

Research Article

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Applicability of Hydrological Models for Flash Flood Simulation in Small Catchments of Hilly Area in China

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Abstract: Flash flood in small catchments of hilly area is an extremely complicated nonlinear process affected by catchment properties and rainfall spatio-temporal variation characteristics including many physical-geographical factors, and thus accurate simulation of flash flood is very difficult. Given the fact that hundreds of hydrological models are available in the literature, how to choose a suitable hydrological model remains an unsolved task. In this paper, we selected five widely used hydrological models including three lumped hydrologic models, a semi-distributed hydrological model and a distributed hydrological model for flash flood simulation, and studied their applicability in fourteen typical catchments in hilly areas across China. The results show that the HEC-HMS distributed hydrological model outperforms the other models and is suitable to simulate the flash floods caused by highly intense rainfall. The Dahuofang model (lumped) has higher precision in peak runoff time simulation. However, its performance is quite poor on the flood volume simulation in the small catchments characterized by intense vegetation coverage and highly developed stream network. The Antecedent precipitation index and Xinanjiang models (lumped) can obtain good simulation results in small humid catchments as long as long-term historical precipitation and runoff data are provided. The TOPMODEL also shows good performance in small humid catchments, but it is unable to simulate the flash floods characterized by the rapid rise and recession. Our results could be very beneficial in practice, since these provide a solid foundation in the selection of hydrological model for flash flood simulation in small catchments in hilly area.

Keywords: Hydrological model applicability; Flash flood; Hilly area; Physical-geographic; Small catchments

1 Introduction

Flash floods are among the most dangerous natural hazards with possible significant damages and human casualties. In China, due to the frequently occurred summer rainstorms and the complex topo-geological conditions, flash flood in hilly area is one of the most severe natural hazards in terms of human deaths and economic losses, constituting 87.6% of the deaths in all kinds of flood disasters [1]. During 2011~2015, 758 small-sized and medium-sized flash flood disasters occurred in China, resulting in 1594 deaths and missing [2]. Therefore, flash flood forecasting should be investigated in detail because it can provide early warnings, and thereby is of great significance for flood prevention, disaster relief and public safety.

In general, flash floods are generated by extreme rainfall events with high intensities shortly followed by a strong and fast flow [3], and usually occur in small catchments with a drainage area of a few hundred square kilometers [4]. The short lead time and small size of such catchments enhance the difficulty for authorities to take measures. Over the past decade, there have been a range of developments in flash flood forecasting, among which the early-warning indexes and flow forecasting models are two effective tools [5]. The rainfall threshold (also known as flash flood guidance) is the most commonly used among the early-warning indexes as it is easily understood by the general public [6], whereas it has inadequate explanations of the rainfall-runoff process and the spatial heterogeneity of rainfall and underlying surface. However, the hydrological models, which are theoretical representations of a part of the hydrologic cycle, can take into account the complex generation processes of flash flood, as well as their dependency on different factors related to catchment properties and rainfall spatio-temporal variations. They are widely used for the prediction of flood and for issuing timely warn-

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ings. The use of a hydrological model is necessary since the use of hydrological measurements can be very limited [7]. Based on the hydrological mechanism analyses and hydrological process calculations, the time, location, scale, damage range and possible losses caused by flash flood are estimated in advance, and then decision support for flood prevention and disaster relief is provided.

A variety of hydrological models have been successfully applied in flash flood simulation and forecasting [8, 9]. Empirical models (e.g., neural network, statistical) are data-driven that use statistical relationships derived from rainfall events and river discharge data to generate flow forecasts. They usually require long-term data records to train or calibrate, and are site-specific. The conceptual model, such as HBV-96 and TOPMODEL, use semi empirical equations and require several hydrological and meteorological data. Kobold and Brilly applied the HBV-96 MODEL for flash flood forecasting in Savinja catchment with a shorter time step of one hour, proving that the HBV-96 MODEL is capable of simulating flash floods and can be used in pre-warning systems [10]. The process-based models, however, can explicitly represent the mechanisms and physical processes in the real system. Oleyiblo and Li examined the applicability, capability and suitability of HEC-HMS for flood forecasting in Misai and Wanan catchments in China, obtaining a fairly accurate simulation results in flood events, volume and timing [11]. In addition, a number of studies have applied a mixture of these models and conducted comparative analysis on the applicability of models in flash flood forecasting. Deng *et al.* evaluated the applicability of TOPMODEL and Xinanjiang (XAJ) model in the Buliu River Basin in the southeast of China [12]; the two models are comparably efficient, while TOPMODEL is more advisable due to its simple structure and fewer parameters required. Ye *et al.* applied two widely used hydrological models, i.e., XAJ and Antecedent precipitation index (API) to forecast flash flood in medium and small rivers in humid regions of China [13]. Results indicated that whilst both models perform well, the XAJ model outperformed the API in capturing the peak discharge and deterministic coefficient.

Among hundreds of hydrological models, there is likely no existing a single model that is universally applicable in predicting flash floods for all catchment types. Studies have found that the same model can have completely different applicability in different regions, and the suitability of a hydrological model to a particular catchment depends largely on the local hydro-meteorological characteristics and the conditions of the underlying surface. Kan *et al.* used the XAJ, mix runoff generation (MIX) and Northern Shannxi (NS) models in three arid catchments [14]; while

only the NS model can obtain acceptable results. Compared with the humid regions, the XAJ model generally performed poorly in semi-arid and arid regions with respect to peak flow, total volume and peak flood time, primarily due to the differences in rainfall characteristics (e.g., intensity, duration, total amount) and runoff generation mechanisms. Thus, it is essential to have a better understanding on the applicability of various models in regions under different climate conditions and underlying features.

At present, a single hydrological model is developed to simulate flash floods for a particular catchment, seldom studies attempt to compare the performance of different hydrological models applied to multiple catchments based on available data in hilly area. The selection of the hydrological models is usually done based on the experience of the researchers, which can lead to great randomness. Further, the terrain and climate characteristics vary greatly across China. The properties of small catchments in hilly area distributed in different locations are all unique, the uniqueness will certainly exacerbate the difficulties in hydrological model selection. In short, suitable hydrological model selection for specific catchment remains a difficult challenge that is yet to be solved; the problem is compounded with the fact that monitoring facilities for hydrological data is poor in hilly areas.

In this paper, five widely used hydrological models, varying in runoff mechanism and complexity, are selected for flash flood simulation. Their comparative analysis and applicability in fourteen typical catchments of hilly area across China are summarized. The expected research results could provide guidance for hydrological model selection according to the characteristics of small catchment and available data in flood disaster prevention and control work. The remainder of this paper is organized as follows: section 2 briefly describes five widely used hydrological models, and the model parameter calibration algorithm. Section 3 introduces the study catchments and the data used for simulation. Section 4 consists of results and discussion. Finally, summary and conclusions are drawn in Section 5.

2 Methods

2.1 Brief Description of Hydrological Models

Various hydrological models have been developed around the world with different degrees of complexity, from simple empirical formulae or correlations to the complex mathematical models. In this paper, five frequently used

hydrological models were selected from large variety of available models to simulate the hydrologic processes, including three lumped hydrologic models (the Antecedent precipitation index (API), the Xinanjiang (XAJ), the Dahuofang (DHF)), a semi-distributed hydrological model (TOPMODEL), and a distributed hydrological model (HEC-HMS). The hydrological models are briefly described below.

