Examining the functioning of a multilayer karst system. The case of Toulon springs (Dordogne, FRANCE)

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Abstract Hydrodynamic and hydrochemical responses of Toulon springs are examined to identify the functioning of the karst system. First, analysis of the recession curve coupled to univariate and bivariate analysis are conducted to determine storage capacity and relationship between rainfall and discharge. Results show a complex system which could provide fast hydrodynamic responses to rainfall solicitation, but have an ineffective drainage network and then high storage capacity. In addition, temporal evolution of hydrochemical parameters leads to identify quick variation of hydrochemical responses during flood events. Furthermore, a principal component analysis (PCA) is conducted on 61 samples and confirms that springs are fed with waters from different origins.

1 Introduction

Hydrochemical and hydrodynamic responses observed at the outlet of karst systems depend upon the flow conditions which prevail in the aquifer. The joint use of hydrodynamic and hydrochemical techniques, within the framework of a multidisciplinary approach, provides a more reliable characterization of the hydrogeological functioning of karst aquifers [Lastennet and Mudry, 1997; Perrin et *al.*, 2003; Mudarra and Andreo, 2011 ; Bicalho et *al.*, 2012]. It can give information about the relative participation of the saturated and the unsaturated zone in carbonate aquifers. Previous studies [Lastennet, 1994 ; Lastennet and Mudry, 1997; Emblanch et *al.*, 1998 ; Batiot et *al.*, 2003 ; Emblanch et *al.*, 2003 ; Minvielle et *al.*, 2015] have considered the joint use of natural hydrochemical tracers (dissolved organic carbon

(DOC), NO_3^-, $\delta^{13}C$, Mg^{2+}) to improve knowledge about functioning of these complex systems.

This work deals with Toulon springs. These springs have been supplying water to the metropolitan area of Périgueux (Dordogne, France) since the 19th century. One of the particularities of this karst system is its functioning. Toulon springs are fed by a multilayer karst aquifer from the upper Cretaceous. This study aims to contribute to the characterization of the functioning of a multilayer karst aquifer using hydrodynamic responses and natural hydrochemical tracers. Multivariate statistical analysis of hydrochemical data collected from February 2014 to February 2016 is used to identify different water types at Toulon springs.

2 General characteristics of the study area

Toulon springs, major springs in Dordogne county, are located in Périgueux. It is a Vaucluse-type spring, with a main conduit developed below spring level and is located on a major regional fault [Lastennet et *al.*, 2004]. Toulon springs are the main perennial outlet of the karst system that can reach 1000 L/s during flood events, with annual average discharge of 450 L/s.

Geologically, Toulon karst system consists of upper Cretaceous and upper Jurassic carbonate rocks (Fig.1), with a thickness of 200-250 m for Cretaceous rocks, and 100-150 m for Jurassic rocks [Von Stempel, 1972]. At the top, Cretaceous rocks consists of limestones while Jurassic rocks consists of dolomitic limestones. The geological structure of the Toulon karst system is characterized by the existence of folds and fractures in mainly NW-SE direction (Fig.2).

