THE ROLE OF THE MRS IN THE HYDROGEOLOGICAL RESEARCH

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HYDROGEOLOGICAL CONCEPTS AND HYDRODYNAMIC PARAMETERS APPLICABLE IN MRS

Classical geophysical methods are frequently used in subsurface water exploration. These methods are not water selective and ambiguous with respect to quantitative water content evaluation in subsurface. The new magnetic resonance sounding (MRS) technique is water selective and less ambiguous than classical methods (Lubczynski and Roy 2004). Therefore it is considered as the first in hydrogeophysics, fully quantitative method for groundwater assessment. The MRS survey is time consuming as compared to classical geophysical methods therefore it is not considered as a groundwater exploration tool (yet?) but rather as groundwater evaluation tool to define or confirm groundwater potential of the analyzed field and to describe that potential in the form of hydrogeological parameters. Such information has a great application in groundwater management.

The most straightforward use of MRS in hydrogeology refers to determination of the storage related parameters based on the measured MRS water content (Φ_{MRS}) derived from inversion of the initial signal amplitude. The storage parameterization is based on the assumption that the MRS water content is comparable with hydrological term called free water content (Φ_f). Based on this assumption the MRS can contribute to the evaluation of the following storage-related parameters: effective porosity, total porosity, specific yield, elastic storage, specific storage, specific drainage, specific retention and hydrostatic water column.

A depth-wise evaluation of water content only, is not always sufficient in judgment of groundwater potential as in the case of clayey deposits indicating high Φ_{MRS} but low groundwater potential. The other, signal relaxation-type of parameter called decay time constant (T_d) allows discriminating water-rich rocks with high water extractability (e.g. sands) from water-rich rocks but low water extractability (e.g. clays). The extractability of water described by T_d, has also its quantitative, although still empirical translation into hydrogeological parameter of hydraulic conductivity (K). The depth-wise aquifer integration of K, allows defining important hydrogeology parameter called aquifer transmissivity (T).

New developments in MRS technology, allow imaging not only saturated zone but also unsaturated zone. In that respect particularly useful is a multi-decay analysis that allows defining not only volumetric water contents but also water film thickness/droplet size constraining unsaturated water flow. The moisture content (definable with MRS) that is physically related with matric potential according to the soil-specific pF curves, constrains also unsaturated hydraulic conductivity parameter. This constrain contains memory effect (hysteresis), is dependent upon the soil composition and texture, and is described by various empirical and not always reliable non-linear relations.

In an unsaturated zone assessment, MRS can contribute not only to defining parameters, but also water fluxes such as recharge and groundwater evapotranspiration. The processes of vertical water movement leading to recharge or groundwater evapotranspiration are largely unknown in hydrology. This is because any disturbance of a soil e.g. by using invasive in situ methods, destructs measurements and also because the moving water changes its phase from liquid to vapor depending on a soil condition. The unsaturated water flux evaluation cannot be realized by standard, one-time MRS survey, but only through analyzing the complexity of vertical movement of infiltrating (within the access of root zone) and percolating (below the root zone) water using MRS in monitoring mode.

MRS AND THE USE OF GEOPHYSICS IN HYDROGEOLOGY

Geophysics can be applied to water searching, aquifers control, environmental and geotechnical water related questions, etc. For the study of geological structures (basin morphology, location of faults, etc.) and of the geometric parameters of aquifers and aquitards (depth, thickness, extension), all the surface geophysical methods can be used, whenever the proposed problem is related to a lateral or vertical contrast of some petrophysical property: density, electrical resistivity, dielectric constant, magnetic susceptibility, velocity of seismic waves, etc. The resistivity is the parameter most affected by porosity, permeability, water content, and water salinity of the rocks. For the evaluation of hydraulic and hydrodynamic parameters (porosity, permeability, velocity and direction of water flux, phreatic level, water quality, etc.), surface geophysical methods are very limited, and geophysical logging of boreholes is the most appropriate technique.

Plata (1999) shows that in about 57% of the hydrogeophysical surveys, the geoelectrical methods are used. Induced Polarization and Ground Radar occupies 10 %. Seismic, Gravity and Magnetic have a share of 30%. The remaining 3% refers to other methods (Spontaneous Potential, Thermometry, Remote Sensing), that, in spite of their little use, may be of a great importance as complementary methods. Normally, more than one method has to be used.

