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The use of magnetic resonance sounding for quantifying specific yield and transmissivity in hard rock aquifers: The example of Benin

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ABSTRACT

Hundreds of thousands of boreholes have been drilled in hard rocks of Africa and Asia for supplying human communities with drinking water. Despite the common use of geophysics for improving the siting of boreholes, a significant number of drilled holes does not deliver enough water to be equipped (e.g. 40% on average in Benin). As compared to other non-invasive geophysical methods, magnetic resonance sounding (MRS) is selective to groundwater. However, this distinctive feature has not been fully used in previous published studies for quantifying the drainable groundwater in hard rocks (i.e. the specific yield) and the short-term productivity of aquifer (i.e. the transmissivity). We present in this paper a comparison of MRS results (i.e. the water content and pore-size parameter) with both specific yield and transmissivity calculated from long duration pumping tests. We conducted our experiments in six sites located in different hard rock groups in Benin, thus providing a unique data set to assess the usefulness of MRS in hard rock aquifers. We found that the MRS water content is about twice the specific yield. We also found that the MRS pore-size parameter is well correlated with the specific yield. Thus we proposed two linear equations for calculating the specific yield from the MRS water content (with an uncertainty of about 10%) and from the pore-size parameter (with an uncertainty of about 20%). The later has the advantage of defining a so-named MRS cutoff time value for indentifying non-drainable MRS water content and thus low groundwater reserve. We eventually propose a nonlinear equation for calculating the specific yield using jointly the MRS water content and the pore-size parameters, but this approach has to be confirmed with further investigations. This study also confirmed that aquifer transmissivity can be estimated from MRS results with an uncertainty of about 70%. We conclude that MRS can be usefully applied for estimating aquifer specific yield and transmissivity in weathered hard rock aquifers. Our result will contribute to the improvement of well siting and groundwater management in hard rocks.

1. Introduction

Hard rocks of plutonic and metamorphic origin are the basement of continents and they outcrop over large areas throughout the world. Groundwater in hard rocks is the only water source for many human communities in Africa and India (Calow et al., 2010; Mukherji, 2008). The weathering processes of hard rocks result in a heterogeneous groundwater reservoir which is fissured at depth and unconsolidated on top. This groundwater reservoir is conceptually described as a two layer reservoir where the fissured layer is located just below the unconsolidated saprolite layer (Lachassagne et al., 2011). Vertical fissured zones also exist but to a much less extent within or in the surroundings of pre-existing discontinuities as geological fault or lithological discontinuity (Dewandel et al., 2011).

The conceptual layered model of weathered hard rock aquifers has been confirmed by a number of research works (e.g. Dewandel et al., 2006) and by hundreds of thousand boreholes which have been drilled since the eighties for supplying people with groundwater in Africa and India. Hard rock aquifers are generally poor, i.e. they can produce few hundreds to few thousand litres per hour (MacDonald et al., 2012). Boreholes producing less than 700 l per hour (i.e. the minimum usually required for supplying a hand pump) are considered as negative and are quite common (Courtois et al., 2010). In Benin, the national data base indicates that 40% of the wells drilled in hard rocks are negative (population of 3172 wells). Moreover the pumped yields of positive boreholes are often not sustainable for supplying the increasing needs coming from the significant number of urban areas mushrooming in developing countries.

Hydrogeologists optimize the siting of boreholes in order both to reduce the number of negative wells and to increase the sustainable yield of pumping. Based on the conceptual model of hard rock aquifers, the

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strategy for selecting the best location for drilling in a non-or-partly eroded weathering profile is to identify the thicker saprolite and fissured layers. But estimating the geometry of the layers is not sufficient since the layers also have to be saturated and not clogged (i.e. not too clayey). Thus, hydrogeologists would also like to know before drilling the additional characteristics of the aquifer as its transmissivity (i.e. the short-term productivity) and its storativity (i.e. the amount of stored groundwater which can be drained when pumping). Storativity of unconfined aquifer (the so-named specific yield *Sy*) is a fundamental property since it controls the available space for storing drainable groundwater and recharge. Therefore, specific yield buffers the effect of rainfall/recharge variability and it partly controls the sustainability of the yield.

Geophysical methods are commonly used for siting boreholes in hard rock aquifers and most of the drilling campaigns are still based on common Electromagnetic (EM) and/or Direct Current (DC) resistivity methods (e.g. Dutta et al., 2006; Yadav and Singh, 2007). The electrical resistivity of rocks has been successfully used for estimating the geometry of the weathered layer and the structure of the rocks but it is not appropriate for quantifying transmissivity and storativity in clayey environments as saprolite and fissured layers. As compared to EM and DC resistivity methods, Magnetic Resonance Sounding (MRS) method is selective with respect to groundwater and thus it can provide a more direct link to hydrogeological properties (Legchenko et al., 2002). MRS has been already used to investigate hard rock aquifers but no quantitative relationships between MRS parameters and specific yield have been proposed in most of the published works (Baltassat et al., 2005; Legchenko et al., 2004, 2006; Portselan and Treshchenkov, 2002; Wyns et al., 2004). To our knowledge, only one paper tried to establish quantitative relationships between MRS results and hydrogeological properties of hard rock aquifers (Vouillamoz et al., 2005). The reason is because obtaining both MRS and hydrogeological properties is time and money-consuming and thus rarely carried out. In their published paper, Vouillamoz et al. (2005) used a data set obtained in a single area (located in Burkina Faso) for assessing the link between specific yield and MRS data. Their results are not universal considering the great variety of lithology in hard rocks. Moreover, part of the pumping data set was issued from (semi) confining layers which do not allow a proper assessment of the specific yield. Finally, the authors concluded that the storativity estimated from MRS in their work was not reliable and they recommended the set up of new experiments based on a new comprehensive data set.

This paper presents the results of a new research work carried out in hard rock aquifers in Benin. We tried to overcome the limitations encountered in Vouillamoz et al. (2005). First, we carried out experiments in 6 different geological units to expand the range of aquifer types covered. Second, we implemented long duration pumping tests for assessing both the aquifer specific yield and transmissivity. Third, we estimated the specific yield of aquifer not only using the MRS water content (i.e. the former approach) but also using the MRS pore-size parameters (i.e. a new approach derived from the oil industry; Vouillamoz et al., 2012, 2014). We also checked how transmissivity can be estimated from the MRS results.

