

MAGNETIC RESONANCE SOUNDINGS FOR CHARACTERIZING THE QUATERNARY AQUIFER IN THE LAKE CHAD BASIN– A CASE HISTORY FROM CAMEROON AND NIGER

¹Kemgang, D.T., ²Boucher, M., ¹Ngounou Ngatcha, B., ³Favreau, G., ¹Mvondo, V.Y.E., ³Ibrahim, M., ²Legchenko, A. and ⁴Goni, I.B.

¹ Department of Earth Sciences, Faculty of Science, University of Ngaoundéré, BP: 454 Ngaoundéré, Cameroon

² Laboratoire d'étude de Transfert en Hydrologie et Environnement, IRD / UJF / CNRS / G-INP, BP: 53, 38041 Grenoble, France

³HydroSciences Montpellier, IRD / UM / CNRS, Nouvelle Université de Montpellier, CC MSE, 34095 Montpellier cedex 5, France

⁴Department of Geology, University of Maiduguri, Borno State, Nigeria.

ABSTRACT

In the semiarid Lake Chad Basin (LCB), the transboundary quaternary sedimentary aquifer is the main source of drinking water. Climate variability and the increase in population around the Lake raise concern on the issues of water supply and water management. The knowledge about the availability of groundwater resources in LCB is limited due to the scarcity of information about hydrodynamic parameters of the aquifers. To fill this gap, geophysical surveys based on Magnetic Resonance Sounding (MRS) method were performed in the Yaere aquifer (Northern Cameroon) and in the Kadzell aquifer (Southeastern Niger). The MRS method is a non-invasive technic which has the advantages to be directly sensitive to groundwater, and to allow estimating hydrodynamic parameters. Six representative sites were investigated by MRS (three per aquifer) and are presented in this paper. MRS results are compared to measured piezometric level and to geological description when available. Despite naturally challenging field conditions (high natural electromagnetic noise, and low geomagnetic field), MRS data of good quality were obtained. The piezometric levels estimated with MRS are close to the water level measured in neighboring wells or boreholes. The results also show contrasts in MRS water content and transmissivity in good agreement with expected behavior of aquifers: high values of water content (16%-32%) and transmissivity ($2 \cdot 10^{-4} \text{ m}^2/\text{s}$ – $4 \cdot 10^{-2} \text{ m}^2/\text{s}$) were recorded near the Lake and the rivers (e.g. near the Komadugu Yobe and the El beid River), and lower values were obtained at distance or in flat clayey areas. These encouraging results promote the use of MRS at the basin scale, to better estimate the available volume of fresh groundwater resources.

KEY WORDS: Lake Chad Basin (LCB), Magnetic Resonance Sounding (MRS), groundwater resources, hydrodynamic parameters, Quaternary sedimentary aquifer (Chad formation).

INTRODUCTION

Semiarid regions are usually characterized by low water resources due to harsh climatic conditions for most of the year.

Water surfaces are more often non-permanent, and their presences are linked to rainy season. Therefore, most of the water needs in semiarid regions are supported by groundwater

resources, which are exploited through several boreholes and wells. In the Lake Chad area, the main use of groundwater resource concerns the domestic needs. These domestic needs include the irrigation for agriculture (e.g. sweet peppers in the vicinity of Komadugu Yobe valley or rice culture near the Logone valley) and cattle farming which increase water demand. MacDonald et al. (2012) mentioned that hydrogeological field surveys are rare in Africa and sustainable exploitation of the aquifers requires urgent knowledge on the availability and the recharge of groundwater resources. This issue is especially important in the Lake Chad Basin (LCB) because Lake Chad surface area showed rapid shrinkages in response to climate variability during the 20th century (e.g. the Lake water surface decreased from 15 000 to 1800 km² in the few years during the 1970-80s Lemoale et al. 2011). In addition, the management of the LCB water resources is particularly complex due to its transboundary nature. One of the aims of the Lake Chad Basin Commission (LCBC) is to evaluate the available groundwater resource. This evaluation is an ongoing process that needs global management approach at LCB scale Ngounou Ngatcha et al. 2008.

In the LCB, the most accessible aquifer for the population is the shallow quaternary

sedimentary aquifer. The previous hydrogeological studies on this aquifer evidenced several naturally occurring piezometric depressions systems in groundwater around the Lake: the Borno depression in Nigeria, the Yaere depressions in Cameroon, the Chari-Baguirmi depression in Chad and the Kadzell depression in Niger. These depressions have been described in several PhD thesis such as the works by Ngounou Ngatcha, 1993; Djoret, 2000; Goni, 2002; Leblanc 2002; Gaultier, 2004; Zaïri, 2008; Le Coz, 2010; Abderamane, 2012. Hydrochemical characteristics of these depressed aquifers were described by Arad and Kafri, (1975) but the question about their possible common origin is still unanswered. A poor documentation about the hydrodynamic properties of these shallow aquifers (few pumping tests in the literature at the basin scale) is often claimed to strongly limit modeling of lake – groundwater fluxes and no comparison between these aquifers exists to see if hydrodynamic properties are more or less homogeneous at the LCB scale. Thus, it is difficult to propose a global functioning and to build a hydrodynamic model of the whole transboundary quaternary aquifer.

The Magnetic Resonance Sounding (MRS) method is a non-invasive geophysical tool which has the advantage to be directly

sensitive to groundwater, hence allowing the estimate of hydrodynamic properties. It has already been used in sedimentary and basement context in many countries of Africa: Benin (e.g. Descloitres et al. 2011, Vouillamoz et al. 2014); Botswana (e.g. Lubczynski and Roy, 2004); Burkina Faso (e.g. Vouillamoz, 2005); Cameroon (Kemgang et al. 2014); Chad (Bernard et al., 2012); Equatorial Guinea (Portselan and Treshchenkov, 2002); Madagascar (Baltassat and Legchenko, 2001); Mauritania (e.g. Bernard et al. 2004); Morocco (Delaporte et al. 2003); Mozambique (Vouillamoz, 2003); Namibia (e.g. Lange et al. 2000); Niger (e.g. Boucher et al. 2012, Descloitres et al. 2013); South Africa (e.g. Meyer et al. 2006); Uganda (Lawson et al. 2015). But, to the best of our knowledge, no study or comparisons was realized at the scale of a transboundary aquifer.

In this study, the MRS method was used with the objective to assess hydrodynamic parameters for better understanding the functioning of LCB quaternary aquifer. Our study focusses on two parts of LBC area and the comparison of results obtained in each part can represent the first step for getting a more complete view of the quaternary aquifer heterogeneities at the whole aquifer scale.

STUDY AREA

The study area (figure 1) focused on two parts of Lake Chad Basin. The first part is located in the Far North region of Cameroon, between the foothills of Mandara Mountains and the southern shore of Lake Chad. It includes the piedmont plain and the Yaéréflood plain. The second part is located in Diffa region of Niger, between the Manga plateau and the borders with Chad and Nigeria. It includes the Lower Komadugu valley, the Kadzell plain and the North Lake Chad area (mostly dry since the 1970s).

The superficial geological formation of interest in the present study consists of quaternary deposits (Tillement, 1970; Greigert and Bernert, 1979). These quaternary deposits cover a surface area of 550,000 km² at the LCB scale. They consist of sandy-clayey sediments with gravels from fluvial-lacustrine origin. These sediments are related with the transgressions and regressions of Lake Chad during dry and humid periods of plio-quaternary age (Servant and Servant-Vildary, 1973). They lie down continental and marine deposits from tertiary and Cretaceous ages (Pias, 1970). In the piedmont plain of Cameroon (the southern border of Lake Chad sedimentary basin), the quaternary deposits directly lie on the Precambrian basement

formed by granites and/or gneisses (NgounouNgatcha, 1993).

