Hydraulic parameters evaluation of the Pan-African aquifer by applying an alternative geoelectrical approach based on vertical electrical soundings

Zakari Arétouyap*, Dieudonné Bisso, Jorelle Larissa Méli'i, Philippe Njandjock Nouck, André Njoya and Jamal Asfahani

Resumen

Para este estudio se realizaron cincuenta Sondeos Eléctricos Verticales (SEVs), de los cuales en 14 sitios se tenía información de muestreos de agua. Estos sondeos se interpretaron para determinar los parámetros hidráulicos del acuífero Pan-Africano en la región de Adamawa-Camerún, y estos fueron Transmisividad (T) y Conductividad Hidráulica (K). El enfoque utilizado es efectivo y aplicable a otras áreas similares, si se toman las suposiciones adecuadas. La resistencia transversal (RT) del acuífero oscila entre 24 y 31,350 Ω.m² con un promedio de 7476 Ω.m²; la resistencia transversal modificada (RTM) oscila entre 1526 y 28209 Ω.m² con un promedio de 7873 Ω.m²; la Transmisividad (T) oscila entre 4 y 17,4 m²/día con un promedio de 7.23 m²/día y una desviación estándar de 3.42 m²/día; y la Conductividad Hidráulica (K) varía de 0,07 a 0,74 m/día con una media de 0,31 m/día y una desviación estándar de 0,17 m/día.

Palabras clave: conductividad hidráulica, resistencia transversal modificada, transmisividad, resistencia transversal, Pan-Africano, mediciones *SEV*.

Abstract

The present article aims at determining hydraulic parameters of the Pan-African aquifer in the region of Adamawa-Cameroon, namely the transmissivity (T) and the hydraulic conductivity (K). For this, fifty vertical electrical soundings (*VESs*),including 14 performed near existing boreholes with known values of water resistivity, have been conducted in the region using the Terrameter ABEMSAS-1000 with a spacing of current electrodes (AB) varying from 2 to 600 m.The curve matching technique is used to set structural parameters then, an inverse technique algorithm fits both theoretical and field curves for each experimental. The transverse resistance TR and the transmissivity T for the interpreted 14 *VES* are computed, then used to establish two relationships: one between the modified transverse resistance (MTR) andthe transverse resistance (TR) and another between MTR and the transmissivity (T).This enabled to compute MTR (ranged from 1526 to 28209 Ω.m² with an average of 7873 Ω.m²),TR (ranged from 24 to 31350 Ω.m² with an average of 7476 Ω.m²), T (ranged from 4 to 17.4 m²/day with an average of 7.23 m²/day) and K (ranged from 0.07 to 0.74 m/day with an average of 0.31 m/day) values in the whole region. The approach used for this purpose is effective and exportable to other Pan-African regions in the world.

Key words: hydraulic conductivity, modified transverse resistance, transmissivity, transverse resistance, Pan-African, *VES* measurements.

Z. Arétouyap*
D. Bisso
J. Larissa Méli'i
P. Njandjock Nouck
Faculty of Science
University of Yaounde I, P.O. Box 812
Yaounde, Cameroon
*Corresponding author: aretouyap@gmail.com

A. Njoya
Institute of Fine Arts
University of Dschang, P.O. Box 32
Foumban, Cameroon

J. Asfahani
Geology Department
Atomic Energy Commission, P.O. Box 6091
Damascus, Syria

Introduction

Because of its relatively better quality (compared to surface water) and its potential ubiquity, groundwater plays a very important role in water resources management policies. However, aquifers that provide groundwater are mostly characterized among others by the hydraulic conductivity (Arétouyap *et al*., 2015). Indeed, the modelling and the behaviour of the groundwater during the upcoming exploitation strongly depend on this parameter as it informs us about the recharge capacity of the aquifer (Asfahani, 2007).

Nowadays, because of the imprecision and the low efficiency of the traditional methods of pumping test, geo-electrical methods are increasingly used since the late 70s through the world to model and predict groundwater behavior during the upcoming exploitation (Kelly, 1977). Jones and Bufford (1951) and Croft (1971) established a sound relationship between permeability and formation factor. Similar relationships were established between resistivity and well productivity (Vincenz, 1968), transmissivity and transverse resistance (Ungemach *et al*., 1969), saturated thickness resistivities and hydraulic conductivities (Kelly,1977), aquifer transmissivity and transverse resistance (Mazáč and Landa, 1979). Scarascia (1976) estimated the transmissivity through interpreting the electrical soundings in Italy. Asfahani (2007) applied the vertical electrical soundings technique to characterize the Neogene aquifer (Salamiyeh region in Syria) in terms of hydraulic conductivity, transmissivity, transverse resistance and thickness. Tahmasbi-Nejad (2009) and Anomohanran (2013) used also this resistivity method to study the water potential in areas of Behbahan-Azad (Iran) and Ukelegbe (Nigeria) respectively. Asfahani (2016) used surficial vertical electrical sounding technique (VES) to compute the aquifer hydraulic conductivity. Those alternative approaches have been successfully applied for characterizing the transmissivity of the Quaternary and Paleogene aquifers in the semi-arid Khanasser valley region (Northern Syria), and for determining the hydrodynamic parameters of the Pan-African aquifer in the Adamawa-Cameroon region (Arétouyap *et al*.,2015).

More recently, Asfahani (2016) developed a new practical and easy approach for computing the hydraulic conductivity of aquifer by taking into consideration only the groundwater salinity. The main objectives of the present paper are therefore the following:

1. to check the efficiency and the effectiveness of the recent Asfahani (2016)'s method, by applying his approach in another region than Syria;

2. to use his method to locate and characterize local aquifers in terms of hydraulic conductivity and in order to re-compute the hydraulic parameters of the Pan-African aquifer in the Adamawa-Cameroon region;

3. to compare the results of hydraulic conductivity and the transmissivity obtained by Asfahani's approach with those obtained previously.

Previous geophysical research

In hydrological terms, 150 to 300 km wide, the Adamawa plateau is called "the water tower of the region" because it feeds three of the four major watersheds of the country. The most recent hydrogeophysical survey conducted in the region (Arétouyap *et al*., 2015) enabled to infer major hydrodynamic parameters of the local aquifers. It revealed that almost all of them are made of the fractured portion of the granitic bedrock located at a depth ranging between 7 and 84 m, the thickness between 1 and 101 m, the resistivity between 3 and 825 Ω.m, the hydraulic conductivity between 0.012 and 1.677 m/day, the transmissivity between 0.46 and 46.02 m²/day, and the product $K\sigma$ between 2.1×10^{-4} and 4.2×10^{-4}. Those results were derived from an empirical relationship established by Arétouyap *et al*. (2015) between the aquifer resistance R and the product $K\sigma$, in a region considered as a single uniform geological unit.

Geomorphology and hydrogeology of the Adamawa Plateau

This study is conducted in the Adamawa-Cameroon region, located in the heart of Central Africa between 6° -8° north and 11° -16° east (Figure 1). The study region extends over a length of about 410km from west to east between the Federal Republic of Nigeria and the Central African Republic, with an area of 6782 km². The morphology of the region is of volcanic highlands, resulting from tectonic uplift and subsidence accompanied by intense magmatic emissions (Vincent, 1970; Tchameni *et al*., 2001). Although the average altitude is 1100 m, this region of a rugged terrain is limited at the North by a large cliff and an uneven escarpment of several hundred meters that dominates the area.

