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## Global sensitivity analysis of Magnetic Resonance Sounding simulated responses to the hydraulic parameters of a catchment hydrogeological model

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### SUMMARY

We apply a global sensitivity analysis of magnetic resonance sounding (MRS) data to the hydraulic parameters of a hydrological model at a catchment scale. The methodology used provides a quantitative estimate of the proportion to which the explored parameters influence the simulated MRS response. The sensitivity analysis is performed through a variance-based approach that provides indicators to infer how the MRS sensitivity to the different parameters might vary in space and time. We also apply the sensitivity analysis to water table depth estimates. We show that MRS measurements complement fruitfully classical water table depth acquisitions. Indeed, MRS is sensitive to the model water content at saturation while this parameter does not influence significantly the water table depth estimates.

**Key words:** MRS, hydrological model, sensitivity analysis, catchment scale

a pumping test. Boucher et al. (2012) used MRS measurements to constrain the hydraulic conductivity at saturation of a hydrological model applied at a catchment scale. Similarly, the fitting of MRS data covering a catchment with estimates from a hydrological model highlighted the necessity to divide the aquifer in two vertical layers with a deeper less porous medium (Lesparre et al., 2020). More recently, the acquisition of time-lapse MRS measurements helped modelling the water flow in an unsaturated medium (Legchenko et al., 2020).

Applications of time-lapse MRS acquisitions are progressing and a recent study showed its interest to monitor water infiltration during a rainy event (Mazzilli et al., 2020). In this paper, we explore how such time-lapse MRS simulated measurements are sensitive to the parameters of a hydrological model in order to discriminate which parameters MRS could help constraining in practice. For this purpose, we perform a global sensitivity analysis (GSA) of MRS data to the hydraulic parameters of a hydrogeological model applied on the Strengbach catchment (Fig. 1). We applied the measured meteorological forcing during a six-month period and analyse the variability of the MRS estimate at two stations presenting contrasting hydrological behaviours. We perform the same analysis with water table depth estimates to illustrate the complementarity between MRS and piezometric head data.

### INTRODUCTION

Magnetic resonance sounding (MRS) is a geophysical method directly sensitive to the underground water content. Beyond the estimate of the water content state at a given time, the method has been successfully applied to constrain the parameters of hydrological models. At the scale of one MRS acquisition setup (a few tens of meters), Costabel & Günther (2014) explored how MRS data can help estimating the water retention parameters. At a similar scale, Herckenrath et al. (2012) studied the relevance of coupled MRS and gravity measurements repeated over time to retrieve the aquifer characteristics during

### METHODS

The hydrological model applied covers the whole Strengbach catchment of 0.8 km<sup>2</sup>, located in the Vosges mountains (North-East of France). The catchment climate is temperate of oceanic mountainous type with a mean temperature of 6°C. 90% of the catchment is covered by forest with 80% of spruces and 20% of beeches. The underlying bedrock is of granitic type and the soils are coarsely grained, sandy and rich in gravels and pebbles.

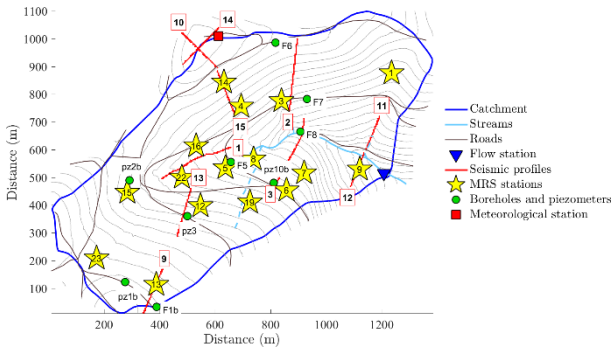


Figure 1. Distribution of MRS measurement stations and seismic profiles acquired on the Strengbach catchment.

We use the Normally Integrated Hydrological Model (NIHM) to simulate the water flow in the underground and at the surface through a coupling between the two compartments (Pan et al., 2017, Weill et al., 2017, Jeannot et al., 2018). We run 2500 synthetic models with randomly selected hydrological model parameter values. We focus the analysis on, the water content at saturation  $\theta_s$ , the hydraulic conductivity at saturation  $K_s$  and the  $\alpha$  parameter of the Van Genuchten equation. The aquifer is divided in two vertical layers corresponding to the soil and the saprolite, the last one being less porous. The soil and the saprolite thicknesses are defined through a statistical analysis of seismic profiles covering the catchment (Fig. 1). Geostatistical models are generated to reproduce the measured seismic velocity at the profile location and their statistical variability at the catchment scale. The soil and saprolite bottom interfaces are then determined by fixing a seismic velocity threshold of 700 m/s and 2000 m/s, respectively. The soil and saprolite thicknesses vary then normally in each element of NIHM.  $\theta_s$  and  $\alpha$  vary uniformly, while  $K_s$  follows a uniform distribution in the logarithmic domain. The variation ranges of those three parameters are summarized in Table 1.

Table 1: Range of variations of the explored parameters.

