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Hydrogeophysical Characteristics of Pan-African Aquifer Specified Through an Alternative Approach Based on the Interpretation of Vertical Electrical Sounding Data in the Adamawa Region, Central Africa

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This study was carried out in the Adamawa region, which connects Cameroon, Central African Republic, and Nigeria together. The main objective of this work is to assess the geophysical aspects of the local Pan-African hydraulic conductivity (K), using the vertical electrical sounding technique (VES) as an alternative approach to pumping test. This economical, less-time consuming, and easy-to-process alternative technique provides more accurate hydraulic conductivity values than the traditional pumping test technique. The K values obtained by the VES technique (ranging between 0.4 and 6.0 m/day) match those obtained by the pumping tests results. A thorough analysis of the transmissivity values reveals the existence of two aquifer trends in the region: Trend-1 with transmissivity values ranging from 34.22 to 39.27 m^2/day with an average value of 35.44, and Trend-2, with transmissivity values of 7.87–34.44 m^2/day with an average value of 16.56. Maps of transmissivity (T), resistivity (ρ), thickness (h), transverse resistance (TR), and hydraulic conductivity (K) of the Pan-African aquifer, derived from quantitative VES data interpretation, are established. These parameters are of paramount importance to the management of groundwater resources. They are important in the sense that geological contexts similar to that of Pan-African aquifer cut across Africa and South America. Therefore, this article will be valuable to regions worldwide that are geologically similar to the Adamawa Region.

KEY WORDS: Geophysical methods, Groundwater exploration, Pan-African, Pumping test, Transmissivity.

INTRODUCTION

Quality water is becoming scarcer throughout the world especially in developing countries. This is due among others to climate change and such specific factors as drought, flood and pollution. Water scarcity is one of the major concerns worldwide (Allan 1998; Arétouyap et al. 2014; Srinivasan et al. 2017; Vogel 2017). Since surface water is the most pre-occupying category due to its poor quality, numerous stakeholders adapt their water resources management policy to the aquifers' characteristics. The present study investigates the groundwater sector in Central Africa, an area located just above

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the equator, where people, surprisingly, face serious water problems. The aquifer systems in this area have shortcomings. In fact, their hydrodynamic characteristics are unknown. Therefore, this article studies their productivity in terms of hydraulic conductivity, transmissivity, resistivity, thickness, and transverse resistance, with the aim of making their use successful and sustainable. Groundwater must be exploited very carefully to ensure its sustainability and avoid its depletion. Accordingly, an accurate aquifer modeling is needed for efficient management of groundwater resource. Hydraulic conductivity, which is of primary importance to the productivity of an aquifer, was initially determined using pumping test. However, because of its technical shortcomings, traditional pumping test is gradually being replaced by surficial VES technique since the late 1940s (Maillet 1947).

Geophysical surveys reveal that the bedrock of the area under study is intensely faulted (Cornacchia and Dars 1983; Dumont 1986; Ngako et al. 1991; Robain et al. 1996; Toteu et al. 2004; Njonfang et al. 2008). These studies highlight clearly that the Pan-African belt was tectonically active and portrays many lineaments, faults, etc. There is no doubt as to the existence of groundwater because a relationship between aquifer productivity and bedrock alteration has already been established although Arétouyap et al. (2015) were able to detect local aquifers and compute their major hydrodynamic parameters such as hydraulic conductivity, depth, thickness, resistivity, transmissivity, and the product $K\sigma$. That investigation revealed that the local aquifer system comprises the fractured portion of the granitic bedrock located at depths between 7 and 84 m. The hydraulic conductivity varies between 0.012 and 1.677 m/day, the resistivity between 3 and 825 Ω m, the thickness between 1 and 101 m, the transmissivity between 0.46 and 46.02 m^2/day, the product $K\sigma$ between 2.1×10^{-4} and 4.2×10^{-4}. However, within this survey, the whole region was assumed to be geologically uniform in the VES interpretation. Hence, there is apparently no recent study that describes the location and distinctive features of local aquifers. The desire to fill this information gap prompted this research. Based on that previous research, this study endeavors to extend the implementation of the same approach to the whole region and is carried out by taking into consideration the degree of relationship between transverse resistance and transmissivity of each VES with pumping test.

The study aims to: (a) apply the latest approach developed by Asfahani (2012), with the intention of dividing the area into two main hydrogeological zones according to the degree of relationship between transverse resistance and transmissivity of each VES with pumping test the resulting empirical relationships will help describe as precisely as possible the Pan-African aquifer in Central Africa; (b) compute Pan-African aquifer parameters such as thickness (h), resistivity (ρ), transverse resistance (TR), transmissivity (T) and hydraulic conductivity (K); (c) establish thematic maps of these parameters.

DESCRIPTION OF THE ADAMAWA PLATEAU

Location and Geology of the Region

This study was conducted in the Adamawa-Cameroon region, located between 6°–8°N latitudes and 11°–16°E longitudes in Central Africa (Fig. 1). The region is made up 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 to the north by a large cliff and an uneven escarpment of several hundred meters that dominates the area.

According to Toteu et al. (2000), the geological history of the region is marked by some major events such as a long period of continental erosion from Precambrian to Cretaceous, the onset of volcanism from Cretaceous to Quaternary and recurrent basement tectonics that explains the horst and graben structure of the Adamawa Plateau. Njonfang et al. (2008) further summarize the tectonic history of the area into three steps: Precambrian, Mesozoic, Tertiary, and Quaternary. They also confirmed the gneiss-granitic characteristics of the local basement and then classified major fractures encountered in the local Pan-African bedrock into two main directions: the most common being N 30°E and the other N 70°E.

