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title: # Interpretation of pumping tests in a mixed flow karst system

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INTRODUCTION

Mixed flow karst systems (MFKS) can be conceptualized as dual or triple flow systems comprising localized and often turbulent flow in solution conduits and Darcian flow in the fractures and in the porous rock (Atkinson, 1977). Pumping tests carried out in wells intercepting the solution conduits of a MFKS are difficult to interpret because the geometry of cave networks and connections to the matrix are very often unknown. The present paper describes such a long-duration pumping test. The response of the system is analyzed into the solution conduit and the surrounding carbonate rocks (matrix). An approach using a double-continuum model is developed for the interpretation of drawdown into both the conduit and the matrix. The exchange of flow between the two reservoirs is explicitly modeled using a physically-based approach (varying difference in hydraulic heads) through the application of the superposition principle. The method is applied to a real case study (Maréchal et al. 2008), the Cent-Fonts karst system in the Hérault region of Southern France (Fig. 1).

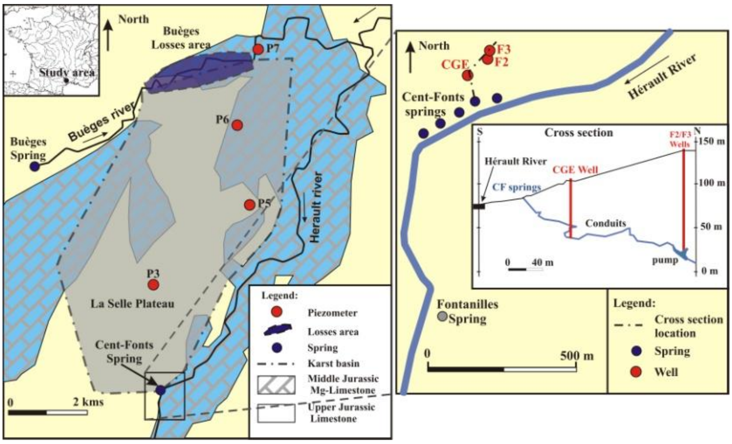

Figure 1. (a) Geological and location map of the Cent-Fonts karst system. (b) Location of pumping well (F3); cross section showing the wells intersecting the conduit network.

STUDY AREA AND DATA

The Cent-Fonts karst (Figure 1) is a MFKS located north of Montpellier (Hérault region, Southern France) in a thick limestone and dolomite series. The Cent-Fonts spring, located on the right bank of the Hérault River, is the only outlet of the karst system (Figure 1a). Its discharge ranges from $Q_S = 0.220$ m^3/s to more than 12 m^3/s ($Q_{Smoy} = 1$ m^3/s). The Cent-Fonts spring is the outlet of a water-saturated karst conduit network that has been partially explored and mapped by divers to a depth of 95 m in the vicinity of the spring (Figure 1b). Three wells intercept the karst network near the spring (Figure 1b): CGE is about 60 m deep, F3 is located about 100 meters upstream from CGE and reaches the largest part of the conduit at a depth of 128 m, and F2 is located 3 meters from F3 in the same conduit. The observation wells located within the karst basin (P3, P5, P6 and P7, Figure 1a) do not intersect the karst conduit.

The plateau, called "Causse de la Selle", is deeply cut by the Hérault River, which flows near the spring and constitutes the present-day base level of the karst system. Sinkholes in the Buèges

River (Figure 1a) provide 50 % of the annual mean recharge of the Cent-Fonts karst aquifer system, the rest being diffuse recharge on the karst catchment area.

Pumping tests were done on the Cent-Fonts karst system (well F3) in 2005 (Maréchal et al., 2008). The main objectives of the pumping tests were to evaluate the capacity of the tapped conduit to mobilize the reserves of the karst aquifer and to identify the potential impact of the pumping on adjacent groundwater systems. The long duration pumping test began with a 0.4 m^3/s flow rate on August 1, 2005. During this pumping test, which lasted more than one month (01/08/2005–06/09/2005), pumping was halted twice on-purpose (09/08/2005 and 02/09/2005) and stopped once due to electrical problems (22/08/2005 less than one hour).

The Buèges river losses contribution was constant at L = 0.015 m3/s during the entire test. Infiltration of Hérault River water to the conduits occurs only in the immediate vicinity of the spring and reaches QR = 0.030 m3/s after August 1 when the hydraulic head in the karst conduit drops below 75 m [Ladouche et al, 2005]. The initial discharge rate at the spring before pumping (July 27, 2005) was measured at QS(0) = 0.255 m3/s with a recession coefficient ⍰ = 0.0021 d-1 (Fig. 2).