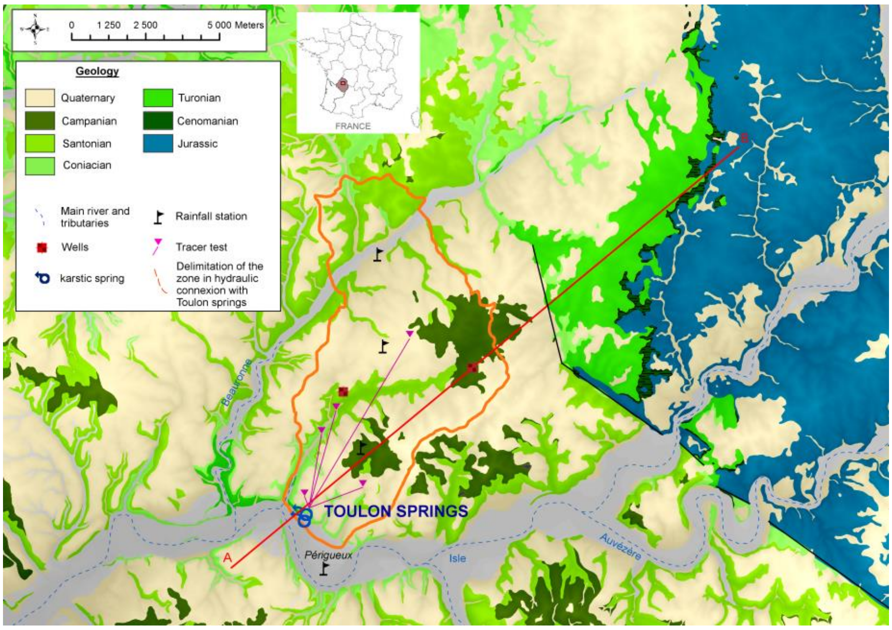

Fig.1 Map of localisation of Toulon karst system

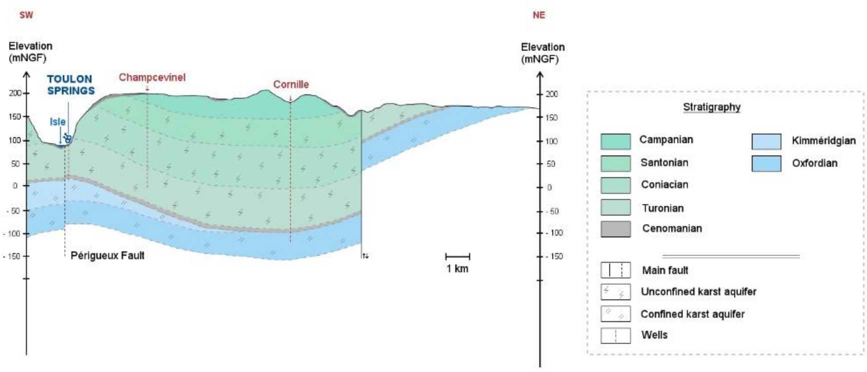

Fig. 2 SW-NE geological cross section of Toulon karst system.

Regional hydrogeological situation consists of two main multilayer karst aquifers. Fractured and karstified Cretaceous limestones constitute the first main aquifer. It is a multilayer karst aquifer divided into Turonian aquifer, Coniacian aquifer and Santonian aquifer. Below, Jurassic dolomitic limestones constitute the second main aquifer of the study area. The marls of the Cenomanian constitute the boundary of these two main aquifers.

The study area is characterized by these two main aquifers. They are supposed unconnected but groundwaters flowing through the Périgueux fault can reach some springs near Toulon springs (Fig.2).

This study aims to delineate the participation of each aquifer either by direct transfer or by exchange by vertical leakance.

The hydrogeological catchment of Toulon springs has an area of about 100 km². A large part of the hydrogeological catchment is relatively permeable, due to the presence of limestone of the Santonian and the Coniacian. Most of the recharge is diffuse through outcrops located by the north of Toulon springs (Fig1). Localized infiltration occurs through sinkholes along the basin.

3 Strategy and methodology

3.1 Water sampling and data continuous monitoring

At Toulon springs, water samples were collected semi-monthly from February 2014 to October 2015 and weekly from October 2015 to February 2016, with daily sampling during flood events. A total of 71 samples were collected from Toulon springs. Samples collected from Toulon springs were filtered to 0.45 µm and preserved at 4°C in 60 mL HDPE flasks. Contents of the cation flasks were acidified using HNO_3 and ion concentrations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, NO_3^{-} and SO_4^{2-}) were determined by chromatography using a Dionex ICS 1500 equipped with CS12 columns for the cations and using a Dionex ICS 1100 equipped with AS15 columns for the anions (accuracy measurement 2%).

Electrical conductivity (EC) is measured continuously since 2011 at the outlet of the karst system, using a MDS5 light SEBA (accuracy measurement 0.5%).

Study site has four rainfall station (Fig.1) in order to cover the whole hydrogeological basin of Toulon springs. Although the average annual precipitation varies between 800 and 1000 mm, evapotranspiration from vegetation leads to a computed effective rainfall ranging 200 to 350 mm per year.

Discharge is measure continuously at the outlet of the system since July 2005 using a miltronics probe ultrasonic liquid level.

3.2 Methodology

A multidisciplinary approach is conducted to determine hydrogeological functioning of Toulon karst system.

First, an analysis of the recession curve is performed to determine the storage capacity of the system. Based on Maillet equation, Mangin [1975] concluded that exponential equation was suitable for modeling the baseflow. Although Maillet

[1905] developed equation from catchments with aquifers consisting of granulated media, it has been used for karst media. Integrating the recession curve over time provides the dynamic storage (V_{dyn}) of the aquifer.