	Soil	Saprolite
$K_s$ (m/s)	$10^{-5}$ - $10^{-3}$	$10^{-6}$ - $10^{-4}$
$\theta_s$ (%)	5 - 60	2 - 10
$\alpha$ ( $m^{-1}$ )	0.1 - 2	0.1 - 2

The models run from the 1<sup>st</sup> of June 2012 to the 31<sup>st</sup> of May 2013, the first 6 months are used to “warm-up” the simulations and the GSA is applied from the 1<sup>st</sup> of December 2012. The studied period shows several distinct rainy events (Fig. 2), so we can examine the influence of different water content states on the MRS and water level depth variability. The measured precipitation and the estimated evapotranspiration are provided as a model input, such data come from the OHGE meteorological station (Fig. 1). The temperature is also given to determine the nature of the precipitation (rain or snow) and in case of snow, the infiltration is delayed depending on the temperature and on the previous height of snow accumulated.

NIHM provides as outputs the flow at the outlet, the water head at each MRS and piezometric stations and daily maps of the underground water content used to estimate the MRS signal as described in Lesparre et al (2020). The global sensitivity of each

data type to the parameters explored is then analysed through variance-based sensitivity indices (Mara and Tarantola, 2008). Such indices distinguish the contribution of each parameter to the signal total variance (Sobol’ 2001). Let’s consider a model defined with  $P$  independent random parameters  $X = \{x_1, \dots, x_P\}$  and a resulting signal estimate  $y(X)$ , the first order sensitivity Sobol’ index  $S_i$  corresponding to  $x_i$  writes:

$$S_i = \frac{V[E[y(X) | x_i]]}{V[y(X)]}. \quad (1)$$

$E[ \mid ]$  is the conditional expectation operator and  $V[ \ ]$  represents the variance.  $S_i$  represents the amount of the total signal variance that is related to the  $x_i$  parameter only.

We compute the Sobol’ indices through Polynomial Chaos Expansion (PCE; Wiener, 1938). Such representations are indeed particularly suited to perform variance-based GSA (Younes et al., 2018). The Sobol indices are directly computed from the PCE coefficients, without running the surrogate models, at a daily rate at each measurement point and for each data type.

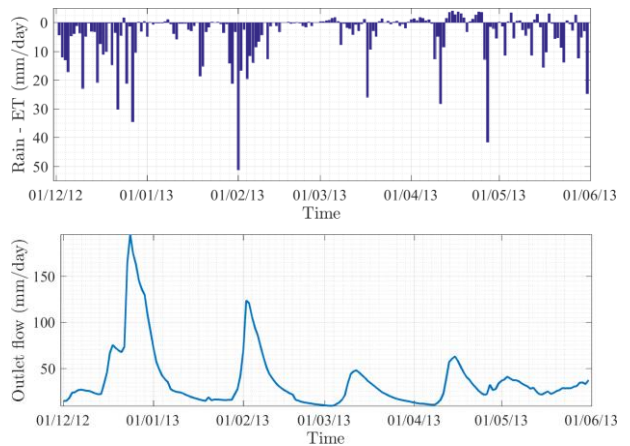


Figure 2. Rain minus the evapotranspiration measured on the Strengbach catchment used as the meteorological forcing inserted in NIHM (top). Flowrate measured at the catchment outlet (below).

## RESULTS

The contribution of the explored parameters to MRS signal variance as function of time is represented for station 7 and 22 Fig. 3. For sake of concision we limit here the analysis to those stations since they present a distinct hydrogeological behaviour. Station 7 is situated in a steep region that favours water drainage. Conversely, station 22 is located on a relatively flat region more suitable for water storage. We note that the variance of the MRS signal is much stronger at station 22 than at the 7<sup>th</sup>. We observe that at both stations the MRS signal is mainly sensitive to the soil  $\theta_s$  and the saprolite  $K_s$ .

However, we note that this sensitivity varies with time, notably concerning the  $K_s$  parameter. At station 7, the contribution of  $K_s$  is higher in winter during the drainage periods that follow high flow events. At station 22,  $K_s$  shows also a higher contribution in a period of drainage, but in spring when precipitations are less intense and more scattered across time. Both stations are also sensitive to the saprolite  $\theta_s$ , station 7 is more significantly sensitive to the soil  $\alpha$  value, while station 22 is sensitive, at times, to the saprolite  $\alpha$ . Station 22 is also much more sensitive to the soil thickness than station 7. We also observe that a large part of the signal variance is related to contributions concerning several parameters in interaction since the total variance (blue lines) is well above the respective contributions of each explored parameter.