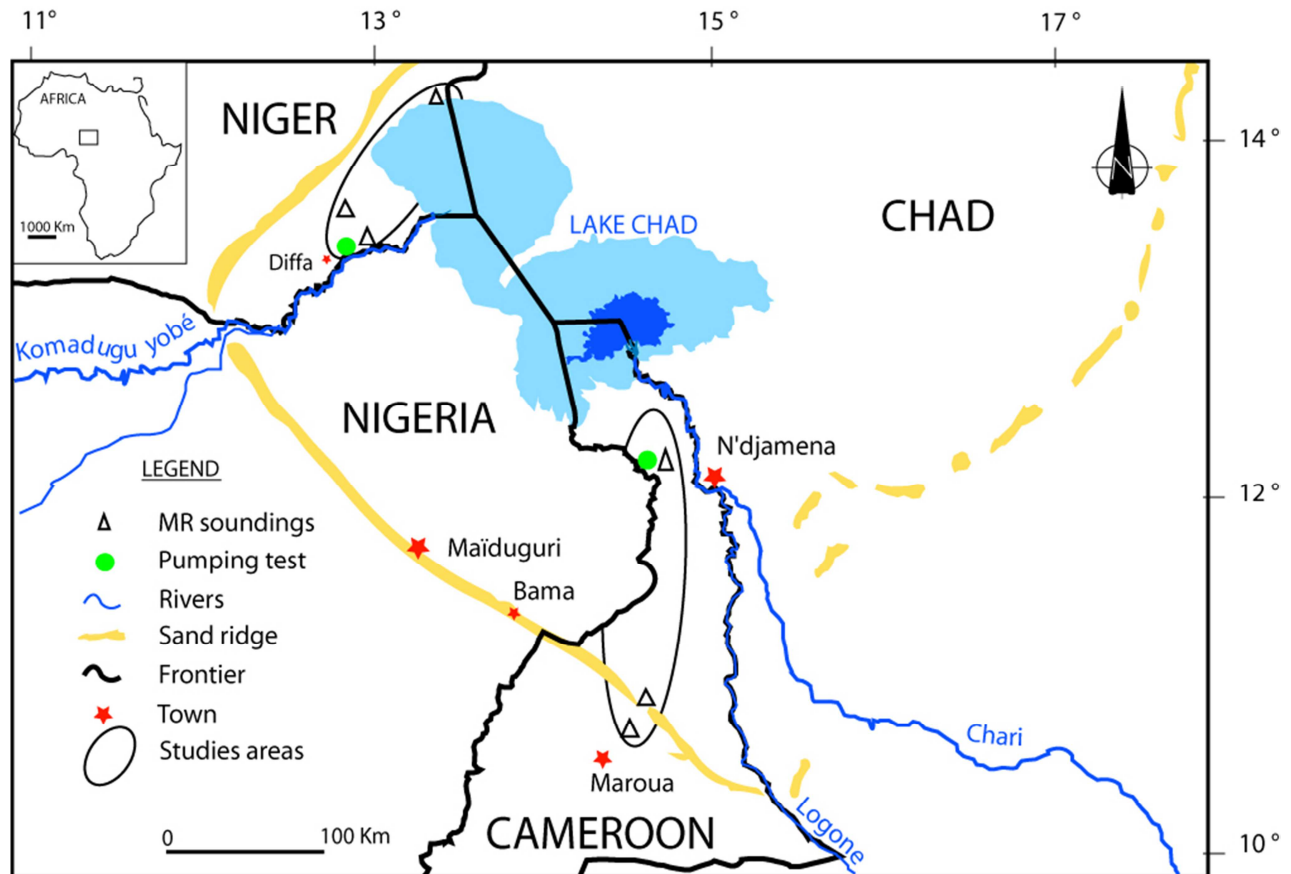


Figure 1: Map of the Lake Chad study area. Cameroon (Piedmont plain aquifer and Yaere aquifer) and Niger (Kadzell aquifer) investigated areas.

The quaternary sedimentary (upper Chad) formation contains the most exploited aquifer for the population water needs in the whole regions. At the LCB scale, it is considered as a continuous unconfined aquifer (PNUD-FAO-CBLT, 1973). In Niger, the two main aquifers tapped for water uses are the Upper quaternary aquifer (unconfined) and the Pliocene aquifer (artesian waters, mostly). In Cameroon and in Nigeria, more complex

systems are observed. In the Yaere plain, NgounouNgatcha et al. (2007a) evidenced that the Quaternary aquifer has two separated layers with different hydrochemical properties. In the piedmont plain, two hydrogeological units are also identified: (1) the sub-regional aquifer up to 40 m thick and (2) numerous perched aquifers of local importance (Tillement, 1972 in Njitchoua and NgounouNgatcha, 1997). In Nigeria, the

quaternary formation has three aquifer horizons separated by thick confining beds (Barber, 1965 in Edmunds et al. add coma1999). The upper aquifer zone of this system ranges from confined to semi-confined and unconfined in places (Goni, 2006).

At regional scale, the aquifer recharge during rainy season is controlled by both direct and indirect infiltration. In the Southern border of LCB in Cameroon, the aquifer recharge generally occurs through percolation of water surface in bed's river during a rainy season (Tillement, 1970). According to NgounouNgatcha et al., (2007b), direct infiltration of effective rainfall also improves groundwater recharge during the months of July through September. In the northwestern part of LCB (Niger), the main recharge process is indirect infiltration of temporary surface water bodies (rivers and pounds) during the rainy season (Zaïri, 2008). The discharge of aquifer is mainly linked either to direct evaporation process where groundwater level is near soil surface or to plant (ligneous) transpiration for the unconfined aquifers. The discharge by pumping remains limited in volume to < 1 mm/yr for the unconfined aquifer (Leblanc, 2002).

The quaternary aquifer is characterized by piezometric depressions and domes (e.g. Durand, 1982; Leblanc et al. add coma 2003).

The depressions also called "hollow aquifers" are located in Cameroon (Yaéré depressions), in Chad (Barh Chari-baguirmi depression), in Niger (Kadzell depression) and in Nigeria (Borno depression). Various theories to explain their origins were proposed (e.g. Durand, 1982, Dieng, 1987; Aranyossy and Ndiaye, 1993) but none of these have obtained unanimous agreement from the scientific community. As pointed out by NgounouNgatcha et al. (2007a), a better understanding of these aquifers requires additional data that can be obtained by geophysical methods.

MAGNETIC RESONANCE SOUNDING (MRS) METHOD

Basic principle

MRS is non-invasive method which is particularly adapted to hydrogeological investigations, being exclusively sensitive to free groundwater (Lubczinski and Roy, 2004; Legchenko et al., 2004). Its principle is based on Nuclear Magnetic Resonance (NMR) theory (Legchenko et al., 2002). This principle, illustrated in figure 2, is associated to the physical properties of hydrogen atoms in a static magnetic field such as the geomagnetic field. In the natural state (equilibrium), the magnetic moments of H protons are oriented according to the static geomagnetic field.

