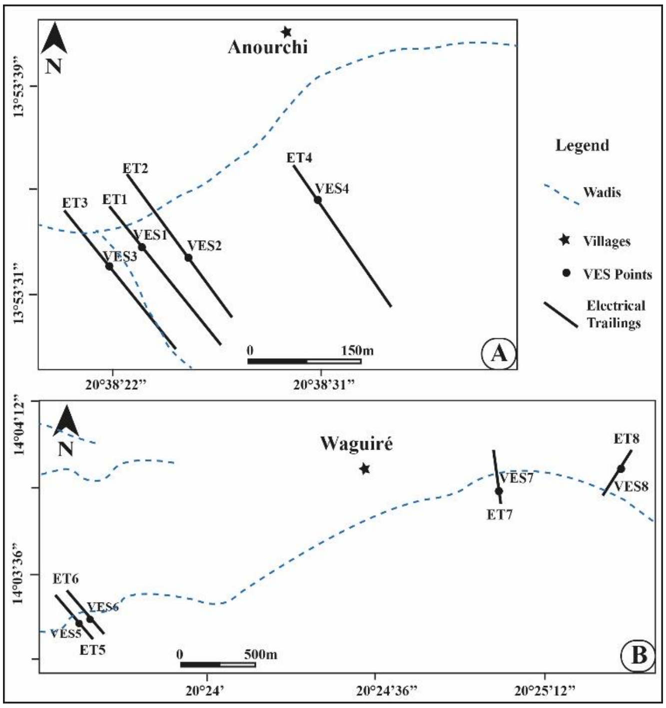

Figure 3. Sampling sites for geo-electrical prospection at (A) Anourchi and (B) Waguiré

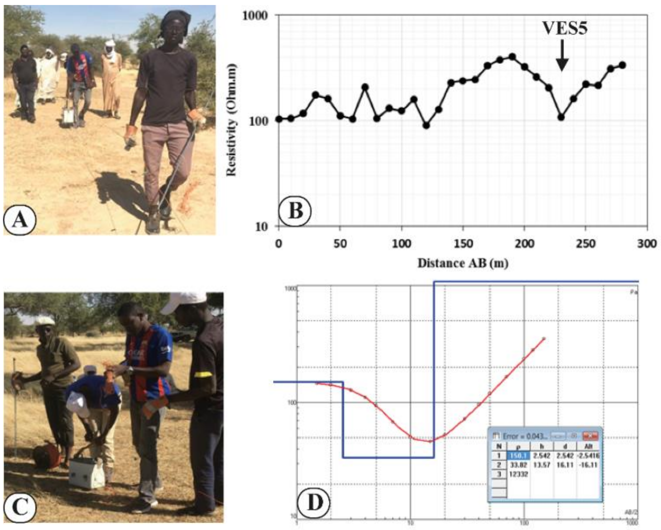

Figure 4. Implementation of geoelectrical methods on field and graph obtained (A and B) for Electrical trailing and (C and D) for VES

Geo-hydraulic parameters estimated from eight VES realized concern hydraulic conductivity, transmissivity and porosity. These hydraulic parameters were determined before choosing the point where to realize a borehole. Based on curves modelled, layers with lowest resistivity values are considered as aquifers and their resistivity with thickness are used to computed hydraulic conductivity (K in m/day), transmissivity (T in m²/day) and porosity (ϕ in %), using Eqns. (1), (2) and (3) extracted from previous work [14, 15], where they were applied to assess hydrogeological potential of aquifers.

$$K = 386.4\rho^{-0.93283} \quad (1)$$

$$T = K * h \quad (2)$$

$$\emptyset = 25.5 + 4.5\, lnK \quad (3)$$

where, ρ is the resistivity (Ω.m), h the thickness (m), of the aquifer layer.

After transmissivity values obtained, they were comparing to standards (Table 1) proposed in Refs. [14, 21], to assess aquifer potential and groundwater yielding potential.

At the end values of yield obtained from two boreholes realized where compare to those from previous study in the same lithological context to determine factors to take into consideration for choosing the right point in term of minimization of borehole failure.