The center of the plateau is marked by soft forms barely accented and swampy valleys, dotted with mountains or/and volcanic cones. At the East, there are massifs resulting from the former erosion and tectonic movements around the regions of Meiganga and Bagodo. In the West, the terrain is mountainous with hills. Volcanic inheritance covers the North, the East and the South areas. One notes the presence of an assembly line which occupies an important part of the region, reaching altitudes greater than 2240 m at Mount Tchabal-Mbabo. There are also plains and basins such as the Tikar plain in the Mayo-Banyo division. The southern part is characterized by a huge plateau that gradually drops until the penepla in Djerem (Toteu *et al*., 2000).

The geological history of the Adamawa-Cameroon region is marked by three major events (Toteu *et al*., 2000):

- A long period of continental erosion from Precambrian to Cretaceous;

- The onset of volcanism from Cretaceous to Quaternary;

- Recurrent basement tectonics that explain the horst and graben structure of the region.

An investigation of superficial formations in the region has highlighted the Pan-African granite-gneiss basement, represented by Ordovician granites, gneisses and Pan-African migmatites. The main geological units present inthe study region are basalts, trachytes and trachyphonolites based mostly on concordant ttcalco-alkaline granites and discordant alkaline granites (Toteu *et al*., 2000). The presence of metadiorites of Paleoproterozoic basement it is also observed (Toteu *et al*., 2001). According to the same authors, major fractures of the Pan-African bedrock fall into two main directions:

- The most common direction oriented N 30 °E, is that of the "volcanic line of Cameroon";

- The second directed N 70 °E, corresponds to the "line of Adamawa" or "Adamawa shear zone".

Geophysical surveys revealthat the bedrock of the study area is intensely faulted (Robain *et al*., 1996; Cornacchia and Dars, 1983; Dumont, 1986; Njonfang *et al*., 2008; Toteu *et al*., 2004). Such tectonic activities augur potential existence of groundwater in the region. However, apart from Arétouyap *et al*. (2015) that considered the whole region as a single geological unit, there is no recent study
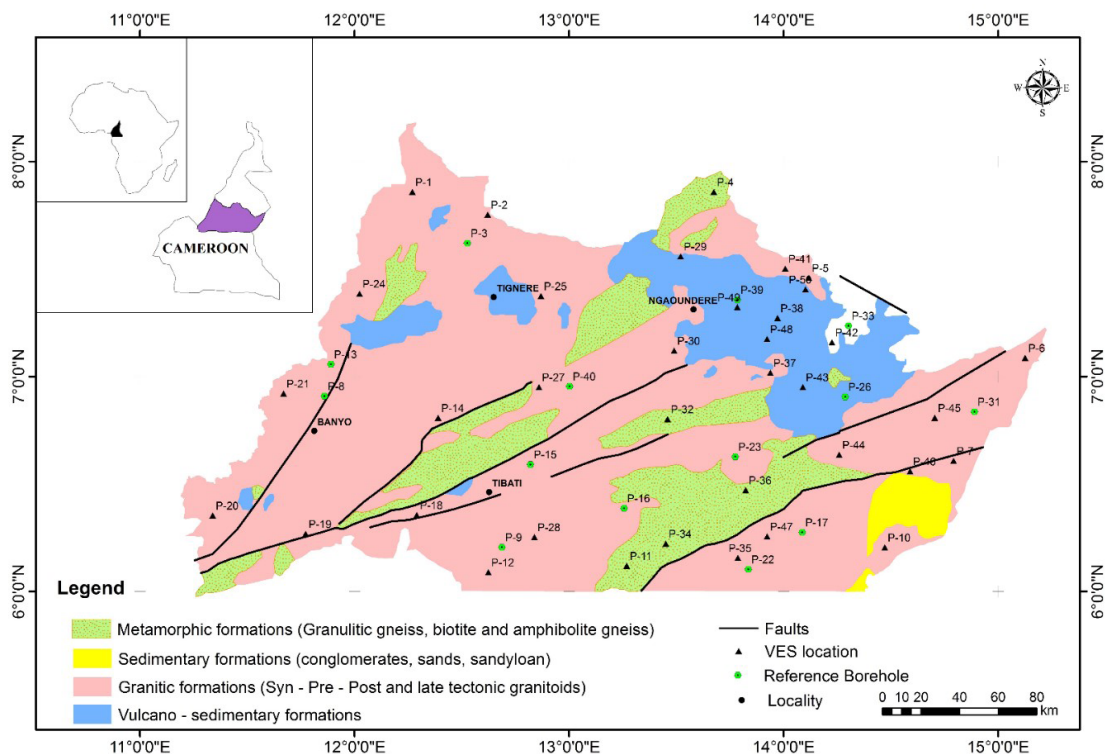
Figure 1. Geological map of the study area, with the locations of VES measurements (Maréchal, 1976) as amended.

to locate and characterize the local aquifers. This situation justifies the interest of the present paper.

Methodology

VES data recording and interpretation

A vertical electrical sounding (VES) with Schlumberger configurationis conducted in the region in order to locate and characterize the aquifers in the study region. With this technique, the electrical resistivity variations are expressed as a function of depth. Fifty vertical electrical soundings (*VES*) including 14 with available water samples have been conducted in the region using the Terrameter ABEMSAS-1000 with a spacing of current electrodes (*AB*) varying from 2 to 600 m.

In the present research, the curve matching technique is used to set structural parameters (Orellana and Mooney, 1966). Then, an inverse technique algorithm developed by Zohdy (1989) and Zohdy and Bisdorf (1989) fits both theoretical and field curves for each experimental. Dey and Morrison (1979) mentioned the possibility of considering and assuming the medium to be as a one-dimensional model (1D). The geological conditions in the study area were favorable and allowed us to assume and apply the 1D model. The 1D quantitative interpretation of the 50 VES has already enabled the identification of geoelectrical characteristics of the Pan-African deposits (Arétouyap *et al.*, 2015).

Hydraulic conductivity estimation

This section is the main core of the survey. The hydraulic conductivity is estimated by using the approach proposed by Asfahani (2016), which consists of the seven steps reminded below.

Determination of the water resistivity ρ_w

14 experimental VES measurements are carried out in the vicinity of available water samples(boreholes in function). Values of water conductivity (σ_w)from those 14 available water samples are measured, their water resistivity (ρ_w) values are thereafter deduced by using equation 1.
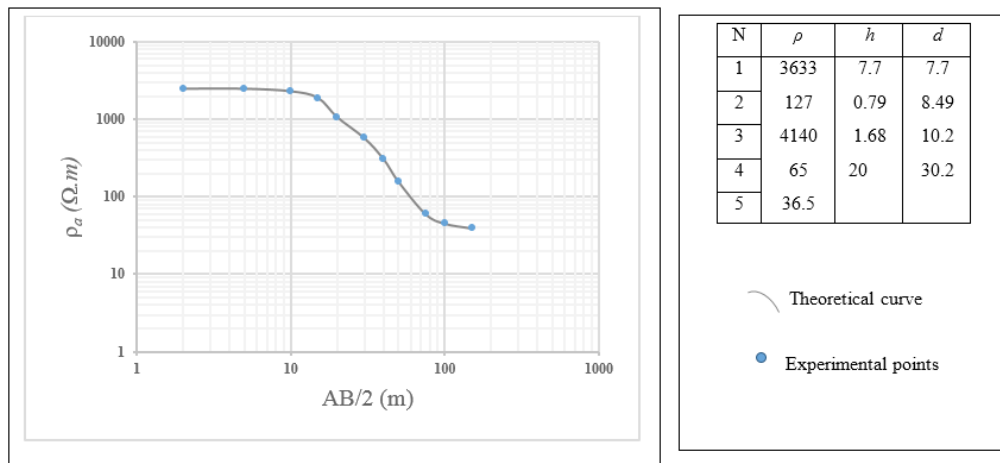
$$\rho = {}^1\!/\sigma_w \qquad (1)$$

Hence, the factor formation (*F*) used in Archie's law becomes a function of both σ_w and (ρ_w).