2.1.1 The Antecedent Precipitation Index Model

The Antecedent precipitation index (API) model is a classic lumped hydrological model based on empirical rainfall-runoff relationship, and the concentration process is usually simulated by unit hydrograph. Detailed descriptions of the API hydrological model can be found in relevant literatures [15, 16]. API model uses the average precipitation of multi-field floods and the total runoff, as well as the main flood affecting factors (the most commonly used is antecedent precipitation, P_a) to establish the P - P_a - R curves (P : precipitation, R : runoff). The API model is widely used in humid areas because of its simplicity to understand and use.

For a long time, China's economy developed very slowly in hilly areas. Therefore, monitoring facilities for hydrological data and investment in these areas are insufficient. Until recent years, China has started to build automatic monitoring system in provinces where serious flash floods occur [17]. As a consequence, small catchments in hilly area in China usually lack long-term observed data, this brings difficulties to obtain standard P - P_a - R curves and limits the application of API model to some degree. In this paper, the traditional P - P_a - R curves are simplified to adapt to the limited observed data. In general, flash floods are characterized by their rapid onset (usually within six hours after rainfall), the period between the flood peak and the rainfall is very short. Therefore, the infiltration process in humid and semi-humid region is not obvious and can be neglected for practical convenience. As it will be shown in this paper, the runoff process is divided into two lines to approximate the smooth P - P_a - R curves, in which the turning point is judged on the occurrence of the whole catchment storage excess runoff. By doing so, we can expand the application of the API hydrological model in hilly areas with less observed data.

2.1.2 The Xinanjiang Model

The Xinanjiang (XAJ) model is a lumped hydrological model which takes the influence of uneven underlying sur-

face to runoff yield area into consideration by using storage capacity curve of the catchment. The concept of runoff formation on repletion of storage is applied to calculate runoff production, which implies that runoff is not produced until the soil water content of the aeration zone reaches its field capacity, and thereafter the excess rainfall becomes runoff without further loss [18, 19]. The total runoff is subdivided into three components, including surface runoff, interflow and groundwater runoff, based upon the free water capacity distribution curve, the surface runoff is the fastest and the groundwater is the slowest in terms of flow velocity. The flooding process is divided into two stages, namely overland flow and the river networks concentrations. The overland flow concentration is calculated by multiple linear reservoirs method. The runoff is then routed down the river channels to the whole catchment outlet using the Muskingum successive routing method [20]. The core of the XAJ model is the concept of storage excess runoff generation mechanism, it has been widely applied in China for decades and has achieved great success in humid and semi-humid areas.

2.1.3 The Dahuofang Model

The Dahuofang (DHF) model [21] is a lumped hydrological model which adopts an eight-parameter excess infiltration runoff mode and a double-layer infiltration rate curve for loss reduction calculation [22]. The distributions of surface water storage and subsoil permeability rate are described by the parabolic equation. The convergence part is calculated by a parameter variable-strength, variable-speed empirical unit hydrograph. The model can calculate runoff generation based on the characteristics of each unit and concentrate the outflow of each unit along the river course to the basin outlet to obtain the runoff at the basin outlet [23]. The evapotranspiration component is represented by double-layers mode, in which the surface adopts the average evapotranspiration capacity of the whole catchment and the subsoil begins to evaporate when the water demand in surface is evaporated. The DHF hydrological model is mainly applied in the arid and semi-arid areas in northern China.

2.1.4 The TOPMODEL

The TOPMODEL is a semi hydrological distributed model which uses the relationship between topographic information and runoff generation [24]. It can also be recognized as a variable contributing area conceptual model. The total

runoff is generally the sum of two major flow components: saturated excess overland flow from variable contributing areas and subsurface flow from the vadose zone. When the water content in the aeration zone reaches saturated water content, indicating that the water content of the complete gravity drainage is satisfied, the water in the soil becomes free water that flows completely under the action of gravity [25]. It can be used in single or multiple sub catchments using gridded elevation data of the catchment. The major factors considered in the model are the catchment topography and soil transmissivity [26]. The TOPMODEL can be used to predict runoff in data scarce areas because of its parameter parsimony, structural simplicity and explicit interpretation of the physical concepts, which has been proved to have a good performance in wet, semi-humid and semi-arid areas [7, 27].

2.1.5 The HEC-HMS Model

The HEC-HMS is a distributed hydrological model that contains three sections HEC-GeoHMS, HEC-DSSVue and HEC-HMS [28], which play different roles in the model. The HEC-GeoHMS is a GIS companion product used to create catchment and meteorological models by processing the distributed data such as DEM, land use and soil type reflecting the characteristics of the underlying surface. The HEC-DSS is a data management system which can effectively store and update precipitation and runoff data. The HEC-HMS hydrological model simplifies the actual runoff process, without considering the interaction between the river, the ground and underground aquifers, it merges the overland flow and interflow into direct runoff. The model has the advantages of simple structure and comprehensive consideration of climate and underlying conditions, and can choose different calculation methods according to different catchments, data situation or calculation requirements [29], it has a wide range of adaptability. In this paper, among the loss methods, the simple “Initial and Constant Loss” method is selected for the event-based simulation studies. The method is simple and practical because it requires only three input parameters, *i.e.*, initial loss (mm), constant rate (mm/h) and impervious area (%). Snyder unit hydrograph is selected for flow concentration, and motion wave is selected for flood wave movement in the river. The combination is simple in principle and has few parameters, which is easy to apply or implement in the area with less observed data.

2.2 Hydrological Model Calibration

2.2.1 Calibration Method

To obtain more accurate hydrological model parameters, we used multi-objective optimization algorithm NSGA-II to calibrate the parameters of the hydrological model. NSGA-II is nowadays one of the most widely used multi-objective genetic algorithms, it has three special characteristics, fast non-dominated sorting approach, fast crowded distance estimation procedure and simple crowded comparison operator. NSGA-II can reduce the complexity of the non-dominated sorting genetic algorithm and ensure that excellent individuals in the evolutionary process are not discarded [30, 31], which improves the accuracy of the optimization results and provides more reliable and comprehensive solution in practical application.

2.2.2 Objective Functions

In traditional hydrological model, single objective function was often applied for parameter calibration. However, the practical application of hydrological model shows that the optimization of hydrological model parameters based on a single objective only considers one aspect of hydrological process, thus unable to fully reflect the different dynamics characteristics of hydrological system. In this study/paper we selected four objective functions based on the accuracy of flood simulation and evaluated the simulation results from three aspects: flood volume, flood peak and flood profile. The objective functions are defined as follows:

1. Average relative error of runoff depth:

$$R_{rel} = \frac{|R_{sim} - R_{obs}|}{R_{obs}} \times 100\% \quad (1)$$

$$\overline{R_{rel}} = \frac{\sum_{i=1}^n R_{rel}}{n} \quad (2)$$

where R_{sim} and R_{obs} are simulated and observed values of runoff depth of a session of flood, respectively, mm; R_{rel} is the relative error of runoff depth; n is the number of flood events; $\overline{R_{rel}}$ is the average relative error of runoff depth of all the flood events.

