Paper 108

MRS: New GW Geophysical Technique

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ABSTRACT

Humanity needs for fresh water are increasingly met by groundwater (GW). Exploration geophysics contributes to the exploration, assessment and management of GW. On top of progress with classical geophysical techniques, during the last decade, a new technique, MRS, Magnetic Resonance Sounding, is particularly suited for GW work. It is an in-situ application of NMR (Nuclear Magnetic Resonance) and it uses the earth's magnetic field as static field. It has now reached a depth capability of ~ 150 m in resistive formations. Of all ground geophysical techniques, MRS has the highest selectivity with respect to GW because it selectively detects and quantifies free hydrogen a major component of the water molecule. The field implementation has similarity with single loop time domain electromagnetics (TDEM). The inversion results supply free water content and signal decay rate as a function of depth. This last parameter is closely linked to water bearing pore-size itself related to hydraulic conductivity and transmissivity. Thus, each MRS station characterizes the depth and thickness of near-surface aquifer and aquitards together with their ratings in terms of GW storage and flow properties. The MRS technique is still being improved with respects to its sensitivity to ambient noise, development toward 2D and 3D versions and limitations due to specific geological conditions such as magnetic rocks or self-masking layering of aquifers with conductive horizons. MRS has been used in over 30 countries and teams in various areas are working toward its optimal integration within groundwater exploration, assessment and exploitation projects.

INTRODUCTION

One of the most fundamental natural resource for humanity is fresh water. With raising demand for a finite resource, groundwater is increasingly used to fulfill these growing needs for water. Exploration geophysics has made valuable contribution to the exploration, quantification and management of groundwater. Groundwater (GW) geophysics and hydrogeophysics identify these applications of exploration geophysics. During the last decade, GW geophysics made highly significant progress through the wider applications of the classical techniques and their joint integration (Kirsch, 2006; Rubin and Hubbard 2005; Butler, 2005; Vereecken et al. 2006). Among such classical techniques we have resistivity, induced polarization (IP), spontaneous polarization (SP), time and frequency domain electromagnetics (TDEM, FDEM), ground penetrating radar (GPR), very low frequency EM (VLF), seismic, magnetics and gravity. During that interval, however, one technique stands out as a new and highly relevant geophysical technique for GW: MRS (Magnetic Resonance Sounding).

MRS

Functionally, MRS fits between two known techniques: AAS (Atomic Absorption Spectrometry) and TDEM. AAS is used in laboratories, on carefully prepared samples and has no in-situ depth of penetration but it has good performance for element discrimination and determination of their concentration. TDEM has good depth of penetration, i.e. in suitable cases, it can measure in-situ ground conductivity as a function of depth down to several hundred meters but it has no element discrimination. MRS shares some of these characteristics: it has excellent element selectivity but for 1 element only: hydrogen, a major component of the water molecule. Also, MRS allows moderate depth of penetration in particular over resistive terrain i.e. up to 150 m while quantifying water content and pore-size as a function of depth. MRS is a field application of NMR (Nuclear Magnetic Resonance) to groundwater investigations.

NMR IN A NUTSHELL

NMR (Slichter, 1996) is one of the numerous processes of interaction between electromagnetic (EM) fields and matter. Most of the ones we are familiar with are occurring at the level of electrons, while NMR is a process at the nuclei level. NMR

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exploits two nucleus properties: (1) a net angular momentum l, (2) a net magnetic moment μ Only ~ 42 isotopes (30 elements involved) have both of these properties in exploitable magnitude. The gyromagnetic ratio $\gamma = \mu / l$ is an atomic constant that uniquely characterizes each of these isotopes. Here, we are only concerned with hydrogen nuclei ($^1H^+$) with $\gamma = 2.675 \times 10^8$ rad•$s^{-1}T^{-1}$. At equilibrium, the net magnetic moment of the volume investigated for a given isotope is aligned with the ambient (static) magnetic field B_s. We can put it out of this alignment (1) by momentarily changing B_s or (2) by exciting the volume at the resonance, Larmor, frequency $f_L = \gamma B_s/2\pi$. After excitation, because of their angular momentum, the excited nuclei will not immediately return to their equilibrium orientation but will rather precess around this direction at the frequency f_L during a relaxation time characterized by decay time constant T_d. The various NMR decay time constants (T_1, T_2 and T_2^*) and their significance in petrophysics are reviewed by Dunn et al. (2002). In ground geophysics, we exploit the NMR process both for magnetometers and for MRS. Table 1 summarizes the distinction between these two applications. In borehole geophysics, NMR logging tools provide diagnostic information for petroleum exploration; due to cost factors, NMR logging is not yet generalized for GW projects.