2. Material and method

For assessing the links between MRS parameters and hydrogeological properties of various types of hard rock aquifers, we carried out 39 MRS in a large variety of hard rocks. Then we selected six experimental sites where MRS parameters have a broad range of values, each site being located in a different hard rock group. At each experimental site, we drilled 3 boreholes (i.e. one pumping well and 2 observation wells) and we carried out pumping experiments for quantifying the specific yield and the transmissivity. Finally, we compared the MRS output parameters with the specific yield and transmissivity known from pumping tests. Our study does not intend to assess the properties of the fissured and saprolite layers separately because the success and the sustainability of a borehole are controlled by the combined properties of each individual layer. Moreover, the boundary between the two layers is a conceptual boundary, i.e. it is not sharp but rather smooth since the layers resulted from the same weathering processes. Thus, our study focussed on average properties of aquifers, i.e. the properties of a single layer which behave as the saprolite and fissured layers together.

Detailed description of the well known MRS and pumping test methods is not in the scope of this paper and it can be found in numerous publications (e.g. Legchenko (2013) for the MRS method, Renard et al. (2009) for the pumping test methods). The investigated spatial scale of both conventional pumping test and common MRS is about the same, thus making the comparison of results possible (Lubczynski and Roy, 2003; Vouillamoz, 2003).

A conventional pumping test refers to the analysis of groundwater head response to a pumping (Kruseman and de Ridder, 2000). Short duration single well tests are commonly carried out to estimate the properties of the well (e.g. head losses, appropriate pumping yield, etc) and the local transmissivity of the aquifer. However, a more comprehensive pumping test which requires at least 2 wells (i.e. a pumping well and an observation well) and longer pumping duration is needed for assessing the aquifer specific yield and a larger scale transmissivity. The storativity and transmissivity are usually calculated from the groundwater head and pumping yield recorded during the field experiment using an analytical solution which has to be carefully chosen. The log-derivative of the measured drawdown as a function of time together with knowledge about aquifer condition and groundwater flow type are used by hydrogeologists for choosing the appropriate analytical solution (Renard et al., 2009). The aquifer parameters derived from the pumping test analysis are some average values of the properties of the volume of aquifer which is investigated by the test (Meier et al., 1998; Sánchez-Vila et al., 1999).

MRS is the field scale implementation of the nuclear magnetic resonance method. To carry out a measurement, the nuclei of the hydrogen atoms of water molecules in the subsurface (i.e. protons) are energized with an EM pulse, and the signal response of the hydrogen nuclei is measured after the energizing pulse is switched off. The recorded signal of the hydrogen nuclei oscillates at the Larmor frequency ω_L and has an exponential envelope that decays at time rate T_2^*. This so-named Free Induction Decay (FID) signal is:

$$e(t,q) = E_{0FID}(q) \cdot \exp\left(-t/T_2^*(q)\right) \cdot \sin(\omega_L + \varphi(q)) \quad (1)$$

where $e(t,q)$ is the envelop of the decaying FID, E_{0FID} is the amplitude of the signal just after the energizing pulse q has been turned off, and φ is the phase shift of the signal. The decay parameter T_2^* of the FID signal is usually dominated by interactions between the hydrogen nuclei of water and the solid surface of the geological reservoir. $1/T_2^* \approx \rho_2 \cdot S_{pore}/V_{pore}$ where ρ_2 is the surface relaxivity (i.e. the property of the surface of the rocks to enhance relaxation) and S_{pore}/V_{pore} is the ratio of pore surface to pore volume: the smaller is the average pore size, the smaller is the value of T_2^* (Schirov et al., 1991). Nowadays, short FID signals (i.e. T_2^* values smaller than of 10 to 40 ms) cannot be recorded by the commercial instrumentations. Thus, in aquifer with small grain size (i.e. small values of T_2^*) the MRS groundwater content θ_{MRS} which is obtained from E_{0FID} is less than the total porosity n of the saturated rock $\theta_{mrs} < n$ (Lubczynski and Roy, 2007). Moreover, when pumping in an unconfined aquifer, a portion of the water that generates FID signal in saturated condition (i.e. before pumping) cannot be drained by gravity forces: the smaller is the average size of the pore, the higher is the amount of water that cannot be drained (Vouillamoz et al., 2014) and:

$$\theta_{MRS} \geq S_y. \quad (2)$$

The difference between θ_{MRS} and Sy decreases towards coarser pore size (i.e. longer T_2^*) and the problem is then to quantify the relationship (2) to be able to calculate Sy from θ_{MRS}. Note that the decay T_2^* can be affected by the magnetic property of the rocks and thus it can be poorly linked to the geometry of the pores (Legchenko et al., 2010; Vouillamoz et al., 2011). The use of the so-named T_1 decay time of the MRS signal can be more appropriate since T_1 is poorly affected by the magnetic property of rocks (Legchenko et al., 2002). However the accurate measurement of T_1 is time consuming and thus it is only carried out when the use of T_2^* is not appropriate (Walbrecker and Behroozmand, 2012).

Besides the storage properties of aquifer that can be assess from MRS parameters (Eq. (2)), the relationship between the MRS signal and the mean size of the saturated pore has been successfully used for estimating transmissivity of saturated rocks from (e.g. Legchenko et al. (2002); Ryom Nielsen et al. (2011); Vouillamoz et al. (2002, 2007, 2008):

$$T_{MRS} = C_T \cdot \theta_{MRS}{}^a \cdot T_i{}^b \cdot \Delta z \tag{3}$$

where T_{MRS} is the transmissivity, T_i is the MRS decay and Δz is the thickness of saturated layer. C_T, a and b are parametric factors which are calculated comparing T_{MRS} with known transmissivity.

2.1. Area of investigation

Field measurements were conducted in 2013 in the hard rocks environment of Benin, Africa. We selected six experimental sites located in different hard rock units of the country (Fig. 1). The geology of the investigated area is composed of metamorphic rocks. According to the geological map, the main rocks are gneiss and migmatites in the central part of the area, and granitic rocks in the eastern part (Office Béninois des Mines, 1984). The drilling cuttings collected at each experimental site confirmed the geological map and reveal gneiss, migmatites, granite and mica schist rocks (Table 1).

Table 1
Geological formation and rocks encountered at each experimental site.

Experimental site	Geological formation (from the geological map)	Rocks (drilling cuttings)
ARA	Djougou formation	Mica schist
FD19	Donga formation	Gneiss
F68	Migmatites of We We	Gneiss migmatitic
FD30	Migmatites of the axial zone	Gneiss migmatitic
FD17	Sillon of Oueme group	Gneiss
F117	Nikki Perere complex	Granite

2.2. Hydrogeological measurements

We drilled three boreholes at each experimental site to perform pumping experiments. Depending on the site, the Static Water Level (SWL) was ranging in-between 3.7 and 8 m below ground surface at the time of pumping experiments. At each site, we pumped for 72 h in one well (PW) and we used the other boreholes as observation wells (OW) for monitoring the groundwater level. We choose the pumping yield according to the results of a preliminary pumping step-test carried out before the 72 h test (Kruseman and de Ridder, 2000). Depending on the site, the pumping yield was ranging in-between 330 and 12,000 l/h.