Table 1. Groundwater potential based on transmissivity magnitudes classifications (T1 after [14] and T2 after [21])

T1 (m²/day)	T2 (m²/day)	Aquifer potential	Groundwater yielding potential
	> 1000	Very high	Very high withdrawal of great regional importance
> 500	1000-100	High	Withdrawal of lesser regional importance
500 – 60	100 – 10	Moderate	Withdrawal for local water supply (Small community and plants)
59 – 6	10 – 1	Low	Smaller withdrawal for local water supply (Private consumption)
5 – 0.5	1 – 0.1	Very low	Withdrawal for local water supply with limited consumption
< 0.5	< 0.1	Negligible	Sources for local water supply are difficult

3. RESULTS AND DISCUSSION

3.1 Trailing curves and their implications

Results of trailing curves was representing as a profile for a best interpretation (Figure 5). All these electrical profiles show resistivity values less than 1000 Ω.m with low levels of resistivity values which correspond to conductive fault zones [10]. Analysis of these profiles help to identify four types of conducting anomalies favorable for VES realization: U, V, H, and W (Figure 5). Anomalies "U" and "W" were obtained at Anourchi and Waguiré, while "H" and "V" anomalies were observed only at Waguiré. [10] classify different types of electrical trailing anomalies types in function of their potential yield. They show that hydrogeological potential decreasing from W, U, H and V shape respectively. Concerning "U – shape" anomalies (Figure 5A, 5B and 5C), it was observed along ET1, ET3 and ET7 where VES1, VES3 and VES7 were realized respectively. This anomaly corresponds to "large broad conducting compartment type" where productivity could be 7.2 m³/h, if borehole is drilled [10]. The width of conducting compartment is 30 m with apparent resistivity ranging from 158 to 195 Ω.m at Anourchi and from 55 to 73 Ω.m at Waguiré. "V-shape" anomalies (Figure 5D and 5E) with “H – shape” anomalies (Figure 5F) observed along ET5, ET8 and ET6 where VES5, VES8 and VES6 were realized respectively, correspond to a narrow conducting compartment type [10]. Measurement of conducting compartment width show average value of 20 m with apparent resistivity ranging from 90 to 205 Ω.m. “W – shape” anomalies (Figure 5G, and 5H) were observed along ET2 and ET4 where VES2 and VES4 were realized respectively.

This anomaly corresponds to “large broad conducting compartment type” which is recommend for borehole drilling [10]. The width of conducting compartment is 50 m with apparent resistivity ranging from 151 to 202 Ω.m.

