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ORIGINAL ARTICLE

Aquifer porosity in the Pan-African semi-arid context

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Abstract Water scarcity is one of the major concerns that
people are facing worldwide. Although the liquid is abso-
lutely abundant through the globe, its availability poses too
much problems specifically to each region. Those problems
can result in one or a combination of three basic situations:
declining water (drought), overabundance of surface water
(floods) or degradation of the quality of water (pollution).
All these situations are reflected in the scarcity of good
quality water. Arid regions are particularly concerned. In
such areas where groundwater contained in aquifers is
usually perceived as providence, any project of ground-
water exploration and exploitation must be preceded by
prior careful and meticulous investigation, in order to avoid
early and premature drying. This investigation is likely to
predict the future behaviour of aquifers and to improve the
groundwater resources management. Beside fundamental
properties as hydraulic conductivity, the present paper that
addresses the water sector in the semi-arid region of
northern Cameroon emphasizes the importance of porosity
on aquifer productivity and consequently on the ground-
water resources management. The porosity of the local
aquifer has then been determined using the Waxman and
Smits model which establishes a reliable relationship
between the apparent and corrected formation factors, F_a
and F_c, taking the clay effects into consideration. This
approach can be applied in other similar semi-arid regions
through the world.

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Introduction

Water scarcity is one of the major concerns that people are
facing worldwide. Although the liquid is absolutely abun-
dant through the globe, its availability poses too much
problems specifically to each region. These problems can
result in one or a combination of three basic situations:
declining water (drought), overabundance of surface water
(floods) or degradation of the quality of water (pollution).
All those situations are reflected in the scarcity of good
quality water (Arétouyap et al. 2014a, b). Arid and semi-
arid regions are particularly concerned. In such areas where
groundwater contained in aquifers is usually perceived as
providence, any project of groundwater exploration and
exploitation must be preceded by prior careful and metic-
ulous investigation, in order to avoid early and premature
drying. This paper addresses the groundwater sector in the
Central Africa region, an area located just above the
equator where populations curiously are experiencing a
serious water stress.

Because of the poor spatial distribution of populations
with respect to the surface water courses, and the relative best
quality of groundwater, many officials of the water sector
nowadays direct their water resources management policy
towards the exploitation of groundwater contained in aqui-
fers (Asfahani 2012). Actually, about 98% of the freshwater
on the planet is made of groundwater, discounting that in the
polar icecaps. This makes groundwater fundamental for
human life and economic development. In fact, a portion of
rainfall infiltrates the soil, whereas the other evaporates or
runs off to rivers. The infiltrated portion is divided into two

proportions: one taken up as moisture by plants roots, and another infiltrated more deeply, reaching a waterproof bed, saturating existing pore space and forming an underground reservoir. Aquifers are thus formed and characterized by the water table that indicates the ground saturation in water. The water table divides the local ground into two zones: the unsaturated zone above and the saturated zone below. The productivity of an aquifer strongly depends on the porosity as this parameter sets the aptitude of the aquifer to both store and transmit water. Unconsolidated granular sediments, because of the abundance of pore space they contain, have relatively high content of water (greater than 30% of their total volume). As a result, the original porosity (the one before the insertion of fine sediments into the void spaces) decreases progressively both with the proportion of finer materials such as silt or clay and with cementation of the grains. Note that global new porosity may be even higher than the original one. In other hand, when rock is highly consolidated, only fractures contain a little groundwater (less than 1% of the total volume of rock mass). However, in the case of limestone, these fractures are more important because of the solution and preferential flow, and are so-called fissures and caverns. Even when the total storage is relatively small compared to unconsolidated aquifers, one result is that there is less water available to dilute contaminant pulses (Jones et al. 2000; Jocson et al. 2002).

This can explain why porosity stands as a key parameter of aquifer productivity. Actually, porosity impacts groundwater both in quantity and in quality as raised by many researchers worldwide. This is the case of Al-Assa'd and Abdulla (2010) during the simulation of the artificial groundwater recharge to a semi-arid basin of Mujib aquifer (Jordan) Pérez and Sanz (2011), during the hydrodynamic characterization a karst aquifer in the Cabrejas range (Spain) Bejranonda et al. (2013), when modelling the dynamic interaction between surface and groundwater (Thailand) Radfar et al. (2013), when investigating drought impacts on long-term hydrodynamic behaviour of groundwater in the tertiary–quaternary aquifer system of Shahrekord Plain (Iran), etc.