Those 14*VESs* have been quantitatively interpretedusing curve matching method (as illustrated in Figure 2), where the resulting resistivity (ρ_{rock}) and thickness (*h*) values are shown in Table 1.

Determination of the formation factor

The formation factor (*F*) used in Archie's law (Worthington, 1993) is computed as the ratio of ρ_{rock} and $\overline{\rho}_w$ (Equation 2).

$$F = \frac{\rho_{rock}}{\overline{\rho}_w} \qquad (2)$$

N	ρ	h	d
1	3633	7.7	7.7
2	127	0.79	8.49
3	4140	1.68	10.2
4	65	20	30.2
5	36.5		

Theoretical curve

Experimental points

Figure 2. An illustration of CMM interpretation of VES measurements.

In this Equation (2), ρ_{rock} represents the saturated aquifer resistivity estimated from the quantitative interpretation (using curve matching method as illustrated above) of *VES*, and $\bar{\rho}_w$ is the average pore fluid resistivity for the 14 reference *VES*. Water resistivity ρ_w is obtained through converting water conductivity σ_w since the conductivity is the inverse of the resistivity (see Equation 1).

Computation of the corresponding hydraulic conductivity

The formation factor *F* obtained previously using *VES* method is related to the hydraulic conductivity (Salem, 1999) as expressed by equation 3.

$$K\ (m/day) = 0.66528 \times F^{2.09} \qquad (3)$$

Estimation of the transverse resistance and the transmissivity for the 14 experimental VES

The transverse resistance *TR* and the transmissivity *T* for the interpreted 14 *VES* are computed using Equations 4 and 5.

$$TR = \rho_{rock} \times h \qquad (4)$$

$$T = \bar{K} \times h \qquad (5)$$

where $\bar{K}$ is the average value of hydraulic conductivity of the available 14 water samples shown in Table 1.

Expressing the MTR as a function of TR

The modified transverse resistance (*MTR*) is expressed by Equation 6 (Niwas and Singhal, 1985).

$$MTR = TR\ \frac{\rho_w}{\rho_w} \qquad (6)$$

Where $\bar{\rho}_w$ is the average water resistivity of the available fourteen water samples shown in Table 1, and ρ_w is the water resistivity at the location of the *VES* point (Table 1). Knowing $\bar{\rho}_w$ and ρ_w, *MTR* for the 14 *VES* points is plotted versus *TR* (Figure3).

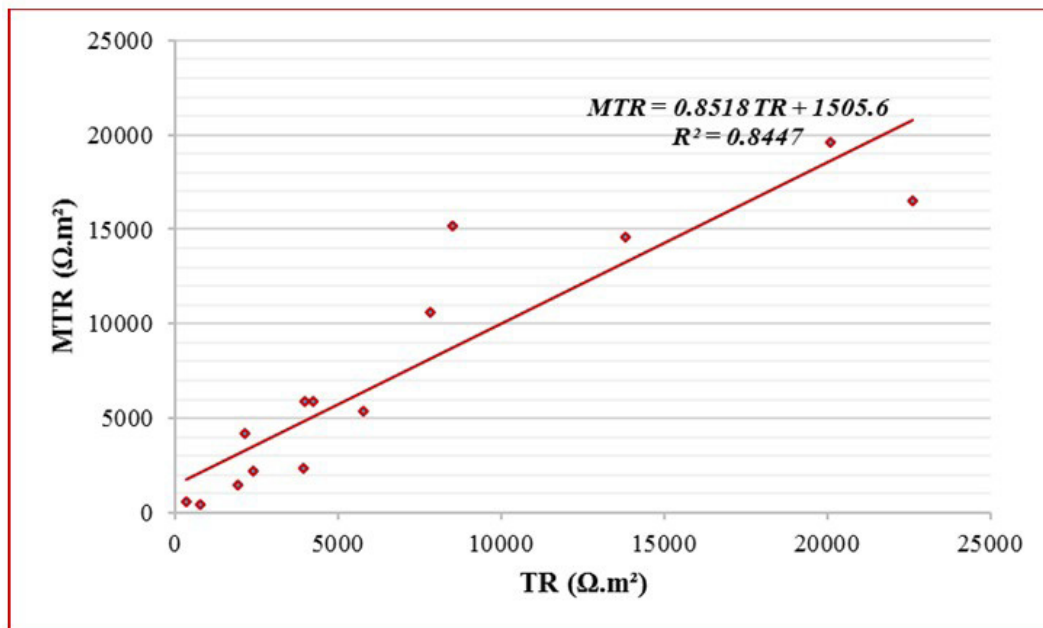This plot enabled to establish an empirical relationship between both parameters (equation 7).

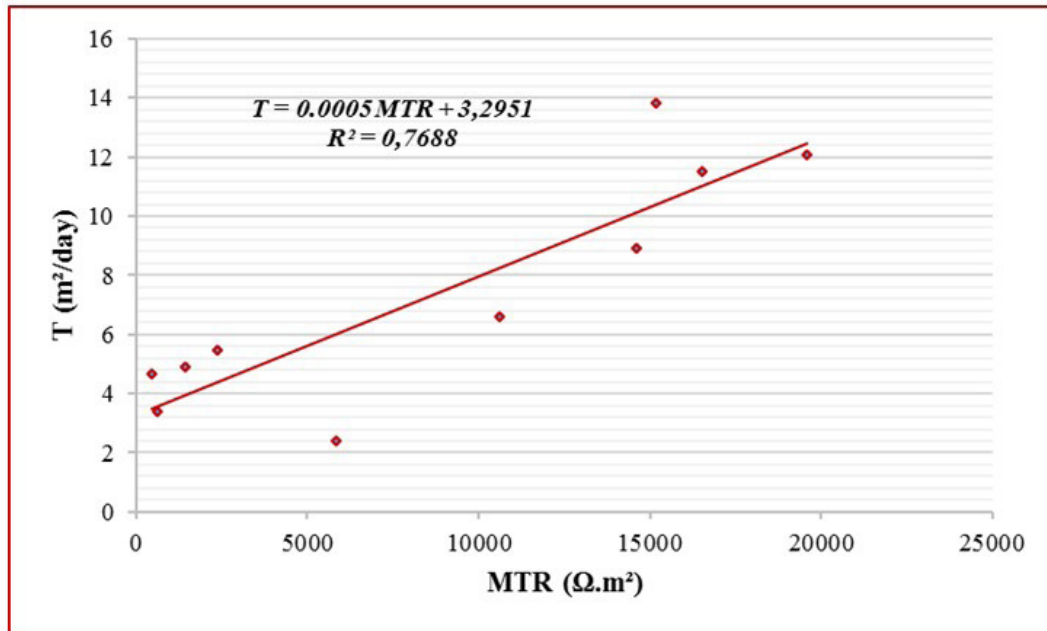$$MTR = 0.8518\ TR + 1505.6 \qquad (7)$$

With $R^2 = 0.8447$

Equation 9 will be used to extrapolate *MTR* values at the remaining *VES* points where no water sample exists.

