Magnetic Resonance Soundings

INTRODUCTION

The proton Magnetic Resonance Sounding (MRS) method for groundwater investigation was developed in Russia in the early eighties by a team of Russian scientists who then built the first MRS equipment named HYDROSCOPE (Semenov, 1987; Semenov et al., 1987, 1988). The starting point of their research programme was the Varian patent (Varian, 1962), which proposes the use of Nuclear Magnetic Resonance (NMR) for the non-invasive detection of proton-containing liquids (hydrocarbons or water) in the subsurface. Since 1996, when the MRS equipment NUMIS became commercially available through IRIS Instruments, an interest has developed in the international scientific community to learn more about this method.

The vertical distribution of water content provided by MRS reveals the depth and thickness of aquifers. Recent results show that by combining MRS data with experience gained through NMR logging it is also possible to estimate the effective porosity and permeability of aquifers. Accuracy of the estimation depends on the empirical relationships between the amplitude and relaxation time of the magnetic resonance signal and the hydrodynamic characteristics of the aquifer. Different empirical estimators exist based on laboratory and borehole measurements. However, as permeability is a scale-dependent parameter, and because the MRS provides data averaged over a large volume, the MRS results should be compared with both laboratory measurements and borehole pumping test data.

The basic principles of the MRS method are presented and, based on numerical modeling and field examples, we demonstrate the performance that users can expect from this technique.

NUCLEAR MAGNETIC RESONANCE

Nuclear magnetic resonance, a phenomenon that can be observed in nuclei possessing a magnetic moment (Slichter, 1990), was discovered by Bloch and Purcell in 1946. The nuclei are generally in equilibrium with the environment, and are able to absorb and transmit electromagnetic energy at a specific frequency called the Larmor frequency \( f_0 = \gamma H_0 / 2\pi \).

\( H_0 \) is the magnitude of the static magnetic field and \( \gamma \) is the gyromagnetic ratio. \( \gamma \) has a specific value for each type of nucleus, and hence the Larmor frequency is a physical property.
of the nuclei. By selecting the Larmor frequency, one can decide which nuclei will be investigated, thus rendering the NMR method selective.

In the classical model, nuclei are represented as macroscopic magnetic moments \( M \). A typical magnetic resonance experiment consists of three phases (Figure 1).

![Typical phases of a magnetic resonance experiment](image)

**Typical phases of a magnetic resonance experiment**

1) **Undisturbed state**

2) **Pulse transmission**

3) **Signal measurement**

**Corresponding magnetic resonance measurement**

- Ambient electromagnetic noise
- Pulse of oscillating current
- Received signal

\[ e(t) = E_0 \exp(-t/T_2^*) \cos(2\pi f_0 t + \varphi_0). \]

(1)

**Fig. 1. Typical phases of a magnetic resonance experiment.**

In the natural undisturbed state (equilibrium), all magnetic moments \( M \) are oriented according to the static magnetic field \( H_0 \) and nuclei are able to absorb electromagnetic energy at the Larmor frequency. When an external electromagnetic field is applied to the sample, the magnetic moments precess from their equilibrium. When this field is terminated, they return to their initial position and generate a magnetic field, which is also oscillating at the Larmor frequency. This field can be measured and then analysed. For data acquisition, an oscillating current pulse at the Larmor frequency is fed into the transmitting coil. The magnetic resonance response

\[ e(t) = E_0 \exp(-t/T_2^*) \cos(2\pi f_0 t + \varphi_0). \]

(1)
is recorded at the same frequency after the pulse is terminated. A typical example of data acquisition is presented in the lower part of Figure 1. Ambient electromagnetic noise is recorded over a few hundreds of milliseconds before the external pulse is transmitted. After an instrument delay known as "dead time", the magnetic resonance signal is measured. The records before and after the pulse are compared to determine whether a magnetic resonance response is detected or not. As noise is independent of the transmitted pulse, a stacking procedure is used to improve the signal to noise ratio (S/N).

Amplitude of the magnetic resonance response is proportional to the volume of sample investigated and to the square of the static magnetic field $E_0 \sim H_0^2 V$. Thus, the static magnetic field and/or the volume of sample can be increased so as to increase the signal to noise ratio.

Generally, NMR equipment can be classified according to the volume of investigated sample (Figure 2).

