ORIGINAL ARTICLE

A detailed analysis of hydro-parameters of the Adamawa Plateau watershed derived from the application of geoelectrical technique

Zakari Aretouyap[1] · Dieudonné Bisso[2] · William Teikeu Assatse[2] · Janvier Domra Kana[3] ·
Franck Eitel Kemgang Ghomsi[2] · Robert Nouayou[4] · Philippe Njandjock Nouck[2] · Jamal Asfahani[5]

Abstract

This research revises and improves previous studies conducted in the Adamawa region regarding aquifer characterisation. Linear regression technique is used to predict hydrogeological parameters from electrical data, where different empirical relationships are established on the basis of geological settings. Hence, for each parameter to be predicted, there are two relationships, the equal number of geological groups encountered in the study area, namely metamorphic and sedimentary rocks. For this, electrical data were interpreted using conjointly curve-matching method and inverse slope method to improve the previous results, taking into account geological inhomogeneities of the region. Hydraulic conductivity and transmissivity values are determined from pumping tests conducted on 13 VESs out of a total of 50. From those experimental values, strong relationships are established between these hydrogeological parameters and electrical data, with regard to the two main geological settings existing within the region. Aquifer parameters are consequently improved. Hydraulic conductivity, transmissivity, resistivity, thickness and transverse resistance changed in their mean values, respectively, as follows: 2.74–0.3 m/day, 31.15–31 m²/day, 225–30.8 Ω m, and 31–4.9 m. Same change trends are also noted in the extremum values. Major changes are observed in aquifer resistivity and thickness. In addition to those changes, "Pan-African" syntax does no more fit to design this aquifers system because it refers to a regional stratigraphic and plate tectonic setting which does not have strong impact on the major aquifer parameters.

Keywords Adamawa Plateau · Correlation · Hydrogeological properties derived from electrical data

Introduction

Water is a vital resource for human, animal and plant species. It is important for the existence of all living beings, the survival of the environment as well as the blooming of industry and businesses. Water is also very important for agricultural activities. Unfortunately, in most parts of the world, water is a scarce resource. Hence, groundwater is an important part of the policy of water resources management in many countries. This is the case of Cameroon where a series of investigations are focussed on the Adamawa region, nicknamed "water tower". This region gave room to a lot of investigations; the outcomes are to be revised, updated and improved in the present article. The interest observed nowadays in groundwater resources is due among others to the scarcity of surface water resources or their poor quality (Aretouyap et al. 2020; Stelmach and Clasen 2015).

For a lasting and sustainable exploitation of groundwater resource, geoelectrical methods are of paramount importance as they allow assessment of hydrogeological parameters, such as transmissivity and hydraulic conductivity, as well as flow from transverse resistance, longitudinal conductance, etc. In fact, strong relationships are possible between electrical data measured by geoelectrical methods

✉ Zakari Aretouyap
aretouyap@gmail.com

1 Department of Architecture and Engineering Art, Institute of Fine Arts of Foumban, University of Dschang, P.O. Box 31, Foumban, Cameroon

2 Faculty of Science, University of Yaounde I, P.O. Box 812, Yaoundé, Cameroon

3 Faculty of Mines and Petroleum Industries, University of Maroua, P.O. Box 46, Maroua, Cameroon

4 National Institute for Cartography, P.O. Box 800, Yaoundé, Cameroon

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

and hydrogeological parameters. Lesmes and Friedman (2005) established several relationships between the hydrogeological and the electrical properties of soils and rocks. From basic electrical data, such as low-frequency conductivity and high-frequency permittivity, these relationships are useful for lithological characterization, saturation monitoring, salinity prediction and assessment of the porosity of fully saturated geological formations as well as the water content of the partially saturated geological formations. Inversely, some electrical data such as the electrical conductivity can be predicted from petrophysical properties. Mawer et al. (2015) built a numerical model from electrical properties to generate hydrogeological ones. Then, they established a useful power exponent equation to compute the aquifer hydraulic conductivity. The resulting prediction was very accurate when the electrodes are properly arranged with regard to the presence of clay. Kirkby and Heinson (2015) also modelled and used random resistor networks to link aquifer hydraulic and electrical properties. Singh and Singh (2016) combined electrical parameters with pumping test data and deduced the hydrogeological characteristics of Tuticorin aquifers. They determined the true thickness and resistivity by interpreting the data measured in the neighbourhood of the pumping test location. Finally, several empirical relationships were established and used to estimate the hydrogeological parameters from the electrical data. Tijani et al. (2018) estimated the hydraulic properties of basement aquifer from resistivity sounding data in Ibadan. In the same way, Youssef (2020) characterised and assessed the aquifer hydraulic properties in Ain El-Soukhana from electrical data. More recently, De Almeida et al. (2021) used VES to estimate the hydraulic parameters of a porous aquifer at the experimental farm of the University of Brasilia.

The present investigation uses the same approaches abovementioned. Electrical data have been collected from 50 VESs conducted within the region with the purpose of deducting the hydrogeological parameters of the local aquifers. Those parameters have been determined progressively since 2014 with significant gradual improvements. The main objective is to revise, update, organize and improve various significant results gathered in the area (Aretouyap et al. 2014a, b, 2015, 2017, 2018, 2019a, b; Bisso et al. 2019).

Geophysicists have realized that a correlation between the hydrogeological parameters and geoelectrical properties of an aquifer is of paramount importance. So, selecting the correct hydro-geophysical methodology is considered as an optimal solution. Many relations between hydraulic and geoelectrical parameters of various aquifer types have been studied and reviewed by several researchers (Kelly 1977; Niwas and Singhal 1981, 1985; Mazac et al. 1985; Huntley 1986; Frohlich et al. 1996; Chen et al. 2001; Niwas and de Lima 2003; Singh and Frevert 2005; Hubbard and Rubin 2000; Soupios et al. 2007; Chandra et al. 2008; Khalil

and Santos 2009; Massoud et al. 2010; Niwas et al. 2011; Sikandar and Christen 2012; Niwas and Celik 2012; Singh and Singh 2016). Such relations can be used as a helpful tool to estimate the hydraulic parameters mathematically with an acceptable degree of accuracy and allow getting the maps of transmissivity and hydraulic conductivity of the entire study area.

