Impacts of precipitation and topographic conditions on the model simulation in the north of China

Long Sun, Zhijia Li, Ke Zhang and Tingting Jiang

ABSTRACT

The evaluation of hydrological models for a specific catchment is normally based on the model performance according to the selected performance criteria. However, the catchment rainfall-runoff characteristics could be used for the selection of a suitable hydrological model in study area, which, also, for the problem solve of the model application in ungauged basins. In this study, six conceptual models were applied in three semi-humid or semi-arid catchments to investigate the correlation between catchment characteristics and model structure selection. In addition, the impacts of precipitation and topography in model simulation were analyzed. The results show that runoff generation are highly impacted by catchment topographic index and land cover change, and the influence of slope for river channel is greater than mean slope for the whole catchment due to the runoff generation for partial area. For the catchments under similar climate condition, the impact of topographic features for runoff generation process is greater than the difference of precipitation. It indicates that for a specific catchment, the selection of appropriate model should base on better understanding of the rainfall-runoff relationship. The method of incorporating additional runoff generation module in the traditional model can significantly improve the accuracy of flood simulation.

Key words | flood forecasting, infiltration-excess runoff, semi-humid or semi-arid region, topographic characteristics

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HIGHLIGHTS

- Six conceptual models were applied in three semi-humid or semi-arid catchments.
- The model obviously led to better model performance.
- Runoff generation and production process are highly influenced by catchment topographic index.
- The influence of slope for river channel is greater than mean slope.
- The saturation-excess and infiltration-excess runoff mechanism.

INTRODUCTION

Hydrological models with different model structures are widely used around the world. The hydrologists have developed various conceptual hydrological models since the first application of the Stanford model (Singh 1997; Adnan *et al.* 2020). Conceptual hydrological models are effective tools to explore and understand the complex hydrological cycle processes and mechanisms, and they are also effective ways to solve the key problems in hydrology (Kavetski *et al.* 2006; Liu *et al.* 2017). Hydrological processes vary enormously across different landscapes (Winter 2010). For example, two general runoff generation mechanisms, saturation-excess runoff and infiltration-excess runoff, may

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occur simultaneously in semi-humid or semi-arid regions (Horton 1933; Huang et al. 2016). As the rainfall-runoff relationship of a catchment is highly related to the topographic information, the investigation of the influences of topography and climate conditions on model performance could help us to better understand the model and can also provide information for the region with similar climate condition and catchment characteristics.

Catchment geomorphic properties play a significant role in rainfall-runoff simulation, which is one of the most important factors that should be taken into account in the application of hydrological models (Euser et al. 2015; Chao et al. 2019). Different catchments always have different underlying surface conditions. A great number of studies have been carried out on the measurement of catchment similarity (Hrachowitz et al. 2013; Alhassan & Jin 2020). It is assumed that the catchments are similar if the differences for the underlying surface characteristics is within a certain range. Similar catchments have similar rainfall-runoff behavior that can be simulated using the same model and same parameters. However, if the differences are greater than a certain value, the model structures used for different catchments should be modified (Dunne & Black 1970). Chirico et al. found that in Maheuangi catchment, a single power-law function is not sufficient to reflect the soil lateral water transport capacity, dual-power law parallel structure can describe the non-linear drainage characteristics (Chirico et al. 2003); Clark et al. studied the Panola mountain area and their result shows that the non-linear function of runoff can be avoided by using a simple linear reservoir parallel structure (Clark et al. 2009). In order to investigate the relationship between catchment characteristics and conceptual model structures, Fenicia et al. used 12 model structures, which including single reservoir structure, tandem reservoir structure and parallel reservoir structure, to three catchments with different underlying surface characteristics. Result indicates that there is a certain relationship between catchment characteristics and model structure. For example, the parallel reservoir structure is suitable for the region with strong permeability and multiple aquifers, the series reservoir structure is suitable for the weak infiltration of bedrock, as the linear structure is suitable for the catchment with stable and smooth runoff variation (Fenicia et al. 2014).