Table 1: Comparison of the MRS technique with the familiar precession magnetometer, assuming resistive ground and earth's magnetic field = B_e

	Precession Mag	MRS
Excitation type	DC field >> B_e	AC field << B_e
Excit. field shape	~ uniform	non-uniform
Excit. volume	~ 10^{-4} m^3	up to 10^{+6} m^3
Max Excit. power	~ 10^1 W	~ 10^6 VA (reactive)
What is excited: $^1H^+$	fluid in sensor	in situ GW 150 m
Time/station	10^{-1} to 10^1 s	~ 10^4s
What is measured:	signal frequency	signal E_0 , T_d , phase
System mass	~ 10 Kg	~ 300 Kg
Info obtained	B_e at sensor's location	θ_{MRS} , T_d depth-wise

MRS IMPLEMENTATION

For MRS work, we use the earth's magnetic field, B_e, as static field i.e. $B_s = B_e$. The practical implementation uses a large loop laid on the ground in a layout quite similar to a single loop time-domain EM set-up (Figure 1). Additional loop shapes are also used. The MRS instrument energizes this loop during the excitation step and uses the same loop as an EM sensor during the detection step. A laptop PC provides control, monitoring, data recording, processing and inversion; it is an essential component of the system. In this implementation (NUMIS^{PLUS}), each module is 20 Kg (IRIS Instrument, 2001) allowing for easy transportation in a back pack.

MRS DATA ACQUISITION

MRS data acquisition starts with a magnetic survey to check field homogeneity and determine the local value of f_L. In conductive areas, we add an EM sounding to get the subsurface geoelectrical section at the site. The MRS system is tuned to the local Larmor frequency and a sounding is implemented by varying the 'strength' or pulse moment of the excitation. The pulse moment (Q in A•ms) is the product of loop current times pulse duration. Due to signal to noise ratio (S/N) consideration, each measurement is repeated a number of times for signal stacking purpose in order to improve the S/N. Figure 2 illustrates the summary of such sounding acquired just a few months after Exploration 97 at the margin of a dunes area. The work was done in a park in South-West Netherlands. In this data summary (left panel), three quantities are displayed for each Q value used: the initial value (E_0 - *) of the NMR signal in nV, the average noise level (•) and the signal decay time constant (T_2^* -) in ms – using right Y-axis. The sounding parameter, Q for MRS, is the variable that allows depth discrimination. For example, in a Schlumberger vertical electric sounding, the sounding parameter is the operator-controlled, AB inter-electrode distance.

MRS DATA INVERSION

Prior to data inversion, we generate a model of the subsurface MRS response using the value of B_e and its dip, the geoelectrical section and some of the data acquisition parameters e.g. loop size and shape. Typical descriptions of the underlying MRS numerical model include: Goldman et al. (1994), Weichman et al. (2002). Using such model, the data inversion step allows least square fit of the observed data set to the model, using free water content θ_{MRS} and signal decay rates (e.g. T_2^*) as inverted parameters over discrete depth intervals. Below the water table, θ_{MRS} is an estimate (Φ_{MRS}) of the effective porosity, while the signal decay rate is related to the water bearing pore size. In some cases, a more complex excitation scheme is used e.g. Legtchenko et al. (2003), from which an estimate of T_1 e.g. T_1^* is made. Coming back to Figure 2, the two rightmost panels display the result of such inversion step. The center part shows water content as a function of depth while the right part shows the signal decay time again as a function of depth. On the left panel, the full line passing near the "*" symbol shows inverted model response compared to E_0 measured values. Often, because of mixed grain-size or presence of fine sediment, the transition near the water table is gradual rather than abrupt. At the Waalwijk-1 site (Figure 2), the estimated depth of the water table is ~ 8 m. The data inversion strategy and parameters also contribute to a smooth transition between vadoze zone and saturated formations inversion results.

