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Identifying the impact of climate and anthropic pressures on karst aquifers using wavelet analysis

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SUMMARY

This paper assesses the implications of climate and anthropic pressures on short to long-term changes in water resources in a Mediterranean karst using wavelet analysis. This approach was tested on 38-year (1974–2011) hydrogeological time series recorded at the Lez spring (South France), which is exploited for water supply. Firstly, we investigated inter-relationships in the frequency domain by cross-correlation across multiresolution levels. Our results showed that rainfall and spring discharge are highly correlated in the high frequency domain which reflects the hydrogeological response during flood events of typical highly karstified systems. Pumping and groundwater level are correlated in a lower frequency domain, illustrating seasonal to multi-year relationships. Secondly, continuous wavelet transform was applied to characterize the temporal variability of the inter-relationships involved. On the contrary to examples of "non-managed" karst aquifers in the literature, our results showed that the 10-year rainfall component was attenuate in the discharge signal. We assume that the reason is that the storage variations are strongly affected by pumping. This interesting result shows that possible long-term impacts of rainfall variability due to climate change may be masked by a high pumping rate. We showed also that despite an increase of the pumping rate from the 1980s, the stress on the groundwater resource does not increase from year to year. The present pumping strategy does not affect the drawdown in the long term, avoiding an over-exploitation of the aquifer. Finally, this study highlights the effectiveness of wavelet analysis in characterizing the response variability of karst systems where the hydrogeological regime is modified by pumping.

1. Introduction

Groundwater is a major global water supply resource and is currently affected by two main stressors: climate and anthropic pressures. This is essentially true for aquifers pumped for water supplies in Mediterranean areas due to increased abstraction to meet the needs of the growing population in regions where the aquifer is irregularly recharged from one year to the next. Evaluating the impacts of climate and anthropic pressure on water resources in such regions is a major challenge, as most large aquifers are located in carbonate rocks subject to karstification. The hydrogeological response of karst systems is highly non-linear due to spatial and dynamic heterogeneities linked to fact that the void structure leads to the formation of preferential drainage axes (for reviews see Bakalowicz, 2005; Goldscheider et al., 2007). Some of karst aquifers are an important water source for major cities, particularly in Mediterranean regions. In these cases, the aquifer may be referred to as "actively managed" if the pumping rate is higher than the low water stage discharge rate of the system under natural conditions in summer. Then, groundwater storage is highly mobilized before the rainy autumn period that contributes most of the annual recharge each year. In this paper, we investigate climatic and anthropic impacts on the groundwater resource in a Mediterranean karst system under active water management. We ask whether pumping modified the hydrogeological response.

Wavelet analysis has become a powerful technique to study geophysical processes or signals (Kumar and Foufoula-Georgiou, 1997; Torrence and Compo, 1998). Decomposing a time series into time-scale space, this method localizes power variations within a time series. It is ideal for analysing non-stationary signals and identifying short- to large-scale periodic phenomena. In the field of hydrology, continuous wavelet transforms (CWT) have recently been used to study the effect of climatic phenomena on the stream flow regime (Labat et al., 2005; Massei et al., 2007; Labat, 2010; Fu et al., 2012), or to study runoff processes (Lafrenière and Sharp, 2003; Schaefli et al., 2007). CWT has been widely used to study the hydrogeological behavior of karst systems. Comparing three

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springs, Labat et al. (2000, 2002) demonstrated the potential of wavelet analysis in identifying karst properties in relation to the degree of karstification. Structural heterogeneity also determines similar filtering properties on a small basin scale (Chinarro et al., 2011) and on a large scale (Hao et al., 2012): (i) short time-scale signals are generally less filtered showing the transmissive role of the conduit network, (ii) and high-energy large timescale signals can penetrate through the aquifer, illustrating the buffered role of the storage zone. In a Mediterranean context, this allows us to visualize annual and multi-annual scale components in relation to North Atlantic Oscillation (Andreo et al., 2006). The hydrogeological response has also been studied from a physico-chemical time series: to investigate transport properties and turbidity dynamics (Massei et al., 2006), to highlight temperature-runoff relationships during snowmelt (Mathevet et al., 2004), or to study groundwater variations in relation to the geological context (Slimani et al., 2009). Surface–groundwater interactions were also studied using CWT to improve understanding of river flow components in karst environments (Salerno and Tartari, 2009). But, there is a lack of knowledge regarding the identification of the respective role of climatic and anthropic pressures on the resource of karst aquifers.

Generally, CWT provides a good representation of energy distribution in time-scale space in all these works, highlighting the non-stationary nature and multi-scale behavior of karst systems. However, to overcome limitations arising from intrinsic redundancy of the CWT representation, Labat et al. (2000, 2001) applied an orthonormal wavelet representation, conserving the signal information, as a complementary approach. This multiresolution analysis (discrete wavelet transform DWT) can be used to decompose a signal into successive resolution levels. It allows the energy distribution across levels to be characterized and the slow and fast components in a spring discharge time series to be distinguished. This complementary DWT technique allows easier and more efficient interpretation of the energy distribution across decomposition scales, assisting the study of the time–frequency space of time series. It can thus greatly improve hydrogeological understanding of karst systems, but is rarely found in the literature. From these latest studies showing the significant potential of combined CWT and DWT, we expect that both approaches will be adapted to characterize on groundwater resources the response to the cumulative effect of climatic and anthropic pressures.

