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Semi-distributed lumped model of a karst system under active management

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SUMMARY

In this paper inverse modeling is used to characterize the regime of a karst aquifer subjected to extensive pumping in a conduit located upstream of its main outlet. The systemic approach uses a transfer model that is based on computing the convolution integral of up to several signals, e.g., efficient rainfall, pumping, to simulate flow rates and groundwater levels in both the karst conduit and the carbonate matrix at the aquifer outlet and in several parts of the catchment area. The model is a semi-distributed lumped model which simulates the hydrological response of a heterogeneous karst aquifer made up of different hydrologic compartments, and is applied to the Lez karst system, France. Groundwater is abstracted near the system's major outlet at a higher rate than the low-water spring discharge, thereby mobilizing stored groundwater during low-water periods ('active management').

The model's results are very satisfactory, especially for the karst system outlet, where the water levels are particularly well reproduced. The model can also simulate the natural, i.e., non-pumping, state of the karst system and thereby estimate the impact of active management on the water resource.

1. Introduction

Numerical models for karst aquifers usually fall within two main categories (Goldscheider and Drew, 2007): lumped-parameter or reservoir models (Dreiss, 1983; Pinault et al., 2001a,b, 2004) and distributed physical models (Birk et al., 2003; Liedl et al., 2003). Owing to the high degree of heterogeneity of karst aquifers, distributed models (Birk et al., 2000; Teutsch and Sauter, 1998) can be relatively difficult to implement and calibrate because of difficulties in obtaining the necessary input data. These difficulties have limited the use of such models in karst hydrogeology. Dual-porosity models with implementation of discrete pipe networks within a limestone matrix (Cornaton and Perrochet, 2002) represent a promising approach for testing hypotheses on the conceptual representation of water interactions between the matrix and pipe networks. However, because the available data on karst conduit geometry are generally very limited, this modeling approach is difficult to implement. The lumped-parameter model is simpler and considers the karst as a whole; it uses the relationship between rainfall and discharge (bivariate analysis) to characterize the karst flow regime, and can potentially be used for a karst hydrosystem in which these data are available (Denic-Jukic and Jukic, 2003; Dorfliger et al., 2009; Padilla and Pulido-Bosch, 2008; Jukić and Denić-Jukić, 2009; Martínez-Santos and Andreu, 2010; Moussu et al., 2011; Long and Mahler, 2013). However, some karst aquifers are characterized by geographical or hydrogeological subsystems that can be considered as homogeneous units at the scale of interest which potentially are hydraulically connected to each other at the scale of the karst catchment area. In such cases, a lumped parameter model applied to the overall catchment cannot take this hydrodynamic heterogeneity into account. One option, if the necessary data are available, is to consider a lumped parameter modeling approach for each subsystem and then to aggregate the results in order to represent the overall flow regime of the karst aquifer at its outlet. This is an intermediate approach between the lumped parameter model and the distributed physical model, and here is termed a semi-distributed lumped parameter model.

Karst aquifers can form major groundwater reservoirs (Bakalowicz, 2005) and are locally pumped to meet growing drinking-water requirements due, in particular, to population growth. 'Active management' through pumping from the main karst conduit in the vicinity of its outlet enables optimal exploitation of a karst groundwater by avoiding the negative effects of large low-water discharge variations at the springs. Active management can thus be defined as pumping at a flow rate greater than the spring's low-water discharge rate so as to mobilize the

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aquifer's stored reserves (Avias, 1995). These reserves are then replenished during the following rainy season, resulting in less intense floods at the start of the season (Fleury et al., 2008). In such cases the karst system is characterized by two distinct types of flow regime: (i) a high-water flow regime when the natural outlet discharge is greater than the pumping rate and the system functions naturally; and (ii) a low-water flow regime when the natural outlet discharge is lower than the pumping rate, and the pumped flow rate is the sum of the natural outlet discharge plus the mobilized karst storage flow desaturating the conduits and the matrix (Maréchal et al., 2008). Generally, when a karst system has been exploited over a long period, no observations of the system's natural flow regime are available and it is therefore difficult to reconstruct the system's 'natural' rainfall–discharge relationship: this is a similar to attempting to determine hydrological processes in ungauged basins (Sivapalan, 2003).

The Lez spring karst system, in southern France, has been an ideal site since the 1970s for studying and modeling a flow regime. Most of the numerical models developed for studying the aquifer's hydrodynamics with a view to groundwater exploitation are based on the laws for draining several reservoirs (Guilbot, 1975; Thiery et al., 1983; Fleury et al., 2008). These models are thus unable to describe the functioning of the various hydrogeological units of the hydrosystem, and especially that of the western compartment of the Matelles Fault (Mazzili, 2011; Mazzilli et al., 2011). The main aim of our work here was to develop a lumped parameter modeling approach suitable for (i) a karst system whose overall flow regime results from the juxtaposition of identified subsystems, and (ii) a system that was under 'active management' for a long period of time and for which the natural flow regime, in particular at the outlet, is unknown. The final objective of this work was to develop a modeling approach that is able to predict the water levels and spring discharge so that the impact of global change scenarios on the Lez karst system could be assessed.