MRS DATA EXPLOITATION

Information acquired through MRS surveys allows, under suitable conditions, not only detection and positive identification of water bearing layers but also, the determination of their vertical geometry, i.e. depth and thickness, their free water content i.e. the amount of water free to move under realistic hydraulic gradients and an estimate of key parameters such as hydraulic conductivity, *K*, and transmissivity T (Legtchenko et al., 2004). For a given lithology/mineralogy, the longer the NMR decay rate, the coarser the water bearing pore-size below the water table. This important observation was first explained by Korringa et al. (1962) in their "KST" model. Later, Kenyon et al. (1989) showed empirical observations, which confirmed this model. In fact, the relationship between NMR decay rate and pore-size allows, through decay rate spectra analysis, the determination of pore-size distribution. Because of the close link between pore-size, throat size, hydraulic permeability and hydraulic conductivity, NMR logs can reliably supply flow properties information. MRS, which is less advanced than its borehole-logging counterpart, is less reliable in environments where magnetic minerals are present. Also in most cases, MRS supplies an average decay rate instead of a decay rate spectrum. Above the water table, in particular at depths below GPR reach, MRS can supply information difficult to acquire non-invasively, such as water content and water film thickness or water drop size (Roy and Lubczynski, 2005). However, the exploitation of MRS in the vadoze zone still needs calibration.

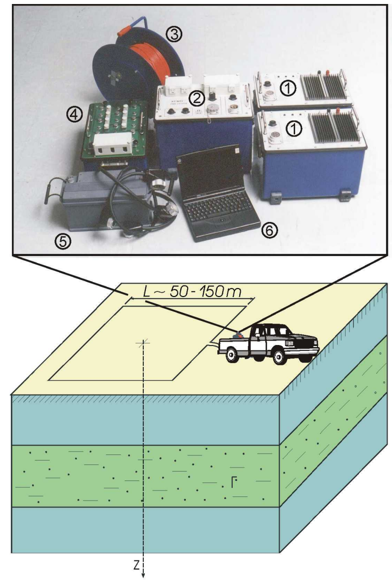

Figure 1: MRS set-up: - bottom: typical MRS field layout using a square loop; top inset: NUMIS^{PLUS} system - IRIS Instruments (2001): (1): DC/DC converter, (2) main unit, (3) wire loop, (4) tuning box, (5) rechargeable battery, (6) control & data acquisition PC.

