LINKS BETWEEN MRS AND THE PARAMETERS USED BY THE HYDROGEOLOGISTS: A METHODOLOGICAL APPROACH FOR THE QUANTITATIVE HYDROGEOLOGICAL CALIBRATION OF MRS MEASUREMENTS

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INTRODUCTION

A comprehensive interdisciplinary (geophysical, geological, and hydrogeological) study performed by BRGM was aimed at developing an optimal methodology for applying magnetic resonance soundings (MRS) to hydrogeological studies, and making this new geophysical method more accessible to the hydrogeological community (Lachassagne *et al.* 2003).

For hydrogeological purposes, three parameters derived from MRS data are useful: the MRS water content (*w*), the relaxation times (T_2* and T_1), and the geometry of 'detected aquifers' (depth intervals or 'layers' to which this couple of parameters is applicable: z location of top and bottom).

Being products of inversion of MRS measurements, these parameters require a certain calibration before they can be used by hydrogeologists.

POROSITY - STORATIVITY

In the saturated zone of an aquifer, ***w*** is related to the **effective porosity** [%] and quantifies the amount of water stored within. Effective porosity is always less than total porosity, the difference between the two being mainly linked to the pore size distribution.

In *unconfined aquifers* only (Figure 1), ***w*** also characterizes the **storativity** or **storage coefficient** of the aquifer, in which case, storativity is equal to effective porosity. In *confined* aquifers (Figure 1), storativity is mainly linked to the compressibility of both the aquifer and water; therefore w does not characterize the storativity of the aquifer. Depending on the rock type, MRS

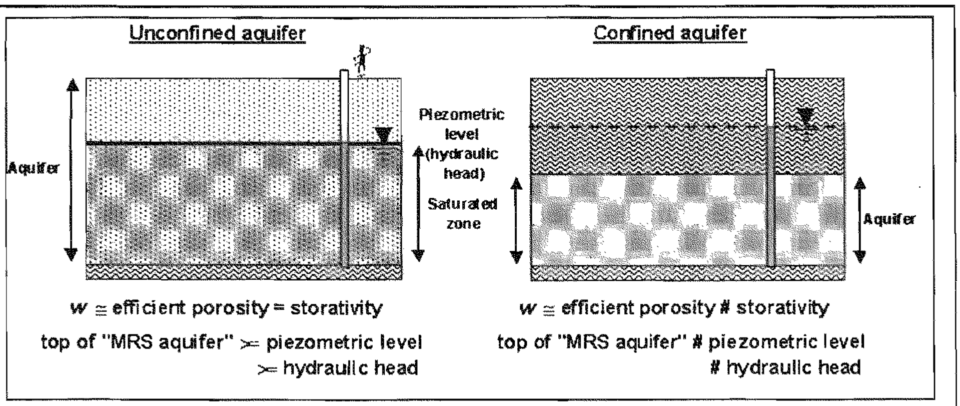

Figure 1

measurements may (i) overestimate the effective porosity by integrating both free and, partly, fixed water; or (ii) underestimate the effective porosity if loosing fixed and, partly, free water. These uncertainties can be corrected by calibrations carried out for each geological formation.

Nevertheless, even if the theoretical reasons for this are not yet clearly understood, the experience of numerous MRS measurements shows that, in most cases [porous (Legchenko et al. 2002), karstic, hard-rock (Wyns et al. 2003) aquifers], the difference between measured w and effective porosity is less than the uncertainty on this last parameter (or the lack of numerous porosity data, if not a total lack of data). The MRS tendency to overestimate effective porosity seems particularly important in chalk aquifers.

Thus, as effective porosity is a relatively expensive parameter to acquire at field scale (requiring at least a pumping test with two boreholes – a well and a piezometer - or tracer tests), MRS appears to be a very valuable method to hydrogeologists, particularly when dealing with pollutant transport problems.

HYDRAULIC HEAD

In unconfined aquifers, MRS measurements can provide data on the hydraulic head [m] within the aquifer, as the piezometric level merges with the top of the saturated zone of the aquifer (Figure 1), which is detected by MRS.