Flash floods caused by rainfall of high intensity and short duration occur frequently in the semi-humid or semi-arid regions that within a size of 3,000 km^2. For the northwest of China, due to the problems of data shortage and the complex of underlying conditions, the accuracy of flood forecasting is often too low to fulfill the needs of flood warning (Kan et al. 2017). A single model structure is unlikely to precisely describe a diverse range of runoff generation mechanisms (Castillo et al. 2003; Clark 2008). So far, the application of conceptual models for flood simulation in semi-humid and semi-arid regions still requires further study (Pilgrim et al. 1987). Therefore, it is worth investigating the application of existing models. It is also important to explore which kind of rainfall-runoff model could accommodate the runoff generation mechanisms for this region, as well as the main impact factors for model performance. In this study, six conceptual hydrological models were tested in several semi-humid or semi-arid catchments that located in Shannxi Province, China. The difference in runoff generation for spatial proximity catchments with different climate and geographic properties was investigated and compared. According to the model performance, the applicable of models in the study region will be discussed based on the simulation result, catchment characteristics, model structure and the observed data.

The objective of this work is to investigate the influence of precipitation and geographic conditions on model performance. The study catchments are described in the section Study area, followed by the models and methodology in the section Models and methodology. Results and discussion present the simulated model performances and the discussion of the results. The conclusion is summarized in Conclusion.

STUDY AREA

Three typical semi-humid and semi-arid catchments: Maduwang, Banqiao and Zhidan, which are all sub basins of the Yellow River Basin, were selected to investigate the model performance using different types of models (Figure 1). These three catchments are located in Shannxi province of China with varying catchment characteristics and climate conditions. The meteorological characteristics for the study catchments are listed in Table 1. The distribution of

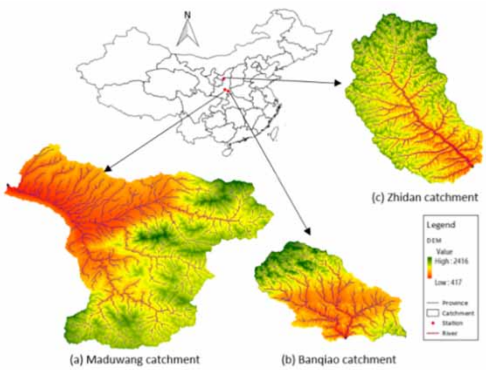

Figure 1 | Location of the selected catchments in Shannxi Province, China.

vegetation types (Table 2) is also calculated based on the global 1 km land cover data provided by the University of Maryland (Friedl *et al.* 2002).

Maduwang catchment has the largest size of 1,604 km^2. The annual precipitation for this catchment is about 630 mm and shows gradually increasing trend from north to south. The mountains and valleys in this area are quite steep with a good coverage of vegetation. The valleys in the hilly areas are extremely developed with large cutting depth, broken terrain and poor vegetation. The plain is flat and the soil is fertile, which is suitable for crop cultivation. The average annual precipitation in the Banqiao River Catchment is around 730 mm with an area of 502 km^2. The terrain is high in the northwest, low in the southeast, most hilly areas contain clayey and sand layer clay, rock type include schist and phyllite, and cultivated land is distributed in river valleys. Zhidan catchment has only 510 mm precipitation per year, and covers a drainage area of 777 km^2. The geographic features of Zhidan can be roughly divided into three types of landforms: valley terraces, beam-shaped gullies and earth-rock mountains. The topographic terrain is distributed with mountains, canyons and barren beaches. The slope varies greatly in Zhidan catchment and the soil erosion is serious because of the poor vegetation cover.

The determination of the humid condition is usually based on water balance, while Liu suggested that the aridity index could be used for natural zonation division in Shaanxi province when the requiring data for calculating water balance is not available (La Vigna *et al.* 2016). The aridity index, which represents the ratio of long-term potential evapo-transpiration to precipitation, is about 1.4 for Maduwang, 1.6 for Banqiao and 2.0 for Zhidan, respectively. According to Liu's study on natural zonation in the Shannxi province, based on the aridity index and annual precipitation, Maduwang and Banqiao catchments are identified as semi-humid region, while Zhidan is regarded as semi-arid region due to the low precipitation and high dryness fraction.

