Active water management resources of karstic water catchment: the example of Le Lez spring (Montpellier, South France)

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Abstract

In Mediterranean karst groundwater has potentially important reserve which represents a high interest for the future in numerous countries under global and climatic changes. Karst groundwater environment is characterised by heterogeneity and consequently, classical hydrological model at catchment scale is not appropriated. Either double continuum model is developed integrating hydrodynamic parameters distribution of the aquifer or lumped model is used, such as inverse modelling approach based on the determining of transfer function on the whole hydrological cycle allows reproducing the hydrological behaviour of such system, and such as reservoirs model (Fleury, 2005 ; Fleury et al, 2007). Then, karst water is generally captured for water supply at the level of their springs; due to the important temporal variations of spring discharges, water pumping through boreholes intercepting the water saturated karst conduit allows carrying out an active management: higher rate of pumping than the low water stage discharge of the system under natural condition during low water period, as the reserve of the system will recover rapidly during the recharge period.

The karst system of the Lez, used for the water supply through an active water management for Montpellier is presented as a study case. The Lez karst system is one of the rare sites where an active water management is carried out. As it is a Mediterranean karst system, such karst system is sensitive to extreme events such as Cévennes events (heavy rain during a short period of time on a restrictive area). According namely to the degree of water saturation of the system, the intensity of flooding of the Lez river downstream of the spring will be of various intensity (Roesch et Jourde, 2006).

The aim of this study is (i) to summarize the knowledge concerning the karst hydrogeology of this aquifer based on the update interpretation of water level and discharges time series, (ii) to present results of recent studies concerning the demonstration of the effect of the active water management on the hydraulic functioning of the system, and (iii) to draw perspectives in terms of water management under global changes conditions, including the possible mitigation scenario of flooding in an urban area such as Montpellier. Such active water management may be also a new challenge for a pluri-objective management of a system integrating socio economic issues, environmental issues and flood mitigation.

Keywords : water management, Mediterranean basin, Karst aquifer

Introduction

The Mediterranean region is characterized by a large extent of carbonate rocks, most of them being karstified and potentially hosting significant aquifers. Karst aquifers thus represent interesting potential resources, partially underexploited in general; they will be more and more targeted with high priority to fulfil the current and future water needs. They thus represent future groundwater resources for several countries.

Karst aquifer is characterised on one hand, by its heterogeneity of hydraulic parameters with the presence of karst conduits network within a bulk mass of fissured rock and on the other hand, by the uniqueness of each system. The karst network characterises a transmissive system, although the fissured rocks where large cavity may take place, characterise the storage capacity of the system. The karst aquifer then exhibits a dual flow system (Kiràly, 1998) consisting of a fissured or “diffuse system” and a conduit system. Exchange between the two systems is controlled by hydraulic head differences as well as the hydraulic conductivities and the geometry of the setting (Bauer et al., 2005). The main water storage of the karst aquifer takes place within the saturated karst in large cavity or in the fissured matrix, commonly hydraulically connected to the karst conduits network. The main karst drainage network shows a certain degree of organisation, function of various factors, such as geological framework, climate and water chemistry, hydraulic head and base-level fluctuations. The Mediterranean karst aquifers were strongly influenced by the Messinian salinity crisis, during which the sea level dropped up to -1500m below present sea level. Consequently, water level basis of karst system has been accommodated to the sea level; karstic network developed then in the depth, investigation depth of karst network with -235m (under sea level) in Fontaine de Vaucluse and -47m (u.s.l)in Lez gives evidence.

According to the structure of the karst aquifer, different types of hydrodynamic processes may occur: quick flow occurring at the outlet of the system is related to wide fissures and karst conduits, while slow flow is attributed to flow through fine cracks, fissures and the porosity of matrix. In the epikarst, which often contains a perched aquifer, two main features may take place: slow percolation of air and water into narrow fissures (water storage), and rapid drainage through connected pipes (flow concentration) (Ford and Williams, 1991; Labat et al., 2000)

When the karst aquifer is of purely karstic typology and resources are enough to satisfy the water demand, the aquifer is generally tapped for water supply at their spring (gravitational derivation of a fraction or of the totality of the natural discharge of the spring). This traditional method doesn’t enable to mobilize the water stored in the reserves of the aquifer. Moreover, as a consequence of the hydrological functioning of such aquifers, the important temporal variations of the spring discharge along the year often limit the available water resource during the dry periods, most of them coinciding with high water needs. Pumping groundwater through borehole(s) intercepting, at a large depth below the aquifer’s spring, the water saturated karst conduit allows carrying out an active management of the aquifer and mobilizing partly or in totality the reserves of the aquifer.

The present paper deals with the analysis of the impact of an active management on the Lez karst spring (Montpellier, South France) based on the hydrograph at the spring as well as groundwater level time series, for several decades. Some conclusion in terms of management of karst aquifers for water supply and possible consequence for the mitigation of flooding in a Mediterranean climate based on pumping within a karst system will be drawn.

Case study presentation

The Lez karst spring is the major outlet of the karst aquifer of the Jurassic and Cretaceous limestone. This aquifer, referred to as the Lez aquifer, is limited by the following rivers: Hérault to the West and Vidourle to the North and to the East [Drogue, 1963 and 1969]. The Lez spring is a Vauclusian spring, water discharges through a basin whose overflow is at +65 m NGF, and supplies the Lez River. The Lez outlet is located 15km northern to Montpellier, whose water supply is ensured by this karst aquifer.