When interpreting the pumping tests, we were monitoring for a year at each experimental site the groundwater electrical conductivity and level together with the rainfall. The records suggest that the aquifers are unconfined. The unconfined condition was confirmed by the drawdown log-derivative analysis of the pumping tests (Renard et al., 2009). We selected the Tartakovsky and Neuman (2007) and Moench (1997) analytical solutions implemented in AQTESOLV^{TM}/Pro v4.5 software to interpret the experiments and to compute a delayed gravity response with noninstantaneous drainage of the unconfined aquifers. The best solution was chosen to minimize the average difference δ between the field drawdown measurements and the fitted model. The uncertainty in the transmissivity and specific yield estimates was calculated from the 95% confidence interval for each parameter. The confidence interval is approximated under the assumptions that the model is linear in the

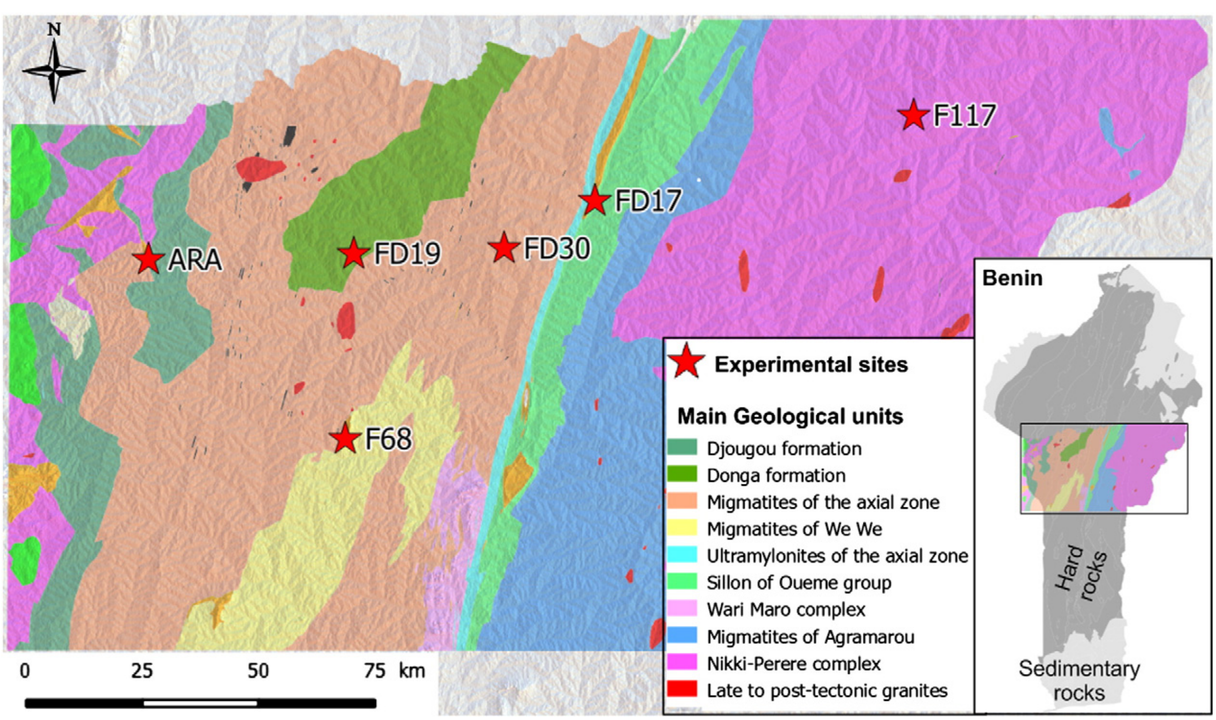

Fig. 1. Location of experimental sites and simplified geological map (modified from Office Béninois des Mines, 1984).

Table 2
MRS measuring conditions and obtained signal to noise ratio.

Experimental site	MRS loop shape and size	Larmor frequency	#Stack	Signal to noise ratio
ARA	Eight, 75 m	1412 Hz	400	5.6
FD19	Square, 125 m	1413.5 Hz	130	4.6
F68	Square, 125 m	1411 Hz	250	2.2
FD30	Eight, 62.5 m	1414 Hz	240	6.2
FD17	Eight, 62.5 m	1414.5 Hz	400	2.2
F117	Square, 125 m	1424 Hz	400	2.8

neighbourhood of the minimum of the objective function δ and the errors are normally distributed.

2.3. MRS measurements

MRS measurements have been carried out with the NUMIS^{PLUS} apparatus from Iris Instruments (Bernard, 2007). The shape of the MRS loop was selected according to EM noise conditions encountered in the field (Trushkin, 1994; Table 2). The size of the loop (i.e. the length of the sides) was chosen as large as possible for increasing the amplitude of the MRS signal, and the number of stacks was chosen to maximize the signal to noise ratio.

MRS Free Induction Decay (FID) measurements were interpreted with Samovar V11.3 software (Legchenko et al., 2008). The chosen MRS result is the single layer model which fits well the field records. The uncertainty in the MRS results is calculated by estimating the space of acceptable solutions (i.e. the equivalence analysis). The solutions are considered acceptable if the difference ε between the field data and the calculated solution is lower than a threshold value which is given by the noise in the data.

3. Results

We first present an example of results obtained at ARA experimental site, and then the synthesis of the 6 investigated locations.

3.1. Example of measurements at ARA site

The MRS sounding has been carried out with a Larmor frequency of 1412 Hz. The data has a good signal to noise ratio (i.e. 5.6 on average) and uncertainties of the MRS parameters are low (Fig. 2 and Table 3). Because our study focuses on the average properties of hard rock aquifers (see Section 2. Material and method), the inversion is carried out using a single layer model. It results in a layer located from 1.5 to 22 m deep with $\theta_{MRS} = 3.9\%$ and $T_2^* = 150$ ms. The lithology obtained from the boreholes clearly identifies this single MRS layer as the saprolite layer (Fig. 3A). As already observed in other studies (e.g. Vouillamoz et al., 2014) the MRS model indicates the presence of water at a depth of 1.5 m although the Static Water Level (SWL) measured in the boreholes is located at 3.7 m deep. MRS signal is generated above the SWL by the capillary fringe which is the zone above the water table where capillary forces draw water up from the saturated zone.

An inversion carried out using a smooth multi-layer model identifies the geometry of the saprolite and the fissured layers better than the single layer model (Fig. 3B). The difference ε between the data and the model is slightly lower for the multi-layer model as compared to the single layer model ($\varepsilon = 5.8$ nV and $\varepsilon = 8.5$ nV respectively) but both ε are close to the value of the mean noise (i.e. 8 nV). Moreover, both models are equivalent since the product of their water content times thickness is about the same (Legchenko, 2013): 0.98 m and 1.01 m respectively. Thus, we consider the single layer model as representing the average properties of the aquifer.

