Application of an improved distributed Xinanjiang hydrological model for flood prediction in a karst catchment in South-Western China

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Abstract
Hydrological processes in karst aquifer systems are controlled by highly permeable media, so studying flood processes in karst-dominated regions is very important; however, it is still a challenge to model the hydrological dynamics in such strongly heterogeneous conditions. This study proposed a distributed Xinanjiang karst hydrological model (DXAJKHM) for simulating the flood processes in karst catchments, which was based on topographical information extracted from a digital elevation model. Considering the dual-porosity in karst aquifer systems, the DXAJKHM was coupled with a traditional Xinanjiang conceptual hydrological model and utilized two karst reservoirs that simulated both the rapid underground run-off and the slow underground run-off in each grid cell. The uncertainty in the model parameters is estimated by the generalized likelihood uncertainty estimation method, and the parameters are determined by the shuffled complex evolution approach optimization algorithm. The simulation results demonstrated that the proposed DXAJKHM satisfactorily simulated the flood processes, and the model has better simulation effects for floods with larger flood peaks. In order to analyse the flood recession error, one run-off signature index was employed to improve the model runs. This study thus provides a new approach to simulating and predicting floods in karst areas.

KEYWORDS
catchments, forecasting and warning, hydrological modelling, modelling

1 | INTRODUCTION

The anisotropy of aquifers in karst aquifers and complex water conditions have led to strong spatial and temporal differences in floods occurring in karst basins (Bonacci, Ljubenkov, & Roje-Bonacci, 2006), and the flow patterns of water in karst systems are also complex. At the same time, karst aquifer systems have weak water holding capacity and water storage capacity. When the cumulative rainfall of a rainfall event is greater than the capacity of the karst conduits and fissures in aquifer systems (Gázquez, Calaforra, & Fernández-Cortés, 2016), it is easy...
to trigger karst flash floods (Demiroglu, 2016; Martinotti et al., 2017). With the increasing risk of extreme weather events worldwide, the probability of sudden floods in karst watersheds has increased significantly (Gázquez et al., 2016); therefore, it is of great practical significance to study flood prevention countermeasures in karst basins. Constructing a reliable flood forecasting scheme for karst watersheds based on hydrological modelling is an extremely important nonengineering measure for flood control, but due to the complexity of karst aquifer systems, hydrological modelling and accuracy issues in karst watersheds compared to nonkarst watersheds make it more difficult to simulate and predict water dynamics in karst areas (Bakalowicz, 2005; Hartmann, Goldscheider, Wagener, Lange, & Weiler, 2014).

At present, two kinds of models are mainly used in the simulation of hydrological process in a karst basin: distributed models and lumped models (Hartmann et al., 2014). The lumped models focus on the overall hydrological process of the entire karst aquifer system and neglect modelling the spatial distribution. The popular lumped modelling approaches are black-box and reservoir models. The black-box model describes the karst aquifer system as a completely unknown system, which overlooks the hydrodynamic characteristics and mechanisms. The other modelling approach is the reservoir-type model, which can describe the dual-flow systems used to simulate the water flow in karst systems. Therefore, it is mostly applied to simulate the hydrological processes of karst aquifer systems with matrix flow and conduit flow (Fleury, Plagnes, & Bakalowicz, 2007; Jukić & Denić-Jukić, 2006). Nevertheless, due to a lack of consideration of the inhomogeneity of the basin, it is difficult to precisely quantify the spatial structure of karst aquifer systems (Birk, Liedl, & Sauter, 2006; Hartmann, Barberá, Lange, Andreo, & Weiler, 2013; Ronayne & Michael, 2013), and its application in flood forecasting is very limited.