Lithologically, the karst system takes place within massive limestone of the Late Jurassic (Argovian to Kimmeridgian) and the lower part of the Early Cretaceous (Berriasian). Marls and marly-limestone of the Middle Jurassic (Oxfordian) constitute the lower limit of the aquifer. The marly series and marly-limestone of the Early Cretaceous (Albian) constitute the upper limit of the aquifer.

The area of the groundwater basin (recharge area), determined by tracer experiments, the identification of the impervious structural boundaries and an analysis of groundwater levels in boreholes, is about 380 km^2 (Thiéry and Bérard, 1983). Recharge is through limestone outcrops of the karst aquifer. These outcrops have a surface area of approximately 100 km^2, i.e. 26 % of that of the groundwater basin (*Figure 1*). Some infiltration, of which no estimation has yet been made, occurs in river losses (swallow holes) in the limestone and marly-limestone layers of the aquifer, along tectonic faults (the Matelles-Corconnes fault, in particular).

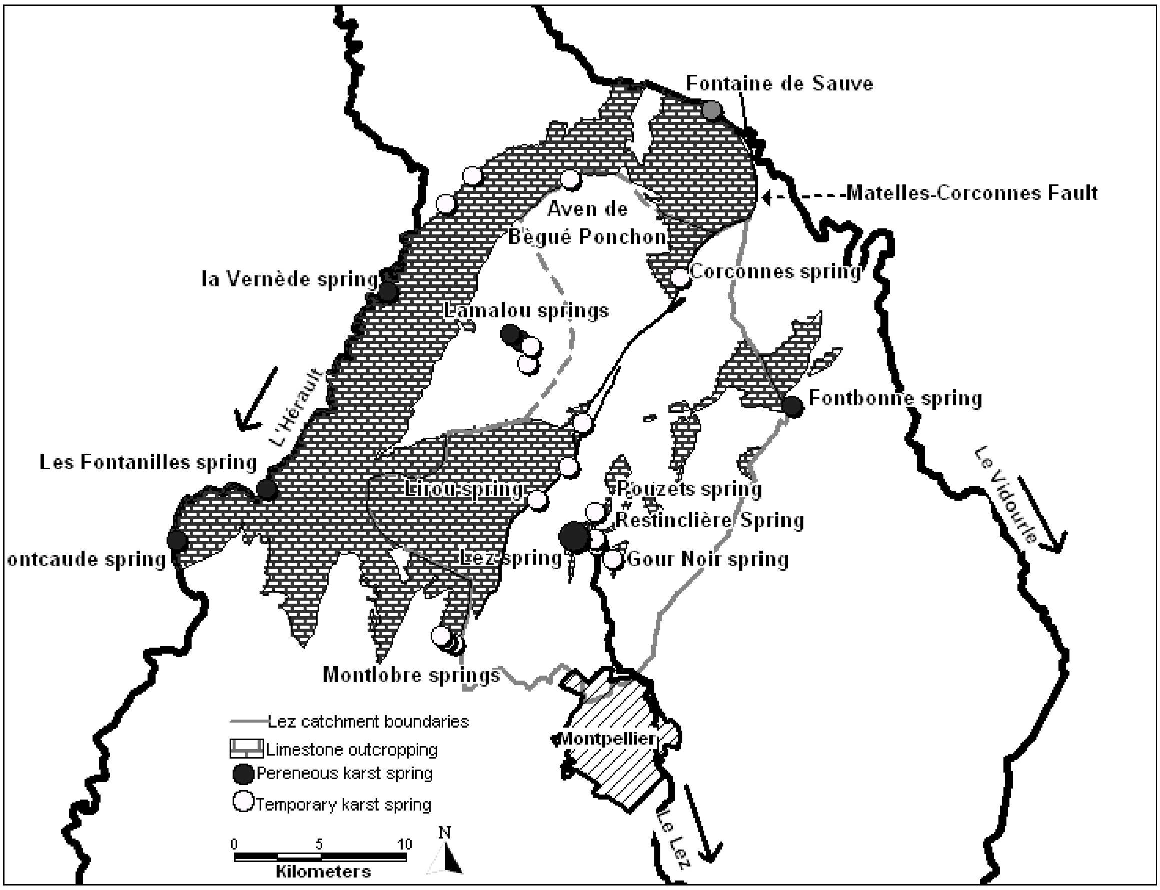


Figure 1: Limestone outcrops of the karst aquifer within the recharge area of the Lez spring (Fleury et al., 2008).

During low water stage, the spring dried up, when water was pumped directly at the outlet. For this reason, in 1981, an active water management procedure of the Lez aquifer was implemented: four boreholes were drilled into the main karst conduit, upstream of the outlet, allowing up to 1700 L/s pumping rate. The characteristic of this karstic system lies in the active management of the water resource. This consists in pumping water directly from the drain below the level of the spring (*Figure 2*). Preliminary studies carried out in the 1960s and 1970s (Avias, 1995) made it possible to characterize the system, design the pumps and actively manage the resource.

An active management can be described as follow: groundwater exploitation by pumping at a higher rate than the low water stage discharge of the karstic system under natural condition, thus mobilizing the aquifer's reserves, particularly during the low water period (summer), the reserve of the aquifer recovering (often very rapidly) during the recharge period. Karstic aquifers are particularly adapted to such an active management as (i) their reserves may be huge and quite easily accessible near the spring, (ii) a well drilled on a karst conduit may provide a very high yield (several hundred l/s) and may thus be able to mobilize an important amount of the aquifer reserves, (iii) their recharge is very efficient as most of the efficient rainfall infiltrates within the aquifer.

