Modification of the Xin’anjiang Model for Flood Forecasting in Karst Area, Southwestern China

Rucheng Jiang, Shixiang Gu, Mi Zhou
Yunnan Survey and Design Institute of Water Conservancy and Hydropower, Kunming 650021, China.

Abstract: Hydrological modeling of a karst environment is challenging because of the characteristically thin soil and low soil water retention capacity. The purpose of this study was to simulate floods in a complex karstic river basin that comprised a large karst depression, high mountainous karstic areas, springs, and downstream karst areas. In such an environment, deterministic models (e.g., SWAT) are unable to compute the additional contribution from the subsurface. In this paper, a modified Xin’anjiang model was proposed and a specific method was presented for characterizing the karst aquifers flow systems by calibrating parameters from a spring hydrograph analysis. The simulated results indicated that the karst depression, as a storage element, provides a considerable buffer to the effects of a rainstorm. The application of the modified Xin’anjiang model demonstrated its applicability to the karst regions in southwestern China. Thus, it can provide better understanding of such hydrological systems and offer an improved basis for their future hydrological management.

1. Introduction
The area of Karst terrain is approximately 2.2 million km² (accounts for 15% of the world’s land area) (Yuan and Chai 1988) and about 25% of the world’s population is supplied largely or entirely by karst waters (Ford and Williams 1989). These aquifers constitute a valuable freshwater resource; however, the freshwater is often difficult to exploit and it is always subject to contamination because of the specific hydrogeological properties. The karst areas of southwestern China constitute a typical vulnerable ecological region that represents the largest consecutive distribution and very strong karst development in the world (Yang and Yuan 2013). These areas, which lie within the subtropical zone, have favorable water and temperature conditions but exhibit extremely heterogeneous water distributions due to long-term karstification. This has led to the formation of a karst soil and water resource environment that has a number of problems, such as structural water shortages, infertile soil, and ecological vulnerability (Yuan 1996). These issues, together with the growing population and an increasing demand for water in the region, have highlighted the importance of the water stored in this type of medium.

This study considered the Dianwei Basin in southwestern China, which is an important source of both drinking water for the city of Kunming and agricultural water for the surrounding area. Therefore, for effective operation of the water resource system, it is very important to be able to forecast streamflow for periods of up to hours, days, months, or even longer. However, hydrological modeling of this region is challenging because of the dynamic and complex processes of karstic watershed runoff, which result from the nonlinear distribution of subsurface rivers, fractures, sinkholes, and underground channels (Bakalowicz 2005). Existing process-based karst models can be generally classified as either lumped or distributed modeling approaches (Jakeman and Hornberger 1993). In
actual applications, parameter-poor conceptual models might yield more satisfactory results, which is because of the complexity and heterogeneity of karst systems and the limitations of detailed and quantifiable information about physical parameters (Salerno and Tartari 2009).

The region of interest of this study displays typical karstic landforms at the surface. Karst depressions (dolines, uvalas, and poljes) play an important role in the recharge and hydrodynamics of water flow. They can trap sediment and retain large amounts of water, delaying its percolation toward the water table or toward the networks of conduits when their detrital filling reaches a certain thickness. Therefore, field mapping of such depressions is of great importance. However, their delineation could be difficult because the study area might be very large, or the depressions might be inaccessible or hidden by vegetation (Király 1975; Padilla et al. 1994; Pardo-Igúzquiza et al. 2015). Furthermore, points data are only representative of the ambient environment and they can rarely be extrapolated to the entire system. An alternative method is to use spring discharge as the dynamic change of a karst spring, which is always the outlet of a karst drainage system, to reflect the regional hydrogeological characteristics. In most cases, time series of spring discharge data are available and most karst springs reflect the areal recharge events of an entire karst system (Király 1975; Dreiss 1982, 1989; Sauter 1992; Teutsch 1992; Padilla et al. 1994; Lakey and Krothe 1996). The spring hydrograph recession coefficient is an comprehensive parameter of an aquifer which can provides important information about the system’s hydraulic characteristic (Kovács 2005). Although several authors has analyzed the dynamic change of a karst spring (e.g., Maillet 1905; Berkaloff 1967; Bagarić 1978), it has been used rarely as a method of determining the appropriate model input parameters necessary for global karstic watershed flood modeling.