![Classification of NMR equipment by volume of investigated sample.](image)

Chemical NMR spectrometers and Magnetic Resonance Imaging (MRI) instruments used in medicine, which offer a very high spatial resolution and are commonly used in laboratories, operate on a broad artificial static magnetic field and a small sample volume (mm$^3$). Much larger sample volumes (a few cm$^3$) and smaller artificial static magnetic field are used in borehole geophysics (e.g. the Schlumberger and NUMAR tools), whereas surface NMR equipment (such as HYDROSCOPE and NUMIS) operates on the geomagnetic field and sample volumes of a few thousand m$^3$. 
THE PROTON MAGNETIC RESONANCE SOUNDING METHOD

A comparison between the MRS tool and the well-known proton magnetometer is shown in Figure 3.

Fig. 3. The MRS tool and a proton magnetometer.

The acquisition coil of the MRS tool is larger than that of the magnetometer and forms a circular (or square) wire loop that is laid down on the surface. Subsurface water-saturated layers represent the investigated sample. The natural geomagnetic field is used as the static magnetic field that defines the Larmor frequency for protons (between 800 and 2800 Hz around the world). Since only protons in groundwater can generate a magnetic resonance signal at this frequency (for the first 100-200 m), MRS is in reality a direct method for groundwater detection from the surface.

Three parameters of the magnetic resonance signal (Equation 1) are measured after the “dead time” delay $\tau_{\text{dead}}$: amplitude $E_{0d}$; relaxation time $T_2^*$ and phase $\varphi_{0d}$. The initial amplitude of the signal $E_0$ depends on the number of protons and hence on the quantity of
water. It is obtained by extrapolation using the measured amplitude $E_{0d}$ and the relaxation time $T_2^*$ as

$$E_0 = E_{0d} \exp \left( \tau_{\text{dead}} / T_2^* \right).$$

(2)

The initial amplitude $E_0$ is a function of the pulse parameter $q = I_0 \tau$, where $I_0$ and $\tau$ are respectively the pulse amplitude and duration, and the sounding consists in measuring $E_{0d}$, $T_2^*$, and $\varphi_{0d}$ whilst varying the pulse parameter $q$.

The phase $\varphi_{0d}$ correlates with the electrical conductivity of the rocks, but it is not currently used for MRS data interpretation.

**MRS water content**

In the MRS method, the water content in layer $i$ is defined as

$$w_i = \frac{E_{0i,\text{meas}}}{E_{0i,\text{ref}}},$$

(3)

where $E_{0i,\text{meas}}$ is the measured amplitude of the magnetic resonance signal from a horizontal, infinite, water-saturated layer with a thickness $\Delta z_i$ and at a depth $z_i$, and $E_{0i,\text{ref}}$ is a theoretical signal calculated assuming that the same layer $(z_i, \Delta z_i)$ is filled with 100% of water. However, this definition does not take into consideration relaxation effects that may make the signal shorter than the MRS equipment is able to detect in certain parts of the investigated volume. For the layer $(z_i, \Delta z_i)$ with an investigated volume $V$, let $V_w$ be the part of the layer filled with water, and $V_R$ be the part occupied by rock ($V = V_w + V_R$). The water volume $V_w$ can be divided into two parts, namely water in pores (between grains) known as "free water" that can be extracted ($V_{\text{free}}$), and water attached to grains known as "bound water" that cannot be extracted ($V_{\text{bound}}$), thus $V_w = V_{\text{free}} + V_{\text{bound}}$. Because of the small distances involved, interactions between grain surfaces and protons of “bound water” mean that the relaxation time of the magnetic resonance signal from “bound water” is less
than that from “free water”. Since the very short signals from bound water cannot be measured by currently available equipment, the water content measured by MRS can be defined as the part of the total volume of the subsurface occupied by free water:

$$w = C_w \frac{V_{free}}{V}. \quad (4)$$

As no direct relationship exists between the mobility of water in the aquifer and relaxation time of the magnetic resonance signal used in MRS to discriminate between bound and free water, a calibration constant $C_w$ is needed that establishes an empirical relationship between these two parameters for different rocks. When calibration is possible, water content can be considered as an estimate of effective porosity, for example, $w=0\%$ for dry material and $w=100\%$ for bulk water in a lake.

In order to establish a quantitative correspondence between the water content derived from MRS data and the effective porosity used in hydrogeology a further research is required.