2. Average relative error of peak runoff:

$$Q_{rel} = \frac{|Q_{sim} - Q_{obs}|}{Q_{obs}} \times 100\% \quad (3)$$

$$\overline{Q_{rel}} = \frac{\sum_{i=1}^n Q_{rel}}{n} \quad (4)$$

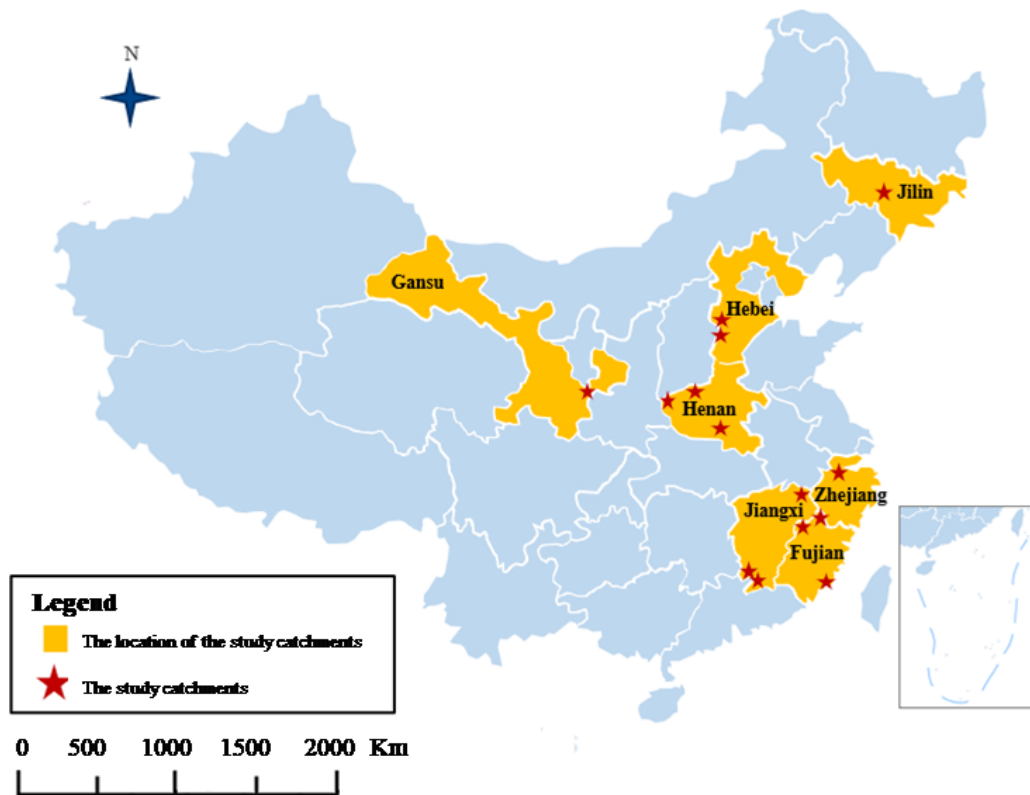


Figure 1: Spatial distribution of study catchments.

where Q_{sim} , Q_{obs} are simulated value and observed value of peak runoff of a session of flood, respectively, m^3/s ; Q_{rel} is the relative error of peak runoff; n is the number of flood events; $\overline{Q_{rel}}$ is the average relative error of peak runoff of all the flood events.

3. Error of peak time:

$$\Delta T = |T_{sim} - T_{obs}| \quad (5)$$

where T_{sim} , T_{obs} are simulated value and observed value of peak time, respectively, h; ΔT is the error of peak time; if $\Delta T \leq 2h$, the simulation for flood peak time is considered qualified.

4. Nash-Sutcliffe efficiency coefficient:

The objective function applied for average deterministic coefficient was the well-known Nash-Sutcliffe efficiency coefficient [32], as given below:

$$NSE = 1 - \frac{\sum_{i=1}^N (Q_{is} - Q_{io})^2}{\sum_{i=1}^N (Q_{io} - \overline{Q_o})^2} \quad (6)$$

where Q_{is} , Q_{io} are simulated and observed values of runoff for each time step i , respectively, m^3/s ; $\overline{Q_o}$ is the mean observed runoff; N is the total number of

all the time steps calculated by adding up the durations of all the flood events. It should be noted that NSE is calculated by connecting all flood events, and therefore can represent the performance for the catchment rather than for a single flood event.

3 Study Catchments and Data

Owing to the varying complexity of geological topography and climatic conditions in China, the flash floods on runoff generation and confluence mechanisms demonstrate distinctive regional features. Therefore, to adequately study the performances and applicability of different hydrological models, it's necessary to choose as many representative small catchments as possible. In this paper, fourteen small catchments in typical hilly areas from seven provinces including Henan, Hebei, Jilin, Gansu, Fujian, Jiangxi and Zhejiang are chosen as study area, as shown in Figure 1. The selected catchments are situated from the south to north of China, covering different climate, hydrological and geographical conditions.

The basic characteristics of the fourteen catchments can be found in Table 1. The drainage area of these catch-

Table 1: Basic characteristics of catchments for simulation and comparison.

Province	Catchments	Drainage area (km ²)	Mean annual precipitation (mm)	Density of precipitation station (km ² /precipitation station)	Number of flood events	Elevation (m)	Average gradient (°)	Major soil type	Major land use
Henan	Luanchuan	343.0	784	49.0	22	733-2082	29	Sandy loam	Forest land
	Xiahecun	208.0	600	34.7	16	404-1811	22	Sandy loam	Forest land
	Peihe	21.6	1313	10.8	16	93-771	34	Sandy loam	Forest land
Hebei	Xitaiyu	125.9	605	63.0	13	378-1508	23	Clayey loam	Cultivated land
	Wangan	425.9	650	71.0	8	621-1910	33	Clayey loam	Grassland
Jilin	Zhouhutun	527.5	651	105.5	5	16-861	6	Clayey loam	Grassland
Gansu	Huating	274.9	607	91.6	15	1393-2736	27	Clayey loam	Forest land
Fujian	Siqian	128.3	1864	32.1	27	416-1806	36	Clayey loam	Forest land
	Xiaoanxia	76.2	1700	38.1	7	321-1213	27	Clayey loam	Forest land
	Yongchun	389.7	1487	55.7	14	395-1358	24	Clayey loam	Cultivated land
Jiangxi	Anhe	251.0	1497	31.4	41	180-1302	27	Sandy clay	Grassland
	Dutou	432.3	1526	43.2	32	242-1106	21	Sandy clay	Grassland
	Shangliu	172.5	1841	34.5	18	204-1379	34	Clayey loam	Grassland
Zhejiang	Xufan	61.0	1651	20.3	6	81-736	29	Sandy clay	Cultivated land

ments varies from 21.6 to 527.5 km², all are characterized as small catchments. The mean annual precipitation varies from 600 mm to 1864 mm in these catchments and eight catchments exceeds 800 mm. The density of precipitation stations varies from 10.8 to 105.5 km²/precipitation station. The number of flood events selected ranges from 5 to 41. The land use of eleven of the selected catchments are dominated by forest and grass, and the major soil types are sandy loam and Clayey loam. All data for runoff simulation, including DEM, land-use type, soil type, precipitation and runoff, were obtained from the China Institute of Water Resources and Hydropower Research (IWHR). According to the historical data, the number of flood events differs among catchments. There are more flood events in Anhe, Dutou, Siqian, and Luanchuan, while Zhouhutun, Xiaoxian, Xufan, and Wangan have less than 10 flood events.

4 Results and Discussion

The five hydrological models with different runoff mechanisms and levels of complexity were applied for flash flood simulation in the selected fourteen catchments. Comparative analysis were further conducted to assess the applicability of different models in catchments under different climate conditions and geological features, which thus can provide guidance for hydrological model selection in small catchments in hilly areas. In this study, the hydrological models are calibrated using NSGA-II algorithm; the model performances are presented in Table 2.

