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Research papers

Identification of the dominant hydrological process and appropriate model structure of a karst catchment through stepwise simplification of a complex conceptual model

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ABSTRACT

Conceptual models often suffer from the over-parameterization problem due to limited available data for the calibration. This leads to the problem of parameter nonuniqueness and equifinality, which may bring much uncertainty of the simulation result. How to find out the appropriate model structure supported by the available data to simulate the catchment is still a big challenge in the hydrological research. In this paper, we adopt a multi-model framework to identify the dominant hydrological process and appropriate model structure of a karst spring, located in Guilin city, China. For this catchment, the spring discharge is the only available data for the model calibration. This framework starts with a relative complex conceptual model according to the perception of the catchment and then this complex is simplified into several different models by gradually removing the model component. The multi-objective approach is used to compare the performance of these different models and the regional sensitivity analysis (RSA) is used to investigate the parameter identifiability. The results show this karst spring is mainly controlled by two different hydrological processes and one of the processes is threshold-driven which is consistent with the fieldwork investigation. However, the appropriate model structure to simulate the discharge of this spring is much simpler than the actual aquifer structure and hydrological processes understanding from the fieldwork investigation. A simple linear reservoir with two different outlets is enough to simulate this spring discharge. The detail runoff process in the catchment is not needed in the conceptual model to simulate the spring discharge. More complex model should need more other additional data to avoid serious deterioration of model predictions.

1. Introduction

In contrast to other porous media aquifers, karst aquifers are much more complex systems due to the development of secondary porosity caused by the rock dissolution (Ford and Williams, 2007). Large fractures or conduits often exist in karst aquifers which lead to the duality of flow system with rapid flow in the conduit system and relatively slow permeability in the fissured rock matrix (Goldscheider and Drew, 2007). Additionally, there is always a highly weathered layer (epikarst) with higher porosity and permeability beneath the land surface which divides the autogenic recharge on the saturated zone into diffuse and point infiltration (Kiraly et al., 1995; Williams, 2008). These complex aquifer structures lead to a big challenge to simulate these karst systems.

Conceptual hydrological models commonly operate with several connected reservoirs or stores representing different physical elements in the catchment which are widely used to simulate karst aquifers due to their low data demands (Chang et al., 2015; Fleury et al., 2009, 2007; Hartmann et al., 2013a, 2012b; Tritz et al., 2011). The establishment of the conceptual model is mainly based on the perception of actual hydrological process that occurs in the catchment. The different hydrological processes are often represented by the different reservoirs or stores in conceptual simulation models (Le Moine et al., 2008). With the deep investigation in the catchment over time, more detail runoff processes are found which leads to much more complex model accompanying by an increase of the number of parameters. In the conceptual model, most parameters represent the average characteristics of the whole

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catchment and cannot be measured directly. Calibration is the only way to identify the values of these effective parameters. However, for most catchments, rainfall-streamflow (for the karst aquifer, rainfall-spring discharge) data are the only available information that could be used to calibrate the conceptual model. Previous results show this time-series variables could just identify up to five or six parameters in such conceptual model (Beven, 1989; Jakeman and Hornberger, 1993; Ye et al., 1997; Perrin et al., 2001). Complex conceptual model consisting of large number of parameters may suffer from over-parameterization problem which could lead to poor parameter identification or equifinality (Beven, 2006), and bring considerable uncertainty. On the one hand, we want to include all hydrological processes observed in the catchment as many as possible in the conceptual model; on the other hand, the limited data may not support such complex model structure. The involvement of so many hydrological processes in the conceptual model just increases the complexity and uncertainty of the model which inversely bring the deterioration of prediction. How to explore the trade-off between the complexity of conceptual models and limited available data, and find the appropriate mode structure supported by the available date is still a big challenge in the hydrological research.