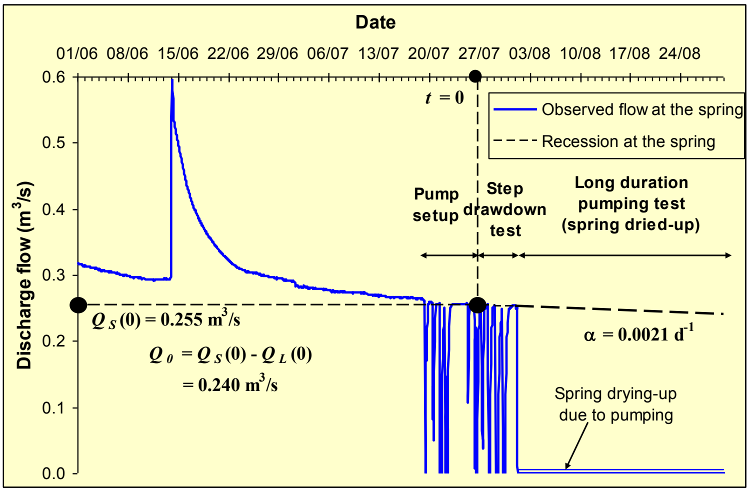

Figure 2. Discharge at the spring before and during the pumping test.

During the pumping test, the drawdown in the matrix is low ($s_{m\,max}$ ≈ 5.1 m as an average on P5, P6 and P7 at the end of the long-duration pumping test, Fig. 3) and depends on the location of the observation wells to karst heterogeneities and pumped conduit network. Measured water level decline in the matrix includes the natural recession of the karst system and is therefore not only induced by the pumping test. Based on the average natural water level recession before pumping tests, the water level decline observed in P5 during the long-duration step is due to both natural recession (25%) and pumping (75%). In P6 and P7, natural recession represents approximately 50% of the observed water level decline.

The final drawdown in the karst conduit is high ($s_{c\,max}$ = 52.17 m; Fig. 3) and does not show any sign of stabilization after one month of pumping. These results show that both matrix (several kilometers away from the pumping well) and conduits are affected by the test but the matrix is much less affected by pumping than the karst conduit. Therefore, the interpretation of the pumping test was focused on the drawdown in the main karst conduit.

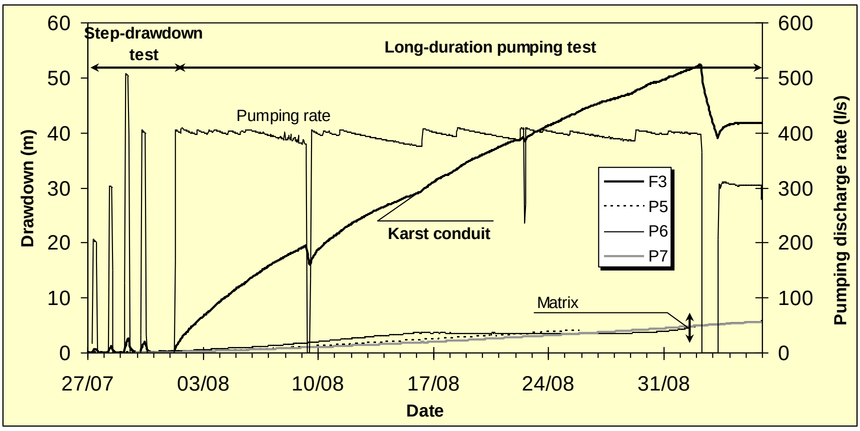

Figure 3. Drawdown during the pumping test. Drawdown is high in the karst conduits (well F3) and low in matrix (P5, P6 and P7).

INTERPRETATION AND MODELLING

Karst water hydraulics is strongly governed by the interaction between a highly conductive conduit network and a low-conductive rock matrix under variable boundary conditions (Liedl et al., 2003). Fig. 4 shows a conceptual model of the Cent-Fonts MFKS with well F3 intersecting the conduit.