This region is underlain by a Pan-African granite-gneissic basement, represented by granites, gneisses and Pan-African migmatites. Geological formations encountered in this region are basalts, trachytes, and trachyphonolites (Toteu et al. 2000). The study area consists of two major geological domains (Bachelier and Laplante 1953): (1) the
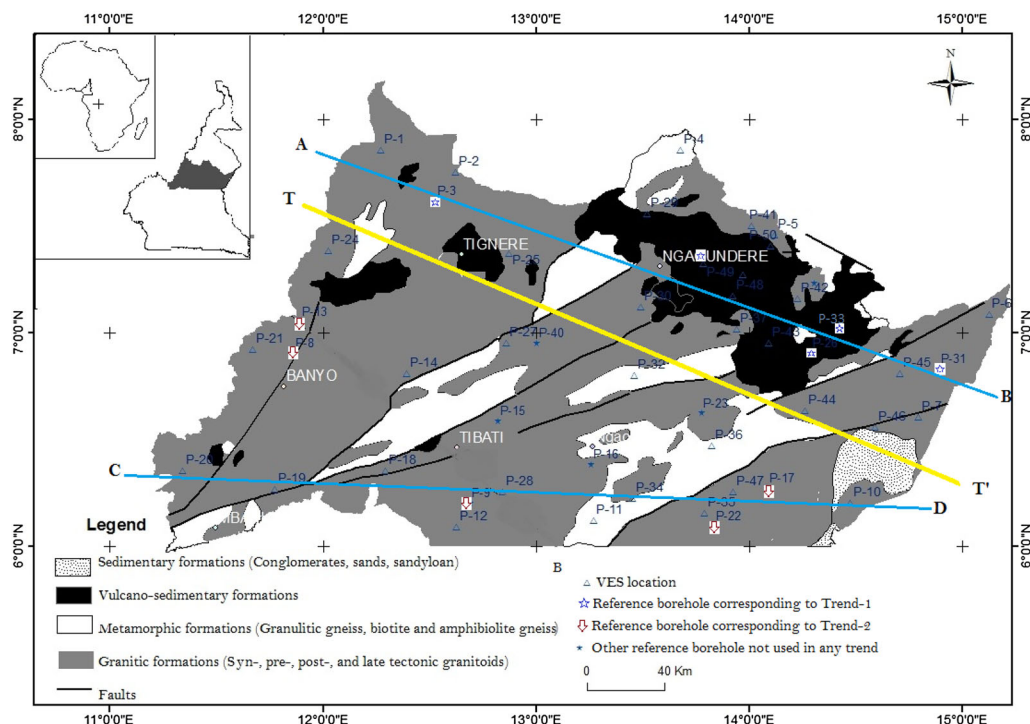
Figure 1. Geological map of the study area, with the locations of VES measurements (Maréchal 1976) as amended. Blue lines AB and CD represent two trend directions along which experimental boreholes were drilled. *TT'* is the demarcation line which divides the study area into parts according to the range of transmissivity values obtained.

former basement that includes highly metamorphosed formations (migmatitic, gneiss and mica), and intrusive bodies composed of granites, and (2) the cover formations made of red lateritic, sedimentary (sandstones and conglomerates), and volcanic (basalt and trachyte) rocks.

Hydrogeology of the Region

In hydrological terms, the 150–300-km-wide Adamawa plateau is called ''the water tower of region'' because of the important role it plays for the regional watersheds. Indeed, many local rivers derive from this region. There are also many crater lakes including Tyson, Mbalang, and Vina, which resulted from a long volcanic history in the region (Nguetnkam et al. 2002). Based on the work of Tillement (1972), Cameroon can be divided into two hydrogeological units, namely the crystalline basement and the sedimentary areas. Djeuda (1988) showed that the crystalline basement consists

essentially of two superimposed aquifers: a nearly isotropic upper aquifer located in arenas and regolith between 8 and 20 m depth, and a lower anisotropic aquifer, located in the fractured zone of the basement (bedrock) beyond 20 m deep. This configuration gives a captive dominant role for regolith reservoirs and a driver role for reservoirs in fractured bedrock. Therefore, these reservoirs have different hydrodynamic behaviors and properties.

MATERIALS AND METHODS

VES Data Recording

Schlumberger configuration was used to locate and characterize aquifers. With this technique, whereby electrical resistivity variations are expressed as a function of depth, 50 VES have been carried out in the study area using the Terrameter ABEM SAS-1000. The current electrodes expand from 2 to 600 m. The layer resistance $\Delta V/I$ was di-

rectly measured, and then its apparent resistivity ρ_a was calculated using the Ohm's law (Eq. 1), taking into account Eq. 2. The principle of this method is illustrated in Figure 2. Apparent resistivity depends on several factors such as true layer resistivities, their boundaries, and the electrodes location. However, lack of uniformity or layers split can be observed. This problem can be solved by generating alternative well-fitted curves and by adding further test wells (Asfahani 2007a, 2013).

$$\rho_a = k\frac{U_{MN}}{I} \tag{1}$$

where

$$k = \frac{2\pi}{\left(\frac{1}{AM} - \frac{1}{BM} - \frac{1}{AN} + \frac{1}{BN}\right)} \tag{2}$$

The curve-matching technique was used in this study for calibrating and interpreting the sounding curves (Orellana and Mooney 1966). Calibration was conducted with experimental boreholes drilled in the vicinity of several VES points. These experimental parameters were thereafter accurately interpreted using an inverse technique programme (Zohdy 1989; Zohdy and Bisdorf 1989). This was performed taking into account several cautions such as the precision in various calculations, a reasonable geological concept, and the assumption of a one-dimensional (1D) medium (Dey and Morrison 1979). The geological conditions of the region under study are favorable for assuming 1D model for VES data interpretation.

Hydrogeophysical Model Parameters

The methodology used for computing the hydrogeophysical parameters is the one used by Asfahani (2013). He established the expressions of major geoelectrical parameters as follows. The total transverse unit resistance R is given by Eq. 3.

$$R = \sum_{i=1}^{n} h_i \rho_i \tag{3}$$

The Dar Zarrouk parameters, namely aquifer transmissivity, resistivity, hydraulic conductivity, and transverse resistance are also used in this work in order to characterize as precisely as possible the Pan-African aquifer in the Adamawa Plateau. The transverse resistance (TR) was also determined for the Pan-African aquifer, and computed for the 10

interpreted VES by Eq. 4, where 10 close available pumping tests are available.

$$TR = \rho h \tag{4}$$

In this equation, ρ and h represents, respectively, the true resistivity and the saturated thickness of the Pan-African strata at the VES location.

Pumping Test

The pumping test was carried out by making flow levels, with constant flow for a short period of 1–8 h. Three parameters (time, drawdown, and flow) were measured. Each flow level was followed by a pumping break for a period at least equal to the rise of water level and measuring the residual drawdown. This operation aimed at determining in an experimental manner the values of the flow rate Q and then transmissivity T (Eq. 5) for each point, before calculating the transverse resistance.

$$T = \frac{0.183Q}{\Delta s} \tag{5}$$

This operation also enabled the plotting of two curves of the empirical relationships between the transmissivity T obtained from pumping tests, and the transverse resistance TR obtained from quantitative VES interpretations.

Extrapolation of Transmissivity Values

Transmissivity is the rate of flow under a unit hydraulic conductivity gradient through a unit width of aquifer of a given saturated thickness. Its values enable us to estimate the possibility of groundwater abstraction, in the first approximation. The alternative approach recently developed by Asfahani (2012) to compute aquifer transmissivity, based on the use of VES close to the wells with available pumping tests, was used in this work to determine the aquifer transmissivity. It consists in finding an empirical relationship between transverse resistance TR derived from VES interpretation and transmissivity T derived from the 10 available pumping tests. This approach was successfully applied in computing the Quaternary aquifer in the Khanasser valley in Northern Syria (Asfahani 2012).