When producing an external electromagnetic field at a specific frequency (Larmor frequency), the hydrogen nuclei alternately absorb and emit energy and the magnetic moments precess from their equilibrium. When the disturbing field is stopped, the magnetic moments return to their initial position and generate a relaxation magnetic field, which is oscillating at the Larmor frequency. For generating the excitation field and for measuring the relaxation magnetic field, a loop laid out on the ground is used for injecting and recording an alternating electrical current. Most often the same loop is employed for transmission and reception. The choice of the Larmor frequency for the injected current ensures the selectiveness of the MRS method to hydrogen proton of water molecules. Therefore, this method is less ambiguous than other classic geophysical methods (e.g. electric methods) used in groundwater assessment. The depth of investigation is controlled by the pulse moment $q = I_0 \cdot \tau$ where I_0 is the current intensity and τ is the duration of the pulse. Thus a MR sounding in depth is composed of several signal recordings for different pulse moments generally obtained in increasing the

current intensity. More details on the physical principle of MRS technique can be found in the literature (e.g. Legchenko and Valla, 2002; Legchenko, 2013; Behroozmand et al. 2015).

The main MRS recorded parameters are the signal amplitude E_0 (usually expressed in nanovolt), and the decay times (T_2^* and potentially T_1 or T_2 usually expressed in millisecond). The amplitude of MRS signal is directly linked to MRS water content (Θ_{MRS}): high amplitude of MRS signal corresponds to high water content (%) and vice versa. Θ_{MRS} is defined as the volume of water per unit volume of rock with a sufficiently long T_2^* decay time constant (>30 ms) (Legchenko et al., 2002). Signals with short decay time constants are generated by bound water, i.e. water attached to rocks due to forces of molecular attraction. Due to an instrumental dead time between pulse injection and signal recording, signal with short T_2^* decay time cannot be detected by the available MRS equipments. Consequently, clayey formations which have a high water content but only bound water are not “seen” by the current MRS equipments. Θ_{MRS} is often considered as a good estimate of effective porosity (Lubczynski and Roy, 2004).

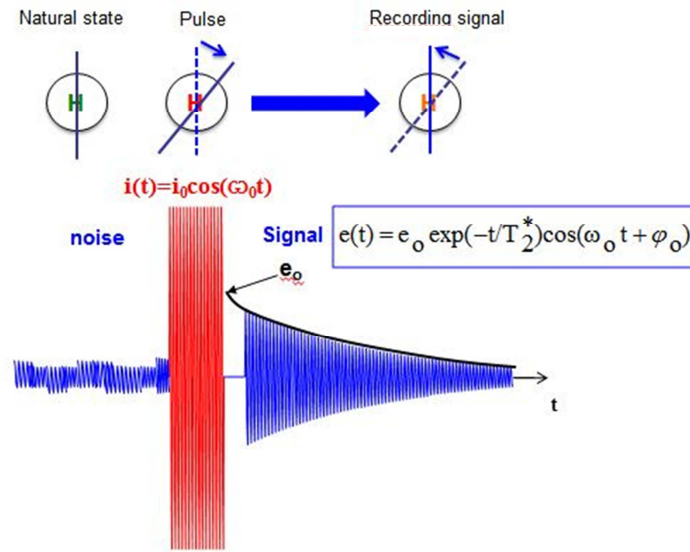


Figure 2: Typical sequence of magnetic resonance measurement (modified after Legchenko 2013)

The decay times T_1 and T_2 (usually expressed in millisecond) are related to the exchange of energy, respectively between protons and their environment and between protons. The estimate of these decay times requires a complex measuring sequence. The simple MRS measurement only allows estimating the T_2^* decay time which is related

$$K_{\text{MRS}} = C_p \cdot \Theta_{\text{MRS}} \cdot (T_i)^2 \quad \text{Equation 1}$$

$$T_{\text{MRS}} = C_p \cdot \Theta_{\text{MRS}} \cdot (T_i)^2 \cdot \Delta z \quad \text{Equation 2}$$

where K_{MRS} (in m/s), T_{MRS} (in m^2/s), Θ_{MRS} (dimensionless), T_i (in ms), and Δz (in m) are respectively MRS hydraulic conductivity, MRS transmissivity, MRS water content, decay time (T_1 or T_2^*) and thickness of saturated layer. Using of T_1 or T_2^* are specified in Vouillamoz et al., (2014). C_p (in

to T_2 and the spatial inhomogeneities in the static geomagnetic field caused by magnetic particles. Decay times (T_i) depend on the mean distance between the water molecules and the solid surface, i.e. mean pore size in saturated media. MRS can thus be used for estimating permeability and transmissivity by applying empirical equations (Legchenko et al., 2002):

m/s^3) is a parametric factor which depends on geological context and should be calibrated with at least one but preferably several pumping tests for absolute value of permeability and transmissivity (Legchenko et al., 2002). Without accurate calibration, K_{MRS} and T_{MRS} can be used in relative values.

Field implementation

In this paper, we present six MR soundings: three in Cameroon and three in Niger (table 1). These soundings are representative of different units of LCB: the piedmont plain, the border of the Limani-Yagoua sand ridge, the Yaere plain in Cameroon, the Komadugu Yobe valley, the Kadzell plain and the Lake Chad area in Niger. The sites were preferentially selected where geological log and eventually pumping test data were available for comparison with MRS results. The comparison of MRS results with independent information (geological log, water level measured in well /boreholes and pumping test) can allow us to confirm the ability of MRS method to characterize this complex aquifer. Our MRS surveys were carried out with Numis© equipments manufactured by IRIS Instruments (www.iris-instruments.com) and with Numrrun© software. In Niger, MR soundings were performed with Numis^{Plus} equipment in order to reach the maximum depth of investigation. In Cameroon, as the aquifer is shallower, we used Numis^{Lite} equipment which is easier to transport (~100 kg instead of ~300 kg for the Numis^{Plus}). The theoretical maximum depths of investigation for Numis^{Plus} and Numis^{Lite} are respectively 150 m and 50 m in favorable conditions (Bernard, 2007). In our field

conditions, we were limited to 80-100 m in Niger and 30-35 m in Cameroon.

When the ambient electromagnetic noise was low, we employed a simple square loop. Otherwise, we used an eight-shape loop formed with two squares (table 1). In Cameroon the eight-shape loop was systematically required because of the relatively dense electrification network. The size of the square side was: 100 m and 50 m for respectively simple square and eight-shape loop in Niger, and 40 m for eight-shape loop in Cameroon. The Larmor frequency that depends on the geomagnetic field ranged between 1473 and 1504 Hz with minimum values in the south (Cameroon) and maximum values in the north (Niger). The other acquisition parameters were selected for compromising between quality and duration of measurements. Note that, in the study area, we often observed an increase in the natural electromagnetic noise in the afternoon. This noise is probably due to distant stormy activities and it makes impossible MRS measurements after 2 P.M. Finally, we managed to perform one sounding per day.

Data inversion and interpretation

All MRS data were inverted with Samovar© software (version 11). We first applied a smooth inversion with 40 layers in

order to have a rough idea of the water content distribution versus depth (fig. 7). A use of one-layer inversion allow to estimate the depth of aquifer, the average water content, thickness of aquifer and the mean T_2^* value. Note that, as often the case in geophysics, the solution of the inversion is not unique and several models can fit the data (figure 3). On all the models of figure 3, one can observe that the depth of water table is similar. The total quantity of water (water content multiplied by thickness) is also almost the same for each model. Then these models are equivalents. These two parameters are thus robust in the inversion.

