MRS: NEW GEOPHYSICAL TECHNIQUE FOR GROUNDWATER (GW) WORK: (1) CONCEPTS & IMPLEMENTATION

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GROUNDWATER (GW)

Now and in the foreseeable future, humanity needs for fresh water (drinking, agriculture, ecosystems etc.) is going to be increasingly met by groundwater. UNESCO/BGR assessment of global GW resources is summarized in Figure 1.

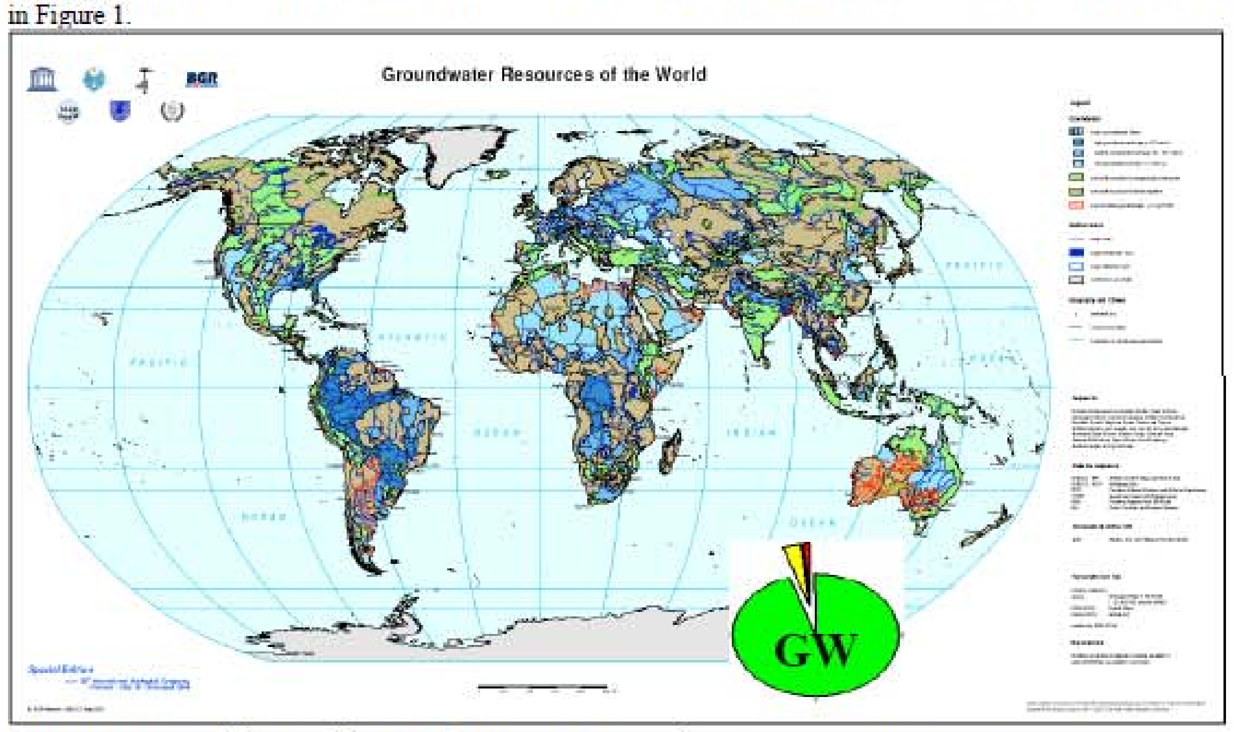

Figure 1: *GW of the world – BGR/UNESCO – pie chart = 'new' water; green sector = GW*

During the last 10 years applied geophysics techniques have made significant progress for 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 (Pellerin et al. 2009). 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, gravity and gamma-ray spectrometry. 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 exploits two nucleus properties: (1) a net angular momentum ℓ, (2) a net magnetic moment μ. Only ~ 42 isotopes (30 elements involved, see also Figure 2) have both of these properties in exploitable magnitude. The gyromagnetic ratio $\gamma = \mu/\ell$ 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. See analogy with precessing top on Figure 3. A quantum perspective is also useful for several aspects. Two rotations are of particular interest: *precession* of the nuclei around B_s and *nutation* around the excitation field B_{ft}. 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. Various tables summarize the application of NMR to non-invasive sub-surface exploration for water. Table 1 recalls the three magnetic field involved in MRS (excluding noise fields). Table 2 is a simplification of the main observed relationships while Table 3 summarizes the distinction between nuclear precession magnetometer and MRS. 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 but lower cost units are now being evaluated for GW.