Two relationships were thereafter established between the transmissivity T (derived from pumping
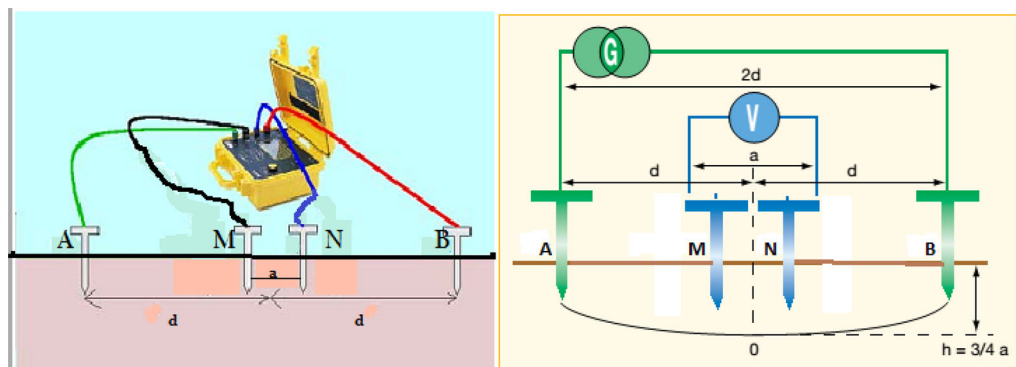
Figure 2. Schlumberger configuration used for recording VES data.

tests) and the transverse resistance TR (derived from VES interpretations). The first one was established in the northern part above the demarcation $T–T'$ line, and the second was established in the southern part below the demarcation $T–T'$ line as shown in Figure 1. These relationships reveal the existence of two major aquifers, according to the transmissivity expression, in the region under investigation. For each trend corresponding to an aquifer, a logarithmic regression fits with the two parameters as expressed by Eqs. 6 (Trend-1) and 7 (Trend-2).

$$T = 4.350\ln(\mathrm{TR}) - 11.91 \qquad (6)$$

$$T = 1.239\ln(\mathrm{TR}) + 28.63 \qquad (7)$$

In this study, transmissivity variation may be due to the nature of geologic formations, their degrees of alteration and metamorphism, the presence of any other subordinate lithology within the geological formation, and other factors. Indeed, as an unaltered formation, clay is mostly unfractured and has low-transmissivity values. As a result, layers altered to clay are generally not aquifers. In addition, aquifers overlain by clay are generally less productive. In contrast, layers made of fractured rock like cracking granite are very transmissive and mostly constitute the local aquifer.

RESULTS AND DISCUSSION

VES Interpretation and Correlation with Existing Boreholes

Calibration was conducted with experimental boreholes drilled in the vicinity of several VES points (Fig. 3). The lithology obtained from borehole P-9 displays, from top to bottom, clay, cracking granite, and granite. The interpretation of the VES, using inverse slope method, conducted in the vicinity of this point reveals that the first layer has a thickness of 1 m and a resistivity of 713 Ωm, the second layer has a thickness of 34 m and a resistivity of 301 Ωm, and the third layer has a resistivity of 1164 Ωm with an infinite thickness.

The lithology obtained from borehole P-13 displays, from top to bottom, laterite, clay and basalt. The interpretation of the VES, using inverse slope method, conducted in the vicinity of this point reveals that the first layer has a thickness of 2 m and a resistivity of 311 Ωm, the second layer has a thickness of 3 m and a resistivity of 656 Ωm, and the third layer has a resistivity of 318 Ωm with an infinite thickness. The interpretations of P-14 and P-23, performed in the same way, are presented in Figure 3.

The 1D quantitative interpretation of the 50 VES helped to characterize the Pan-African deposits (Arétouyap et al. 2015). Figure 3 presents the geoelectrical interpretation of some VES points (P-9, P-13, P-14, and P-23) and shows the resistivity and thickness of the Pan-African aquifers located in the study area. These profiles were selected on the basis of two criteria: the accessibility of the area and especially the existence of almost all geological formations present in the region (sedimentary, granitic, metamorphic, volcano-sedimentary formations). All these geological formations are contained in both profiles. The weathered horizon (with lower resistivity), in blue color in Figure 4, represents the aquifer. Both Trend-1 and Trend-2 cross the aquifer horizon interpreted from, respectively, VES points sets {P-3, P-48, P-33, P-31} and {P-20, P-28, P-34, P-
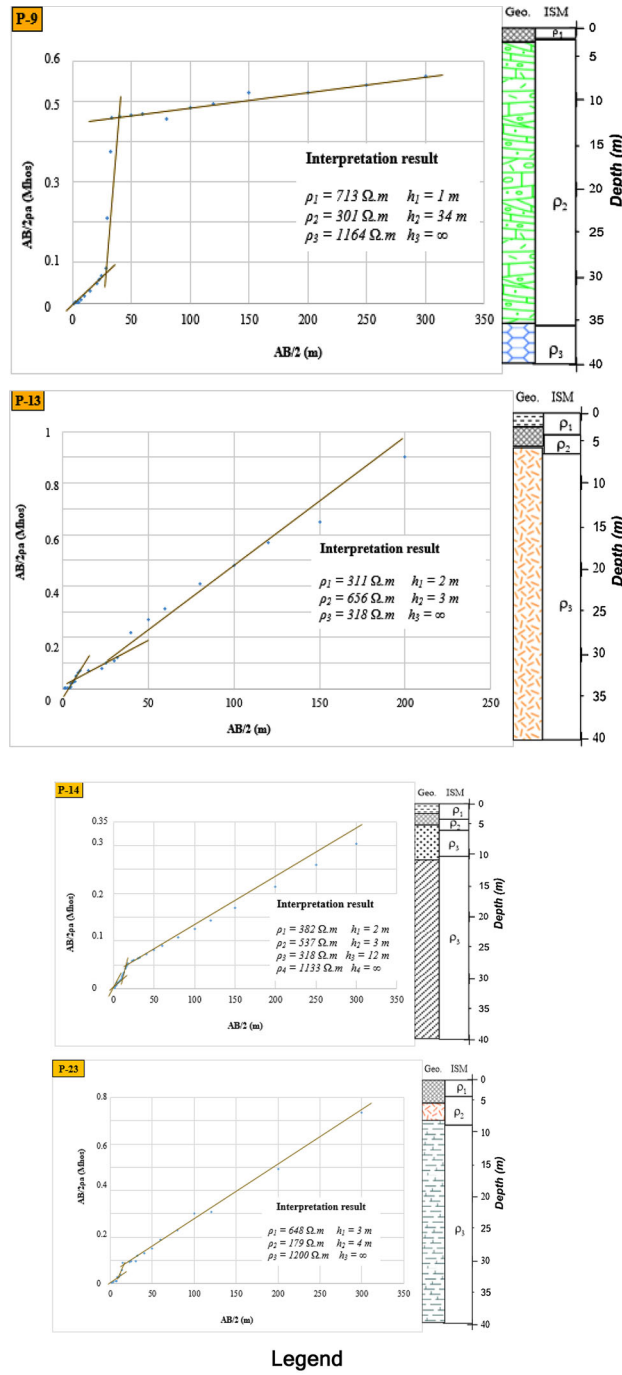
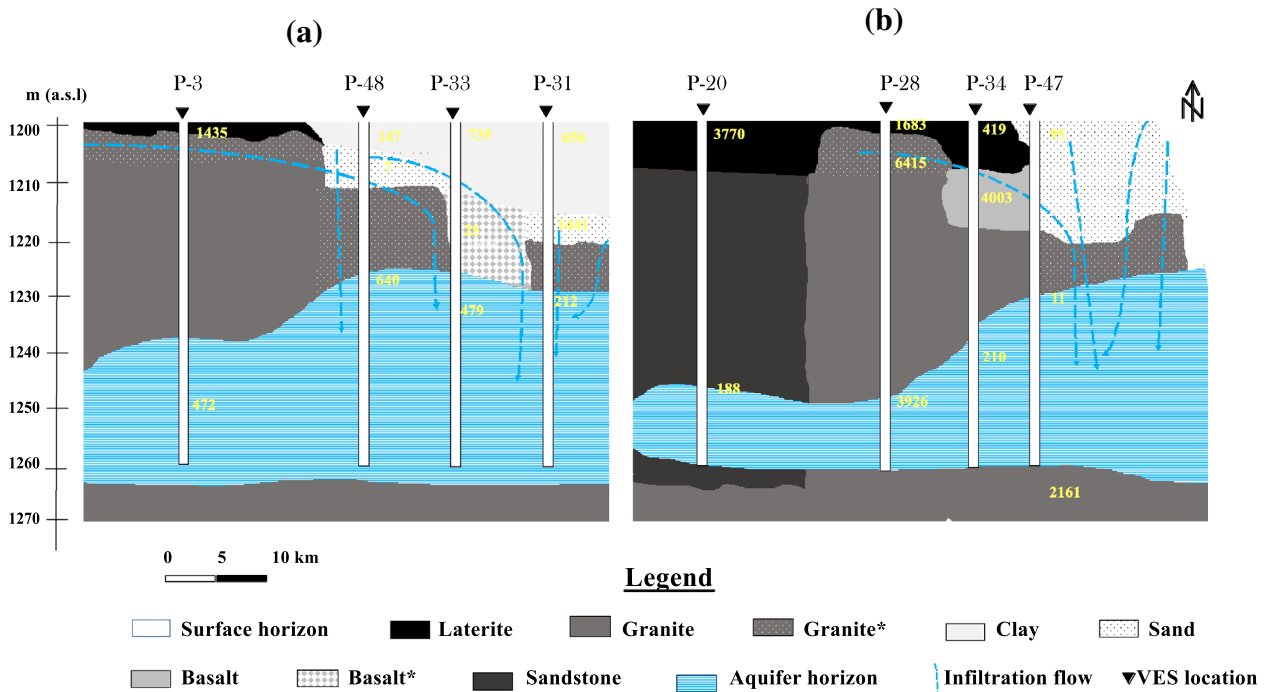**Figure 3.** Correlation between experimental boreholes and VES interpretation of pits P-9, P-13, P-14 and P-23.