Magnetic Resonance Sounding (MRS) is changing the above scene. Though it is still a very young method to be part of statistics, it deserves special attention because of its singularity and novelty: it is the only method able to detect directly the presence of water in the subsurface, and as research is going ahead, it reveals its capacity to evaluate hydraulic parameters, being nowadays a real alternative to the use of boreholes in some circumstances.

BASIC THEORY OF THE MAGNETIC RESONANCE SOUNDING METHOD

MRS is a particular application of NMR (Nuclear Magnetic Resonance). When energy, in the form of a specific electromagnetic field, is sent to the subsurface, part of it is absorbed exclusively by the water molecules. When the excitation field is removed, the absorbed energy is released in the form of a new electromagnetic field, which can be detected by a receiver at the surface. This response can only be produced by the water, and has some identity characteristics. The physical phenomenon is due because atom particles, in the presence of the geomagnetic field B_0 can absorb energy E at only a certain (Larmor) frequency $\omega = \gamma B_0$, and at specific amounts, multiples of Planck´s constant (*h)*: $E = \omega h$. The constant γ is the gyromagnetic ratio of the atom particle. When the value of γ for hydrogen protons is selected to calculate the frequency of the excitation electromagnetic field, only these particles will be able to absorb the energy. As water is the most important component with hydrogen in the first few hundred meters of the subsurface, the released energy will come fundamentally from the water in the rocks. The signal induced in the receiver is expressed by (Trushkin et al.,1995)

$$E(t) = E_0 \sin(\omega t + \varphi)\, e^{-t/T_d} \text{ with } \quad E_0 = \int K(r,q)\, w(r)\, dv$$

where φ is the phase difference between the primary and secondary electromagnetic fields, T_d the decay rate of the signal, E_0 the maximum initial value and w(r) is the water content in the volume dv at the distance r. The Kernel function K(r,q) contains the information of the electromagnetic fields created, including the magnitude $q = I\,\tau$, named pulse amplitude or excitation moment (I is the intensity of the current used in the transmitter during a time τ to produce the excitation field), that controls the depth from where the signal comes. After these equations, E_0 for a given value of q is proportional to the amount of water. The decay time constant T_d correlates with the mean size of pores of the water saturated layers.

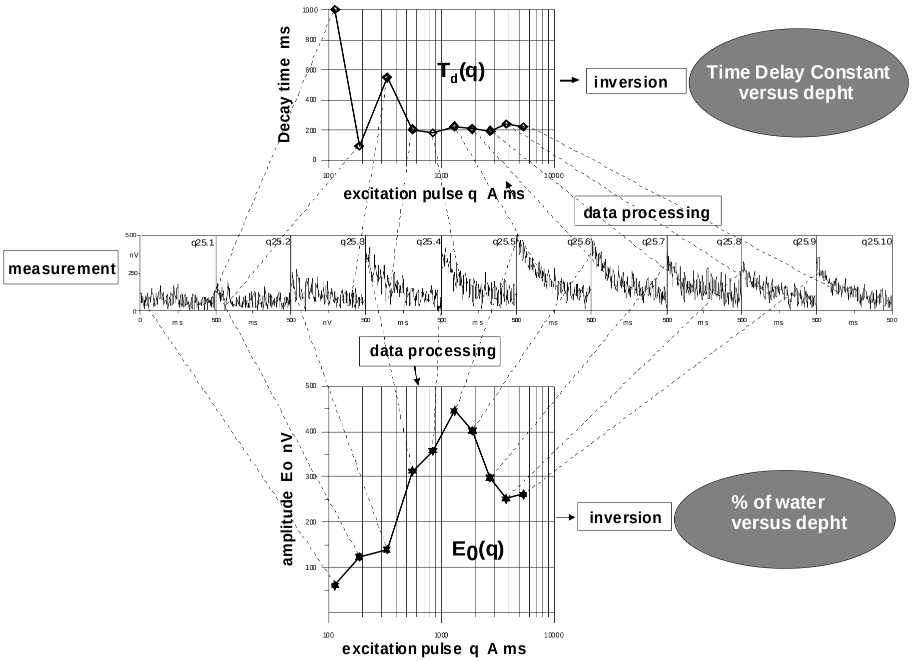

Figure 1. Scheme of the performance of a Magnetic Resonance Sounding (Plata and Rubio, 2001)

The diagram in Figure 1 shows the process of making a MRS. The measurement sequence is composed of the recording of several E(t) decay curves obtained from the increasing values of the excitation moment q. For each curve, the maximum value E_0 and the time constant T_d are calculated, forming the functions $E_0(q)$ and T_d (q). The inversion provides the distribution of the water content Φ_{MRS} and decay time constant with depth. The reliability of the solution found depends upon the simplifications and assumptions made in the theoretical model: homogeneity of the geomagnetic field, horizontal stratification, the influence of the conductivity and magnetic susceptibility of the rocks, and the effect of external electromagnetic noise (Legchenko et al. 1997; Legchenko, 2005).

