Karst–River Interaction, Elaboration of an Indicator of the Karst Hydrological Conditions Applied to the Cèze River (Gard, France)

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Abstract

In the interest of creating a point of reference allowing to know the hydrological conditions of the karst system and for the purpose of using it as a parameter in a modelling procedure, a Hydric Indicator of the Karst (HIK) was established from the knowledge acquired on the functioning of the karstic hydrosystem of the Cèze. This indicator makes it possible to identify and qualify if at a specific moment "t" the karst is more able to contribute to the flow of the river or on the contrary to infiltrate precipitation water.

The HIK is constructed from the data collected at the Ussel spring and the MétéoFrance rain gauge at the karst plateau of Méjannes-le-Clap (Gard, France). Chronic rainfall and discharge measurements from the source include two hydrological cycles. The discharge of the spring is calculated from the recordings of water amounts from autonomous water level probes. These water levels are converted into discharge through a calibration curve drawn for this study. For rain events with at least 4 mm of precipitation, ten parameters on rainfall characteristics and the flow rate of the Ussel spring are analyzed to obtain the HIK. In total, 74 events were analyzed.

Finally, this indicator is a relevant entry for the simulation of flow variations in the river within its karst canyon. It is also a relevant tool for institutions which monitor the condition of the karst aquifer and thus can be a useful tool for the management of the aquifer. Our goal was to develop an approach, with which we can calculate and predict, what will be the response at karst spring, if we know current discharge of the Ussel spring and expected amount of rainfall.

Introduction

Karst aquifer studies arouse a great interest given the fact that they represent important freshwater resources. According to (Ford and Williams, 1989 / 2007), the karst rocks cover 7-10 % of the Earth's surface and supply drinking water to about 25 % of the world's population and most of studies mention larger areas underlain by carbonate rocks from 15 % to 20 % (WoKAM 2017, White 1988, Ford & Williams 2007). Karst systems are characterized by the underground flows (Bakalowicz, 2005). In order to understand the underground flows, many models integrate data of karst system (Kiraly, 1998; Jourde et *al.*, 2007; Johannet, 2011; Fleury et *al.*, 2011; Bailly-Comte et *al.*, 2010 and Bailly-Comte et *al.*, 2012) but this work focuses to elaborate an indicator which represents the hydrological condition of the karst. The results of this work can give perspectives for future modelling of the karst system.

The interactions between the karst system and the river, in terms of flow quantities, vary during a hydrological cycle. Identification of responses of karst aquifers is very important to protect people from flooding and for sustainable development of groundwater management.

Hydrogeological context of the studied area

Located in a large karstic area in the South of France between the Ardèche and the Cèze Rivers, both tributaries of the Rhône River (Fig. 1), the study area is the subject of a multidisciplinary study which aims to characterize exchanges between aquifer and Cèze river (Ré-Bahuaud et *al.*, 2015). This study area is an attempt to meet a territorial policy, in order to obtain a sustainable management of streams and aquifers. In this location, the Mediterranean climate induces a period of drought in summer and high-flood in autumn. The karst area is a calcareous plateau incised by the Cèze River. Sometimes during drought period the Cèze River may dry up and the water from the river infiltrates into the calcareous aquifer (Chapuis, 2017). This calcareous plateau is geologically and hydrogeologically well studied, including by borehole investigations, karstic network investigations and especially previous groundwater tracing (Jolivet, 2013 and Pouzancre, 1971). The size of the recharge area is about 200 km2, amount of the outflow can be estimated to 2 m^3/s for the minima flow during dry period and can rise to 200 m^3/s in winter so that, average is not relevant. Highest discharge of studied springs are about 2m3/s (Maranade spring). Geological studies suggest interactions between river and Lower Cretaceous formations, Barremian and Lower Aptian (so called Urgonian) formations which is a highly karstified calcareous geological unit. Whether on the Cèze right bank, some springs may dry up during drought period. The interactions between the karst system and the river, in terms of flow quantities, vary during a hydrologic cycle. In this karst system, water sinking is caused by contacts between specific formations and fault thrust zones.

Hydrological indicator of the karst

The construction of the approach is based on the observation of the different parameters recorded at karst springs and rainfall events, for settings that might range from exhausted to saturated. Following the design of this indicator, the aim of the study is the construction of the model with the help of this hydrological indicator. The information about the water balance in karst aquifer can then be used for anticipating the accentuated or attenuated shape of a river or spring hydrograph after a rainfall event.

Though many data may be available, for a simplified and manageable job it is imperative to have a well-adapted time step. Representative data set of the karst hydrosystem is required to design a reliable model. For this reason, the Ussel spring data were selected, as a tracer data showing that they probably represent a large karst basin. Precipitation data from Méjannes-le-Clap Plateau also represent as well as the Méjannes-le-Clap precipitation data from MeteoFrance that represent an uninterrupted longterm data set.