Figure 4. Geoelectrical cross sections established in the study area: **a** Trend-1; **b** Trend-2.

47}. For the first set of VES points, aquifer resistivity varies between 212 and 640 Ω m and its thickness between 20 and 30 m. For the second trend of VES points, the aquifer resistivity ranges from 111 to 3962 Ωm and the thickness from 10 to 30 m. These results have been confirmed by several boreholes drilled in the area. The variability gap can be explained by the fact that local aquifer is essentially made of the fractured portion of the gneiss-granitic portion of the Pan-African basement. The more the rock is cracked, the more the thickness of the resulting aquifer is high and the lesser important is its resistivity.

Estimation of Aquifer Parameters at VES Points Without Pumping Test

The calibrated Eqs. 6 and 7 are used to evaluate T and K in the other 36 VES locations where no pumping tests are available.

The specific use of the 10 available VES points simply aimed at developing an alternative technique and showing a field example of computing and establishing the distribution of transmissivity values in the region. However, precise characterization of the Pan-African aquifer was insufficient by using only such a limited number of VES points. The regression Eqs. (6, 7) obtained from graphs plotted in Figure 5 were therefore used to estimate transmissivity at each of the other 36 VES locations without pumping tests. This procedure allows a precise characterization of the transmissivity distribution in the local aquifer.

Ten VES points with their quantitative interpretations were carried out near 10 boreholes with known hydrodynamic parameters. These experimental results are then used in this research to establish the appropriate empirical relationships between T and TR. These empirical relationships (6 and 7) were then used to estimate the transmissivity values in all the VES locations, in order to bring out precise characteristics of the Pan-African aquifer in Central Africa. It should be noted that T values used in graphs plotted in Figure 5 are derived from pumping tests for the 10 available tested wells as indicated in Table 1.

The results of quantitative VES interpretations have been calibrated and referred to: geoelectrical response acquired from surface outcrops of different formations. The interval of resistivity response of each formation, treated geostatistically, was considered as an electrical signature, which helped delineate the subsurface extension of the formation, as

Table 1. Parameters obtained from 10 available experimental boreholes used to establish Trend-1 and Trend-2

VES no	Q (m³/h) obtained from pumping tests	T (m²/day) from pumping tests	Thickness h (m)	Resistivity ρ (Ω m)	TR (Ω m²) computed consequently
P-3*	0.2	25.0	8	472	3776
P-8**	1.8	33.0	5	2	10
P-9**	8.1	33.8	22	12	264
P-13**	0.9	36	10	144	1440
P-17**	0.4	42.8	31	446	13,826
P-22**	3.2	39.3	23	341	7843
P-26*	4.2	34.9	38	1108	42,104
P-31*	2.3	30.1	40	565	22,600
P-33*	4.1	17.4	11	25	275
P-39*	1.8	6.1	12	16	192

*Experimental boreholes used for Trend-1
**Experimental boreholes used for Trend-2

performed in several previous investigations (Asfahani 2007b, 2012; Arétouyap et al. 2015); and geological cross sections constructed from the geological map of the area, which are used to establish a reliable subsurface image (Asfahani 2007a, b, 2012; Arétouyap et al. 2015). These two criteria allow good hydrogeophysical interpretation in the study area, disclosing the subsequent discussion.

Ten pumping tests were performed and pumping curves were plotted (Fig. 6). The pumping tests enabled us to measure flow rates and transmissivity directly, as well as hydraulic conductivity of the 10 experimental boreholes. The 10 experimental boreholes (P-3, P-8, P-9, P-13, P-17, P-22, P-26, P-31, P-33, and P-39) were used to establish two logarithmic relationships (Trend-1 and Trend-2) between TR and T as presented in Table 1.

A layer of relatively trivial resistivity with respect to upper and lower adjacent layers is considered to be an aquifer. This principle helped determine aquifer resistivity and thickness by interpreting sounding curve as shown in Figure 3. Afterward, the transverse resistance is gradually computed using Eqs. 4, 6, and 7 for transitivity, and then Eq. 8 for the hydraulic conductivity, per VES locations without pumping test in the Adamawa Plateau.

$$K = \frac{T}{h} \qquad (8)$$

These parameters are presented in Table 2, summarized in Table 3, and represented in Figure 7.

Figure 7a shows the distribution of the Pan-African aquifer resistivity obtained from the use of 36 VES points: Minimum values of $190 \, \Omega$ m resistivity are observed in the northeastern part of the region above VES location P-4, and maximum values of $270 \, \Omega$ m are observed in the southwestern part where VES P-20 is located, with mean resistivity of $244 \, \Omega$ m. The resistivity map divides the area into two zones: a high-resistive zone in the southwest and a low-resistive zone in the northeast. Therefore, groundwater therefore may flow from the northeast (where the recharge area is concentrated) to the southwest.