To assess the impacts of climatic and anthropic pressure on groundwater resources in a karst system under active water management, this study aims to distinguish between the role of rainfall and pumping on the karst response using wavelet analysis. As a first step, a multiresolution analysis was performed in order to characterize the energy distribution across scales. To identify the frequency domain where rainfall and pumping may influence the karst system, we also present a cross-correlation across multiresolution levels. As a second step, continuous wavelet analysis was applied to track changes in phenomena over time, providing information on the temporal variability of the karst response to climatic and anthropic stressors. We applied these techniques on rainfall, pumping, discharge and piezometric time series over a 38-year period (1974–2011) in the Lez aquifer in the South of France.

2. Site and measurements

2.1. Study site

2.1.1. Presentation

The Lez karst is located to the north of Montpellier in the Cévennes area in the South of France, in the western section of the Mediterranean zone. The Lez karst system is part of the North Monpelliérains karst hydrogeological unit bounded to the west by the Hérault River and to the north and east by the Vidourle River (Fig. 1). The Lez karst aquifer is located in Upper Jurassic formations between 650 m and 800 m thick, located on both sides of the Matelles fault. The aquifer is unconfined to the west of the fault, while the section located to the east may be partially captive. In the zone lying under a Tertiary overburden, the aquifer is found in the Upper Jurassic and the Lower Cretaceous. A more detailed description of the study area can be found in Ladouche et al. (2014).

The Lez spring is the main outlet of the karst system (Fig. 1). The spring outlet has been explored by cave-divers. They discovered a huge saturated sub-horizontal karst conduit developing more than 400 m inland (Fig. 2), with a diameter ranging between 5 and 10 m. The exploration ended at 113 m deep below the spring outlet (−48 m ASL) in a zone where the conduit become wider. The hydrogeological basin is estimated to cover an area of 380 km^2 (Thiery et al., 1983). Different recharge zones can be distinguished, depending on the nature of the geological overburden. Recharge of the aquifer takes place predominantly in Jurassic limestone, occupying an area of 80–100 km^2 (Fig. 1). Within the Cretaceous overburden (120 km^2), losses occur locally along temporary watercourses and feed the aquifer locally during flood events. The Tertiary formations occupy an area of about 160 km^2. In general these are considered as impermeable or almost impermeable and do not contribute to recharging the Lez karst aquifer.

The drinking water supply of the Montpellier agglomeration (with about 340,000 inhabitants) comes from the Lez karst spring since the 19th century (1854). Before 1968, this resource was used by gravity extraction, varying between 25×10^{-3} and 0.6 m^3/s (Paloc, 1979). From 1968 to today, the Lez karst spring is pumped according an active management strategy, the pumping flow rate during summer periods is greater than the spring's low-water discharge so as to mobilize the aquifer's stored reserves (Avias, 1995). From 1968 to 1982, water was abstracted by pumping in the Lez Spring basin (Fig. 2a) at a rate of the order of 0.8 m^3/s. From 1983 onwards, deep boreholes located in the main karst conduit located upstream from the spring (Fig. 2) have allowed pumping at a rate of up to 1.7 m^3/s (Avias, 1995). The pumping flow rates during low groundwater levels (1.2–1.7 m^3/s) currently exceed the pumping flow rates during high groundwater levels (0.9 m^3/s). The minimum groundwater level is fixed at 35 m a.s.l in the main conduit. The maximum drawdown permitted from pumping is thus 30 m below the overflow threshold of the spring (65 m a.s.l., Fig. 2b). The lowest water level (i.e. 35 m a.s.l.) was reached during the 1995 hydrological cycle. For environmental reasons, a reserve flow rate of 0.160 m^3/s is restored for the Lez River downstream of the spring when it is not overflowing.

2.1.2. Hydrogeological background

The conceptual scheme of the Lez aquifer, built by Salado and Marjolet (1975) and completed recently by Bicalho et al. (2012), shows that the water from the Lez spring comprises a mixture of water from three main units in the aquifer: (i) water from the aquifer in the Upper Jurassic limestone and the Lower Cretaceous; (ii) surface water (losses) after interacting with the Cretaceous formations; and (iii) water from deep circulation in the underlying Middle Jurassic, having long residence time.

The hydrogeological functioning of the Lez karst system has been characterized using various rainfall-discharge modelling approaches accounting for pumping (Guilbot, 1975; Thiery and Bérard, 1984; Fleury et al., 2009). These works showed that pumping during low water periods draw out reserves coming from less transmissive zones in addition to the well-drained reserves. An assessment of this pumping influence area around the network