The 72 h pumping test has been carried using borehole #1 as pumping well (PW#1) and monitoring the water levels in boreholes #2 and #3. Analytical solution for unconfined aquifer fits well the data with a mean difference δ of 3 cm for both OW#2 and OW#3 (Fig. 4). As observed in sedimentary rocks (Boucher et al., 2009; Vouillamoz et al., 2012) the specific yield obtained from the interpretation of the pumping test is lower than the MRS water content: $Sy = 2.3\%$ and $\theta_{MRS} = 3.9\%$ (Table 3). This observation indicates that part of the MRS signals is generated by water which is not drained by gravity when pumping.

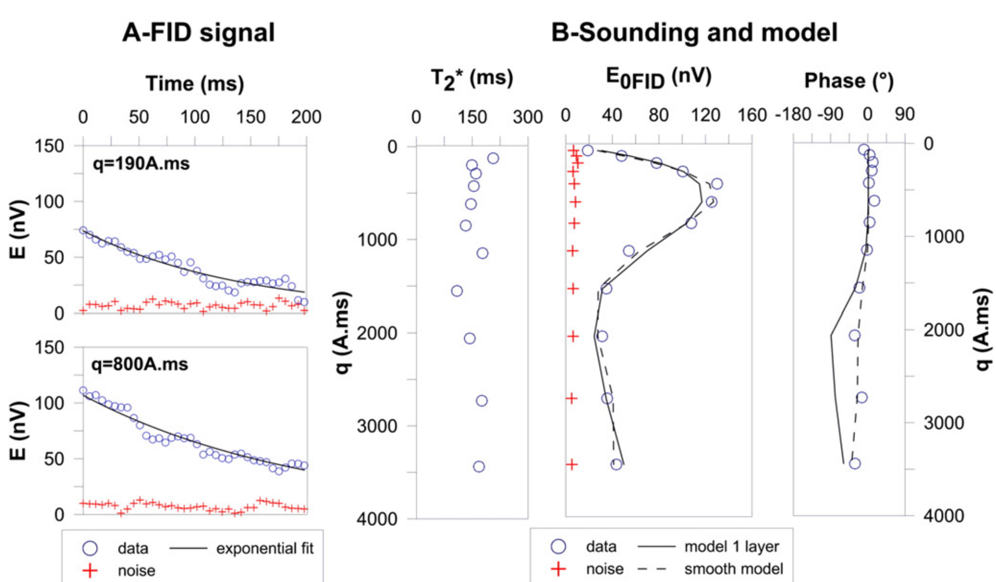

Fig. 2. MRS measurement at ARA site. A: Examples of FID signal. B: MRS data and fitted models.

Table 3
MRS and pumping test results, Ara site (uncertainty calculated as mentioned Section 2. Material and method).

	MRS water content	Decay T_2*	Specific yield
Best model (single layer)	3.9%	150 ms	2.3%
Relative uncertainty	10%	20%	47%

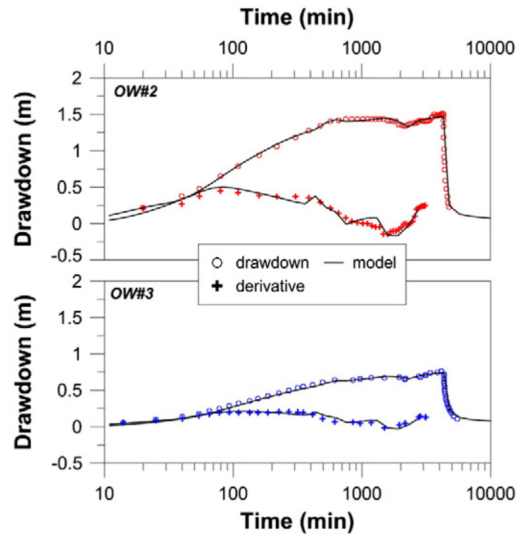

Fig. 4. Pumping test at ARA site.

3.2. Relationship between MRS parameters and specific yield

Let us first use the common approach which consists in comparing θ_{MRS} to the specific yield *Sy* (Fig. 5A). We observe that θ_{MRS} is always higher than *Sy* and that a linear relationship can be fitted according to:

$$S_y = 0.53 \cdot \theta_{MRS} + 0.007. \tag{4}$$

The Eq. (4) is consistent with Vouillamoz et al. (2005; 2012; 2014) and Boucher et al. (2009) who also observed that MRS water content is higher than specific yield. As mentioned by the latter, the relationship is probably not linear but within the range of encountered MRS water content in our study (i.e. $2 < \theta_{MRS} < 13\%$, Table 4) the linearity is acceptable (Fig. 5A, determination coefficient of 0.95). Note that Eq. (4) is theoretically valid down to very low MRS water content, i.e. $S_y \leq \theta_{MRS} \Rightarrow \theta_{MRS} \geq 1.5 \cdot 10^4$.

Eq. (4) indicates that about half the MRS water content θ_{MRS} is water that is not drained by gravity when pumping, i.e. capillary water. The amount of capillary water is controlled by the size of the pores and thus it can be linked with the decay T_2^* of MRS signal. This assumption is the basis of the so-named Apparent Cutoff Time (ACT) approach recently presented by Vouillamoz et al. (2012; 2014). Our data set confirms that specific yield has a linear relationship with T_2^* (Fig. 5B). A threshold value of T_2^* can be identified (i.e. the ACT value) correspondingly to $Sy \to 0 \Rightarrow T_2^* = 109ms$. Thus, when $T_2^* < \approx 110ms \Rightarrow S_y \to 0$ because the MRS signals are generated by non-drainable water. When $T_2^* > \approx 110ms$ the MRS signals are generated by both drainable water (i.e. specific yield) and non-drainable water (capillary water) and:

$$S_y = 7.8 \cdot 10^{-4} \cdot T_2^* - 0.085 \ \ (\text{with } T_2^* \text{ in millisecond}). \tag{5}$$

Eq. (5) is the first experimental evidence that the specific yield of hard rock aquifers can be derived not only from θ_{MRS} but also from T_2^*. The use of θ_{MRS} alone is not sufficient for assessing extractable groundwater because magnetic resonance signals that exhibit $T_2^* < ACT$ are not generated by drainable water.