The purpose of this study was to characterize the functioning of a karst aquifer that has complex hydrogeology and for which the detailed information about the physical parameters were limited. In this study, a modified Xin'anjiang (XAJ) model was used to simulate the flooding of this karst system. The hydrological and geochemical signals at the principal karst spring in the study area were analyzed both to examine how karst systems operate to produce floods and to calibrate some of the model parameters. This permitted the definition of the role of the karst aquifer (especially the depressions) in the hydrogeological functioning of this system and the identification of the relationship between the spring recession coefficient and a linear reservoir outflow coefficient.

2. Methodology

2.1 Study area and data acquisition
The Dianwei River Basin is located in Yunnan Province, southwestern China and it incorporates the lower part of the Jinshajiang River. The characteristics of the regional karst hydrogeology are shown in Fig. 1. The Dianwei Basin karst area is a NE–SW-trending basin covering an area of 143.5 km² and its geomorphic forms are karst-hill depressions. The region has a sub-tropical monsoon climate with an annual mean temperature of 14.7 °C and seasonally variable precipitation; the rainy season (May to Oct) produces 793-913mm of precipitation, which is 78.8%-90.7% of the annual total (1006.5mm). The annual amount of sunshine is around 2470.3 h and the annual water surface evaporation is 1870.6 mm.

The study area displays typical surface karstic landforms. In the Dianwei River Basin, the examples of karst geomorphology, which comprise mainly sinkholes, caves, blind valleys, and other subsurface karst drainage features beneath the sinkhole plain, occur in the upstream part of the basin. The Baiyi Depression is the largest and most easily waterlogged depression within the system. Because of the convergence of several conduits with many water outlets, it is very important to understand the groundwater status of the area. The dominant soil type is loose rock (composed mainly of sand, clay, and gravel) and carbonatite, covering 50% of the watershed. In downstream areas, quaternary unconsolidated sediments are exposed. Karst groundwater resources are abundant and the Qinglongtan Spring is the main spring draining groundwater toward the Lenshui River. A hydrological station was established in 1976 to monitor the water discharge. Subsequent processing and analyses of these data
have led to the calculation of the spring’s recession coefficient and dynamic volume and have provided information regarding water flow within the karst aquifer and the behavior of the spring. Although the flood peak in the area is relatively small, the flood volume is large and it lasts a long time during the flooding period.

In this work, we chose to apply the hydrograph analysis technique to attempt to derive meaningful model parameters. The time series of discharge data from the karst spring was used to characterize the hydrogeological processes (e.g., infiltration, residence time, and functioning) of the aquifer. The analysis of these processes provided information regarding the volume of water transferred from the recharge area to the discharge zone, as well as the lag time and recession constant of groundwater storage of the karst aquifer.

Two categories of data were used in this study. (1) Hydrological data were used for the calibration and validation of the hydrological model’s parameters, including daily and hourly rainfall and runoff, and daily evaporation rate. The rainfall data, obtained from six permanent rain gauges (Dianwei, Longtannao, Baiyi, Dashiba, Pingdi, and Maichong) within the Dianwei River Basin, were employed with an equal weighting of 0.17. Evaporation and streamflow data were obtained from the Dianwei hydrological station at the outlet of the catchment. Nine flood events in the Dianwei Basin from 1964 to 1987 were selected for the test. Daily and hourly discharges from the Qinglongtan Spring from 1976 to 1987 were also used. (2) A digital elevation model with 90 × 90 m grid resolution was used to derive the topographical and geographical characteristics of the watershed, such as the contour lines, main-channel slope, drainage density, and total length of the channels.