MODELS AND METHODOLOGY

Six conceptual hydrological models are tested in the study catchments: the Sacramento model (named as M1)

Table 1 | Meteorological characteristics for the three catchments

Catchment	Area (km^2)	Annual precipitation (mm)	Annual potential evapotranspiration (mm)	Average temperature (°C)	Average elevation (m)	Annual runoff (mm)	Aridity index
Maduwang	1,601	630.9	1,186	13.3	1,027	307	1.4
Banqiao	493	729.4	1,300	12.8	880	174	1.6
Zhidan	774	509.8	1,556	7.8	1,417	41.6	2

Table 2 | Distribution of vegetation types for the three catchments

Catchment	Evergreen coniferous forest	Broadleaved deciduous forest	Mixed forest	Forest	Forest steppe	Shrubbery	Grass land	Crops
Maduwang	0.163	0.095	0.026	0.219	0.119	0.002	0.175	0.200
Banqiao	0.017	0.001	0.006	0.295	0.390		0.137	0.154
Zhidan					0.004	0.473	0.523	

(Anderson *et al.* 2006), TOPMODEL model (M2) (Beven 1997), Xin'anjiang model (M3) (Zhao 1992), Infiltration-Excess runoff model (M4), first Infiltration-Excess then Saturation-Excess runoff model (M5), and the Xin'anjiang model combined with Infiltration-Excess runoff (M6). The Sacramento model, TOPMODEL and Xin'anjiang model are very popular rainfall-runoff models that applied widely across the world. In Infiltration-Excess runoff model, the Green-Ampt equation is used to describe the infiltration process (Winchell *et al.* 1998). It assumed that the infiltration-excess process occurs on the subsurface and the subsurface runoff is not considered in the model. The infiltration capacity distribution curve is introduced to account for the inhomogeneity of infiltration process and underlying surface. The first Infiltration-Excess then Saturation-Excess runoff model is a two runoff-components model and the runoff concentration calculation is similar to Xin'anjiang model that uses the concept of linear reservoirs. The last model is the combination of Xin'anjiang and Infiltration-Excess runoff model, compared with the traditional Xin'anjiang model, this model contains the infiltration-excess process for the unsaturated zones. It should be noted that only the infiltration-excess surface runoff is generated in the unsaturated area, the interflow and subsurface flow are not considered in the model. More details about the description of the models can be found in Huang (Huang *et al.* 2016).

Firstly, the sensitivity of model parameters was analyzed for the six conceptual models. The most sensitive parameters for each model were selected according to the previous studies to reduce the total number of parameters required in parameterization (Perrin *et al.* 2001). The simplex method is a classical optimization algorithm (Nelder & Mead 1965). Thanks to characteristics of being easy-to-code, fast in searching speed and an excellent performance in approaching optimal solution, the method has been widely used in the research of hydrology and water resources. Compared with SCE-UA algorithm (Guangyuan *et al.* 2016), the simplex method is relatively simple and requires fewer calculations for finding the optimal parameters. In addition, the simplex method is not limited by the number of variables; the increasing of the parameter dimension does not lead to a significant increase in computation. However, the simplex method is still in the stage of empirical method. It is very useful to solve the problem that contains only a few variables. When the number of variables is increasing to a specific value, the accuracy of model calibration using simplex method is generally lower than using the SCE-UA algorithm. Here only the sensitive parameters were considered to be calibrated based on historical data, thus the simplex method was selected to identify the model parameters.

The following four performance criteria were evaluated for study catchments.

