XXXVIII IAH Congress

Groundwater Quality Sustainability
Krakow, 12–17 September 2010

Extended Abstracts

Editors:
Andrzej Zuber
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University
of Silesia
Press 2010

abstract id: **314**

topic: **3**
Aquifer management

3.3
Geophysical, geological and geochemical methods in groundwater exploration

title: **Efficiency of magnetic resonance soundings applied to the characterization of aquifers**

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keywords: magnetic resonance sounding, geophysics, transmissivity, geometry, water table

INTRODUCTION

In our changing world, improved groundwater development and resources management based on comprehensive knowledge of aquifers are required. Especially, aquifer properties as reservoir geometry, storage-related parameters and flow-related parameters are most needed for both well setting in complex environments and for supplying groundwater flow models that are commonly used for resource management. One of the most reliable ways to gather aquifer properties is drilling exploration boreholes and carrying out hydraulic tests. However, in situ estimates of aquifer properties are often scarce because dense field surveys are expensive in terms of time and money.

Non-invasive surface geophysical methods capable of providing rapid, dense and low cost data coverage can be very useful if they provide accurate estimates of aquifer properties. However, most geophysical parameters result from several factors including, but not limited to groundwater. As compared to other geophysical methods, magnetic resonance sounding (MRS) is selective with respect to groundwater (Legchenko and Valla, 2002). This distinctive feature makes it possible to use MRS parameters for characterizing aquifers.

MAGNETIC RESONANCE SOUNDING

The physics and mathematics of the method are beyond the scope of this paper and are available in numerous publications (e.g., Legchenko, Valla, 2002). MRS is based on exciting the nuclei of the hydrogen atoms in groundwater molecules, i.e. protons, and measuring the magnetic resonance signal that is generated by the precessing nuclei after the stimulation signal is terminated. To conduct field measurements, a loop of electrical wire is laid out on the ground (Figure 1). The shape of the loop is usually square, and measures 20 to 150 meters on a side, depending on the required maximum depth of the investigation (the greater the size of the loop the deeper the investigation).

Figure 1. MRS equipment (Numis device from Iris Instrument).

A pulse of alternating current is then generated in the loop. The energizing pulse causes a deflection of the magnetic moments of hydrogen nuclei from their equilibrium position. When the pulse is switched off, the nuclei revert to their pre-pulse position creating an alternating electromagnetic field that is measured usually with the same loop. To carry out a sounding, signals are recorded while the pulse moment is varied $q = I_0 \cdot \tau$ (where I_0 is the current and τ is the pulse duration): the higher the pulse moment the deeper the investigation.

HYDROGEOLOGICAL RELEVANCE OF MRS PARAMETERS

Two parameters of the recorded magnetic resonance signal are instructive for hydrogeological applications: the initial amplitude $E_0(q)$ and the decay rate $T_i(q)$ of the signal. The higher the initial amplitude of the signal the higher the number of hydrogen nuclei that generated the signal and thus the higher is the water content of the investigated rocks. The decay rate of the recorded signal is sensitive to the geometry of the pores that contain water: the longer the decay rate of the signal the larger are the pores of the rocks. The interpretation of the recorded $E_0(q)$ and $T_i(q)$ gives the distribution of the MRS water content $\theta_{MRS}(depth)$ and decay rate $T_i(depth)$ with depth (Legchenko and Valla, 2002). Note that the recorded signal is an integral signal over the investigated volume. The maximum investigated volume of a MRS can roughly be approximated by an area of 1.5 times the loop size for a depth corresponding to the loop size (Vouillamoz et al., 2003). Considering a typical size of 100 meters length (square shape loop), the output MRS parameters are integrated values over $150^2 \cdot 100 \approx 2 \cdot 10^6 m^3$. This scale of measurement makes the MRS result comparable to the result of a pumping test commonly used in hydrogeology for characterizing aquifers.

MRS storage related parameters

The MRS water content is defined as the volume of water which is measured with the instrumentation, over the total volume sampled by the MRS sounding (Legchenko et al., 2002). The signals which are undetected with the actual instrumentation likely reflect bound water, i.e. water which is attached to the rocks due to the forces of molecular attraction. In sediments where unconnected and dead-end pores are negligible, this leads to the assumption that θ_{MRS} is comparable to the effective porosity n_e : $\theta_{MRS} \approx n_e$ (Vouillamoz et al., 2005). In unconfined aquifers, storativity is mainly described by a gravitational component represented by the specific yield S_y (the elastic storage is negligible). Specific yield and effective porosity have comparable values for coarse grain rocks. However, in fine-grained rocks and particularly in clayey materials $n_e > S_y$ and thus (Vouillamoz et al.,2007b):

$$\theta_{MRS} \approx n_e \geq S_y \qquad (1)$$

In confined aquifer, storativity is described by an elastic component that is quantified by the storage coefficient. The storage coefficient can be calculated with the MRS parameters using its hydrogeological expression (Vouillamoz et al., 2007b):

$$S_{MRS} = \rho \cdot g \cdot \Delta z \cdot \left(\alpha + \theta_{MRS} \cdot \beta \right) \qquad (2)$$

where ρ is the mass per unit volume of water, g is the acceleration of gravity, α and β are the compressibility coefficients of the water and the aquifer respectively and Δz is the saturated thickness obtained from MRS result.