Expressing T as a function of MTR

The transmissivity *T* is expressed as a function of the modified transverse resistance *MTR* (Equation 8) thanks to the plot (Figure 4).

Figure 3. *MTR* expressed as a function of *TR* for a suitable empirical relationship purpose.

Figure 4. *T* expressed as a function of *MTR* in order to establish an empirical relationship between both parameters.

$$T = 0.0005 \, MTR + 3.2951 \qquad (8)$$

With $R^2 = 0.7688$

Equation 10 will be used to extrapolate *T* values at the remaining 36 *VES* points where no water sample exists.

Extrapolation of T in the whole region

In order to estimate *MTR* values in the remaining 36 VES points without water sample, the formula established in equation (7) is applied. Equation 8 is thereafter used to compute *K* values in those VES without water sample. In other terms, since the transverse resistance of each point is known (as the product of rock resistivity by its thickness as expressed by earlier Equation 5) from VES interpretation, the empirical relationship established in Equation 7 enables us to obtain the modified transverse resistance as the product of the transverse resistance by 0.8518 plus 1005.6. Finally, the transmissivity of each point is obtained as the product of the modified transverse resistance by 5×10^{-4} plus 3.2951. This methodology takes into account the geological context of the study area as exposed in Section 3.

Results and discussion

This geoelectrical investigation consisted in applying the approach developed and proposed recently by Asfahani (2016) on 14 reference *VES*, then using the above calibrated relationships established to extrapolate aquifer parameters in the whole study area. Two relationships have been established: one between *MTR* and *TR* (Equation 7), and another between *T* and *MTR* (Equation 8). Those relationships were established assuming that the study area is geologically homogeneous and regular.

Hydrogeophysical parameters of 14 reference VES

Fourteen *VES* were conducted near existing boreholes with available water samples. Interpretation of those *VES* enabled to compute rock resistivity (ρ_{rock}) and aquifer thickness (h) at those points. The corresponding transverse resistance (*TR*), modified transverse resistance (*MTR*), formation factor (*F*) and hydraulic conductivity (*K*) are thereafter computed since the expression of water resistivity (ρ_w) is known. These parameters are represented in Table 1.

Those 14 reference boreholes have an average value of water resistivity $\overline{\rho}_w = 3.0$ Ω.m and an average value of hydraulic conductivity $\overline{K} = 0.29$ m/day. Those average values have been used respectively to compute *MTR* and *T*. Geophysical and hydrogeological parameters of those 14 reference *VES* points are summarized in Table 2.

Table 1. Hydrological and geophysical parameters of 14 reference *VES*.

VES	ρ_{rock} (Ω.m)	ρ_w (Ω.m)	h (m)	TR (Ω.m²)	MTR (Ω.m²)	F	K (m/day)	T (m²/day)
P-3	472.0	2.03	8.4	3964.8	5856.5	157.4	0.62	2.4
P-8	134.0	3.21	43.0	5762.0	5382.5	44.7	0.09	12.4
P-9	207.0	5.01	19.0	3933.0	2354.0	69.0	0.09	5.5
P-13	177.0	1.68	48.0	8496.0	15164.2	59.0	0.23	13.8
P-15	112.9	4.01	17.0	1919.3	1435.2	37.7	0.55	4.9
P-16	46.0	1.51	46.0	2116.0	4202.0	15.3	0.12	13.2
P-17	446.0	2.84	31.0	13826.0	14598.0	148.7	0.89	8.9
P-22	341.0	2.22	23.0	7843.0	10593.6	113.7	0.13	6.6
P-23	48.0	5.21	16.2	777.6	447.5	16.0	0.22	4.7
P-26	110.8	2.15	38.0	4210.4	5872.2	37.0	0.56	10.9
P-31	565.0	4.10	40.0	22600.0	16528.7	188.4	0.09	11.5
P-33	479.0	3.08	42.0	20118.0	19586.1	159.7	0.19	12.1
P-39	28.0	1.64	11.8	330.4	604.1	9.3	0.09	3.4
P-40	40.0	3.29	60.0	2400.0	2187.4	13.3	0.16	17.3

Table 2. Averaged statistical hydraulic and geophysical parameters of the 14 reference *VES* points presented in Table 1.

Parameter	Min	Max	Average
h (m)	8.40	60.00	31.67
ρ_{rock} (Ω.m)	28.00	565.00	229.05
ρ_w (Ω.m)	1.51	5.21	3.00
F	9.34	188.42	76.39
TR (Ω.m²)	330.40	22600.00	7021.17
MTR (Ω.m²)	447.54	19587.12	7486.57
K (m/day)	0.09	0.89	0.29
T (m²/day)	2.42	17.27	9.12

Hydrogeophysical parameters of 36 remaining VES without available water sample

MTR ant *T* at the 36 *VES* points without available water samples are obtained using the established empirical Equations 7 and 8. The resulting *MTR*, *T*, and *K* values enable to approximately characterize the Pan-African aquifer. Those values are presented and compared with previous results (Arétouyap *et al.*, 2015) as shown in Table 3. Significant changes between those results are visible in hydraulic conductivity and transmissivity values. This difference attests the necessity and the advantage of using this alternative approach, where salinity variations from place to place are taken into consideration.

Table 3. Hydrological and geophysical parameters of the 36 *VES* points without available water samples, in comparison with previous results (Arétouyap *et al.*, 2015).

VES	h (m)	ρ (Ω.m)	TR (Ω.m²)	MTR (Ω.m²)	T (m²/day)	T* (m²/day)	K (m/day)	K*(m/day)
P-1	25	811.0	20275.0	18775.85	12.68	26.62	0.51	1.06
P-2	47	362.1	17018.7	16002.13	11.30	39.25	0.24	0.84
P-4	48	175.7	8433.6	8689.34	7.64	8.09	0.16	0.17
P-5	20	608.0	12160.0	11863.49	9.23	16.93	0.46	0.85
P-6	6	157.0	942.0	2308.00	4.45	10.06	0.74	1.68
P-7	10	137.0	1370.0	2672.57	4.63	0.09	0.46	0.09
P-10	19	114.1	2167.9	3352.22	4.97	28.40	0.26	1.49
P-11	40	410.0	16400.0	15475.12	11.03	48.60	0.28	1.21
P-12	37	22.0	814.0	2198.97	4.40	43.25	0.12	1.17
P-14	8	8.0	64.0	1560.12	4.08	1.87	0.51	0.23
P-18	43	408.0	17544.0	16449.58	11.52	38.71	0.27	0.90
P-19	34	26.0	884.0	2258.59	4.42	6.91	0.13	0.20
P-20	61	188.0	11468.0	11274.04	8.93	13.76	0.15	0.23
P-21	19	221.5	4208.5	5090.40	5.84	42.63	0.31	0.55
P-24	17	112.9	1919.3	3140.46	4.87	3.29	0.29	0.33

For each *VES* point presented in Table 3, the K^* value of the hydraulic conductivity can be obtained as a ratio of the transmissivity T to the saturated thickness h obtained at that point. The spatial distribution of h is shown in Figure 5, where its values range from 6 to 84 m, with an average of 32 m.