The relative error of runoff depth (ΔR):

$$\Delta R(\%) = \left| \frac{R_{sim} - R_{obs}}{R_{obs}} \right| \times 100\% \quad (1)$$

The relative error of peak flow (ΔQ_p):

$$\Delta Q_p(\%) = \left| \frac{Q_{psim} - Q_{pobs}}{Q_{pobs}} \right| \times 100\% \quad (2)$$

where R_{sim} and R_{obs} refer to the simulated and observed runoff depth, and Q_{psim} and Q_{pobs} refer to the simulated and observed peak flow.

The Nash-Sutcliffe efficiency (NS) (Nash & Sutcliffe 1970)

$$NS = 1 - \frac{\sum_{i=1}^{n} [Q_{sim}(i) - Q_{obs}(i)]^2}{\sum_{i=1}^{n} [Q_{obs}(i) - \bar{Q}_{obs}]^2} \quad (3)$$

where $Q_{sim}(i)$ and $Q_{obs}(i)$ are the simulated and observed discharge at given time i, and $\bar{Q}_{obs}$ is the average discharge over the whole period.

The difference of simulated peak flow appearance time T_{qpsim} and the real flow appearance time T_{qpsim} is also calculated:

$$\Delta T_{qp} = |T_{qpsim} - T_{qpobs}| \quad (4)$$

According to the standards of 'Forecasting norm for hydrology intelligence' in China (Fan *et al.* 2016), the accuracy of flood prediction is evaluated based on the qualification rate of runoff depth, peak flow and flood peak appearance time. Therefore, the Equations (1), (2) and (4) are transformed into a binary function in order to make the forecasting result more distinct:

$$QU_R = \begin{cases} 1, & \Delta R(\%) \leq 20\% \\ 0, & \Delta R(\%) > 20\% \end{cases} \quad (5)$$

$$QU_p = \begin{cases} 1, & \Delta Q_p(\%) \leq 20\% \\ 0, & \Delta Q_p(\%) > 20\% \end{cases} \quad (6)$$

$$QU_{T_{qp}} = \begin{cases} 1, & \Delta T_{qp} \leq 3h \\ 0, & \Delta T_{qp} > 3h \end{cases} \quad (7)$$

where QU_R, QU_p and $QU_{T_{qp}}$ denote the qualification rate of runoff depth, peak flow and peak appearance time. Value of 1 indicates qualified and 0 means unqualified, respectively.

The magnitudes of floods differ from catchments, for dry catchment the total runoff depth might be small. The error of runoff depth and the Nash-Sutcliffe efficiency might not be appropriate to evaluate the ability of models for flood forecasting. The most focus of flood forecasting in the semi-humid and semi-arid region of China is the predicting of peak flow value and flood leading time. In this study, the combination of qualification rate for runoff depth and peak flow was taken as objective function for model calibration using the simplex method.

RESULTS AND DISCUSSION

The hourly records of precipitation and discharge for the three catchments is only observed during the flood season. Therefore, the models were simulated based on flood events. A total of 12 flood events in Maduwang, 13 floods in Banqiao and 15 floods in Zhidan were selected. Figure 2 shows one of the simulated hydrographs (Mdduwang: 070713; Banqiao: 030824; Zhidan: 100618) for the study catchments using different types of models. It has been detected from the flow curves that Maduwang catchment is mainly occupied by saturation-excess runoff. But there are also several narrow floods along with sharply increasing and decreasing flow, which indicates that infiltration-excess surface runoff also has relatively important impact on flood. The infiltration-excess process occurs more often in Banqiao than in Maduwang, as Banqiao has very steep hydrographs for most of the flood events and the flow curve is sharp with a relatively high peak value. The hydrograph of Zhidan fluctuate obviously indicates that it is a typical catchment with infiltration-excess runoff mechanism.

