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Application of Muskingum routing method with variable parameters in ungauged basin

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Abstract: This paper describes a flood routing method applied in an ungauged basin, utilizing the Muskingum model with variable parameters of wave travel time K and weight coefficient of discharge x based on the physical characteristics of the river reach and flood, including the reach slope, length, width, and flood discharge. Three formulas for estimating parameters of wide rectangular, triangular, and parabolic cross sections are proposed. The influence of the flood on channel flow routing parameters is taken into account. The HEC-HMS hydrological model and the geospatial hydrologic analysis module HEC-GeoHMS were used to extract channel or watershed characteristics and to divide sub-basins. In addition, the initial and constant-rate method, user synthetic unit hydrograph method, and exponential recession method were used to estimate runoff volumes, the direct runoff hydrograph, and the baseflow hydrograph, respectively. The Muskingum model with variable parameters was then applied in the Louzigou Basin in Henan Province of China, and of the results, the percentages of flood events with a relative error of peak discharge less than 20% and runoff volume less than 10% are both 100%. They also show that the percentages of flood events with coefficients of determination greater than 0.8 are 83.33%, 91.67%, and 87.5%, respectively, for rectangular, triangular, and parabolic cross sections in 24 flood events. Therefore, this method is applicable to ungauged basins.

Key words: *Muskingum model; flood routing; variable parameters; ungauged basin; HEC-HMS*

1 Introduction

Flood routing is a mathematical method for predicting the changing magnitude and celerity of a flood wave as it propagates down rivers or through reservoirs (Tewolde and Smithers 2006). Generally, two basic methods are used to route the flood wave in natural channels, one based on hydrologic routing and the other on hydraulic routing. The hydrologic method is based on the storage continuity equation, while the hydraulic method is based on the Saint-Venant equations consisting of the continuity and momentum equations (Choudhury

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et al. 2002). Many different simplified routing models were developed in the 20th century. Some of them have been successfully applied to rivers and reservoirs (Hashmi 1993). Currently, the Muskingum method (McCarthy 1938) and Muskingum-Cunge method (Cunge 1969) are widely accepted and used in flood routing models due to their adequate levels of accuracy and the reliable relationships between their parameters and channel properties (Fread 1983; Haktanir and Ozmen 1997).

As is well known, the Muskingum model seeks a parameter estimation method to determine the values of wave travel time K and weight coefficient of discharge x. Many methods or optimization techniques, including the trial-and-error method, recession analysis (Yoon and Padmanabhan 1993), least squares procedure (Al-Humoud and Esen 2006), feasible sequential quadratic programming (Kshirsagar et al. 1995), chance-constrained optimization (Das 2004, 2007), genetic algorithm (Chen and Yang 2007), particle swarm optimization (Chu and Chang 2009), harmony search (Kim et al. 2001), Broyden-Fletcher-Goldfarb-Shanno technique (Geem 2006), immune clonal selection algorithm (Luo and Xie 2010), and hybrid algorithm (Lu et al. 2008; Yang and Li 2008), have been used to identify the parameters. However, these studies and methods are more applicable to flood routing in gauged basins due to their requirement of large amounts of observed data.

It is difficult to predict flow characteristics in ungauged basins (Sivapalan et al. 2003) because sufficiently long streamflow time series for parameter calibration are typically not available. Two common ways to deal with this problem are (a) use of physically based models, and (b) regionalization of model parameters according to the physical characteristics of basins (Yadav et al. 2007). A number of regionalization models have been developed, including parametric regression, the nearest neighbor method, and the hydrological similarity method (Li et al. 2010). To improve the streamflow prediction accuracy in an ungauged basin, stream flow observations must be available nearby, but it is difficult to find a basin with adequate similarity to the study basin. The physically based models are strongly related to observable physical properties of the watershed, so many physically based distributed hydrological models have been developed and used to simulate and predict runoff in ungauged basins. However, differences in scale, over-parameterization, and model structural error have so far prevented this objective from being achieved, and some calibration criteria are usually required.