The spatial distribution of the transverse resistance (*TR*) shown in Figure 6 reveals that *TR* values range from 330 to 22600 $\Omega.m^2$ with an average value of 7021 $\Omega.m^2$.

The distributions of the modified transverse resistance (*MTR*), transmissivity (*T*) and hydraulic conductivity (*K*) are also shown respectively in Figures 7, 8 and 9, and summarized in Table 4. Many similitudes are observed between *TR* distribution (Figure 6) and MTR distribution (Figure 8). Respective minimum and maximum values are located in the same regions. However, one can observe a minor dissimilarity in the variation rate and direction. This change can be explained by several factors as electric anisotropy, mineralogical variation, hydraulic anisotropy and lithological disparity. Furthermore, since the local aquifer results from the bedrock alteration/weathering, it is possible to have many mini aquifers confined in unconnected aquitards.

The transmissivity distribution shown in Figure 9 exhibits the existence of a poor-transmissive zone in the eastern part of the study area. Transmissivity values are low in this area contrary to the west and the center, where values can reach 17 m²/day. The presence of sedimentary formations can explain the easy spread of water in horizontal direction unlike the western area, covered by surficial granite.

However, it is important to note that hydraulic conductivity K varies in the opposite sense to transmissivity. Indeed, higher K values are observed eastward while lower ones are observed westward (Figures 8 and 9). This distribution can also be explained by the geological and lithological setting as in transmissivity distribution. On the other hand, the inverse proportion between hydraulic conductivity (derived from vertical flow) and transmissivity (derived from horizontal) can be due to the presence of vertical faults and lineaments in the region.

Transmissivity and hydraulic conductivity of the Pan-African aquifer are determined through the proposed alternative approach (Asfahani, 2016). However, the application of this approach recommends the respect of three fundamental principles:
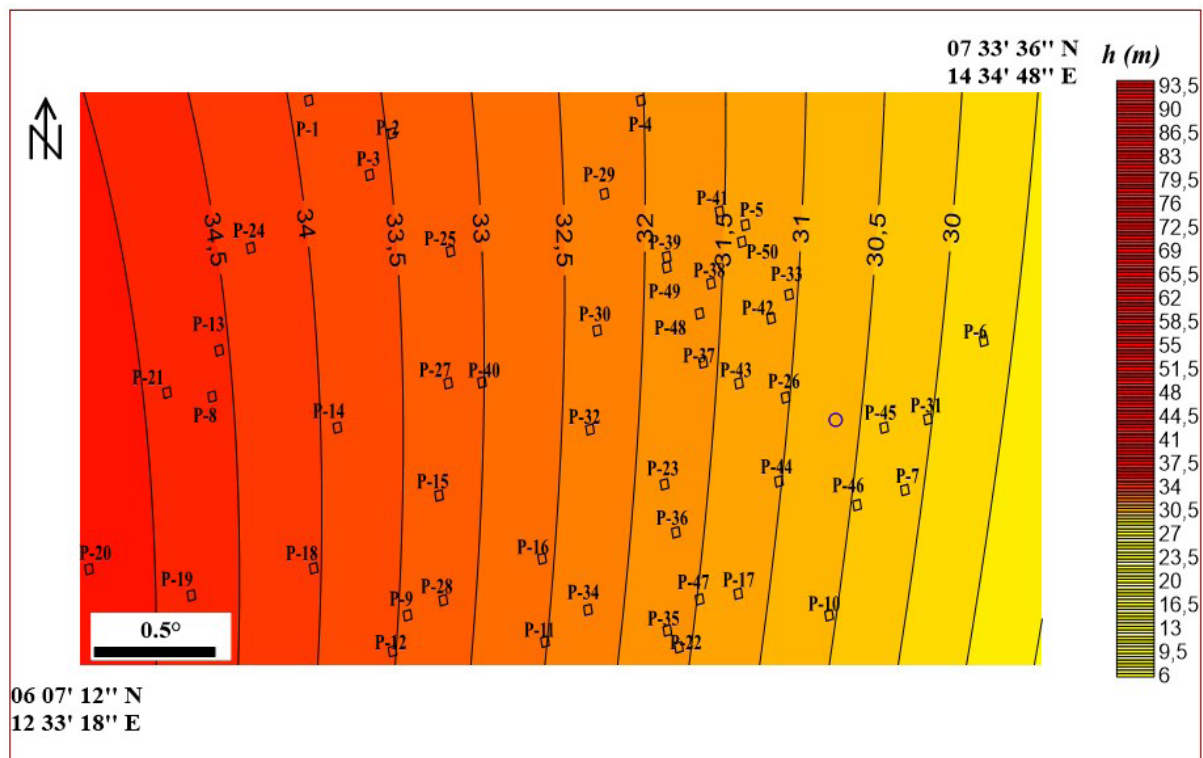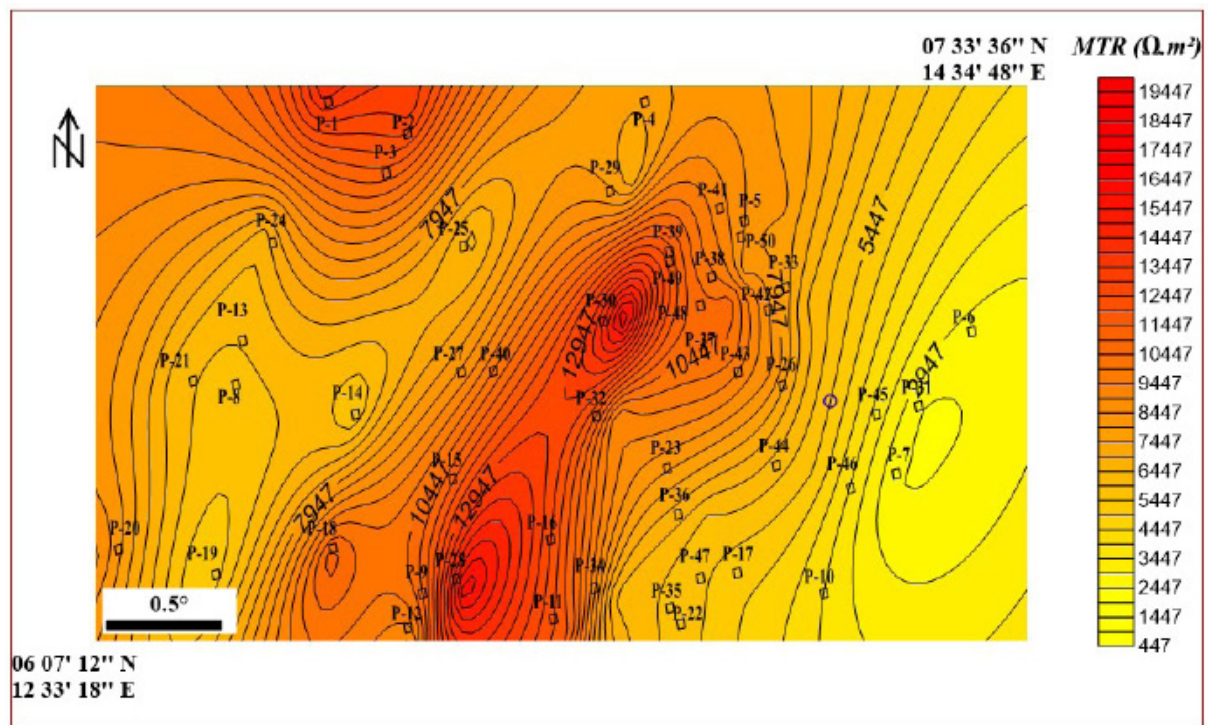