MRS flow related parameters

As the well-known formulations used by hydrogeologists to estimate the permeability from the porosity and from the size/geometry of grains (e.g. the Hazen and the Kozeny-Carman formula), Seevers (1966) proposed to estimate the intrinsic permeability from θ_{NMR} and T_i. Indeed, the decay constant T_i of the MRS signal is linked to the ratio of the pore volume to the pore surface V_{pore}/S_{pore}. For hydrogeological applications, Legchenko et al. (2002) proposed to estimate the hydraulic conductivity K_{MRS} and the transmissivity T_{MRS} as:

$$\begin{aligned} K_{MRS} &= C_k \cdot \theta_{MRS}{}^{a} \cdot T_i^{b} \\ T_{MRS} &= K_{MRS} \cdot \Delta z \end{aligned} \tag{3}$$

Several studies assessed the values of exponents *a* and *b* in several geological contexts (Vouillamoz et al., 2007a). Usually $a=1$ and $b=2$ as proposed by Seevers (1966) and C_k is a parametric factor that need to be calculated comparing pumping test and MRS results at parameterization sites.

USEFULLNESS OF MRS FOR HYDROGEOLOGY

Comparisons between the geometry, the transmissivity and the storativity of saturated aquifers estimated by MRS and by borehole/pumping test indicate that MRS contribution to characterize aquifers down to about 100 meters deep is highly valuable in rocks that behave as non or poorly-consolidated aquifer, that are young sediments and sandstones, weathered and fissured hard-rocks, densely fissured or highly interstitial porous carbonates (Vouillamoz et al, 2007a). In rocks that behave as fractured aquifer, that are low density fractured crystalline basements and limestone, MRS is a useful complementary method but is not always effective for common engineering studies. Indeed, MRS is nowadays not appropriate to characterize saturated aquifers when the water content is less than about 1% (depending on the thickness and depth). For example, a fractured and weathered zone in a granitic rocks that is 5 meters width and 20% of specific yield have a water content integrated over the MRS sampled volume of 0.7% (use of a square loop of 100m per side). Moreover, fractured aquifers and karsts have usually to be characterized in 2 or 3D because of their structural heterogeneities. However, 2D measurements and interpretation are not yet easily accessible for engineering work, but experiences of interpolated 1D or 2D inversion of MRS (used with complementary geophysical methods) has been efficient to characterize weathered and fractured crystalline basement (Legchenko et al., 2004 and 2006) and to localize shallow water-filled karst conduit (Vouillamoz et al., 2003; Boucher et al., 2006). Note that the recent development of MRS spin echo methodology makes it possible to carry out measurements in presence of magnetic rocks that are quite common in hard rocks context (dykes, volcanic rocks) (Legchenko et al., in press).

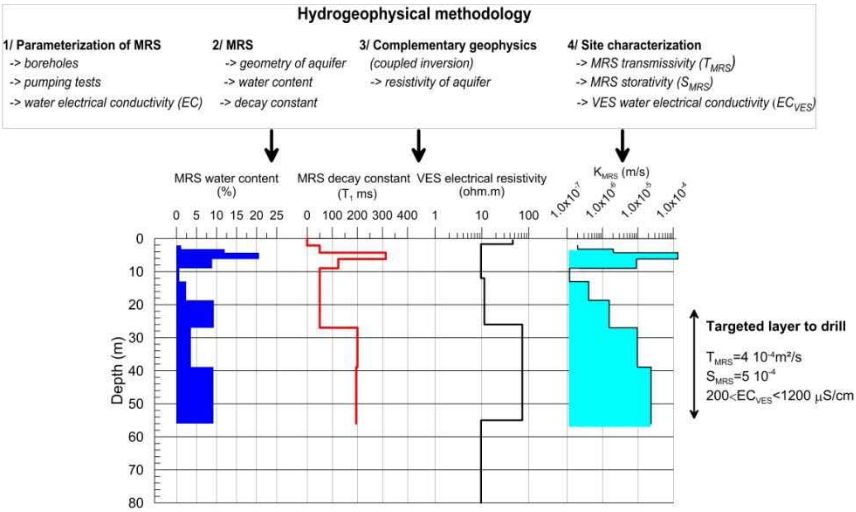

Figure 2. Use of MRS and VES in Myanmar (modified from Vouillamoz et al., 2007b).