In addition, univariate (auto-correlation function, ACF) and bivariate (cross-correlation function, CCF) analysis are performed to confirm the previous results. These analysis characterize the temporal structure of hydrologic signal under linear-stationary hypothese [Mangin, 1984 ; Padilla and Pulido-Bosh, 1995]. Correlogram, memory time and delay time are often used to describe the karstification degree and the response of the aquifer.

The memory time, which stands for the lag time when ACF=0.2, is used to describe the time that discharge is influenced by the initial condition (rainfall).

The delay time, the lag time between 0 and the time when maximum CCF value appears, can reflect the response time of the aquifer to the rainfall event. Shorter delay time means faster aquifer transfer.

Furthermore, a principal component analysis (PCA) is employed to identify relations and correlations between variables of water. It is based on samples variations on variables. Variations can be represented in a factor plane composed by two factor axes. PCA is performed with standardized data i.e. subtracted data from their average and divided by their deviations.

4 Results and discussion

4.1 Hydrodynamic responses

Analysis of the recession curves conducted on 5 hydrological cycles show a low baseflow coefficient (10^{-4} day^{-1}). Fig.3 illustrates the recession of the hydrological year 2014-2015. Consequently, the dynamic storage calculated is high (60.10^{6} m^{3}). These calculations show the high storage capacity of this karst system.

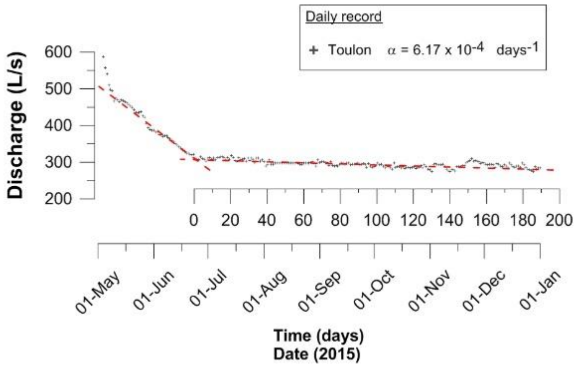

Fig. 3 Analysis of the recession curve corresponding to the hydrological year 2014-2015

In addition, ACF and CCF confirm that Toulon karst system possesses ineffective karst drainage network and high storage capacity. The ACF, for the year scale, illustrates a memory effect of 77 days (Fig.4), which is high for a karst aquifer. Similar results are found in higher karst system, e.g. Fontaine de Vaucluse : 75 days [Moussu, 2011]. Furthermore, the CCF has a delay time of 4 days in year scale, indicating that the average response time of this aquifer to rainfall solicitation was 4 days within a hydrological year (Fig.4). Maximum value is 0.22, indicating a low correlation between rainfall and discharge. The CCF show a steep slope 20 days after the maximum value then a low slope. These results show a complex system which could provide fast hydrodynamic responses to rainfall, but which possesses high storage capacity.

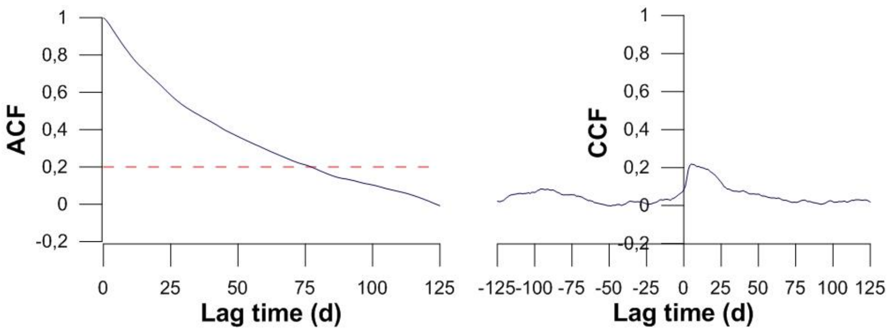

Fig. 4 Auto-correlation of discharge and cross-correlation function of the stream discharge and rainfall

Calculated parameters can situate Toulon springs into the classification of karst systems. According to Fig.5, Toulon springs are located into the domain 5 added by El-Hakim and Bakalowicz [2007]. The domain 5 (k > 1) should be considered as the domain of karst systems with a deep phreatic zone, partly or totally confined, and largely karstified during previous karstification phases. These karst systems possess a complex drainage structure responsible for very long residence time (multiannual). Touvre karst system was the only French karst system which was also located in the domain 5. Touvre springs are fed by swallow holes (50 %) implying stable baseflow during low stage period [Larocque,1997]. Despite of the proximity of Toulon springs and Touvre springs in the classification of karst system, these two springs don't have a similar functioning.