4.1 The Analysis of API Model

The results of the API model are strongly affected by $P\sim Pa\sim R$ correlation diagram. For most of very humid small catchments with mean annual precipitation over or closed to 1500 mm in Fujian, Jiangxi and Zhejiang provinces, the soil moisture is usually very high, and the water shortage is very low in vadose zone. The soil water content, therefore, can easily reach its field capacity, the flash floods in these provinces belong to storage excess runoff generation mechanism. The distribution characteristics of measured $P\sim Pa\sim R$ points is obvious and easy to fit, thus the API model shows a generally good capability of flash flood simulation in small-scale humid catchments, which is not surprising given the fact that API model is based on storage excess runoff generation mechanism.

However, as shown in Table 2, the performance of the API model in Yongchun catchment is obvious worse than all the other hydrological models. This is mainly due to the obvious inaccuracy of the calculated Pa , caused by discontinuous rainfall data and incomplete observed runoff data before flash flood begins. It can be found from Figure 2a that the $P\sim Pa\sim R$ curves fitted to Yongchun catchment is poor with some flood points obvious deviated from $P\sim Pa\sim R$ curves, which seriously affects the accuracy of flash flood simulation. Similarly, in Xiaoxian catchment, due to the lack of antecedent rainfall data before flash flood, and insufficient flood events used for fitting $P\sim Pa\sim R$ curves, the $P\sim Pa\sim R$ curves are unreliable thus resulting in negative NSE in Xiaoxian catchment, and meanwhile, the result of Zhouhutun catchments is also significantly worse than other hydrological models, as shown in Figure 2b-c and Table 2. The coexistence of storage excess runoff generation mechanism and infiltration excess runoff generation mechanism is an important feature in the semi-humid and semi-arid catchments, especially under the condition of excessive rainfall in short duration, the infiltration excess-based flash floods are prone to occur. Furthermore, the measured $P\sim Pa\sim R$ points for these catchments are mostly at the stage of unsaturation excess runoff, therefore the accuracy of the API model is limited. For example, the API model is obviously inferior to the other models in Xiahecun, Wangan, and Huating catchments, where the NSEs are negative.

Overall, as a typical excess storage model, the API model is not applicable to all small humid catchments because of its high requirements for observed data. Uncontinuous precipitation and runoff data or insufficient flood events can lead to poor fitting of $P\sim Pa\sim R$ curves and result in poor forecasting capability of the API model.

4.2 The Analysis of XAJ Model

In this paper, the mean annual precipitation for most selected small catchments in hilly area is over 800 mm. Considering the storage excess runoff generation, the XAJ model seems very suitable to these humid catchments. In addition, the parabola distribution is adopted in the tension water storage capacity and surface free water capacity curves in the XAJ model, which can effectively account for the spatial distribution characteristics of the underlying surface. Even under the condition of dry soil, part of the catchment will still yield runoff when rainfall occurs. Therefore, as seen from Table 2, the XAJ model performs well for most humid small catchments in hilly area.

Table 2: Model performance for the fourteen catchments.

Catchments	Hydrological models	$\overline{R}_{rel}(\%)$	$\overline{Q}_{rel}(\%)$	Qualified number of time to peak	NSE
Luanchuan	API	42.6	33	17/22	0.58
	XAJ	27.8	19.3	18/22	0.83
	DHF	59.4	29.7	18/22	0.71
	TOPMODEL	62.2	34.4	18/22	0.57
	HEC-HMS	23	30.5	20/22	0.71
Xiahecan	API	67	90.8	14/16	-0.65
	XAJ	32.5	59.6	12/16	0.59
	DHF	48.4	39.1	13/16	0.72
	TOPMODEL	35.6	46.7	10/16	0.61
	HEC-HMS	8.9	27.9	15/16	0.72
Peihe	API	28	21.2	14/16	0.72
	XAJ	16.3	22.2	16/16	0.84
	DHF	19.8	18.5	15/16	0.83
	TOPMODEL	15.6	15.7	16/16	0.84
	HEC-HMS	14.7	15.8	14/16	0.90
Xitaiyu	API	40.9	35.2	10/13	0.72
	XAJ	19.8	30	10/13	0.82
	DHF	143.9	42.3	11/13	0.01
	TOPMODEL	101.4	99.5	10/13	0.75
	HEC-HMS	23.4	29.2	12/13	0.76
Wangan	API	133.3	113	5/8	-0.83
	XAJ	65.1	60.6	4/8	-0.21
	DHF	181.9	79.7	3/8	-0.15
	TOPMODEL	126	58.7	6/8	0.58
	HEC-HMS	17.9	40.1	8/8	0.77
Zhouhutun	API	44.6	51	3/5	0.73
	XAJ	67.5	51.1	3/5	0.74
	DHF	38.7	54.3	3/5	0.80
	TOPMODEL	28.1	51.9	4/5	0.87
	HEC-HMS	16.7	24.8	5/5	0.85
Huating	API	130.8	101.3	13/15	-4.88
	XAJ	59.4	50.9	12/15	0.38
	DHF	94.5	53.3	12/15	0.28
	TOPMODEL	268.6	38.5	10/15	0.07
	HEC-HMS	41.3	38	10/15	0.72
Siqian	API	16.6	14.6	29/33	0.89
	XAJ	14.2	14.4	28/33	0.95
	DHF	20.5	21.2	30/33	0.93
	TOPMODEL	21.5	22.2	27/33	0.92
	HEC-HMS	14.9	17.3	32/33	0.92
Xiaoanxia	API	17.6	31.9	7/7	-0.65
	XAJ	41.8	38.7	7/7	0.77
	DHF	19.2	29	7/7	0.89
	TOPMODEL	19.5	39.9	7/7	0.77
	HEC-HMS	8.6	23.5	7/7	0.80
Yongchun	API	42.7	40.2	11/14	0.37
	XAJ	33.6	42.4	12/14	0.72
	DHF	35.3	33.5	14/14	0.73
	TOPMODEL	24.8	24.6	13/14	0.79
	HEC-HMS	17.3	34.2	10/14	0.65
Anhe	API	22.9	31	32/41	0.73
	XAJ	17.6	22.4	37/41	0.89
	DHF	30.6	23.6	38/41	0.82
	TOPMODEL	22.7	20.6	35/41	0.81
	HEC-HMS	18.9	19.2	38/41	0.85
Dutou	API	35.2	27	19/32	0.71
	XAJ	19.4	20.9	28/32	0.89
	DHF	45.5	26.1	27/32	0.71
	TOPMODEL	35.8	21.3	27/32	0.60
	HEC-HMS	13.8	20.2	29/32	0.86
Shangliu	API	21.2	18.6	17/18	0.86
	XAJ	22.2	19.4	18/18	0.92
	DHF	23.6	20.5	14/18	0.75
	TOPMODEL	20.8	16.6	16/18	0.86
	HEC-HMS	15.2	18.3	17/18	0.86
Xufan	API	11.5	19.4	5/6	0.84
	XAJ	26.4	16.6	6/6	0.83
	DHF	15.7	18.6	6/6	0.86
	TOPMODEL	13	14.5	6/6	0.89
	HEC-HMS	22.2	20.8	5/6	0.83