The capture work is located more than 400 m upstream within the limestone massif. Pumping takes place 48 m under the spring pool level, at +17 m NGF level (*Figure 2*).

Discharge at the Lez spring is therefore influenced by pumping. When the river discharge is lower than the pumped flow, part of the pumped flow is channelled to the river. This return flow, set by the Declaration of Public Utility of June 5, 1981, is 160 l/s.

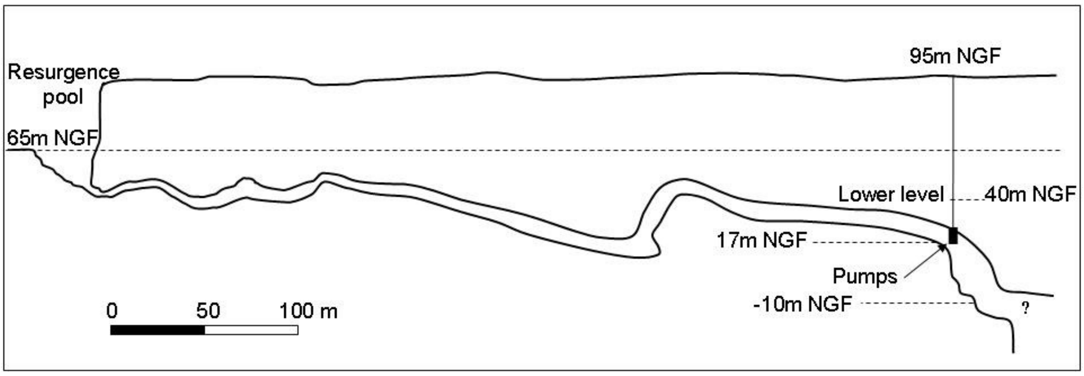


Figure 2: Karstic network of Lez spring and taping system device (Fleury et al.,2008, after Paloc 1979,).Lower level (40m NGF) corresponds to the maximum monitored level, when 35m NGF is the authorized lower level.

Data and method

Hydrologic data used in the framework of this study are discharges measured downstream the spring and the return-flow from pumping towards the river, and groundwater level at the capture work, for the following period: 1946-2006. Concerning discharges, available data are related to effective water sampling, i.e. pumping volume since 1968 and gravitational part of the discharge for period when there is some flow out of the spring pool, to the return flow to the Lez River (mean daily discharges for 1983 to 1987 and 1997 to 2005) and finally to the flow at gauging stations downstream of the spring Lez (1987 to 2006) and Lavalette (1975 to 2006). The available data related to groundwater level are (i) water level time series within the spring pool (limnigraph, 1946 to 1982 with some lack of data between 1946 and 1949) and (ii) within one of the fourth borehole at the capture work (daily and/or hourly groundwater level for the following periods: 1982-1987, 1994-

1995 and 1997 to 2006. Climatic data used in the present study are: air temperature (10 days time step, from Météo France) and rainfall time series (daily data from three stations [St Martin de Londres, Valflaunes and Montpellier Fréjorgues], from 1970 until 2006).
Concerning discharge time series, there were several lacks of data. A reconstruction of time series was carried out based mainly on extrapolation of water level monitored at the spring basin and discharges (outflow and gravitational discharges for various periods 1946-1968, 1068-1982, 1982-2005) relation and rainfall-discharges transfer model. Statistical comparison between reconstructed data and monitored data was done in order to verify the general validity of rebuilt data. Natural discharges at the spring basin for the 1946-1968 period, period without pumping, correspond to the sum of overflow discharges and gravity out taking discharges.