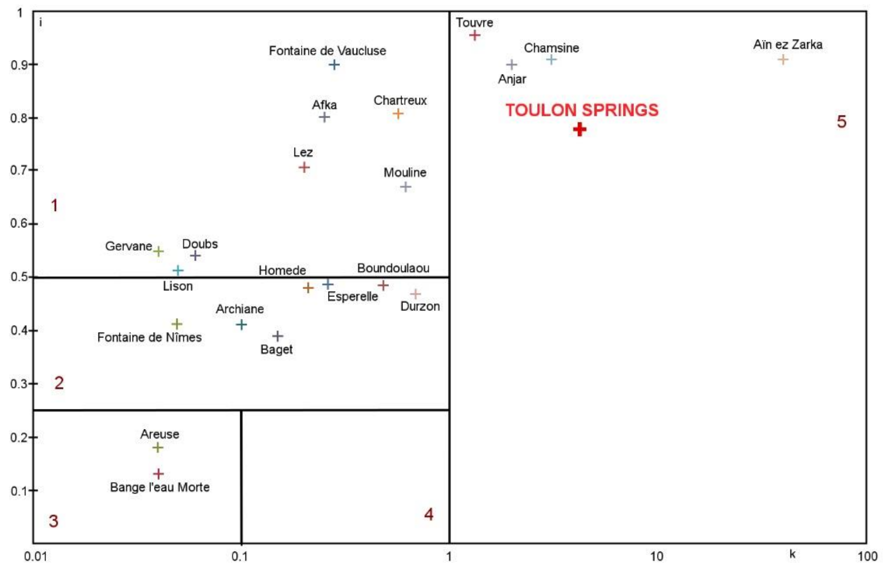

Fig. 5 Classification of karst systems based on indices from the recession analysis (adapted from El-Hakkim and Bakalowicz, 2007)

4.2 Hydrochemical responses

Fig.6 shows the temporal evolution of discharge, EC, together with the hydrochemical parameters analyzed in the water drained by Toulon springs. Analysis of data obtained shows quick hydrochemical variations as response to rainfall events. Variations of hydrochemical responses exhibit different types of water associated to discharge. Waters of deep origin (Mg^{2+}, HCO_3^-, EC) are identified during low stage period. In opposition, natural tracers illustrate recent waters participation during flood events (dissolved oxygen (O_2), DOC, NO_3^-, SiO_2). These fast variations are linked to high rainfall events and appear when the multilayer Cretaceous aquifer is activated.

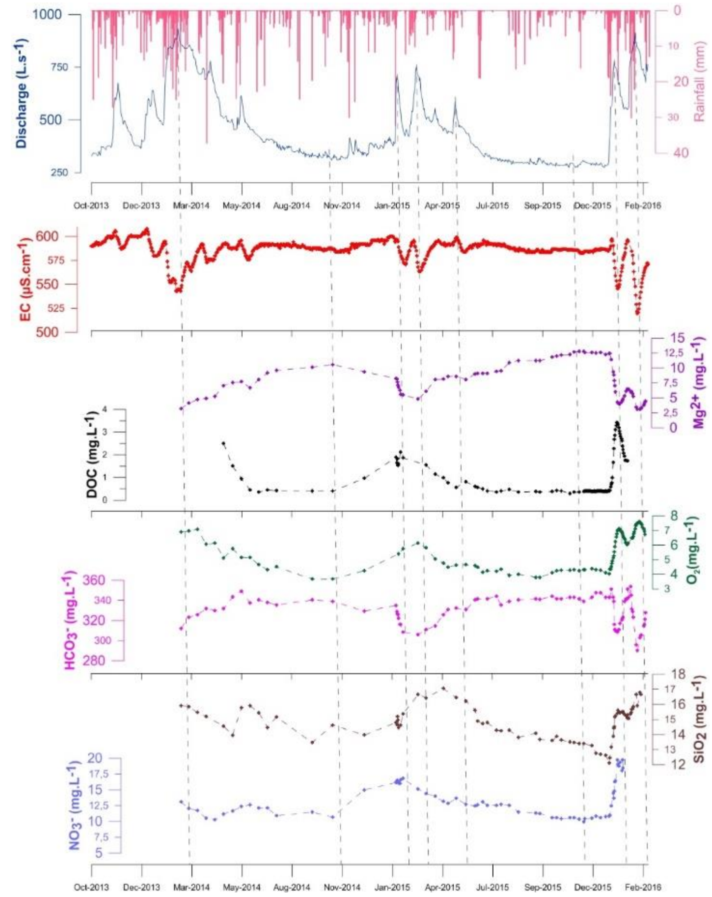

Fig. 6 Temporal evolution of discharge and hydrochemical parameters from Toulon springs with respect to rainfall events.