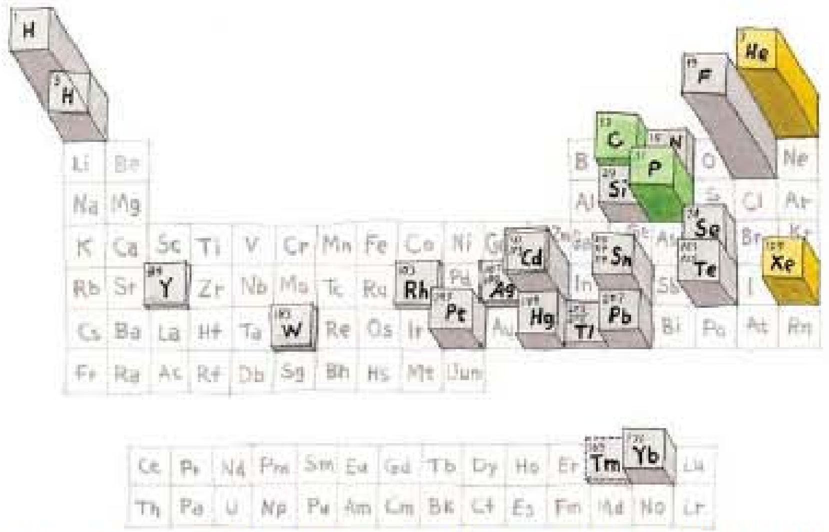

Figure 2: *Some of the isotopes suitable for NMR (Kadlecek, 2002)*

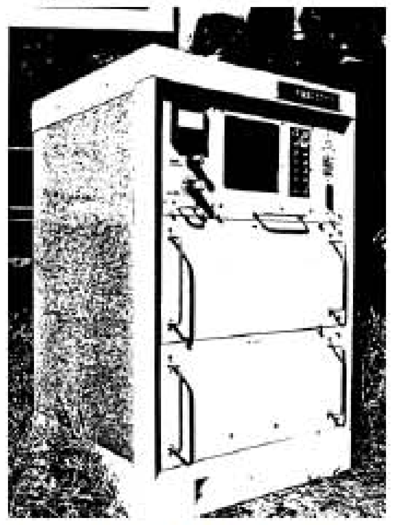

Figure 4: *Hydroscope*

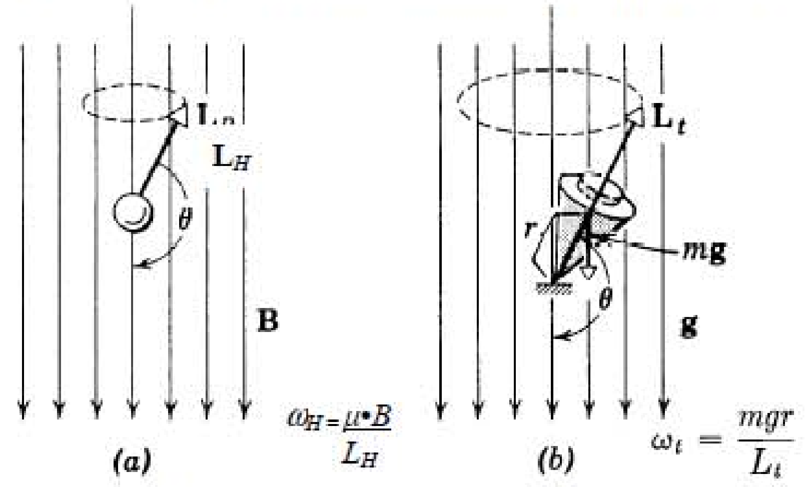

Figure 3: *a) A spinning hydrogen nucleus ($^1H^+$) precessing in the ambient magnetic field: ω_H is the $^1H^+$ precession angular frequency, μ is its magnetic moment ($1.4 \cdot 10^{-26}$ J/T), B is the magnetic field (in T) and L_H is the $^1H^+$ spin angular momentum ($5.3 \cdot 10^{-35}$ J·s). The ratio $\mu/L_H = \gamma$ is called the gyromagnetic ratio. For hydrogen, $\gamma = 2.675 \times 10^8$ rad•s^{-1}T^{-1} b) A spinning top precessing in the ambient gravitational field: ω_t is the top precession angular frequency, mg is its weight, r is the distance between the contact point and the top center of gravity and L_t is the top's angular momentum. In each case the angular frequency is equal to the torque divided by the angular momentum (Halliday & Resnick, 1962).*

Table 1: *The 3 magnetic fields involved in the MRS technique*

Magnetic field	Frequency	Use
Earth's field	DC	Determine f_l e.g.: at 50000 nT, f_l = 2.1 kHz
Excitation field	AC @ f_l	$^1H^+$ resonance excitation
$^1H^+$ field	AC @ f_l	GW [$E_0 \rightarrow \theta_{MRS}$] and pore-size [$T_d \rightarrow$ T] characterization

