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Temporal variability of karst aquifer response time established by the sliding-windows cross-correlation method

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SUMMARY

We study the temporal variability of water transfer through the infiltration zone of a karst aquifer by estimating the impulse response of the system using cross-correlogram analyses between rainfall and piezometric level time series. We apply a sliding-window cross-correlation method, which calculates cross-correlograms on partially superposed short time series windows. We apply this method for rainfall and piezometric level time series at six boreholes in a fractured karstic aquifer located in Burgundy, France. Based on cross-correlogram functions, we obtain a time series of response time. At most of the boreholes, the cross-correlation functions change over time, and the response times vary seasonally, being shorter during the summer. This unusual structure can be partly explained by the seasonal variability in rainfall intensity, which is higher during the summer (May–September), inducing the seasonal behaviour of the epikarst. During the summer, when rainfall intensity is higher, the epikarst is more easily and quickly saturated. This induces an increase in lateral water transfer within the epikarst and an increase in concentrated fast flows. We also show that the response time seems to tend towards a limit which represents the maximum saturation of the epikarst.

1. Introduction

Karst aquifers are usually characterised by heterogeneous physical properties and multiple transfer velocities due to the presence of open conduits created by the dissolution of calcite (Aquilina et al., 2005; White, 2002). However, regardless of the degree of karstification and the extent of the conduit network, aquifers present a distribution of transfer velocity from low and diffuse flow to fast and conduit flow (Atkinson, 1977; Larocque et al., 1998; White, 1969).

Numerous methods have been proposed to decipher and describe the functioning of karst aquifers. Classical techniques include geologic and geomorphologic observations, pumping tests (McConnell, 1993; Thrailkill, 1988), tracer tests (Goldscheider et al., 2008; Käss, 1998; Kogovsek and Petric, 2003; Smart, 1988), analysis of chemographs of major chemicals, stable isotopes and carbon-13 (Aquilina et al., 2005; Emblanch et al., 2003), analysis of recession curves (Atkinson, 1977; Birk and Hergarten, 2010; Kovács and Perrochet, 2008; Mangin, 1984; Milanovic, 1981; Shevenell, 1996), spectral and correlation analysis, wavelet analysis (Angelini, 1997; Jukić and Denić-Jukić, 2011; Labat et al., 2000; Larocque, 1997; Mangin, 1975; Panagopoulos and Lambrakis, 2006; Rahnemaei et al., 2005), geophysical investigation (Jacob et al., 2008), reservoir models (Fleury et al., 2007; Geyer et al., 2008; Jukić and Denić-Jukić, 2009; Tritz et al., 2011), spring hydrograph models from spectral analysis (Jukić and Denić-Jukić, 2004) and numerical and physical models (Dreybrodt, 1996; Dreybrodt et al., 2005; Eisenlohr et al., 1997; Scanlon et al., 2003).

The karst investigations previously presented have defined a basic conceptual model of the karst system in two parts: the infiltration, or unsaturated, zone and the saturated, or phreatic, zone.

The infiltration zone consists of two parts: the epikarst and the transition zone. The epikarst is the uppermost zone of carbonate rocks that are particularly corroded or fractured, due to stress

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release, weathering and dissolution (Klimchouk, 2004). The contrast in permeability between the epikarst and the transition zone gives the epikarst the ability to regulate water infiltration and storage (Aquilina et al., 2005; Bakalowicz, 2010; Mangin, 1975; Perrin et al., 2003). The infiltration from the epikarst towards the transition zone is divided into two components: a slow seepage from the base of the epikarst and a concentrated flow through high conductivity conduits. The lateral component flow is significant in the epikarst, allowing the water to converge towards vertical fissures (Perrin et al., 2003). The transition zone is the zone between the epikarst and the saturated zone. The flow is essentially vertical. Two types of water flow coexist: slow flow in small fractures and quick flow in large conduits.

The saturated zone can be divided into two subparts: conduits that mostly drain water towards the karst spring and a low permeability volume where water is stored. The storage capacity of the saturated zone is still in question, and several models have been proposed: a model in which water is stored in matrix or fractures (Drogue, 1974; Mudry, 1990) and a model in which water is stored in karst voids (Mangin, 1975).

The goal of this project is to characterise the functioning of a karst aquifer located in Burgundy, France, to protect water resources from accidental pollution. In this paper, we analyse the seasonal variability of the impulse response of this aquifer. We determine the impulse response of the karst aquifer from cross-correlation analyses between rainfall and piezometric levels and adapt this method to study the variability of the impulse response over time with the application of cross-correlation analyses over three-month periods by sliding windows.

Correlation and spectral analyses are methods based on statistical tools developed principally by Jenkins and Watts (1968) and Box et al. (1994) and adapted to karst systems by Mangin (1975). A karst aquifer can be viewed as a filter transforming an input signal into an output signal by a transfer function (Mangin, 1984; Mathevet et al., 2004; Walliser, 1977). Once defined, this function can be interpreted to define the functioning, organisation and structure of karst aquifers.