The region of Adamawa, because of its important role as major catchment for four riparian countries, namely Cameroon, Central African Republic, Congo and Nigeria, has been the focus of intense research in the domain of groundwater resources for several years (Aretouyap et al. 2014a, b, 2015, 2017, 2018, 2019a, b; Bisso et al. 2019). Results include the impact of climate change on local water resources, analysis of the groundwater quality, describing the local lithology and the evaluation of geoelectrical and hydrogeological parameters of the local aquifer. However, with these investigations, values of hydrogeological parameters obtained made only slight or moderate improvements. This paper aims at revising geological conception, datasets, geophysical approaches and key results found in previous works related to groundwater resources in the region. The main outcome will be the update of key groundwater parameters.

Geology and morphology

The present paper focuses on the Adamawa region because of its hydrogeological importance. As it is, 150–300 km wide, the Adamawa Plateau is called "the water tower of the region" because it feeds major watersheds in Cameroon, Central African Republic, Congo and Nigeria. This region is located between 6°–8° N and 11°–16° E in the heart of Central Africa as shown in Fig. 1. It extends 410 km from west to east between the Central African Republic and the Federal Republic of Nigeria, for a total area of 6782 km^2. The morphology of the region is dominated by volcanic highlands, resulting from tectonic uplift and subsidence (Tchameni et al. 2001). The local 1100 m altitude terrain is very rugged with an uneven escapement of several hectometres and a large cliff in its northern part.

In the centre of the area, one can observe gentle topography and swampy valleys, scattered with mountains and volcanic cones. The eastern part is marked by huge massifs resulting from erosional and tectonic events. In the west, high mountains and hills are observed. One notes also plains and basins such as the Tikar plain. A huge plateau sloping gradually is found in the southern part of the region (Toteu et al. 2000).

The local basement is made up of the Pan-African granite-gneiss, represented by Ordovician granites, gneisses and migmatites. The main geological units present in the
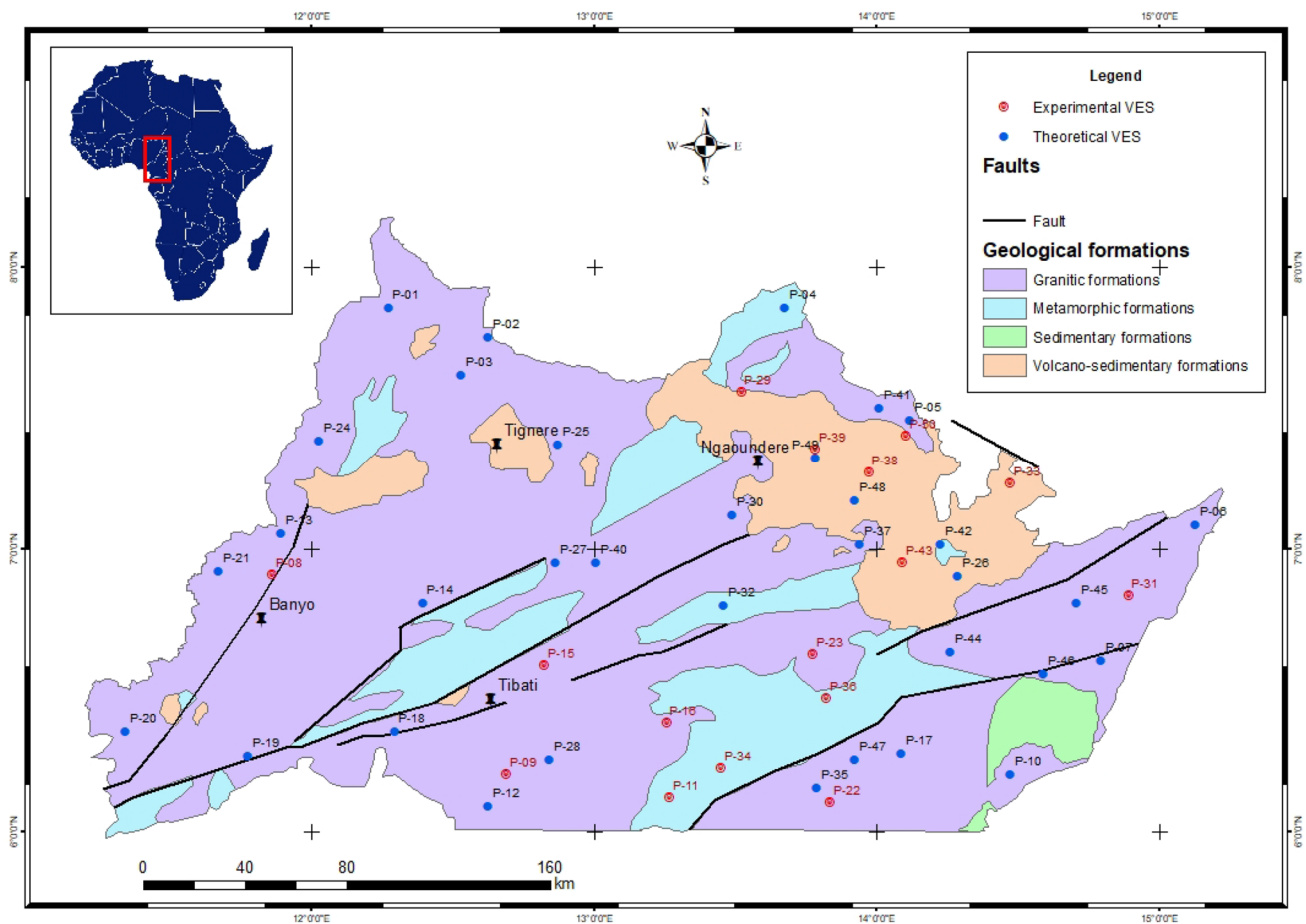
Fig. 1 Geological map of the Adamawa Plateau (Maréchal 1976) as amended

region are trachytes, basalts and trachyphonolites based mostly on concordant calco-alkaline granites and discordant alkaline granites (Toteu et al. 2000). There is also the presence of metadiorites of Paleoproterozoic basement in some places (Toteu et al. 2001). Faults observed in this region are grouped into two main directions:

– "Volcanic line of Cameroon" that contains the most common direction-oriented N 30° E;
– "Adamawa shear zone" oriented N 70° E.

Contrary to previous studies (e.g. Aretouyap et al. 2015) where the region was considered as a unique and homogeneous geological unit when determining and interpreting aquifer parameters, we subdivide the VES database into two groups corresponding each to a major geological formation: metamorphic and sedimentary as shown in Fig. 1. The granite-gneiss bedrock is represented by Ordovician granites, gneisses and Pan-African migmatites (Toteu et al. 2000). This setting results from a series of three geologic events: a long period of continental erosion

from Precambrian to Cretaceous, an onset of volcanism from Cretaceous to Quaternary and recurrent basement tectonics.