Time Domain Electromagnetic (TDEM) results (Descloitres et al. add coma 2013; not described in this paper) was used on each site to take into account the electrical resistivity of the ground in the MRS inversion processes in order to improve their accuracy. The frequency shift due to the diurnal variation of geomagnetic field was also considered in the inversion.

For estimating the aquifer transmissivity, we used the typical empirical equation (equation) with T_2^* . We chose T_2^* because the signal was low in some sites, then T_2^* is more accurately measured than T_1 . The parametric factor (C_p) was calculated for two sites (one in Cameroon and one in Niger) where short pumping tests (≤ 12 hours) were available in technical reports. Most often, the estimate of MRS transmissivity is more robust than permeability because the transmissivity is determined with the product θ_{MRS} times Δz (eq. 2) which is sturdily resolved in MRS inversion, whereas θ_{MRS} alone is less accurate (Legchenko et al., 2004). However, it was not possible to assess the aquifer thickness with MRS on one of our calibration site (MRS cam1). For determining the C_p on this site we used the permeability (equation 1). The permeability was calculated by dividing the pumping-test transmissivity by the thickness of the screened layer (available on the technical report of borehole).

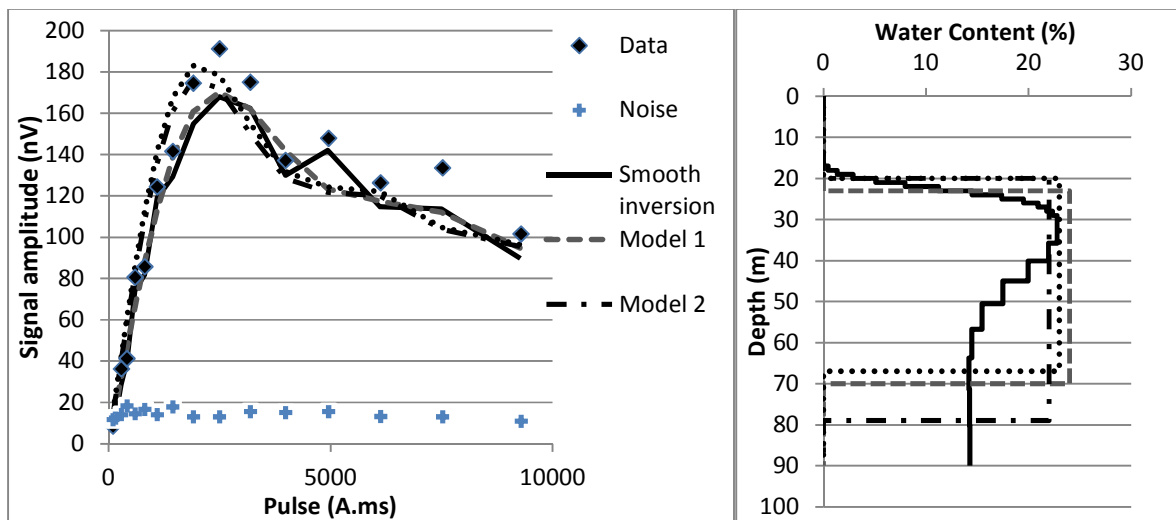


Figure 3: Example of non uniqueness in the MRS inversion (site MRS nig1). (a) Measured and modeled MRS signal, (b) Different models of water content distribution that fit the data.

RESULTS

Raw MRS signal

The low values of mean noise (≤ 18 nV, Table 1) indicate MRS data of good quality. A mean noise of 18 nV corresponds to an uncertainty of 2% on the MRS water content for a eight square loop of 40 meter length and to 0.7% for a square loop of 100 meter length, in our measurement conditions. The mean noise is similar on each site (standard deviation of 1.8 nV). This implies that the soundings with low signal-to-noise (S/N) ratio (MRScam3 and nig2) are not related to higher noise (i.e. lower quality) but to lower signal (that can be explained by less water).

The maximum of signal amplitude do not exceed 150nV in southern part of LCB (Cameroon) while it locally reaches 1100 nV in the northern part near the Niger-Chad border (figure 4). More generally, the signal amplitude is high (> 100 nV) in the Lake (MRS nig3) and close to the rivers (MRS nig1, cam2); it is low for other sites far from surface water reservoirs (MRS cam3 and nig2). The difference of signal amplitudes on different site can be due to the loop size, the water content and/or the depth of aquifer. When the same loop is used (e.g. all sites in Cameroon), the variation of signal amplitude only depends on the hydrogeological properties: water content and depth of the aquifer.

Table 1: MRS parameters

Site/Abbreviation	Loop shape, and size	Frequency (Hz)	Mean noise (nV)	Max Signal (nV)	Signal/Noise ratio
Ouroungoulmo/MRS cam1	eight square, 40m	1486.3	17.4	76	1.82
Abirou/MRS cam2	eight square, 40m	1473.2	13.4	146	3.66
Ngaba/MRS cam3	eight square, 40m	1475.0	13.8	30	1.18
Ngagam/MRS nig1	eight square, 50m	1492.5	14.3	168	4.61
Kosseyri/MRS nig2	square, 100m	1496.1	17.2	59.	1.27
Blabrim/MRS nig3	square, 100m	1504.3	18.0	1106	25.2

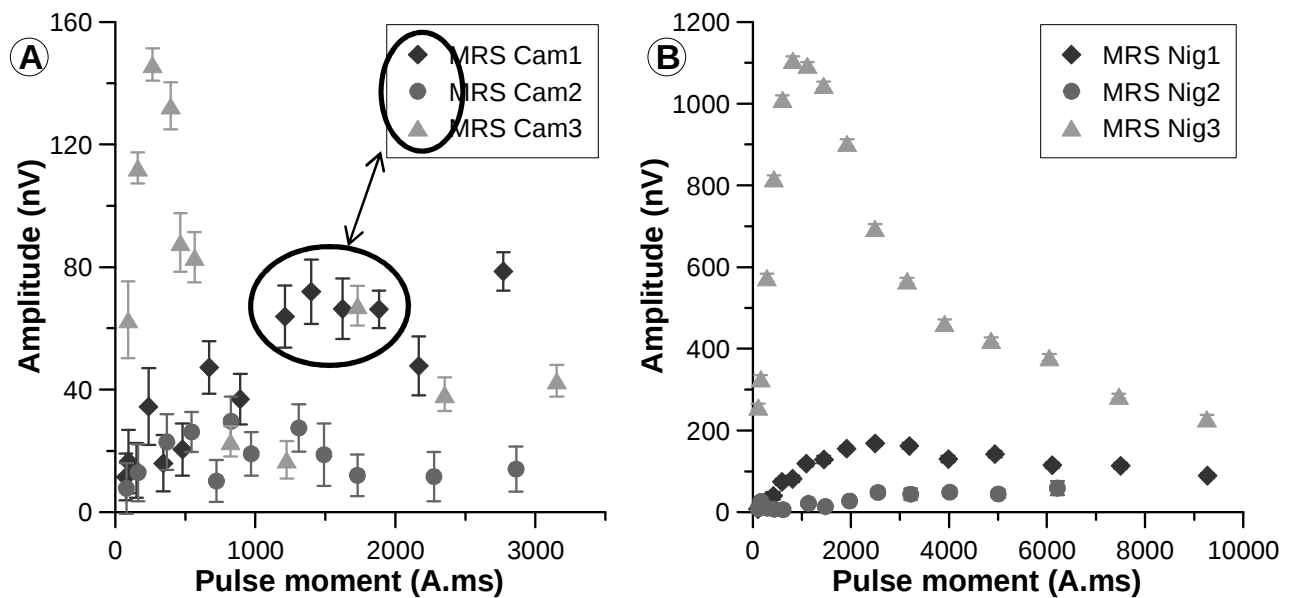


Figure 4: Measured MRS signal in the LCB (A-sites in Cameroon and B-sites in Niger) represented with error bars.