The relationships between model parameters and physical characteristics of gauged basins are useful to the flood routing models in ungauged basins (Tewolde and Smithers 2006). Therefore, as noted by Kundzewicz and Strupczewski (1982), the modification and the interpretation of the Muskingum model parameters in terms of the physical characteristics extends the applicability of the method to ungauged basins.

In this study, our objective was to establish the relationships between the Muskingum parameters (K and x) and the physical characteristics of different types of channel cross sections (rectangular, triangular, and parabolic) in an ungauged basin. A method based on the physical characteristics of channels or reaches, including the values of slope (S), reach length (L), and reference discharge (Q_0), was adopted to estimate the model parameters. Then, the variable parameters of the Muskingum model were used in the HEC-HMS model, developed by the Hydrologic Engineering Center of the U.S. Army Corps of Engineering, and the model was applied in the Louzigou Basin in Henan Province of China. Finally, we established and selected an optimizing scheme for flow prediction in Louzigou Basin through comparison of measurements with the simulated results of three types of channel cross sections.

2 Muskingum model with variable parameters

The derivation of the original Muskingum routing model is based on Eqs. (1) and (2) for a channel or river reach without lateral inflow:

$$\frac{\mathrm{d}W}{\mathrm{d}t} = I - Q \tag{1}$$

$$W = K\left[xI + \left(1 - x\right)Q\right] \tag{2}$$

where W is the water storage, t is time, I is the inflow, and Q is the outflow. Eq. (1) represents the mass balance, and Eq. (2) expresses the channel storage volume, which is a simple linear combination of the inflow discharge of the upstream section and the outflow of the downstream section. In Eqs. (1) and (2), K and x are the two model parameters determined from observations; they represent the storage-time constant, which has a value reasonably close to the flow travel time through the river reach, and a weighting factor usually ranging from 0 to 0.5. Therefore, the key objective of the Muskingum model is to estimate the parameters K and x.

2.1 Estimation of *K*

The wave travel time K can be estimated by Eq. (3):

$$K = \frac{L}{3\,600 V_{\mathrm{c}}} \tag{3}$$

where L is the reach length, and V_{c} is the flood wave celerity, which can be calculated by Eq. (4):

$$V_{\mathrm{c}} = \frac{\mathrm{d}Q}{\mathrm{d}A} \tag{4}$$

where A is the flow area at a cross section, and $\mathrm{d}Q$ and $\mathrm{d}A$ are the differential values of the outflow and flow area, respectively. Q can be obtained by the Manning formula (Eq. (5)):

$$V_{\mathrm{av}} = \frac{Q}{A} = \frac{1}{n} R^{2/3} S^{1/2} \tag{5}$$

where V_{av}, n, R, and S are the average velocity, Manning's roughness coefficient, hydraulic radius, and slope, respectively. In addition, R is computed from the flow area and wetted perimeter P as follows:

$$R = \frac{A}{P} \tag{6}$$

The relationship between flood wave celerity and velocity can be obtained from the following formula (Todini 2007):

$$V_{\mathrm{c}} = \frac{5}{3}\left(1 - \frac{4}{5}\frac{A}{BP\sin\alpha}\right)V_{\mathrm{av}} = \lambda V_{\mathrm{av}} \tag{7}$$

where B is the water surface width, and α is the angle formed by dykes over a horizontal plane. λ is the wave celerity coefficient or shape coefficient of the channel cross section, whose values are $5/3$, $4/3$, and $13/9$ for rectangular, triangular, and parabolic channel cross sections, respectively (Lin 2001).

The wetted perimeter can be estimated by the Lacey equation for stable river channels (Kong and Wang 2008):

$$P = c\sqrt{Q_0} \tag{8}$$

where c is a coefficient whose value is between 4.71 and 4.78. The reference discharge Q_0 was defined by Wilson and Ruffini (1988) as follows:

$$Q_0 = Q_{\mathrm{b}} + 0.5\left(Q_{\mathrm{p}} - Q_{\mathrm{b}}\right) \tag{9}$$

where Q_{b} and Q_{p} are minimum discharge and peak discharge, respectively.