USE OF MRS FOR HYDROGEOLOGICAL SYSTEM PARAMETERIZATION AND MODELING

Storage related parameters

Free water content (Φ_f) is defined as the percentage of water that is outside the field of molecular forces of attraction of solid particles that can be displaced by gravity or pressure gradients, as compared to the total rock volume. The principle of evaluating storage related parameters is in the proper definition of Φ_f from the MRS-measured water content (Φ_{MRS}), i.e. in the proper MRS determination of the boundary between free and bound water. That boundary determination is mineralogy dependent i.e. the assumption $\Phi_f \sim \Phi_{MRS}$ is reasonable for sandstones and quartz-rich clastics but is likely to be less accurate for carbonates. The inaccuracy of the $\Phi_f \sim \Phi_{MRS}$ assumption can cause problems in assessment of unsaturated zone but has less relevance in groundwater resources evaluation.

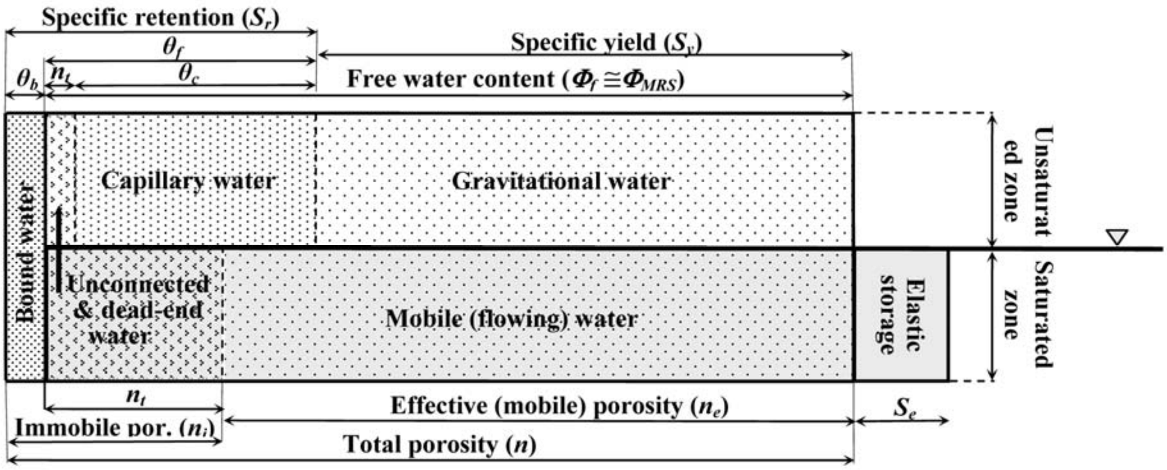

Figure 3. Aquifer storage concept (Lubczynski and Roy, 2005).

The concept of deriving hydrological storage-related parameters with MRS is introduced in the Figure 3. Parameters such as effective porosity, total porosity and hydrostatic water column can be derived directly from Φ_{MRS} inversion under assumptions that bound water and/or unconnected and dead-end porosity is negligible whereas the other parameters such as specific yield, elastic storage, specific storage, specific drainage, and specific retention require additional hydrological measurements (Lubczynski and Roy, 2003).

Hydraulic conductivity and aquifer transmissivity

Aquifers flow properties are introduced here following the terms of Darcy law (Freeze and Cherry, 1979). A distinction is made between hydraulic conductivity *K* as used in hydrogeology and permeability *k* as used in petrophysics and logging for petroleum. Both parameters, in the case of a permeable medium with cylinder cross section can be defined through the relationships: $Q/A = - K \bullet \Delta h/\Delta l$ and $Q/A = - k \bullet (\rho \bullet g/\mu) \bullet \Delta h/\Delta l$ where: Q is a constant flow rate, A is the cross section, Δh is the hydraulic head drop observed over the length Δl, the density ρ and viscosity μ are fluid properties while g is the earth's gravity acceleration. Based on the Poiseulle law for flow in a tube, simple models e.g. Kozeny-Carman, show that *k* is a function of porosity and pore radius and of some other variables e.g. specific surface, tortuosity, pore shape factor etc. NMR-derived information can supply diagnostic information in terms of pore-size, defined in NMR petrophysics as the ratio of pore-volume/pore-surface. Under such perspective, specific surface, tortuosity and shape factors are lumped together in a lithology-dependent constant while the pore-size is taken as an analogue of the pore radius leading to a *k* model where the main parameters are a lithology constant (proportionality factor) and NMR-estimated porosity and pore-size to the power 2.