Compared with lumped models, distributed models have a great advantage in representing detailed hydrological processes. The distributed models discretize the karst system in two-dimensional or three-dimensional grids, and the hydrology or hydraulics parameters are assigned to each grid so that they can account for the spatial variability characteristics of hydrological parameters and elements, which are affected by topography, soil, vegetation, land use, and precipitation in the watershed (Kordilla, Sauter, Reimann, & Geyer, 2012; Reimann, Rehrl, Shoe-maker, Geyer, & Birk, 2011; Worthington, 2009). At present, the major distributed models used in karst basins, such as MODELFLOW and FEFLOW, utilize groundwater dynamics, which can simulate the recharge process of groundwater in karst aquifer systems and are often used in the comprehensive simulation of flow conditions and solute migration in dual-porosity systems (Birk et al., 2006; Ronayne & Michael, 2013). These kinds of models, however, are not suitable for flood forecasting in karst basins. Distributed hydrological models can describe the spatial variability characteristics of surface run-off, interflow run-off, groundwater run-off, and evaporation in watersheds, which are widely used for flood forecasting (Chen, Li, & Xu, 2016; Kauffeldt, Wetterhall, Pappenberger, Salamon, & Thielen, 2016; Krajewski et al., 2017; Vieux, Cui, & Gaur, 2004). General distributed hydrological models rarely consider the hydrological behaviour of karst aquifer systems, however. In order to provide a solution for flood forecasting in karst basin, some scholars have attempted to improve the distributed hydrological model. Since obtaining sufficient information about conduit geometries and roughness is difficult, these scholars have improved the run-off generation and routing modules to describe the hydrological characteristics of karst aquifer systems, without considering detailed knowledge about the spatial distribution of the fracture network. Based on the multilayer structure of the distributed hydrology–soil–vegetation model, Zhang, Chen, Ghadouani, and Shi (2011) developed a model for a karst basin by integrating mathematical routings of different kinds of flow, using ‘cubic law’ which is associated with fractural width, direction, and spacing to express the flow movement within epikarst fractures (Zhang et al., 2011).

The studies above indicate that improved distributed hydrological models have great potential in terms of boosting karst flood simulations and forecasting capabilities, but the large number of parameters in the above models hinders their application at large scales, and the empirical parameters in the distributed models are difficult to constrain. In general, the observed data quality and quantity in karst aquifer systems are very limited, making modelling the karst hydrology process challenging and also affecting the model evaluation, which may lead to great uncertainties in parameters and outputs. Calibration schemes using objective functions to compute the statistical fit between the simulations and observations can only indicate the mathematically optimum value, which may differ from the hydrologically optimum value (Andréassian et al., 2012); this does not guarantee that the model reflects the function of the catchment adequately, especially under the circumstances of karst systems (Gunkel, Shadeed, Hartmann, Wagener, & Lange, 2015). In order to solve the problem, some indices and time series of the response behaviour of a catchment (called signatures) were proposed (Gupta, Wagener, & Liu, 2008) to serve as constraints for model parameter optimization or good model runs. Typical signatures include flow duration curves (FDCs), run-off ratios, aridity indices, or measures of discharge timing
(Gunkel et al., 2015). Gunkel et al.’s (2015) study shows that hydrologic signatures helped to constrain the possible model outcomes and provided insights into the model structure and parameterization.

The Xinanjiang model is a conceptual hydrological model of run-off simulation and flood forecasting widely used in humid and semi-humid areas of China (Jayawardena & Zhou, 2000; Xu, Xu, Chen, Zhang, & Li, 2013; Zhao, 1992). Yao, Li, Bao, and Yu (2009) developed a distributed Xinanjiang model, the Grid-Xinanjiang model, and this model outperformed the original Xinanjiang model in predicting run-off and floods. The model also demonstrated that it has some advantages in terms of generating flood forecasting in Chinese watersheds compared with other physically based distributed hydrological models, for example, the MIKE System Hydrological European Model and Institute of Hydrology Distributed Model (Yao et al., 2009). For these reasons, herein we proposed a distributed hydrological model that addressed each of these issues by improving the original conceptual Xinanjiang model.

The aims of this study are to (a) add two reservoirs simulating the conduit flow and matrix flow to the run-off separation module on the basis of the original conceptual Xinanjiang model; (b) develop a grid-based distributed hydrological model used for karst areas based on the improved Xinanjiang model and analyse the optimal modelling interval; (3) analyse the sensitivity of the parameters in the model using the generalized likelihood uncertainty estimation (GLUE) method and optimize the parameters with the shuffled complex evolution approach (SCE-UA) method; (d) apply the newly distributed karst hydrological model in a typical karst basin in southwest China for flood simulation and prediction; and (e) determine the run-off signatures that can be computed with the observed data to evaluate the applicability of the model and analyse the flood recession errors.