The hydraulic radius can be calculated as follows:

$$R = \left(\frac{Q_0 n}{P\sqrt{S}}\right)^{3/5} \tag{10}$$

The parameter K for rectangular, triangular, and parabolic channel cross sections can be estimated as follows:

$$K = \begin{cases} \dfrac{0.6n^{0.6}Lc^{0.4}}{3\,600Q_0^{0.2}S^{0.3}} & \text{for rectangular channel cross section} \\ \dfrac{0.75n^{0.6}Lc^{0.4}}{3\,600Q_0^{0.2}S^{0.3}} & \text{for triangular channel cross section} \\ \dfrac{0.69n^{0.6}Lc^{0.4}}{3\,600Q_0^{0.2}S^{0.3}} & \text{for parabolic channel cross section} \end{cases} \tag{11}$$

2.2 Estimation of *x*

The parameter x of the Muskingum model is a physical parameter that reflects the flood peak attenuation and hydrograph shape flattening of a diffusion wave in motion (Rui et al. 2008). In 1969, the French hydraulic scientist Cunge found numerical diffusion phenomena while examining the numerical solution to the kinematic wave equation, and then obtained an estimation formula of the parameter x as shown in Eq. (12):

$$x = \frac{1}{2} - \frac{D}{V_{\mathrm{c}}L} \tag{12}$$

where D is the diffusion coefficient of a diffusion wave. Eq. (12) can also be expressed as follows (Cunge 1969):

$$x = \frac{1}{2} - \frac{Q_0}{2SPV_c L} \tag{13}$$

Thus, we can calculate the value of x for rectangular, triangular, and parabolic channel cross sections as shown in Eq. (14):

$$x = \begin{cases} \dfrac{1}{2} - \dfrac{0.3Q_0^{0.3}n^{0.6}}{S^{1.3}c^{0.8}L} & \text{for rectangular channel cross section} \\ \dfrac{1}{2} - \dfrac{0.375Q_0^{0.3}n^{0.6}}{S^{1.3}c^{0.8}L} & \text{for triangular channel cross section} \\ \dfrac{1}{2} - \dfrac{0.35Q_0^{0.3}n^{0.6}}{S^{1.3}c^{0.8}L} & \text{for parabolic channel cross section} \end{cases} \tag{14}$$

3 HEC-HMS model

The hydrologic model HEC-HMS is designed to simulate the precipitation-runoff processes of dendritic drainage basins and the surface runoff response of a basin to precipitation by dividing the basin into interconnected hydrologic and hydraulic components (Oleyiblo and Li 2010).

Simple mathematical relationships are used to represent model component functions, including meteorological, hydrologic, and hydraulic processes, which are divided into precipitation, interception, infiltration, direct runoff, baseflow, and flood routing. Each element in the model performs different functions of the precipitation-runoff process within a sub-basin. The result of the modeling process is the computation of streamflow hydrographs at the basin outlet.

The required input parameters for the HEC-HMS model are K, x, and the number of sub-reaches N in flood routing using the Muskingum model. The number of sub-reaches N can be estimated by Eq. (15):

$$N = \frac{K}{\Delta t} \tag{15}$$

where Δt is the time interval. The parameter N must be an integer, and the value of the parameter K can be estimated by $K = N\Delta t$.

In this study, a precipitation hydrograph based on Thiessen polygons was used to compute the temporal distribution of the mean areal precipitation. The initial and constant-rate method, user synthetic unit hydrograph method (Kong et al. 2007), and exponential recession method were used to estimate runoff volumes, the direct runoff hydrograph, and the baseflow hydrograph, respectively. Then, the Muskingum model with variable parameters was used in the HEC-HMS model for channel routing.

4 Case study and results

The proposed flood routing model was applied in the Louzigou Basin in Henan Province of China, in a tributary basin of the Huaihe Basin, with a drainage area of 1 244 km^2 and an average annual rainfall of 1065 mm. The basin was divided into 63 sub-basins as shown in Fig. 1 using the HEC-GeoHMS module and ArcView software, according to the distribution of the precipitation gauges and the natural drainage network. HEC-GeoHMS, as a geospatial hydrology toolkit, allows users to visualize spatial information, document watershed characteristics, perform spatial analysis, delineate sub-basins and streams, and construct inputs for hydrologic models (e.g. the HEC-HMS model). The ten precipitation gauges and the Thiessen polygon division of the basin are shown in Fig. 1. The HEC-HMS model for the Louzigou Basin is shown in Fig. 2.