These data were subjected to an event-related analysis. In fact, within these two time-related data sets, we analyzed the hydrological response of the spring for a rainfall event with at least 4 mm of precipitation. Selection of such intensive rainfall events enables identification of event that affects spring discharge. If the analysis comprises events of such a weak intensity it is to clearly mark the distinction between rainfall events that affect spring flow, and those that are too weak and thus are buffered by the karst network and also capped by evapo-transpiration. Depending on initial conditions, rain events which have less than 4 mm of precipitation have no influence on springs discharge and are not significant since there are buffered by the karst network. Such rainfall and flow-rate data provide several parameters for each event:

- volume of precipitated water (in mm),
- intensity of precipitation (mm per 1h, 2h, 5h and per 10h),
- maximum intensity of precipitation,
- centre of gravity of the rainfall hydrograph (in mm/h),
- cumulative rainfall several days before a remarkable rainfall event (mm in 3d, 15d and 30d),
- initial stage at the spring (in L/s),
- total water volume transiting through the spring during one high water event,
- total water volume transiting through the spring during one high water event less base volume (m^3),
- centre of gravity of the spring hydrograph (m^3)
- maximum flow rate transiting through the spring (m^3/s).

These parameters are obtained by the analysis of the hydrological response at the rainfall events. The flow rate parameter of the Ussel spring result from the stage recorded with an autonomous probe. This database is converted in flow rate thanks to a tare curve.
A total of 74 events have been analyzed from 2013 to 2015.

HIK is given by the correlation curve of precipitation versus Ussel spring discharge.

Construction of the hydrological indicator

The hydric conditions of karst system are divided in three ranges corresponding to the colors green, yellow and black in figure 2.
This study was done using manual iteration (without computer assistance) and comparing the evolution of ten parameters, previously described.
The first range = HIK 1 (hydric indicator of karst) = initial flow rate of Ussel spring is lower than 220 L/s.
The second range (consider as the period of transition between HIK 1 and HIK 3) = HIK 2 = initial flow rate of Ussel spring is ranging from 220 L/s to 350 L/s.
The third range = HIK 3 = initial flow rate of Ussel spring is higher than 350 L/s (in high level water period before one rain event).

Results obtained with HIK

Figure 2 shows the peak flow transiting through Ussel spring (ordinate) in terms of maximum hourly rainfall over the Méjannes-le-Clap plateau (abscissa). The three colorful points on the figure 2, green, yellow and black, are the third variable integrated from all described parameters. This third parameter called "HIK" calculates the karst-system water balance. An example on Figure 2 shows the initial flow rate before the rain event begins. According to spring discharge HIK is divided to three classes and represented with aforementioned colors. From HIK 1 to HIK 3, this parameter represents a karst network passing from a ~~drying~~-up stage to a saturated stage. The result shown on figure 2 shows that the Ussel spring behaves differently according to rainfall intensity, as shown by the green, yellow and black points. In fact, HIK 1 represents the group of events, where the maximum flow rate of the spring does not increase strongly, even though the rainfall is strong. Even though the green points follow an exponential curve, only more than 60 mm of rain in one hour increases the spring flow (1.7 m^3/s), which normally does not exceed 0.5 m^3/s (current measurements of the Ussel spring discharge should confirm the exponential shape of the curve). Distribution of events, belonging to class HIK 3 (black points) shows a more-or-less linear curve where the maximum flow rate of Ussel spring increases by about 1 m^3/s for an amplification of 10 mm of precipitation in one hour.

Presented results enable qualitative expression of hydrological conditions of the karst system, and we can design an indicator for the water balance of karst. After construction of the indicator we can predict the reaction of the Ussel spring, if its initial discharge and predicted amount of the rain (by MeteoFrance) are known.

Conclusion

The creation of karst spring database in response to the precipitation events gives many possibilities for interpretation of hydrological conditions of the karst system and its response to rainfall event.

In our case, this database allows to identify the hydrological conditions of studied karst system. This information is important because it’s the crucial parameter which determines the groundwater dynamics in the karst system. The proposed methodology can be very useful and applied in further studies or in other karst systems under the same availability of data.
Indeed, hydrological indicator is needed to integrate relevant data into a groundwater model. In that case, this could be possible to use also this approach for other karst systems with well measured water level (discharges) of springs and rain precipitation. This indicator can be integrated in a hydrologic model in order to provide a relevant parameter on the interactions between the karst system and the river. The hydrological indicator of the karst informs the model if the karst system has a less restitution of the infiltrated water (HIK 1) or conversely the karst system is saturated and restitutes the infiltrated water by the karstic springs, see figure 3.
On this figure 3 (left side), initial hydrological conditions in aquifer given by HIK and spring hydrograph for the same event will be marked.
In the middle and right side: the modelling process which provides river water flows with the contribution of the karst.

After determining the flow rate ranges corresponding to the hydric conditions of the karstic system, this indicator can be a useful tool to determine the hydrological conditions of the hydrosystem and prevent of exploitation risks of the aquifer if there are pumping in low water period.

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