Estimate of hydrodynamic parameters

The hydrodynamics parameters estimated by MRS method with Samovar software in the study are (table 2): MRS water

content ($\theta_{\text{MRS}} \approx$ effective porosity), the water level in favorable case, the thickness of whole aquifer (ΔZ) and the transmissivity (T_{MRS}).

Table 2: Hydrodynamic parameters

site/ Abbreviation	MRS						Measurements in wells or boreholes	
	Θ_{MRS} (%)	water level (m)	ΔZ (m)	T_2^* (ms)	T_{MRS} (m ² /s)	C_p (m ² /s ³)	SWL (m)	T (m ² /s)
Ouroungoulmo/ MRScam1	20 (16 - 20)	18 (16.5 - 18.5)	/	210	4.1×10^{-4}	2.55×10^{-3}	19.6	4.1×10^{-4}
Abirou/MRS cam2	16.5 (16 - 19.2)	1 (1 - 3)	8 (6.5 - 9.5)	275	2.5×10^{-4}	/	3.4	/
Ngaba/MRS cam3	< 3	> 35 m if exists	/	/	/	/	Dry	/
Ngagam/MRS nig1	24 (24 - 27)	23 (23 - 27)	47 (30 - 65)	135	7.0×10^{-2}	3.40×10^{-1}	24	7.0×10^{-2}
Kosseyri/MRS nig2	6 (6 - 6.5)	40 (38 - 45)	/	/	/	/	40	/
Blabrim/MRS nig3	32 (31 - 32.8)	6 (4 - 7)	64 (63 - 76)	260	4.7×10^{-1}	/	9.5	/

Θ_{MRS} : water content; ΔZ : aquifer thickness; T_2^* : decay time; T_{MRS} : transmissivity estimated by MRS; C_p : parametric factor; SWL: static water level (from soil surface); T: transmissivity from pumping test. Uncertainties are shown in brackets.

Water content

The MRS water content or effective porosity ranges from less than 3 to 32%, and is related to signal amplitudes when comparing similar loops (table 1). The highest value (32 %) is recorded on the site located in the Lake (MRS nig3). The lowest values (<3% and 6%) are recorded on sites located in clayey areas: MRS cam3 in the piedmont plain near a sterile area identified by Tillement (1970), and MRS nig2 in Kadzell plain. Intermediate values (15-25%) are recorded in sandy areas near rivers or stream (MRS cam1 near El Beid river, MRS cam2 very close to a seasonally flowing

stream and MRS nig1 in Komadugu Yobe valley).

Geometry of the aquifer

Water level ranges from 1 to 40 m in the studied area. The lowest value is recorded in MRS cam2 which is located near a seasonally flowing stream, while the highest value is recorded in MRS nig2 in the center of the Kadzell piezometric depression. For the site MRS cam3, the water level cannot be determined because no significant signal is recorded (signal to noise ratio ~ 1.2 , table 1) In this case MRS reveals absence of aquifer within the investigation depth(~ 35 m in our field conditions).

The thickness of aquifer ranges from 8 to 64 m, for the soundings where the bottom of aquifer is assessed by MRS (in only half of sites). The two higher values are recorded in Niger and the lower value in Cameroon. This can be due to difference of aquifer structures (generally thinner in the border of the sedimentary basin like in Cameroon), but these results could be biased by the depth investigation which depends on the equipment: ~90 m for the Numis^{Plus} used in Niger and less than 35 m for the Numis^{Lite} used in Cameroon. This maximum depth of investigation limits the possibility 1) to determine the bottom of deep aquifers (e.g. in MRS nig2 / MRS cam1) 2) to detect a second aquifer as suggested by Tillement (1970) in the area where MRS cam2 is located and where a deep sub-regional aquifer was expected.

Parametric factor and Transmissivity

Parametric factor (C_p in equation 1) are very different for each country: C_p is $2.55 \times 10^{-3} \text{ m/s}^3$ in Cameroon and $3.40 \times 10^{-1} \text{ m/s}^3$ in Niger. The parametric factor in Niger is very close to the value ($C_p = 1.3 \times 10^{-1} \text{ m/s}^3$) calculated by Descloitres et al. (2013) in the Komadugu Yobe valley. Descloitres et al. (2013) asserted that this C_p value is exceptionally low compared with other C_p in similar geological context and is probably

valid only very locally in the vicinity of the Komadugu Yobe. The C_p value obtained in Cameroon is closer to the ranges usually encountered in sandy aquifers (e.g. $C_p = 1.4 \times 10^{-2} \text{ m/s}^3$ in continental terminal aquifer in western Niger after Boucher et al., (2009) or $C_p = 8.4 \times 10^{-3} \text{ m/s}^3$ in alluvial sandy aquifers in Denmark after Ryom Nielsen et al. (2011)). The calibration of these parametric factors would be improved by using more numerous and/or longer pumping test.

MRS transmissivity was calculated for 3 sites where the thickness of aquifer is assessed by MRS, and for one site where thickness is estimated from technical report of borehole. The order of magnitude of transmissivities is $10^{-4} \text{ m}^2/\text{s}$ for the two sites in Cameroon and $10^{-2} \text{ m}^2/\text{s}$ for two sites in Niger. These differences in transmissivity, combined with the variability of MRS water content mentioned above, illustrate the heterogeneity of quaternary deposits in the Lake Chad Basin such as described by Tillement (1970) or Servant and Servant-Vildary (1973).

DISCUSSION: COMPARISON OF MRS RESULTS WITH INDEPENDENT DATA

Comparison with water level measured in wells or boreholes

Static water level (SWL) was measured simultaneously with MRS acquisition in

neighboring boreholes and/or wells (less than few hundred meters from the MR soundings). MRS water levels are in a good agreement with SWL measured in wells/boreholes (table 1, figure 5). However, we observe that MRS water levels are occasionally slightly underestimated. This is particularly the case for MRS Nig3 site, where MRS water level is significantly shallower than the water level measured in the well. This difference can be due to the detection by MRS of capillary water in the unsaturated zone. This phenomenon is probably amplified for MRS Nig3 which is located in a site where the Lake has withdrawn and where, the static level has certainly decreased in the past few years. There, MRS may detect water in the capillary fringe without distinction with water in saturated

zone. In MRS Cam3 site (represented by the point (0;0) in fig 5), the MRS results agree with the observation in wells: no or very low MRS water content recorded near dry wells. According to Tillement (1970) this area is sterile, which confirms that the absence of MRS-detected water corresponds to a reality.

The uncertainties on MRS water level (few meters in average) are more important than direct measurements in wells (few millimeters or centimeters). Thus, MRS cannot improve our knowledge about water level in well-known aquifer, but for sites without SWL information (no wells/boreholes), the MRS method allows assess rough estimate of these levels. This information can be used, for example, in preliminary studies before drilling boreholes.

