Groundwater dynamics in karst hydrosystem unsaturated zone; evidences from a 2-years SNMR monitoring

K. Chalikakis[1], N. Mazzilli[1], S.D. Carrière[2], G. Massonnat[3], C. Danquigny[1,3], A. Legchenko[4]

[1] Avignon University, UMR 1114 EMMAH (INRAE-AU); [2] Sorbonne University, UMR 7619 METIS (UPMC-CNRS-EPHE); [3] Total S.E., CSTJF; [4] Grenoble Alps University, Institute of Research for Development, IGE

Summary

The unsaturated zone (UZ) of karst aquifers plays an important role in groundwater recharge processes. Comprehensive knowledge of UZ structure and hydrodynamic functioning is a key to better assess and manage groundwater resources in karst. In this extended abstract we present the results from a 2-year long Surface Nuclear Magnetic Resonance (SNMR) monitoring implemented in the Low-Noise Underground Laboratory (LSBB) site located within the Fontaine de Vaucluse karst hydrosystem in south-France. This exceptional 2-years SNMR monitoring demonstrated the efficiency of SNMR firstly to assess and validate the permanent presence of groundwater within karst hydrosystem UZ and secondly to monitor his temporal variations. Compared to boreholes, SNMR provides an integrated but accurate estimation of groundwater dynamics without disturbing the media.

Groundwater dynamics in karst hydrosystem unsaturated zone; evidences from a 2-years Surface Nuclear Magnetic Resonance monitoring

Introduction

Karst hydrosystems contain more than 25% of the wolrd's water resources [e.g. Chen et al., 2017]. The structural and functioning complexity that govern karst environments are limiting their groundwater resources sustainable exploitation and management. The context of climate change gives rise to an additional stress on the groundwater resources combining intense exploitation, water scarcity and rainfall unequal temporal and spatial distribution over the catchment area [e.g. Bakalowicz, 2005]. Unsaturated zone (UZ) is playing an important role in karst hydrosystems recharge processes [e.g. Emblanch et al., 2003]. Investigating its structure and hydrodynamic functioning is a very challenging task that needs interdisciplinary approaches but it is also a key to better assess and manage groundwater resources. Hydrogeophysics can provide suitable characterization of karst UZ but applicability and efficiency methods remain site and target related [e.g. Chalikakis et al., 2011].

In this extended abstract we present the results from a 2-year long Surface Nuclear Magnetic Resonance (SNMR) monitoring implemented in the Low-Noise Underground Laboratory (LSBB) site located within the Fontaine de Vaucluse karst hydrosystem in south-France. Compared to other geophysical methods SNMR is directly related to groundwater content which makes it particularly well suited for hydrogeological studies [e.g. Mazzilli et al., 2020; Vouillamoz et al., 2003]. The aim of this one of the kind, in karst media, SNMR monitoring was to evaluate the adequacy and the efficiency of the method to assess groundwater stocks and recharge dynamics of karst hydrosystem UZ. The presented results are part of the INTERWELLS4D research project in karst media who benefits collaboration between three French Universities (Avignon, Grenoble and Pau) and Total S.E. During this project, we combined hydrogeological, hydrochemical and isotopic measurements accessed by the artificial tunnel within the karst media and three boreholes implemented at the surface with hydrogeophysical surface-based measurements and boreholes logging. The INTERWELLS4D research project was a part of a larger research project, the ALBION R&D project (https://www.ep.total.com/en/expertise/reservoir/albion-dynamic-analogues-heart-carbonate-reservoirs-southeastern-france). In this extended abstract we are focused on this unique SNMR monitoring results compared to rainfall and boreholes hydrodynamic observations.

