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Effects of the conduit network on the spring hydrograph of the karst aquifer

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SUMMARY

Spring hydrograph, especially the recession curve, is widely used to understand the internal information of the karst aquifer. However, how the turbulent conduit network influences the spring hydrograph is still unclear. Generally, the spring hydrograph could be divided into the early portion from the point recharge and late portion from the diffuse recharge. In this paper, MODFLOW-CFP is used to understand the influence of turbulent conduit on the spring hydrograph from the diffuse recharge and different influences of the turbulent and laminar conduit on this spring hydrograph. And then, a conceptual model is used to further interpret it. Based on the analysis results, the influence of turbulent conduit on the spring hydrograph from the point recharge is also discussed. For the spring hydrograph from the diffuse recharge, when ignoring the storage variation of the conduit network, the turbulent conduit just influences the early recession curve and this influence decreases with the spring discharge or rainfall intensity until it disappears. When the spring hydrography is strongly reshaped by the storage of the turbulent conduit network, only the early recession behavior is influenced by the turbulent conduit network as well. However, the laminar conduit network has a strongly influence on the whole recession behavior. The late exponential recession coefficient decreases with the conduit diameter and conduit storage. These different influences of turbulent and laminar conduit on the spring hydrograph are mainly caused by their different flow characteristics. Although the turbulent conduit could also strongly influence the early spring hydrograph from the point recharge, the late spring hydrograph is mainly controlled by diffuse recharge and the influence from the turbulent conduit may also disappear.

1. Introduction

Karst aquifers are widely distributed around the world and provide the water resources for about one quarter of the world's population (Ford and Williams, 2007). Acquiring the reliable information about karst aquifers is very necessary for effective management and protection of karst water resources. However, due to the heterogeneity and complex internal structure of the karst aquifer, this information is often hardly obtained using traditional investigation techniques, such as pumping tests. Many other indirect methods, such as hydrochemistry analysis (Birk et al., 2004; Emblanch et al., 2003; Mudarra and Andreo, 2011; Raeisi et al., 2007), time series analysis (Larocque et al., 1998; Mangin, 1975; Padilla and Pulidobosch, 1995), spring hydrograph analysis (Baedke and Krothe, 2001; Bonacci, 1993; Covington et al., 2009; Fiorillo, 2009; Geyer et al., 2008; Padilla et al., 1994) and so on, are widely used to understand the internal structure and properties of the karst aquifer. In these methods, analysis of the spring hydrograph, especially the recession curve, is a very effective way to understand the internal properties or acquire some hydraulic parameters of the aquifer.

The spring hydrograph is the response of the aquifer to the recharge event. When the rainfall signal propagates through the aquifer, it should be altered by the aquifer. So the spring hydrograph could contain internal information of the karst aquifer. This is also the physical fundament of the spring hydrograph analysis. Generally, the karst aquifer is a complex hydrological system. For the recharge process, the recharge on the aquifer could be diffuse or concentrated, may derive from the outcrops of carbonate rocks (autogenic recharge), or from the surrounding non-karst areas (allogenic recharge) (Goldscheider and Drew, 2007). For the aquifer structure, the karst aquifer behaves as a dual-flow system consisting of highly conductive conduits and a relative low

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permeability fractured rock matrix with high significant storage (Ford and Williams, 2007; White, 2002). In addition, there is a highly weathered carbonate rocks (epikarst zone) locating at the top of vadose zone which plays an important role in the karst aquifer (Williams, 2008). The complex hydrological process in the karst aquifer determines the spring hydrograph may be influenced by many factors, such as recharge process, internal structure, hydraulic properties of unsaturated zone, matrix and conduit network (Bonacci, 1993; Covington et al., 2009; Eisenlohr et al., 1997; Geyer et al., 2008; Kiraly et al., 1995; Kovács and Perrochet, 2008; Kovács et al., 2005).

The conduit network is an important part of the karst aquifer and has very different characteristics with the surrounding matrix. It is always the main drainage passage and connects to the spring directly in the karst aquifer for its high hydraulic conductivity. Several works have shown the conduit network could exert a strong influence on the spring hydrograph. Halihan et al. (1998) found that the constriction in the conduit network could delay the flood water and the spring hydrograph could be controlled by these local constrictions. Covington et al. (2009) showed that the spring hydrograph might be strongly influenced by the reservoir/constrictions structure in the conduit network, whereas the full pipes or open channels in the conduit network could hardly influence the spring hydrograph. Reimann et al. (2011b) focused to investigate the effect of variable filled conduits and matrix-conduit coupling on the transmission of recharge pulses.