Figure 7b shows the distribution of the saturated Pan-African aquifer thickness h obtained from the use of the 36 VES points: the minimum thickness of 20 m is observed in the northern part above P-4 point and the maximum of 60 m observed in the eastern part at P-6, with the mean value of 29 m. The aquifer formations match with the low-resistivity layers. Hence, they have almost the same thickness. This is derived from the results of VES interpretation, calibrated by referring to the geoelectrical response obtained from surface outcrops of several geological formations and to the lithological information acquired from 10 boreholes logged in the area (Arétouyap et al. 2015). Higher aquifer thickness is observed in the eastern part of the region. These results are substantiated by experimental boreholes presented in Figure 3.

The empirical Eqs. 6 and 7 between TR and T (derived from pumping tests at the 10 reference boreholes) were applied to estimate the transmissivity T of the Pan-African aquifer (Fig. 6c). Transmissivity values range from 15 (P-14) to 43 m²/day (above P-4) with an average of 31 m²/day. It is observed that the demarcation line $T-T'$ (blue color in Figure 7c) divides the area into two zones: a low-
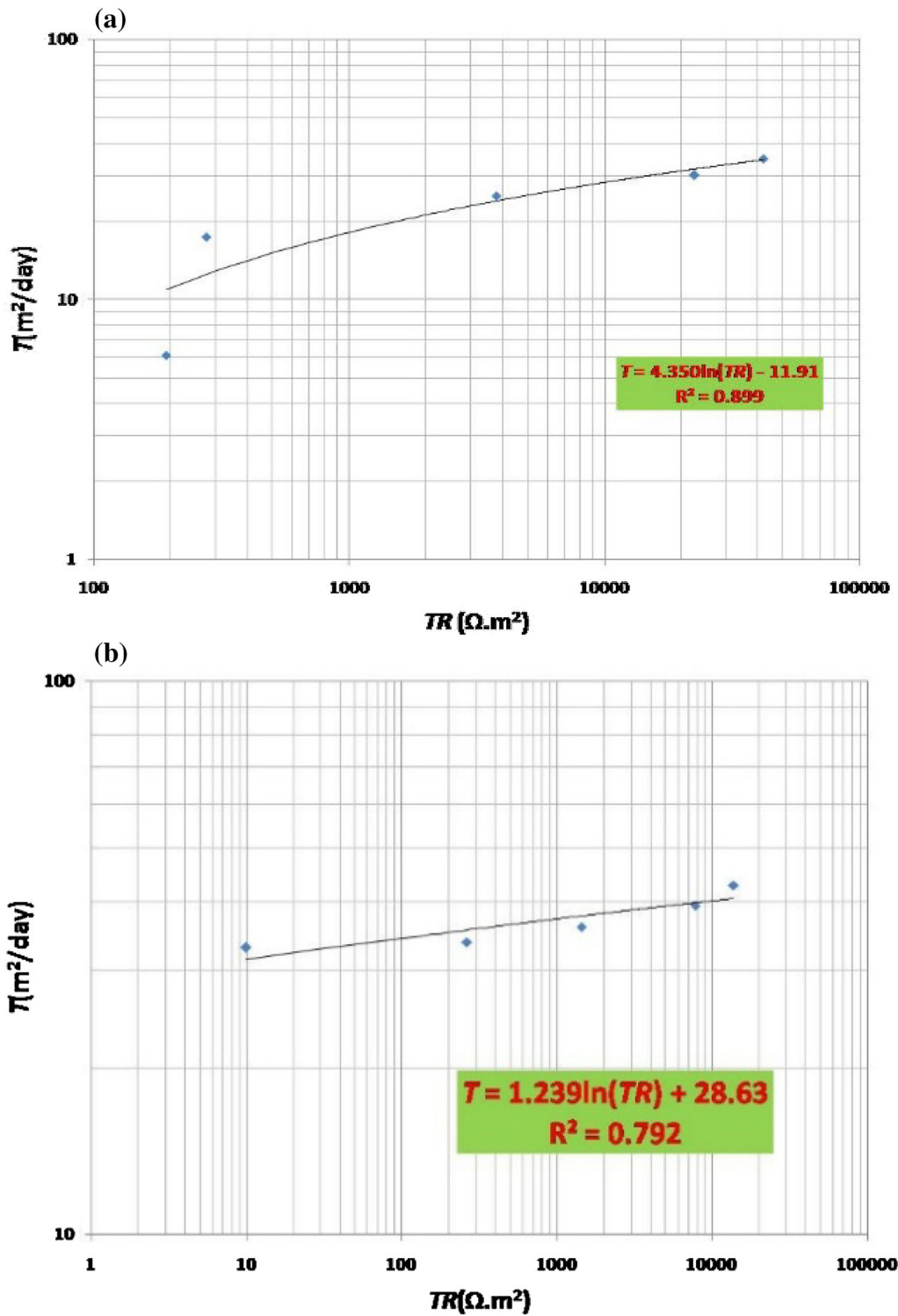
Figure 5. Empirical relationships between TR and *T* (from pumping tests of 10 available drilled wells, nearest to the mentioned VES locations) for the Pan-African aquifer, deduced by the alternative approach developed by Asfahani (2012). **a** Trend-1 using the VES of P-3, P-26, P-31, P-33, and P-39. **b** Trend-2 using the VES points of P-8, P-9, P-13, P-17 and P-22.
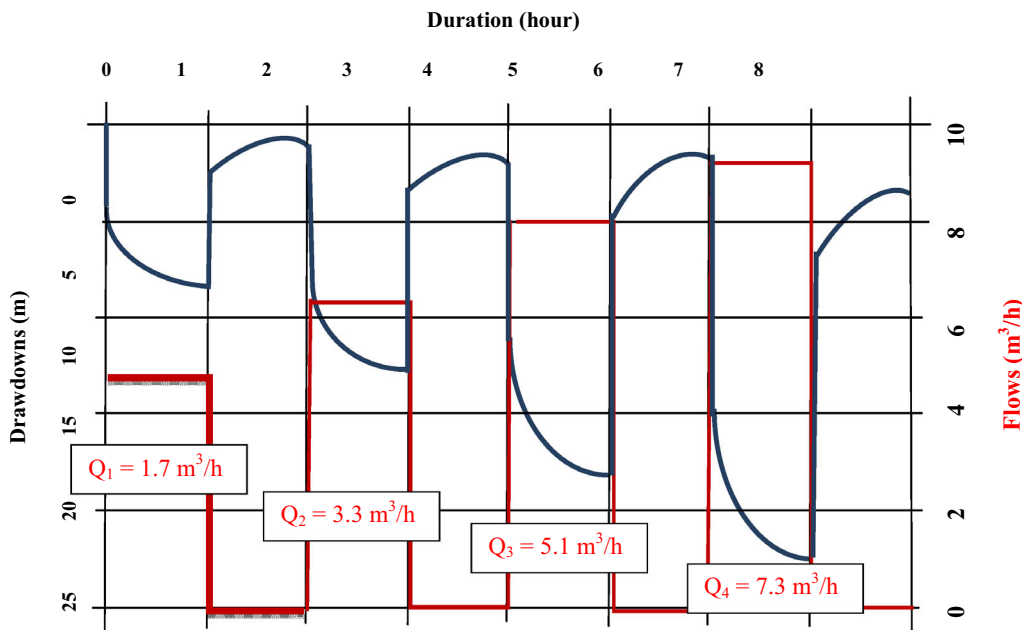
Figure 6. An example of pumping test curve.