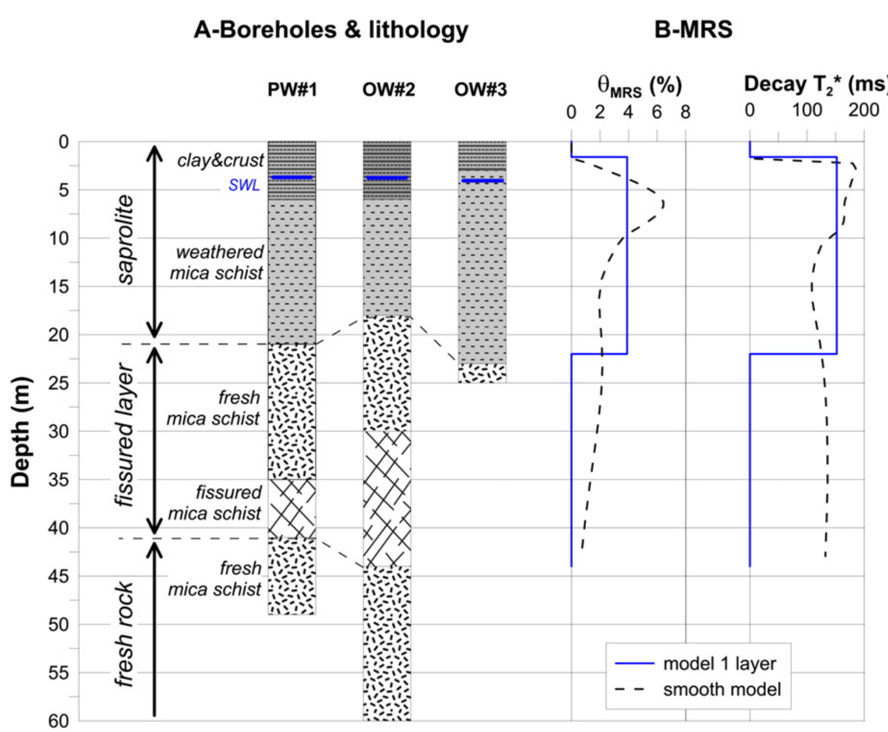

Fig. 3. Experiments at ARA site. A: Borehole lithology. SWL is the static water level. B: MRS model.

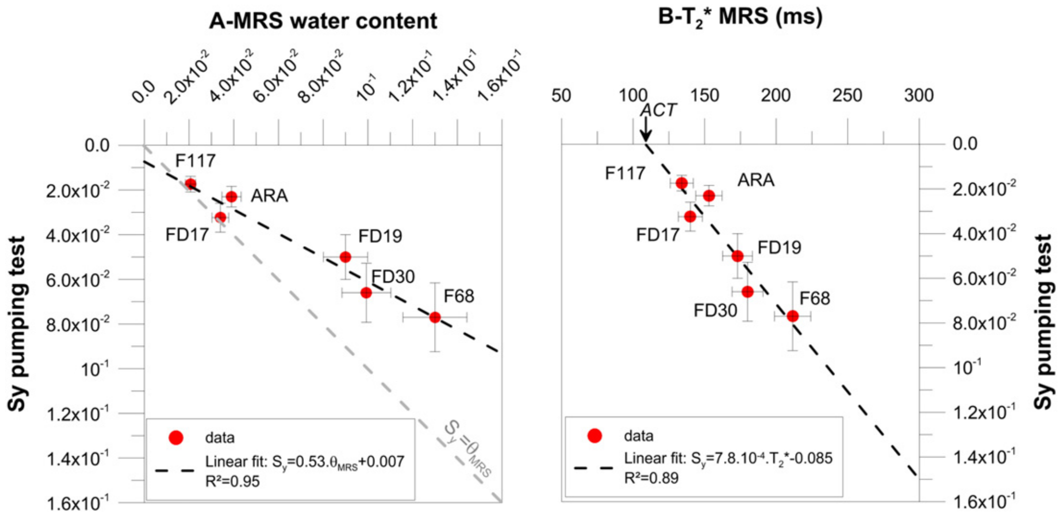

Fig. 5. Comparison of MRS parameters with specific yield. R^2 is the coefficient of determination. A-MRS water content. B-MRS decay T_2*.

3.3. Relationship between MRS parameters and transmissivity

We compare MRS transmissivity calculated from Eq. (3) with transmissivity obtained from pumping test at our 6 experimental sites. The best fit is obtained with $a = 1$, $b = 2$ and $C_T = 3 \cdot 10^{-3}$ $(m \cdot s^{-3})$ (Fig. 6). The value of C_T is in the range of published values for hard rock aquifers using the same values of a and b ($1 \cdot 10^{-3} < C_T < 7 \cdot 10^{-3}$ $m \cdot s^{-3}$; Plata and Rubio, 2008).

4. Discussion

4.1. Quantification of specific yield

The estimates of the specific yield from both θ_{MRS} and $T_2{}^*$ are accurate since the mean differences with the specific yield calculated from the pumping test are less than the uncertainty of the pumping test result (Tables 4 and 5). Moreover these differences between pumping test and MRS specific yield are far less than the difference found in the previous work carried out in hard rock aquifers (i.e. 80% in Vouillamoz et al., 2005). As mentioned by the latter, the reason is that the previous estimate was not reliable since some of the aquifers were (semi) confined.

We observed that θ_{MRS} is about twice the specific yield in a large variety of hard rocks. This observation is in accordance with Hector et al. (2013) who estimated the specific yield from gravity monitoring at a distance of 650 m away from our experimental site ARA, and concluded that the ratio $S_y/\theta_{MRS} \approx 0.63 \pm 0.15$.

We also observed that the recently developed ACT approach can be successfully used to estimate the specific yield from $T_2{}^*$. The main advantage of the ACT approach as compared to the use of θ_{MRS} is the definition of a site specific threshold value $T_2{}^* \approx 110ms$ which indicates the boundary between drainable and not drainable MRS water content. The practical application of the ACT is to determine from a MRS measurement if the water content can be used by pumping and thus if a borehole can be drilled. The knowledge of the value of θ_{MRS} is not sufficient to achieve a successful borehole siting. However, Eq. (5) is site specific and one still has to cross reference MRS parameters with pumping test prior to applying the appropriate equation in the concerned area or as suggested by Baroncini-Turricchia (2014) in area of similar hydraulic model.