The principal component analysis (PCA) is based on 61 samples from February 2014 to February 2016, and 10 variables (temperature (T), electrical conductivity, dissolved oxygen, magnesium, bicarbonate, nitrate, silica, saturation index with respect to calcite (SI_c), dissolved organic carbon, turbidity). Results of PCA are presented through the variable space (Fig.7a). The first factor plane (F1-F2) is the best-described for variables. These two principal components explain 80.66 % of the total variance.

The first axis (F1) explain most of the total variance with 67.50 %. It is explained by EC, HCO_3^-, Mg^{2+}, T and SI_c in its positive part ; O_2, NO_3^-, DOC, turbidity and SiO_2 in its negative part (Fig 7a). Temporal evolution of discharge and normalized F1 (Fig. 7b) shows the relationships between discharge and F1 axis. Water with shallow origin are with high discharge and waters with deeper origins are with low discharge. This result is the first indication as a possible deep aquifer (Mg^{2+}, HCO_3^- ; Jurassic dolomitic limestone aquifer) participating at the discharge.

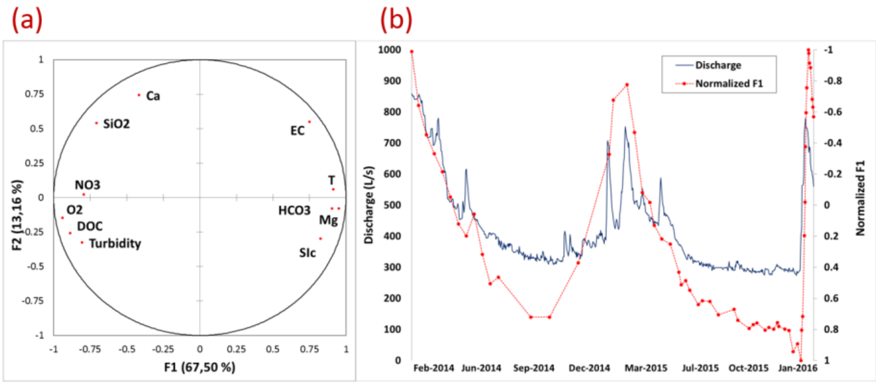

Fig. 7 Principal component analysis of the samples taken into Toulon springs**. a** Diagram variable. **b** Temporal evolution of discharge and normalized F1

5 Conclusion

In despite of a karstic environment, hydrodynamic responses are more buffered. Temporal evolutions of hydrochemical responses during more than two years complete hydrodynamic results. During low stage period, discharge at Toulon springs is steady. During flood events, Toulon springs have a typical karstic functioning with flow waters passing through fissures of the Cretaceous aquifers.

Toulon springs are fed by a multilayer karst system. First, upper Cretaceous multilayer aquifer (Turonian, Coniacian, Santonian) contribute to fed Toulon springs with a typical karstic functioning, possessing a transmissive role and responsible of quick hydrochemical responses to rainfall events. In addition, Jurassic dolomitic limestone aquifer could contribute to fed Toulon springs continuously, acting like a storage reservoir. These deep waters are responsible of the high magnesium and bicarbonate concentrations identified during low stage period.

From these previous observations, it is possible to consider that the geological history (structures, sedimentology, periods of karstification) is responsible of the functioning of Toulon springs. Polyphase karstification and multilayer aquifers are also probably responsible of this functioning.

To confirm these assumptions, a high-resolution auto-monitoring is conducted to Toulon springs (temperature, pH, electrical conductivity, turbidity, redox potential, dissolved oxygen, total organic carbon, dissolved organic carbon, nitrate). In addition, nitrate isotopes ($\delta^{15}N$-NO_3, $\delta^{18}O$-NO_3) and dissolved gas (CFC, SF_6) are used to identify origins of water.

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