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Spatial organization of the impulse response in a karst aquifer

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SUMMARY

Karst aquifers are characterized by a strong heterogeneity in their physical properties. The purpose of the study is the spatial variability of water transfers in a carbonated karstic aquifer. To this end, a high spatial density of information about the water transfer is needed. The characteristics of the site, a topographic hill of 13 km^2 with eight boreholes, which was monitored hourly over four years, allows the study of the spatial variability of water transfers. The variability of the impulse response of the system is studied using autocorrelation and cross-correlation analysis between the rainfall and piezometric level time series. The shapes of the autocorrelation and cross-correlation functions vary according to the geographical location of the boreholes, that proves a spatial organization of the groundwater transfer. The response time varies depending on the thickness of the unsaturated zone by an unusual inverse correlation. In this case, the water level signal spatially integrates the signal transfer of the unsaturated zone and the signal transfer of the saturated part of the aquifer. Consequently, inertia and response time increased with the distance between the borehole and the top of piezometric dome. This description supports highly organized fast transfers in this karst aquifer and a highly connected fracture network.

1. Introduction

Karst aquifers represents a large part of the groundwater resource used for the drinking water in the world (Ford et Williams, 1989). Nevertheless, karts aquifers are characterized by a high vulnerability to the pollution. Karst aquifers are known to hold several types of streams: quick flows in a large porosity (conduit or fracture porosity) to diffusive flows in a matrix porosity (Atkinson, 1977; Delbart et al., 2014a; White, 1969). The presence of conduits and fractures induces a spatial variability of the permeability. Thus, to protect the groundwater resources in karst aquifers, a better understanding of the dynamics in this type of reservoir is necessary. Particularly, the question about the spatial organization and more exactly, know if in despite the wide permeability and porosity distribution, the groundwater flows in a karst aquifer could be organized is essential. Indeed, it could improve the modeling of karst aquifers, notably in attempts to define vulnerability maps or to model diffuse pollutions in groundwater.

Not many studies are interesting of the spatial variability of water transfer in karst at high resolution. Indeed, most karst catchment studies are based on either the study of one or two springs or boreholes (Amraoui et al., 2003; Bouchaou et al., 2002; Chen et Goldscheider, 2014; Fiorillo et Doglioni, 2010; Panagopoulos et Lambrakis, 2006). Alternatively, in the cases studying the spatial distribution, the scale is typically regional with poor spatial resolution (Doctor et al., 2006; Larocque et al., 1998; Rahnemaei et al., 2005; Slimani et al., 2009; Valdes et al., 2007, 2014). Nevertheless, several authors have attained high spatial resolution but only in the case of well-developed conduit networks and the presence of gallery (Barbel-Perineau et al., 2015; Perrin et al., 2003).

Signal processing tools, such as correlation and spectral analysis, can be used to decipher the behaviors of the karst aquifers. These statistical methods have been developed principally by Jenkins and Watts (1968) and Box et al. (1994) and adapted to karst systems by Mangin (1975). Spectral and correlative analysis can be applied between rainfall and spring discharge to provide information about the water transfers in the entire aquifer (Angelini, 1997; Eisenlohr et al., 1997; Fiorillo et Doglioni, 2010; Jukić et Denić-Jukić, 2015; Mangin, 1984; Zhang et al., 2013) or between rainfall and the piezometric level to provide information about several parts of the aquifer (Larocque et al., 1998; Lee et

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Lee, 2000; Lee et al., 2006; Valdes, 2005). Two types of correlation analyses are typically used: the auto-correlation and cross-correlation function. The autocorrelation analysis characterizes the individual structure of the time-series and its linear dependency over a period of time. The cross-correlation analysis characterizes the link between the input and output signals and usually considers rainfall as an input and spring discharge or water level as an output (Mangin, 1975). If the rainfall can be considered random, the cross-correlation between rainfall and water level or discharge time series characterizes the impulse response of a karst system. From correlation analyses, several parameters that define the karst aquifer can be determined, such as the inertia and response time. In the case of a weak surface area, we can assume the input signal, the rainfall, homogeneous over the entire site. Thus, any variability in the impulse response is a result of the karst function.

In this paper, we take advantage of a study site, located in Burgundy (France), characterized by a high density of monitored boreholes: 7 boreholes in a 13 km^2 topographic hill (0.6 boreholes/km^2). This high spatial resolution is exceptional in a karst context and aids in describing the details and the spatial variability in water transfer processes.