Result of Maduwang

For the 12 flood events from Maduwang, seven of them were used to calibrate the models and the remains were used for

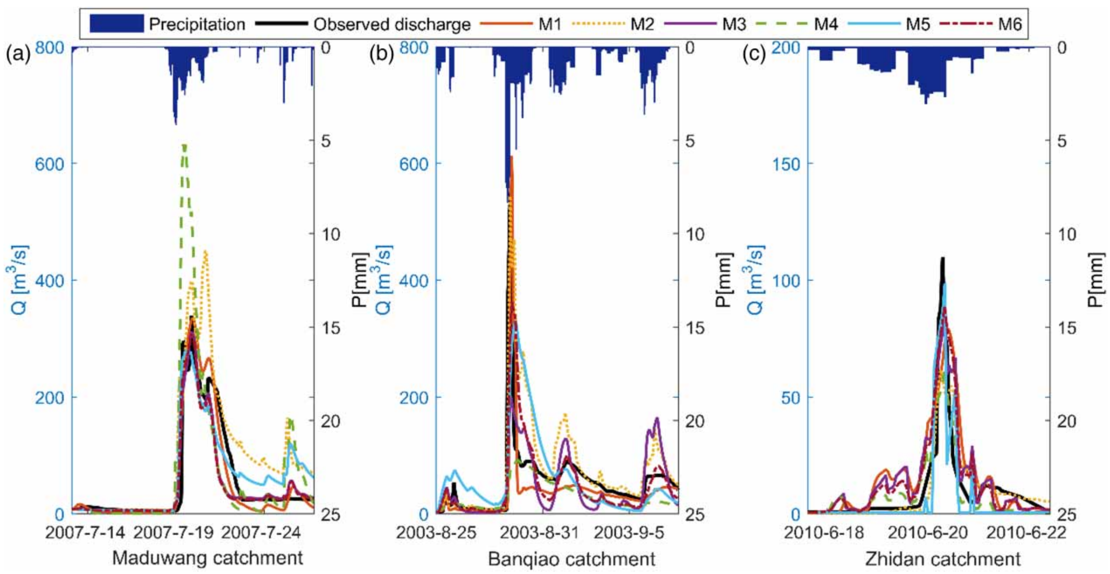

Figure 2 | Simulated hydrograph for three study catchments using different models.

validation. Table 3 presents the model simulation results for both calibration and validation period. Meanwhile, the result of Nash-Sutcliffe efficiency and qualification rate of peak flow were shown in Figure 3.

Result shows that the Xin'anjiang model combined with Infiltration-Excess runoff has the best performance, followed by Xin'anjiang model. The first Infiltration-Excess then Saturation-Excess runoff model shows poorer behavior in the qualification rate of runoff depth compared with the Sacramento model and Xin'anjiang model, but it obtains the best performance in the qualification rate of peak flow. Sacramento model and Infiltration-Excess runoff model are comparable in terms of obtaining reasonable qualification rate of peak flow, while Sacramento model performs better in reduction of the error of runoff depth. TOPMODEL was not able to perform well for all performance criteria in this catchment. It can be seen clearly from Figure 3 that the performance of validation period is generally higher than the calibration period both for NS efficiency and the simulation of peak value. It is because the flood events of the calibration period are more complex than the validation period, some of the steep floods could not be reproduced reasonable by the models that leads to a decreasing of model performance. For the validation period, the dynamic behaviors of the floods are similar to some flood events that used for calibration.

The reason for poor performance of TOPMODEL was investigated. TOPMODEL model is a semi-distributed model that based topography. The interflow is calculated as the negative exponential function of the mean depth of groundwater, and the surface flow is only generated until the groundwater level rises to the surface. In semi-humid region, such as Maduwang catchment, the groundwater level is too deep to reach the surface. The generated surface

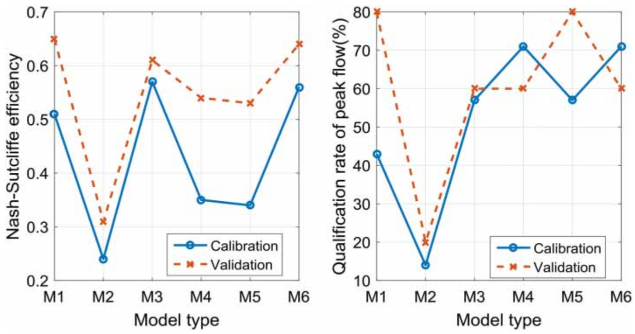

Figure 3 | Model performance for Maduwang catchment.

flow and interflow is small that leads to the underestimation of peak flow. The model performance of Xin'anjiang combined with Infiltration-Excess runoff model is prior to the traditional Xin'anjiang indicating that infiltration-excess runoff element plays an important role in the runoff simulation for Maduwang catchment.