Since θ_{MRS} and T_2^* carry different information about the aquifer, they can probably complement each other for estimating Sy. According to Eq. (2) $\theta_{MRS} \geq Sy$, thus we can write $Sy = \theta_{MRS} - Sr_{MRS}$ where Sr_{MRS} is the MRS specific retention, i.e. the amount of water that generates MRS signal but that cannot be drained when pumping. Because Sr_{MRS} is linked to the mean size of the saturated pores (see. Section 2. Material and method), Sr_{MRS} may be estimated from T_2^* and then:

$$Sy = \theta_{MRS} - f(T_2^*). \tag{6}$$

We suppose that the relationship between the MRS specific retention Sr_{MRS} and the mean size of the saturated pores T_2^* is similar in shape to the relationship between the hydrological specific retention and the mean grain size of the aquifer material, i.e. a sigmoid function (e.g. Lubczynski and Roy, 2007) and we propose the formula:

$$Sy_{MRS} = \theta_{MRS} - 0.5 \cdot \left[\frac{(T_2^*)^{-s}}{(T_2^*)^{-s} + (C)^{-s}}\right] \tag{7}$$

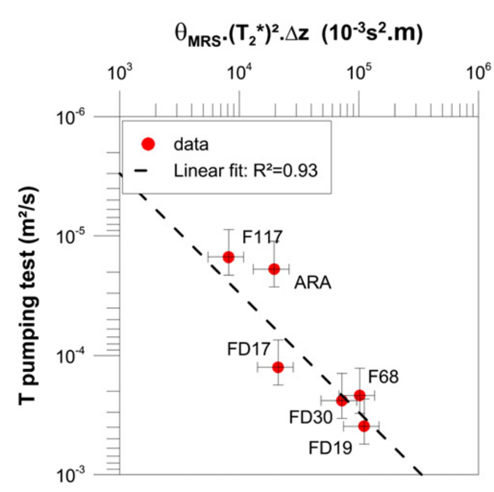

Fig. 6. Comparison of MRS parameters with transmissivity. R^2 is the coefficient of determination.

Table 4
Calculated data and uncertainties (population of 6).

Parameter/property	Max value	Min value	Average uncertainty
MRS water content	13%	2%	11%
MRS decay T_2^*	210 ms	135 ms	6%
Pumping test specific yield	7.7%	1.7%	20%
Pumping test transmissivity	3.9.10^{-4} m^2/s	1.810^{-5} m^2/s	40%

Table 5
Comparison of hydrogeological properties estimated from MRS and from pumping test (population 6, T_2* in second and Δz in metre).

Parameter/property	Equation	Mean difference
Specific yield	$S_y = 0.53 \cdot \theta_{MRS} + 0.007$	12%
Specific yield	$S_y = 0.78 \cdot T_2^* - 0.085$	18%
	$ACT \rightarrow T_2^* \approx 0.11s$	
Transmissivity	$T_{MRS} = 3 \cdot 10^{-3} \cdot \theta_{MRS} \cdot T_2{}^{*2} \cdot \Delta z$	70%

where s is the sloping parameter of the sigmoid function and C its pseudo-centroid. When parameterizing Eq. (7) on our dataset in Benin, we obtain a mean difference between Sy calculated from pumping tests and from Eq. (7) of 60% with $C = 40$ ms and $s = 2$ (Fig. 7). This difference of 60% is higher than the differences obtained with linear Eqs. (4) and (5): 12% and 18% respectively. However, Eq. (7) has a real theoretical advantage over the linear equations and in practice it also results in defining two ACT values (Fig. 7):

- when $T_2^* < ACT_{low} \Rightarrow Sy \rightarrow 0$ ($ACT_{low} \approx 130ms$ for our dataset),
- when $T_2^* > ACT_{high} \Rightarrow Sy \rightarrow \theta_{MRS}$ ($ACT_{high} \approx 400ms$ for our dataset).

To check the interest of Eq. (7) a dataset that exhibits a broader range of T_2^* value has to be used (e.g. $ACT_{high} < T_2^* < ACT_{low}$).

4.2. Quantification of transmissivity

We found that the mean difference between transmissivity values estimated from MRS and calculated from pumping test is 70%, which is more than the uncertainty on the pumping test result (Tables 4 and 5). For checking the robustness of our estimate and mainly of the C_T value (Eq. (3)), we compared 7 additional MRS carried out at sites where of pumping test of 4 h had been carried out by private actors. As mentioned in Section 2, Material and method, short duration pumping test in a single well can be used for estimating a local transmissivity (Kruseman and de Ridder, 2000). The difference between the MRS transmissivity calculated from Eq. (3) and the local transmissivity is 80% (Fig. 8), thus confirming that the estimate of transmissivity is less accurate than the estimate of the specific yield when using MRS results (Table 5). It can be understood because the fissured layer is not always well resolved although it can play the first role as compare to the saprolite for controlling the transmissivity (e.g. when the saprolite is clayey or eroded). Our result confirms two published works that already showed such misestimate of the transmissivity in hard rock aquifers because of the difficulty in characterizing well the fissured layer (Baltassat et al., 2006; Vouillamoz et al., 2005). However, if the transmissivity is not mainly controlled by the fissured layer but also by the saprolite layer, the estimate of the transmissivity is likely more reliable. Note that the use of a MRS single layer solution does not really impact the estimate of the transmissivity: at ARA experimental site, the transmissivities calculated with Eq. (3) using the single layer model and using the multi-layer model are about the same, i.e. 5.4 and $5.9 \cdot 10^{-5}$ m^2/s respectively.

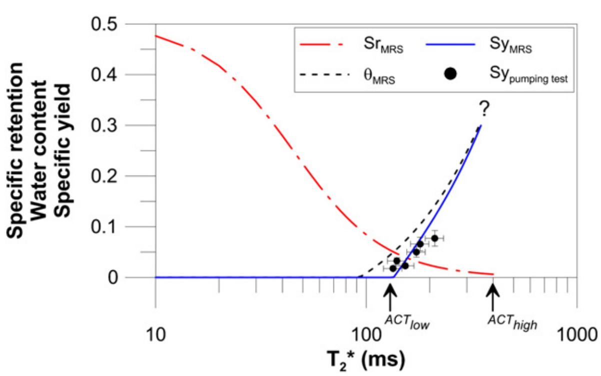

Fig. 7. Model of MRS specific retention and MRS specific yield (Eq. (7)) as a function of T_2* decay.

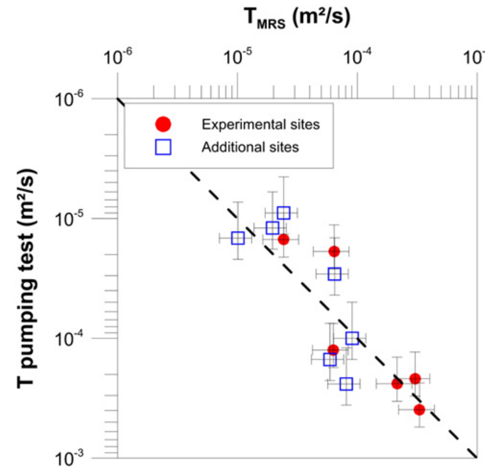

Fig. 8. Validation of the transmissivity estimated from MRS.