2.2 Spring discharge
In the study area, aquifer recharge takes place through direct infiltration of rainwater. Discharge is mainly produced through springs located at the northern border of the carbonate outcrops (Fig. 1). The hydrodynamic and discharge time series data of two springs draining the karstic aquifers of the Dianwei River Basin were analyzed. Although they are located in close proximity, the Qinglongtan and Heilongtan springs exhibit distinct hydrogeological behaviors. Figure 2 shows the temporal evolution of the discharge from these two springs and the rainfall recorded in the area during the study period. It can be seen that the Qinglongtan Spring data show relatively quick variations in flow rates in response to precipitation events (range: 0.057-4.9 m³/s), whereas the Heilongtan Spring is characterized as an underflow karst spring (range: 0.226-0.392 m³/s).
2.3 Description of model structure

The XAJ model is a conceptual hydrologic model developed by Zhao et al. (1980) based on extensive observational data from the Xin’anjiang reservoir watershed (Zhao 1992, Zhao 1993).
Based on extensive field research, it has been determined that the hydrological features of karst catchments within southwestern China on the daily scale could satisfy the assumptions of the XAJ model (Shi and Zhou 2014). However, the depression that acts as the storage element shows considerable buffering to the effects of a rainstorm. The arrival at the spring of a flood previously stored within the epikarst and the lag until the peak at the spring outlet could be indicative of the transit time of the water from the epikarst to the spring. The Dianwei Basin spring respond to the most important precipitation events with significant increases in groundwater flow (fastest and highest at the Qinglongtan Spring), although sometimes with a slight delay (Fig. 3). This buffering effect is strong for floods, and therefore it is necessary to describe the main characteristics relevant to the phenomenon for process modelling. To improve the simulation precision, the model was enhanced by the addition of one further linear reservoir, representing the part of the groundwater of the free water sluice reservoir, to simulate the hydraulic buffering function of the karst aquifer to a flood. The spring hydrograph was used to identify the relationship between the spring recession coefficient and the added linear reservoir outflow coefficient.

The epikarst zone is represented by the additional groundwater linear reservoir (hereafter, denoted as “H”). This is a structure usually associated with local groundwater storage and that receives an incoming $RG$. The volume of water stored in reservoir H is denoted by $H$. Part of water contained in H might flow outside of the catchment with a discharge of $QG$, provided that $H$ exceeds a given threshold $H_{sec}$. Another discharge path for the water is direct connection to the spring with a discharge of $QKG$. A classical, linear transfer function is proposed to account for the influence of karst connectivity, as an initial state in the response of the catchment to sudden rainfall events (Fig. 4).
Figure 5 Flowchart of the modified Xin’anjiang model

Figure 5 shows the flowchart of the modified XAJ model. All symbols inside the blocks are variables including inputs, outputs, and state and internal variables, whereas those symbols outside the blocks are parameters (Zhao 1992, Zhao 1993).

The model has 18 parameters: the evapotranspiration parameters $K$, $WUM$, $WLM$, and $C$; runoff production parameters $WM$, $B$, and $IMP$; parameters of runoff separation $SM$, $EX$, $KI$, and $KG$; runoff concentration parameters $CS$, $CI$, $CG$, $\beta$, and $E_{sec}$; and the Muskingum parameters $KE$ and $XE$.

2.4 Governing equations

2.4.2 Runoff production

Figure 6 Distribution of tension water capacity in the basin
2.4.1 Distribution of free water capacity
It is assumed in the XAJ model that the free water storage and its capacity are both nonuniformly distributed over the area \((FR)\) from which the runoff is produced. The distribution curve is illustrated in Fig. 6. The free water storage capacity \(S'M\) is assumed distributed over \(FR\) between zero and a maximum point \(MS\) in a parabolic manner:

\[
(1 - f / FR) = \left(1 - S'M / MS\right)^{Ex},
\]

where \(f\) is the portion of the basin area for which the free water storage capacity is less than or equal to \(S'M\) and \(Ex\) is a parameter.

The areal mean free water storage capacity \(SM\) may be used instead of \(MS\) as a parameter:

\[
SM = MS / (1 + Ex) .
\]

By integration of \(S'M\) in eq. (1) and substitution of \(SM\) for \(MS\) from eq. (2), the equivalent free water storage \(S\) over the runoff producing area \(FR\), can be found from the following equation:

\[
1 - S / SM = \left(1 - BU / MS\right)^{(1 + Ex)} .
\]

2.4.4 Runoff separation
The runoff \(R\) generated in accordance with Fig. 6, and expressed as the depth \(P - K \cdot EM\) over the runoff producing area of the basin, is applied by adding \(P - K \cdot EM\) to \(BU\) in Fig. 7, which yields the contribution \(RS\) to surface runoff.