Recent geophysical investigations conducted by Njonfang et al. (2008) reveal intense faults in the bedrock. As a result, the groundwater potential is important in the studied zone. This potential has been explored, with various electrical methods, by Aretouyap et al. (2015, 2017, 2018, 2019a, b) and Bisso et al. (2019). In addition to the fact that those investigations considered the whole region as a single geological unit, electrical methods and techniques used for investigation have improved gradually. As a result, the parameters determined successively have also progressively changed. This situation justifies the interest of this paper which aims at updating key parameters of groundwater in the region. More accurate hydro-parameters of the regional aquifers obtained from various recent investigations will be produced. The study area has up to 50 VESs with the same number of boreholes mostly tapping a fractured aquifer. Thirteen of these boreholes have been used for experimental pumping test operations.

Methodology

The methodology section brings together field investigations and previous works carried out within the study area to establish different relationships between electrical data and hydrogeological parameters. For this, VES data adjacent or close to experimental wells (with pumping tests results) are used to draw correlations between electrical and hydrological parameters. Then, these correlations are used to predict and interpolate the hydrological parameters from VES results which are not close to wells. For this geophysical campaign, 50 VESs in a Schlumberger configuration with the half current electrodes separation varying from 1 to 300 m were carried out. 13 of these soundings are carried out in the vicinity of experimental wells used for pumping tests. Before any interpretation, the curve-matching technique, as stated by Orellana and Mooney (1966), was used for calibration.

Establishing relationships between electrical data and hydrological parameters

Thirteen out of fifty relevant wells/boreholes randomly distributed within the study area were used for pumping tests and other experimental measurements to determine several parameters, such as transmissivity, hydraulic conductivity, depth, thickness, etc. For the VES points located nearby those experimental boreholes, electrical data were interpreted using a conventional curve-matching method (CMM), as in Zohdy (1989). The outputs of this interpretation are relationships between aquifer parameters and geoelectrical data as well as the aquifer modelling. In addition to CMM, ISM was also used. The ISM approach consists in plotting the conductance $(AB/2)/\rho_a$ versus the electrode separation $(AB/2)$. Each line segment resulting from this graph represents a layer; and the intersection of the line segments, multiplied by a factor of 2/3, corresponds to the depth of a particular layer. Thus, if t_1, t_2, ..., t_n are intersection points (along the $AB/2$ axis), then $2/3 \times t_i$ is equal to the depth of the ith interface (Asfahani 2016). Similarly, when $(AB/2)/\rho_a$ is plotted versus $AB/2$, the inverse slope of the segment gives the resistivity of the ith layer except when a segment, representing the high-resistivity layer, shows a negative slope. In this case, the resistivity of the layer is taken as infinity (Asfahani 2016). This method has the ability to decipher thin layers even if they are buried at great depths.

Hence, five main parameters of the local aquifer have been computed and updated using resistivity methods. These parameters are aquifer transmissivity, hydraulic conductivity, resistivity, thickness and depth which are very useful for groundwater extraction in this region. For example, it is possible to correlate the resistivity with the hydraulic conductivity as well as the transverse resistance with the transmissivity (Kelly 1977).

The interpretation of thirteen VES points located in the vicinity of experimental wells allowed determination of the aquifer resistivity (ρ_e), thickness (h) and transvers resistance (TR). By measuring the water resistivity (ρ_w) from those wells, the formation factor (F) is calculated using Eq. 1.

$$F = \rho_e/\rho_w. \tag{1}$$

The aquifer hydraulic conductivity (K) and transmissivity (T) are measured from the pumping tests. These electrical data and hydrogeological parameters are presented in Table 1.

Predicting hydrological parameters from VES data without experimental wells

From the experimental data presented in the above Table 1, hydrogeological parameters were plotted against electrical data as shown in Fig. 2 and linear empirical regressions as expressed in Eqs. (2)–(5) are established. These allow the computation of hydrogeological parameters elsewhere within the study area based on the measured VESs. The equations are specific to the various geological settings observed in the region and the calculated values of T and K are also shown in Table 1.

Results and discussion

Correlation between hydraulic parameters and formation factor led to linear relationships expressed in Eqs. (2)–(5).

− Expression of the hydraulic conductivity as a function of the formation factor for metamorphic rocks:

$$K = -0.0132 * F + 0.8749 \tag{2}$$

− Expression of the hydraulic conductivity as a function of the formation factor for sedimentary rocks:

$$K = -0.0695 * F + 1.5499 \tag{3}$$

− Expression of the transmissivity as a function of the transverse resistance for metamorphic rocks:

$$T = 0.0631 * TR + 3.0461 \tag{4}$$

− Expression of the transmissivity as a function of the transverse resistance for sedimentary rocks:

$$T = 0.0111 * TR + 33.521 \tag{5}$$

Table 1 Hydrogeological parameters from the thirteen experimental sites

Rocks	Location	ρ_e (Ω m)	ρ_w (Ω m)	h (m)	$F=\rho_e/\rho_w$	TR (Ω m^2)	K (m/day)		T (m^2/day)	
							Experimental	Predicted	Experimental	Predicted
Sedimentary	P-29	13	3.24	6	4.0	78	5.64	1.3	34.0	34.4
	P-38	4	1.83	2.1	2.2	8.4	1.62	1.4	34.1	33.6
	P-39	28	1.64	11.8	17.1	330.4	0.19	0.4	36.1	37.2
	P-43	21	3.51	5.2	5.9	109.2	0.87	1.1	33.1	34.7
	P-50	47	2.5	8.5	18.8	399.5	0.46	0.2	38.9	37.9
Metamorphic	P-08	13	3.21	4.3	4.0	55.9	0.09	0.1	33.0	31.3
	P-09	20	5.01	1.9	3.9	38	0.09	0.1	31.8	31.2
	P-15	11	4.01	1.7	2.7	18.7	0.1	0.1	31.0	31.1
	P-16	46	1.51	4.6	30.5	211.6	0.2	0.2	32.0	32.3
	P-22	34	2.22	2.3	15.3	78.2	0.13	0.15	31.3	31.5
	P-23	48	5.21	6.2	9.2	297.6	0.12	0.1	36.0	35.9
	P-31	57	4.1	4	13.9	228	0.17	0.1	33.1	32.4
	P-33	48	3.08	4.2	15.6	201.6	0.19	0.2	31.4	32.2