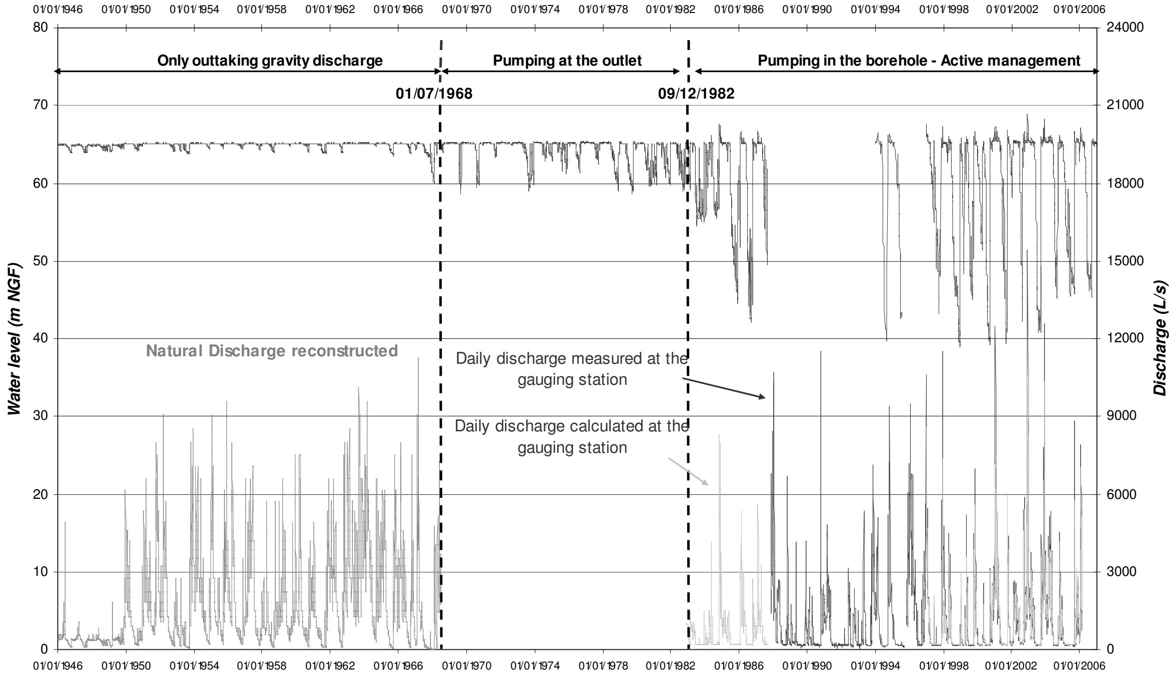


Figure 3: Discharge time series and groundwater level of the Lez karstic spring.

The method used in order to study the impact of an active management on a karst system is the methodological approach using inverse modelling (Pinault et al., 2001 a, 2001b and 2004). The inverse model aims at calculating hydrographs, determining transfer function using all hydrograph time series. This type of model allows (i) reconstituting natural discharges of Lez spring during low water stage in order to fulfil available time series including high water stage data and (ii) to carry out analysis on the whole time series for previous active management period and from active management period till present day.

Data processing is performed using the TEMPO code ©BRGM, (Pinault 2001). The principle of the model includes two models whose structure consists of the following steps (*Figure 4*): (1) the input of the system is defined as the quantity of rain which will induce a flow variation, considering that a part of the rain is lost out of the system. A threshold (Ω), variable with time, allows, using rainfall and air temperature time series, to determine efficient rainfall, considering the following equations:

$$R_{efficient} = R_{total} - \Omega\ (t) \text{ if } R_{total} > \Omega\ (t) \text{ and } R_{efficient} = 0 \text{ if } R_{total} \leq \Omega\ (t).$$

In the case of a rainfall-discharge model, W (t) can be considered as the water deficit of the utile reserve of soils.

(2) The rainfall is then separated into two components, the quick and the slow flow components (transfer functions or impulse responses) that take place within the system. A parameter will define the relative proportion of each component at each moment. (3) The impulse response of the outflow to each component is computed through an iteration process.

The output of the first transfer model (1) (figure 4) is the Natural Discharge of the Lez spring. The second transfer model (2) (figure 4) includes several inputs such as: a solicitation function due to the pumping, the simulated discharge of the spring (output of the first transfer model (1)) and a threshold (Ω) (based on air temperature time series as defined above) in order to determine efficient rainfall. The solicitation function is defined as the karst reserve solicitation discharge, used when pumping discharge at the spring is higher than the natural discharge of the spring. The output of this second model is the groundwater level in the karst conduit at capture work of the Lez spring. This second model is used in order to validate the liability of simulated natural discharge of the Lez spring.

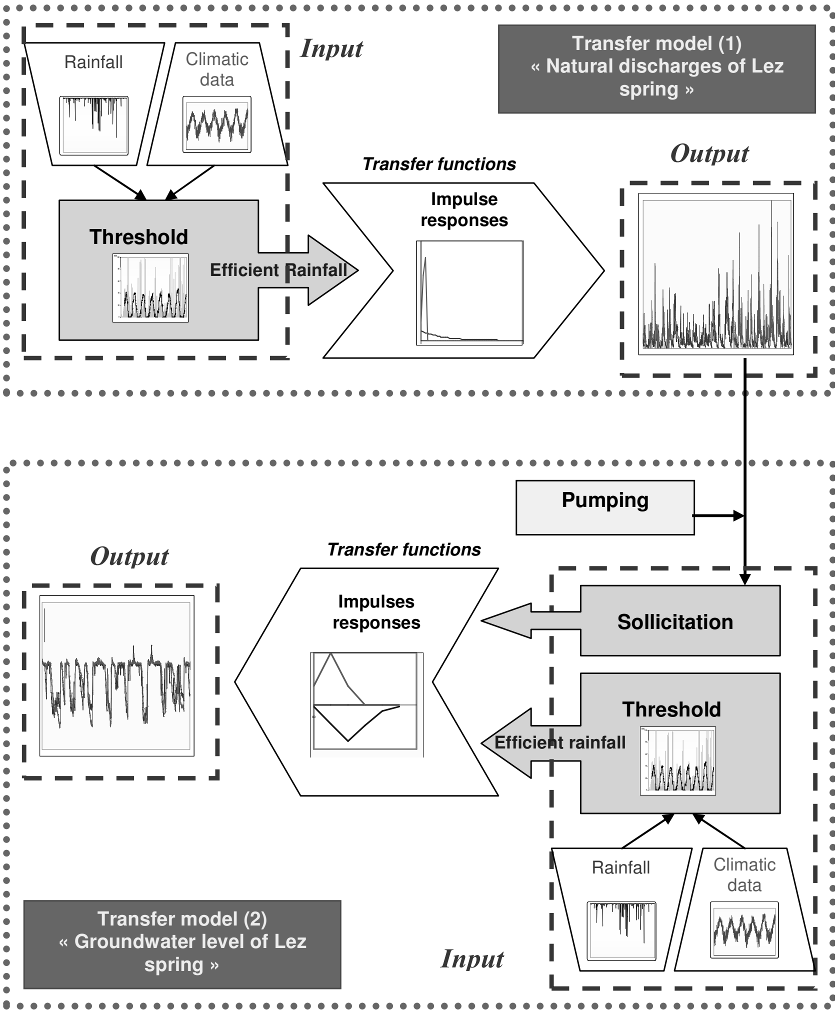


Figure 4: Principles of the transfer model using TEMPO, allowing the groundwater level of Lez spring simulation.