However, the MRS technique also measures signals from water in the capillary fringe within the aquifer and can thus underestimate the depth of the piezometric level. Capillary fringes can be particularly thick (over one meter) in porous fine-grained aquifers (in chalk for instance, the thickness of the capillary fringe can reach several meters within the matrix of the aquifer). In addition, some small perched aquifers, not measured with the commonly available piezometers, but that can be detected by careful observations during drilling for example, can be characterized through MRS measurements, providing their size is sufficient compared to that of the MRS antenna loop.

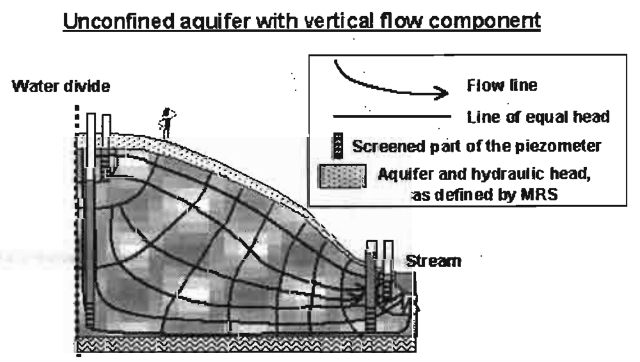

Figure 2

In the case where groundwater shows a significant vertical flow component (Figure 2), the water level measured in a well can vary considerably (from a few centimeters to decimeters, and locally a few meters) from the depthn of the top of the saturated zone of the aquifer, depending on the vertical hydraulic gradient, but also on the depth and length of the piezometer's screen. Thus, the piezometric level as deduced from MRS measurements is equal to the hydraulic head that would be measured at the top of the aquifer.

In *confined aquifers*, MRS measurements cannot provide information on the hydraulic head. The increase in water content measured by the MRS log corresponds only to water-saturated rocks. For example, in the case where a sandy aquifer overlain by clay is located at a depth of between 20 and 30 m and the piezometric level is at 5 m, then MRS will only locate the aquifer's top and bottom, between 20 and 30 m. Therefore, MRS does not measure any characteristics related to piezometric level or hydraulic head.

GEOMETRY OF THE AQUIFER

Beyond the above limitations, both in *confined and unconfined aquifers*, the **top and the bottom of the aquifer**, and thus its **thickness** (Figure 1, Figure 2), can be determined though MRS measurements.

As the vertical resolution of MRS is limited, available inversion software provides a better accuracy for the shallowest aquifer than for multi-aquifer systems, as deeper aquifers can be partly masked by shallower water-saturated layers.

HYDRAULIC CONDUCTIVITY

The **hydraulic conductivity** (or permeability) [m/s] is a vectorial parameter that not only relies on the physical properties of the medium (anisotropy, heterogeneity, etc.), but also on flow direction, the scale of the measurement (depending on the duration of a pumping test for example), etc. This parameter is highly variable and ranges over several orders of magnitude.