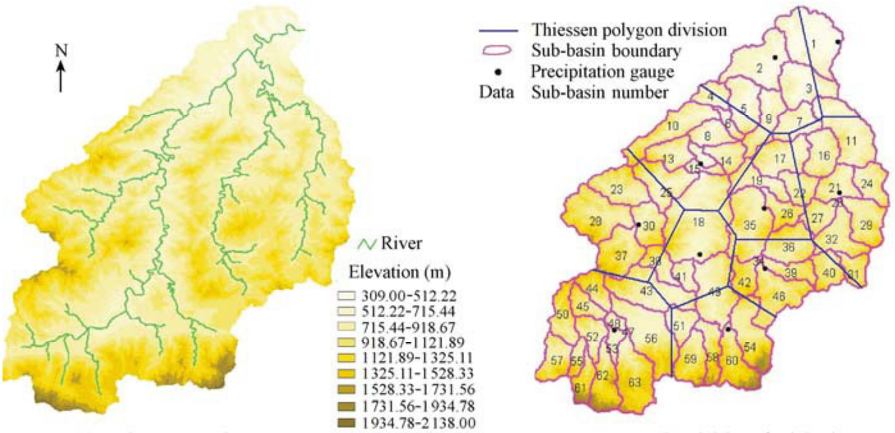

Fig. 1 Diversion of Louzigou Basin

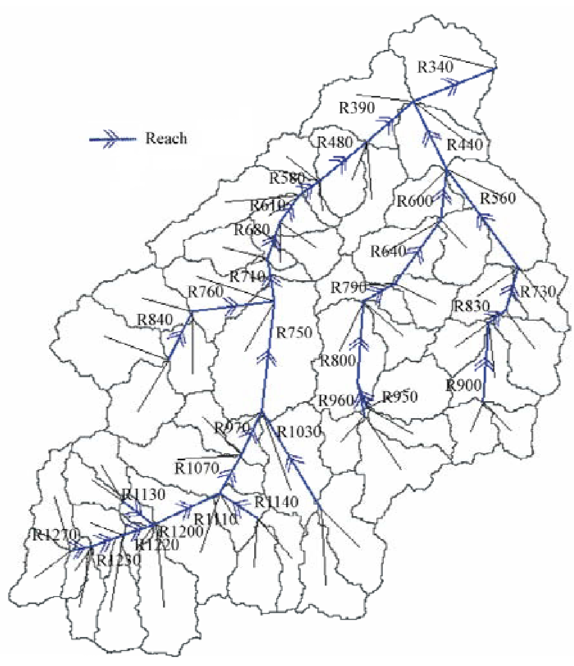

Fig. 2 HEC-HMS model for Louzigou Basin

For the HEC-HMS model, we obtained the values of the initial loss I_a, constant rate f, initial baseflow Q_{b0}, recession rate k, ratio of threshold flow to peak flow r, and coefficient a from Li (2008), and the slope S and reach length L for each reach are shown in Table 1.

Table 1 Estimated values of K, x, and N in flood event 730701 for different channel shapes