Then recession curves analysis, sorted spring discharges analysis as well as univariate and bivariate methods of time-series analyses are carried out on the whole time series, monitored data and time series resulted of transfer models. Sorted spring discharges method aims to characterize flow regimes at the outlet of a system; a statistical law, classically a normal or a log-normal distribution law is applied on data, shown with a cumulative distribution. Interpretation of perturbations of distributions (existence of breaks on the line) has to be related to hydraulic behaviour of the system. The recession curves analysis allows determining namely recession coefficient α, using Maillet's (1905) or Mangin's (1970) concept of hydrograph decomposition based on hyperbolica and/or homographic equation in order to reproduce recession of the hydrograph. Finally, univariate and bivariate methods applied on time series permit characterizing namely inertia of the system; how the system filters rainfall, what is the so called memory effect? They are few questions that may be answered using these methods.

Results

The analysis of 18 hydrological cycles for the natural discharges of the Lez spring (1946-1968) without reconstruction using the first transfer model (1) points out that the natural status of the system is characterized by a mean daily discharge of 2 m^3/s. Fifty percent of discharge values are comprised between 0.6 and 2.7 m^3/s for the selected period. The mean inter years volume of water is $62 \pm 24 \cdot 10^6$ m^3.

Three types of models were used in order to simulate natural discharges of the Lez spring, two parametric models (either two asymmetric reservoirs in parallel with two recession parameter and a partitioning parameter, or one reservoir with two recession coefficient) and a third model allowing to take into consideration a homograhic function and the Maillet law (Samani and Ebrahimi,1996). All these models permit to calculate discharges time series, using two transfer functions: (i) a fast impulse response for fast recharge with a maximum between the 2nd and 3rd day, (ii) a slow impulse response with a very slow water level decreasing for which there is no more influence of efficient rainfall after 60 days. A mean recession coefficient of the saturated zone of the aquifer globally equals to 0.028 ± 0.011 d^{-1} is used in these models.

The model is calibrated for various hypotheses of discharges time series related to different periods. Then it is used to forecast, given satisfactory results (*Figure 5*).

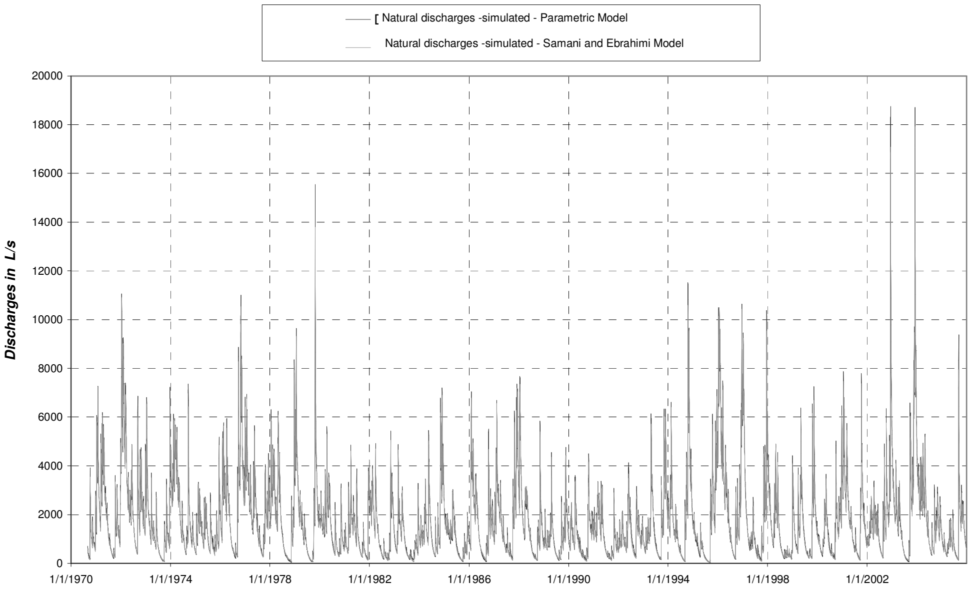
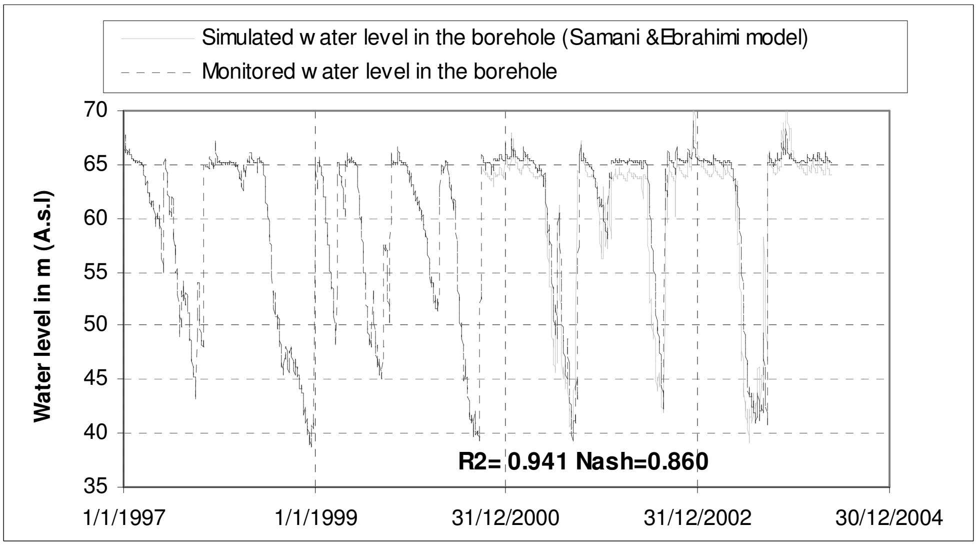
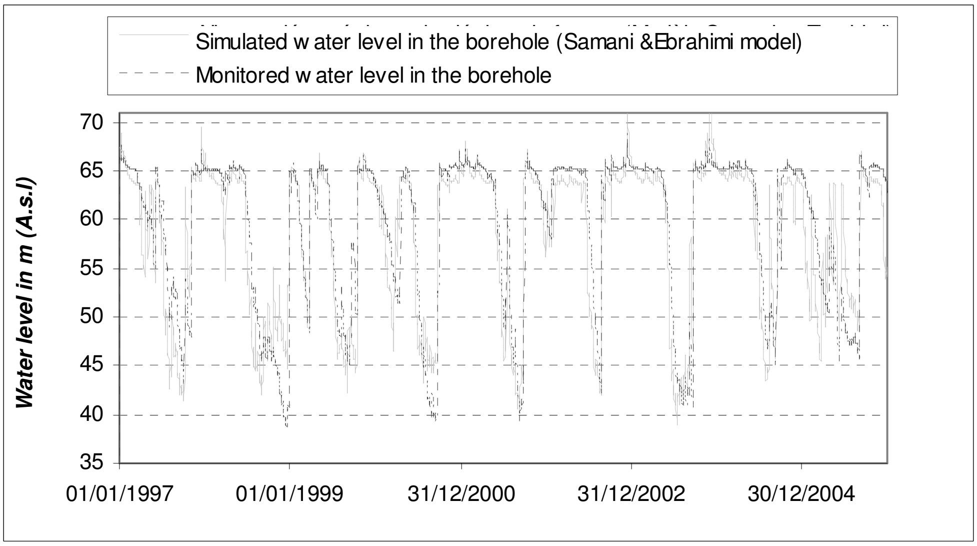