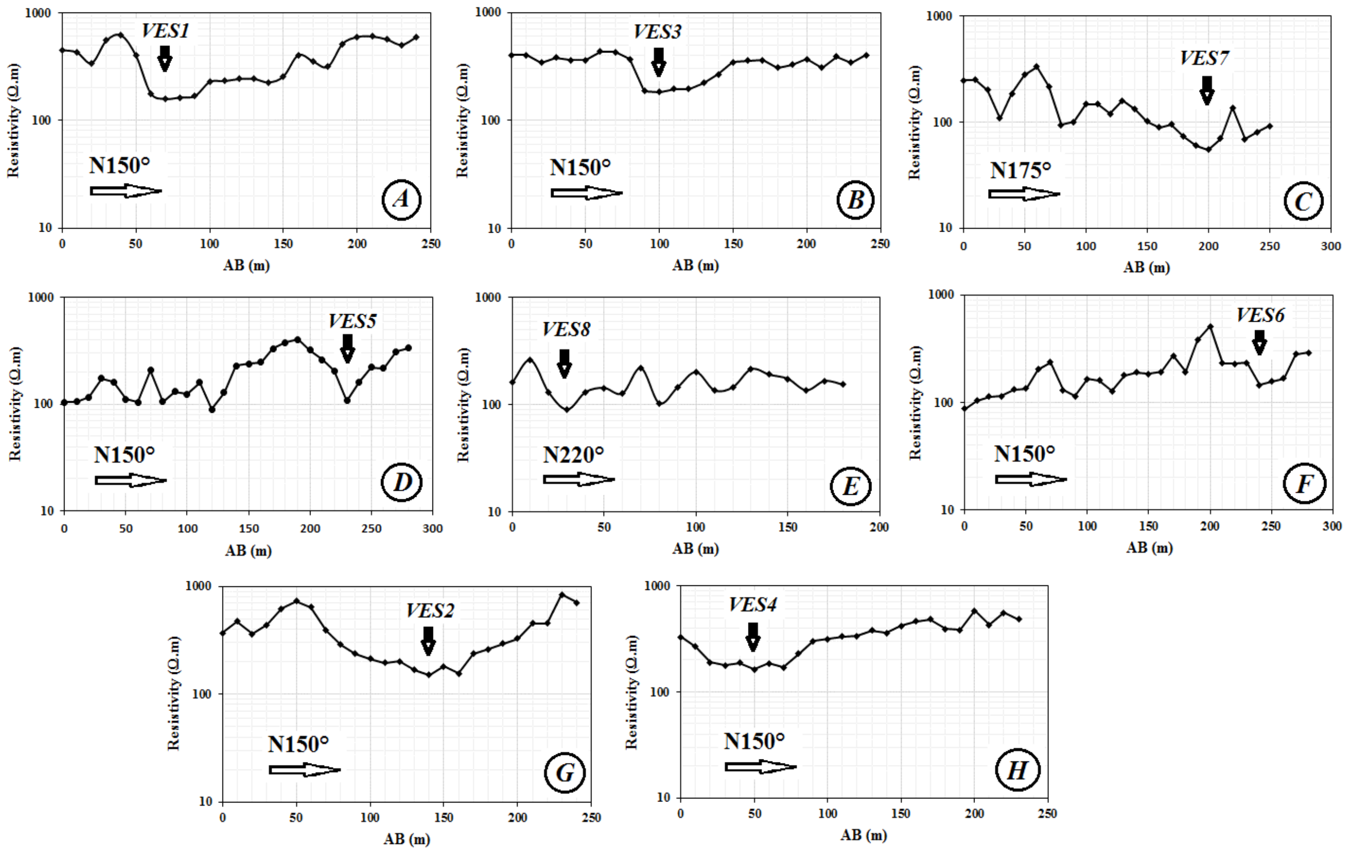

Figure 5. Electrical trailing shapes and location point of VES emplacement (A, B and C, U-shape; D and E, V-shape; F, H-shape; G and H, W-shape)

3.2 Sounding curves and aquifers location

Vertical electrical sounding analysis shows four types of curves: H, HA, QH and HKH (Table 2; Figure 6). All VES computed are recorded in table 1 and they show three to fifth electrically distinct layers. H-curve type (VES 1, 3 and 4) shows three electrically distinct layers (Figure 6A). First layer is resistive with resistivity values ranged from 48.17 to 150.10 Ω.m, and its thickness ranged from 0.75 to 2.54 m. This layer corresponds to topsoil and it is considered as the surface layer. High resistivity was obtained where we have indurated soil and low resistivity values, where sandy clay was observed. Second geoelectrical layers which are conductive corresponds to weathered layers or fractures zones that could be a potential aquifer. These layers have resistivities ranged from 4.6 to 43.79 Ω.m and thickness from 7.60 to 13.56 m. The last geoelectrical layers is very resistive with resistivity ranging from 9961 to 26456 Ω.m. This layer corresponds to less or more fresh massive hard granite. HA-curve type (VES 5; Figure 6B) and QH-curve type (VES 2 and 7; Figure 6C), shows four distinctive electrical layers, where the first layers which correspond to topsoil, are resistive with resistivities ranged from 30.82 to 545.4 Ω.m and thickness from 0.40 to 0.74 m. The second and third layers compare to the first and fourth layers are conductive with resistivities ranged from 4.60 to 43.79 Ω.m and thickness from 0.36 to 9.20 m. These two layers which are conductive could be a weathered layers with a high clay content, and/or fractures zones that could be a potential aquifer. The last fourth layer is resistive with values ranged from 5271 to 26456 Ω.m and correspond to basement rock. Based on resistivity, lower value observed on VES7 could be a less fractured bedrock, while high value observed on VES 2 correspond to fresh and unfissured basement rocks. HKH-curve type (Figure 6D) shows five electrically distinct layers (three resistive and two conductive layers). First layers with resistivity ranged from 51.78 to 100.40 Ω.m and thickness ranged from 0.64 to 0.90 m, are resistive and also considered as topsoil. In the field where observation was made, resistivity is high when proportion of quartz sand is high. Second layers are conductive with resistivity ranged from 7.05 to 21.51 Ω.m and average thickness around 1 m. This layer is considered as a weathered layer and could be a superficial aquifer.

