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MRS characterisation of a mountain hard rock aquifer: the Strengbach Catchment, Vosges Massif, France

Marie BOUCHER
IRD, LTHE
08BP841, Cotonou, Benin
marie.boucher@ird.fr

Marie-Claire PIERRET
University of Strasbourg, LHyGES
1, rue Blessig, 67084 Strasbourg, France
marie-claire.pierret@unistra.fr

Marc DUMONT
CNRS, LTHE
BP53, 38041, Grenoble, France
dumont.mrc@gmail.com

Daniel VIVILLE
CNRS, LHyGES
1, rue Blessig, 67084 Strasbourg, France
dviville@unistra.fr

Anatoly LEGCHENKO
IRD, LTHE
BP53, 38041, Grenoble, France
anatoly.legchenko@ujf-grenoble.fr

Antoine CHEVALIER
Joseph Fourier University, LTHE
BP53, 38041, Grenoble, France
chevaliera@laposte.net

Sebastien PENZ
BRGM
BP36009, 45060 Orleans, France
sebastien.penz@gmail.com

SUMMARY

The study of mountainous crystalline aquifers is a scientific challenge due to their complexity and is an important issue for the water resources in a context of changes in precipitation regime. The small Strengbach catchment (0.8 km2) was densely investigated with MRS (23 sites). Our results allowed constructing a conceptual model of hydrogeological functioning that will aid to better resolve the hydrological balance at the catchment scale. The approach we used here can be applied to other small complex hydrological systems.

From a methodological geophysical point of view, we tested both FID (free induction decay) and SE (spin echo) sequences. FID measurements seem more suited to the study site, but is slightly perturbed in the northern part of the area where geology differs from south.

Key words: basement aquifer, groundwater functioning, MRS methodology.

INTRODUCTION

Understanding how the environment reacts to anthropogenic or natural disturbances is one of the major future societal and scientific challenges in the field of natural resource management and conservation. One perturbation related to climate change will be the change of precipitation regime (with more frequent and more intense drought and flood), which can impact various components of hydrological cycle (water storage dynamic and capacity, infiltration rate…). This response is of great importance for the availability and quality of drink water in mountainous regions.

But for these natural systems the hydrological functioning is still poorly understood, especially in crystalline environments where the aquifer can be fractured with complexity. In that case it's difficult to have good approximations of water content and porosity of soils or bedrocks. MRS can then be a great tool to characterize these parameters.

This study was conducted in the Strengbach watershed (France, Vosges Massif) where 4 MRS campaigns were realized. Previous recent paper proposed that different and independent water pathways in the Strengbach fractured granite system control the different geochemical and isotopic signatures of the waters (Pierret et al., 2014). The aim of this study was to identify the groundwater resource and to characterize their hydrodynamic parameters.

STUDY SITE

The Strengbach catchment is a small granitic watershed (80ha) where hydrological and geochemical data are recorded since 1986 (Observatoire Hydro-Géochimique de l'Environnement; http://ohge.u-strasbg.fr). It is situated in the North East of France in the Vosges Mountain with elevation between 880 and 1150 m omsl and with highly incised side slopes (mean 15°). The bedrock is mainly composed of Hercynian Ca-poor granite which was subjected to various intensities of hydrothermal alteration. The soils are brown acidic to ochreous podzolic series and are generally about 1 meter thickness. The forest covers 90% of the area. The climate is temperate oceanic mountainous (mean annual temperature of 6°C; mean monthly temperature range from –2 to 14°C; OHGE data) with an average rainfall of 1370 mm/yr (the snowfall 2-4 month/yr), ranging from 896 to 1713 mm/yr over the period 1986-2011 (OHGE data). The mean annual runoff for the corresponding period is 760 mm (24.5 $ls^{-1}km^{-2}$) with variations ranging from 494 to 1132 mm/yr (Viville et al., 2012, OHGE data).

MRS SET-UP

Data acquisition

Four MRS campaigns were carried out according the schedule shown in table 1. A total of 56 soundings were performed on 23 sites. For the 3 first campaigns we used Numis Plus device from Iris Instruments and for the last field trip, we used both Numis Plus and Numis Lite devices. Data were acquired with Num run software.

Date	Objectives	Number of soundings
Oct. 2011	Feasibility study	6
Apr. 2013	Intensive mapping	17
May 2013	Intensive mapping	15
May 2014	Accurate estimate of decay time	18

Table 1. Schedule of fieldworks.