The recession curve of the spring hydrograph is widely used to analyze the aquifer characteristics or obtain some hydraulic parameters (Amit et al., 2002; Baedke and Krothe, 2001; Birk and Hergarten, 2010; Bonacci, 1993; Dewandel et al., 2003; Eisenlohr et al., 1997; Fiorillo, 2011; Padilla et al., 1994). Most analysis methods on the recession curve just consider the hydraulic properties of the matrix and neglect the influence of the conduit network on the recession curve. However, the recession curve may also influenced by the conduit network. Eisenlohr et al. (1997) pointed that the recession coefficient of recession curve is a global parameter that should contain the information of the conduit network, such as its density or conductivity. Eisenlohr (1996) investigated the influence of the conduit network, including its density, conductivity, storage coefficient and orientations, on the spring baseflow recession using a series of 2D synthetic models. Kovács et al. (2005) also pointed that the baseflow recession would be strongly influenced by the conduit conductivity when the conduit network in the karst aquifer deviates from the fixed head boundary. Otherwise, the baseflow recession is not influenced by the conduit when the conduit conductivity is large enough that the conduit network acts as the fixed head boundary in the aquifer.

Although these authors investigate the influence of conduit network on the recession coefficient in detail, their analysis results all depend on the model proposed by Kiraly and Morel (1976) which only considers the laminar flow in the conduit network. In the real karst aquifer, the flow in the conduit is often turbulent and only changes to be laminar in very dry period. The flow characteristics in the conduit and laminar conduit have obvious differences. Therefore, how the turbulent conduit influences the spring hydrograph especially the recession curve and what are the differences between the effects of turbulent and laminar conduit on the spring hydrograph are still needed further investigation. The objective of this paper is to answer these two questions.

In the karst aquifer, the conduit network always drains two recharge resources. On the one hand, the conduit network receives the point recharge from the epikart zone or surface flow and translates this recharge to the spring directly. In this process, the water in the conduit network may also flow into the matrix inversely when the hydraulic head of conduit network is higher than the matrix (Kiraly et al., 1995; Martin and Dean, 2001). On the other hand, the matrix around the conduit network receives the diffuse recharge and then is dewatered by the conduit network. Covington et al. (2009) pointed the response timescales of the conduit flow and matrix flow are always significant different which allows the separation of spring hydrographs into early portion that is mainly from the point recharge and late portion from the diffuse recharge. Therefore, we could analyze the influence of conduit network on the spring hydrograph from these two recharge resources seperately to understand how the conduit network influences the whole spring hydrograph. In this paper, we firstly analyze the influence of conduit network on the spring hydrograph mainly recharged by the diffuse recharge. To this end, the MODFLOW-CFP model (Shoemaker et al., 2008) is used to model the hydrological process of the karst aquifer. This model could simulate the duality of the karst aquifer and turbulent or laminar flow in the conduit network which is widely used by other authors to analyze the conduit evolution and interpret the spring discharge hydrographs and solute tracer tests (Bauer et al., 2003, 2005; Birk et al., 2005a,b, 2006; Liedl et al., 2003). Based on the simulation results, the influence of turbulent conduit on the spring hydrograph from the point recharge is discussed.

The paper is organized as follows: Section 2 briefly describes the background of the hybrid model MODFLOW-CFP. In Section 3, a simple karst aquifer and three simulation scenarios are described which are mainly used to analyze the influence of turbulent and laminar conduit on the spring hydrograph of karst aquifer recharged only by diffuse recharge. The analysis results are shown in Section 4 and then interpreted using a simple conceptual model. Based on the analysis results, the influence of turbulent conduit on the spring hydrograph from the point recharge is discussed. Finally, a simple example is shown.

2. Model description

In MODFLOW-CFP, the low-permeability matrix is conceptualized as an equivalent porous media and groundwater flow in the matrix is described by a partial-differential equation (McDonald and Harbaugh, 1988).

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h_m}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h_m}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h_m}{\partial z}\right)\pm\varphi=S_s\left(\frac{\partial h_m}{\partial t}\right)\quad(1)$$

where K_{xx}, K_{yy}, K_{zz} are the hydraulic conductivities ($\mathrm{L\,T^{-1}}$) along the x, y, and z axes, respectively, h_m is the groundwater head of the matrix (L), ψ is the external volumetric flux per unit volume and represents sources or sinks of water including the recharge and well pumping ($\mathrm{T^{-1}}$), S_s is the specific storage ($\mathrm{L^{-1}}$), and t is the time (T).

The conduit network is conceptualized by multiple cylindrical tubes that connect at nodes. The conduit nodes are located at the center of matrix cells in 2D plane and their heights could be specified by users. In a 3D grid, each node can be connected to six tubes from six different directions. Each tube has its own diameter and length. Two nodes locating at both ends of each tube control the conduit location and hydraulic gradient (Fig. 1). The bottom and top height of each tube are calculated by average height of two nodes plus or minus the radius of each tube. Whether the conduit is under pressure or unsaturated depends on the average head of two nodes and the top height of tubes.

The flow in cylindrical conduits could be laminar or turbulent. The Hagen–Poiseuille equation is used to describe the laminar flow in the conduit (Young et al., 2010).

$$Q_c=-A\frac{gd^2}{32\nu}\frac{\partial h_c}{\partial x}\quad(2)$$

where A is the flow cross sectional area of the conduit ($\mathrm{L^2}$), d is conduit diameter (L), ν is the kinematic viscosity of groundwater