Third layers are more resistive than the second one with resistivity ranged from 422.5 to 426.1 Ω.m and thickness ranged from 1.98 to 2.48 m. This layer according to field observation correspond to saprolite with residual basement rocks. The fourth layers are conductive and show resistivity ranged from 28.50 to 29.50 Ω.m and thickness ranged from 5.54 to 17.35 m. According to field observation, this layer corresponds to saprolite made of sandy clays with residual bedrock and / or fracture basement rocks which constitute fractures aquifers exploited by boreholes drilled in this area to satisfy water need of people. The fifth layer is resistive than the last one with the resistivity ranged from 536.2 to 60382 Ω.m. This layer corresponds to less fractured or fresh basement rocks.

All VES curve type obtained in this study are the same than those obtained in granitic environment in Nigeria [4, 12], Ivory Coast [10] and Cameroon [5, 7, 13]. Two geo-electric sections (respectively in Anourchi and Waguiré) were drawn to appreciate lateral and vertical structure of field (Figure 7). These curves and sections confirm lateral and structural heterogeneity of crystalline aquifers and their multilayers characters. Low resistivity value of aquifer obtained should be due to high clay content.

Table 2. Summary of VES results after inversion

VES Code	Number of layers	Resistivity (Ω.m) $\rho1 / \rho2/ ... / \rho n+1$	Thickness (m) $h_1 / h_2 / ... / h_{n+1}$	Curve type	Locality
VES1	3	83.16 / 17.15 / 14840	1.80 / 7.60 / -	**H**	**Anourchi**
VES3	3	150.10 / 33.84 / 9961	2.54 / 13.56 / -	**H**	
VES4	3	48.17 / 22.16 / 14653	0.75 / 11.50 / -	**H**	
VES2	4	96.89 / 39.09 / 22.35 / 26456	0.50 / 4.00 / 9.20 / -	**QH**	
VES7	4	545.4 / 43.79 / 6.09 / 5271	0.40 / 3.90 / 6.05 / -	**QH**	**Waguiré**
VES5	4	30.82 / 4.60 / 28.10 / 16727	0.74 / 0.36 / 6.15 / -	**HA**	
VES6	5	51.78 / 21.51 / 422.5 / 28.50 / 60382	0.90 / 1.11 / 2.48 / 5.54 / -	**HKH**	
VES8	5	100.40 / 7.05 / 426.1 / 29.50 / 536.2	0.64 / 1.03 / 1.98 / 17.35 / -	**HKH**	