4.3. Limitation

Our approach for estimating the hydrogeological properties using MRS is limited in its applications by a main assumption: we assume the T_2^* decay to be mainly controlled by the pore geometry. However T_2^* is also affected by the heterogeneity of the geomagnetic field caused by the magnetic property of the rocks (Legchenko et al., 2010; Vouillamoz et al., 2011). Numerical and laboratory experiments indicate that magnetic susceptibility does not impact the T_2^* in low susceptibility rocks ($\chi < \sim 10^{-5}$ SI) and in medium susceptibility rocks ($\sim 10^{-5}$ $SI < \chi < \sim 10^{-3}$ SI) when the size of the pores is small (e.g. fine sands, Grunewald and Knight, 2011). Now, the specific yield encountered in hard rock aquifers are low (Sy < 8% in our study), and the magnetic susceptibility values that we measured on 694 borehole cuttings collected in-between 1 and 70 m below ground surface are medium: 80% of the values are $7 \cdot 10^{-5} < \chi < 5.1 \cdot 10^{-4}$ SI and the median value is $\chi = 1.4 \cdot 10^{-4}$ SI (Fig. 9). Consequently, we expect that the variation of T_2^* in our study is mainly controlled by the average pore volume.

5. Conclusion

Although hard rock aquifers are very common all over the world, only one published paper tried unsuccessfully to quantify the relationship

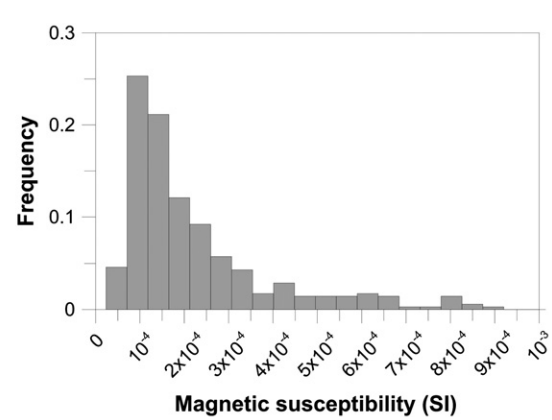

Fig. 9. Histogram of magnetic susceptibility measured on 694 rock samples.

between the specific yield and the MRS water content at the field scale (Vouillamoz et al., 2005).

In this study, we not only improve the estimate of specific yield from MRS in a variety of hard rock aquifers (i.e. granite, gneiss, migmatite, and mica schist) but we also successfully applied the recently developed apparent cutoff time approach (ACT, Vouillamoz et al., 2012). We proposed two empirical relationships to estimate with a good accuracy (less than 20%) the specific yield from either the MRS water content or the decay time T_2^* (ACT approach). Based on the ACT approach, we found in the investigated hard rock aquifers in Benin that the cutoff value $T_2^* \approx 110ms$ is the boundary between non drainable and drainable MRS water content. We eventually proposed a new approach for estimating specific yield by the joint use of MRS water content and decay time T_2^*. This new approach takes into account the nonlinear relationship of the specific yield with the MRS parameters, but is has to be confirmed with new experiments. Our study also confirms the capability of MRS to estimate the transmissivity of hard rock aquifers with an accuracy of about 70%.

Our results open new areas of application to the non-invasive MRS method in hard rock aquifers. The estimate of specific yield together with transmissivity can improve the siting of boreholes by reducing the number of too low yield (based on the estimate of the transmissivity) and by reducing the number of poorly-sustainable pumping yield (thanks to the use of specific yield for estimating groundwater storage and recharge). The parameterization of groundwater flow models will also benefit from non-invasive MRS estimates of specific yield and transmissivity (Baroncini-Turricchia, 2014). Finally, our results should encourage hydogeologists to use MRS as a complementary tool to pumping test for characterizing hard rock aquifers.

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References

Baltassat, J.-M., Legchenko, A., Ambroise, B., Mathieu, F., Lachassagne, P., Wyns, R., Mercier, J.L., Schott, J.-J., 2005. Magnetic resonance sounding (MRS) and resistivity characterisation of a mountain hard rock aquifer: the Ringelbach Catchment, Vosges Massif, France. Near Surf. Geophys. 3, 267–274.

Baltassat, J.M., Krishnamurthy, N.S., Girard, J.F., Dutta, S., Dewandel, B., Chandra, S., Descloitres, M., Legchenko, A., Robain, H., Ahmed, S., 2006. Geophysical characterization of weathered granite aquifers in Hyderabad region, Andra Pradesh, India. Proceedings 3rd MRS International Workshop, pp. 89–92.

Baroncini-Turricchia, 2014. Integrating MRS data with hydrologic model — Carrizal Catchment (Spain). Near Surf. Geophys. 12, 255–269.

Bernard, J., 2007. Instruments and field work to measure a magnetic resonance sounding. Bol. Geol. Min. 118, 459–472.

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). Hydrogeol. J. 17, 1805–1815.

Calow, R.C., Macdonald, A.M., Nicol, A.L., Robins, N.S., 2010. Ground water security and drought in Africa: linking availability, access, and demand. Ground Water 48, 246–256.

Courtois, N., Lachassagne, P., Wyns, R., Blanchin, R., Bougaïré, F.D., Somé, S., Tapsoba, A., 2010. Large-scale mapping of hard-rock aquifer properties applied to Burkina Faso. Ground Water 48, 269–283.

Dewandel, B., Lachassagne, P., Wyns, R., Maréchal, J.C., Krishnamurthy, N.S., 2006. A generalized 3-D geological and hydrogeological conceptual model of granite aquifers controlled by single or multiphase weathering. J. Hydrol. 330, 260–284.

Dewandel, B., Lachassagne, P., Zaidi, F.K., Chandra, S., 2011. A conceptual hydrodynamic model of a geological discontinuity in hard rock aquifers: example of a quartz reef in granitic terrain in South India. J. Hydrol. 405, 474–487.

Dutta, S., Krishnamurthy, N.S., Arora, T., Rao, V.A., Ahmed, S., Baltassat, J.M., 2006. Localization of water bearing fractured zones in a hard rock area using integrated geophysical techniques in Andhra Pradesh, India. Hydrogeol. J. 14, 760–766.

Grunewald, E., Knight, R., 2011. The effect of pore size and magnetic susceptibility on the surface NMR relaxation parameter T2*. Near Surf. Geophys. 9, 169–178.

Hector, B., Séguis, L., Hinderer, J., Descloitres, M., Vouillamoz, J.-M., Wubda, M., Boy, J.-P., Luck, B., Moigne, N.L., 2013. Gravity effect of water storage changes in a weathered hard-rock aquifer in West Africa: results from joint absolute gravity, hydrological monitoring and geophysical prospection. Geophys. J. Int. 194, 737–750. http://dx.doi.org/10.1093/gji/ggt146.

Kruseman, G.P., de Ridder, N.A., 2000. Analysis and Evaluation of Pumping Test Data. Wageningen, ILRI,.