The present paper intended as an educational handbook aims to present the importance of porosity in the aquifer productivity, and the steps necessary to determine it in an arid context. This is applied in the present study area where the approach developed by Asfahani (2013) is used to compute the porosity of the Pan-African aquifer system.

Geomorphology and hydrogeology of the Adamawa plateau

The present study is conducted in the Adamawa, Cameroon, region presented in Fig. 1 (6°–8° north and 11°–16° east). This region is a junction between the Federal Republic of Nigeria, the Central African Republic and Cameroon with an area of 6782 km^2. 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 limited at the north by a large cliff and an uneven escarpment of several hundred metres that dominates the area has a rugged terrain.

The centre 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 more than 2240 m at Mount Tchabal Mbabo. There are also plains and basins such as the Tikar plain in the division of Mayo-Banyo. The southern part is characterized by a huge plateau that gradually drops until the peneplain area of Djerem (Toteu et al. 2000).

In hydrological terms, 150–300 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 detect local aquifers and compute their major hydrodynamic parameters such as depth, hydraulic conductivity, resistivity, thickness, transmissivity and the product Kσ. Yet, the porosity aspect was not tackled.

Methodology

VES data recording and interpretation

Schlumberger configuration is used to perform fifty VES in the study area in order to locate and characterize aquifers. The Terrameter ABEM SAS-1000 used with a spacing of current electrodes from 1 to 300 m directly measures the resistance U_{MN}/I, which enables to calculate the apparent resistivity of the rock using the Ohm's law and expressed by Eq. 1, taking into consideration Eq. 2.

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

where

$$k = \frac{2\pi}{\left(\frac{1}{AM} - \frac{1}{BM} - \frac{1}{AN} + \frac{1}{BN}\right)} \tag{2}$$
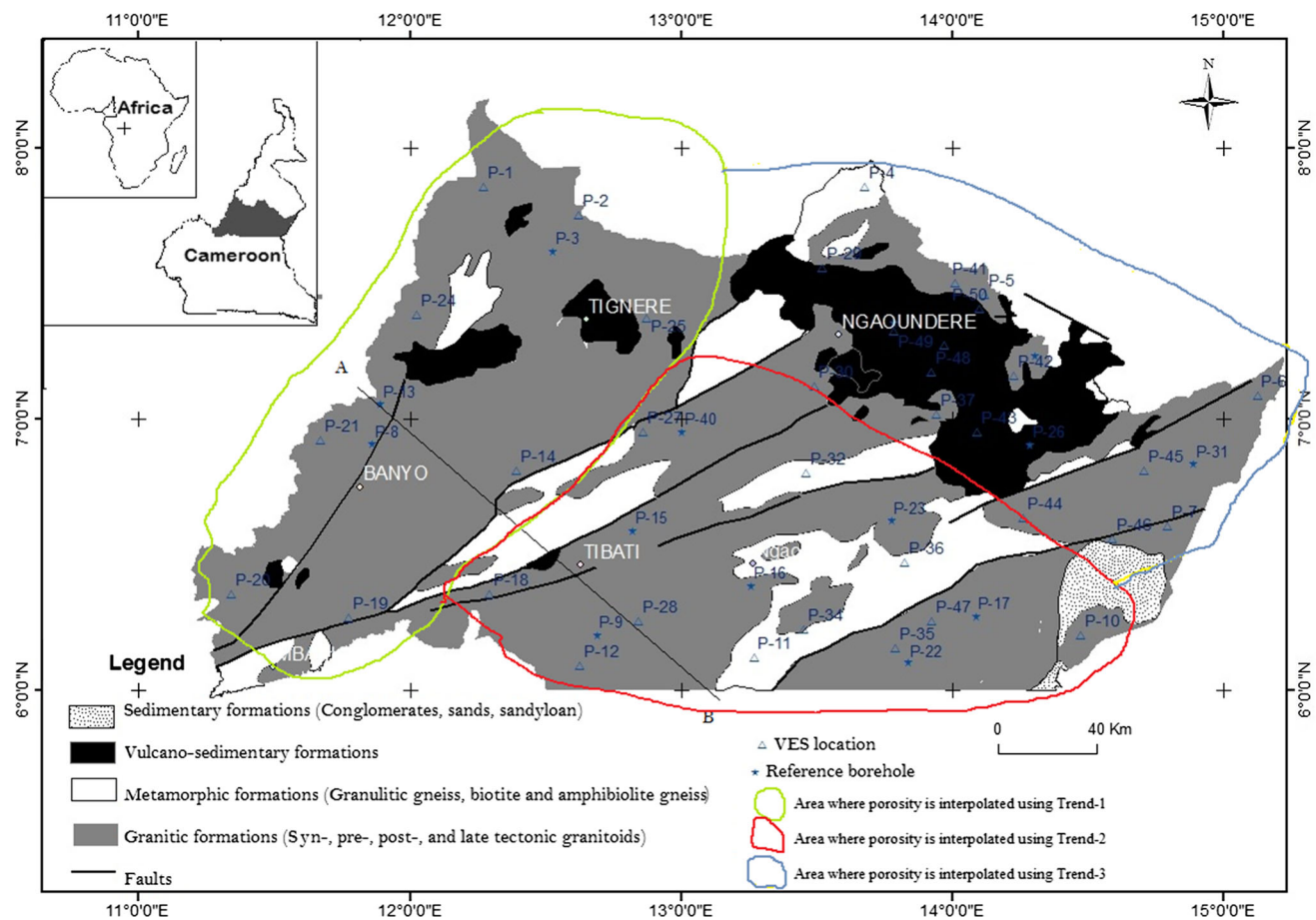
Fig. 1 Geological map of the study area, with vertical electrical sounding (VES) points