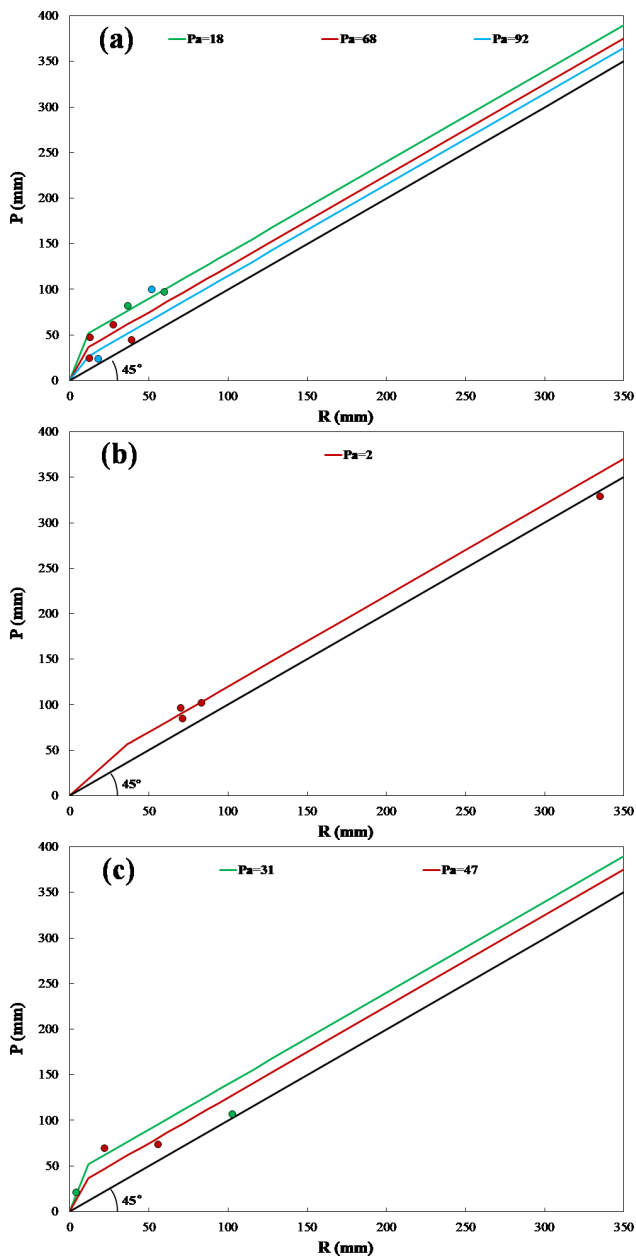


Figure 2: P~Pa~R curves for catchments: (a) Yongchun; (b) Xiaoxian; (c) Zhouhutun.

However, for Xiaoxian and Zhouhutun catchments where the antecedent observed data is lacking, the performance of the XAJ model is poor in terms of the runoff production evaluation index ($\overline{R_{rel}}$), and the average relative error is nearly 20% to 30% higher than the other hydrological models. This is due to the fact that the antecedent soil moisture content is seriously underestimated, caused by the lack of precipitation data in the pre-flood period, therefore, the accuracy of the XAJ model is affected accordingly.

Figures 3 and 4 present the typical flash flood events of Xiaoxian and Zhouhutun catchments. The mean aver-

age tension water storage capacity (W_m) is an important parameter controlling the total runoff production. Generally, lower W_m usually results in higher total runoff production because the soil has little power to contain water for a single flood event. However, even when the parameter W_m for both catchments is about 100 mm, which is obviously lower than the normal range of 120~200 mm, the simulation results are severely underestimated. For Yongchun catchment, where the precipitation data in the pre-flood period is also lacking, the accuracy of the XAJ model is similar to other models especially the $\overline{R_{rel}}$ index. This is probably due to the fact that the parameter W_m for Yongchun catchment is 95 mm, the irrational parameter value help to increase the runoff generation to some degree and thereby increasing the simulation accuracy.

4.3 The Analysis of DHF Model

Based on infiltration excess runoff generation mechanism, the DHF model has been successfully applied in arid and semi-arid catchments in northern China. Since most of the selected catchments in this study have high vegetation coverages (from 80% to 95%) and well developed hydrographic networks, the flash flood simulation by the DHF model is relatively poor compared to other hydrological models. However, the performance of the DHF model on peak runoff and peak time simulation is prominent. $\overline{Q_{rel}}$ is around 20% in humid catchments, which can be beneficial in practice when used in operation flash flood forecasting. The peak flow is very significant for flood warning due to the fact that flood caused disasters in hilly area is mainly determined by whether the flood peak greater than the threshold discharge for flooding at the target site or not. Worldwide research on flash flood prevention focuses on the early-warning index, especially rainfall threshold [6], which is exactly calculated by whether the flood peak exceeds the warning value with inverse method. Moreover, in Wangan and Xitaiyu catchments, the simulations of flood peak flow are in the intermediate level, despite the fact that their runoff production indices are the worst among other hydrological models used in this study. The DHF model adopts the variable-strength, variable-speed empirical unit hydrograph, which has the ability to characterize the rapid rise and fast recession, and thus is suitable for the flash flood peak simulation. It is obvious that the DHF model has great potential for application in flash flood forecasting; however, its runoff production module has to be improved so as to increase the runoff simulation accuracy. Li *et al.* pointed out that even in the arid region, there exist factors representing the storage excess runoff genera-