MRS is acquired under earth's magnetic field condition i.e. with $f_l = \omega/2\pi \sim 1$ to 3 kHz while NMR laboratory instruments operates with $f_l \sim 0.2$ MHz to 1 GHz. Such large shift in operating frequency must be kept in mind when using NMR petrophysics results even if they were specifically acquired for MRS. Legtchenko et al. (2002) and Vouillamoz (2003) verified the relationship between NMR responses and hydraulic conductivity rather than permeability. In addition, Vouillamoz (2003) clearly showed two additional items: the lithology constant (broadly classified as granites, sands and chalk) and the influence of temperature on viscosity and therefore on flow property estimation. With respect to transmissivity (T), Legtchenko et al. (2004) provided a graphical comparison of MRS-determined T versus T estimated from pump tests. Once proper calibration becomes available for a given lithology in a given environment, no other applied geophysics technique comes that close to a 'virtual pump test'.

Aquifer geometry

Aquifer geometry includes the lateral coverage of the porous and permeable materials e.g. shape and position of significant boundaries and aquifer depth extent. The topic also includes interconnections between different units through partial barrier, open fracture, discontinuous aquiclude, buried channel etc., which currently, except for 2DMR (see below), are best mapped with complementary techniques (e.g. hydrogeological, surface geophysics, borehole geophysics).

In its classic configuration, MRS supplies depth-wise hydrostratigraphy. Sub-horizontal layering is assumed. Each MRS data set is inverted in terms of water-bearing layers characterized (Φ_{MRS} and T_d) as a function of depth while the distribution of these soundings' inversion over the area of interest, supplies area-wise information on aquifer properties. This defines the overall geometry of the aquifer with a spatial resolution much coarser area-wise than depth-wise due to practical limitations in the number of MRS stations. In practice, often aquifers have other contrasting geophysical properties with respect to neighboring aquitards so that a combination of geophysical techniques can be used with advantage. A significant development in the topic of aquifer geometry determination is 2DMR, two-dimensional magnetic resonance also termed MRT or magnetic resonance tomography e.g. Kirsch (2006). 2DMR brings both lateral and depth resolution through new levels where loops separation (excitation and detection loops) allow enhanced spatial discrimination. Currently 2DMR is possible at the cost of more work in the field and limitations in data inversion. Progress in terms of multi-channel hardware and 2DMR modeling software is expected to bring new capabilities in aquifer geometry definition.

Parameterization and flux evaluation in unsaturated zone

Hydrogeologists characterize the unsaturated zone through its matric potential ψ, its moisture content θ and its unsaturated hydraulic conductivity K_{unsat}. Except for methods exploiting permittivity contrast, e.g. GPR, few classical geophysical techniques can provide vadoze zone moisture content because of highly non-linear response e.g. seismic and resistivity; Archie law often fails in fresh water aquifers due to the surface conductivity of clay films on pore walls. However, MRS offers unique non-invasive insight into the unsaturated zone water storage and flow. According to wettability, unsaturated pores allow water flow partitioning between smaller, more saturated channels and larger less saturated ones. Water flow is a function of water film continuity and water film thickness. Contrary to the saturated case, below a critical moisture content, hydraulic conductivity is higher in small pores than in larger ones. In severe case of poor wettability, water will form isolated droplets instead of continuous films and only vapor diffusion will contribute to water flow. Through NMR signal decay time constant analysis, distinction is possible between cases of thin or thick water films and isolated droplets. Thus, MRS can supply moisture content through signal amplitude inversion and film thickness/droplet size discrimination through decay time analysis. Through empirical calibrations, these two items of information are related to matric potential and unsaturated hydraulic conductivity.

At the conceptual level, MRS unsaturated flux evaluation is done through discrete recharge and/or evaporation events. Through time-lapse series of MRS measurements, rain events are followed through downward infiltration contributing to recharge or in the opposite way, through upward mass water movement and its loss through evaporation.