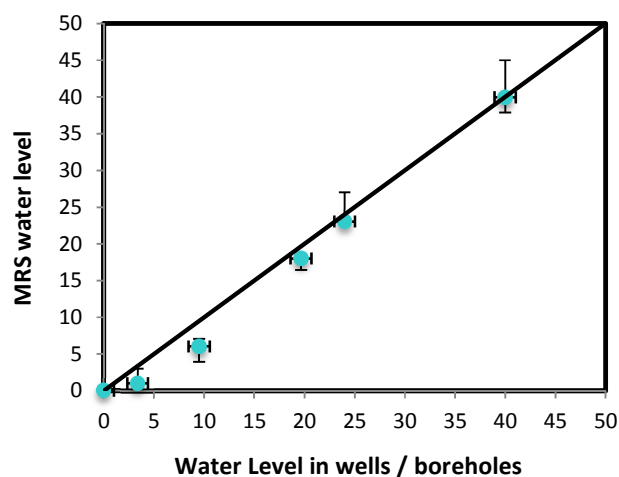


Figure 5: Comparison of MRS water level with direct measurement in wells / boreholes. Each measured point is presented with their error bars.

Comparison with geological log

The distribution of MRS water content versus depth on each site is compared with geological log (when available) in figure 6. One can remark that MRS water content does

not allow reconstituting all fine variations in the lithology such as described on geological logs, but the formation which contains water is always marked by an increase of MRS water content.

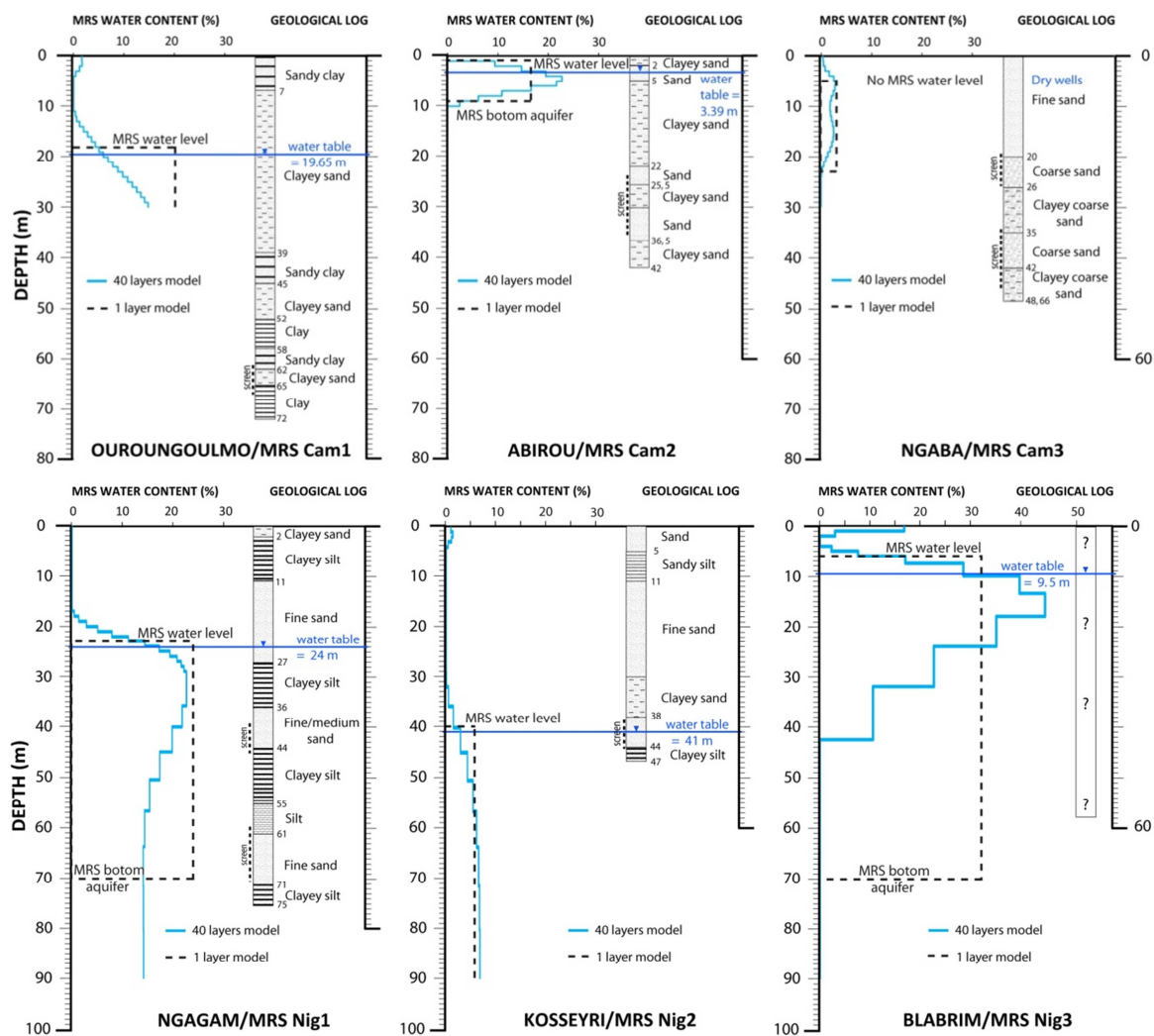


Figure 6: comparison between MRS aquifer geometry and geological log description of boreholes in Cameroon (top) and in Niger (bottom)

No obvious link are observed between the mean relaxation time value (T_2^*) and the material depicted in geological logs (figure 7). In our case, the classification based on grain size - T_2^* relationship such as proposed by Schirov et al. (1991) seems too simplistic for the heterogeneous quaternary aquifer composed of several layers with more or less clay. In addition, the description of geological logs has been realized by different authors with different geological perceptions. The types of materials (clay, clayey silt, fine and coarse sands) within geological logs are not derived from quantitative analyses and may be fairly subjective. The same materials could be described differently by different observers. Consequently, it is difficult to compare MRS

results with borehole data. Nevertheless, at a regional scale, MRS results which give integrative information are consistent with the main tendencies documented in literature. Low MRS water content and T_2^* are observed in the clayey formations in the piedmont plain (Cameroon) and in the Kadzell plain (Niger); high water content and T_2^* are recorded in sandy formations in the Komadugu Yobe valley (Niger) and in perched aquifers in Cameroon that are known to be of local importance (Tillement, 1970). In the vicinity of the lake, the MRS results show a high water content and T_2^* on a site where no geological information does exist locally but where surface observation shows Aeolian sand dune morphology (Olivry et al. 1996).