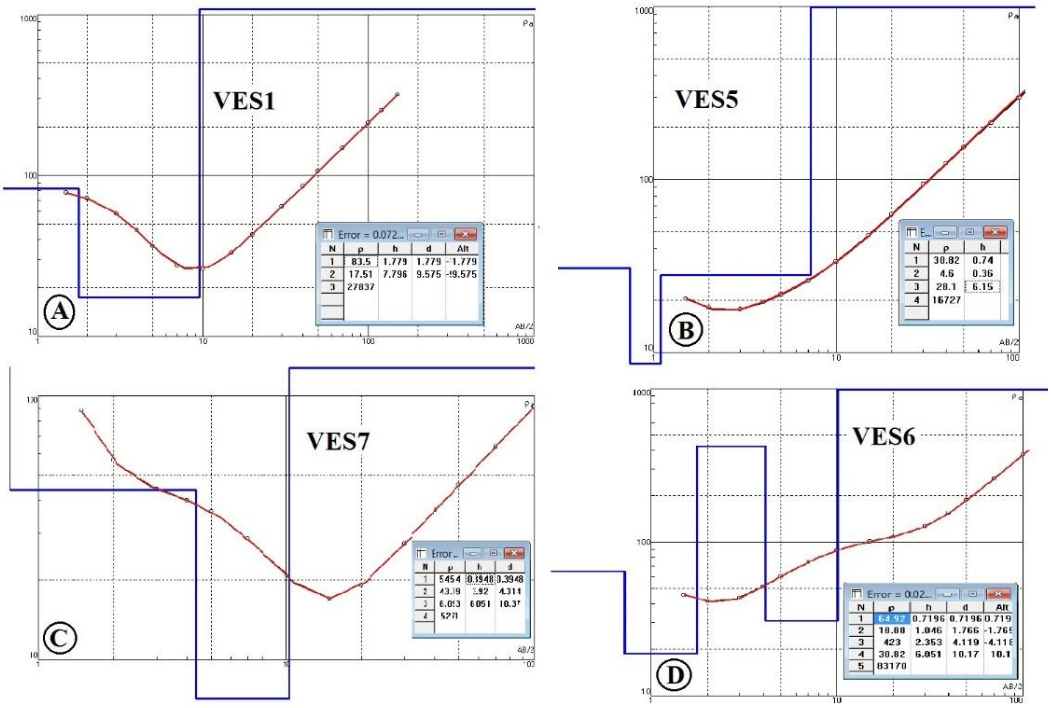

Figure 6. Main VES curve types A) H-type; B) HA - type; C) QH - type and D) HKH - type

3.3 Geo-hydraulic parameters of aquifers

The aquifer hydraulic conductivity (K) in general ranges from 14.19 (VES3) to 70.93 m/day (VES7) with an average value of 25.46 m/day (Table 3). This parameter which is an indicator for aquifer recharge potential, measure the ease with which a fluid will recharge aquifer vertically [15, 22]. Because of the need to choose a drilling point in each location, this parameter shows the following order of choice VES1 - VES4 - VES2 - VES3 in Anourchi, and VES7 - VES5 - VES6 - VES8 in Waguiré. The transmissivity (T) value ranges from 92.36 to 429.13 m²/day with an average value of 217.16 m²/day. This parameter describes according to the Ref. [23], lateral movement of groundwater in the aquifer and it should be lies directly to the borehole yields [15, 24].

The values obtained shows that aquifers in these localities have a moderate potential [14] or Moderate to high potential [21], and the order of choice the right point to drilled a borehole is VES4- VES1 – VES2 – VES3 in Anourchi, and VES7 - VES5 - VES6 - VES8 in Waguiré. [14] and [15], shows that areas with high transmissivity values correspond to those with high water bearing potential, and aquifer materials are highly permeable to fluid movement; then based on this remark the two points to be choose are VES4 (in Anourchi) and VES7 (in Waguiré). The estimated value of porosity of aquifer shows an average of 39.405% with range values from 37.44 to 44.68%. It shows that where porosity increases, aquifer resistivity reduces, and this may be due to clay content in lithological structure of the ground like suggested [3].

Table 3. Aquifer parameters estimated from VES results

VES Code	Aquifer Resistivity (Ω.m)	Thickness (m)	K (m/day)	T (m²/day)	Porosity (%)	Aquifer Potential	
						T1	T2
VES1	17.15	7.60	26.85	204.05	40.31	**Moderate**	**High**
VES3	33.84	13.56	14.19	192.41	37.44		
VES4	22.16	11.50	21.11	242.77	39.22		
VES2	22.35	9.20	20.94	192.66	39.19		
VES7	6.09	6.05	70.93	429.13	44.68		
VES5	28.10	6.15	16.89	103.89	38.22		
VES6	28.50	5.54	16.67	92.36	38.16		**Moderate**
VES8	29.50	17.35	16.14	280.03	38.02		**High**

3.4 Drilling data and aquifers productivity

The construction of a borehole to the right of VES4 (F_1) and VES7 (F_2) show the same structural model of lithology, from surface to 40.2 m and 32.3 m depth respectively at Anourchi and Waguiré (Figure 7). This lithological structure was made of four layers with different thickness: topsoil, saprolite layer (made of clayey sand and sandy clay), less or more fractured granites (aquifers) and fresh basement rock of granite (Figure 7).