k represents the geometric factor of the quadrupole device used, I the intensity of the electrical current injected into the Earth by the electrodes A and B, and U_{MN} the voltage potential between the electrodes M and N.

Values of the apparent resistivity ρ_a depend on several factors as the true layer resistivities, the layer boundaries and the electrodes location. In case of homogeneous substratum, both parameters are almost identical. Generally, ambiguity occurs during the interpretation of VES data. This ambiguity substantially results in non-uniqueness of results. In order to overcome the impacts of this ambiguity, the interpretation modelling must be tested prior for each project. When it is so complex to overcome the non-uniqueness, additional surveys such as seismic or test wells are conducted for that purpose. Asfahani (2007) precised how to overcome such problems in the case of thinner layers. The same author proposed the determination of the product of thickness and resistivity rather than their true values (Asfahani 2013). The interpretation of VES is used according to the approach developed by Zohdy (1989).

When calculations are precise and judicious geological concepts incorporated in the interpretation process, the quantitative interpretation is considered as correct. The present study takes into consideration the assumption of one-dimensional medium, where layers are horizontal and stratified, with the last layer bottomless (Anomohanran 2013).

Figure 2 shows an example of field VES curve obtained at point P-23 and its digital model obtained from 1D theoretical interpretation. The assumption of a 1D medium was verified in the field. The 1D quantitative interpretation of the 50 VES enabled identification of geoelectrical characteristics of the Pan-African deposits (Arétouyap et al. 2015).
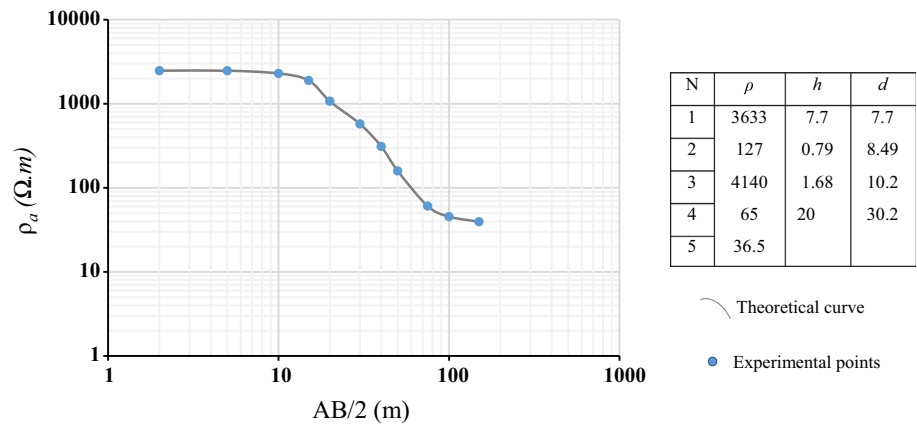
Porosity processing

The aquifer porosity, Φ, of the 14 reference VES points is determined using Archie's law expressed by Eq. 3 (Archie 1942).

$$\rho_e \sigma_w = \alpha \emptyset^{-m} \tag{3}$$

in which ρ_e is the bulk resistivity, σ_w is the water conductivity, and $\emptyset$ is the porosity expressed by a void fraction,

Fig. 2 Example of VES field measurement at point P-23 and its digital model obtained from theoretical interpretation (Arétouyap et al. 2015)

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

and the dimensionless coefficients $\alpha = 0.88$ and $m = 1.37$ depend on the rock type.