ρ_e, h and TR represent, respectively, the aquifer resistivity, thickness and transvers resistance while ρ_w is the water resistivity and F the formation factor
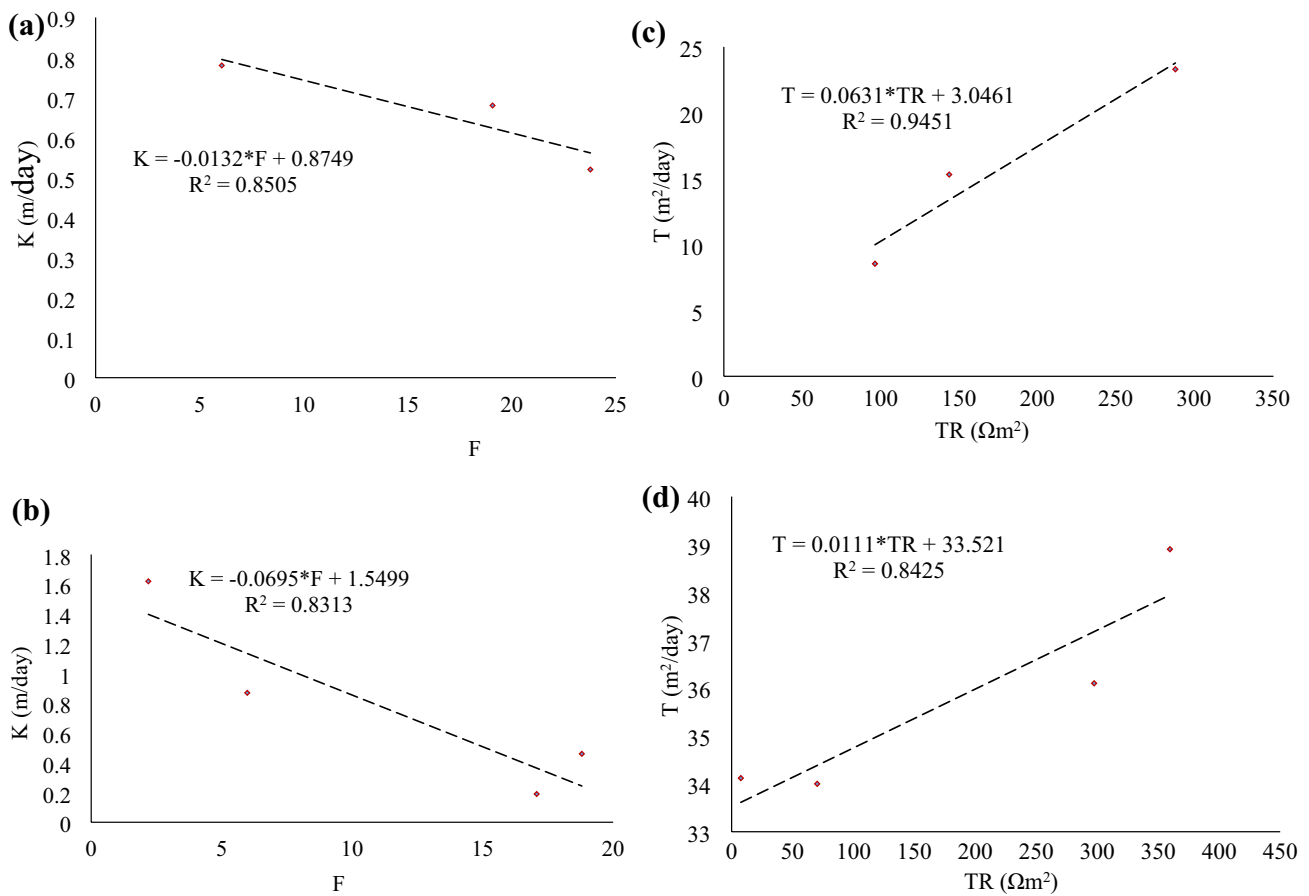

Fig. 2 Correlation between hydraulic conductivity and formation factor in **a** metamorphic rocks and **b** sedimentary rocks as well as between the transverse resistance and transmissivity in the same geological formations, respectively, **c** and **d**

The transmissivity and hydraulic conductivity of the regional aquifer have been calculated using Eqs. (2)–(5) and are mapped as shown in Fig. 3, which also indicates the spatial distribution of other key data useful for groundwater exploration in the context of man-made wells. These parameters are aquifer resistivity, thickness and depth summarized in Table 2 with regard to geological formations.

Low values of the hydraulic conductivity are observed in the western part of the study area as well as in the eastern part, corresponding to granitic formations, where values are ranged between 0.09 and 0.19 m/day. On the other hand, higher values are observed within volcano-sedimentary formations. A comparison of the transmissivity and hydraulic conductivity maps (Fig. 3a, b, respectively) shows that those parameters are inversely proportional. The more an aquifer is transmissive the less it is hydraulically conductive. Resistivity values are ranged from 3 to 83 Ω m (Fig. 3c). Aquifer thickness ranges from 1.4 to 16.2 m (Fig. 3d). Aquifers located on the granitic formation in the western part of the region show lower thickness whereas those located in the eastern part as well as on sedimentary formations are thicker. The thickness is an important parameter to predict a sustainable and groundwater lasting exploitation. The aquifer depth is very important for two main reasons. In a context of man-made wells, this parameter helps population to select a site where the resource is easily accessible. In this situation, it is desirable to have very low depth values as in the middle part of the study area where those values are ranged from 10 to 28 m (Fig. 3e). On the other hand, shallow aquifer can be very vulnerable to various pollution due to infiltration. In this case, deeper aquifers are the most desirable ones.

Previous computation of transmissivity values did not consider the geological disparity. Yet, the region is huge and exhibits evident geological discrepancy. To address these previous shortcomings, the present paper (1) combines CMM and ISM to interpret VES, (2) performed further pumping tests and (3) take the geological discrepancy of the region into account. As a result, regression equations used to compute hydraulic conductivity as well as transmissivity from the electrical data differ from one geological formation to another, hence these results are more accurate. In fact, the geological setting is a very important factor in such a survey. A prediction equation becomes unreliable when exporting from a particular geologic environment—where it was established—to another.