2. Study area

The Lez karst system forms part of the North Montpellieran Garrigue hydrogeological unit delimited by the Hérault river (to the west) and the Vidourle river (to the north and east, Fig. 1). The Lez karst aquifer, between 650 and 800 m thick, lies within the Upper Jurassic layers on both sides of the Matelles-Corconne Fault (here termed the 'Matelles Fault'). The aquifer is unconfined in the western compartment of this fault and locally confined in the eastern compartment (Fig. 2a). The base and top of the Lez karst aquifer in the eastern compartment are respectively Callovian–Oxfordian marls (Middle Jurassic) and a thick succession of Lower Valanginian (Lower Cretaceous) marls and marly limestone; the aquifer itself straddles in the Upper Jurassic and the Berriasian (Lower Cretaceous). The karstification of the main conduit below its top wall in the eastern compartment was confirmed as −10 m (a.s.l.) by diving, and down to −48 m (a.s.l.) by drilling (Fig. 3). The geometry of the conduit is known only between the spring and a few boreholes located 400 m away: this lack of knowledge at the watershed scale prohibits the application of any distributed modeling approach. A southward structuring of the aquifer, with the development of karstification at depth and an underground drainage in the direction of the Mediterranean, is probable and almost certainly related to the Messinian salinity crisis (Clauzon et al., 2005; Avias, 1992). However, the compressive tectonics of the Eocene Pyrenean–Provençal phase, in addition to filling the paleo-outlet with impermeable Miocene and Pliocene sediments from the Messinian canyons, gave this large karst aquifer a 'confined karst' character with the presence of upstream overflow springs, such as the Lez spring and the intermittent Lirou spring.

The Lez spring with its overflow at 65 m (a.s.l.) is the main outlet from the karst system. The area of the hydrogeological catchment is estimated to be 380 km^2, based on the geology, identification of the impervious structural limits, dye tracings, and groundwater level dynamics in the network of observation boreholes during the drawdown in the spring's conduit (Thiery et al., 1983, Fig. 1). Several recharge zones can be identified within this basin according to the nature of the exposed geological formation: (i) the Jurassic limestone outcrop (between 80 and 100 km^2) is the main area of recharge from effective rainfall (Fig. 1); (ii) the Cretaceous marly-limestone formations (120 km^2), which are much less permeable than the Jurassic, provide leakage to the underlying Jurassic and contain identified loss zones with direct recharge to the underlying Jurassic aquifer from surface streams (swallow holes) and in particular along tectonic faults; (iii) the Tertiary formations (160 km^2), which are generally impervious and which contribute insignificantly to the karst aquifer recharge.

The Lez spring has been supplying the city of Montpellier since 1854. Prior to 1968, the resource was exploited through spring overflow collection, which ranged between 25 and 600 l/s (Paloc, 1979). From 1968 to 1982, abstraction was carried out by pumping in the panhole at a rate of some 800 l/s. This period was the prelude to 'active management' of the Lez karst system, with pumping rates in the summer periods being greater than the natural discharge without any pumping. By the end of the 1970s increased demand for drinking-water supply had motivated the managers to extract the resource at a rate higher than 800 l/s. For this reason, in 1982 deep wells were drilled into the main karst conduit upstream of the spring in order to obtain a maximum yield of 2000 l/s (Avias, 1995). The current pumped rates at the low-water stage (between 1200 and 1700 l/s) are greater than those pumped at high water (900 l/s). The maximum pumping rate is now fixed at 1700 l/s so that the minimum water level (Fig. 4) is no lower than 35 m a.s.l., i.e., 30 m below the elevation of the spring's outlet. A reserve flow of 160 l/s returns to the Lez River downstream of the spring when the spring is not overflowing.

The karst system's natural discharge (Q_n) is unknown, because the Lez spring has been tapped since 1854 (Paloc, 1979). However, the pumping rate (Q_p) has been measured since 1974 and the spring's residual overflow discharges (Q_r) were reliably measured between 1987 and 2007. The natural high-water flows over this period can be estimated by the equation $Q_n = Q_r + Q_p$ (Fig. 3a) – the natural discharges (Q_n) estimated from these measurements are shown in Fig. 5a.

At low-water stage (Fig. 3b), the pumping rate (Q_p) is between 1200 and 1700 l/s, which is higher than the natural discharge (Q_n) would have been in the absence of pumping. The pumping caused the spring to dry up ($Q_r = 0$). Accordingly, the pumped discharge (Q_p) during the low-water period is interpreted as the sum of the flow that would have occurred naturally in the absence of pumping (Q_n) and the storage flow (Q_s) mobilized by the pumping: $Q_p = Q_n + Q_s$. The yield obtained from the karst storage (Q_s) is interpreted as coming from depletion of the karst conduits and mobilization of matrix water from the carbonates in which the karst drainage network has been developed (Maréchal et al., 2008). Pumping thus mobilizes the karst system's water reserves that are barely or not at all accessible under the karst's natural flow regime. This is reflected in a lowering of the piezometric head (H_4) in the karst conduit (35 m < h_4 < 65 m a.s.l. Fig. 3b).

The Suquet borehole (Fig. 2a) intersects the karst conduit connected to the Lirou spring, which is the main outlet from the Western compartment of the Lez karst system (Paloc, 1987): it thus enables a description of the overall hydrodynamics of this part of the system. During high-water periods (H_2 > 65 m a.s.l.) the groundwater-level response to effective rainfall recharge is very similar to that recorded at the Claret observation borehole. This