SNMR method

The SNMR method is based on the resonance behaviour of the magnetic moments of protons from the groundwater molecule. Thus, SNMR is the only ground-based geophysical method that can obtain a signal related to groundwater [Legchenko et al., 2002]. The moments of protons are excited with an electromagnetic field at a specific frequency (the Larmor frequency) produced by a surface loop. After the energizing pulse is cut off, protons emit back an electromagnetic field at the same frequency. The use of this specific frequency ensures selective sensitivity of the method to groundwater. The depth of investigation depends on the intensity and duration of the injected pulse. The amplitude of the signal is proportional to the number of hydrogen nuclei of water molecules that generate the signal, and the decay of the signal is linked to the mean distance between a water molecule and the pore wall. The MRS signal has very low amplitude of the order of tens of nanovolts (nV) and may be easily disturbed by the presence of both anthropogenic and natural electromagnetic noise. The Larmor frequency is directly proportional to the magnitude of the geomagnetic field and varies between 800 and 2800 Hz around the world. It can also vary with time at the same site. Comprehensive explanations of the method can be found abundantly in the scientific literature [e.g. Legchenko, 2013]

Experimental site

The experimental site of Buissonnière is located in southern France within the Fontaine de Vaucluse (FdV) karst hydrosystem (Figure 1A and B). With a recharge area of 1162 km^2 the FdV hydrosystem with cretaceous limestones is one of the largest karst aquifer in Europe. The Buissonnière test site is located at an altitude of 530 a.s.l. in the southern part of FdV hydrosystem and is a part of the Low Background Noise Underground Research Laboratory (LSBB) of Rustrel, which is a ground- and underground-based facility for interdisciplinary research, development and innovation (www.lsbb.eu). The Fontaine de Vaucluse/LSBB observation site is part of OZCAR Critical Zone network (https://www.ozcar-ri.org/fr/ozcar-3/), the H+ observatory network (http://hplus.ore.fr/en/), and KARST observatory network (http://sokarst.org/).

The mean thickness of the UZ in the FdV karst hydrosystem is about 800 m. Due to thickness and lithology, the UZ plays an important hydrological role as a buffer stock of water [e.g. Carriere et al., 2016; Emblanch et al., 2003]. The LSBB tunnel crosses the Buissonnière test site at a depth of 33 m below the ground surface (Figure 1C). The site is covered by typical Mediterranean forest and is a good example of the surface conditions found in the FdV hydrosystem. There is no major karstification features (i.e. cave, sinkhole) or major tectonic accident (i.e. fault). A permanent flow called "*point D*" is located within the UZ below the site and was monitored since 2003. Locally, the general saturated zone is located at more than 300 m below the experimental site (Figure 1C). Three boreholes of 50 m depth and 18 m distance in between (Figure 1D) were implemented in 2015 following the hypotheses developed by Carriere et al., 2016, assuming the presence of water buried layers within the UZ. These boreholes are monitored and a static water level was observed uninterruptedly until today.

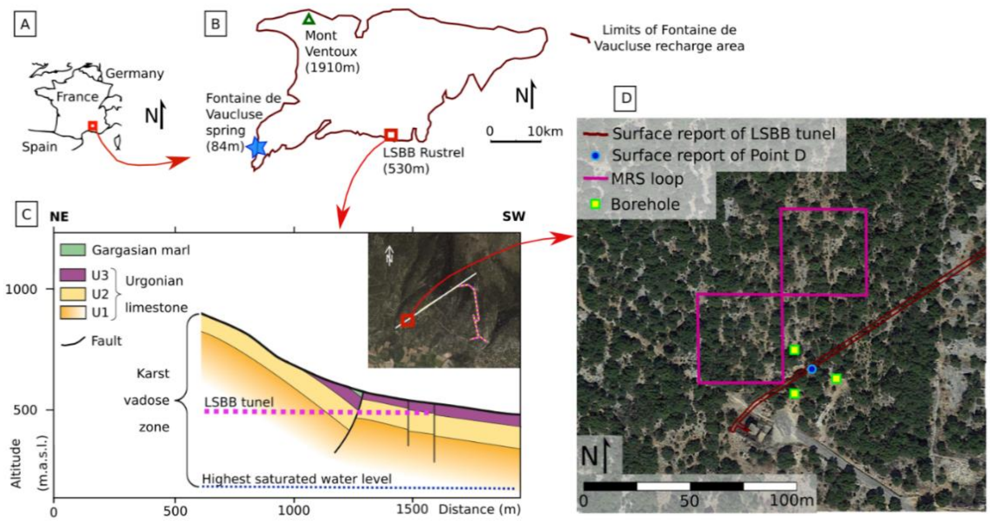

Figure 1 *Location of (A) test site in France; (B) in the Fontaine de Vaucluse karst hydrosystem; (C) schematic cross-section across LSBB; (D) overview of the respective locations of the LSBB tunnel, the three boreholes and the SNMR loop [Mazzilli et al., 2020, modified]*