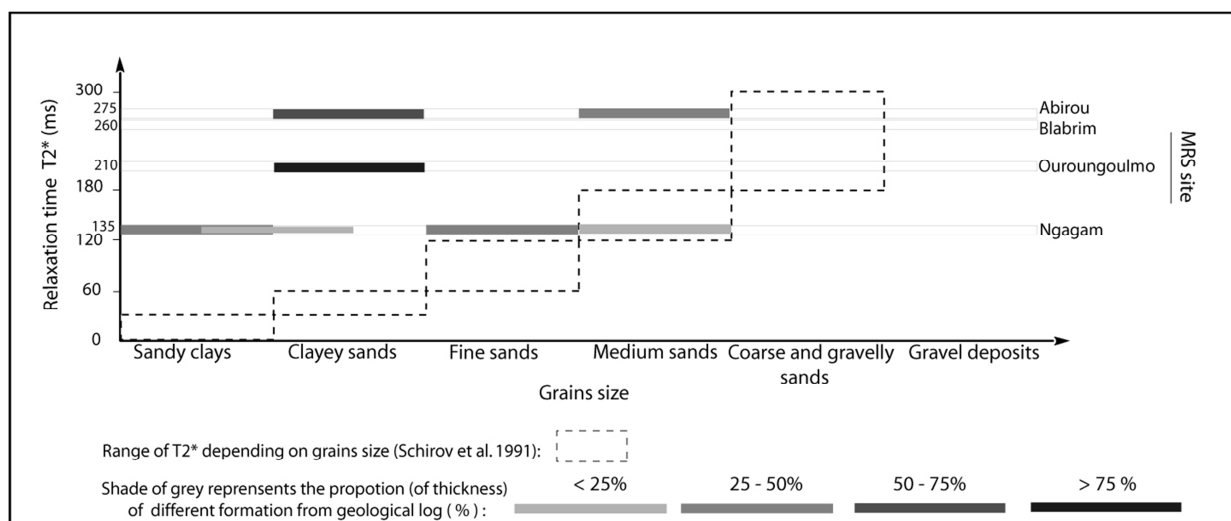


Figure 7: Correspondence between T_2^* and water containing strata

CONCLUSION AND PERSPECTIVES

Magnetic Resonance Sounding (MRS) method was successfully applied to study the quaternary aquifer at the LCB scale. Despite difficult conditions due to the tropical context (low geomagnetic field and high natural ambient noise), six MRS of good quality (maximum uncertainty on MRS water content ~2%) were obtained in representative sites of southeastern Niger and northern Cameroon.

MRS water content and decay time $T2^*$ which characterizes pore sizes show contrasted values depending on the investigated aquifer units. Both reveal high values in the Lake Chad area and near rivers. Low values are evidenced in clayey area (Kadzell plain in Niger and piedmont plain in Cameroon). The transmissivities are also contrasted at the LCB scale. However, due to limitation in depth of investigation, this parameter was assessed only on 4 sites, reducing the possibility of interpretation in different contexts. Moreover, the calibration of the empirical equation that allows estimating transmissivities is based on few data (2 short duration pumping tests) and could be improved with several other pumping test / MRS comparisons.

MRS results are in a good agreement with independent data: water level measured in neighboring wells and with geological

tendencies at basin scale. However, MRS is not able to resolve all the lithostratigraphic variations described within geological logs. MRS hydrodynamic parameters are integrative and represent means values for the whole aquifer thickness.

Based on these interesting results, MRS can be recommended for hydrogeological investigation in LCB context and for improving groundwater resources knowledge. However, the result interpretation should be carefully adapted in geological context for suitable determination of hydrodynamic parameters that could be used for numerical groundwater modeling and long-term aquifer management.

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REFERENCES

- Abderamane, H. (2012). Étude du fonctionnement hydrogéochimique du système aquifère du Chari Baguirmi (République du Tchad). Thèse de doctorat. Université de Poitiers. 324p.
- Arad, A. and Kafri, U. (1975). Geochemistry of groundwaters in the Chad basin. *Journal of Hydrology* 25, (1/2): pp. 105-127.
- Aranyossy, J.F. and Ndiaye, B. (1993). Etude et modélisation des formations piézométriques en creux en Afrique sahélienne. *Revue des Science de l'eau* 6: pp. 81-96.
- Baltassat, J.M. and Legchenko, A. (2001). Caractérisation par Résonance Magnétique Protonique (RMP) des aquifères du socle de la région d'Andalatanousy (Madagascar). Rapport BRGM/RP-50900-FR.
- Barber, W. (1965) Pressure water in the Chad Formation of Bornu and Dikwa emirates, north-eastern Nigeria. Geological Survey of Nigeria. Bulletin 35 p.
- Behroozmand, A.A., Keating, K. Auken, E. (2015) A review of the principles and applications of the NMR technique for near-surface characterization. *Surv Geophys* 36: pp. 27–85.
- Bernard, J., Lemine, M., Diagana, B., Ricolvi, M. (2004). Combination of electrical resistivity and magnetic resonance sounding data for mapping an aquifer layer in Mauritania. *Proceedings of SEG meeting, Denver, Colorado, USA.*
- Bernard, J. (2007). Instruments and field work to measure a Magnetic Resonance Sounding. *Boletín Geológico y Minero*, 118 (3): pp. 459-472.
- Bernard, J., Leite O., Vermeersch, F. (2012) Case studies of the MRS method in various geological backgrounds. *Proceedings of 5th Magnetic Resonance Sounding Workshop, Hannover, Germany*, p.75.
- Boucher, M., Favreau, G., Vouillamoz, J. M., Nazoumou, Y., Legchenko, A. (2009). Estimating specific yield and transmissivity with magnetic resonance sounding in an unconfined sandstone aquifer (Niger). *Hydrogeology Journal*, 17: pp. 1805–1815.
- Boucher, M., Favreau, G., Nazoumou, Y., Cappelaere, B., Massuel, S., Legchenko, A. (2012). Constraining groundwater modeling with magnetic

- resonance soundings. *Ground Water* 50(5): pp. 775–784.
- Delaporte, J. P., Boutaleb, S., Chibout, M., Boualoul M. (2003). A groundwater prospecting strategy in discontinuous grounds and arid climate: methodology and case studies in Morocco. *Proceedings of 2nd Magnetic Resonance Sounding Workshop*, Orleans, France, p.25-28.
- Descloitres, M., Séguis, L., Legchenko, A., Wubda M., Guyot A. Cohard J.M. (2011). The contribution of MRS and resistivity methods to the interpretation of actual evapotranspiration measurements: a case study in metamorphic context in north Bénin. *Near Surface Geophysics*, 9, pp. 187-200.
- Descloitres, M., Chalikakis K., Legchenko A., Moussa A.M., Genthon P., Favreau G., Le Coz M., Boucher M., Oï M. (2013). Investigation of groundwater resources in the Komadugu Yobe Valley(Lake Chad Basin, Niger) using MRS and TDEM methods. *Journal of African Earth Sciences*, 87: pp. 71–85.
- Dieng, B. (1987). *Paléohydrologie quantitative du bassin sédimentaire du Sénégal : essai d'explication des anomalies piézométriques observées*. Thèse de doctorat de 3eme cycle. Ecole nationale des mines de Paris.
- Djoret, D. (2000). *Etude de la recharge de la nappe du Chari Baguirmi (Tchad) par les méthodes chimiques et isotopiques*. 161 p.
- Durand, A. (1982). Oscillations of Lake Chad over the past 50 000 years: New data and new hypothesis, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, 39, 37–53.
- Edmunds, W.M., Fellman, E., Goni, I.B. (1999). Lakes, groundwater and paleohydrology in the sahel of NE Nigeria: evidence from hydrogeochemistry. *J. Geo. Soc.* 156: pp. 345-355.
- Gaultier, G. (2004). *Recharge et paléorecharge d'une nappe libre en milieu Sahélien (Niger oriental) : approche géochimique et hydrodynamique*. XI - Orsay, 179 p.
- Goni, I.B. (2002). *Hydrogeochemical approach to groundwater recharge studies in the Nigerian sector of the Chad basin*. PhD Thesis. University of Avignon and Pays de Vaucluse, 122 p.
- Goni, I.B. (2006). *Tracing stable isotope values from meteoric water top groundwater in the southwestern part*