Reach code	L (m)	S	Rectangular			Triangular			Parabolic		
			K	x	N	K	x	N	K	x	N
R340	12 980.9	0.003 6	0.75	0.494	9	0.94	0.492	11	0.87	0.493	10
R390	6 997.2	0.004 4	0.38	0.491	5	0.48	0.489	6	0.44	0.490	5
R440	14 491.3	0.005 9	0.73	0.497	9	0.91	0.496	11	0.84	0.497	10
R480	809.3	0.003 3	0.05	0.390	1	0.06	0.362	1	0.06	0.372	1
R580	5 753.4	0.002 1	0.39	0.472	5	0.49	0.465	6	0.46	0.467	5
R600	4 860.6	0.008 0	0.22	0.494	3	0.28	0.493	3	0.25	0.493	3
R610	1 875.3	0.005 9	0.09	0.478	1	0.12	0.472	1	0.11	0.474	1
R680	8 585.8	0.003 1	0.52	0.489	6	0.65	0.486	8	0.60	0.487	7
R560	10 029.6	0.009 2	0.44	0.498	5	0.55	0.497	7	0.51	0.497	6
R710	4 899.1	0.004 5	0.27	0.488	3	0.33	0.485	4	0.30	0.486	4
R640	2 480.0	0.009 0	0.11	0.490	1	0.14	0.488	2	0.13	0.489	2
R790	3 246.0	0.004 3	0.18	0.481	2	0.22	0.476	3	0.20	0.477	2
R730	2 131.7	0.017 0	0.08	0.495	1	0.10	0.494	1	0.09	0.494	1
R760	6 127.7	0.011 1	0.25	0.497	3	0.32	0.496	4	0.30	0.496	4
R830	17 694.2	0.009 5	0.77	0.499	9	0.96	0.498	12	0.89	0.499	11
R840	2 426.3	0.012 1	0.10	0.493	1	0.12	0.492	1	0.11	0.492	1
R900	10 631.9	0.011 9	0.43	0.498	5	0.54	0.498	6	0.50	0.498	6
R800	2 086.2	0.009 9	0.09	0.490	1	0.11	0.487	1	0.10	0.488	1
R950	1 307.5	0.020 0	0.05	0.493	1	0.06	0.492	1	0.05	0.492	1
R750	3 450.3	0.004 8	0.18	0.484	2	0.23	0.480	3	0.21	0.481	3
R960	5 750.9	0.013 0	0.23	0.497	3	0.28	0.497	3	0.26	0.497	3
R970	4 470.8	0.003 9	0.25	0.484	3	0.32	0.480	4	0.30	0.481	4
R1070	10 899.0	0.004 0	0.61	0.494	7	0.77	0.492	9	0.71	0.493	9
R1030	734.6	0.011 3	0.08	0.476	1	0.08	0.469	1	0.07	0.471	1
R1140	4 320.1	0.012 1	0.17	0.496	2	0.22	0.495	3	0.20	0.496	2
R1130	1 593.0	0.027 6	0.05	0.496	1	0.06	0.496	1	0.06	0.496	1
R1200	4 417.6	0.004 9	0.23	0.488	3	0.29	0.485	4	0.27	0.486	3
R1110	7 175.0	0.005 4	0.37	0.493	4	0.46	0.492	6	0.42	0.492	5
R1220	5 768.1	0.010 8	0.24	0.497	3	0.30	0.496	4	0.28	0.496	3
R1230	8 007.3	0.009 0	0.35	0.497	4	0.44	0.496	5	0.41	0.496	5
R1270	13 703.2	0.016 3	0.51	0.499	6	0.63	0.499	8	0.58	0.499	7

From Eq. (11) and Eq. (14), we can obtain the values of parameter K and x for different channel cross sections and flood events. For this study, 24 flood events were chosen from 1973 to 1995. Taking one flood event (730701) as an example, the estimated results of parameters K, x

and N are shown in Table 1. In this study, the Manning coefficient n was 0.025, the reference discharge Q_0 was 317 m^3/s (for flood event 730701), and coefficient c was 4.76. The values of parameters K and x of other flood events are not given in this paper due to space constraints.

In comparing the model simulation results with the observed data, criteria must first be identified, and then some statistical goodness-of-fit approaches are employed to evaluate the model. The difference in the observed and computed hydrograph was analyzed with the root-mean-square error (E_{RMS}) and other goodness-of-fit statistics. This study used the coefficient of determination (D_{C}) as the goodness-of-fit statistic, defined as follows (Bao 2006):

$$D_{\mathrm{C}} = 1 - \frac{\sum_{i=1}^{n}\left(y_{\mathrm{c},i} - y_{\mathrm{o},i}\right)^2}{\sum_{i=1}^{n}\left(y_{\mathrm{o},i} - \overline{y}_{\mathrm{o}}\right)^2} \tag{16}$$

where $y_{\mathrm{c},i}$ is the computed discharge, $y_{\mathrm{o},i}$ is the observed discharge, $\overline{y}_{\mathrm{o}}$ is the mean value of the observed discharge, and n is the number of samples.