Figure 5: Simulated discharges time series resulting from two different types of models implemented under TEMPO for 1970-2005 period, after calibration phase (Conroux, 2007)

Results of the second transfer model (2) (figure 4) concern simulated groundwater level at the spring level. Globally this model allows reproducing important groundwater level variation due to pumping (30 metres about) in comparison to the effect of the rainfall (3 metres max); Nash coefficient value is between 0.83 and 0.95 according to selected model and the selection of natural discharge time series. The solicitation parameter value used in this model is not constant along exploitation period; in 1974-1982 the solicitation value is 44%, however in 1982-2005, this value is higher (55%). There are still uncertainties on results, but it is assumed to be of enough good quality to carry out further analysis related to hydrodynamic behaviour.





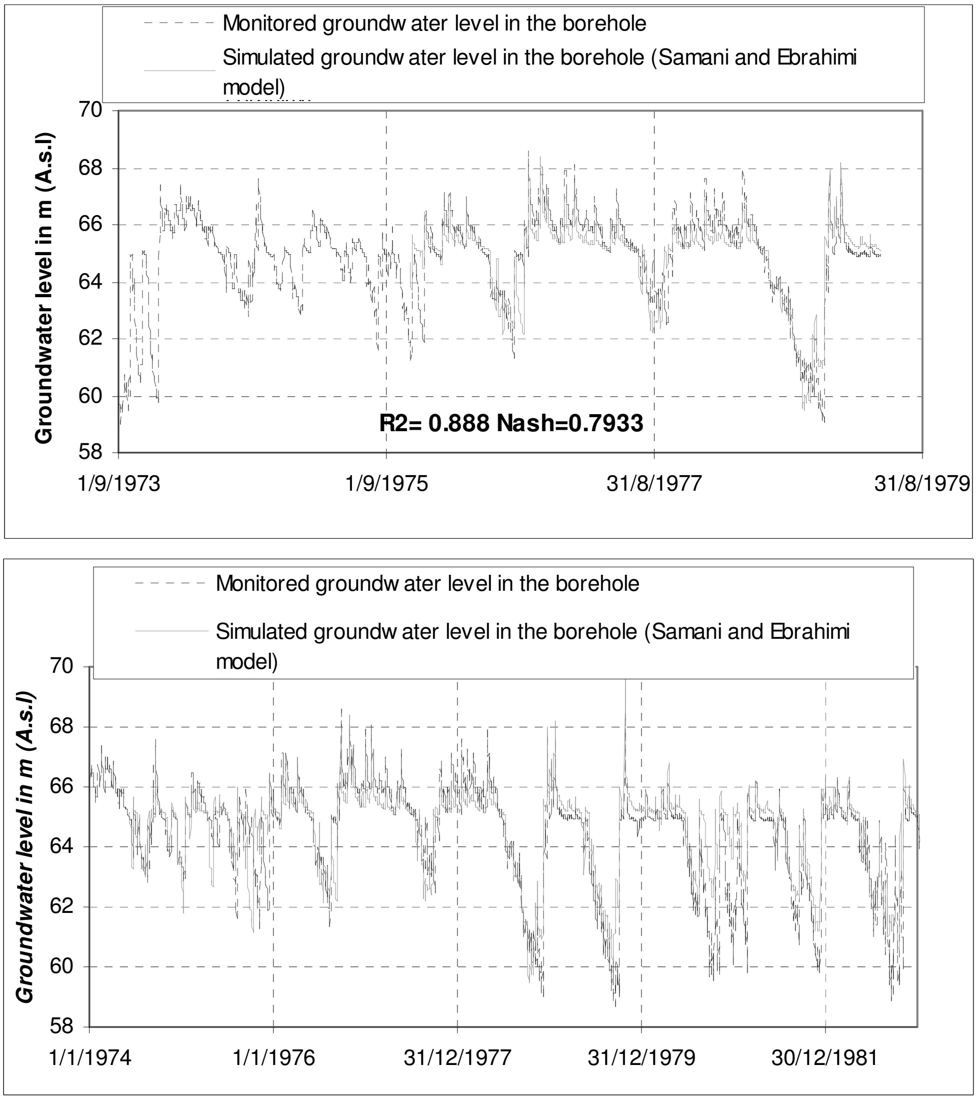


Figure 6: Example of validation of simulated groundwater level and forecasting at the Lez spring (between 1997 and 2005 and between 1974 and 1981) (Conroux, 2007)).

Results of recession curves analysis carried out on recession curves of two periods (1949-1968) and (1974-2005) are given in the following table:

Parameters	**Minimum**	**Mean**	**Maximum**	**Standard deviation**
Period 1949-1968				
Recession coefficient (d^{-1})	0.007	0.0086	0.012	0.005
Dynamic volume (10^6 m^3)	2.49	5.2	10.5	2.1
Total water volume of the flow during recession (10^6 m^3)	10.2	13.88	17.61	2.44
Delay to infiltration i	0.635	0.767	0.892	0.081
Regulation power K	0.036	0.089	0.158	0.042
Period 1974-2005				
Recession coefficient (d^{-1})	0.026	-	-	0.011
Dynamic volume (10^6 m^3)	5.8	-	-	2
Regulation power K	0.1	-	-	0.04

The sorted discharges analysis on time series since 1949 until present time indicates, that an improvement of groundwater flow within the aquifer for discharges higher than 2 m^3/s. The univariate and bivariate analysis carried out on rainfall and discharges time series, indicates first that rainfall has a random structure, second that the memory effect of the system is around 40 days, directly due to the filter effect of rainfall by the aquifer. For the various periods of analysis, it is shown that memory effect globally is longer (between 40 to 70 days) for period before 1982. For the present period, this memory effect is slightly shorter with values between 35 to 55 days (Conroux, 2007).

Discussion