The main encountered difficulty was the low signal due to low water content in the investigated geological context. Similar issue was already observed in a neighboring small catchment (Baltassat et al. 2005). The main identified source of electromagnetic noise is a radio antenna located on the northern border of the Strengbach catchment. Several loop arrays were tested: large simple square, square with compensation loop, eight-shape loop. Finally, the best solution for improving signal-to-noise ratio (S/N) was the eight-shape loop with two squares of 37.5 or 40 m sides depending on the available cables. Soundings were performed with high number of stacks (220 to 400) in order to decrease the noise down to a level close to the instrumental noise. Thus, we obtained data of good quality: the EN/IN ratio (external noise to internal noise) was most often lower than 1.5. However due to low signal only third of soundings had S/N > 2.

Suspicion of magnetic rocks led us to conduct surveys with both the standard FID (free induction decay) sequences and SE (Spin Echo) sequences (Legchenko et al. 2010). In the end, no SE signal was recorded in the southern part of the catchment. In northern part where the geology is different, SE signal seems mixed with the FID signal.

Data processing and method of interpretation

MRS data were inversed with samovar software (version 11) using a smooth model (40 layers with automatic regularization). A typical example of inversion result is shown in Figure 1. Previous works in basement aquifers (e.g. Vouillamoz et al. 2014) showed that MRS is poorly sensitive to the water in fissured zone and the MRS signal mainly comes from the weathered zone. Consequently, the bottom of the layer where MRS water content is detected was interpreted as the transition depth between weathered and fissured zones. This depth was evaluated on the whole study area.

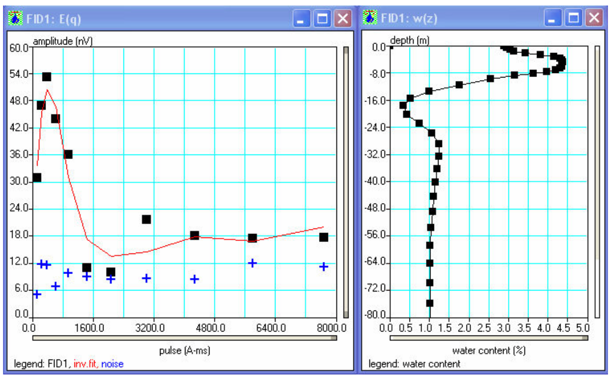

Figure 1. Typical example of MRS results in the study area. (Sounding 5)

From MRS inversions, we directly deducted the volume of free water in m^3/m^2 on each investigated site. Samovar software also allowed computing the uncertainty on this volume. The transmissivity (T_{MRS}) was estimated with the usual empirical equation:

$$T_{MRS} = Cp \cdot \int_z \theta_{MRS} \cdot (Ti)^2 \cdot dz$$

where Cp is a parametric factor, θ_{MRS} is the MRS water content, Ti is the decay time (T1, T2 or T2*), z is the depth. As we were not able to accurately measured T1 and T2 on each site, we decided to used T2* despite probable magnetic effect. As no pumping test was available on the study area, we chose to use the Cp value calculated by Vouillamoz et al. 2014 in another hard rock aquifer, i.e. 3.10^{-3} $m.s^{-3}$ which is in the range of previous published values for hard rock aquifers. Because of the use of T2* and an arbitrary Cp value, the transmissivity calculated in this study only brings a qualitative information and should not be taken as an absolute value.

RESULTS

Mapping of hydrodynamic parameters

The bottom of the weathered zone where water is detected by MRS is rather shallow (< 15 m), except near the spring of the Strengbach river where it reaches ~20 m deep. The MRS water content is low (< 6%). Thus the total volume of free groundwater is low in average which is consistent with the geological context. Both this volume of water and the MRS transmissivity show heterogeneities at the scale of the study area (Fig 2).