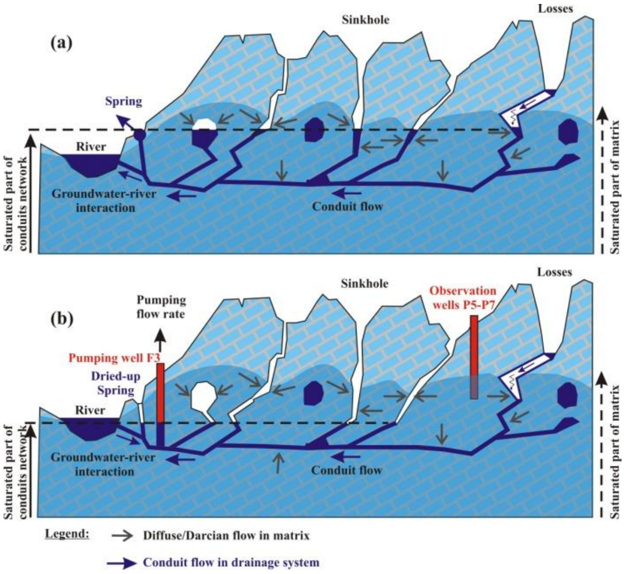

Figure 4. Conceptual model of the Cent-Fonts karst system (a) under natural low flow conditions and (b) when pumping is done in a well intersecting the solution conduit of the same karst system (dark blue: Water in solution voids and conduits; light blue: Water in matrix).

The karst system (Fig. 4a) comprises a main spring connected to a conduit network recharged by surface water losses in a sinkhole system and by flow from the matrix to the conduits. During the pumping tests (Fig. 4b), the highly permeable solution conduits act collectively as the initial source of the water being pumped. Consequently, the hydraulic head in the solution conduits decreases (high drawdown in the conduit network), resulting in an increase in the hydraulic gradient between the matrix and karst conduits. This causes water in the fractures and/or in the porosity of the matrix to flow toward the larger solution conduits at a higher rate than before pumping. At the karst basin scale, since the matrix has a much higher storage capacity than the conduits, the hydraulic head fluctuates much less in the matrix than in karst conduits during the pumping test (very low drawdown in the matrix, Fig. 3).

A modelling approach is proposed for this interpretation. The developed double continuum model consists of two reservoirs-karst conduits and the surrounding carbonate rocks - between which exchange flow rate is modeled (Fig. 5). The total exchange flow β is divided into two components: the natural contribution Q_{α} (recession flow at the spring, Fig. 2) and the induced contribution Q_{IND} (modelled using the superposition principle and the hypothesis of Darcian flow in the matrix considered as an equivalent porous media with transmissivity T_m and storage ϕ_m, Maréchal et al., 2008). The karst conduits are assumed to have an infinite hydraulic conductivity and a finite length.

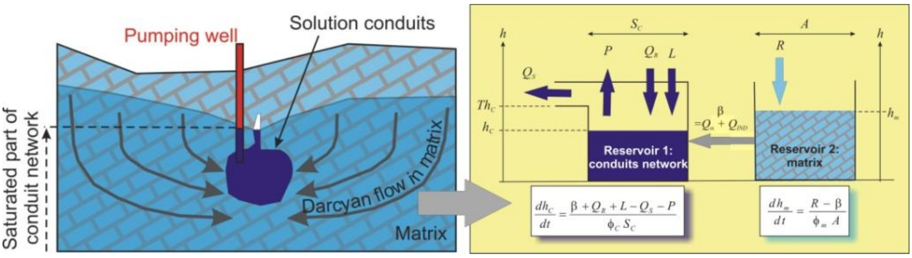

Figure 5. Interaction between matrix and conduit (a) Vertical section of a MFKS (b) sketch of the double reservoir model and volume conservation equations.

Model calibration results (Fig. 6) in a very good match (relative root mean square [rRMS] = 2.3 %) with drawdown measured at the pumping well (karst conduit). It shows that the matrix hydrodynamic parameters (transmissivity T_m=1.6 x 10^{-5} m^2/s and drainage porosity ϕ_m = 0.007) have a greater influence on the drawdown than the storage capacity of the conduit network (ϕ_c = 6 x 10^{-5} at the basin scale). The accuracy of the model relies mostly on a very good knowledge of both pumping rate P and natural discharge at the spring Q_S (with and without pumping).

The sum of the pumping rate and the spring discharge results from the natural contribution of the matrix (Qα), the additional flow from the matrix due to the pumping (QIND), the Hérault river contribution (QR), the Buèges river losses contribution (L) and the dewatering of the karst conduit network. According to the recession function incorporated in the model (Fig. 2), the natural flow from the matrix decreases exponentially from Q_0 = 0.240 m^3/s at the beginning of the pumping down to about 0.219 m^3/s at the end of the test. The additional flow from the matrix induced by pumping increases with time along with the drawdown from Q_{IND} = 0 m^3/s at the beginning of pumping (no induced flow) and up to 0.105 m^3/s (maximum induced flow) at the end of the 0.4 m^3/s pumping step.

