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Towards a better estimate of storage properties of aquifer with magnetic resonance sounding

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SUMMARY

Providing people with fresh water is one of the greatest challenges of the century. Since most of the world's liquid fresh water is groundwater, the knowledge of aquifer storage properties is essential. Moreover, there is a need to focus research on poor aquifers (i.e. capable of providing about 100 m^3/day) which will play an increasing role for supplying many human communities. This paper concerns a study carried out in a clayey sandstones aquifer in Northern Cambodia.

Conventional hydraulic methods used to characterize aquifers are costly, time-consuming and thus they are usually not used in most of the water projects in developing countries. Therefore, geophysical methods can be useful if they improve aquifer characterization. As compared to other non-invasive geophysical methods, magnetic resonance sounding (MRS) is selective to groundwater. MRS results are the distribution of both water content and pore-size related-parameters as a function of depth. However, relationships between the field scale MRS results and hydrogeological storage-related properties have not been well established yet. We present in this paper a comparison of MRS results with both specific yield calculated from pumping tests and effective porosity calculated from tracer tests. We found that the MRS water content is equal or higher than the specific yield and the effective porosity, thus indicating that MRS also measures capillary water in unsaturated zone and part of the bound groundwater attached to the aquifer solid matrix. We also found that the MRS pore-size parameter is linearly correlated with both the effective porosity and the specific yield, thus suggesting that the hydrogeological storage properties are mainly controlled by the size of the pores of the aquifer. Consequently, we adapted an approach used in the oil industry for differencing gravitational water from capillary water and from bound water, based on the MRS pore-size parameter. In the clayey sandstones of Cambodia, our approach named MRS apparent cutoff time approach, allowed calculating specific yield with an average error of 23% (which is far less than the previous published results), and for the first time it allowed calculating effective porosity (with an average error of 11%). We conclude that the MRS apparent cutoff time approach is useful for estimating aquifer storage properties down to 50–80 m deep, in a single day and at an affordable cost.

1. Introduction

Sustainable management of fresh water resource is one of the main challenges of the century. Climate change and rapid population growth in Africa and Asia will probably impact all water sources. Since most of the Earth's liquid fresh water is groundwater, the potential buffer role played by groundwater will be a key issue to support adaptation strategies (MacDonald et al., 2011). However, there is limited knowledge of groundwater resources in many African and Asian countries particularly in the so-named poor aquifers capable of supplying small pumping of about 100 m^3/day for local communities. Increasing the knowledge of aquifer storage properties is then essential.

Drilling boreholes and carrying out hydraulic test is the conventional method for estimating aquifer properties because it is an in situ measurement thus revealing a ground truth (with potential errors). Conventional pumping test refers to the analysis of groundwater head response to a pumping and it requires at least 2 wells (i.e. a pumping well and an observation well). The hydrogeological parameters calculated from conventional pumping test are some average values of the properties of the volume of aquifer which is investigated by the test (Meyer et al., 1998; Sanchez-vila et al., 1999). However, the averaging property of conventional

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pumping test has been questioned in heterogeneous aquifers (e.g. Wen et al., 2010; Wu et al., 2005; Yeh and Lee, 2007) and the hydraulic tomography method has been proposed for improving the spatial resolution of conventional test (Butler et al., 1999). The hydraulic tomography involves the simultaneous analysis of groundwater head responses recorded at numerous locations and produced by a sequence of pumping stressing different portions of the aquifer. Although hydraulic tomography created a high level of enthusiasm among the hydrogeological community, it has an inherent physic-imposed nonunique solution (Bohing and Butler, 2010). Moreover, both conventional pumping test and hydraulic tomography require the drilling of numerous boreholes for providing a spatial density of aquifer properties appropriate to most of the groundwater studies. Finally, considering the great challenge of assessing and managing groundwater resource in the developing countries, hydraulic tests are expensive, time-consuming and thus rarely used for routine works.

There is an agreement within the scientific community that new procedures which involve the use of independent data sources have to be designed for improving the characterization of aquifers. Geophysics are the most cited tools for complementing hydrogeological approach (e.g. De Marsily et al., 2005; Bohing and Butler, 2010) even thought most of the geophysical parameters result from several factors including but not limited to groundwater. A geophysical method can provide a more direct link to the presence of water: as compared to other geophysical methods, magnetic resonance sounding (MRS) is selective with respect to groundwater (Legchenko and Valla, 2002). Since the 1990s, this distinctive feature has been used to assess the links between the MRS parameters and the hydrogeological properties (e.g. Legchenko et al., 2002, 2004; Lubczynski and Roy, 2007; Plata and Rubio, 2011; Vouillamoz et al., 2002, 2007b, 2008). Although there is a strong theoretical basis for the relationship between MRS parameters and aquifer storage-related parameters, no ready-to-use quantitative link has been proposed to date (Vouillamoz et al., 2007a). This paper presents a modified form of an approach used in the oil industry for differencing bound water from capillary water and from gravitational water (Dunn et al., 2002). The so-named MRS apparent cutoff time (ACT) approach is based on the use of the pore-size related MRS parameter for estimating aquifer storage properties, and it has been developed in Sandstones of Northern Cambodia.