For hydrogeological applications, experiences showed that the characterization of aquifer using MRS can efficiently be used:

- To improve boreholes setting in a variety of hydrogeological contexts including coastal aquifers (Vouillamoz et al, 2002; Vouillamoz et al., 2005; Vouillamoz et al, 2007b). The aquifer characterization is improved when MRS is used in the framework of a hydrogeological methodology and jointly with complementary geophysical methods. An example of joint use of MRS and vertical electrical sounding (VES) to implement boreholes in young alluviums of Myanmar is presented Figure 2. MRS and VES results are first compared to boreholes and pumping tests results to parameterize Equations 2 and 3, and then MRS and VES are jointly used to locate the best sites to drill (Vouillamoz et al., 2007b).
- To better constrain groundwater model (Boucher et al, 2009, Vouillamoz et al, 2008). MRS results can be used to analyse the distribution of specific yield and hydraulic conductivity and to choose the best range of acceptable values used to setup the numerical model.
- To estimate the groundwater recharge by supplementing observations of water table fluctuations (Vouillamoz et al., 2008), and by time laps measurements of MRS water content (Descloitres et al., 2008).

MRS estimate of water table

MRS estimates the depth of saturated layer that is the water table in unconfined aquifer, but MRS can not estimate the static water level of a confined aquifer. The average difference d between the water table measured in wells and estimated by MRS is $d \approx \pm 13\%$ (considering, Sandstone in Niger, Figure 3). MRS supplements but can not replace a monitoring well, but MRS can be useful in area with few existing data for estimating initial head condition in groundwater modelling for example.

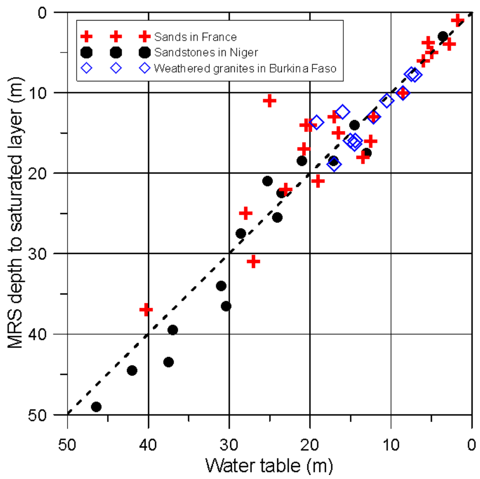

Figure 3. Examples of MRS estimate of the depth to water table (modified from Vouillamoz et al. 2005; 2007a).

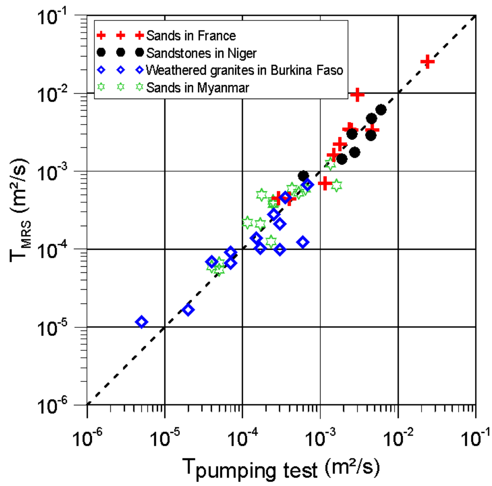

Figure 4. Examples of MRS estimate of the transmissivity (modified from Vouillamoz et al. 2005; 2007a; 2008).

MRS estimate of transmissivity

Equation 3 has been used in several geological contexts to estimate aquifer transmissivity (Figure 4). The appropriate C_k value is calculated comparing T_{MRS} and transmissivity obtained from pumping test interpretation (Vouillamoz et al., 2007a). The average difference d between transmissivity estimated from MRS and from pumping test is $-50\% \le d \le +100\%$. Note that this difference is comparable with the average uncertainty on transmissivity estimated from pumping test.

MRS estimate of storativity

As predicted by Equation 1, values of θ_{MRS} are usually higher than specific yield obtained from pumping test interpretation (Vouillamoz et al., 2005). However, usable relationship between MRS water content and specific yield has not yet been proposed mainly because dedicated studies still need to be conducted (Boucher et al., 2009). For confined aquifer, Equation 2 gave acceptable results in Myanmar with a difference between storage coefficient estimated from MRS and pumping tests results of $-2\% \le d \le +76\%$ (Vouillamoz et al., 2008).

CONCLUSION

One the one hand, MRS has already proved its unique interest to characterize saturated aquifers. On the other hand, MRS is a geophysical method that has common limitations in the field of geophysics (limited range of resolution, non-uniqueness of the solution…). Nowadays, the main limitation to the use of MRS is the electromagnetic noise that makes urban areas difficult to survey. But works are already in progress for reducing the vulnerability of MRS to electromagnetic noise. It will hopefully improve in a near future the capability of the method to investigate urban area, but also low porosity rocks as hard rock reservoirs and probably unsaturated zone. It will also make the 2/3D measurements more accessible to engineering work.

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International Association of Hydrogeologists

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2-vol. set + CD
ISSN 0208-6336
ISBN 978-83-226-1979-0