2 | MATERIALS AND METHODS

2.1 | Study site

The Qiaoyin Karst River Catchment (QYKRC), a typical small karst catchment in Southern China, was chosen as the study site to verify the application of the distributed Xinanjiang karst hydrological model (DXAJKHM). The QYKRC is located at 24°28′–24°45′N and 106°54′–107°6′E with a drainage area of 348 km². The QYKRC is affected by the subtropical monsoon; thus, precipitation mainly occurs in the flood season from April to September each year. The average annual precipitation of the QYKRC is 1,548.9 mm, 55.2% of which occurs in the summer (853.9 mm). The average annual evaporation is 1,367.9 mm. Karst landforms in complicated hydrological conditions account for 11% of the study area, that is, 45% of Fengshan County. A rough map of the QYKRC is shown in Figure 1.

2.2 | Data collection

The topographic data required for the distributed karst hydrological model for flood prediction in this study are a digital elevation model (DEM), which is downloaded from the Shuttle Radar Topography Mission database (http://srtm.csi.cgiar.org/download) with an initial resolution of 30 m × 30 m.

There are six precipitation gauges and one hydrological station in the QYKRC. In this study, we consider 10 karst flood events that happened during the period of 2010–2015, most of which were flash floods, and hourly precipitation data are collected as well. The six precipitation gauges are distributed evenly over the entire QYKRC, and the hydrological gauge (Fengshan gauge) is located close to the outlet of the catchment, as shown in Figure 1. We use evaporation data from the Fengshan gauge to represent the actual evaporation of the study site. Some information about hydrology and real floods in the region is shown in Table 1, these data are provided by Bureau of Hydrology and water resources of Guangxi, China.

2.3 | Distributed hydrological karst model

2.3.1 | Structure and foundation

The DXAJKHM is a distributed hydrological model which models the hydrological process in each computational element. The raster format of the catchment topographic map is used as the derived information in the distributed karst hydrological model alongside observed rainfall and evaporation data. There are four modules in the distributed karst hydrological model: a run-off generation module, evapotranspiration module, run-off separation module, and flow routing module, which are developed from the original lumped Xinanjiang model proposed by Zhao (Zhao, 1992).

The pixels for the DEM are used as the computational elements in the DXAJKHM. The active cells obtained from the DEM are classified into two categories: slope-cell and channel-cell. The run-off production calculation process of the sloping-cell element is shown in Figure 2. The outflow of every pixel converges on the outlet of the entire catchment, which depends on the routing from cell to cell. The method applied to simulate the flow routing...
### TABLE 1  
Some information of real floods in Qiaoyin Karst River Catchment (QYKRC)

| Floods   | Start time (month, date, year and hours) | End time (month, date, year and hours) | Lasting (hours) | Precipitation (mm) | Observed peak flow (m³/s) | Observed run-off (mm) |
|----------|------------------------------------------|----------------------------------------|-----------------|--------------------|----------------------------|------------------------|
| 20110609 | June 10, 2011, 5:00                      | June 11, 2011, 20:00                   | 40              | 37.1               | 27.5                       | 3.96                   |
| 20110614 | June 15, 2011, 4:00                      | June 17, 2011, 0:00                    | 61              | 31.2               | 25.0                       | 4.77                   |
| 20110630 | June 30, 2011, 10:00                     | July 3, 2011, 4:00                     | 67              | 89.7               | 39.7                       | 13.24                  |
| 20110709 | July 10, 2011, 16:00                     | July 12, 2011, 6:00                    | 39              | 49.9               | 35.9                       | 5.57                   |
| 20120607 | June 7, 2012, 21:00                      | June 9, 2012, 12:00                    | 41              | 67.2               | 186.0                      | 37.19                  |
| 20140603 | June 3, 2014, 22:00                      | June 5, 2014, 14:00                    | 41              | 113.4              | 503.0                      | 104.21                 |
| 20150519 | May 20, 2015, 3:00                       | May 21, 2015, 17:00                    | 39              | 70.8               | 58.0                       | 11.53                  |
| 20150620 | June 20, 2015, 2:00                      | June 22, 2015, 19:00                   | 66              | 79.7               | 336.0                      | 55.80                  |
| 20150818 | August 19, 2015, 3:00                    | August 22, 2015, 21:00                 | 91              | 77.8               | 276                        | 58.51                  |
| 20150910 | September 10, 2015, 6:00                 | September 13, 2015, 15:00              | 82              | 57.8               | 91.1                       | 33.38                  |

**FIGURE 1**  
Sketch map of Qiaoyin Karst river catchment
in the slope-cell elements is the linear reservoir-type model, and the Muskingum–Cunge method is used to simulate the flow routing in the channel-cell elements. Both routing methods are based on the computed order among the DEM grid cells.