Lachassagne, P., Wyns, R., Dewandel, B., 2011. The fracture permeability of hard rock aquifers is due neither to tectonics, nor to unloading, but to weathering processes. Terra Nova 23, 145–161.

Legchenko, A., 2013. Magnetic Resonance Imaging for Groundwater, (ISBN 9781848215689 1848215681).

Legchenko, A., Baltassat, J.M., Beauce, A., Bernard, J., 2002. Nuclear magnetic resonance as a geophysical tool for hydrogeologists. J. Appl. Geophys. 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, 363–373.

Legchenko, A., Descloitres, M., Bost, A., Ruiz, L., Reddy, M., Girard, J., Muddu, S., Mohan Kumar, M., Braun, J., 2006. Resolution of MRS applied to the characterization of hard-rock aquifers. Ground Water 44, 547–554.

Legchenko, A., Ezerski, A., Girard, J., Baltassat, J.M., Boucher, M., Camerlynk, C., Al-Zoubi, A., 2008. Interpretation of magnetic resonance soundings in rocks with high electrical conductivity. J. Appl. Geophys. 66, 118–127.

Legchenko, A., Vouillamoz, J.M., Roy, J., 2010. Application of the magnetic resonance sounding method to the investigation of aquifers in the presence of magnetic materials. Geophysics 75, 91–100.

Lubczynski, M., Roy, J., 2003. Hydrogeological interpretation and potential of the new magnetic resonance sounding (MRS) method. J. Hydrol. 283, 19–40.

Lubczynski, M., Roy, J., 2007. Use of MRS for hydrogeological parameterization and modeling. Bol. Geol. Min. 118, 509–530.

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.

Meier, P.M., Carrera, J., Sánchez-Vila, X., 1998. An evaluation of Jacob's method for the interpretation of pumping tests in heterogeneous formations. Water Resour. Res. 34, 1011–1025.

Moench, A.F., 1997. Flow to a well of finite diameter in a homogeneous, anisotropic water table aquifer. Water Resour. Res. 33, 1397–1407. http://dx.doi.org/10.1029/97WR00651.

Mukherji, A., 2008. Spatio-temporal analysis of markets for groundwater irrigation services in India: 1976–1977 to 1997–1998. Hydrogeol. J. 16, 1077–1087.

Office Béninois des Mines, 1984. Notice explicative de la carte géologique à 1/200 000 (Feuille Djougou-Parakou-Nikki).

Plata, J., Rubio, F., 2008. The use of MRS in the determination of hydraulic transmissivity: the case of alluvial aquifers. J. Appl. Geophys. 66, 128–139.

Portselan, A.A., Treshchenkov, V.V., 2002. Application of the NMR-tomography technique for groundwater investigations in Equatorial Africa: a case-history in Guinea. J. Appl. Geophys. 50, 123–127.

Renard, P., Glenz, D., Mejias, M., 2009. Understanding diagnostic plots for well-test interpretation. Hydrogeol. J. 17, 589–600.

Ryom Nielsen, M., Hagensen, T.F., Chalikakis, K., Legchenko, A., 2011. Comparison of transmissivities from MRS and pumping tests in Denmark. Near Surf. Geophys. 9, 211–223.

Sánchez-Vila, X., Meier, P.M., Carrera, J., 1999. Pumping tests in heterogeneous aquifers: an analytical study of what can be obtained from their interpretation using Jacob's method. Water Resour. Res. 35, 943–952.

Schirov, M., Legchenko, A., Creer, G., 1991. New direct non-invasive ground water detection technology for Australia. Explor. Geophys. 22, 333–338.

Tartakovsky, G.D., Neuman, S.P., 2007. Three-dimensional saturated–unsaturated flow with axial symmetry to a partially penetrating well in a compressible unconfined aquifer. Water Resour. Res. 43. http://dx.doi.org/10.1029/2006WR005153 (n/a–n/a).

Trushkin, D.V., 1994. The potential of a noise-reducing antenna for surface NMR ground water surveys in the earth's magnetic field. Geophys. Prospect. 42, 855–862.

Vouillamoz, J.M., 2003. PhD: La caractérisation des aquifères par une méthode non invasive: les sondages par Résonance Magnétique Protonique. hydro-géophysique, Orsay, Paris XI.

Vouillamoz, J.M., Descloitres, M., Bernard, J., Fourcassié, P., Romagny, L., 2002. Application of integrated magnetic resonance sounding and resistivity methods for borehole implementation, a case study in Cambodia. J. Appl. Geophys. 50, 67–81.

Vouillamoz, J.M., Descloitres, M., Toe, G., Legchenko, A., 2005. Characterization of crystalline basement aquifers with MRS: comparison with boreholes and pumping tests data in Burkina Faso. Near Surf. Geophys. 3, 205–213.

Vouillamoz, J.M., Chatenoux, B., Mathieu, F., Baltassat, J.M., Legchenko, A., 2007. Efficiency of joint use of MRS and VES to characterize coastal aquifer in Myanmar. J. Appl. Geophys. 6, 142–154.

Vouillamoz, J.M., Favreau, G., Massuel, S., Boucher, M., Nazoumou, Y., Legchenko, A., 2008. Contribution of magnetic resonance sounding to aquifer characterization and recharge estimate in semiarid Niger. J. Appl. Geophys. 64, 99–108.

Vouillamoz, J.M., Legchenko, A., Nandagiri, L., 2011. Characterizing aquifers when using magnetic resonance sounding in a heterogeneous geomagnetic field. Near Surf. Geophys. 9, 135–144.

Vouillamoz, J.M., Sokheng, S., Bruyere, O., Caron, D., Arnout, L., 2012. Towards a better estimate of storage properties of aquifer with magnetic resonance sounding. J. Hydrol. 51–58.

Vouillamoz, J.-M., Sophoeun, P., Bruyere, O., Arnout, L., 2014. Estimating storage properties of aquifer with magnetic resonance sounding: a field verification in northern Cambodia of the gravitational water apparent cutoff time concept. Near Surf. Geophys. 12, 211–216. http://dx.doi.org/10.3997/1873-0604.2013038.

Walbrecker, J.O., Behroozmand, A.A., 2012. Surface-NMR measurements of the longitudinal relaxation time T1 in a homogeneous sand aquifer in Skive, Denmark. J. Appl. Geophys. 87, 46–52.

Wyns, R., Baltassat, J., Lachassagne, P., Legchenko, A., Vairon, J., Mathieu, F., 2004. Application of proton magnetic resonance soundings to groundwater reserve mapping in weathered basement rocks (Brittany, France). Bull. Soc. Geol. Fr. 175, 21–34.

Yadav, G.S., Singh, S.K., 2007. Integrated resistivity surveys for delineation of fractures for ground water exploration in hard rock areas. J. Appl. Geophys. 62, 301–312.