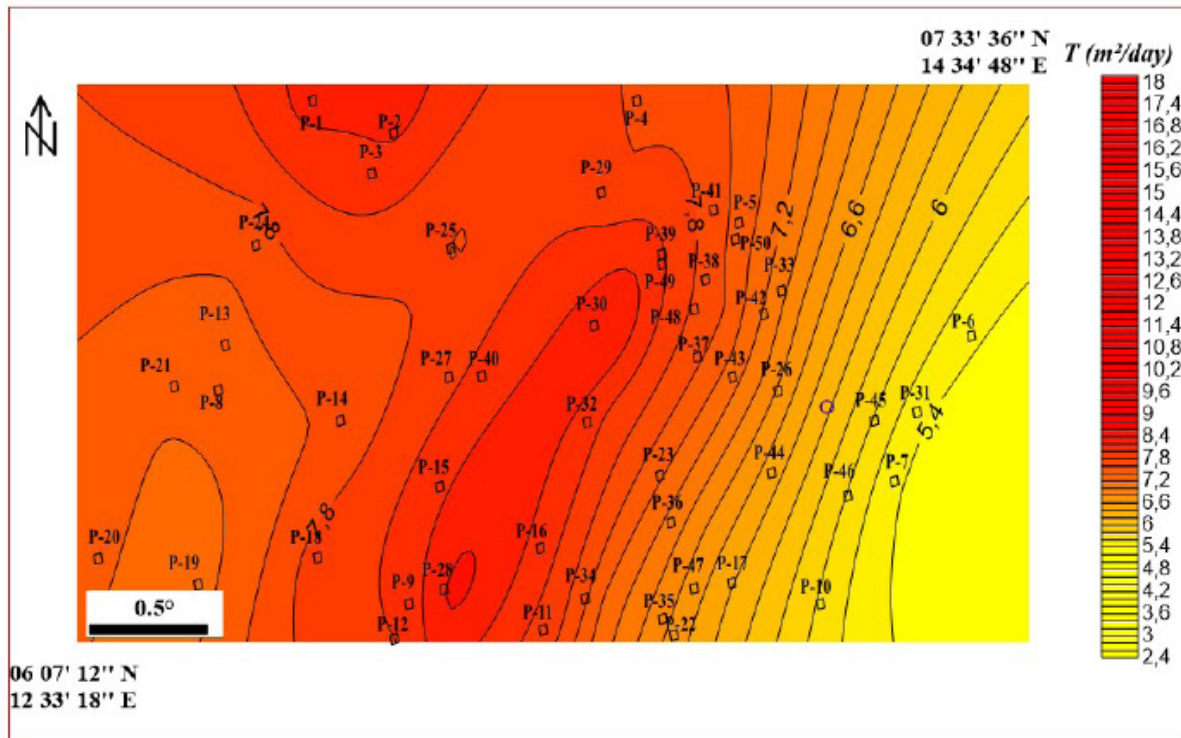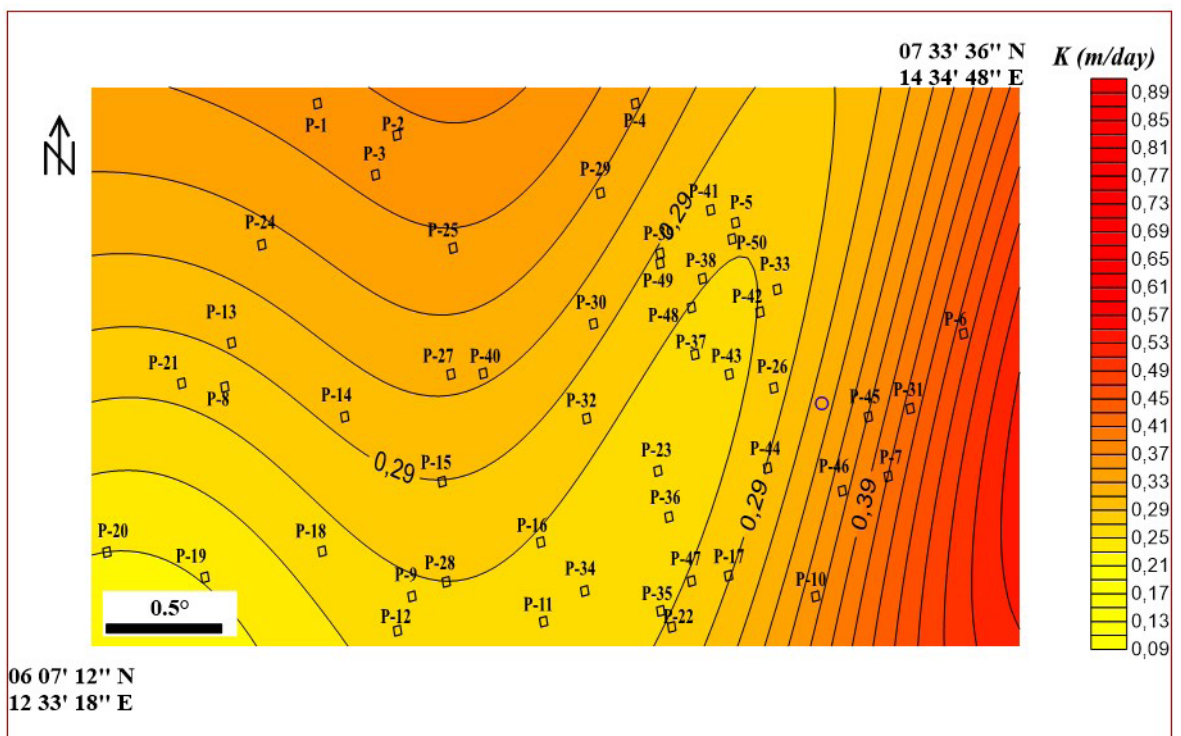**Figure 5.** Thematic map of the Pan-African thickness.
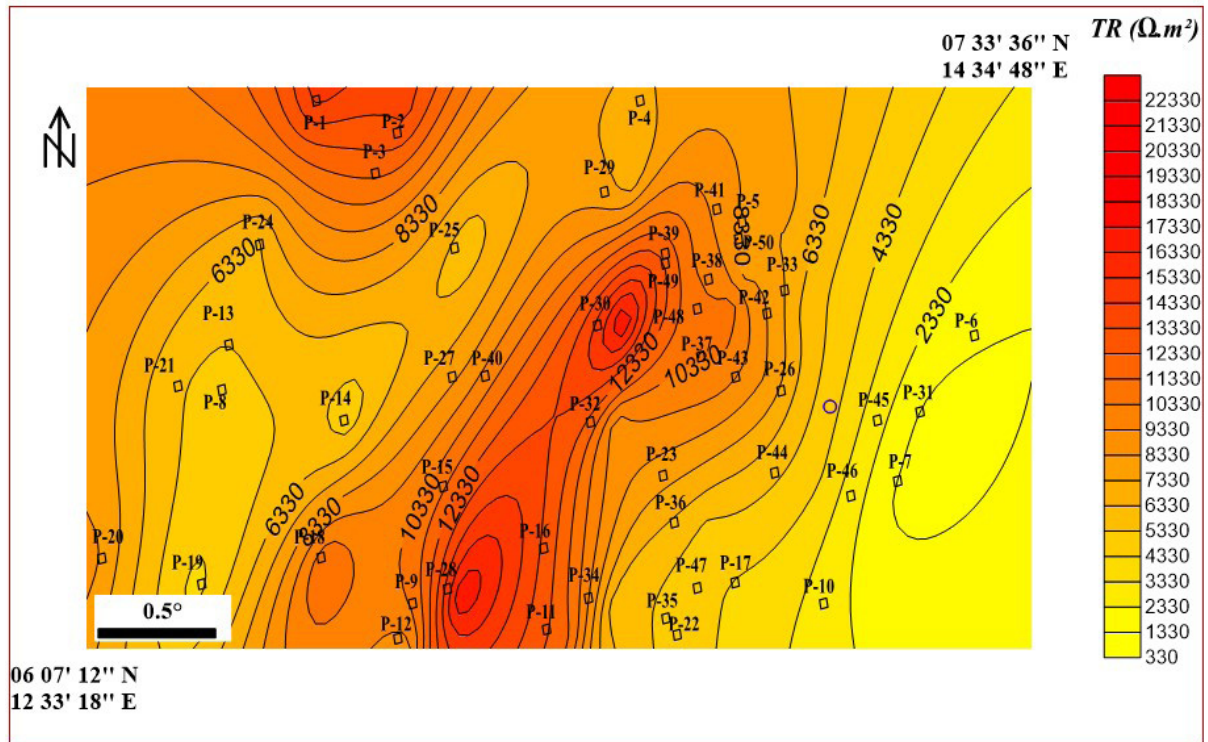
Figure 6. Thematic map of the Pan-African transverse resistance.