Since December 1982 the Lez spring is under active management; the flow regime of the spring is influenced: the mean pumping rate is 1.1 m^3/s corresponding to 33 *10^6 m^3 water volume per year. The various analyses carried out on the discharges time series indicate a hydrodynamic change of the system before and after 1982. The present recession coefficient (0.026 ± 0.011 d^{-1}) obtained with the simulated discharges time series for the 1974-2005 period indicates an improvement of groundwater flow drainage of the saturated zone of the aquifer. These results are coherent with the results of univariate and bivariate analysis (shorter memory effect) and with the sorted discharges analysis. This improvement may be due to the clay expulsion out of karst conduits and/or to the reactivation of some conduits by the pumping. However the water storage seems not to be modified. The Lez system appears to be more transmissive since the active water management.

The model developed based on the conceptual model of the Lez karstic aquifer functioning Lez under pumping condition, is well adapted both for discharges and for drain water level simulations. This model can thus be used to simulate various water management scenario as well as scenario related to predict contribution of the karst on the floods of the catchment basin of Lez River. The impact of precipitations on the Lez system depends of the state of filling of the karst (Jourde et al., 2007). Thus two similar rainy events do not have the same impact according to whether pumping pulls out or not aquifer reserves. Once the system is recharged, only one fraction of precipitations infiltrates the remainder runoffs. The whole karstic system is then characterized by overflows supplying surface runoff. Roesch and Jourde (2005) show for similar climatic events in amplitude that Lez discharges 10 km downstream the spring can changeover from 100 to 400 m^3/s. With this model it is possible to assess the volume of water necessary to recharge the aquifer and to induce high flood. Thus over the period of study, the levels minima were of approximately -0.8m (Fig. 6). That represents a drawdown of 25 m, which means, integrated on the recharge area, a volume of 10 millions m^3, a rainfall of approximately 150 mm. The system under active management may allow removing first floods due to 150mm rainfall at the end of the low water stage period. Considering the present location of pumps, the maximum drawdown until the pumps elevation would permit to reduce floods until 300 mm rainfall (Fleury et al.,2008).

Conclusion

Facing the scarcity and overexploitation of surface water in the Mediterranean countries, the sustainable and groundwater management of karst regions will gain recognition in the future. The Mediterranean karst systems include groundwater resources that are widely under-exploited (about 10 billions m^3/year); one day will come to solicit them in order to satisfy the increasing water demand (+ 93 billions m^3/year in 2025) [Plan Bleu, Margat J.,(2004)]. For karst Vauclusian system, the active water management allows improving the transmissivity of the aquifer. The developed methodology can be transferred to other system where an active management could be implemented.