Considering that $\sigma_w = 1/\rho_w$, the ratio $F = \rho_e/\rho_w$ is called the formation factor. In the following text, F_c refers to the formation factor corrected due the presence of clays, while the apparent formation factor, F_a, refers to a simple ratio of interpreted bulk resistivity over pore water resistivity.

Taking away F_c from F, the apparent porosity can be therefore expressed by Eq. 4.

$$\emptyset = \exp\left(\frac{1}{m}\log(\alpha) + \frac{1}{m}\log\left(\frac{1}{F_c}\right)\right) \quad (4)$$

Worthington (1993) stated that the application of Archie's law is indicated only when there is no clay in the environment. This is due to the phenomenon of high cation exchange that characterizes the clay (Waxman and Smits 1968; Vinegar and Waxman 1984). In general, higher clay content lowers the resistivity and lowers the hydraulic permeability. Hence, clay content may affect the aquifer porosity.

Two main geological arrays are observed in the study area, along the profile A–B (Arétouyap et al. 2015):

1. The first array type, located at the middle of the profile, is made up of three geological horizons. The first horizon is laterite or topsoil with a thickness varying between 0.5 and 1.5 m and a resistivity up to 4000 Ω m. The second horizon corresponds to a clayey soil, with a thickness ranged from 5 to 15 m, and resistivity varying between 200 and 700 Ω m. The last horizon corresponds to the granitic bedrock, whose the upper fractured part is aquifer, with thickness ranged between 1 and 101 m, and resistivity varying between 3 and 825 Ω m.
2. The second type of geological array is observed at the ends of the profile and has four geological horizons. The first and the second horizon remain, respectively, laterite/topsoil and clayey soil with the same proprieties. The third horizon is a sandy soil. Its thickness varies

from 1 to 15 m, and its resistivity ranges between 100 and 1300 Ω m. In the south-west region, the fourth horizon representing the aquifer is composed of sandstone. Its thickness varies between 20 and 61 m, and its resistivity varies between 47 and 355 Ω m. This geological disposition is illustrated in Fig. 3.

The Pan-African aquifer system in the Adamawa Plateau is made of cracked upper part of granite or sandstone. It is characterized by the presence of clayey soil at the second/third horizon (Arétouyap et al. 2015). For this, an adequate correction of the apparent formation factor, F_a (Eq. 5), is required (Asfahani 2012). The resulting corrected formation factor is denoted as F_c (Waxman and Smits 1968; Worthington 1993).

$$F_a = F_c(1 + BQ_v\rho_w)^{-1} \quad (5)$$

where BQ_v (Worthington 1993) is proportional to cation-exchange capacity, Q_v and equivalent conductance of clay exchange cations, B.

This equation can be arranged so that a linear relationship between $1/F_a$ and ρ_w is obtained as shown in Eq. 6.

$$\frac{1}{F_a} = \frac{1}{F_c} + \left(\frac{BQ_v}{F_c}\right)\rho_w \quad (6)$$

Consequently, plotting the water resistivity ρ_w as a function of $1/F_a$ (Fig. 4) enables to obtain the value of the corrected F_c, and the porosity can be obtained from Eq. (4) as shown in Table 1.

Figure 4 reveals three correlation trends leading to three relationships established as follows:

• Trend 1 has the following relationship (Eq. 7):

$$\frac{1}{F_a} = -0.0721\rho_w + 0.5046. \quad (7)$$

Trend 1 is established by using three VES points, which is the minimum acceptable number of points from statistical point of view.
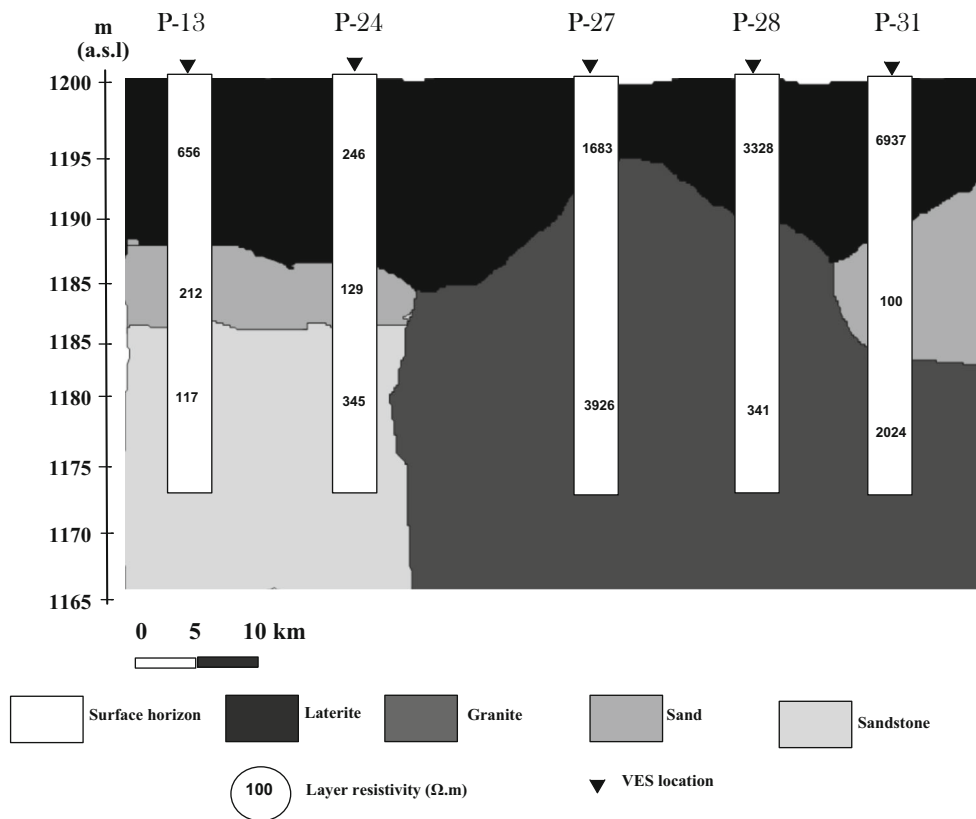
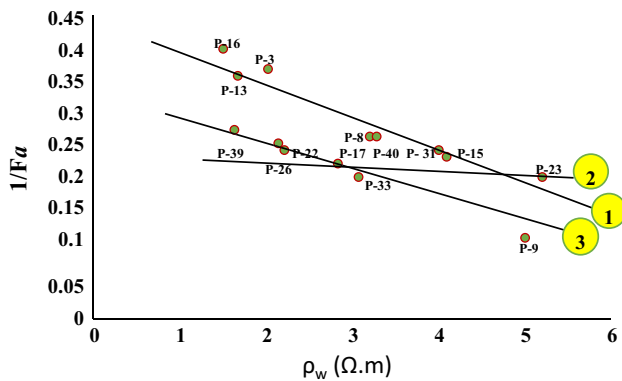Fig. 3 Geological cross section established along the A-B profile

Fig. 4 Water resistivity ρ_w as a function of $1/F_a$

- Trend 2 has the following relationship (Eq. 8):

$$\frac{1}{F_a} = -0.0118\rho_w + 0.2818. \tag{8}$$

- Trend 3 has the following relationship (Eq. 9):

$$\frac{1}{F_a} = -0.0492\rho_w + 0.3628. \tag{9}$$

The corrected F_c is computed from those trends and therefore is site dependent.

Table 1 Geophysical and hydrological parameters of the studied fourteen VES points

VES	ρ_e (Ω m)	ρ_w (Ω m)	h (m)	$1/F_a$	$1/F_c$	Φ	K (m/day)
P-3	472.0	2.03	8.4	0.37	0.50	0.04	0.62
P-8	134.0	3.21	43.0	0.27	0.50	0.02	0.09
P-9	207.0	5.01	19.0	0.12	0.50	0.08	0.09
P-13	177.0	1.68	48.0	0.36	0.50	0.05	0.23
P-15	112.9	4.01	17.0	0.25	0.50	0.06	0.55
P-16	46.0	1.51	46.0	0.4	0.50	0.07	0.12
P-17	446.0	2.84	31.0	0.21	0.28	0.14	0.89
P-22	341.0	2.22	23.0	0.23	0.28	0.12	0.13
P-23	48.0	5.21	16.2	0.21	0.28	0.15	0.22
P-26	110.8	2.15	38.0	0.26	0.36	0.19	0.56
P-31	565.0	4.10	40.0	0.24	0.28	0.11	0.09
P-33	479.0	3.08	42.0	0.21	0.36	0.30	0.19
P-39	28.0	1.64	11.8	0.28	0.36	0.21	0.09
P-40	40.0	3.29	60.0	0.27	0.28	0.09	0.16