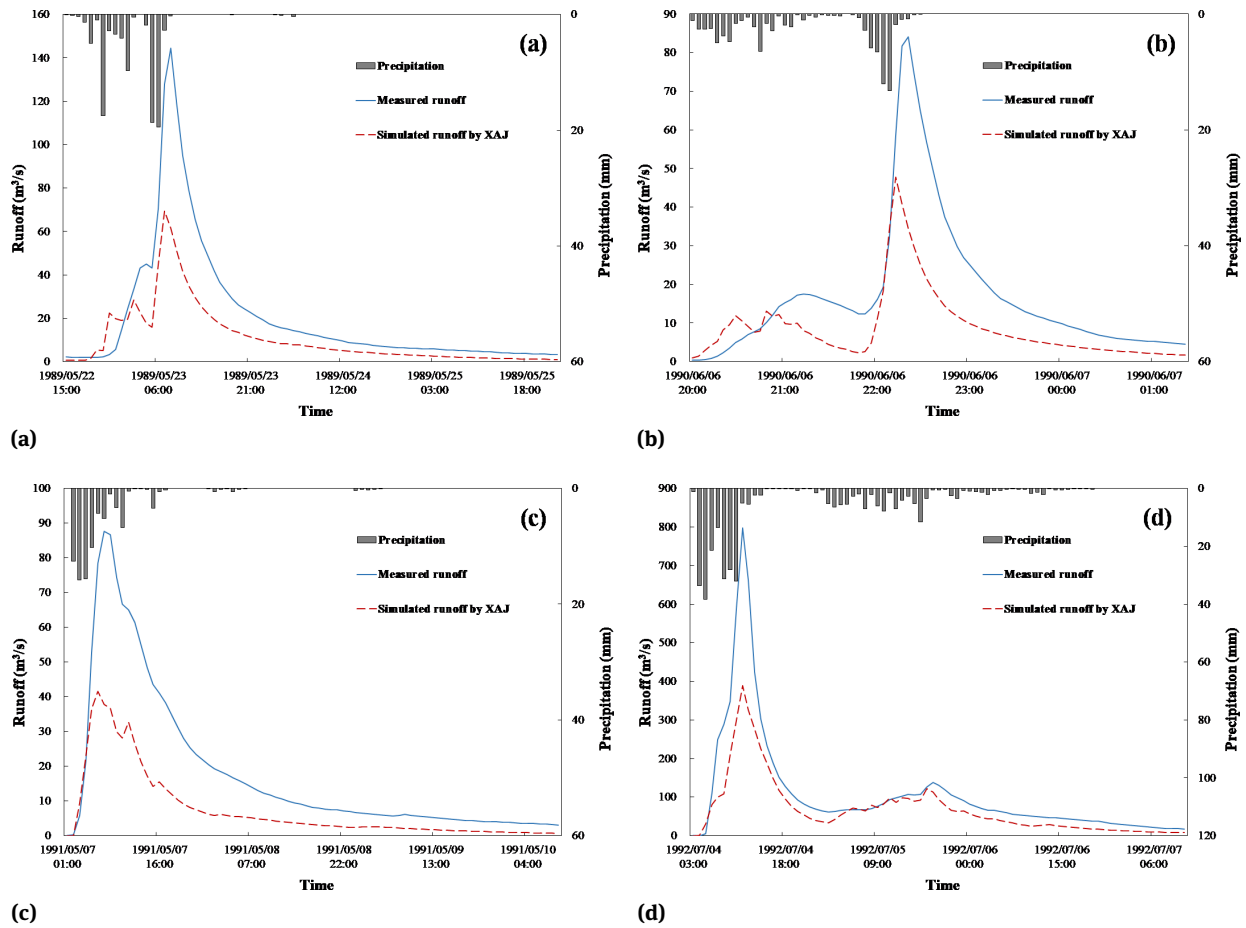


Figure 3: Simulation of typical flash flood events using XAJ model in Xiaoxian catchment: (a) "19890521"; (b) "19900606"; (c) "19910506"; (d) "19920704".

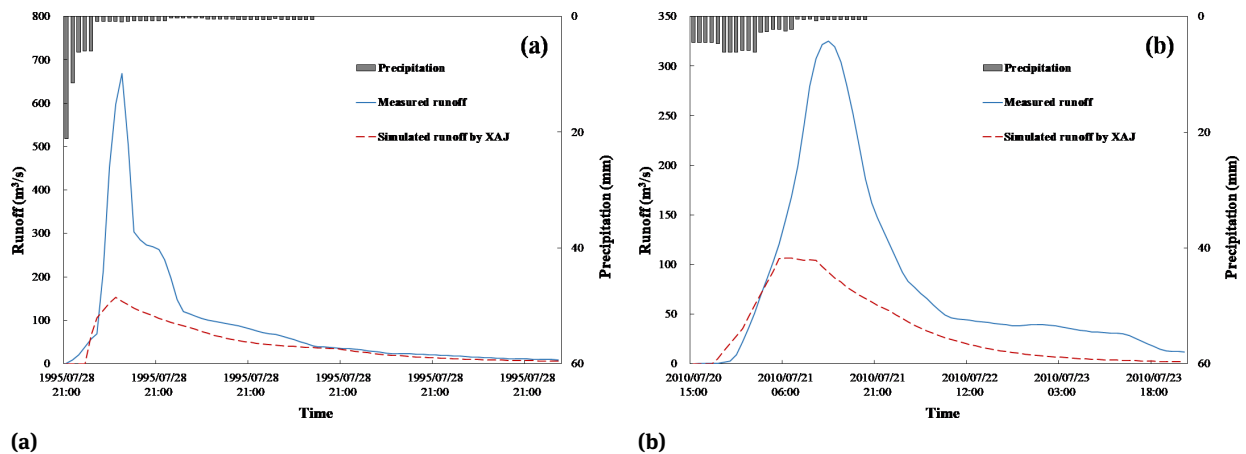


Figure 4: Simulation of typical flash flood events using XAJ model in Zhouhutun catchment: (a) "19950728"; (b) "20100720".

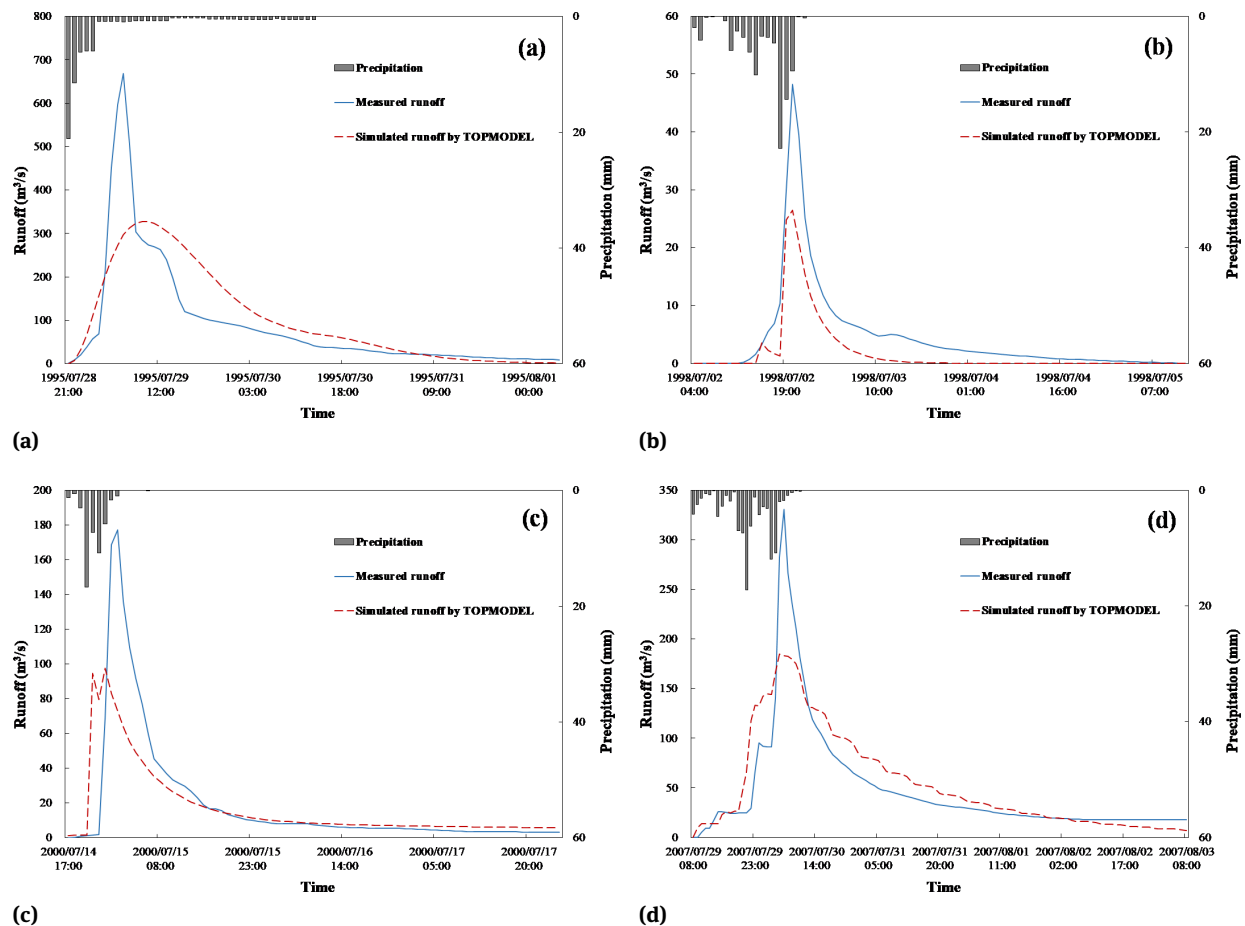


Figure 5: Simulation of four typical flash flood events using TOPMODEL: (a) Zhouhutun catchment “19950728”; (b) Peihe catchment “19980702”; (c) Xiahecun catchment “20000714”; (d) Luanchuan catchment “20070729”.

tion, and the hydrological models based purely on infiltration excess runoff generation mechanism can only simulate the flood peak [33], while unable to simulate the flood volume, which is consistent with our results of the DHF model in this paper.