Figure 7. Thematic map of the Pan-African modified transverse resistance MTR.

Figure 8. Thematic map of the Pan-African transmissivity.

Figure9. Thematic map of the Pan-African hydraulic conductivity.

Table 4. Statistical hydraulic and geophysical parameters of the 36 *VES* points without available water samples.

| Parameter	Min	Max	Average	SD
h (m)	6	98	32.08	21.49
ρ_{rock} (Ω.m)	3	825	225.21	222.18
TR (Ω.m²)	24	31350	7476.20	----
MTR (Ω.m²)	1526.04	28209.53	7873.83	6844.31
K (m/day)	0.07	0.74	0.31	0.17
T (m²/day)	4.06	17.40	7.23	3.42
TR (Ω.m²)	24	31350	7476.20	----
MTR (Ω.m²)	1526.04	28209.53	7873.83	6844.31

1. Where there are water samples (the case of 14 reference *VES* points presented in Table 1), the hydraulic conductivity *K* is firstly estimated by such an alternative approach, while the transmissivity *T* is secondly computed by assuming an average constant hydraulic conductivity and a variable thickness *h* of the saturated aquifer.

2. Where there are no available water samples (e.g. 36 *VES* presented in Table 3), the transmissivity is firstly estimated by the proposed approach, while the hydraulic conductivity is secondly computed.

3. A field hydrogeological investigation should be conducted in order to estimate the uncertainty and the confidence level of this new proposed approach in the study area.

The first two rules are followed. In addition, the results obtained are compared with those of Arétouyap *et al*. (2015). This comparison shows a fairly good agreement between the values of the aquifer thickness and a slight agreement regarding the values of hydraulic conductivity and transmissivity (Figure 10). Those differences are due to the basis of the analysis method. In the previous study, Arétouyap *et al*. (2015) used an empirical linear relationship between *Kσ* and the resistance *R* of the aquifer, where *K* and *σ* represent the hydraulic conductivity and the electrical conductivity of the aquifer respectively. Yet in the present investigation, the aquifer hydraulic conductivity is the ratio of the transmissivity to the saturated thickness. Note that transmissivity values are derived from modified transverse resistance computed thanks to an empirical relationship between *MTR* and *T*. Furthermore, the present study has increased the number of reference boreholes, top to 14.
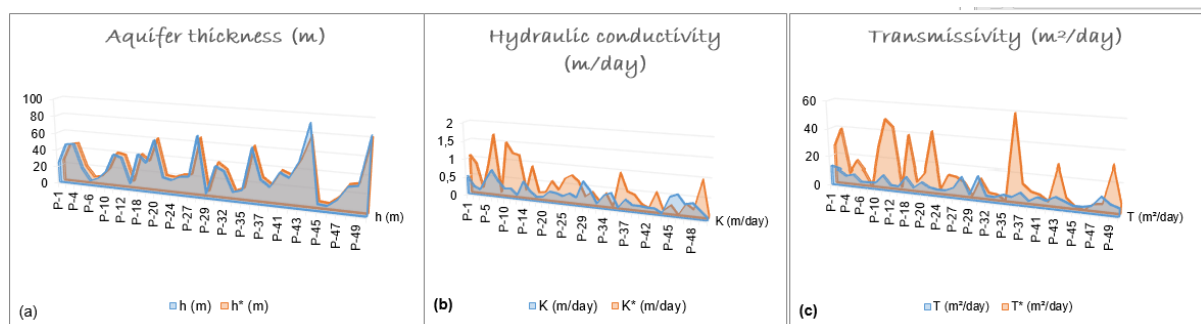
Figure 10. Comparison between aquifer parameters obtained respectively from former approach and newer one.

Discussion

Validation of the approach

The equation used to determine hydrodynamic parameters from this approach isan empirical relationship (Table 3). In order to assess its reliability, the values of transmissivity obtained experimentally from pumping tests and those computed analytically using equation 8, as shown in Table 5, we compared.

This comparison shows an absolute random ranging from 0.003 to 1.576 with an average value of 0.38, which is bearable. Thus, this method that has already been proven inthe Quaternary and Paleogene aquifers in the semi-arid Khanasser valley region of Northern Syria (Asfahani, 2016) can also be used in the Pan-African context.

Further conditions on the approach

Since *VES* results are highly influenced by electrical noise, land use and other economic activities such as agriculture, livestock, tannery etc., measurements may be carried out in locations far away from any electrical line from several anthropogenic activity centers. *K* values are generally influenced. In order to mitigate such negative impacts, *VES* measurements may be calibrated and their 1D quantitative interpretation must necessarily reflect the aquifer lithology. This is the case of *VES* measurements presented in the present study. Geostatistical analysis largely contributes in assuming that *VES* data are not influenced by electrical noise.

Contamination is another technical concern. The methodology proposed by Asfahani (2016) and applied in this paper is entirely based on water resistivity. Any contamination of that water may affect and modify its resistivity, and by consequence will affect the *K* values. This methodology must therefore be applied in a proper area, without any contamination influence. If this is not the case, the contamination factor and its influence on water resistivity must be calibrated and moved away. Fortunately, our study area is free of any relevant contamination.

Conclusions

The transmissivity (*T*) and the hydraulic conductivity (*K*) of the Pan-African aquifer in the region of Adamawa-Cameroon have been determined using an alternative method based on *VES* interpretation. 14 experimental *VES* conducted in the vicinity of existing boreholes with known water resistivity are interpreted using curve matching method. This interpretation led to two mathematical laws (empirical equations). The first equation establishes a strong relationship between the

Table 5. Comparison of analytical and experimental values for the 14 existing boreholes.