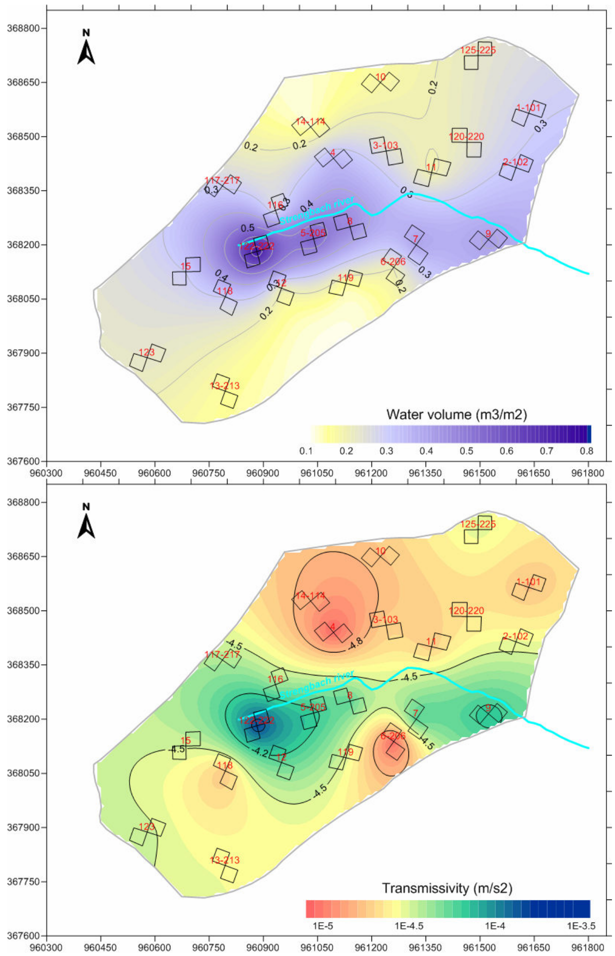

Figure 2. Maps of MRS water volume (top) and MRS transmissivity (bottom).

Hydrogeological interpretation

The MRS water volume and transmissivity maps (Fig 2) completed with available information on the geology allowed us proposing a schematic functioning of the catchment (Fig 3). Five units were defined (from north to south, west to east):

1) Gneiss area. Gneisses are present on the northern crest. Their thickness reaches 40 m deep and their weathered zone does not exceed 12 m according to a borehole. Gneisses are depicted as clayey material, which is consistent with the absence of MRS-detected water.
2) Northern slope. This area consists of fissured granite with strong alteration. As a consequence, MRS water content is quite high. The thickness of weathered zone remains low (<10 m) because of the steep slope. The estimated water volume is rather important (0.20 to 0.35 m^3/m^2) and could support a steady flow over time. Note that the transmissibility is probably underestimated on this area, due to the use of T2* in the empirical formula, while magnetic effects are identified through the recording of SE signal.
3) Colluvium zone. This zone is located in a flat area. The estimated depth of the weathered zone reaches 20 meters. Thus both the volume water (up to 0.75 m^3/m^2) and the transmissivity are high.
4) Wetland. This downstream area receives an important runoff. As for colluvium zone, the volume of water and the transmissivity are high.
5) Southern slope. This area is less altered and fissured than the Northern slope. Water infiltrates less easily. This results in a greater runoff and a low groundwater volume (<0.25 m^3/m^2 according MRS results).

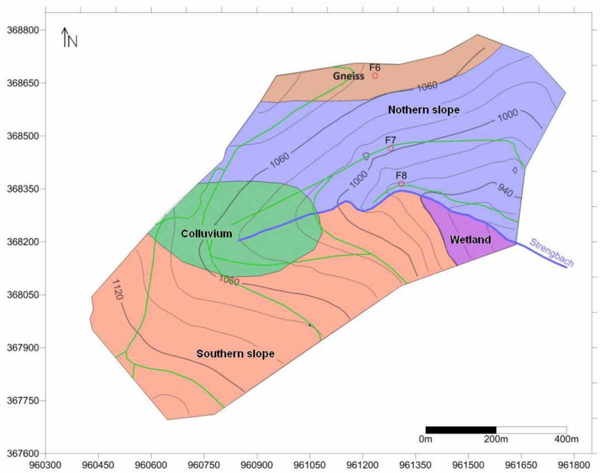

Figure 3. Delimitation of the 5 units of the conceptual model resulting from MRS and geological interpretations.

CONCLUSIONS

This study demonstrated the ability of a dense MRS characterization (~30 soundings per km^2) for describing very heterogeneous and complex media such as hard rock aquifers in mountain. The joint analyse of MRS mapping and geological knowledge allowed constructing a conceptual model of groundwater functioning. This conceptual model and the MRS-derived hydrodynamic properties can now be used in a numerical groundwater modelling. Although the findings about this functioning apply only to the study site, the approach can be used for other small complex catchment, for example in different climatic conditions.

In addition to this hydrogeological topic, our study allowed broaching the methodological issue that concerns the identification of spin echo signal. In our case, it clearly appears that no SE signal is recordable in the southern part of the catchment because of low magnetic properties of the encountered granite. In the northern area, SE and FID signals seem coexist.

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