Result of Banqiao

Table 4 shows the model performance of Banqiao catchments for both calibration (eight flood events) and validation (five flood events) period. The results show that the qualification rate of runoff depth is very low for all the models. As mentioned earlier, that peak flow is the main focus of flood prediction and only the qualification rate of

Table 4 | Comparison of model performance for Banqiao catchment

Model type		M1	M2	M3	M4	M5	M6
Qualification rate of peak flow (%)	Calibration	38	38	50	38	50	50
	Validation	20	20	20	20	40	40
Qualification rate flood peak appearance time (%)	Calibration	63	75	50	50	50	50
	Validation	20	40	60	60	80	80

Table 3 | Comparison of model performance for Maduwang catchment

Model type		M1	M2	M3	M4	M5	M6
Qualification rate of runoff (%)	Calibration	71	14	71	29	29	71
	Validation	60	60	80	60	60	80
Qualification rate flood peak appearance time (%)	Calibration	43	14	57	71	57	71
	Validation	80	20	60	60	80	60
Nash-Sutcliffe efficiency	Calibration	0.65	0.31	0.61	0.54	0.53	0.64
	Validation	0.51	0.24	0.57	0.35	0.34	0.56

peak flow and occurring time have been taken as objective function for model calibration. It can be found that for all six models, only 4–6 flood events could achieve qualified peak flow simulation. In general, the model performance for Banqiao catchment is rather poor. The drainage area of Banqiao catchment is small and the mountain torrents runs very fast to the outlet with a short leading time. Thus, the qualification rate of peak flow appearance time is also a critical indicator. Figure 4 shows the simulated discharge series of flood event 030824 for Banqiao using TOPMODEL. It can be seen from the curve that in spite of the big error in discharge volume, TOPMODEL is able to obtain perfect prediction of peak flow in terms of magnitude as well as the appearance time.

Result of Zhidan

For a total of 15 selected flood events, 11 floods were used for model calibration and the remains used for validation. The simulation result (Table 5) demonstrates that Infiltration-Excess runoff model and the Xin'anjiang model combined with Infiltration-Excess runoff model have the best performance in the simulation of peak value, while the latter shows more skill in the simulation of runoff depth. It indicates that even in an extremely dry region, only considering the surface runoff mechanism in runoff simulation may not be appropriate. For Infiltration-Excess runoff model, the reason for less effective performance than the Xin'anjiang model combined with Infiltration-Excess runoff model is also investigated. The runoff is separated into surface runoff and underground water in Infiltration-Excess runoff model. The surface runoff is generated once the rainfall intensity is greater than the infiltration capacity of soil, and the groundwater is generated when the infiltration amount exceeds the deficit of soil water. Due to the mountain terrain, the surface runoff generation and concentration process could be performed in a short time. However, the model assumes that for some places, the infiltration exceeds the deficit of soil water. This causes the instability of model performance, while some simulated floods match well with the observations, some of them lead to serious overestimating or underestimating of peak flow.