Results and discussion

The approach used in the present investigation consists of establishing three trends (empirical relationships) between $1/F_a$ and ρ_w. This approach has proven its

Table 2 Geophysical and hydrological parameters for the Pan-African aquifer system at the 36 VES locations in the Adamawa Plateau

VES	ρ_e (Ω m)	ρ_w (Ω m)	h (m)	$1/F_a$	$1/F_c$	Φ	K (m/day)	Trend used
P-01	811.0	1.65	25	0.39	0.50	0.19	1.64	Trend 1
P-02	362.1	2.31	47	0.34	0.50	0.19	0.86	Trend 1
P-04	175.7	3.01	48	0.21	0.36	0.32	0.83	Trend 3
P-05	608.0	5.01	20	0.12	0.36	0.32	2.00	Trend 3
P-06	157.0	4.35	6	0.15	0.36	0.32	6.18	Trend 3
P-07	137.0	2.98	10	0.22	0.36	0.32	3.472	Trend 3
P-10	114.1	3.46	19	0.24	0.28	0.43	0.08	Trend 2
P-11	410.0	2.15	40	0.26	0.28	0.43	0.76	Trend 2
P-12	22.0	2.85	37	0.25	0.28	0.43	0.46	Trend 2
P-14	8.0	2.53	8	0.32	0.50	0.19	0.77	Trend 1
P-18	408.0	2.69	43	0.25	0.28	0.43	0.71	Trend 2
P-19	26.0	1.98	34	0.36	0.50	0.19	0.52	Trend 1
P-20	188.0	3.65	61	0.24	0.50	0.19	0.47	Trend 1
P-21	221.5	4.02	19	0.21	0.50	0.19	1.28	Trend 1
P-24	112.9	1.87	17	0.37	0.50	0.19	1.23	Trend 1
P-25	100.0	3.25	22	0.27	0.50	0.19	1.74	Trend 1
P-27	341.0	1.96	23	0.26	0.28	0.43	1.18	Trend 2
P-28	392.6	4.09	70	0.23	0.28	0.43	0.46	Trend 2
P-29	13.0	3.24	6	0.24	0.28	0.43	5.67	Trend 2
P-30	825.0	2.56	38	0.25	0.28	0.43	1.10	Trend 2
P-32	25.0	3.78	33	0.24	0.28	0.43	0.52	Trend 2
P-34	10.0	1.65	11	0.26	0.28	0.43	0.78	Trend 2
P-35	387.0	1.88	14	0.26	0.28	0.43	1.82	Trend 2
P-36	53.0	2.23	62	0.26	0.28	0.43	0.37	Trend 2
P-37	422.0	3.17	28	0.21	0.36	0.32	1.44	Trend 3
P-38	4.0	1.83	21	0.27	0.36	0.32	1.62	Trend 3
P-41	200.0	2.53	38	0.24	0.36	0.32	1.04	Trend 3
P-42	104.0	2.35	33	0.25	0.36	0.32	1.17	Trend 3
P-43	212.0	3.51	52	0.19	0.36	0.32	0.77	Trend 3
P-44	61.0	3.02	93	0.21	0.36	0.32	0.42	Trend 3
P-45	3.0	3.21	8	0.20	0.36	0.32	4.00	Trend 3
P-46	20.0	1.59	7	0.28	0.36	0.32	4.96	Trend 3
P-47	216.1	2.22	15	0.26	0.28	0.43	1.55	Trend 2
P-48	640.0	4.32	30	0.15	0.36	0.32	1.36	Trend 3
P-49	270.4	3.12	32	0.21	0.36	0.32	1.24	Trend 3
P-50	47.0	2.50	85	0.24	0.36	0.32	0.46	Trend 3

efficiency through its application in the Khanasser Valley in Syria, Asfahani (2012). Fourteen experimental wells with available pumping tests and 14 closed VES points with their quantitative interpretations are used in the present study to compute geophysical and hydro-logical parameters (Table 1) and to establish trends and appropriate empirical relationships between water resistivity and $1/Fa$ (Eqs. 7, 8 and 9). Those equations are thereafter used to evaluate F_c in all the VES locations, in order to characterize as precisely as possible the porosity of the Pan-African aquifer system in central Africa.