transmissivity zone located below line $T–T'$ and a high-transmissivity zone above line TT'. Each trend may correspond to an aquifer. The existence of two aquifers with different trend must be proven and therefore requires further hydrogeological research in the region under study. The aquifer transmissivity (Fig. 7c) and the aquifer resistivity (Fig. 7a) are quite asymmetric with respect to each other. This asymmetric configuration between the two parameters means that an area with higher transmissivity, located above the demarcation line, has lower resistivity, and vice versa.

The TR distribution for the Pan-African aquifer (Fig. 7d) varies between 24 Ω m^2 at P-45 and 42,000 Ω m^2 at P-30, with a mean value of 7831 Ω m^2. TR values exhibit almost four sectors with homogeneous distribution. High values can, however, be observed in the zone where VES points P-10, P-17, P-22, P-23, P-35, P-37, and P-47 are located.

Figure 7e reveals two main K trends: a high-value in the eastern part of the area and a low-value zone elsewhere within the same area. The product $K\sigma$, which is generally low in the region, varies slightly from 2.1×10^{-4} to 1.33 with an average of 4.2×10^{-2} and a standard deviation of 0.52. Nevertheless, four points with highest values are observed in Figure 7f. These characteristics are summarized in Table 4.

CONCLUSIONS

The implementation of the VES technique, taking into consideration Dar Zarrouk parameters (Mazáč and Landa 1979), helped specify and describe the hydrogeophysical parameters of the Pan-African aquifer in the Adamawa region, which will be useful for further groundwater modeling. This technique being advocated in this article is cheaper, faster and more accurate compared to the traditional pumping test technique when it is appropriately applied. It was shown that the groundwater potential of the local Pan-African aquifers can be assessed the use of both traditional pumping tests and the VES technique approach with a Schlumberger array. The hydraulic conductivity values (ranging from 0.4 to 6.0 m/day) obtained by applying the VES technique as an alternative approach match those obtained by the traditional pumping tests. This shows the applicability of this alternative approach in the Pan-African context, in Africa and in South America as well. The different Dar Zarrouk parameters in this work have proven their efficiency for determining groundwater areas in the region under study. After analyzing the transmissivity values, two aquifer trends could be identified in the region: Trend-1 in the northeast area and Trend-2 in the southwest area (as demarcated by line TT' line in Figure 1).

Table 2. Hydrological and geophysical and parameters for the 36 VES locations without experimental boreholes

VES no	Thickness h (m)	Resistivity ρ (Ω m)	Transverse resistance TR (Ω m^2)	Transmissivity T (m^2/day)	Hydraulic conductivity K (m/day)	Trend type
P-1	25	811.0	20,275.0	40.92	1.64	Trend -2
P-2	47	362.1	17,018.7	40.7	0.86	Trend -2
P-4	48	175.7	8433.6	39.83	0.83	Trend -2
P-5	20	608.0	12,160.0	40.28	2.00	Trend -2
P-6	6	157.0	942.0	37.1	6.18	Trend -2
P-7	10	137.0	137.0	34.72	3.472	Trend -2
P-10	19	114.1	2167.9	21.5	0.08	Trend -1
P-11	40	410.0	16,400.0	30.31	0.76	Trend -1
P-12	37	22.0	814.0	17.24	0.46	Trend -1
P-14	8	8.0	64.0	6.18	0.77	Trend -1
P-18	43	408.0	17,544.0	30.6	0.71	Trend -1
P-19	34	26.0	884.0	17.60	0.52	Trend -1
P-20	61	188.0	11,468.0	28.75	0.47	Trend -1
P-21	19	221.5	4208.5	24.39	1.28	Trend -1
P-24	17	112.9	1919.3	20.97	1.23	Trend -1
P-25	22	100.0	2200.0	38.2	1.74	Trend -2
P-27	23	341.0	7843.0	27.1	1.18	Trend -1
P-28	70	392.6	27,482.0	32.55	0.46	Trend -1
P-29	6	13.0	78.0	34.0	5.67	Trend -2
P-30	38	825.0	31,350.0	41.45	1.10	Trend -2
P-32	33	25.0	825.0	17.30	0.52	Trend -1
P-34	11	10.0	110.0	8.54	0.78	Trend -1
P-35	14	387.0	5418.0	25.49	1.82	Trend -1
P-36	62	53.0	3286.0	23.3	0.37	Trend -1
P-37	28	422.0	11,816.0	40.25	1.44	Trend -2
P-38	21	4.0	84.0	34.12	1.62	Trend -2
P-41	38	200.0	7600.0	39.70	1.04	Trend -2
P-42	33	104.0	3432.0	38.72	1.17	Trend -2
P-43	52	212.0	11,024.0	40.16	0.77	Trend -2
P-44	93	61.0	5673.0	39.34	0.42	Trend -2
P-45	8	3.0	24.0	32.57	4.00	Trend -2
P-46	7	20.0	140.0	34.75	4.96	Trend -2
P-47	15	216.1	3241.5	23.2	1.55	Trend -1
P-48	30	640.0	19,200.0	40.85	1.36	Trend -2
P-49	32	270.4	8652.8	39.86	1.24	Trend -2
P-50	85	47.0	3995.0	38.90	0.46	Trend -2

Table 3. Summary of characteristics of the Pan-African aquifer in the Adamawa Plateau using 36 VES without pumping tests

	h (m)	ρ (Ω m)	T (m^2/day)	TR (Ω m^2)	K (m/day)	$K\sigma$
Min	6	3	6.18	24	0.08	0.0007
Max	93	825	41.45	31,350	3.4	1.33
Average	31.83	225	31.15	7442	2.37	0.085