The geological setting of this region is not uniform. Its variation affects hydro-parameters of the aquifer. Actually, "Pan-African" which was used to label the zone in the previous investigations refers to a regional stratigraphic and plate tectonic setting. Yet, aquifer in the tropics is rather connected to the weathering zone (ferralsols) and the paleoprofile (plinthites in former topographical lows) both of which are related and influence the thickness of the weathering zone which is related largely to the exhumation fracture system of the protolith. For this, "Adamawa aquifer" fits better than "Pan-African aquifer".

Contrarily to previous investigations where hydro-parameters were interpolated over the study area as a whole, the present paper takes into account the size and the geologic inhomogeneities of the area, and interpolate those parameters based on geologic subset. Statistical analysis was then performed per subsets. This approach improved and updated the hydro-parameters of the Adamawa aquifer.

In the context of sustainable development, VES can be considered as one of the most popular methods used for groundwater exploration. It is generally used for both groundwater quality and aquifer geometry. Various electrical and hydrogeological investigations were carried out in the study area with the purpose of constructing the subsurface lithology, major hydrogeological conditions, and the principal aquifer parameters (Aretouyap et al. 2015, 2017, 2018, 2019a, b; Bisso et al. 2019). Field data have been reinterpreted for determining aquifer resistivity and thickness using either the curve-matching method (CMM) or the inverse slope method (ISM). Values of hydro-parameters of the Adamawa aquifers, derived from various recent investigations, show slight differences. Those variations reflect differences between methods used in data collection and processing, as well as in geological conception. Other contributing factors include database size, quality, density and spatial distribution. In the present investigation, those differences will be investigated to give improved and updated results.

Correlations between electrical data and hydrogeological parameters are plotted in Fig. 3. The hydraulic conductivity is a decreasing linear regression of the formation factor for metamorphic and sedimentary contexts. On the other hand, the linear regression is increasing for the metamorphic formations. Those linear regressions are built with a minimum acceptable statistical number of points because of the nongeological uniformity of the study area. By establishing a linear regression for each geological formation, this reduced the number of experimental points to be used in each relationship. Further explanation for this variation difference may require additional investigation like rock compactivity, etc. It is necessary to conduct supplementary survey for this purpose.