4.4 The Analysis of TOPMODEL

It can be seen from Table 2 that TOPMODEL is successfully applied in almost all the humid catchments but its performance is not competitive with other hydrological models in some semi-humid, *e.g.* Huating, Wangan and Xitaiyu catchments. This is due to the fact that runoff simulated by TOPMODEL is directly related to the groundwater level, therefore the shallower groundwater level will generally produce higher simulated runoff. Meanwhile groundwater is unlikely to rapidly rise and recess. In small humid catchments, the base flow is usually at a relatively high level and the groundwater level is shallow, most of the flash floods

rise more slowly than in arid area, so the TOPMODEL behaves well in humid catchments with $\overline{R_{rel}}$ and $\overline{Q_{rel}}$ within 20% and NSE above 0.7. However, in the semi-humid and semi-arid catchments, the base flow is small, and the soil before flood period is dry, as a result, the peak flows rise up and go down rapidly and the hydrograph is “slim” (with short flood duration). Thus, there are some limitations on the application of TOPMODEL in arid and semi-arid catchments.

Figure 5 shows four typical flash flood events, before which no precipitation occurred for a long period of time, hence the initial runoff is very low around $1 \text{ m}^3/\text{s}$. The initial groundwater depth is determined by the initial flow in TOPMODEL, so it is assumed that the initial groundwater levels of all the four flood events are very deep. The results show that the simulated peak runoff of this type of flash flood is far lower than observed data. Huang *et al.* analyzed the simulation results of TOPMODEL model in semi-humid and semi-arid catchment, and concluded that the

average depth of groundwater in these catchments are too deep so it is difficult to simulate the flood peak well by TOPMODEL [34].

4.5 The Analysis of HEC-HMS Model

The HEC-HMS model generates good simulation results in all 14 catchments, as a simple corollary of our assessment of model performance, HEC-HMS model outperforms other models in simulating flash floods. In semi-humid and semi-arid catchments, the initial loss parameters adopted in runoff production mode effectively consider the vegetation interception and ground filling and other losses. Further, the constant loss parameters represent the maximum infiltration capacity of catchments. Overall, the selected method belongs to infiltration excess runoff generation mechanism and is more suitable for flash flood under the condition of short duration. Therefore, the simulation results are superior to other hydrological models especially in Luanchuan, Wangan and Xiahecun catchments, where most of floods are in short duration under high intensity rainfall. Wang *et al.* compared the simulation results in semi-humid and semi-arid catchments of TOPMODEL, HEC-HMS and XAJ model, and concluded that the HEC-HMS model behaved best [35]. In small humid catchments, the initial losses can be described as the initial storage deficit and the constant losses indicate the infiltration rate of saturated soil. Moreover, the runoff generation losses in humid areas is larger than semi humid and semi-arid area, which reflects storage excess runoff generation mechanism to a certain extent [36], thus HEC-HMS model achieves similar simulation results.

As a typical distributed hydrological model, HEC-HMS model can effectively consider the different spatial distribution of rainfall and shows a satisfactory capability when the spatial distribution of rainfall is uneven. Taking the "20050817" flood event in the Luanchuan catchment for example (shown in Table 3), the average total rainfall in the

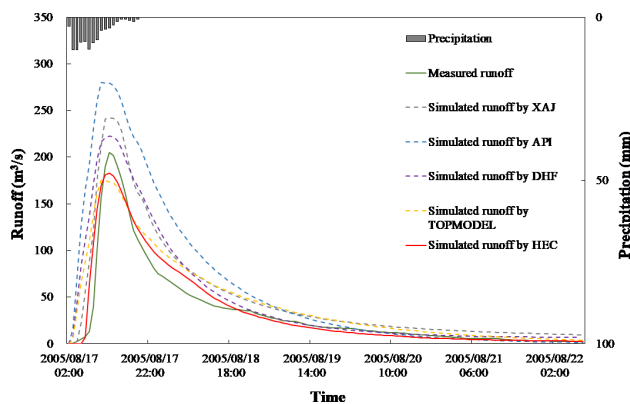


Figure 6: Simulation of the "20050817" flood in Luanchuan catchment.

upstream ($\overline{P}_{up}$) is obviously higher than the average of the whole catchment ($\overline{P}$) with $\overline{P}_{up} > 1.2\overline{P}$. As shown in Table 3, the simulation results of HEC-HMS model on runoff depth is prominent and the NSE is greater than 0.9. By comparing all simulated hydrograph profiles in Figure 6, we can conclude that HEC-HMS model achieved good simulation, especially for the flood recession process.

5 Summary and Conclusions

We have successfully applied five frequently used hydrological models in fourteen typical small catchments to study the hydrological model applicability in hilly areas of China. Overall the simulation for flash flood in hilly area is very difficult, since there is not a single hydrological model that can perform well for all the catchments.

Among five hydrological models, the DHF hydrological model performs worst in general. Although the flood peak simulation is relatively good, the DHF model shows a poor capability for other indices in catchments in hilly area. However, according to NSE results in Table 2, API seems to be worse than DHF in most catchments.

In small humid catchments, the HEC-HMS, API, XAJ, TOPMODEL hydrological models overall generate satisfactory simulation results. However, the API and XAJ models have higher requirements on the length of observed data, and the TOPMODEL showed some limitations in simulating the floods with flow rising up and going down rapidly. Therefore, the simple models like API and the XAJ model can be selected preferentially only when the historical observed data is sufficient. For data insufficient catchments, the HEC-HMS distributed hydrological model can obtain some parameters from underlying surface data rather than

Table 3: Performances of the "20050817" flood in Luanchuan catchment.

Hydrological model	$\overline{R}_{rel}(\%)$	$\overline{Q}_{rel}(\%)$	$\Delta T(h)$	NSE
API	78.3	36.6	-2	-0.07
Xin'anjiang	74.9	18.1	0	0.75
DHF	67.6	8.5	0	0.65
TOPMODEL	31.1	-14.4	-2	0.82
HEC-HMS	6.3	-10.9	0	0.95

using hydrological data to calibrate parameters, thus it is more suitable to be used in small ungauged catchments.

In small semi-humid and semi-arid catchments, under the condition of short duration and high intensity rainfall, the storage excess-based floods are dominant. HEC-HMS model produces best results among the five hydrological models. Despite all this, HEC-HMS model still cannot simulate flash floods well in some catchments, mainly limited by the model structure to capture such complex rainfall-runoff processes in hilly areas and the data availability. For future study, understanding the temporal and spatial conversion mechanism of the mix runoff generation mechanism in semi-humid and semi-arid catchments, and improving the understanding of basic theory of rainfall-runoff process are two important tasks to be studied for developing a hydrological model that can be applied to both semi-humid and semi-arid catchments.