Transmissivity values ranged from 15 to 42 m^2/day with an average value of 30.90 and a standard deviation of 9.89 m^2/day. The calibrated empirical relationships (depicting both trends) established between transverse resistance and transmissivity were used to estimate the transmissivity of the Pan-African aquifer at the VES locations. Such calibrated information is required for modeling and managing water resources in the Pan-African context.
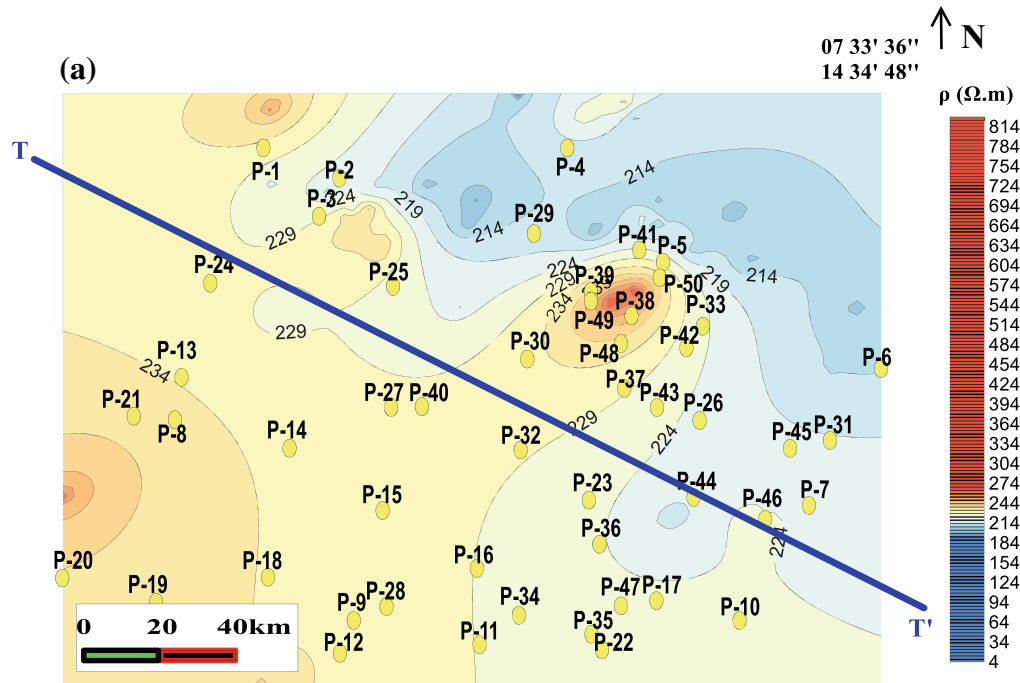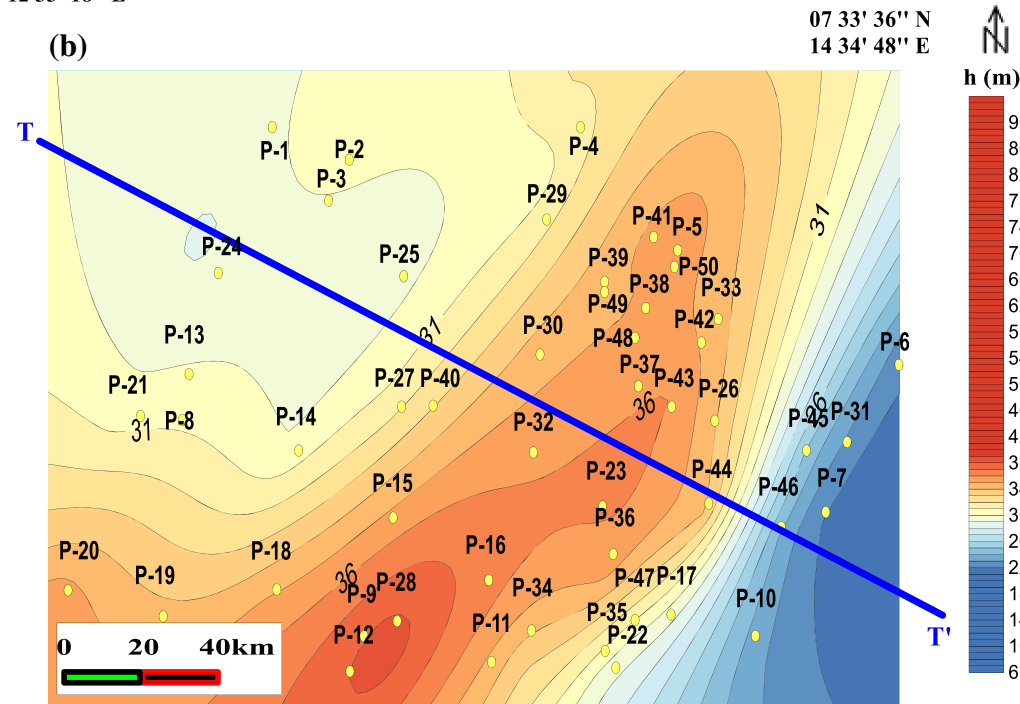
Figure 7. Maps of the Pan-African aquifer in the Adamawa Plateau obtained from the use of 36 VES points (see Table 2): **a** resistivity *ρ*; **b** thickness *h*; **c** transmissivity *T*; **d** transverse resistance TR; **e** hydraulic conductivity *K*; and **f** product *Kσ*.
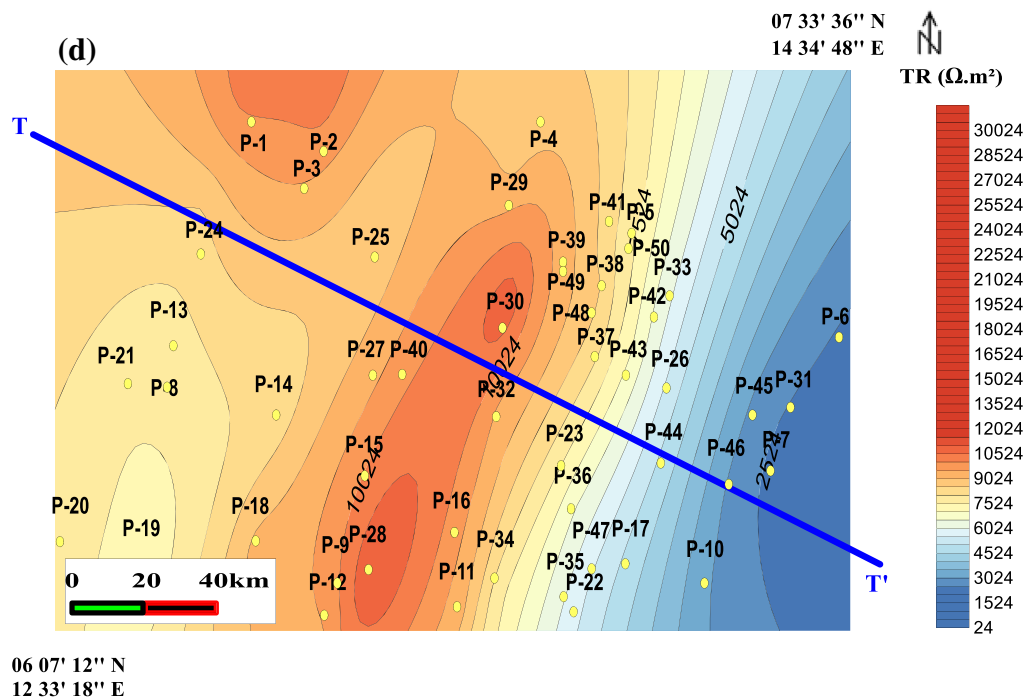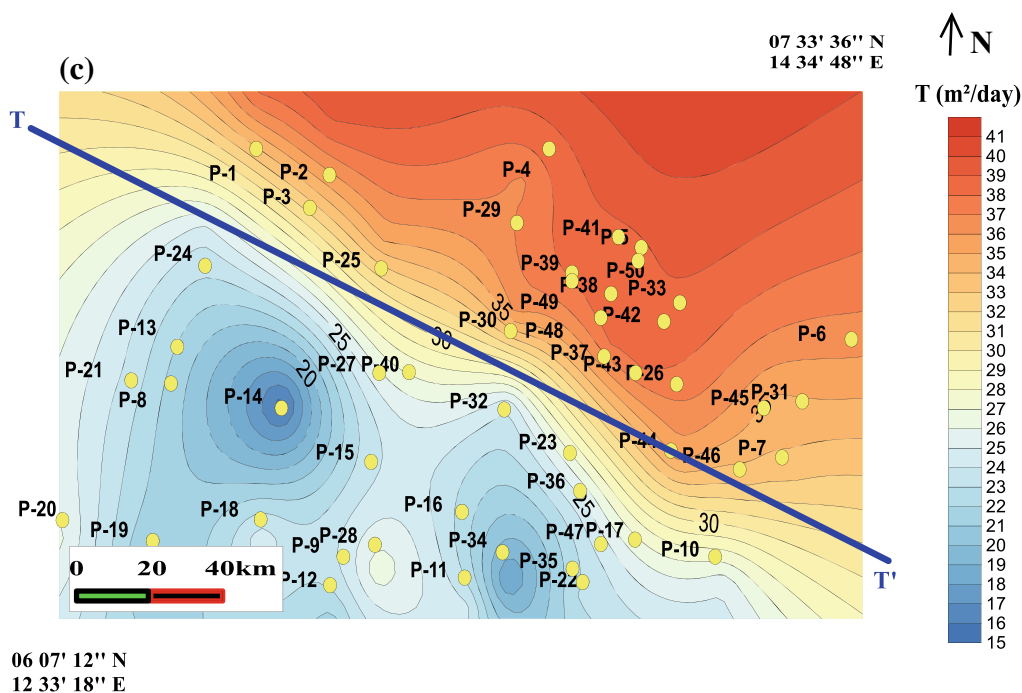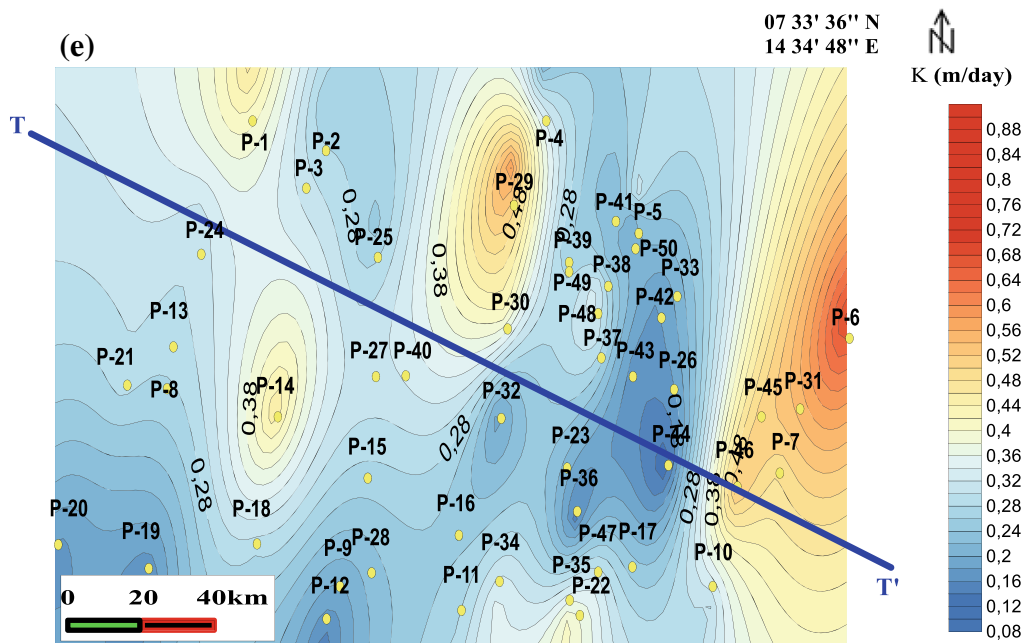
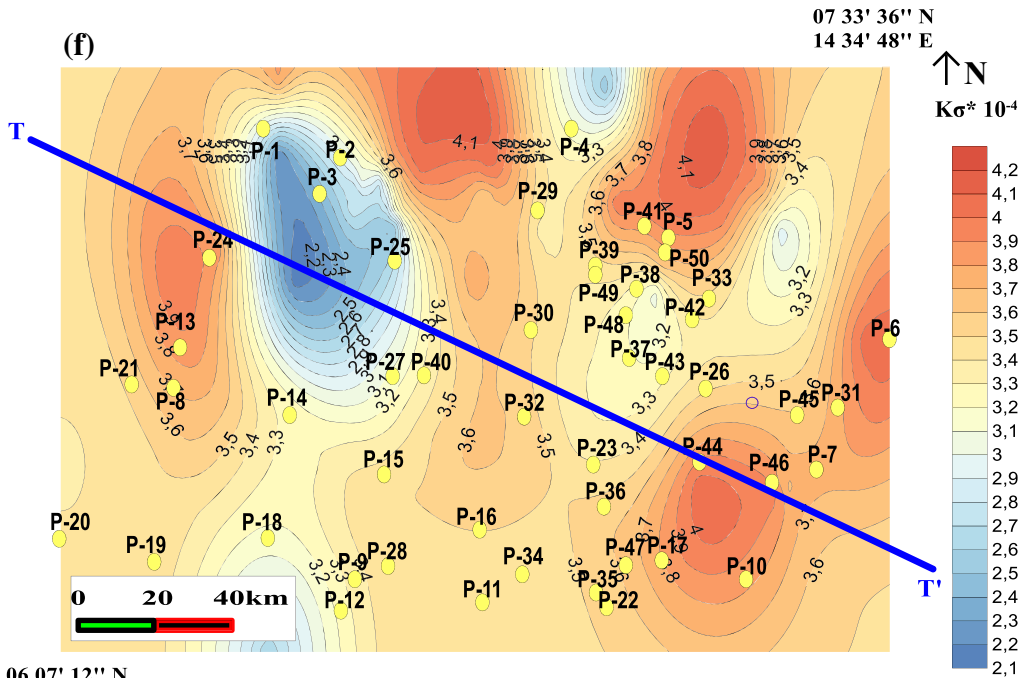Figure 7. continued..

Figure 7. continued..

Table 4. Characteristics of the Pan-African aquifer in the Adamawa Plateau using 46 VES

	h (m)	ρ (Ω m)	T (m^2/day)	TR (Ω m^2)	K (m/day)	$K\sigma$ ($\times 10^{-4}$)
Min	20	190	15	24	0.4	2.1
Max	60	270	42	42,000	6.0	4.2
Average	29.3	244	30.9	7831	2.3	0.085

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