2. The MRS measurement

MRS is the field scale implementation of the nuclear magnetic resonance method that is widely used for medical imagery, laboratory spectrometry and well logging in the oil industry. It became available to the hydrological community in 1996 with the introduction of the first commercial equipment (Bernard, 2007). Basics of the MRS method can be found in Legchenko and Valla (2002). To carry out a MRS, the nuclei of the hydrogen atoms of water molecules in the subsurface (i.e. protons) are energized with an electromagnetic 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 (i.e. the frequency of precession of the magnetic moments of hydrogen nuclei about the geomagnetic field) and has an exponential envelope that decays at time rate T_2^*. This so-called free induction decay (FID) signal is:

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

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 (Fig. 1).

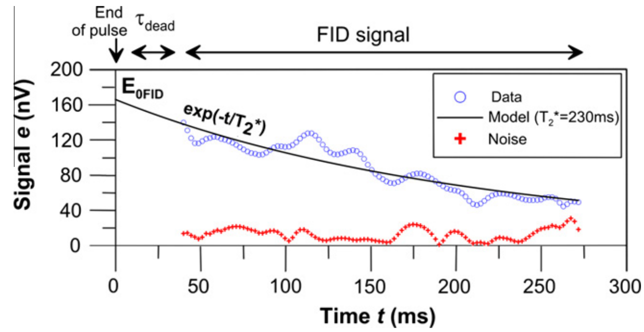

Fig. 1. Example of FID measurement (sounding Kok Sampor 5, q = 730 A ms).

The initial amplitude E_{0FID} is proportional to the total amount of water sampled by the measurement, and the decay time of the signal T_2^* contains information about the geometry of the pores which contain water. The MRS signal can be measured only after an instrumental dead-time 10 ms < τ_{dead} < 40 ms that is needed for switching the instrumentation from transmitter to receiver (Fig. 1). The T_2^* value is usually obtained from fitting an exponential curve to the envelope of the FID signal and E_{0FID} is then extrapolated.

To carry out measurements at several depths, FID signals are recorded using increasing energizing pulses q: the higher the energy of the pulse, the deeper the investigation. The maximum investigation depth corresponding to the maximum q is 50–80 m.

2.1. MRS decay time T_2^*

The T_2^* parameter describes the decay of the measured signal which is usually dominated by the surface relaxation time T_{2S} (Roy et al., 2008). T_{2S} is determined by interactions between the hydrogen nuclei in water and the solid surface of the geological reservoir. $1/T_{2S} = \rho_2 \cdot S_{pore}/V_{pore}$ 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. Thus, T_2^* parameter is referred to as the MRS pore-size parameter as:

$$1/T_2^* \approx \rho_2 \cdot S_{pore}/V_{pore} \quad (2)$$

Reinforcing the approximation of Eq. (2) is the proposal of Schirov et al. (1991) who established an empirical relationship between the value of T_2^* and the grain size of the saturated porous rocks (Table 1). Then, based on hydrogeological formulations linking aquifer grain size and hydraulic conductivity (e.g. Hazen and Kozeny-Carman), the relationship between the MRS signal and the pore size has been successfully used for estimating hydraulic conductivity of saturated rocks from MRS results (e.g. Plata and Rubio, 2008; Ryom Nielsen et al., 2011; Vouillamoz et al., 2002, 2005, 2008).

2.2. MRS water content

The groundwater content θ_{MRS} obtained from the initial signal amplitude E_{0FID} is defined as the volume of water with a sufficiently long decay time to be measured with the instrumentation

Table 1
T_2^* versus grain size, from Schirov et al., 1991.

Signal decay time T_2^* (ms)	Grain class
$30 < T_2^* < 60$	Clayey/very fine sands
$60 < T_2^* < 120$	Fine sands
$120 < T_2^* < 180$	Medium sands
$180 < T_2^* < 300$	Coarse/gravely sands
$300 < T_2^* < 600$	Gravels
$600 < T_2^* < 1500$	Surface water bodies