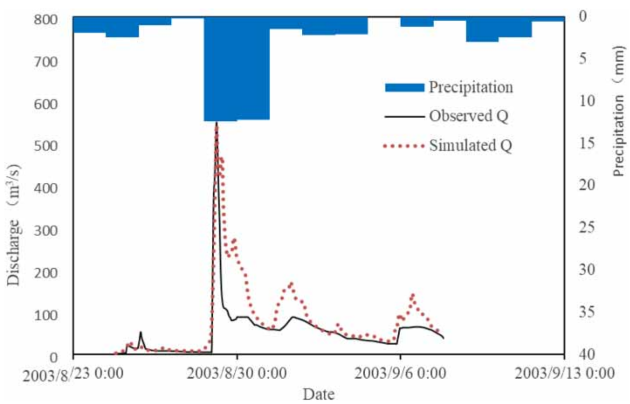

Figure 4 | Hydrograph for the flood event 030824 of Banqiao catchment using TOPMODEL.

Table 5 | Comparison of model performance for Zhidan catchment

Model type		M1	M2	M3	M4	M5	M6
Qualification rate of peak flow (%)	Calibration	27	9	27	27	27	36
	Validation	25	25	25	50	25	25
Qualification rate flood peak appearance time (%)	Calibration	64	64	91	82	64	80
	Validation	25	25	25	50	50	50

Results for different catchments

From the comparison of simulation results for different catchments we can conclude that for the selected models, Maduwang shows the best model performance, followed by Banqiao, and the model simulation for Zhidan could not obtain reasonable performance for most of the flood events. In general, the model performance for these three catchments is not satisfied and could not fulfil the standard requirements of flood forecasting. The poor model performance for the study area might be due to the particular runoff characteristics. Under the long-term drought condition, the runoff generation is dominated by infiltration-excess runoff at the beginning of the rainfalls. If the soil is porous and well developed, the saturation-excess runoff is likely to occur subsequently. However, if the soil is not well developed and packed together, perhaps only infiltration-excess runoff occurs during rainfall. Moreover, the sub-daily rainfall data is normally measured every 6 h for the study area, and the hourly inputs for modeling is based on the mean value of the observed sub-daily rainfall. This results in the reduction of rainfall peak intensity. High temporal resolution of rainfall is required for infiltration-excess runoff model to accurately reproduce the discharge series. The low temporal resolution of rainfall record to some extent causes the low accuracy of model simulation results.

Impacts of topographic features for model performance

Both landscape factors and climate conditions contribute to runoff mechanisms for a specific catchment (Buda *et al.* 2010). In this work, the influence of climate conditions and underlying characteristics to the model performance are investigated. The three catchments are geographically close to each other as they are located in the same province. The climate conditions are relatively different as mentioned in the catchment description but with the same feature of clearly dry and wet seasons. The rainfall-runoff correlation for the catchments is plotted in Figure 5. Here, p denotes areal precipitation, pa denotes antecedent precipitation and R is the observed runoff depth. According to the assumption of saturation-runoff mechanism, all the precipitation produces runoff after the soil is saturated, so the correlation curve close to the diagonal direction indicates the runoff generation is dominated by saturation-runoff mechanism. It can be detected from the figure that for Banqiao catchment, while the rainfall amount of this area is similar to that of Maduwang, the proportion of saturation-runoff is obviously lower than Maduwang. It indicates that variation in precipitation is not the only reason for the great differences in model performance.

It is well known that the spatial and temporal dynamics of runoff generation area highly depends on the landscapes. Topographic index, which is highly related to the runoff concentration area and slope, is usually used for measuring the topographic conditions:

$$T_s = ln\frac{\alpha}{\tan\beta} \tag{8}$$

where T_s is the topographic index, α is runoff concentration area and β is the slope. Figure 6 shows the distribution of topographic index and the corresponding catchment area.