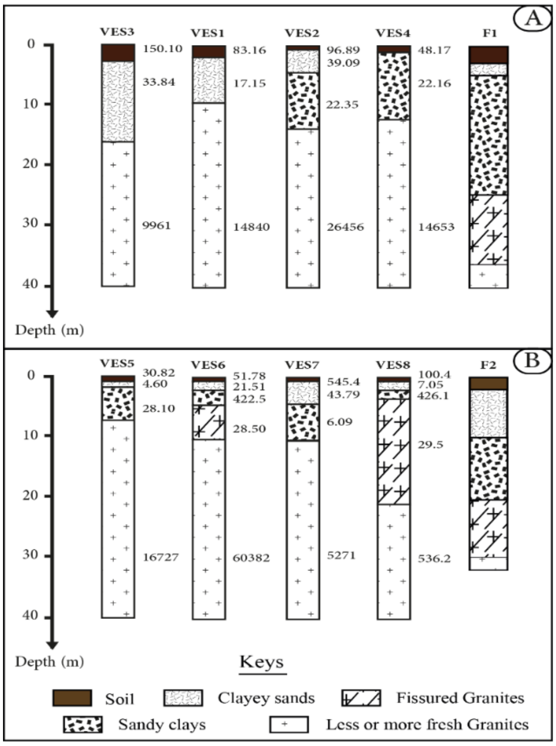

Figure 7. Resistivity section with Lithological structure of boreholes realized at (A) Anourchi for F_1 and (B) Waguiré for F_2

The two boreholes realized at right of "H and QH" VES curve type, shows a fractured aquifer between 25 to 36 m depth with aquifer productivity 3.12 m^3/h for F_1, and 21 to 30 m depth with aquifer productivity 2.72 m^3/h for F_2. The fact that these two boreholes with different yield realized at the different ET shape (W-shape for VES4 and U-shape for VES7), confirm that W-shape is more productive than those from U-shape like suggested [10]. This difference in productivity could be attributed to the width of conducting compartment which in the present case is 50 m from W-shape and 30 m from U-shape. High productivity of F_1 than F_2 could be also justify by the nature and the width of saprolite layer [7] which is more sandy in F_1 while it is more clayey in F_2 where low resistivity value (6.09 Ω.m) were observed.

Lithological structure obtained from borehole data are the same with those obtained in similar environment around the world like suggest many authors ([4] and [15] in Nigeria; [10] in Ivory Coast; [5, 7] and [14] in Cameroon). From these VES curves, H-type is more suitable than QH-type, if these curves are obtained from "W and U-shape" on electrical trailing.

4. CONCLUSIONS

This study shows that combination of hydrogeological and geoelectrical methods (electrical trailing and vertical electrical sounding) allows to locate suitable fractured aquifers and minimize borehole failure. Realization of two boreholes at right of different electrical trailing shape (W and U – shape), confirm that the more productive is borehole F_1, realize at right of W-shape of electrical trailing. Lithological-log show four layers: topsoil, saprolite layers, fractured aquifer and fresh basement rocks. Comparison between lithological structure and borehole productivity show that, the nature and the thickness of saprolite layer combine with the thickness and degree of fractured layer, influence on aquifer productivity. The fractured aquifers made of granites, are located from 21 to 36 m depth, with resistivities ranging from 6.09 to 33.84 Ω.m and yield from 2.72 m^3/h (at Waguiré) to 3.12 m^3/h (at Anourchi). Geohydraulic parameters range from 14.19 to 70.93 m/day, 92.36 to 429 m²/day and 37.44 to 44.68 % for hydraulic conductivity, transmissivity and porosity respectively. Transmissivity values computed suggest that groundwater potential range from moderate to high potential; and it should be taken into consideration before choosing where to drill a hole after geoelectrical investigation. The aquifers resistivities and productivity are more influenced by the high clays content and their thickness. These results obtained from method developed in this study provide more information that could help to understand hydrogeological context of granitic basement in Chad. Then combination of hydrogeological and geoelectrical exploration if applied anywhere in the same environment of Sub-Saharan Africa could reduce borehole failure and improved access to safe drinking potable water.