SNMR field constraints and setup

The first SNMR tests at the Buissonnière site [Carriere et al., 2016] demonstrated temporal SNMR signal distribution also as very variable ambient electromagnetic noise conditions that can seriously disturb SNMR measurements. For the 2-years SNMR monitoring a coincident transmitting/receiving eight-square loop, composed of two squares with 40 m sides, was used (Figure 1D). The eight-square shape was selected to achieve the best signal to noise ratio (S/N). The location and the loop choice was guided by the previous geological and hydrogeological findings, the ambient electromagnetic noise conditions and finally the targeted signal to noise ratio.

Due to the surface conditions (i.e. dense forest) and in order to avoid any positioning error the SNMR loop was permanently placed and protected in the ground to ensure conservation of the same investigated underground volume. The mean duration of each SNMR sounding was approximately 8 to 10 hours. From September 2018 to November 2020 a total of 35 SNMR soundings were conducted using NUMIS^{POLY} equipment from IRIS Instruments. 29 of these SNMR soundings were selected according to the monitoring quality requirements. Each sounding thereafter was post-processed (15 Hz band-pass filter and 50 Hz notch filter) and inverted using Samovar v.12.1 software package developed by A. Legchenko (IRD-IGE).

Results and discussions

The evolution of the SNMR signal amplitude during the 2-years monitoring is presented in Figure 2. This evolution corresponds to the temporal variability of the karst UZ groundwater content for the investigated volume.

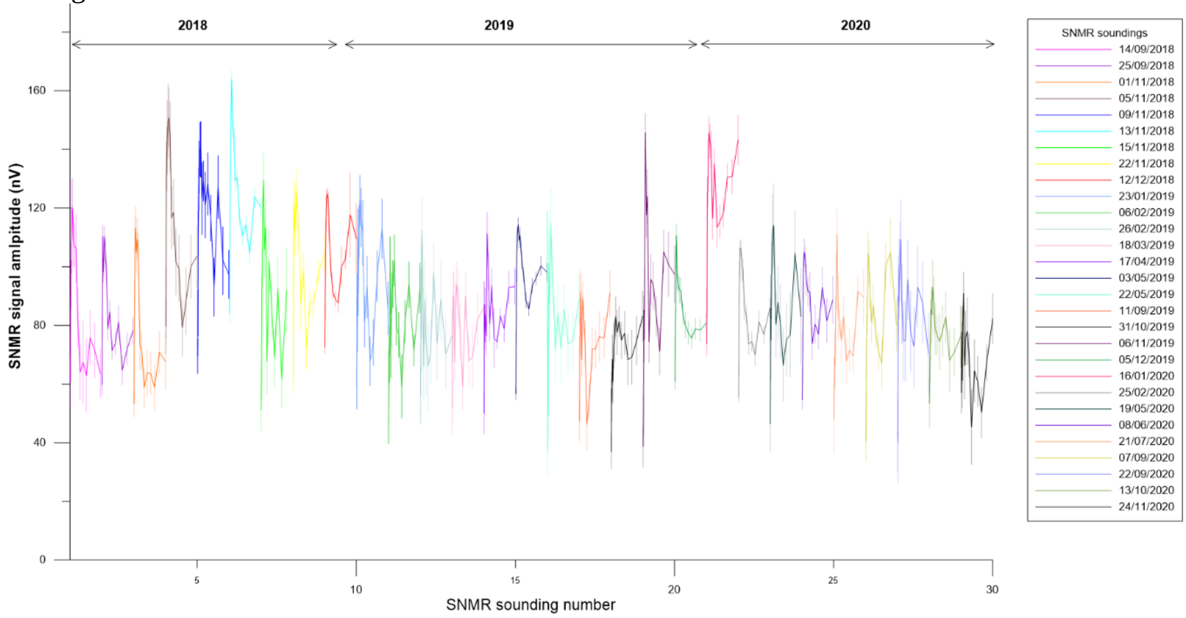

Figure 2 *SNMR signal amplitude as a function of the energizing pulse for all soundings.*