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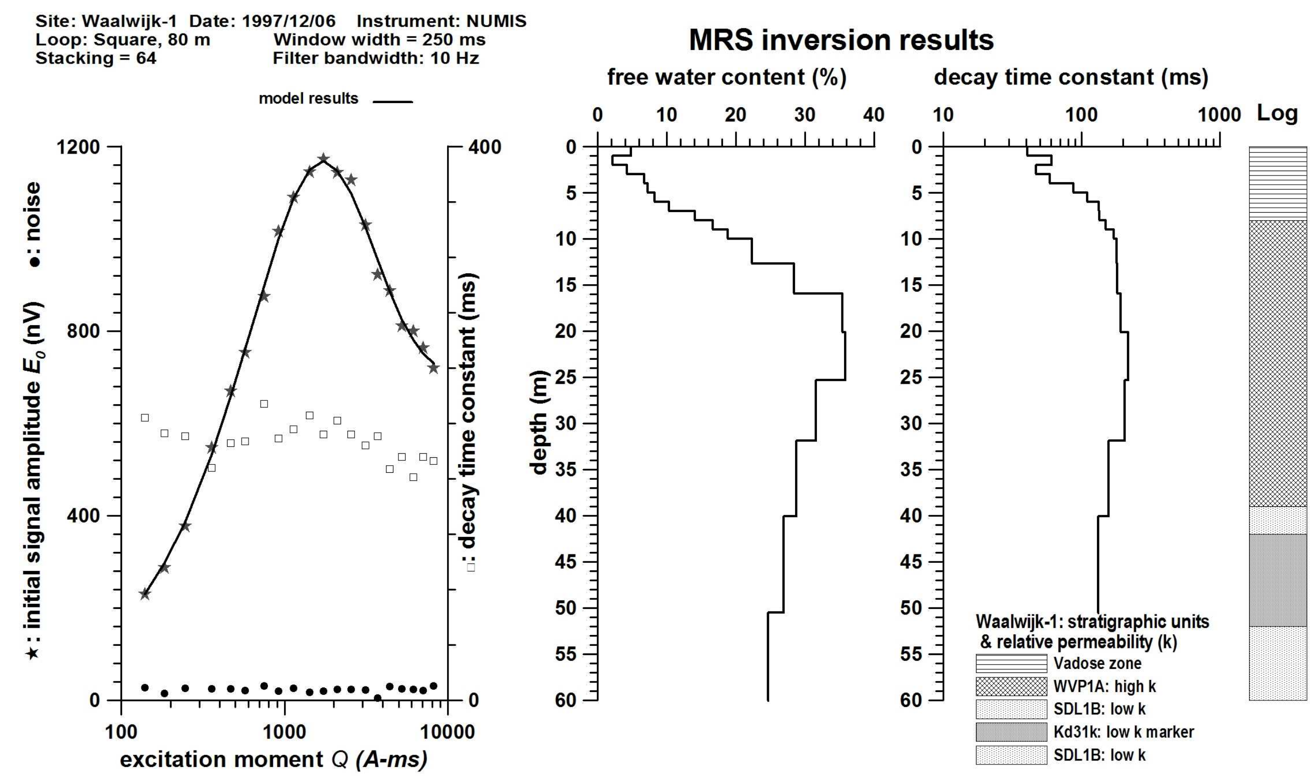

Figure 2: MRS data set & inversion; Waalwijk-1, Netherlands: from left to right (1) MRS data summary, field [* - E_0,   - T_2^*, • - noise] & model [—] vs. Q, (2 & 3) MRS inversion results: water content & decay time constant vs. depth, (4) Lithological log inferred from three nearest boreholes; in this model, the WVP1A unit has a higher permeability than the SDL1B and Kd31k units. (Item 4, TNO, 1998).

MRS CAPABILITIES AND LIMITATIONS

Following a little over a decade of tests and evaluations, the users' perspective is that MRS is highly appropriate for GW work due to (1) its inherent selectivity for $^1H^+$ and therefore in the near surface for GW, (2) its performance as a non-invasive sounding tool, i.e. information as a function of depth, (3) the relevance of its inverted parameters to characterize aquifers and aquitards: θ_{MRS} and T_d. MRS is mostly used in a sounding mode, i.e. 1D, and the most readily available information is the one related to water quantity (θ_{MRS}) as a function of depth for both the vadoze and the saturated zone. Its hydrogeological significance needs careful considerations e.g. Lubczynski and Roy (2005). K and T calibrations have progressed significantly and lithology dependent factors have already been evaluated e.g. Vouillamoz (2003). An example of the use of signal decay spectral analysis is shown in Figure 3. Such technique is currently limited to MRS data sets with high S/N. In this Figure 3, the water content is resolved into 3 components of pore-size: "fine", "medium" and "coarse". The figure also shows an alternate way of displaying the MRS data set summary: the excitation moment Q is displayed along the Y-axis to stress the relationship (sounding parameter) between Q and depth.

On the other hand, the MRS technique is sensitive to ambient noise: MRS cannot be acquired near power lines, industrial installations nor during magnetic storms. The current implementation of the technique is not yet compatible with all geological settings: magnetic materials and some stratigraphic combination of aquifers and conductive layers may generate 'masking' effects e.g. Roy and Lubczynski (2003).