MRS contribution to groundwater modeling

Groundwater resources are nowadays evaluated and managed using numerical distributed models. Such models, regardless their complexity, dimension, importance and type of code used, require spatially variable parameters and spatio-temporally variable input fluxes. In standard model solutions, as a role of thumb groundwater fluxes are assigned as spatially variable but temporally invariant data input and only sometimes, in most sophisticated models, as spatio-temporally variable input fluxes.

So far model parameters are obtained in hydrology either by site specific soil sampling or by pumping tests. Fluxes are typically determined by logger-based, automated sensor monitoring (e.g. recharge). The standard parametric and flux measurements are however expensive and largely affected by heterogeneity problem, not only in the regional scale but also in the local scale comparable with the MRS loop size of ~100x100m. MRS can make large contribution in that respect, improving input data quality for groundwater models. In contrast to small scale hydrological measurements and comparably to expensive pumping test investigations, MRS can investigate large volumes of subsurface (up to 10^6 m^3) according to the size of the expanded loop. In such investigations, MRS provides volumetric averaging, that is particularly applicable in cases of heterogeneous and anisotropic systems, allowing for relatively easy definition of parameters for the model cells corresponding with the MRS survey location. Unfortunately, accurate one-to-one correspondence between the MRS loop position and the analyzed model grid cell cannot be explicitly made yet.

MRS provides various types of model data input. Thanks to the ability of depth-wise water content interpretation, MRS can define subsurface hydrostratigraphic units including vertical aquifer boundaries and storage parameters. The interpretation of decay time constant allows assigning model transmissivities. Current, survey-based MRS applications do not allow determining groundwater fluxes. This however can be done in the monitoring mode requiring continuous scanning of the unsaturated zone at the selected, MRS-investigated location. The unsaturated zone parameterization, if successful and reliable, can facilitate the use of the saturated-unsaturated zone models such as for example HYDRUS (Rassam et al. 2003).

REFERENCES

Freeze, R.A. and Cherry, J.A., 1979, Groundwater; Prentice Hall, Englewood Cliffs, N.J., 604 p.

Kirsch, R. (ed), 2006, Groundwater geophysics – A tool for hydrogeology; Springer, 493 p.

Legtchenko, A., Baltassat, J.M., Beauce, A. and Bernard, J., 2002, Nuclear magnetic resonance as a geophysical tool for hydrogeologists; Journal of Applied Geophysics, **50**, 21-46.

Legtchenko A.,Baltassat, J.M.,Bobachev,A.,Martin,C.,Robain,H. and Vouillamoz,J.M., 2004, Magnetic Resonance Sounding applied to aquifer characterization; Ground Water, **42**, 363-373.

Legchenko A., Beauce A., Guillen A., Valla P. and Bernard J. 1997. Natural variations in the magnetic resonance signal used in PMR groundwater prospecting from the surface. European Journal of Environmental and Engineering Geophysics. 2, 173-190.

Legchenko A. 2005. Improved modelling of the magnetic resonance signal in the presence of shallow aquifers. Near Surface Geophysics vol. 3. n3 121-130.

Lubczynski, M.W. and Roy J., 2003. Hydrogeological interpretation and potential of the new magnetic resonance sounding (MRS) method. Journal of Hydrology 283/1-4, 19-40.

Lubczynski, M.W. and Roy J., 2004. Magnetic resonance sounding: new method for ground water assessment. Ground Water 42 (2), 291-303.

Lubczynski, M.W. and Roy J., 2005. MRS contribution to hydrogeological system parameterization. Near Surface Geophysicas 3, 131-139.

Plata, J.L. 1999. Técnicas convencionales de Geofísica de superficie aplicadas en hidrogeología. Actualidad de las técnicas Geofísicas aplicadas en Hidrogeología. Granada. 1999. IGME. 21-32

Plata, J.L. and Rubio, F.M. 2001. Condiciones para la utilización de los Sondeos de Resonancia Magnética (SRM) en la prospección y gestión de las aguas subterráneas. Congreso Internacional Las Caras del Agua. Libro de Comunicaciones tomo II, 807-813

Rassam, D., Simunek J., and Van Genuchten M.Th. 2003. Modelling Variably Saturated Flow with HYDRUS-2D. ISBN 0-646-42309-6, Australia.

Trushkin D.V., Shushakov O.A. and Legchenko A.V. 1995. Surface NMR applied to an electroconductive medium. Geophysical Prospecting 43, 623-633

Vouillamoz, J.M., 2003, La caractérisation des aquifères par une méthode non-invasive: les sondages par résonance magnétique proton; Thèse de L'Université de Paris XI.