For consistency reasons we present (Figure 3) a comparison of a. the hydrodynamic monitoring of the three observation boreholes within the karst UZ, b. the rainfall (monthly and daily measurements) and c. the variations of the SNMR water column. As for most geophysical methods, SNMR has the inherent problem of equivalence solutions after inversion. Indeed, water layers that have equal water volumes (product of water content per layer thickness) can yield equivalent SNMR responses. Therefore, we used the SNMR water column that corresponds to the entire water quantity "seen" by SNMR from the surface to a certain depth in accordance to measurements uncertainties and resolution. In our case, the SNMR water column is calculated from 0 to 30 m. In Figure 3, we represent the relative variations (in mm) of the SNMR water column compared to its lowest value.

Rainfall behaviour is typical Mediterranean with hot dry summers and intense, but short in duration, rain events, mainly in autumn. At the actual stage, and due to the lack of several parameters, effective rain cannot be accurately estimated. According to groundwater level monitoring, the three boreholes present the same general hydrodynamic behaviour. Indeed, during the SNMR monitoring, two recharge periods (asynchronous to the rain) are observed followed by two long discharge cycles. However, the eastern borehole (BFE) reacts immediately to the rain episodes probably due to direct infiltration through the sealing or some epidermic lateral water movements. The 4 m altitude difference between the southern borehole (BFS) and the other two is linked to the slope of the site.

SNMR water column also varies with time. We noticed the same form observed in the hydrodynamic monitoring of the boreholes. However, the discharge dynamics of the second period (2020) in SNMR seems more important than the one observed by the boreholes. In Mazzilli et al. (2020), we noticed that during an intense rainy event (autumn 2018), followed with temporally dense SNMR measurements, the infiltrated water caused increased SNMR signal during 5 days after the event. A significant draining process of the medium started 15 days after the rain. After 42 days, the SNMR signal returned close to the initial state. This dynamic it was not observed in the boreholes. Finally, the SNMR estimated water column is higher than the amount of rain that is certainly related to lateral groundwater movement.