The interpreted geophysical and hydrological parameters computed for the Pan-African aquifer system at the 36 VES locations in the Adamawa Plateau using the calibrated empirical Eqs. 7, 8 and 9 are summarized in Table 2.

Porosity values are approximately deduced from the trends established in Eqs. 7, 8 and 9. These are, respectively, 0.19, 0.32 and 0.43. Actually, porosity is a very important parameter in the aquifer characterization and groundwater management. Indeed, the productivity of an aquifer depends on the geological characteristics of its lithological log, and especially porosity. Two main situations are commonly encountered as established by Meinzer
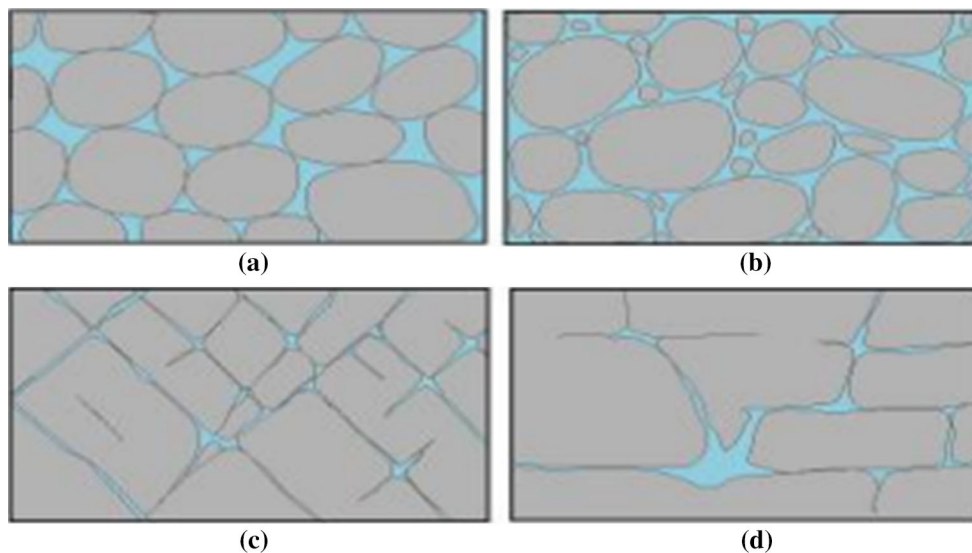
Fig. 5 Rock texture and porosity of typical aquifer materials (modified from Meinzer 1923). **a** Unconsolidated well-stored sand; **b** sand porosity reduced by admixture of fines or cementation; **c** consolidated rock rendered porous by fracturing; **d** consolidated fractured rock with porosity increased by solution

(1923): (1) the porosity is primary (or intergranular), so that water is stored in the interstices between the grains, and (2) the porosity is secondary, where water is stored in and flows through fractures (Fig. 5). The different ways that water is stored and flows through the rock control both the volume of storage and its relative mobility.

The aquifers investigated in the present paper have porosity values ranged from 0.19 to 0.43. These relatively high valued (for fracture aquifers) demonstrate that the study area has experienced serious tectonic activities. In fact, regional aquifers are made up of fractured or weathered portion of granitic basement (Arétouyap et al. 2015). It is then important to compute it during the process of groundwater resources management.

Conclusion

Arid regions are usually characterized by chronic drought. In this context, hydraulic conductivity, transmissivity and transverse resistance are not enough to set an aquifer. It becomes very important to take into account aquifer porosity since the aquifer recharge can be substantially horizontal. Having demonstrated the importance of porosity in the aquifer recharge mechanism, this paper, pedagogically, outlined the various contemporary steps to compute the porosity of an aquifer, based on the case study of the semi-arid region of Adamawa, North Cameroon. In this area, porosity ranges between 0.19 and 0.43. This methodology can be used to determine aquifer porosity in all semi-arid regions throughout the world, and popularizing the use of groundwater to reduce water stress in such zones.

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