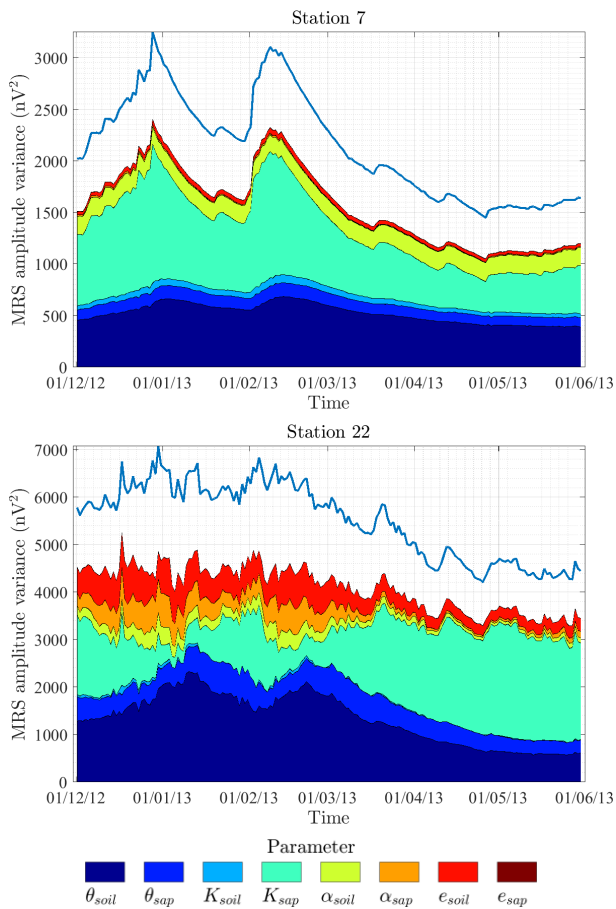


Figure 3. Variance of the MRS signal as function of time estimated at station 7 (top) and 22 (bottom). The blue line represents the total signal variance while the coloured areas indicate the respective contribution of the explored parameters.

The application of the same GSA to water table depth underlines the complementarity between MRS and piezometric data. In particular, the water table depth variance is not significantly impacted by the  $\theta_s$  parameter (Fig. 4). Under both stations, the water table depth variance is mostly sensitive to the saprolite  $K_s$ , and to the  $\alpha$  parameter of both the soil and saprolite. We note that the variance at station 7 is very smooth. At station 22, the variance of the water table depth

presents much more irregularities corresponding to the different precipitation events. We note that the impact of saprolite  $K_s$  on the water table depth signal increases with the spring arrival. As for the MRS signal, a part of the water table depth total variance is related to interactions between several parameters.

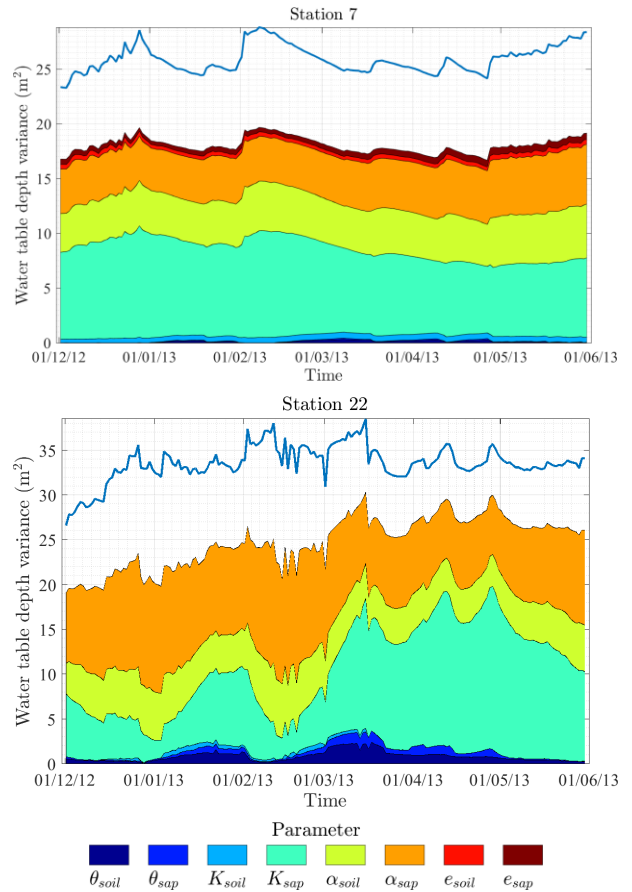


Figure 4. Variance of the water table depth as function of time estimated at station 7 (top) and 22 (bottom). The blue line represents the total signal variance while the coloured areas indicate the respective contribution of the explored parameters.

## CONCLUSIONS

We applied a GSA of MRS data to hydraulic parameter of a hydrological model applied on a headwater catchment. The meteorological forcing input to the model corresponds to a measured chronicle. From that analysis, we show that MRS data are mostly sensitive to the soil  $\theta_s$  and the saprolite  $K_s$  parameters. We observe a distinct behaviour from a measurement station to another. In particular a region favouring drainage is strongly sensitive to the saprolite  $K_s$  parameter in winter during the snow melt period. However, below an area suitable for storage, the sensitivity to that same parameter is more pronounced in spring.

Our study emphasizes the complementarity of MRS acquisitions to piezometric measurements as only the MRS data show a strong influence to the  $\theta_s$  parameter. The preliminary



analysis of these results invites to deepen the study to distinguish which coupled parameters impact both the MRS and piezometric signal. A study of the whole measurement stations variance would also help understanding the respective role of the different parameters to the MRS and water table depth signals. The GSA performed here encourages time-lapse MRS measurements at different places of a catchment to confirm our findings by including aspects such as the measurements noise that could vary in space and time.

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