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# Harmonic pumping tomography applied to image the hydraulic properties and interpret the connectivity of a karstic and fractured aquifer (Lez aquifer, France)

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ABSTRACT

In this work, we present a novel method to interpret, at a field scale, the preferential flows generated by harmonic pumping tests, in which the pumped flowrate varies according to a sinusoidal function with a given period. The experimental protocol relies on the application of harmonic pumping tests in a karstic field located near to Montpellier (Southern France) at 4 different boreholes, each time with a shorter and a longer period, and the analysis of the hydraulic responses recorded at the 13 observation wells. A qualitative analysis of the oscillatory component in the hydraulic responses, in term of amplitude decay and phase lag, permitted to propose a preliminary model of degree of connectivity between the boreholes, through the network of conduits. Then, a quantitative interpretation of the harmonic responses was applied to image the spatial heterogeneity of the hydraulic properties (hydraulic conductivity and storage coefficient) by using a deterministic inverse algorithm called CADI. This algorithm is based on an equivalent porous medium concept and parameterized by a Cellular Automata approach in order to provide a realistic reconstruction of the karstic network. This algorithm is linked to the groundwater flow equation, reformulated in frequency domain, to simulate the amplitudes and phase shifts responses to the harmonic pumping tests. The inverse process was successfully applied on the dataset collected with both periods, in a separate and joint way. The results obtained allowed for a discussion on the efficiency of the harmonic pumping tomography for the characterization of the karstic structures.

## 1. Introduction

The protection and the management of the water resources involve the identification of the preferential flow paths in the ground. Therefore, one needs to characterize the spatial distribution of the hydraulic properties in the field subsurface. A common way to assess the hydraulic properties of a field, such as conductivity and specific storage, is the analysis of the drawdown responses to a pumping test from which local or average properties can be inferred from analytical equations that relate the hydraulic response to the hydraulic properties (Butler, 2005).

However, in the case of karstic aquifers, the assessment of the hydraulic properties is challenging (White, 2002; Hartmann et al., 2014) as the hydraulic properties in this type of aquifer can vary by several orders of magnitude within a short distance (Wang et al., 2016). This makes the characterization of the karstic fields very complex. To face this difficulty, it is then necessary to interpret the responses of the field by taking into account the positioning of the conduits network, which determines the preferential flow paths (Kovacs, 2003; Ghasemizadeh et al., 2012; Saller et al., 2013).

The hydraulic tomography concept has been widely applied to map the spatial variability of hydraulic properties, in both type of aquifers (porous and fractured), by performing a joint interpretation of hydraulic data recorded simultaneously at several wells, as responses to extraction/injection of water (Yeh and Liu, 2000; Bohling et al., 2002; Zhu and Yeh, 2005; Yeh and Lee, 2007; Cardiff et al., 2009a; Castagna et al., 2011; Berg and Illman, 2013; Cardiff et al., 2013a; Zha et al., 2015; Zha et al., 2016; Zha et al., 2017). This approach relies on a numerical technique (such as finite difference, finite element and finite volume) to solve the groundwater flow equation, and the inverse process to reconstruct the heterogeneity of the hydraulic conductivities and the storage properties by fitting the piezometric responses. The inversion process usually provides a non-unique solution which can produce an ambiguous interpretation of the hydraulic data. To overcome this issue, a prior information on the distribution of the properties can be used to constrain and guide the inversion to a more realistic solution (Carrera and Neuman, 1986). In the case of aquifers with a low heterogeneity, the geostatistical constraints remain the most simple and efficient way to find accurate solutions (Hoeksema and Kitanidis, 1984; Kitanidis, 1995; Fischer et al., 2017a). In the context of fractured and

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karstic aquifers, the definition of the a priori model, or even the strategy for the numerical groundwater flow simulation (which can be performed by using various techniques such as equivalent porous media or discrete fractures networks), remain the subject of open debates among hydrogeologists. In fact, for a successful interpretation of hydraulic responses of karstic aquifers, the 'classical' geostatistical inversion method would require a dense network of measurement and a significant resolution of model parameterization because of the high contrasts existing in the distribution of the spatial properties. Recently, several inversion methods have been developed for characterizing karst networks. One way is to directly incorporate a discrete geometry within a background model using a discrete-continuum forward model (Teutsch, 1993; Liedl et al., 2003; de Rooij et al., 2013). In this case, the parameterization of the inverse problems usually relies on a stochastic generation of discrete fracture networks that are conditioned to statistical (Li et al., 2014; Le Coz et al., 2017), mechanical (Jaquet et al., 2004; Bonneau et al., 2013), or structural data (Pardo-Iguzquiza et al., 2012; Collon et al., 2017). Another way is based on a deterministic optimization of the geometry of discrete networks (Borghi et al., 2016; Fischer et al., 2018a).

Previous studies have shown that equivalent porous media models are able to reproduce the hydraulic flows in karstic aquifers at a kilometric scale (Larocque et al., 1999; Abusaada and Sauter, 2013) or a decametric scale (Wang et al., 2016). However, if the scale of investigation is too small, this type of model can become unreliable for the characterization of the properties of fractured rocks, extremely contrasted and structured at a small scale (Illman, 2014). Although the classical geostatistical inverse approaches were originally proposed for inversion of hydraulic fields, they can be made adaptive to discrete geometries with special treatments to the prior model (e.g. the total variation prior model, Lee and Kitanidis, 2013), or using an iterative procedure (e.g. the sequential successive linear estimator, Ni and Yeh, 2008; Hao et al., 2008; Illman et al., 2009; Sharmeen et al., 2012). Other methods for inversion of complex discrete structures involve introducing constraints of a priori knowledge to the inverse model using a guided image (Hale 2009; Soueid Ahmed et al., 2015), a training image (Lochbühler et al., 2015), a probability perturbation (Caers and Hoffman, 2006), a transition probability distribution (Wang et al., 2017), a multi-scale resolution (Ackerer and Delay, 2010), a level-set method (Lu and Robinson, 2006; Cardiff and Kitanidis, 2009b), or based on cellular automata (Fischer et al., 2017b).