Algebraically, if \(BU + P - K \cdot EM < MS\), then

\[
RS = \left(P - K \cdot EM - SM + S + SM \cdot \left(1 - \left(P - K \cdot EM + BU\right) / MS\right)^{(1 + Ex)}\right) \cdot FR ;
\]

otherwise,

\[
RS = \left(P - K \cdot EM - SM + S - SM\right) \cdot FR .
\]

Then, the remainder of \(R\) becomes an addition \((\nabla S)\) to the free water storage \(S\), which in turn contributes \(RI\) laterally to the inflow and \(RG\) vertically to the groundwater, according to the following relations:

\[
RI = S \cdot KI \cdot FR ,
\]

\[
RG = S \cdot KG \cdot FR ,
\]

where \(KI\) and \(KG\) are parameters.

2.4.2 Overland flow concentration
The surface flow is often several orders of magnitude faster than the interflow and groundwater flow. Therefore, surface runoff is treated as unmodified passing over the hillslope and the headwater area.
into the channel systems as $TS$, while the interflow ($RI$) is routed through the linear reservoirs representing the interflow outflow ($TI$) from the reservoir, determined by:

$$TI(t) = TI(t-1) \cdot CI + RI(t)(1 - CI).$$

(8)

Based on the extensive field research and analysis of discharge data, the proposed model uses two linear reservoirs to simulate the hydraulic buffering function of a karst aquifer. The upper reservoir (denoted by $E$) represents the epikarst zone, where groundwater is stored in the sinkholes, caves, blind valleys, and depressions acting as storage elements, and it shows considerable buffering to the effects of a rainstorm. The lower reservoir represents the soil zone. The groundwater $RG$ outflow $TG$ from these reservoirs can be determined as follows.

If $RG + E > E_{sec}$, then

$$QG = (RG + E - E_{sec}) \cdot U,$$

(9)

$$QKG = (e^{-\beta} \cdot E_{sec}) \cdot U;$$

(10)

otherwise,

$$QKG = e^{-\beta} \cdot (RG + E) \cdot U,$$

(11)

$$QG = 0,$$

(12)

$$U = \frac{F}{3.6 \Delta t},$$

(13)

$$TG(t) = TG(t-1) \cdot CG + RG(t)(1 - CG),$$

(14)

where $t$ is the current time, $t-1$ is the preceding time interval, $TI$ and $TG$ are added to $TS$ to become the total sub-basin inflow $T$ to the channel network, and $\beta$ is the outflow coefficient of the upper line reservoir.

Maillet (1905) introduced an analytical expression into hydrotechnical theory and practice for defining a hydrograph recession curve. This interpretation is based on the drainage of a simple reservoir and it presumes that the spring discharge is a function of the volume of water held in storage. This behavior is described by an exponential equation as follows:

$$Q(t) = Q_0 \exp(-\alpha t),$$

(15)

$$\beta = -\ln \left(1 - e^{-\alpha} \right),$$

(16)

where $Q(t)$ is the discharge at time $t$, $Q_0$ is the discharge at the start of the recession, and $\alpha$ is the coefficient of spring recession.

Equation (15) describes the discharge characteristics of a linear reservoir, i.e., one in which the discharge $Q$ is proportional to the storage $V$ with $Q = \alpha V$. Rearranging and allowing for units gives the following (Castany 1968; Mijatovic 1970):

$$V_m = \frac{Q_0 \cdot t}{\alpha},$$

(17)

$$E_{sec} = V_m \cdot F,$$

(18)

where $V$ is the storage capacity or dynamic reserve (m$^3$), $Q$ is the groundwater discharge (m$^3$/s), and $\alpha$ is the discharge coefficient.

2.4.3 River-network confluence

Flow routing from the sub-basin outlets to the entire basin outlet can be achieved by applying any flood-routing method. Here, in the XAJ model, the Muskingum successive reaches model was preferred:

$$Q(t) = C_0 \cdot I(t) + C_1 \cdot I(t-1) + C_2 \cdot Q(t-1),$$

(19)
where $Q_t$ is the outflow at time $t$, and $I_t$ is the inflow at time $t$.