In addition, the active water management of such karst aquifer may allow reducing the flooding risk downstream of the spring. A depleted aquifer may have an attenuation impact, especially in low water period, as the water volume storage of the aquifer may be increased due to the pumping (from 10 up to 20 millions m^3). Various predictive scenarios of water management of this system including climate change scenarios could be simulated.

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References

Avias J., 1995. Gestion active de l'exsurgence karstique de la source du Lez (Hérault, France) 1957-1994, Hydrogéologie 1, 113-127

Bauer S, Liedl R., Sauter M. 2005. Modeling the influence of epikarst evolution on karst aquifer genesis: A time-variant recharge boundary condition for joint karst-epikarst development, Wat. Resourc. Res. 41, et al. (2005):

Conroux Y., 2007. Caractérisation du fonctionnement hydrodynamique de l'aquifère karstique du Lez (Hérault) à l'état naturel. Mémoire de Master II Pro, Hydrogéologie et environnement Université d'Avignon et du Pays de Vaucluse, BRGM, 225p.

Drogue, C. 1963. Essais de délimitation du bassin d'alimentation d'une résurgence des karsts noyés languedociens. Ann. Spéléol., 18, 4, p. 409 -414.

Drogue, C. 1969. Contribution à l'étude quantitative des systèmes hydrologiques karstiques d'après l'exemple de quelques karsts périméditerranéens. Thèse de Doctorat Université des sciences et techniques du Languedoc 482p.

Fleury P., Ladouche B., Conroux Y., Jourde H., Dörfliger N. 2008. Modelling the hydrologic functions of a karst aquifer under active water management – the Lez spring, Journal of Hydrology (submitted).

Fleury P., Plagnes V., Bakalowicz M., 2007. Modelling of the functioning of karst aquifers with a reservoir model: application to Fontaine de Vaucluse (South of France), Journal of hydrology 345 (2007) 38-49

Fleury P., 2005. Sources sous-marines et aquifères karstiques côtiers méditerranéens. Fonctionnement et caractérisation, thèse, université Paris VI, 2005, (286 p).

Ford, D., Williams, P., 1991. Karst geomorphology and hydrology.Chapman & Hall, London.

Jourde H., Roesch A., Guinot V., Bailly-Comte V. 2007. Dynamics and contribution of karst groundwater to surface flow during Mediterranean flood, *Environmental Geology Journal* 51, 725-730.

Kiràly, L, 1998. Modeling karst aquifers by the combined discrete channel and continuum approach. Bulletin d'Hydrogéologie de l'Université de Neuchâtel, 16, 77-98.

Labat D., Ababou R., Mangin A., 2000. Rainfall-runoff relations for karstic springs. Part I: convolution and spectral analyses, *Journal of Hydrology 238* (2000) 123–148

Maillet E., 1905: Essais d'hydraulique Souterraine et Fluviale. *Hermann, Paris, 1905, 218 p.*

Mangin A., 1975. Contribution à l'étude hydrodynamique des aquifères karstiques. *3ème partie. Constitution et fonctionnement des aquifères karstiques, Annales de Spéléologie 30 (1) (1975) 21-124.*

Margat J. 2004. Mediterranean Basin Water Atlas, Plan Bleu, UNESCO, 47p.

Paloc H. (1979) – Alimentation en eau de la ville de Montpellier – Localisation d'un emplacement de captage dans le réseau souterrain de la source du Lez – Détermination de ses principales caractéristiques en préalable à l'exécution des travaux – Rapport BRGM 79 SGN 654 LRO, 16p.

Pinault, J. L., V. Plagnes, L. Aquilina, and M. Bakalowicz. 2001b. Inverse modelling of the hydrological and the hydrochemical behavior of hydrosystems: characterization of karst system functioning. Water Resources Research 37, no 8: 2191-2204.

Pinault, J. L., N. Dörfliger, B. Ladouche, and M. Bakalowicz. 2004. Characterizing a coastal karst aquifer using an inverse modeling approach: The saline springs of Thau, southern France. Water Resources Research 40: 17.

Pinault, J. L., H. Pauwels, and C. Cann. 2001a. Inverse modelling of the hydrological and the hydrochemical behaviour of hydrosystems: Application to nitrate transport and denitrification. Water Resources Research 37, no 8: 2179-2190

Pinault, J. L. 2001. Manuel d'utilisateur de TEMPO: logiciel de traitement et de modélisation des séries temporelles en hydrogéologie et en hydrgéochimie. Projet Modhydro.BRGM report RP51459-FR, 221p.

Roesch A. & Jourde H., 2006. Incidence d'une gestion active de la ressource en eau en milieu karstique sur le risque hydrologique.Exemple du Fleuve Lez (Montpellier, France), GIRE3D Conference, Marrakech, May 2006.

Samani N.& Ebrahimi B, 1996. Analysis of spring hydrographs for hydrogeological evaluation of a karst aquifer system. *Theor. Appl. Karstol.* 9 (1996), pp. 97–112.

Thiery D., Bérard P., 1983. Alimentation en eau de la ville de Montpellier - CAPTAGE DE LA SOURCE DU LEZ - études des relations entre la source et son réservoir aquifère, Rapport n°1, Rapport 83 SGN 167 LRO, BRGM, 1983, 70 p.