Table 2: *MRS fundamental equations where f_l is Larmor frequency, γ is the gyromagnetic ratio for $^1H^+$, B_0 is the earth's magnetic field, E is the NMR signal, t is the time, T_d is the NMR decay time constant, φ is the phase, $B_\perp$ is the component of the excitation field perpendicular to the earth's field, r is the radius vector, M_0 is the magnetic moment of the water molecule, $\theta(r)$ is the spatial distribution of water content, Q is the moment of excitation (pulse width times excitation current) and v is the volume over which the integral is summed.*

Precession (Larmor) frequency, f_l	$f_l = \gamma B_0/2\pi$
Time decay of NMR signal	$E(t) = E_0 \exp(t/T_d) \sin(2\pi f_l t + \varphi)$
NMR signal vs. water content	$E_0 = \int_v 2\pi f_l B_\perp(r) M_0 \theta(r) \sin(\gamma/2 A B_\perp(r) Q)\, dv$

Table 3: *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	~ 10^4 s
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 6 bottom part.). Additional loop shapes are also used see right part of Figure 7. 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) so that we can do back pack carrying. An earlier implementation, Hydroscope from ICKC (see Figure 4 – to the right of Figure 2) was less portable but allowed to experimentally demonstrate the applicability of the concept.

Figure 5: MRS implementations: top left: original NUMIS, top right: Radic SNMR MIDI, bottom left: NUMIS^{LITE}, bottom right: GMR, Clara Vista.