As peak discharge is important in a single flood event model, the relative errors of peak discharge and runoff volume were computed as shown in Eqs. (17) and (18) (Bao 2006):

$$\sigma_{\mathrm{p}} = \frac{Q_{\mathrm{pc}} - Q_{\mathrm{po}}}{Q_{\mathrm{po}}} \times 100\% \tag{17}$$

$$\sigma_{\mathrm{V}} = \frac{V_{\mathrm{c}} - V_{\mathrm{o}}}{V_{\mathrm{o}}} \times 100\% \tag{18}$$

where σ_{p} and σ_{V} are the relative errors of peak discharge and runoff volume respectively, Q_{pc} and Q_{po} are the calculated and observed peak discharge, respectively, and V_{c} and V_{o} are calculated and observed runoff volume, respectively. The calculated results are shown in Table 2 for different channel cross sections and flood events.

As shown in Table 2, from the mean value, the simulation of the triangular cross section has the lowest relative error of peak discharge, while its coefficient of determination is the largest of the three cross sections. For the rectangular channel cross section, the lowest error of peak discharge is –0.02% and that of runoff volume is –0.05%, with the maximum coefficient of determination being 0.991. The lowest errors of peak discharge and runoff volume are 0.25% and –0.11%, respectively, for the triangular channel cross section, and –0.23% and 0.11%, respectively, for the parabolic channel cross section. According to the *Assessment Standard for Hydrological Information and Hydrological Forecasting* (SL250-2000) of China, the qualified rate R_{Q} is defined as follows:

$$R_{\mathrm{Q}} = \frac{m_{\mathrm{qr}}}{m} \times 100\% \tag{19}$$

where m_{qr} is the number of qualified forecasts, and m is the total number of flood events. For a flood event, if the relative errors of peak discharge and runoff volume are less than the corresponding admissible errors, then it is a qualified forecast. Generally, the admissible error is assumed to be equal to 20%. Therefore, in the 24 flood events, the results show that the qualified rate is 100% for all the three types of channel cross sections. Also, the relative error of runoff volume was less than 10% for all events, while the percentage of flood events with a relative error of peak discharge less than 10% was 95.83%. However, the percentages of events with a coefficient of determination greater than 0.9 were 62.50%, 66.67%, and 66.67%, while those greater than 0.8 were 83.33%, 91.67%, and 87.50%, for rectangular, triangular, and parabolic cross sections, respectively. All the events generally had acceptable statistical results, as shown in Table 2. The simulated and observed hydrographs from the applications of the Muskingum model with variable parameters and the HEC-HMS model for the flood events 730701 and 831003 are shown in Fig. 3. From Fig. 3, we can see that the simulated hydrographs are quite similar to the observed hydrograph.