VES	T (m/day)	T#(m/day)	MTR (Ω.m²)	$\Delta T = \left\lVert \dfrac{T^{\#}-T}{T} \right\rVert$
P-3	2.42	6.22	5856.52	1.57
P-8	12.38	5.99	5382.48	0.52
P-9	5.47	4.47	2353.97	0.18
P-13	13.82	10.88	15164.20	0.21
P-15	4.89	4.01	1435.20	0.18
P-16	13.24	5.39	4201.97	0.59
P-17	8.92	10.59	14597.97	0.19
P-22	6.62	8.59	10593.60	0.29
P-23	4.67	3.52	447.54	0.25
P-26	10.94	6.23	5872.18	0.43
P-31	11.51	11.56	16528.71	0.003
P-33	12.09	13.09	19586.12	0.08
P-39	3.39	3.59	604.10	0.06
P-40	17.27	4.39	2187.41	0.75
Average				0.38

#Analytical values obtained from the empirical equation 9

modified transverse resistance (MTR) while the second links the transmissivity (T) to MTR. From those equations, aquifer of the study is characterized as follows: TR ranges from 24 to 31350 Ω.m² with an average of 7476 Ω.m²; MTR ranges from 1526 to 28209 Ω.m² with an average of 7476 Ω.m²; T ranges from 4 to 17.4 m²/day with an average of 7.23 m²/day; and K ranges from 0.07 to 0.74 m/day with an average of 0.31 m/day. A cross validation, comparing T values obtained respectively from pumping test and developed approach (Table 5) reveals a fairly agreement between both sets of values. This approach is then suitable for investigation in the Pan-African context extended from Africa to South America.

Acknowledgement

References

Anomohanran, O., 2013. Geophysical investigation of groundwater potential in Ukelegbe, Nigeria. Journal of Applied Sciences 13, 119-125.

Archie, E., 1942. The Electrical Resistivity Log as an Aid in Determining Some Reservoir Characteristics, vol. 8. Technical Publication 1422, Petroleum Technology. American Institute of Mining and Metallurgical Engineer, New York, USA.

Arétouyap, Z., Nouayou, R., NjandjockNouck, P., Asfahani, J., 2015. Aquifers productivity in the Pan-African context. Journal of Earth System Science,124(3): 527-539.

Asfahani, J., 2007. Neogene aquifer properties specified through the interpretation of electrical sounding data, Sallamiyeh region, central Syria. Hydrol. Process. 21, 2934-2943.

Asfahani, J., 2016. Hydraulic parameters estimation by using an approach based on vertical electrical soundings (VES) in the semi-arid Khanasser valley region, Syria. Journal of African Earth Sciences 117, 1-11.

Cornacchia, M., Dars, R., 1983. Un trait structural majeur du continent africain. Les linéaments centrafricains du Cameroun au Golfe d'Aden. Bulletin de la Société géologique de France 7, 101-109.

Croft, M.G., 1971. A method of calculating permeability from electric logs. In US Geological Survey Staff, Geological Survey Research 1971;Chapter B. US Geological.

Dey, H., Morrison, H., 1979. Resistivity modeling for arbitrarily shaped 3-D structures. Geophysics 44(4), 753.

Dumont, J.F., 1986. Identification par télédétection de l'accident de la Sanaga (Cameroun). Sa position dans le contexte des grands accidents d'Afrique centrale et de la limite nord du craton congolais. Géodynamique 1, 13-19.

Jones, P.H, and Bufford, T.B, 1951. Electric logging applied to groundwater exploration. Geophysics 16, 115-139.

Kelly, W. E. 1977. Geoelectric sounding for estimating aquifer hydraulic conductivity: Ground Water 15, 420-424.

Maréchal, A., 1976. Géologie et géochimie des ressources thermominérales du Cameroun. Doc ORSTOM 59, 169-176.

Mazáč, O. and Landa, I., 1979. On determination of hydraulic conductivity and transmissivity of granular aquifers by vertical electric sounding. Journal of Geological Sciences16, 123–139.

Niwas, S., Singhal, D.C., 1985. Aquifer transmissivity of porous media from resistivity data. Journal of Hydrology 82, 143-153.

Njonfang, E., Ngako, V., Moreau, C., Affaton, P., Diot, H., 2008. Restraining bends in high temperature shear zones: "The Central Cameroon Shear Zone", Central Africa. Journal of African Earth Sciences 52, 9-20.

Orellana, E., Mooney, H.M., 1966. Master Tables and curves for vertical electrical sounding over layered structures. Interciencia.

Robain, H., Descloitres, M., Ritz, M., Yene Atangana, J.Q., 1996. A multiscale electrical survery of a lateritic soil system of the rain forest of Cameroon. Journal of Applied Geophysics 47, 237-253.

Salem, H.S., 1999. Determination of fluid transmissivity and electric transverse resistance for shallow aquifers and deep reservoirs from surface and well-log electric measurements. Hydrological Earth System Sciences 3(3), 421–427.

Scarascia, S., 1976. Contributions of geophysical methods to the management of water resources. Geoexploration14, 265-266.

Tahmasbi-Nejad, 2009. Geoelectric investigation in the aquifer characteristics and groundwater potential in Behbahan Azad University farm, Khuzestan Province, Iran. Journal of Applied Sciences 9, 3691-3698.

Tchameni, R., Mezger, R., Nsifa, N.E., Pouclet, A., 2001. Crustal Origin of Early Proterozoïc Syenites in the Congo (Ntem Complex), South Cameroon. Lithos 57.

Toteu, S.F., Ngako, V., Affaton, P., Nnange, J.M., Njanko, T.H., 2000. Pan-African tectonic evolution in Central and Southern Cameroon: tranpression and transtension during sinistral shear movements. Journal of African Earth Sciences 36, 207-214.

Toteu, S.F., Van Schmus, W.R., Michard, A., 2001. New U-Pb and Sm-Nd data from North-Central Cameroun and its bearing on the pre-pan African history of Central Africa. Precambrian Res 180, 45-73.

Toteu, S.F., Penaye, J., Poudjom, Djomani, Y., 2004. Geodynamic evolution of the Pan-African belt in central Africa with special reference to Cameroon. Canadian Journal of Earth Sciences 41, 73-85.

Vincent, P.M., 1970. Conséquences tectoniques de la présence d'un métamorphisme crétacé au Cameroun, Annuaire Faculté des Sciences, Université de Yaoundé, Cameroun, 431-434.

Ungemach, P., Mostaghimi, F., Dupart, A., 1969. Essais de détermination du coefficient d'emmagasinement en nappe libre, application à la nappe alluviale du Rhin. Bulletin de l'Association Internationale d'Hydrologie Scientifique14, 169-190.

Vincenz, S.A., 1968. Resistivity investigations of limestone aquifers in Jamaica. *Geophysics* 33, 980-994.

Worthington, P.F., 1993. The uses and abuses of the Archie equations: the formation factor-porosity relationship. J Appl Geophys 30(3), 215–228.

Zohdy, A.A.R., 1989. A new method for the automatic interpretation of Schlumberger and Wenner sounding curves. Geophysics 54, 245–253.

Zohdy, A.A.R., Bisdorf, R.J., 1989. Schlumberger sounding data processing and interpretation program. US Geological Survey.