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Structure and water storage capacity of a small karst aquifer based on stream discharge in southwest China

Tonggang Fu [a,b,c], Hongsong Chen [a,b,*], Kelin Wang [a,b]

[a] Key Laboratory of Agro-ecological Processes in Subtropical Region, Institute of Subtropical Agriculture, Chinese Academy of Sciences, Changsha 410125, China
[b] Huanjiang Observation and Research Station for Karst Ecosystems, Chinese Academy of Sciences, Huanjiang, Guangxi 547100, China
[c] University of Chinese Academy of Sciences, Beijing 100049, China

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SUMMARY

Karst spring/stream discharge reflects the global configuration of the aquifer. However, quantitative description of the aquifer structure such as effective porosity (n_{eff}) and water storage capacity by the discharge analysis is difficult because of the complex conduit/fracture system. This study attempted to quantify the characteristics of karst aquifer based on discharge recession and time series analysis methods. Three recession models, including modified Maillet, Mangin and Boussinesq models, were evaluated to choose the most suitable one for analyzing the aquifer structure, and auto-correlation and cross-correlation functions were applied to study the aquifer response in both year and rainfall event time scales. The results showed that the modified Maillet model was more suitable in the study catchment with Mangin model overestimating and Boussinesq model underestimating the discharge. The n_{eff} was 3.73% for the total aquifer, and it was 0.07%, 0.33% and 3.33% for the conduit, fracture and matrix, respectively. Based on a case study of a rainfall event with precipitation of 68 mm, the water volumes drained by the three media were 25.43%, 33.40% and 41.17%, respectively. This indicates that, although conduit network is not very developed with lower n_{eff}, it is still an important water transmissive element (draining more than a quarter of water after the rainfall event). The memory time of the aquifer was 4 days for the year scale and 8 h for the rainfall event (68 mm) scale. This demonstrates that the aquifer has a well developed drainage system with a quick response to the rainfall. The above results provide further insights for hydrological processes modeling and water resources management for the small catchment in karst regions.

1. Introduction

Karst aquifer always has a dual hydrological system where extremely fast and slow water flow can be found in both saturated and unsaturated zone (Ford and Williams, 2007; Ghasemizadeh et al., 2012; Goldscheider and Drew, 2007; Katsanou et al., 2014; Padilla et al., 1994). High heterogeneity is the most important characteristic of the aquifer where the aperture diameters can vary more than five orders of magnitude from fracture to conduit (Mayaud et al., 2014). Quantitative data of pumping or tracing from points can only provide information of surroundings (Liu et al., 2010; Padilla et al., 1994). As a consequence, global methods, including isotope, absolute gravity, hydrochemistry and many other methods, were widely used to study the overall characteristics and the related hydrological processes of karst aquifer (Aquilina et al., 2006; Hu et al., 2015; Jacob et al., 2008, 2009; Kiraly, 2002; Perrin et al., 2003). However, these methods have disadvantages that more parameters and more expensive instruments are required. By contrast, hydrograph or discharge recession analysis method is simpler because fewer parameters, only discharge data, are needed. Although only hydrograph is considered, similar conclusions, perhaps even more numerous and reliable, can be reached (Bonacci, 1993; Dewandel et al., 2003; Fiorillo, 2014; Tallaksen, 1995).

Since the studies of Boussinesq (1877) and Maillet (1905), discharge recession analysis has become a very popular method to study the hydrological processes and to deduce the aquifer characteristics. The recession analysis was firstly developed to study aquifers with homogeneous structures. However, it was gradually, and then widely, used in karst area with a heterogeneous system as its simplicity (Bonacci, 1993; Chang et al., 2015; Dewandel et al., 2003; Eisenlohr et al., 1997; Fiorillo, 2009; Ghasemizadeh et al.,

* Corresponding author at: Key Laboratory of Agro-ecological Processes in Subtropical Region, Institute of Subtropical Agriculture, Chinese Academy of Sciences, Changsha 410125, China. Tel.: +86 731 84615226.
E-mail address: hbchs@isa.ac.cn (H. Chen).

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2012; Kiraly et al., 1995; Kovács et al., 2005; Padilla et al., 1994; Schmidt et al., 2014). Fiorillo (2014) provided a useful review of the recession analysis and categorized the recession models into empirical, semi-empirical, and physically-based models. Boussinesq, Maillet, and Mangin models are three of the widely used empirical or semi-empirical models (Amit et al., 2002; Eisenlohr et al., 1997; Farlin and Maloszewski, 2013; Lo Russo et al., 2014; Padilla et al., 1994; Schmidt et al., 2014). Boussinesq model (Boussinesq, 1904) is a quadratic equation, but Maillet model (Maillet, 1905) is a simple exponential equation. Both of the two models are used to describe the whole recession process of the discharge from an aquifer, but hardly different flow regimes can be noticed. Karst aquifer is always characterized by different flow media with conduit, fracture and matrix (Forkasiewicz and Paloc, 1967). Therefore, modified Maillet equation, which constituted of several exponential components standing for different flow regimes, was always used (Forkasiewicz and Paloc, 1967; Kovács and Perrochet, 2008). There is no problem that the baseflow is an exponential recession. However, whether the quickflow, which always turbulent flow appeared in the conduit, follows the exponential recession is always questioned. Mangin (1975), for example, pointed out that the exponential equation was not suitable for simulating the quickflow. Based on the Maillet model, he described the discharge recession as a sum of infiltration influenced process (quickflow) and baseflow recession process. Mangin model considered the characteristics of karst aquifer with fast and slow water flows, but one or more intermedia flows may be ignored. As can be seen, these models have both advantages and disadvantages. Moreover, which model can provide better results is still under debate (Dewandel et al., 2003; Lo Russo et al., 2014; Padilla et al., 1994).