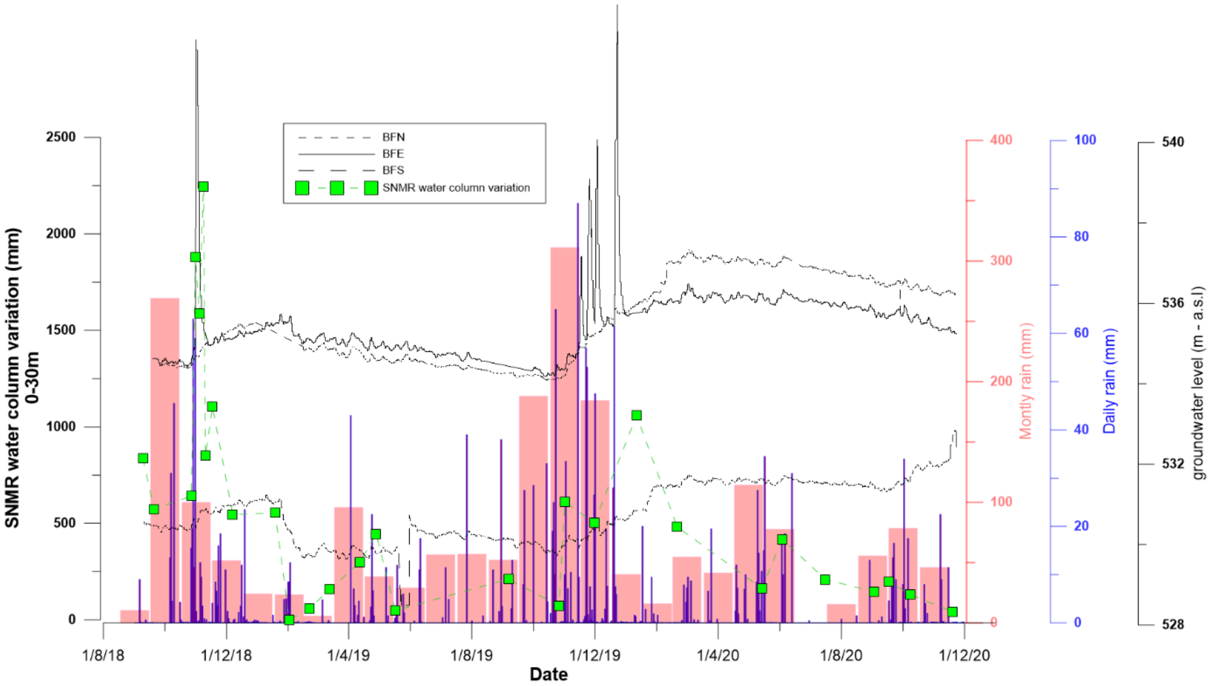

Figure 3 *A comparison of the hydrodynamic monitoring of the three observation boreholes within the karst UZ, the rainfall (monthly and daily measurements) and the variations of the SNMR water column.*

Conclusions/Perspectives

This unique 2-years SNMR monitoring demonstrated the efficiency of SNMR firstly to assess and validate the permanent presence of groundwater within karst hydrosystem UZ and secondly to monitor his temporal variations. Compared to boreholes, SNMR provides an integrated but accurate estimation of groundwater dynamics without disturbing the media. In fact, the observed water level within the boreholes is not necessary representative of the water buried layers of karst UZ. The boreholes may behave as a drain conducting the water from upper layers into the borehole. Additional analysis with hydrochemical and logging data will promote clarification. Finally, new SNMR monitoring campaigns are being programmed to several locations within the FdV basin in order to evaluate the spatial representativity of the our results in the Buissonnière experimental site.

Acknowledgements

The presented results were funded mainly by Total S.E. also as H+ network and Avignon University.

References

Bakalowicz, M. [2005]. Karst groundwater: a challenge for new resources. *Hydrogeology Journal*, *13*(1), 148–160. https://doi.org/10.1007/s10040-004-0402-9

Carriere, S. D., Chalikakis, K., Danquigny, C., Davi, H., Mazzilli, N., Ollivier, C., and Emblanch, C. [2016]. The role of porous matrix in water flow regulation within a karst unsaturated zone: an integrated hydrogeophysical approach. *Hydrogeology Journal*, *24*(7), 1905–1918. https://doi.org/10.1007/s10040-016-1425-8

Chalikakis, K., Plagnes, V., Guerin, R., Valois, R., and Bosch, F. P. [2011]. Contribution of geophysical methods to karst-system exploration: an overview. *Hydrogeology Journal*, *19*(6), 1169. https://doi.org/10.1007/s10040-011-0746-x

Chen, Z., Auler, A. S., Bakalowicz, M., Drew, D., Griger, F., Hartmann, J., … Goldscheider, N. [2017]. The World Karst Aquifer Mapping project: concept, mapping procedure and map of Europe. *Hydrogeology Journal*, *25*(3), 771–785. https://doi.org/10.1007/s10040-016-1519-3

Emblanch, C., Zuppi, G. M., Mudry, J., Blavoux, B., and Batiot, C. [2003]. Carbon 13 of TDIC to quantify the role of the unsaturated zone: the example of the Vaucluse karst systems (Southeastern France). *Journal of Hydrology*, *279*(1–4), 262–274. https://doi.org/10.1016/S0022-1694(03)00180-X

Legchenko, A. [2013]. *Magnetic Resonance Imaging for Groundwater* (Wiley-ISTE).

Legchenko, A., Baltassat, J.-M., Beauce, A., and Bernard, J. [2002]. Nuclear magnetic resonance as a geophysical tool for hydrogeologists. *Journal of Applied Geophysics*, *50*(1–2), 21–46. https://doi.org/10.1016/S0926-9851(02)00128-3

Mazzilli, N., Chalikakis, K., Carrière, S. D., and Legchenko, A. [2020]. Surface Nuclear Magnetic Resonance Monitoring Reveals Karst Unsaturated Zone Recharge Dynamics during a Rain Event. *Water*, *12*(11), 3183. https://doi.org/10.3390/w12113183

Vouillamoz, J. M., Legchenko, A., Albouy, Y., Bakalowicz, M., Baltassat, J. M., and Al-Fares, W. [2003]. Localization of Saturated Karst Aquifer with Magnetic Resonance Sounding and Resistivity Imagery. *Groundwater*, *41*(5), 578–586. https://doi.org/10.1111/j.1745-6584.2003.tb02396.x