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REFERENCES

[1] Sultan, S.A., Mekhemer, H.M., Santos, F.M. (2009). Groundwater exploration and evaluation by using geophysical interpretation (case study: Al Qantara East, North Western Sinai, Egypt). Arabian Journal of Geosciences, 2: 199-211. https://doi.org/10.1007/s12517-008-0028-7

[2] Gombert, P. (1999). Stratégie de prospection hydrogéologique du socle de la bordure orientale tchadienne par optimisation du nombre et de la profondeur des sondages de reconnaissance. Revue des Sciences de l'Eau, 12(3): 597-608. https://doi.org/10.7202/705368ar

[3] Ibuot, J.C., George, N.J., Okwesili, A.N., Obiora, D.N. (2019). Investigation of litho-textural characteristics of aquifer in Nkanu West Local Government Area of Enugu state, southeastern Nigeria. Journal of African Earth Sciences, 153: 197-207. https://doi.org/10.1016/j.jafrearsci.2019.03. 004

[4] Toluwaleke, A., Bola, A., Rereloluwa, B. (2019). Geoelectric assessment of groundwater potential in supare Akoko, Southwestern, Nigeria. Environmental and Earth Sciences Research Journal, 6(2): 59-70. https://doi.org/10.18280/eesrj.060202

[5] Zebaze, A.T., Kopa, A.N., Kwekam, M., Temgoua, E. (2020). Assessment of hydrogeoelectrical characteristics of crystalline aquifers and groundwaters quality in Adamawa plateau: case of Mbakaou (Adamawa–Cameroon). Environmental and Earth Sciences Research Journal, 7(4): 153-163. https://doi.org/10.18280/eesrj.070405

[6] Wyns, R., Baltassat, J.M., Lachassagne, P., Legchenko, A., Vairon, J., Mathieu, F. (2004). Application of SNMR sounding for groundwater reserves mapping in weathered basement rocks (Brittany, France). Bulletin Société Géologique France, 175(1): 21-34. https://doi.org/10.2113/175.1.21

[7] Njueya Kopa, A., Kengni, L., Fonteh Fru, M., Nkouathio, D.G., Mebo Biloa, S.M. (2022). Characterization of aquifers and hydrogeochemical processes in Ngaoundéré, Adamawa region, Cameroon. Arabian Journal of Geoscience, 15: 1024. https://doi.org/10.1007/s12517-022-10294-0

[8] Nono, A., Likeng, J.D.H., Wabo, H., Tabue Youmbi, J.G., Biaya, S. (2009). Influence de la nature lithologique et des structures géologiques sur la qualité et la dynamique des eaux souterraines dans les hauts plateaux de l'Ouest-Cameroun, International Journal of. Biological and Chemical Sciences, 3: 218-239. https://doi.org/10.4314/ijbcs.v3i2.44516

[9] Lachassagne, P., Wyns, R., Dewandel, B. (2011). The fracture permeability of hard rock aquifer is due neither to tectonics, nor to unloading, but to weathering processes. Terra Nova, 23: 145-161. https://doi.org/10.1111/j.1365-3121.2011.00998.x

[10] Coulibaly, A., Lasm, T., Kouadio, K.E., Kouassi, W.F., De Lasme, O.Z., Baka, D., Yao, K.T., Savané, I., Biémi J. (2014). Contribution of electrical resistivity method to the location of aquifers of Precambrian basement in the Department of Tanda (North-Eastern, Côte d'Ivoire). Journal of Scientific Research and Reports, 3(5): 722-741. https://doi.org/10.9734/JSRR/2014/6463

[11] Kouakou, K.E.G., Dosso, L., Kouame, L.N., Sombo Abé, P., Sombo Boko, C. (2015). Contribution des méthodes de résistivité électrique à la recherché d'eau en milieu cristallin: cas de Yakassé-Attobrou et d'Abié, région de la Mé, Côte d'Ivoire. Revue ivoirienne des sciences et technologie, 26: 194-211. https://revist.net/REVIST_26/REVIST_26_12.pdf.