Spatial distribution of hydrogeological parameters derived from electrical data are mapped in Fig. 3. In volcano-sedimentary formations, high transmissivity values are found in the NNE and the centre of the study area. This geological settlement has the highest transmissivity values in the overall study area. On the other hand, lowest transmissivity values are found in the metamorphic formations located the north and south parts of the study area. Similarly, high and intermediate values of the hydraulic conductivity are associated with both high and low transmissivity
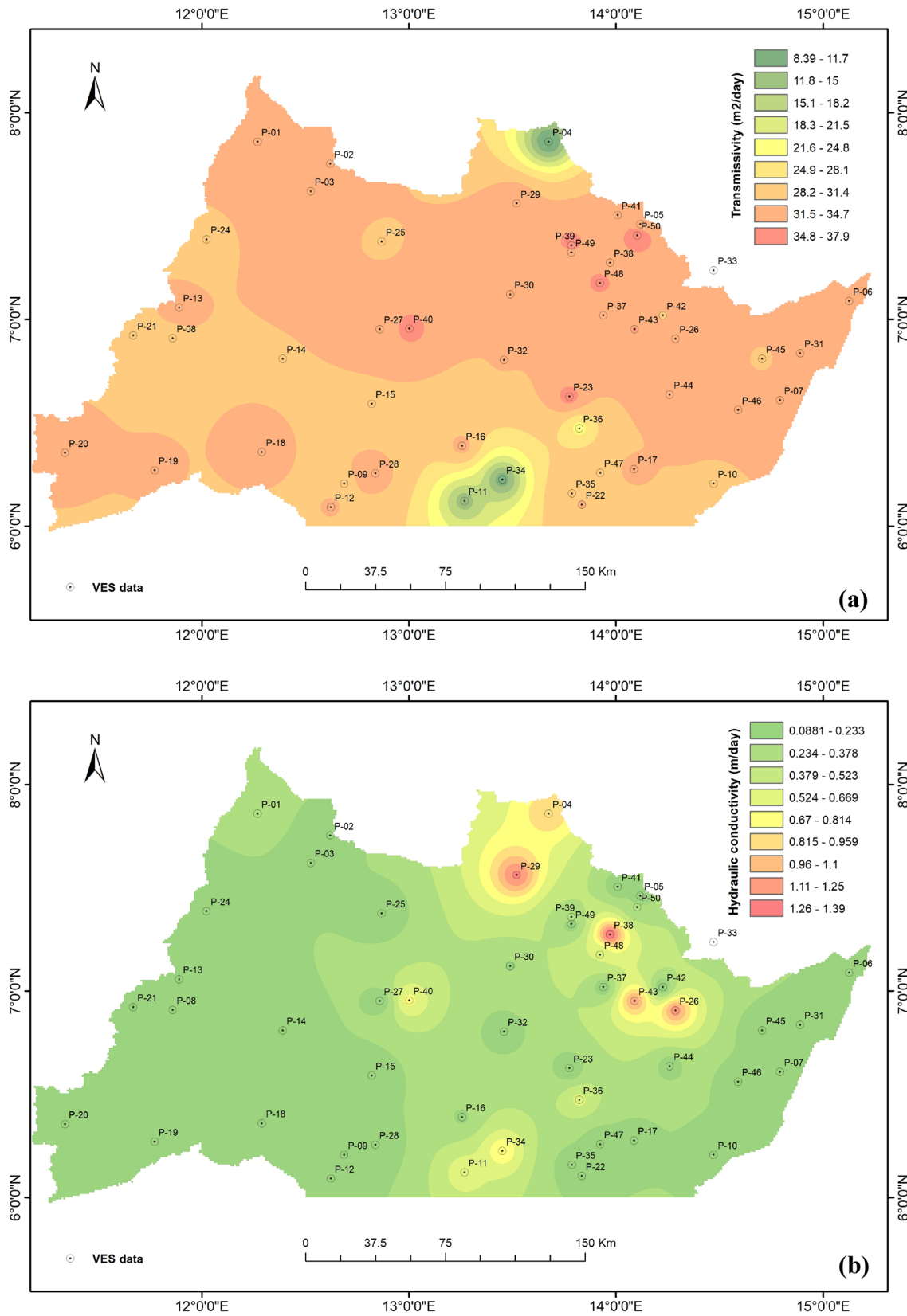
Fig. 3 Thematic maps of **a** transmissivity, **b** hydraulic conductivity, **c** resistivity, **d** thickness and **e** depth
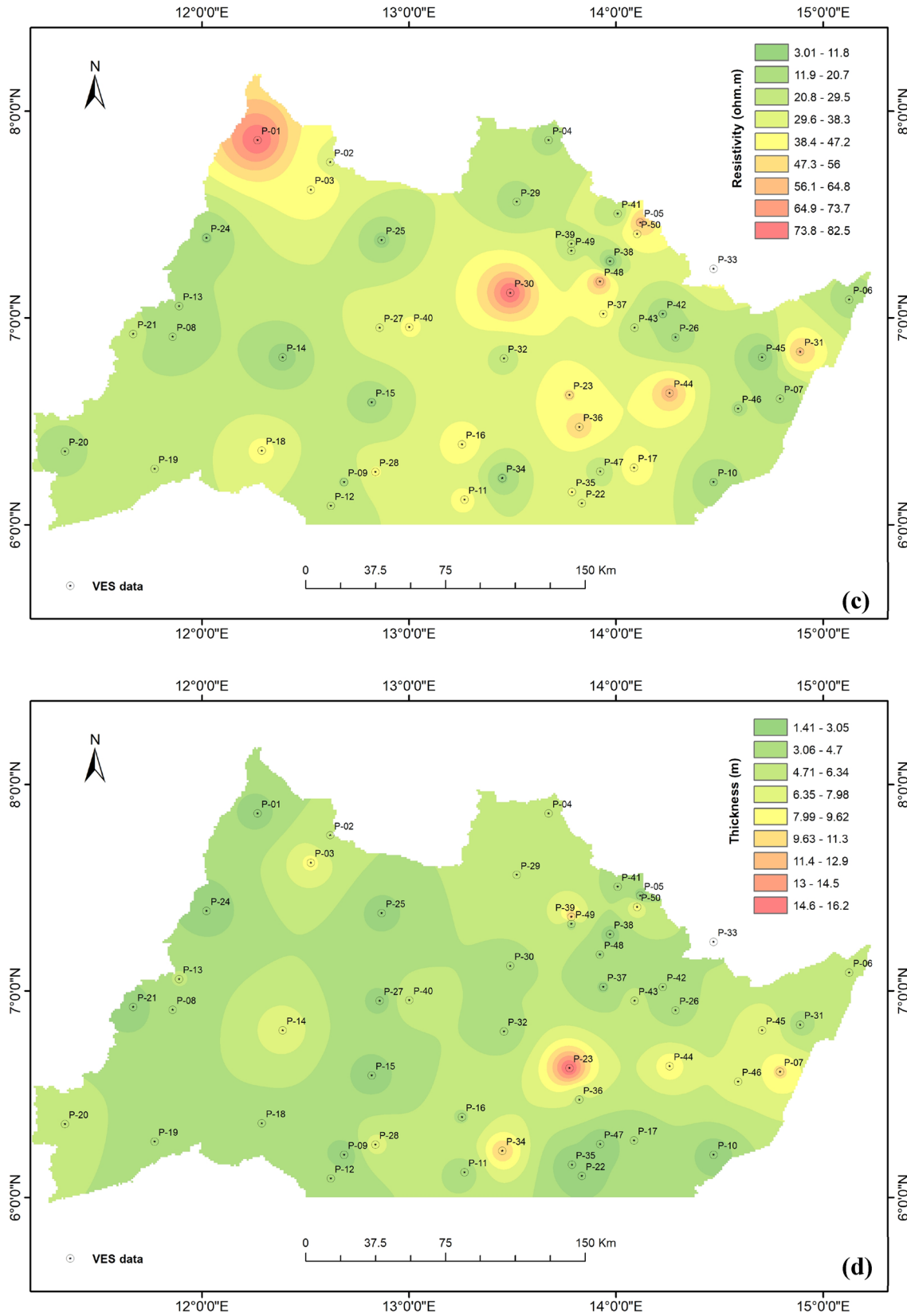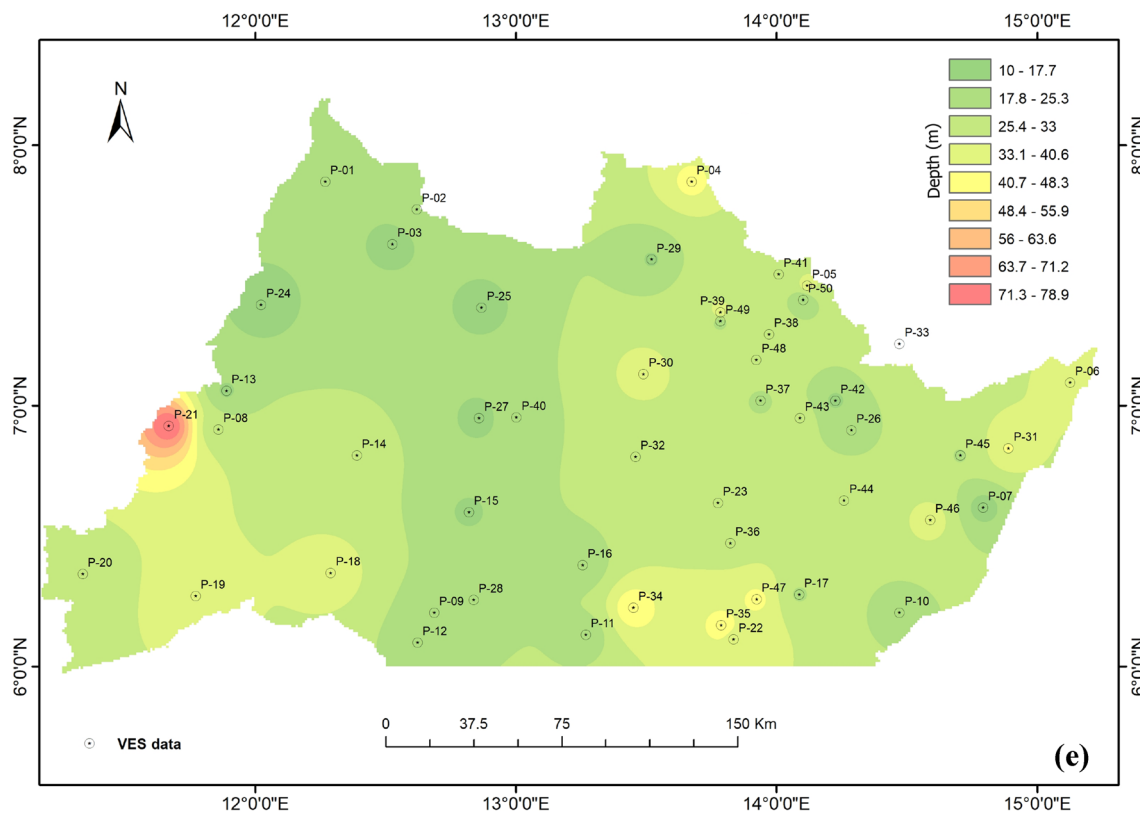
Fig. 3 (continued)