3. Results

3.1 Model calibration and validation

\begin{equation}
\Delta Q_p(\%) = \frac{(Q_{op} - Q_{cp})}{Q_{op}} \times 100\% ,
\end{equation}

\begin{equation}
\Delta R_T(\%) = \frac{(R_{od} - R_{cd})}{R_{od}} \times 100\% ,
\end{equation}

\begin{equation}
R^2 = 1 - \frac{R_{od} - R_{cd}}{R_{od} - R_{cd}}
\end{equation}

Where $Q_{op}$ and $Q_{cp}$ are the observed and calculated peak flows, respectively. $R_{od}$ and $R_{cd}$ are total runoff depth of a flood event calculated from the observed and calculated stream flow discharges, respectively (Yapo et al. 1996; Bao and Li 2012).

The term $\Delta Q_p$ is used to assess the error of peak flow and $\Delta R_T$ is used to estimate the error of runoff. The term $R^2$ is used to evaluate the relative effectiveness.

3.1.1 Calibration phase

Model parameters were assumed first using reasonable initial values according to their physical meanings and value ranges, as described in detail by Zhao (1992).

The calibrated parameters are summarized in Table 1. There were about nine (1964–1987) historical flood events used for this study, the data of which were separated into two parts: one for parameter calibration and the other for model verification. All the parameter values were kept unchanged in the calculation and correction processes.

| Parameter | Value |
|-----------|-------|
| $K$       | 0.45  |
| $WM$      | 150   |
| $WUM$     | 30    |
| $WLM$     | 70    |
| $B$       | 0.3   |
| $C$       | 0.15  |
| $SM$      | 50    |
| $EX$      | 1.5   |
| $KI$      | 0.35  |
| $KG$      | 0.75  |
| $CS$      | 0.805 |
| $CI$      | 0.985 |
| $CG$      | 0.48  |
| $KE$      | 0.05  |
| $XE$      | 100   |
| $\alpha$  | 0.4   |
| $H_{sec}$ | 8     |

Table 1 Calibrated parameters of modified Xin'anjiang model in Dianwei Basin

| Flood number | $P$ (mm) | $R_{od}$ (mm) | $Q_{op}$ (m$^3$/s) | $R_{cd}$ (mm) | $\Delta R_T$ (%) | $\Delta Q_p$ (%) | $R^2$ | $R_{cd}$ (mm) | $\Delta R_T$ (%) | $\Delta Q_p$ (%) | $R^2$ |
|--------------|---------|---------------|--------------------|---------------|------------------|------------------|------|---------------|------------------|------------------|------|
| 650825       | 88.2    | 163.2         | 39.3              | 83.8          | 48.64            | 56.13            | -0.194| 151.1         | 7.41             | 6.71             | 0.871 |
| 660821       | 250.1   | 578.5         | 67.2              | 186.6         | 67.74            | 8.91             | -0.219| 553.7         | 4.29             | -1.67            | 0.850 |
| 671014       | 41.8    | 102.6         | 40.8              | 21.3          | 79.23            | -18.35           | -0.631| 115.9         | -12.88           | -14.95           | 0.810 |
| 680922       | 84.6    | 226.6         | 46.2              | 54.9          | 75.76            | 12.14            | -0.607| 220.3         | 2.78             | -9.74            | 0.750 |
| 690810       | 51.5    | 61.1          | 25.4              | 21.1          | 65.53            | -22.55           | -1.665| 65.9          | -8.04            | -7.82            | 0.700 |
| 710914       | 84.1    | 149           | 36.9              | 43.5          | 70.78            | -15.23           | -0.874| 145.5         | 2.32             | -1.95            | 0.949 |
| 740803       | 118.3   | 282.4         | 46.9              | 90.5          | 67.96            | -20.97           | -1.094| 249.5         | 11.66            | 1.24             | 0.881 |
| 800828       | 28.8    | 54.7          | 18.8              | 15.9          | 70.88            | 7.013            | -3.011| 52.7          | 3.68             | 12.1             | 0.598 |
| 860830       | 104.9   | 155.5         | 36.6              | 66            | 57.57            | 30.43            | -0.758| 162.0         | -4.18            | -13.43           | 0.806 |