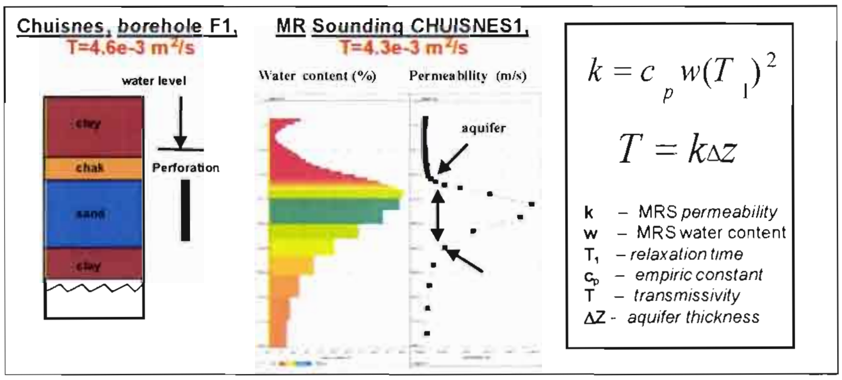

Figure 3

The volume investigated by MRS (generally a cylinder 100 m in diameter, 100 m in depth) is similar to that investigated by pumping tests, the most common method used by hydrogeologists to evaluate the hydraulic conductivity of an aquifer. Following the example of NMR logging, attempts are thus made to find a correlation between a combination of the MRS parameters (water content and relaxation time, with some constants and exponents to be adjusted in the formula), and the hydraulic conductivity (or the transmissivity: integration of the permeability on the thickness of the aquifer), as deduced from pumping tests (Figure 3). The interpretation of NMR geophysical borehole logging also relies on such a search for a correlation. This approach is consistent with the results of the considerable efforts made over previous decades (supported by the petroleum industry in particular), which have shown that only empirical links, to be assessed and calibrated for each kind of geological formation, can be established between porosity (or pore size distribution) and hydraulic conductivity.

Thus, this search for adjustments between pumping test results and MRS parameters seems to be highly promising, even if convincing results are not assured considering the conceptual difficulties involved. In addition to the attention that must be paid to the MRS data inversion (see also below), the hydrogeological data also require a great deal of care if this search is to prove successful. The direct use of permeability/transmissivity values from the literature can lead to important bias. For existing data, it practically imposes the systematic re-interpretation of the pumping tests in order to i) check the adequacy between the scale of the MRS measurement and the volume investigated by the pumping test (and thus choose the part of the pumping test curve to be considered), ii) check the validity of the required hypothesis (type of porosity, homogeneity, isotropy, location and thickness of the well screen in the aquifer, etc.), and iii) build a realistic conceptual geological and hydrogeological model of the studied site. As MRS measurements provide discretized data along the Z axis, it is also very important to acquire geological and hydrogeological data allowing assessment of the vertical distribution of the hydrodynamic parameters.

IMPORTANCE OF THE CALIBRATION PROCESS

As with most geophysical methods, MRS is submitted to the principle of equivalence. The interpretation of an MRS measurement thus requires the simultaneous analysis of all the MRS parameters (water content, relaxation time, thickness of the different layers, etc.). In the quest for hydrogeological parameters and data from MRS measurements, the calibration process is very important. The knowledge of one parameter, or even better two, makes it possible to determine with a much higher accuracy the third, or the second and third, parameters.

Thus, the MRS inversion process must comprise at least the following three steps:

1. (automatic) inversion of the data,
2. calibration of MRS parameters, on the basis of existing data when available, or on the experience of the team of geologists - hydrogeologists - geophysicists. The easiest parameter to be used for calibration is generally the thickness of the various 'layers',
3. estimation of the hydrodynamic parameters (effective porosity, permeability, transmissivity) on the basis of empirical relationships linking them with the MRS parameters, established for the studied site or similar hydrogeological contexts.

These three steps can include certain iterative procedures. For instance, step 2 would allow the precise identification of the depth of the top of a confined aquifer, or the piezometric level in an unconfined one, whereas step 1 would only provide a progressive variation along Z of the medium properties.

CONCLUSION

The MRS method is already able to provide pertinent data to the hydrogeologist, including:

- the direct detection, with a few ambiguities, of the presence of water in the subsurface; this is the basic and decisive advantage of this method, which could thus prove extremely useful, particularly in arid to semi-arid environments,
- the location of saturated formations (top and bottom), situated at depths between 0 and 100 m,
- the evaluation of hydrodynamical parameters of detected aquifers when calibration is available; otherwise, aquifers can be compared qualitatively.

Thus the MRS method provides data that cannot be obtained through other non-invasive geophysical tools. In addition, it is well adapted to the working scale of the hydrogeologist (field scale, well scale).

Through a rigorous inversion and calibration process, the MRS method also enables the quantification of the effective porosity of aquifers. In the present state-of-the–art, MRS only allows the evaluation of aquifer permeability under localized favorable configurations.

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MRS

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