Fig. 3 (continued)

Table 2 Summary of the Adamawa aquifer characteristics derived from VES interpretation and pumping test

	Metamorphic rocks				Sedimentary rocks				General			
	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD
Resistivity (Ω m)	10	53	30.4	17.3	4	64	28.5	19.2	3	82.5	30.8	19.3
Thickness (m)	4	11	6.5	2.7	2.1	11.8	5.8	2.9	1.4	16.2	4.9	1
Depth (m)	20	48	35.2	11	17	38	26.2	7.2	10	79	28.3	11.9
K (m/day)	0.56	0.95	0.73	0.15	0.24	1.40	0.85	0.42	0.09	1.40	0.30	0.34
T (m^2/day)	8.4	23.8	13.9	6	33.6	38	35.5	1.5	8.37	38	31	5.6

values, respectively, in volcano-sedimentary and metamorphic zones. Fundamentally, the transmissivity is the product of the aquifer thickness and hydraulic conductivity. Hence, high values of transmissivity match with either with thick aquifer or high hydraulic conductivity, contrarily to low transmissivity values. However, as for linear regressions, further investigation on the physical characterisation of local rocks would deepen the discussion of these results.

Conclusion

A series of hydro-geophysical investigations have been previously conducted in the Adamawa region to improve water supply to local population. The resulting parameters varied

from an investigation to another because of the difference between methods and datasets used. This paper therefore addressed those dissimilarities by enhancing datasets and combining relevant methods. By augmenting the number of experimental VESs and combining CMM and ISM to interpret VES data taking into account the geological settings, this study led to updated values of aquifer transmissivity, hydraulic conductivity, resistivity, thickness and depth. In addition, "Adamawa aquifer" is more suitable to label this aquifer than "Pan-African" which refers to a regional stratigraphic and plate tectonic setting. For future geophysical investigation with the purpose of characterizing aquifers, it is necessary to subset the study area according to existing geological groups and to combine two or more interpretation methods.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

References

Aretouyap Z, Njandjock Nouck P, Bisso D, Nouayou R, Lengué B, Lepatio Tchieg A (2014a) Climate variability and its possible interactions with water resources in Central Africa. J Appl Sci 14:2219–2233. https://doi.org/10.3923/jas.2014.2219.2233

Aretouyap Z, Njandjock Nouck P, Ekoro Nkoungou H, Meli'i JL, Lepatio Tchieg A (2014b) Investigation of groundwater quality control in Adamawa-Cameroon region. J Appl Sci 14:2309–2319. https://doi.org/10.3923/jas.2014.2309.2319

Aretouyap Z, Nouayou R, Njandjock Nouck P, Asfahani J (2015) Aquifers productivity in the Pan-African context. J Earth Syst Sci 124:527–539. https://doi.org/10.1007/s12040-015-0561-1

Aretouyap Z, Njandjock Nouck P, Nouayou R, Teikeu Assatse W, Asfahani J (2017) Aquifer porosity in the Pan-African context. Environ Earth Sci 76:1–8. https://doi.org/10.1007/s12665-017-6440-0

Aretouyap Z, Bisso D, Njandjock Nouck P, Amougou Menkpa LE, Asfahani J (2018) 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. Nat Resour Res 28:63–77. https://doi.org/10.1007/s11053-018-9373-8

Aretouyap Z, Bisso D, Méli'i JL, Njandjock Nouck P, Njoya A, Asfahani J (2019a) Hydraulic parameters evaluation of the Pan-African aquifer by applying an alternative geoelectrical approach based on vertical electrical soundings. Geofis Int 58:113–126. https://doi.org/10.22201/igeof.00167169p.2018.58.2.1964

Aretouyap Z, Bisso D, Njandjock Nouck P, Asfahani J (2019b) A coupled hydrogeophysical approach to enhance groundwater resources management in developing countries. In: Chaminé H, Barbieri M, Kisi O, Chen M, Merkel B (eds) Advances in sustainable and environmental hydrology, hydrogeology, hydrochemistry and water resources. Advances in science, technology and innovation (IEREK Interdisciplinary Series for Sustainable Development). Springer, Cham, pp 363–365. https://doi.org/10.1007/978-3-030-01572-5_85

Aretouyap Z, Billa L, Jones M, Richter G (2020) Geospatial and statistical interpretation of lineaments: salinity intrusion in the Kribi-Campo coastland of Cameroon. Adv Space Res 66:844–853. https://doi.org/10.1016/j.asr.2020.05.002

Asfahani J (2016) Hydraulic parameters estimation by using an approach based on vertical electrical soundings (VES) in the semi-arid Khanasser valley region, Syria. J Afr Earth Sci 117:196–206. https://doi.org/10.1016/j.jafrearsci.2016.01.018

Bisso D, Arétouyap Z, Nshagali Biringanin G, Njandjock Nouck P, Asfahani J (2019) Variation of Subsurface Resistivity in the Pan-African Belt of Central Africa. In: Rossetti F et al (eds) The structural geology contribution to the Africa-Eurasia geology: basement and reservoir structure, ore mineralisation and tectonic modelling. Advances in science, technology & innovation (IEREK Interdisciplinary Series for Sustainable Development). Springer, Cham, pp 25–27. https://doi.org/10.1007/978-3-030-01455-1_6

Chandra S, Ahmed S, Ram A, Dewandel B (2008) Estimation of hard rock aquifers hydraulic conductivity from geoelectrical measurements: a theoretical development with field application. J Hydrol 357:218–227. https://doi.org/10.1016/j.jhydrol.2008.05.023

Chen J, Hubbard S, Rubin Y (2001) Estimating the hydraulic conductivity at the South Oyster Site from geophysical tomographic data using Bayesian techniques based on the normal linear regression model. Water Resour Res 37(6):1603–1613. https://doi.org/10.1029/2000WR900392

De Almeida A, Marciel DF, Sousa KF, Nascimento CTC, Koide D (2021) Vertical electrical sounding (VES) for estimation of hydraulic parameters in the porous aquifer. Water 13:170. https://doi.org/10.3390/w13020170