The aim of this work is to study the spatial variability of water transfers in a karst aquifer located in Burgundy (France) to (i) provide a better understanding of the dynamics in this karst reservoir to protect this water resource and (ii) analyse how the water flows in a karst aquifer could be organized despite the wide permeability and porosity distribution. Thus, we propose to study the spatial variability of the aquifer response to rainfall events. To achieve this, we analyse the rainfall and water level time series of eight boreholes using autocorrelation and cross-correlation analysis. From these analyses, several characteristic parameters of the impulse response can be compared and placed spatially on a cross-section schematic of the aquifer to determine the detailed water flow processes in this karst aquifer. Furthermore, in a previous publication (Delbart et al., 2014), the application of the sliding window cross-correlation method on the piezometric level and rainfall time series of the study site showed a temporal variability of the response time. Therefore, the issue is to understand if the spatial organization of the flow transfer, on the study site, is time dependent.

First, we present the study area, data acquisition and the correlation analysis methods. We then apply the autocorrelation and cross-correlation between rainfall and piezometric level time series to study the variations of the inertia and response time of the aquifer. Then, we discuss the origin of the response time and inertia spatial variation and discuss the implications for understanding the fast water transfer involved in this karst aquifer.

2. Study area

2.1. Geographic, morphologic and climatic context

The studied system is a 13 km^2 carbonated fractured hill located in Burgundy, 30 km northwest of Dijon in eastern France (Fig. 1). The studied system is in the catchment of the Douix de Léry River (Fig. 1), which is approximately 40 km^2. From a morphologic point of view, the studied site is characterized by an approximately 13

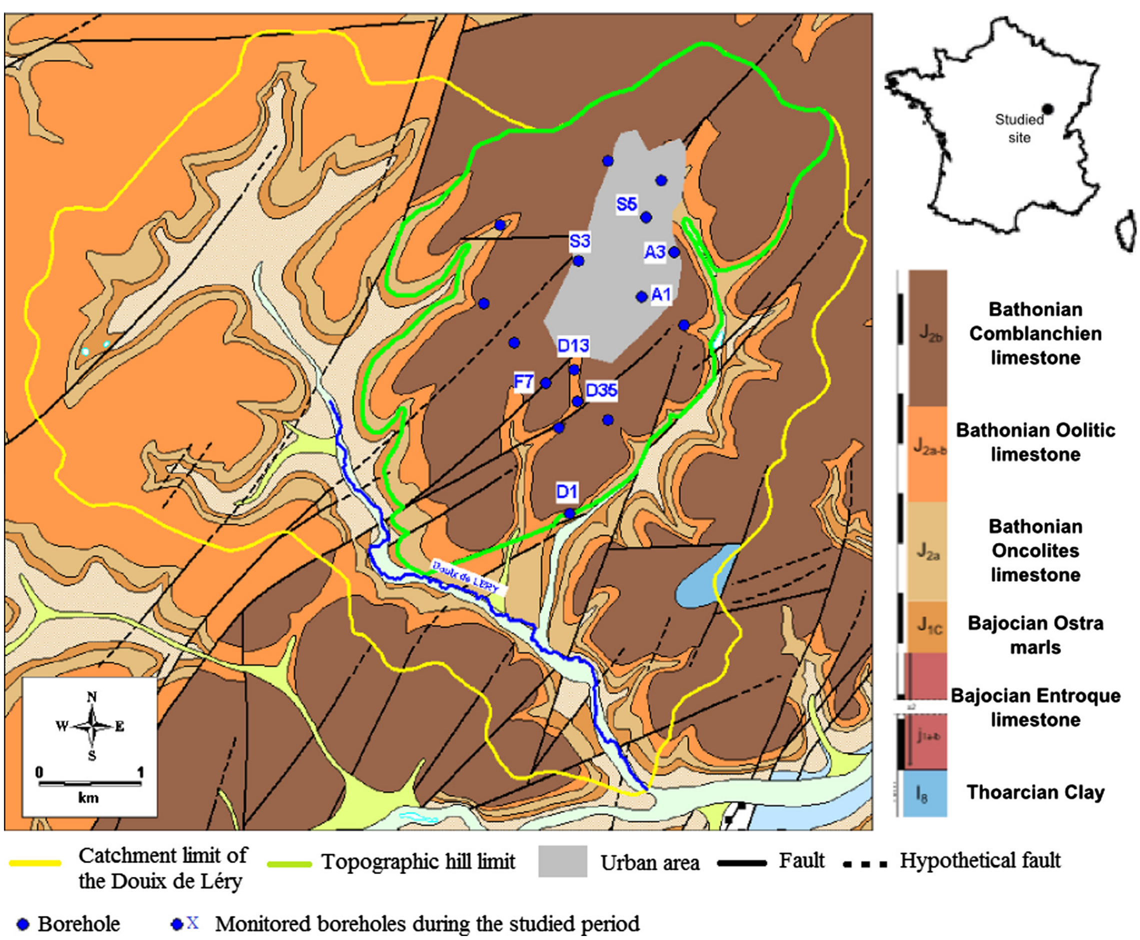

Fig. 1. Description of the studied area (modified from BRGM, 2004).