3.1.2 Validation phase

As Table 2 indicates, the modified XAJ model performed better than the traditional XAJ model. The calculated and observed discharge hydrographs of flood No. 710914 and No. 740803 are shown in Figs. 8 and 9, respectively. These two hydrographs are presented to demonstrate the better
performance of the modified XAJ model. It can be seen that the discharge calculated by the traditional XAJ model is unreasonable. After the model enhancement, the mean relative effectiveness of the six floods of the calibration phase was 0.822 and the mean relative effectiveness of the three floods of the validation phase was 0.762. According to the national criteria for flood forecasting in China, if \( R^2 \geq 0.65 \) and the absolute value \( \Delta R_f \leq 20\% \), the flood simulation can be considered a qualified simulation.

![Figure 8 Comparison of observed flood and flood simulated using traditional and developed Xin’anjiang (XAJ) models (Flood No. 710914)](image)

![Figure 9 Comparison of observed flood and flood simulated using traditional and developed Xin’anjiang (XAJ) models (Flood No. 740803)](image)

4. Discussion and Conclusions

Figures 8 and 9 present examples of the observed and simulated floods. The graphs show very good similarity between the observed floods and those simulated by the improved XAJ model. The goodness of fit of both the calibration and validation graphs is measured by three statistical tests—\( \Delta Q_p \), \( \Delta R_f \), and \( R^2 \)—which are described in Table 2 and show that the model is able to represent the floods generated by rainfall events in study area reasonably well.

The hydrographs show the flood peak is relatively small but that the flood volume is large and that last a long time during the flooding period within the studied area. Therefore, in this circumstance, the flood volume can be considered the most important factor defining the flood hazard. The karst aquifer plays an important role in the recharge and hydrodynamics of the water flow, and it connects the large depressions that have considerable influence upon the flood. These depressions retain a large amount of water, delaying its percolation toward the water table or toward the network of conduits.

This study demonstrated that for the case of a groundwater supply basin, a karst watershed could be considered a relatively weak system in terms of regulation but a strong system regarding the amplification or generation of floods. However, a single precipitation time series cannot describe fully the dynamics of the floods in this karst area, because they also depend on rainfall characteristics and groundwater levels. It can be seen that the regulatory effect of the karst is limited for conditions in
which the water table is low prior to the flood (e.g., No. 710914), whereas an aggravating effect can be seen for conditions when the water table is higher (e.g., No. 680922).

As mentioned above, rainfall events during periods of high water level might generate large floods. The reason for this is that floods are strongly dependent on the initial state of the karst system. In this karst area, hydrographs from Qinglongtan Spring show rapid responses to rainfall events (Fig. 2). The spring hydrograph recession coefficient is a global characteristic parameter of an aquifer with important information about the initial state of the system. It is reasonable to apply the spring hydrograph analysis for meaningful hydraulic parameters mining of the karst aquifer. This methodology of combining spring time series analyses and flow modeling of the Dianwei River Basin allowed an assessment of the influence of the karst on the generation and routing of floods using a modified XAJ model.

Flooding is a serious phenomenon in the karst area of southwestern China, especially in the peak cluster region of Yunnan Province. Understanding karst behavior during floods is a major consideration for improving the accuracy of flood forecasting. Some measures can be used to improve this situation, but they should be based on a clear understanding of the characteristics of karst aquifers. For example, the functions of depressions in controlling flooding should not be considered independently, but rather the entire karst system should be considered as an entity.

This study proposed a modified XAJ model to characterize the functioning of a complex karst aquifer. The method was based on the hydrograph recession coefficient of the springs within the study area. The results indicated that the proposed modified XAJ model could improve the accuracy of the hydrological simulation. However, because of the complex underlying surface conditions and the estimations of potential and actual evapotranspiration, effective rainfall estimations will be more problematic. To improve the precision of model calculations further, it would be necessary to monitor the epikarst/vadose zone and the aquifers over the catchment.

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