[12] Ayodele, F.O., Amigun, J.O., Olatunbosun Kafisanwo, O. (2019). Application of electrical resistivity and very low frequency electromagnetic induction methods in groundwater investigation in Ilara-Mokin, Akure Southwestern Nigeria. Environmental and Earth Sciences Research Journal, 3(6): 125-135. https://doi.org/10.18280/eesrj.060305

[13] Kenzo – Tongnang, M. L.S., Kenfack, J.V., Kengni, L., Njueya Kopa, A., Mouafo Saa, S., Ngantouo, J. (2021). Hydrogeological potential estimation of Ngoua watershed, West Cameroon, using petrography, Shuttle Radar Topography Mission (SRTM), and geophysical data. Arabian Journal of Geosciences, 14(2207): 1-14. https://doi.org/10.1007/s12517-021-08416-1.

[14] Nur, A., Taiyib, A., Nggada, I.S. (2021). Hydro-geoelectrical study for groundwater potential of Lassa and environs, North Eastern Nigeria. European Journal of Environment and Earth Sciences, 5(2): 18-23. http://dx.doi.org/10.24018/ejgeo.2021.2.5.181

[15] Obiora, D.N., Ibuot, J.C., George, N.J. (2016). Evaluation of aquifer potential, geoelectric and hydraulic parameters in Ezza North, southeastern Nigeria, using geoelectric sounding. International Journal of Environmental Science and Technology, 13(2): 435-444. https://doi.org/10.1007/s13762-015-0886-y

[16] Oguama, B.E., Ibuot, J.C., Obiora, D.N. (2020). Geohydraulic study of aquifer characteristics in parts of Enugu North Local Government Area of Enugu State using electrical resistivity soundings. Applied Water Science, 10(5): 1-10. https://doi.org/10.1007/s13201-020-01206-2

[17] Al-Hadj Hamid, Z. (2014). Caractérisation géotechnique des granites de la région de l'Ouaddaï (Est – Tchad) en vue de leur utilisation en Génie civil. Mémoire de Master's, Université de Dschang, Cameroun, p. 46.

[18] Nenadji, F.D. (2018). Croissance et remobilisation crustale au Pan-Africain dans le sud du massif du Ouaddaï (Tchad). Thèse de Doctorat, Université de Toulouse, France, p. 302. https://tel.archives-ouvertes.fr/tel-02401065/document.

[19] Shellnutt, J.G., Pham, N.H.T., Denyszyn, S.W., Yeh, MW., Lee, T.Y. (2017). Timing of collisional and post-collisional Pan-African Orogeny silicic magmatism in south-central Chad. Precambrian Research, 301: 113-123. http://dx.doi.org/10.1016/j.precamres.2017.08.021.

[20] Bakkali, S., Bouyalaoui, J. (2004). Prospection géophysique appliquée à l'évaluation des eaux souterraines de Mediouna (Tanger, Maroc). Journal des Sciences Pour l'Ingénieur, 4: 13-22. https://www.ajol.info/index.php/jspi/article/view/30007

[21] Krasny, J. (1993). Classification of transmissivity magnitude and variation. Groundwater, 31(2): 106–111. https://doi.org/10.1111/j.1745-6584.1993.tb01815.x

[22] George, N.J., Emah, J.B., Ekong, U.N. (2015). Geohydrodynamic properties of hydrogeological units in parts of Niger Delta, southern Nigeria. Journal of African Earth Science, 105: 55-63. https://doi.org/10.1016/j.jafrearsci.2015.02.009.

[23] MacDonald, A.M., Davies, J., Ó Dochartaigh, B.É. (2001). Simple methods for assessing groundwater resources in low permeability areas of Africa. In: British geological survey commissioned report, CR/01/168N, p. 71. https://nora.nerc.ac.uk/id/eprint/501046/1/gw_manual_lr.pdf.

[24] Graham, M.T., Ball, D.F., Dochartaigh, B.Ó., MacDonald, A.M. (2009). Using transmissivity, specific capacity and borehole yield data to assess the productivity of Scottish aquifers. Quarterly Journal of Engineering Geology and Hydrogeology, 42(2): 227-235. https://doi.org/10.1144/1470-9236/08-045