Apart from these challenges in modeling techniques, a further difficulty in karst aquifer characterization raises from characteristics of hydraulic tests. Due to the integration nature of pressure diffusion, the steady state responses of long-term constant-rate pumping tests in a karst aquifer represent the combined effect of the multiple media (conduits, fissures, and matrix) rather than specific components. Although the interpretation of transient responses may provide additional information about the relative importance of each aquifer components, the inclusion of such data in a modeling in the time domain is also computationally demanding. Recently, harmonic pumping tests have been introduced as an alternative for the identification of the networks of preferential groundwater flows. Harmonic characterization designates an investigation in which an oscillatory/sinusoidal signal is used to disturb the water level of an aquifer. Different ways to produce such signals have already been proposed: a pumping-reinjecting system (Rasmussen et al., 2003; Renner and Messar, 2006), a moving mass at the water table interface (Guiltinan and Becker, 2015), or a controlled pumping system (Lavenue and de Marsily, 2001). Then, the response signals among the aquifer contain an oscillatory part (characterized by an amplitude and a phase offset values) that can be easily isolated from the ambient noise (Bakhos et al., 2014; Cardiff and Barrash, 2015). Harmonic characterization has already been successfully applied to a large range of complex cases such as contaminated aquifer (Rasmussen et al., 2003), leakage detection (Sun et al., 2015), or fractured aquifers (Renner and Messar, 2006; Maineult et al., 2008; Guiltinan and Becker, 2015). The theoretical aspects of the application of harmonic pumping to karstic aquifers have also been developed in Fischer et al. (2018b). The imagery potential of harmonic investigations has been studied for mapping the distribution of hydraulic properties in heterogeneous aquifers with models solved in the time domain (Lavenue and de Marsily, 2001; Soueid Ahmed et al., 2016) or in the frequency domain (Cardiff et al., 2013b; Zhou et al., 2016)

In this article we will present a field characterization of karst network based on a harmonic pumping tomography. Hydraulic data were obtained from the Terrieu experimental site located in Montpellier, in Southern France. At the same site, results of hydraulic tomography, in which hydraulic responses were generated with constant-rate pumping tests, have already been presented and discussed in our previous works (Wang et al., 2016, 2017; Fischer et al., 2017c). In this new work, we rely our analysis on a set of responses to harmonic pumping tests with different oscillation periods, to characterize the karst network. We describe in Section 2 the experimental study site, the harmonic pumping investigation led on it, and the processing made on the measured field responses for the later interpretation. Then, in Section 3 we briefly introduce the numerical model setup and the Cellular Automata-based Deterministic Inversion (CADI) algorithm. Further details of our inverse algorithm can be found in Fischer et al., (2017b). In Section 4 we present the inversion results obtained with the CADI method at the Terrieu field site and the efficiency of the method in reproducing the observed hydraulic responses. Finally, Section 5 presents a discussion of the effect of the harmonic signal period on the inversion results.

## 2. Field investigation

### 2.1. Experimental site presentation

The Terrieu experimental site is located ~15 km in north of the town of Montpellier in southern France. The site consists of 22 vertical boreholes drilled within a surface area of approximately 2500 $m^2$ ($40 \times 60$ m) and permits the study of karstic flows at a local scale (Fig. 1). As a part of the network of the French Karst Observatory (SNO Karst, www.sokarst.org) and the Medycyss network (Jourde et al., 2011), the site has been used as a field laboratory for testing new field hydraulic methods and tools developed for the characterization of karstic aquifers (Jourde et al., 2002; Jazayeri Noushabadi, 2009; Jazayeri Noushabadi et al., 2011; Dausse, 2015; Wang et al., 2016; Wang et al., 2017; Fischer et al., 2017c).

The geological logs collected from the different boreholes shows that the subsurface of the field is composed of 35–45 m of thin-layered marly Cretaceous limestones, deposited on pure and massive Jurassic limestones. The interface between these two units is a sloped monocline bedding plane dipping at 20° toward Nord-West (Wang et al., 2016).

The Terrieu field is located in the Lez regional aquifer. Temperature and electrical conductivity measurements, and packer tests in boreholes presented in previous works (Jazayeri Noushabadi, 2009; Dausse, 2015) have shown the existence of preferential flow paths (shown in Fig. 1) along the bedding plane between the Cretaceous and Jurassic limestones. Downhole videos in the boreholes show, that, at this interface, karstic conduits with aperture up to 50 cm are present (Jazayeri Noushabadi et al., 2011).

The massive Jurassic limestones are non-aquifer and the Cretaceous limestones have a low permeability. This causes the aquifer to be confined at the interface between these two layers, in the bedding plane. A network of karstic conduits has developed preferentially on this bedding plane, and controls the fluid circulation within the aquifer.

### 2.2. Harmonic pumping investigation

The main dataset used in this study was collected from an investigation using harmonic pumping tests performed at the Terrieu site. We have conducted pumping sequentially in four different boreholes while