The recession coefficient is one of the most important parameters that reflect the aquifer characteristics. Numerous equations were used to calculate this parameter (Boussinesq, 1877; Dewandel et al., 2003; Maillet, 1905). In general, the recession coefficient varies directly with the hydraulic conductivity but inversely with the aquifer storativity (Bonacci, 1993; Fiorillo, 2014; Forkasiewicz and Paloc, 1967; Katsanou et al., 2015; Kiraly, 2002). Different recession coefficients reflect the flow regimes with different hydraulic conductivities (Bonacci, 1993). Therefore, the recession coefficient was always used to describe the development of the conduit network with high hydraulic conductivity, and also to identify the karstification degree of an aquifer (Bailly-Comte et al., 2010; Bonacci, 1993; Ghasemizadeh et al., 2012; Katsanou et al., 2015; Malík and Vojtková, 2012; Padilla et al., 1994; White, 2003). Most of the descriptions were qualitative. However, the quantification of the effective porosity (n_{eff}) and water storage capacity for each hydraulic conductivity media may be more valuable in understanding the aquifer characteristics (Amit et al., 2002; Li, 2009).

Time series analysis is a useful tool for studying the aquifer characteristics. It was firstly used to study karst aquifer by Mangin (1984). Generally speaking, this method includes both univariate (auto-correlation function, ACF) and bivariate (cross-correlation function, CCF) analysis, which could characterize the temporal structure of hydrologic signals under the linear-stationary hypotheses (Labat et al., 2000; Padilla and Pulido-Bosch, 1995). Correlogram, memory time and delay time are always used to describe the karstification degree and the response of the aquifer to the rainfall (Covington et al., 2009; Katsanou et al., 2015; Lo Russo et al., 2014; Mayaud et al., 2014). The existing studies mainly concerned on long time scale (one year or more). Only few considered short time scale (rainfall event or flood scale) (Bailly-Comte et al., 2008; Mayaud et al., 2014). The results of the long time scale reflect the average response of the aquifer to the rainfall, but the short time scale reflect the response of the aquifer to a given pulse (Bailly-Comte et al., 2008; Mayaud et al., 2014). Therefore, it is necessary to study the processes in both time scales. Moreover, the results can be compared with that of the hydrograph analysis to see whether the two methods reflect the same characteristic of the aquifer.

Karst landscape is widely distributed in southwest China with an area of more than 500,000 km^2 (Yuan, 1994). Precipitation in this area is abundant, more than 1000 mm per year. But water resources shortage is still a problem for both ecosystem and human society due to the heterogeneous aquifer and fast hydrological processes (the rapid water flow in both saturated and unsaturated zone), with much water lost through the underground system (Chen et al., 2013; Jiang et al., 2014). Until now, researchers mainly concerned on the hydrological processes of the soil layer (Chen et al., 2010; Li et al., 2014; Zhang et al., 2011). However, the global characteristics of the water storing and transferring in the total aquifer may be more valuable, because soils in this area are always thin and distributed as mosaic with base-rock outcrop widely spread (Chen et al., 2010; Fu et al., 2015b). Therefore, studies should be done to further understand the aquifer structure and the related hydrological processes in this area. Previous study based on isotope method showed a poor development of conduit system and slow hydrological processes (Hu et al., 2015). It is inconsistent with the generally accepted knowledge that extremely fast and slow flow appear in a dual system. Therefore, a new method is needed to verify such results. Hydrograph method, as aforementioned, is a useful way. However, the hydrograph is influenced by the catchment's geomorphologic characteristics, vegetation community and many other environmental factors (Dewandel et al., 2003; Eisenlohr et al., 1997; Gregor and Malík, 2012; Lacey and Grayson, 1998; Lo Russo et al., 2014), all of which are quite unique in southwest China (Chen et al., 2011; Fu et al., 2015a; Nie et al., 2012). As a consequence, the recession models should be evaluated to see which is more suitable in this area.

The purposes of this study were (1) to characterize the hydrograph of the stream and evaluate three recession models (modified Maillet, Mangin and Boussinesq models), (2) to estimate the proportion of conduit, fracture, and matrix and calculate their water storage capacities, and (3) to verify the results with time series analysis method in a small karst catchment in southwest China.

2. Materials and methods

2.1. Recession analysis

Boussinesq (1904) developed a quadratic equation to describe the discharge recession process based on the simplified assumption that the aquifer was porous, free, homogeneous and isotropic:

$$Q_t = \frac{Q_0}{(1+\alpha t)^2} \tag{1}$$

In which Q_0 is the total discharge at $t = 0$ and α is the recession coefficient.

Unlike the Boussinesq model, Maillet (1905) used an exponential equation to simulate the recession process with the following formula:

$$Q_t = Q_0 \times e^{-\alpha t} \tag{2}$$

where Q_t is the discharge at time t, Q_0 is the discharge at $t = 0$, and α is the recession coefficient. In karst area, modified Maillet model was always used and it can be expressed by a sum of several exponential components (Eisenlohr et al., 1997; Fiorillo, 2014; Forkasiewicz and Paloc, 1967; Ghasemizadeh et al., 2012; Tallaksen, 1995):

$$Q_t = \sum_{i=1}^{n} Q_{0i} \times e^{-\alpha_i t} \tag{3}$$