Run-off yield calculations in cell elements
In the distributed karst hydrological model, the evaporation module calculated in each slope-cell is related to the potential evapotranspiration through a three-layer soil moisture model, and the run-off production calculation conforms to the concept of excess storage, which supposes that the run-off production occurs only on repletion of the tension water storage.

Run-off separation in cell elements
The porosities in karst systems can be divided into micropores, fissures, and fractures; according to their origins, micropores and fissures are classified as matrixes, and the large fractures are called (karst) conduits (White, 2002). The existence of these porosities makes the movement of water at the surface and the underground flow of karst systems strongly inhomogeneous, and the hydrological response under the actions of the karst system indicates a duality in its process and storage dynamics (Bakalowicz, 2005). The flow in the highly permeable conduit is rapid in a manner that can sometimes be described by turbulent flow regimes, while the flow in the slightly conductive matrix is a slow laminar flow (Atkinson, 1977; Bauer, Liedl, & Sauter, 2005; Naughton, Johnston, McCormack, & Gill, 2015; Sauter, 1995). In summary, there is a marked difference between the hydrological processes that occur in a karst matrix and conduit. The run-off in the Xinanjiang model is only separated into three components: surface run-off, interflow run-off, and underground run-off (Zhao, 1992). The underground run-off has not been further separated into conduit flow and matrix flow, which does not conform to the laws of the dual-flow system. This dual-porosity system, including the matrix and conduit, can exert significant influence on the rainfall–run-off process in the basin, especially with obvious flood detention (Halihan, Wicks, & Engeln, 1998); therefore, the dual-porosity should be addressed in the model structure. In order to represent this natural component of the karst, we use two parallel reservoirs—a quick flow reservoir to simulate outflow from the conduit and a slow-flow reservoir to simulate outflow from the matrix.

The diffusively infiltrated flow penetrates slowly through the matrix, but that in the conduit is always fast. The matrix flow is considered a slow flow, and the conduit flow is called a rapid flow. In our study, like many other models (Fleury et al., 2007; Hartmann et al., 2012), we use the matrix and conduit reservoirs method, which has great potential in terms of analysing the karst spring hydrograph to simulate the rapid groundwater flow RG1 in conduit and the slow groundwater flow RG2 in matrix within the karst aquifer systems. Thus, a new parameter KGSF is introduced to describe the division of groundwater run-off.

FIGURE 2  Schematic chart of the run-off generation computing in each slope-cell element. ED, evaporation of deeper layer; EL, evaporation of lower layer; EU, evaporation of upper layer; RG1, quick-flow groundwater run-off yield; RG2, slow-flow groundwater run-off yield; RI, interflow run-off yield; RS, surface run-off yield; TRG1, outflows from the reservoirs of quick-flow groundwater run-off components; TRG2, outflows from the reservoirs of slow-flow groundwater run-off components; TRI, outflows from the reservoirs of interflow run-off components; TRS, outflows from the reservoirs of surface run-off components; WD, tension water of deeper layer; WL, tension water of lower layer; WU, tension water of upper layer
KGSF represents the proportion of rapid flow in the process of total groundwater run-off, that is, \( KGSF = \frac{RG_1}{RG} \). Among them, fast flow and slow flow are considered:

\[
RG_1 = RG \times KGSF, \quad (1)
\]

\[
RG_2 = RG \times (1 - KGSF). \quad (2)
\]

In order to study the influence of various amounts of precipitation on the groundwater partition, we selected eight karst flood recession events during 2011 and 2015 to analyse and deduce the partitioning coefficient parameter KGSF. This method has been applied by many scholars for simulating the different features of the diverse components in karst aquifer systems (Chang, Wu, & Liu, 2015; Geyer, Birk, Liedl, & Sauter, 2008). Both Fleury et al. (2007) and Hartmann et al. (2012) focused on continuous interannual simulation of karst spring discharge, but their models are too economical to simulate other hydrological processes excluding springs; thus, their models are not suitable for flood forecasting.

We separate a karst flood recession hydrograph into two stages: the rapid-flow-drainage stage (quick conduit discharge from a conduit reservoir) and slow-flow-drainage stage (slow matrix discharge from a matrix reservoir). In the semilogarithm plot, recession curves of the selected karst floods with different precipitation magnitudes are divided into two segments (see in Figures 3 and 4). The recession coefficient of each segment was calculated by the following exponential equation (Maillet, 1905):

\[
Q_t = Q_0 e^{-at}, \quad (3)
\]