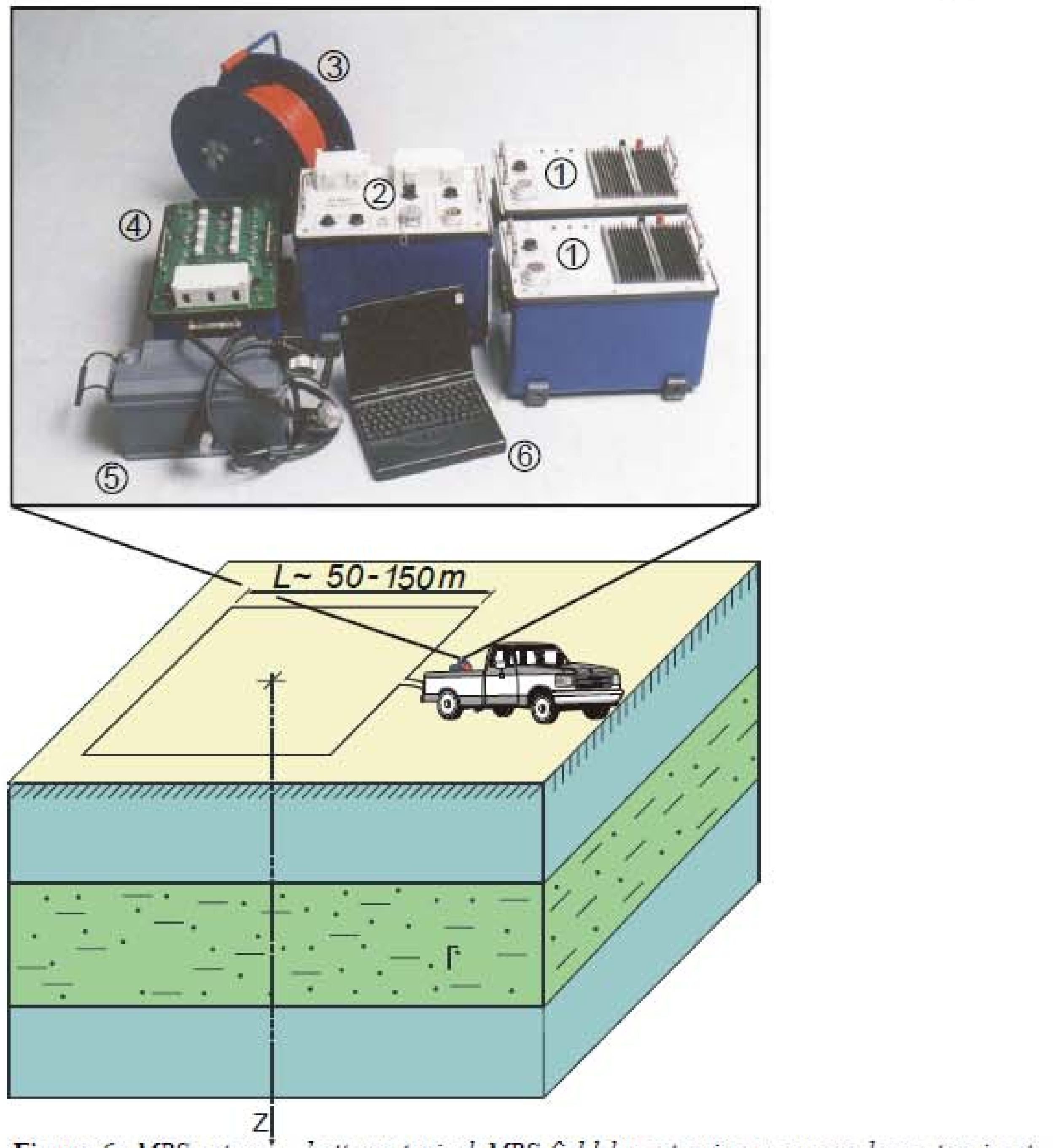

Figure 6: *MRS set-up: - bottom: typical MRS field layout using a square loop; top inset: NUMIS^{PLUS} system - IRIS Instruments (2001): (1): DC/DC converter, (2) main unit, (3) wire loop, (4) tuning box, (5) rechargeable battery, (6) control & data acquisition PC.*

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 8 illustrate the summary of such sounding acquired in 1997 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 the 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 8, 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 8), 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.

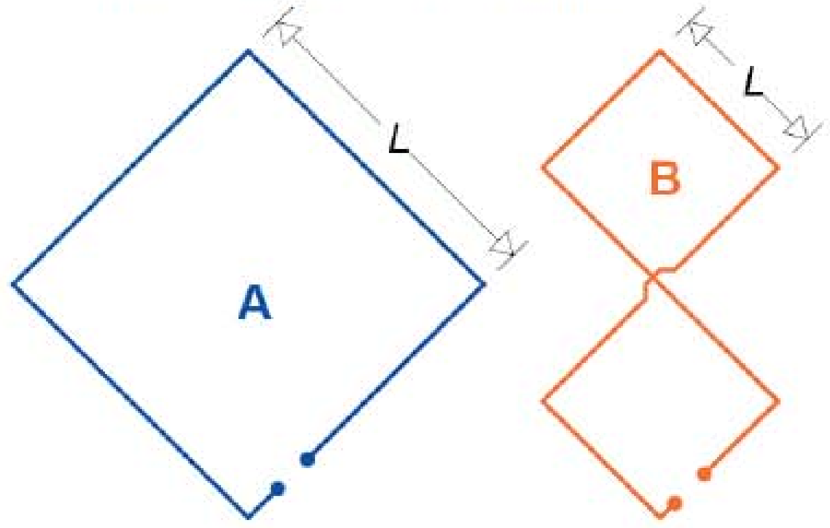

Figure 7: *Two popular loop configuration for MRS: A = 'square', B = 'square-8'*