Table 2 Comparison of calculated results for different flood events

Flood event	Rectangular			Triangular			Parabolic		
	σ_v (%)	σ_p (%)	C_D	σ_v (%)	σ_p (%)	C_D	σ_v (%)	σ_p (%)	C_D
730701	0.22	0.74	0.958	0.17	0.62	0.982	0.15	0.62	0.975
730725	–0.54	–0.04	0.973	–0.61	–1.39	0.942	–0.65	–2.19	0.916
740803	3.52	15.79	0.570	3.49	12.99	0.722	3.47	11.85	0.778
750804	–0.36	5.77	0.940	–0.39	3.85	0.933	–0.41	2.78	0.925
770422	4.86	1.94	0.374	4.63	0.25	0.523	4.54	–0.23	0.604
770710	1.50	–4.01	0.913	1.49	–6.35	0.929	1.49	–7.45	0.920
780711	1.25	0.47	0.968	1.40	–1.17	0.969	1.47	–1.81	0.959
790914	–7.57	–0.99	0.918	–7.60	–1.12	0.923	–7.61	–0.57	0.924
790923	–0.37	6.77	0.944	–0.29	2.68	0.939	–0.26	1.05	0.925
800701	–8.97	4.16	0.869	–9.00	0.84	0.859	–9.02	–0.24	0.851
801009	–3.37	2.04	0.854	–3.62	–3.30	0.901	–3.75	–6.39	0.899
810624	0.81	–0.28	0.974	0.51	–1.40	0.976	0.38	–1.99	0.963
830425	8.42	0.21	0.905	8.13	–1.75	0.952	7.99	–2.67	0.940
830810	–0.05	–1.76	0.859	–0.11	–3.07	0.816	–0.13	–4.05	0.797
830906	0.86	5.86	0.705	0.68	2.11	0.870	0.61	0.76	0.914
831003	0.25	4.97	0.929	0.15	3.10	0.935	0.11	1.77	0.933
840511	–0.46	1.44	0.981	–0.60	–1.90	0.950	–0.66	–3.41	0.919
910531	–1.61	0.82	0.739	–1.57	–3.20	0.834	–1.56	–4.52	0.864
920504	1.85	–1.54	0.925	1.70	–2.85	0.980	1.63	–3.59	0.971
940418	1.69	–6.81	0.861	1.62	–6.45	0.877	1.59	–6.65	0.883
940702	3.68	–2.94	0.966	3.34	–1.94	0.957	3.18	–2.12	0.902
950724	–7.77	–4.02	0.932	–7.46	–5.83	0.892	–7.31	–7.29	0.839
950812	–0.36	–0.02	0.991	–0.44	–1.12	0.983	–0.49	–1.86	0.957
950821	1.18	1.24	0.874	1.23	–2.04	0.962	1.25	–3.35	0.975
Mean	–0.06	1.24	0.872	–0.13	–0.77	0.900	–0.17	–1.73	0.897

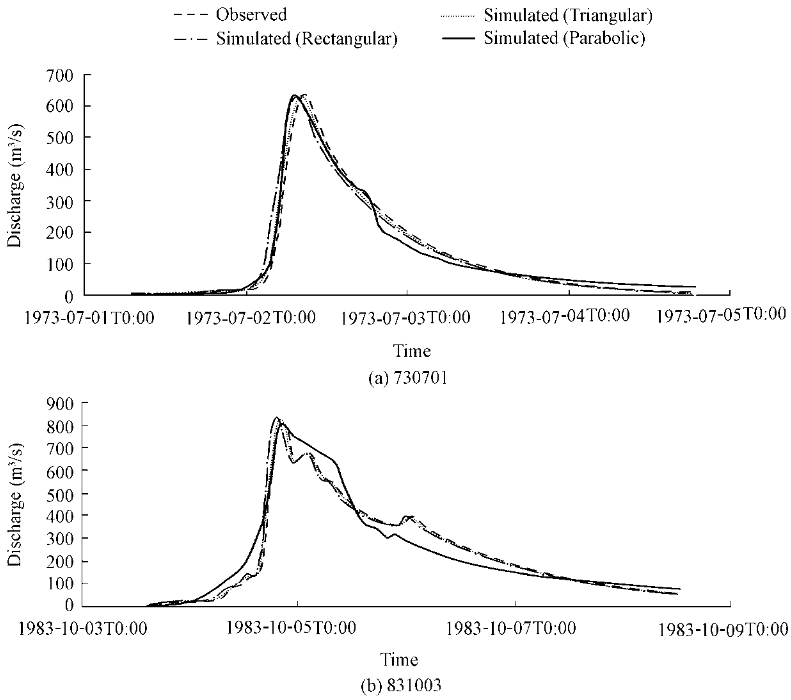

Fig. 3 Comparison of simulated and observed results for flood events 730701 and 831003

5 Conclusions

The Muskingum model with variable parameters based on the characteristics of channel and flood waves was used in an ungauged basin, and the simulation results were satisfactory. Compared with the fixed and constant parameter for different reaches, the variable parameters are more suitable for the physically based distributed hydrological model. The combination of a hydrological model (HEC-HMS) and a geospatial analysis technique (HEC-GeoHMS module) is useful for obtaining important basin topography parameters. It makes the hydrological forecast of ungauged basins possible. The coupling of the HEC-HMS model and Muskingum model for simulation of the ungauged basin shows high simulation accuracy, demonstrating that this is a reliable method for flood forecasting in ungauged basins.

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