Frohlich RK, Fisher JJ, Summerly E (1996) Electric-hydraulic conductivity correlation in fractured crystalline bedrock: Central Landfill, Rhode Island, USA. J Appl Geophys 35:249–259. https://doi.org/10.1016/0926-9851(96)00028-6

Hubbard S, Rubin Y (2000) A review of selected estimation techniques using geophysical data. J Contam Hydrol 45:3–34. https://doi.org/10.1016/S0169-7722(00)00117-0

Huntley D (1986) Relation between permeability and electrical resistivity in a granular aquifer. Groundwater 24:466–475. https://doi.org/10.1111/j.1745-6584.1986.tb01025.x

Kelly WE (1977) Geoelectric sounding for estimating hydraulic conductivity. Groundwater 15:420–425. https://doi.org/10.1111/j.1745-6584.1977.tb03189.x

Khalil MA, Santos FAM (2009) Influence of degree of saturation in the electric resistivity-hydraulic conductivity relationship. Surv Geophys 30:601. https://doi.org/10.1007/s10712-009-9072-4

Kirkby A, Heinson G (2015) Linking electrical and hydraulic conductivity through models of random resistor networks. ASEG Extended Abstr 1:1–5. https://doi.org/10.1071/ASEG2015ab017

Lesmes DP, Friedman SP (2005) Relationships between the electrical and hydrogeological properties of rocks and soils. In: Rubin Y, Hubbard SS (eds) Hydrogeophysics. Water Science and Technology Library. Springer, Dordrecht, pp 87–128. https://doi.org/10.1007/1-4020-3102-5_4

Maréchal A (1976) Géologie et géochimie des ressources thermominérales du Cameroun. Doc ORSTOM 59:169–176

Massoud U, Santos F, El Qady G, Atya M, Soliman M (2010) Identification of the shallow subsurface succession and investigation of the seawater invasion to the Quaternary aquifer at the northern part of El Qaa plain, Southern Sinai, Egypt by transient electromagnetic data. Geophys Prospect 58:267–277. https://doi.org/10.1111/j.1365-2478.2009.00804.x

Mawer C, Knight R, Kitanidis PK (2015) Relating relative hydraulic and electrical conductivity in the unsaturated zone. Water Resour Res 51:599–618. https://doi.org/10.1002/2014WR015658

Mazac O, Kelly WE, Linda I (1985) A hydrogeophysical model for relations between electrical and hydraulic properties of aquifers. J Hydrol 79:1–19. https://doi.org/10.1016/0022-1694(85)90178-7

Niwas S, Celik M (2012) Equation estimation of porosity and hydraulic conductivity of Ruhrtal aquifer in Germany using near surface geophysics. J Appl Geophys 84:77–85. https://doi.org/10.1016/j.jappgeo.2012.06.001

Niwas S, De Lima OAL (2003) Aquifer parameter estimation from surface resistivity data. Ground Water 41:94–99. https://doi.org/10.1111/j.1745-6584.2003.tb02572.x

Niwas S, Singhal DC (1981) Estimation of aquifer transmissivity from Dar-Zarrouk parameters in porous media. J Hydrol 50:393–399. https://doi.org/10.1016/0022-1694(81)90082-2

Niwas S, Singhal DC (1985) Aquifer transmissivity of porous media from resistivity data. J Hydrol 82:143–153. https://doi.org/10.1016/0022-1694(85)90050-2

Niwas S, Tezkan B, Israil M (2011) Aquifer hydraulic conductivity estimation from surface geoelectrical measurements for Krauthausen test site, Germany. Hydrogeol J 19(2):307–315. https://doi.org/10.1007/s10040-010-0689-7

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. J Afr Earth Sci 52:9–20. https://doi.org/10.1016/j.jafrearsci.2008.03.002

Orellana E, Mooney HM (1966) Master tables and curves for vertical electrical soundings over layered structures. Interciencia, Madrid. https://lib.ugent.be/catalog/rug01:001374284

Sikandar P, Christen E (2012) Geoelectrical sounding for the estimation of hydraulic conductivity of alluvial aquifers. Water Resour Manag 26(5):1201–1215. https://doi.org/10.1007/s11269-011-9954-3

Singh VP, Frevert DK (2005) Watershed models. CRC Press, Boca Raton. https://doi.org/10.1201/9781420037432

Singh S, Singh VS (2016) Estimation of hydraulic characteristics from electrical resistivity data in coastal aquifers of southern India. J Geol Soc India 88:77–86. https://doi.org/10.1007/s12594-016-0460-3

Soupios PM, Kouli M, Vallianatos F, Vafidis A, Stavroulakis G (2007) Estimation of aquifer hydraulic parameters from surficial geophysical methods: a case study of Keritis Basin in Chania (Crete–Greece). J Hydrol 338(1–2):122–131. https://doi.org/10.1016/j.jhydrol.2007.02.028

Stelmach RD, Clasen T (2015) Household water quantity and health: a systematic review. Int J Environ Res Public Health 12:5954–5974. https://doi.org/10.3390/ijerph120605954

Tchameni R, Mezger R, Nsifa NE, Pouclet A (2001) Crustal origin of early proterozoïc syenites in the Congo (Ntem Complex), South Cameroon. Lithos 57:23–42. https://doi.org/10.1016/S0024-4937(00)00072-4

Tijani MN, Oluchukwu IN, Oladunjoye MA (2018) Estimation of hydraulic properties from resistivity sounding data: a case study of basement aquifer in Ibadan, SW-Nigeria. J Min Geol 54(1):59–74

Toteu SF, Ngako V, Affaton P, Nnange JM, Njanko TH (2000) Pan-African tectonic evolution in Central and Southern Cameroon: tranpression and transtension during sinistral shear movements. J Afr Earth Sci 36:207–214. https://doi.org/10.1016/S0899-5362(03)00023-X

Toteu SF, Van Schmus WR, 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. Precambr Res 180:45–73. https://doi.org/10.1016/S0301-9268(00)00149-2

Youssef MAS (2020) Geoelectrical analysis for evaluating the aquifer hydraulic characteristics in Ain El-Soukhana area, West Gulf of Suez, Egypt. NRIAG J Astron Geophys 9(1):85–98. https://doi.org/10.1080/20909977.2020.1713583

Zohdy AAR (1989) A new method for the automatic interpretation of Schlumberger and Wenner sounding curves. Geophysics 54:245–253. https://doi.org/10.1190/1.1442648