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References

- [1] Miao, Q.; Yang, D.; Yang, H.; Li, Z., Establishing a rainfall threshold for flash flood warnings in China's mountainous areas based on a distributed hydrological model. *Journal of Hydrology* 2016, 541, 371-386.
- [2] He, B.; Huang, X.; Ma, M.; Chang, Q.; Tu Y.; Li Q.; Zhang K.; Hong Y., Analysis of flash flood disaster characteristics in China from 2011 to 2015. *Natural Hazards* 2018, 90, 407-420.
- [3] Hofierka, J.; Knutová, Monika., Simulating spatial aspects of a flash flood using the monte carlo method and grass gis: a case study of the malá svinka basin (slovakia). *Open Geosciences* 2015, 7(1).
- [4] Kelsch, M., Hydro-meteorological characteristics of flash floods. In *Coping with Flash Floods*, NATO Science Series, Environmental Security, Grunfest E, Handmer J (eds). Kluwer Academic Publishers: Dordrecht, Boston 2001, 77, 181-193.
- [5] Hapuarachchi, H. A. P.; Wang, Q. J.; Pagano, T. C., A review of advances in flash flood forecasting. *Hydrological Processes* 2011, 25(18), 2771-2784.
- [6] Golian, S.; Saghafian, B.; Maknoon R., Derivation of Probabilistic Thresholds of Spatially Distributed Rainfall for Flood Forecasting. *Water Resources Management* 2010, 24, 3547-3559.
- [7] Beven, K. J.; Kirkby M. J.; Schofield N.; Tagg A. F., Testing a physically-based flood forecasting model (TOPMODEL) for three U.K. catchments. *Journal of Hydrology* 1984, 69, 119-143.
- [8] Beven, K. Rainfall-runoff modelling. *The Primer*. John Wiley & Sons, Ltd., England 2001.
- [9] Devia, G. K.; Ganasri, B. P.; Dwarakish G. S., A Review on Hydrological Models. *Aquatic Procedia* 2015, 4, 1001-1007.
- [10] Kobold, M.; Brilly, M., The use of HBV model for flash flood forecasting. *Nature Hazards and Earth System Sciences* 2006, 6, 407 - 417.
- [11] Oleyiblo, J. O.; Li Z., Application of HEC-HMS for flood forecasting in Misai and Wan'an catchments in China. *Water Science and Engineering* 2010, 1, 14-22.
- [12] Deng, P.; Li, Z.; Xie, F., Application of TOPMODEL in Buliu River Basin and comparison with Xin'anjiang model. *Water Science and Engineering* 2008, 1, 25-32.
- [13] Ye, J.; Wu, Y.; Li, Z.; Lu, C., Forecasting methods for flash floods in medium and small rivers in humid regions and their applications. *Journal of Hohai University (Natural Sciences)* 2012, 6, 615-621.
- [14] Kan, G.; He, X.; Ding, L.; Li, J.; Liang, K.; Hong, Y., Study on Applicability of Conceptual Hydrological Models for Flood Forecasting in Humid, Semi-Humid Semi-Arid and Arid Basins in China. *Water* 2017, 9, 719.
- [15] Fedora, M. A.; Beschta, R. L., Storm runoff simulation using an Antecedent precipitation index (API) model. *Journal of Hydrology* 1989, 121-133.
- [16] Descroix, L.; Nouvelot, J. F.; Vauclin, M., Evaluation of an antecedent precipitation index to model runoff yield in the western Sierra Madre (North-west Mexico). *Journal of Hydrology* 2002, 263, 114-130.
- [17] Guo, L.; He, B.; Ma, M.; Chang, Q.; Li, Q.; Zhang, K.; Hong, Y., A comprehensive flash flood defense system in China: overview, achievements, and outlook. *Natural Hazards* 2018, 92, 727-740.
- [18] Zhao, R. J., The Xin'anjiang model applied in China. *Journal of Hydrology* 1992, 135, 371-381.
- [19] Yao, C.; Zhang, K.; Yu, Z.; Li, Z.; Li, Q., Improving the flood prediction capability of the Xinanjiang model in ungauged nested catchments by coupling it with the geomorphologic instantaneous unit hydrograph. *Journal of Hydrology* 2014, 517, 1035-1048.
- [20] Lü, H.; Hou, T.; Horton, R.; Zhu, Y.; Chen, X.; Jia, Y.; Wang, W.; Fu, X., The streamflow estimation using the Xinanjiang rainfall runoff model and dual state-parameter estimation method. *Journal of Hydrology* 2013, 480, 102-114.
- [21] Liu, A.; Wang, B., Application on Microcomputer of DHF model. *Journal of Dalian institute of Technology* 1984, 28.
- [22] Wang, M.; Peng, Y.; Liang, G., Application of DHF model in flood forecasting for shifosi basin. *South-to-North Water Diversion and Water Science & Technology* 2012, 93-97.
- [23] Liu, H.; He, J.; Li, Y., Technical study of distributed flood forecasting based on cellular automata and dahuofang model. *C E Ca* 2017, 42, 2031-2041.
- [24] Devia, G. K.; Ganasri, B. P.; Dwarakish, G. S., A Review on Hydrological Models. *Aquatic Procedia* 2015, 4, 1001-1007.

- [25] Lin, K.; Zhang, Q.; Chen, X., An evaluation of impacts of DEM resolution and parameter correlation on TOPMODEL modeling uncertainty. *Journal of Hydrology* 2010, 394, 370-383.
- [26] Scanlon, T. M.; Raffensperger, J. P.; Hornberger, G. M.; Clapp, R. B., Shallow subsurface storm flow in a forested headwater catchment: Observations and modeling using a modified TOPMODEL. *Water Resources Research* 2000, 36, 2575-2586.
- [27] Franchini, M.; Wendling, J.; Obled, C.; Todini, E., Physical interpretation and sensitivity analysis of the topmodel. *Journal of Hydrology* 1996, 175(1-4), 0-338.
- [28] Halwatura, D.; Najim, M. M. M., Application of the HEC-HMS model for runoff simulation in a tropical catchment. *Environmental Modelling & Software* 2013, 46, 155-162.
- [29] Razi, M. A. M.; Ariffin, J.; Tahir, W.; Arish, N. A. M., Flood Estimation Studies using Hydrologic Modeling System (HEC-HMS) for Johor River, Malaysia. *Journal of Applied Sciences* 2010, 10, 930-9.
- [30] Deb, K.; Agrawal, S.; Pratap, A.; Meyarivan, T., A fast elitist non-dominated sorting genetic algorithm for multi-objective optimization: NSGA-II. *IEEE Transactions on Evolutionary Computation* 2000, 2, 182-197.
- [31] Srinivas, N.; Deb, K., Multiobjective Optimization Using Nondominated Sorting in Genetic Algorithms. *Evolutionary Computation* 1994, 2, 221-248.
- [32] Nash, J. E.; Sutcliffe, J. V., River flow forecasting through conceptual models part I — A discussion of principles. *Journal of Hydrology* 1970, 10, 282-290.
- [33] Li, Z.; Huang, P.; Yao, C.; Zhao, L.; Yu, Z., Application of flexible-structure hydrological models in different runoff generation regions. *Advances in Water Science* 2014, 28-35.
- [34] Huang, P.; Li, Z.; Yao, C.; Hu, C.; Zhang, J., Application and comparison of hydrological models for semi-arid and semi-humid regions. *Journal of Hydroelectric Engineering* 2013, 04, 4-9.
- [35] Wang, L.; Li, Z.; Bao, H., Research for Optimal Flood Dispatch Model for Reservoir Based on POA. *Water Resources and Power* 2008, 4, 46-48.
- [36] Dong, X.; Li, Z.; Li, L.; Application and comparison of three hydrological models in semi-arid region. *Journal of Hohai University (Natural Sciences)* 2006, 132-135.