- of the Chad basin. *Hydrogeology Journal*, 14: pp. 742-752.
- Greigert, J. and Bernert, G. (1979) Atlas des eaux souterraines de la République du Niger – Etat des connaissances. Rapport BRGM [79 AGE 001], Orléans.
- Kemgang, Dongmo, T., Ngounou-Ngatcha B., Boucher M., Favreau G., Goni I.B. (2014). First experiments of Magnetic Resonance Soundings in the Southern Border of Lake Chad in Cameroon. Annual Conference of Nigerian Association of Hydrogeologist, November 2-7, ~~2014~~, Abuja, Nigeria.
- Lange, G., Hertrich, M., Knödel, K., Yaramanci, U. (2000). Surface-NMR in an area with low geomagnetic field and low water content - a case history from Namibia. Proceedings of the 6th EEGS-ES Conference, Bochum, Germany.
- Lawson, F.M.A., Vouillamoz, J.M., Yalo, N., Koita, M., Owor, M., Okullo, J., Tindimugaya, C. (2015). Quantification des réserves en eau souterraine dans les aquifères de socle africain : comparaison des premiers résultats obtenus au Bénin, au Burkina Faso et en Ouganda. Proceedings of International Conference on “Hard-Rock Aquifers: the up to date concepts and the practical applications”, La Roche-sur-Yon, France (accepted).
- Leblanc, M. (2002). Use of GIS and remote sensing for water resources management of large semi-arid regions. A case study of the Lake Chad Basin, Africa, PhD Thesis, University of Glamorgan (UK) and University of Poitiers (Fr). 220 p
- Leblanc, M., Razack, M., Dagher, D., Mofor, L., Jones C. (2003). Application of Meteorological data to map soil infiltrability in the central part of the Lake Chad Basin, Africa. *Geophys. Res. Lett.*, 30(19).
- Le Coz, M. (2010). Hydrogeological modeling of heterogeneous deposits: The Komadugu Yobe alluvium (Lake Chad basin, southeastern Niger). PhD Thesis. University of Montpellier II, 127 p.
- Legchenko, A. and Valla, P. (2002). A review of basic principles for magnetic resonance sounding measurements. *Journal of Applied Geophysics*. 50: 3-19.
- Legchenko, A., Baltassat, J.M., Beauce, A., Bernard J. (2002). Nuclear resonance as a geophysical tool for

- hydrogeologists. *Journal of Applied Geophysics* 50: 21-46.
- Legchenko, A., Baltassat, J.M., Bobachev, A., Martin C., Robain H., Vouillamoz J.M. (2004). Magnetic resonance sounding applied to aquifer characterization. *Ground Water*. 42 (3): 363-373.
- Legchenko, A. (2013). *Magnetic Resonance Imaging for Groundwater*. ISTE-Wiley edition. 158 p. (ISBN 978-1-84821-568-9).
- Lemoalle, J., Baber, J.C., Leblanc, M., Sedick, A. (2011). Recently changes in Lake Chad: observations simulation and management options (1973 - 2011). *Glob. Planet. Change*. doi:10.1016/j.gloplacha.2011.07.004.
- Lubczynski, M.W. and Roy, J. (2004). Magnetic resonance sounding: new method for ground water assessment. *Ground Water* 42, (2): 291–303.
- MacDonald, A.M., Bonsor, H.C., Dochartaigh, B.É.Ó., Taylor, R.G. (2012). Quantitative maps of groundwater resources in Africa. *Environ. Res. Lett.* 7, 024009.
- Meyer, R., Lange, G., Di Battista, M., Soltau, L. (2006). Fractured rock aquifer MRS in high noise, low water content and low frequency environments, South Africa. *Proceedings of 3rd Magnetic Resonance Sounding Workshop*, Madrid, Spain, p.85-88.
- NgounouNgatcha, B. (1993). *Hydrogéologie d'aquifères complexes en zone semi-aride. Les aquifères quaternaires du grand yaéré, Nord Cameroun*. Thèse Université de Grenoble 1. 352p.
- NgounouNgatcha, B., Mudry J., Aranyossy, J. E., Naah, E., Sarrot, R.J. (2007a). Apport de la géologie, de l'hydrogéologie et des isotopes de l'environnement à la connaissance des « nappes en creux » du grand Yaéré (Nord Cameroun). *Revue des sciences de l'eau* 20,(1): 29-43.
- NgounouNgatcha, B., Mudry J., Sarrot R.J. (2007b). Groundwater Recharge from Rainfall in the Southern Border of Lake Chad in Cameroon. *World Applied Sciences Journal* 2 (2): 125-131.
- NgounouNgatcha, B., Mudry, J., Leduc C. (2008). *Water resources management in the Lake Chad basin: Diagnosis and action plan*. *Applied Groundwater Studies in Africa*. IAH selected papers on hydrogeology, volume 13, Edited by Segun Adelenia and Alain MacDonald, Taylor & Francis 2008. DOI; 10.1201/9780203889497.ch5.

- Njitchoua, R. and NgounouNgatcha, B. (1997). Hydrogeochemistry and environmental isotope investigations of the North Diamaré Plain, northern Cameroon. *Journal of Africa Earth sciences* 25 : 307-316.
- Olivry, J.C., Chouret, A., Vuillaumet, G., Lemoalle, J., Bricquet, J.P. (1996). *Hydrologie du Lac Tchad. Monographies hydrologiques*, ORSTOM, Paris. 302p
- Pias, J. (1970). Les formations sédimentaires tertiaires et quaternaires de la cuvette tchadienne et les sols qui en dérivent. *Mémoire ORSTOM*, (43), 407p.
- PNUD-FAO-CBLT. (1973). *Etude des ressources en eau du bassin du lac Tchad en vue d'un programme de développement. Tome I. Hydrogéologie, rapport technique* FAO.
- Portselan and Treshchenkov (2002). Application of the NMR-tomography technique for groundwater investigations in Equatorial Africa: a case-history in Guinea. *Journal of Applied Geophysics* 50: 123– 127.
- Ryom, N. M., Hagensen T.F., Chalikakis K., Legchenko A. (2011). Comparison of transmissivities from MRS and pumping tests in Denmark. *Near Surface Geophysics*, 9: 211–223.
- Schirov, M., Legchenko, A., Créer, G. (1991). New direct non-invasive ground water detection technology for australia : *Expl. Geophys.*, 22: 333-338.
- Servant, M. and Servant-Vildary, S. (1973). *Le Plio-Quaternaire du bassin du lac Tchad. Centre national de la recherche scientifique. Conference Proceeding. Le Quaternaire, géodynamique, stratigraphie et environnement. 1973*, pp. 169-175.
- Tillement, B. (1970). *Hydrogéologie du Nord Cameroun. Bulletin N°6 de la direction des mines et de la géologie*. 294p.
- Tillement, B. (1972). *Hydrogéologie du Nord Cameroun. Thèse de doctorat. Ing., Université de Lyon*, 294p.
- Vouillamoz, J.M. (2003). *Caractérisation des aquifères par une méthode non-invasive : Les sondages par Résonance Magnétique Protonique. Thèse de Doctorat, Université de Paris XI, France*, 342p.
- Vouillamoz, J.M., Descloitres, M., Toe, G., Legchenko, A. (2005). Characterization of crystalline basement aquifers with MRS: a case

study in Burkina Faso. Near Surface Geophysics. 3, no.3: 205-213.

Vouillamoz, J.M., Lawson, F.M.A., Yalo, N., Descloitres M. (2014). The use of magnetic resonance sounding for quantifying specific yield and transmissivity in hard rock aquifers: The example of Benin. Journal of Applied Geophysics, 107: 16–24.

Zaïri, R. (2008). Etude géochimique et hydrodynamique de la nappe libre du Bassin du Lac Tchad dans les régions de Diffa (Niger oriental) et du Bornou (nord-est du Nigeria). Thèse de doctorat. Université de Montpellier 2. 209p.