**Permeability estimation using magnetic resonance measurements**

In NMR logging, $T_1$ and $T_2$ relaxation times are important for analyzing the hydrodynamic properties of geological formations. Although there is a difference between these two parameters, both are used in the analysis, and typically $T_1 \approx 1.5T_2$. $T_1$ and $T_2$ are related to pore size by

$$T_{1(2)} \sim \frac{V_p}{S_p}, \quad (5)$$

where $V_p$ and $S_p$ are the volume and surface area of the pore respectively (Kenyon, 1997).

Since geological formations with the same mean pore size estimated by magnetic resonance may have very different permeability, the estimation of permeability is more reliable when borehole pumping test results are available for calibration of the MRS data.

In NMR logging, permeability estimation is based on the form (Kenyon, 1997)

$$k = C_p \phi_{NMR}^a T_{1(2)}^b, \quad (6)$$

where $\phi_{NMR}$ is the porosity estimated by NMR, $T_{1(2)}$ is $T_1$ or $T_2$ relaxation time, and $C_p$ is an empirical pre-factor. In our study, we compare the estimation form with $a=1; b=2$
introduced by Seevers (1966), and the estimator with $a=4; b=2$ that reportedly gives better results for sandstones (Kenyon et al., 1988). We also replace $T_{1(2)}$ by $T_2^*$ provided by NUMIS equipment.

Scale effect

The permeability of geological formations is scale dependent. Since the samples investigated during laboratory, borehole NMR, and MRS experiments vary considerably in scale (Figure 2), the results obtained with one method cannot be immediately extended to another.

An example of two different types of aquifer is presented in Figure 4.

![Type A](image1)

![Type B](image2)

*Fig. 4. The permeability of aquifers: type A – single porosity; type B – double porosity.*
In aquifers with single porosity (type A), the water is located in similar pores and permeability is thus related to pore size. In this case, information concerning the aquifer derived from magnetic resonance measurements is also related to permeability, even when the investigated samples are of different volumes.

In aquifers with double porosity (type B), however, most of the water is located in large pores, but permeability mostly depends on small pores. In this case, when the volume of investigated sample is small, permeability estimation will depend on whether the selected sample mainly represents small or large pores. A large-scale method such as MRS will provide information mostly related to large pores because they contain a larger quantity of water than small pores. Since large pores do not have a major influence on the permeability of the aquifer, the MRS estimation of the permeability might be erroneous.

These two extreme cases demonstrate the limitations of permeability estimation based on magnetic resonance measurements. In practice, different types of porosity usually co-exist, and the measured magnetic resonance signal is commonly multi-exponential and thus provides information concerning different pores.

Conclusions

The proton Magnetic Resonance Sounding method is a geophysical tool that provides information concerning groundwater distribution in the subsurface. While other geophysical methods are able to detect inhomogeneities in the physical properties of rocks, the magnetic resonance signal that is generated by groundwater molecules can be used for the estimation of the quantity of water in the subsurface and of the hydrodynamic characteristics of aquifers.

MRS is a site-dependent method. The geomagnetic field and the electrical conductivity of the subsurface are major factors that influence the performance of the method. For example, where the resistivity of the subsurface is larger than 50 ohm-m, groundwater can be detected down to more than 150 m in areas with a high geomagnetic field and only down to about 100 m in areas with a low geomagnetic field. Electrically conductive rocks attenuate the magnetic resonance signal and thus diminish the maximum depth of investigation down to 40-50 m.

The water content and the relaxation times $T_1$ and $T_2^*$ measured by MRS equipment can be used to estimate permeability, transmissivity and specific yield when calibration is possible using data from a borehole drilled in the same formation. The best form for permeability estimation was found to be $k \sim w T_1^2 \chi$, where $w$ is water content and $T_1^\chi$ is $T_1$ or $T_2^\chi$ relaxation
time. Since \( T_2^* \) is sensitive to the magnetic properties of rocks, \( T_1 \) should be a more reliable parameter. Preliminary results confirm this theoretical expectation, but as \( T_1 \) measurement is more time and energy consuming, we do not have sufficient experience as yet to draw a definitive conclusion.

MRS is a large-scale method. Since it provides results averaged over the entire loop area, it may not be sufficiently accurate for detecting small targets (for example a single fracture). It is, however, effective for estimating water resources and for mapping the average hydrodynamic properties of an investigated area when some calibration with boreholes is possible.

**References**