A multi-model framework involving a range of models with varying structural complexity is a good tool to diagnose the model complexity and dominant hydrological process through the comparison of the performance of many different models (Clark et al., 2011a; Fenicia et al., 2008b; Krueger et al., 2010; Martinez and Gupta, 2010). This performance-based diagnostic method is mainly based on the two assumptions: (1) the model performance should increase with it complexity, otherwise the complex model is in the high risk of over-parameterization; (2) the model with higher performance corresponds to the more closeness of hydrological process descriptions in this model to the actual hydrological process. According to the principle of parsimony, the appropriate model structure in the multi-model framework should be the one with the simplest structure (small parameters) and good performance (Jakeman and Hornberger, 1993; Schoups et al., 2008; Wheater et al., 1993; Young, 2003). The typical application of this method is the top-down approach which starts with a simple model and progressively increases the model complexity by adding extra components (Jothityangkoon et al., 2001; Lan-Anh and Willems, 2011; Montanari et al., 2006; Sivapalan et al., 2003). The complex model is accepted only when the model performance is improved. Other applications, such as FUSE and SUPERFLEX framework, are also widely used in many studies (Clark et al., 2011b, 2008; Fenicia et al., 2014; Kavetski and Fenicia, 2011; van Esse et al., 2013). For the most frameworks, such as top-down method or SUPERFLEX, the model complexity always increases progressively. However, how to increase the model complexity or add the extra complexity is always arbitrary and subjective (Clark et al., 2011a). Other possible model structures with the equivalent complexity may be ignored. Moreover, in most situations, we always could establish a complex model rather than a very simple model due to the deeper investigation of the catchment. The problem we often have to face is to determine whether this complex model is over-parameterized and if so, how to find the dominant hydrological process in this over-parameterized model and establish the appropriate or balanced model structure supported by the available data? Therefore, unlike the previous strategy that progressively increases the model complexity, in this paper we establish a framework that begins with a complex model according to our perception of the catchment and then decreases the model complexity step by step to identify the dominant hydrological process and find the appropriate model structure supported by the available data.

Although the multi-model comparison method is widely used, the good performance of the model could not guarantee all the parameters in the model could be identified through the available data. The parameter identifiability is an important index to determine whether the model is over-parameterized and it has been used by several authors to judge the model complexity (Jakeman and Hornberger, 1993; Schoups et al., 2008). The model with parameters of low identifiability indicates this model is in the high risk of over-parameterization and the relevant parameters could bring high uncertainty into the model predictions. The model should be simplified by replacing the unidentifiable parameters by constants or directly eliminate them in the model (Wagener et al., 2001). The sensitivity analysis is an effective technique to understand the contribution of the parameter to the simulation result (Song et al., 2015; van Griensven et al., 2006; van Werkhoven et al., 2008). The sensitivity is a necessary but not sufficient condition for identifiability (Reusser et al., 2011; Wagener et al., 2003). Although a sensitive parameter may not necessarily indicate high parameter identifiability as it may be strongly sensitive but have two optimum values at the same time, the parameters with low sensitivity always indicate their poor identifiability. To some extent, the sensitivity is still a good indicator for parameter identifiability and we can use the sensitivity analysis to understand the parameter identifiability. The drawback of sensitivity analysis is that it cannot provide the any information about the model performance. A model with all parameters sensitive to the simulation result may have very bad simulation results. Therefore, the sensitivity analysis always acts as a supplementary method to evaluate the model (Chen et al., 2017; Hartmann et al., 2013b; Moussu et al., 2011; Son and Sivapalan, 2007).

In this paper, we apply a multi-model framework together with the sensitivity analysis to identify the dominant hydrological process of a karst spring and find the appropriate model structure to simulate the discharge of this spring. The paper was organized as follows. Firstly, we briefly describe the karst catchment. According to the perception of this catchment, a conceptual model is established, and then this conceptual model is simplified stepwise to several simple models by gradually removing the model component to establish the multi-model framework. Secondly, the multi-objective optimization and a regional sensitivity analysis are used to compare the model performance and parameter identifiability respectively to identify the appropriate model structure and dominant hydrological process. At the end, the connection between the fieldwork investigation and conceptual model is discussed.

2. Catchment description

Yaji karst experimental site is located in the southeast of Guilin city, China (Fig. 1). This karst system is developed in a thick formation of upper Devonian pure limestone and the geomorphology belongs to a typical peak cluster-depression landform. Due to the massive deforestation in last century, the vegetation in this area is mainly secondary shrub. The karstification degree of this aquifer is very high and various karst features, such as cave, shaft, sinkholes and karren, could all be found in this site. The karst development is mainly controlled by NEE-oriented structures. The dry caves and conduits are all developed along this direction. The borehole logs indicate the epikarst zone exists beneath the surfer with the depth of about 3–10 m. The epikarst springs are widely distributed in many depressions. The climate is subtropical monsoon with an average temperature of 18.8 °C and annual precipitation of 1915 mm. The main rainy season is from April to August and storms are frequent.