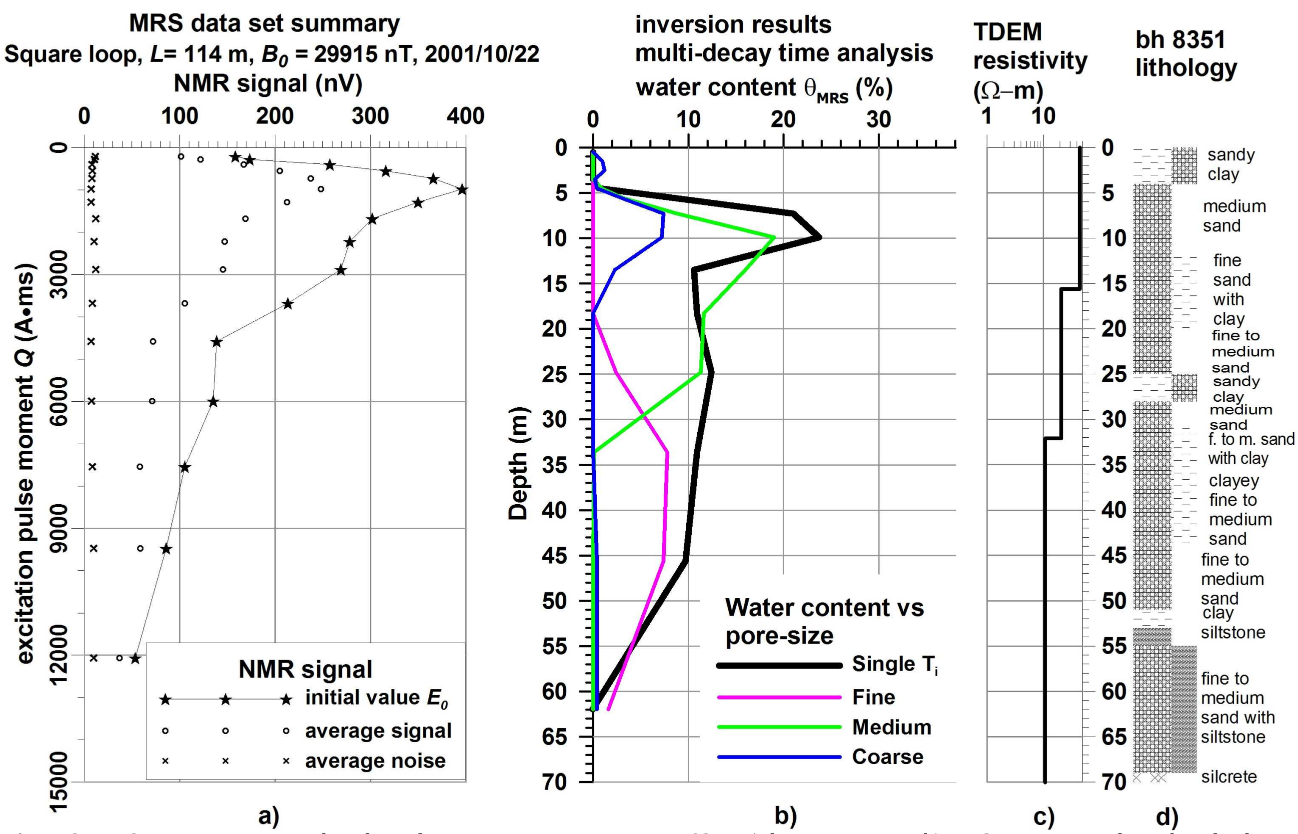

Figure 3: MRS investigation on a paleo-channel near Maun, Botswana, site BH8351; a) data set summary, b) MRS inversion results with multi-decay time analysis, c) TDEM resistivity, d) BH 8351 lithology (after Mangisi, 2004; Roy and Lubczynski, 2005).

MRS ON-GOING R&D

Typical research and development directions involve S/N improvements, 2D & 3D capability and a widening of the NMR signal aperture window. One can expect better ground penetration, higher GW selectivity and higher relevance of inverted parameters than e.g. GPR possibly with less spatial resolution. However, it is most likely that the optimal use of the MRS technique will be tightly integrated with other geophysical techniques to supply the most relevant information in a rapid and cost-effective way. Currently, the technology is available from France and Russia with other implementations being developed to my knowledge at least in Germany and USA. Active working groups in MRS are located in various parts of the world including in Australia, China, France, Germany, India, Netherlands, Russia, USA etc. Three international workshops have allowed users and designers to share their experience and knowledge on the technique (Berlin 1999, Orléans 2003 and Madrid 2006).

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