Two types of correlation analyses are typically used: auto-correlation and cross-correlation. The first analysis characterises the individual structure of the time-series and its linear dependency over a period of time. The second analysis characterises the link between the input and output signals and usually considers rainfall as an input signal and discharge at a spring as an output signal (Mangin, 1975). This cross-correlation is the picture of the impulse response of a karst system, if the rainfall can be considered random. From this analysis, the average response time of the aquifer to a rainfall event can be computed.

Historically, in karst aquifers, spectral and correlative analyses are conducted between precipitation and spring discharge, giving information on the entire system. Some authors use these methods for other types of time series. From piezometric levels, they obtain information at several locations of the aquifer to evaluate the impact of unsaturated or epikarstic zones. Some authors propose to adapt this method to study the mass transfer in aquifers using conductivity (Bailly-Comte et al., 2011; Larocque et al., 1998), turbidity (Amraoui et al., 2003; Bailly-Comte et al., 2011; Bouchaou et al., 2002; Massei et al., 2006) and temperature (Bailly-Comte et al., 2011) time series. Some hydrogeologic processes are underlined by a temporal lag between piezometric and geochemical variation, such as surface water arrival (Hanin, 2010).

The size of time series can vary depending on the goal of the study. Previous studies on long periods (pluri-annual time series) have given global information on the system (Andreo et al., 2006; Larocque et al., 1998; Pulido-Bosch et al., 1995; Rahnemaei et al., 2005). Some authors compared several hydrological cycles and analysed the variability of the impulse response depending on the cumulative precipitation (Hanin, 2010; Larocque et al., 1998). Lee et al. (2006) chose three-month periods, and Larocque et al. (1998) divided the hydrological year along the low and high water table periods. Both authors established that the seasonal variability of the impulse response provides a picture of the seasonal variations of the water table (variability of unsaturated zone thickness, variability of network saturation). A method to study the temporal variation of properties within the aquifer was proposed by Bailly-Comte et al. (2011). They used a sliding cross-correlogram method between temperature and specific conductivity time series and established that residence time variations are connected with flow (high and low flow).

In this paper, we analyse the temporal variability of the impulse response using the sliding cross-correlogram method between rainfall and piezometric level time series to interpret temporal variability in seasonal hydrological processes.

First, we discuss the study area, data acquisition and the sliding cross-correlation method. We then apply this method to study the temporal variation of the response time and discuss the implications for understanding the physical mechanisms involved in this karst aquifer.

2. Study area

The study area is located in Burgundy, 30 km to the northwest of Dijon in eastern France (Fig. 1). The study zone is on the catchment of the Douix de Léry River (Fig. 1). This area is approximately 40 km^2, with a maximum altitude of 501 m NGF and a minimum altitude of 336 m NGF. The land in this catchment is composed of forest (82.5% of total surface), agricultural land (13% of total surface) and urban area (4.5% of total surface). The urban area, located on the north of the study site (Fig. 1), is principally composed of parking lots, roads and buildings, which cause runoff and some preferential zones of infiltration downstream of the urban area.

The climate is continental. The average atmospheric temperature is approximately 9.7 °C, with a maximum temperature in June, July and August, and the cumulative rainfall by hydrological cycle ranges between 689 mm and 1214 mm, with an average of 955 mm (1992–2012, Météo-France data at Saint Martin du Mont station, located 18 km south-southwest of the study site centre).

From June 2007 to October 2012 (the period of study), the cumulative rainfall does not present significant inter-annual changes. The average cumulative rainfall in a hydrological cycle is 916 mm, with a standard deviation of 55 mm. The rainiest hydrological cycle is October 2011–October 2012, with a cumulative rainfall of 978 mm, close to the average over the 1992–2012 period. The least rainy hydrological cycle is October 2010–October 2011, with 832 mm of cumulative rainfall, 13% less than the average values of the last twenty years. The monthly cumulative rainfall is not seasonally distributed. The average intensity of rainfall, in mm/h, which is defined as the average intensity of rainfall in mm/h without taking into account the intensities equal to zero, varies seasonally. The intensity of rainfall is highest in July and August and lowest in January and February (Fig. 2).

The geologic section is composed of tabular Jurassic limestones interspersed by marls, allowing the development of two superposed aquifers. In this publication, only the upper one will be monitored and studied. The subsurface is composed of several layers of limestone: comblanchien, oolitic and oncholite limestones underlain by marls of the Upper Bajocian formation (Fig. 1). The thickness of the limestone layer varies from 0 m (spring location) to 70 m, depending on the location. The studied aquifer is located in the oncholite limestone layer.

The limestones are characterised by three types of porosity. Matrix porosity is related to the internal structure of the limestone,