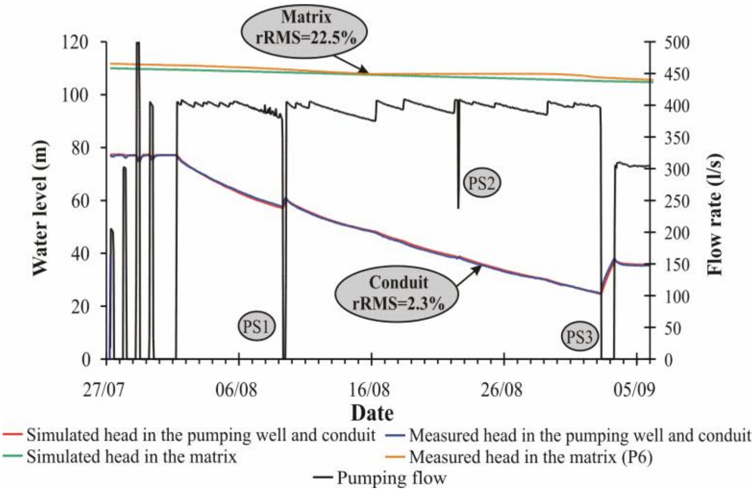

Figure 6. Temporal evolution of simulated and measured drawdown in the conduit and in the matrix using the model (rRMS is computed on drawdown referred to initial water level; PS: pump stop).

The diffuse flow decreases rather quickly after each pumping stop due to recovery in the conduits, and becomes negative when the hydraulic head in the conduit rapidly increases and inverts the hydraulic gradient between matrix and conduits. In that case, the karst conduits recharge the matrix ($Q_{IND} < 0$), similar to what happens during recharge of the aquifer during high-flow periods. The dewatering of the conduit network is the lowest flow component (Fig. 7).

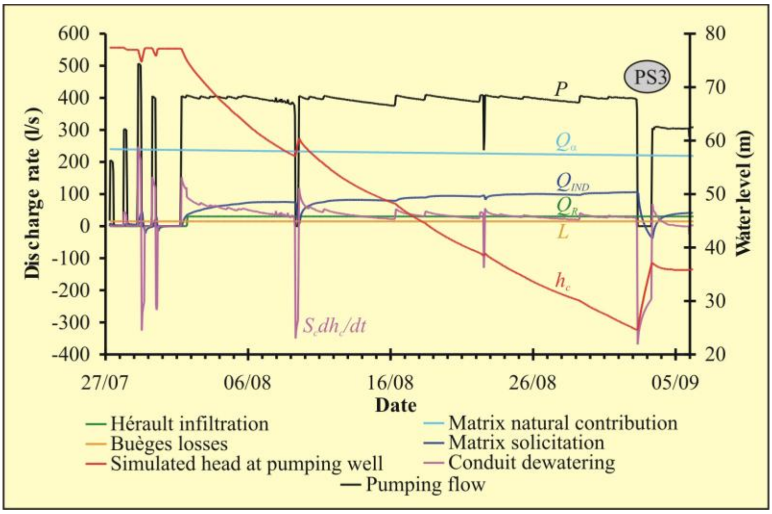

Figure 7. Temporal evolution of the flow contributions simulated by the model during the pumping test.

It decreases with time, proportionally to the decreasing rate of depletion in the conduits. Obviously, the dewatering is proportional to the drawdown in the conduit network, whatever the value of drawdown. The dewatering fluctuates between 0.150 m^3/s at the beginning of the test and about 0.020 m^3/s at the end of the pumping test at 0.400 m^3/s. It suddenly increases after each increase in the pumping rate due to the associated increase in the drawdown rate. It becomes negative during pumping stops, when the hydraulic head in the conduit increases and water from the matrix (and other contributions) is stored in the conduit network (dewatering flow is negative).

CONCLUSION

The hydrodynamics of a mixed flow karst system (MFKS) in which a long-duration pumping test has been done on the main karst conduit was analyzed and modeled. These results show that both the matrix (several kilometers away from the pumping well) and the conduit network are affected by the test. Nevertheless, the conduits are much more affected by pumping than the matrix (drawdown in the conduits ten times higher than drawdown in the matrix) due to their better connection to the pumping well and their low storage capacity at the basin scale (ϕ_c = 6 x 10^{-5}).

The double continuum model composed of two reservoirs (conduit network and matrix) well reproduces the transient response in the pumping well. The sensitivity analysis shows that it is the low-permeability matrix that dictates the pumping test response. The conduits induce a moderate capacitive effect (dewatering of vertical shafts and variably saturated conduits).

Free of deterministic finite-difference/elements modeling, it is simpler than hybrid models and constitutes an advance in double continuum modeling of karst systems notably by an improvement in the calculation of the flow exchange rate between matrix and conduits.

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