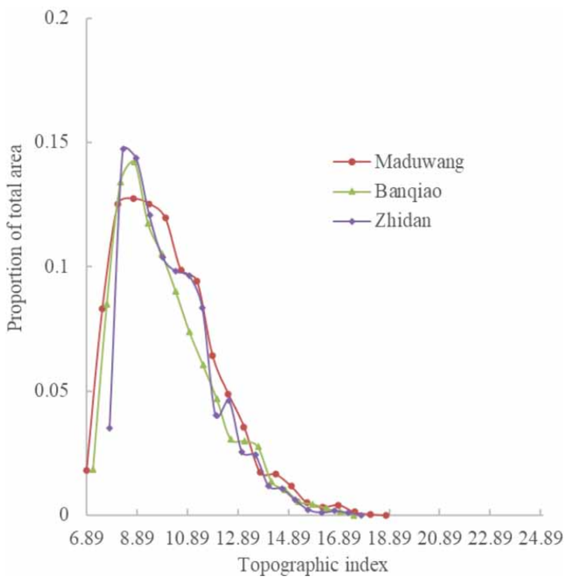

Figure 6 | Relationship between topographic index and the corresponding ratio of catchment area.

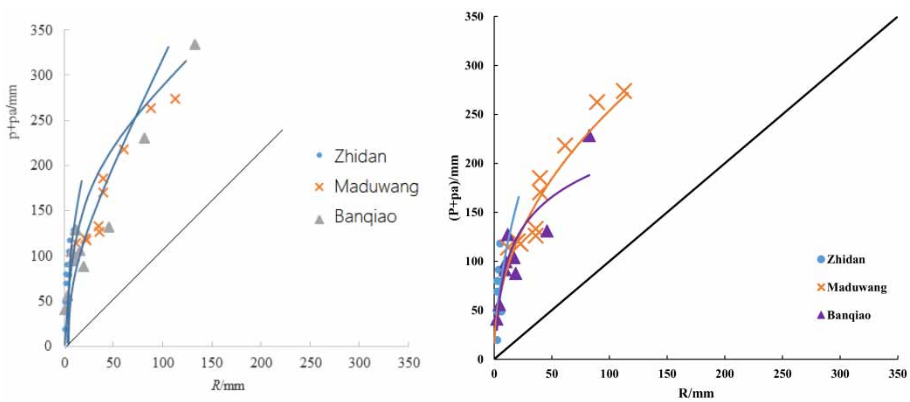

Figure 5 | Rainfall-runoff correlation for the study catchments.

The distribution curve for Maduwang catchment deflects to the right side and over half of the area has the topographic index between 8.8 and 10.8, indicating this catchment has higher proportion of high topographic index area than the other two catchments. Maduwang has the greatest topographic index, followed by Zhidan, while Banqiao has the smallest topographic index. The distribution of soil content that reflected by topographic index could represent the wetness condition of catchment. However, topographic index seems not significantly different between the catchments. Therefore, the types and distribution of vegetation is analyzed to further investigate the impact of surface underlying to runoff generation. As shown in Table 2, Maduwang has various types of well-developed vegetation. The proportion of forest for Banqiao is much less than Maduwang. In Zhidan, most of the area is covered by shrubs and grass. The reason for poorer model performance of Banqiao than Maduwang might be due to the joint influence of topographic index and land cover. The saturation-excess runoff is more likely to occur in Maduwang which has relatively high soil moisture and well-developed vegetation. This is also the reason for the slowness of the flood process and relatively long duration in this catchment.

The average slope and channel gradient are estimated based on digital elevation model (DEM) data. Table 6 shows the average slope and Figure 7 shows the distribution curve for slope. The mean slope of Maduwang is much larger than the other two catchments, while the slope of Banqiao is about 1^0 higher than Zhidan. When the runoff accumulation areas are same, the larger the slope is, the smaller the topographic index is. The sorting of slope for the three catchments is consistent with the result for topographic index, indicating that the effective runoff generation area plays an important role in reflecting the topographic index of the river catchment. Compared to Banqiao, Maduwang has a greater value in the mean of slope degree for the whole catchment, but has a smaller value if it only focuses on the slope degree for the river channel. It is found that Maduwang has rather complex terrain; the high slope degree is distributed in the upstream region that belongs to the hilly and mountainous area. Banqiao has a small catchment size with huge slope in the river channel, which implies the catchment is lack of capacity for water storage. The infiltration-excess runoff is more likely to occur in this catchment at the beginning of rainfall.

Table 6 | Comparison of slope degree for three catchments

Catchment	Mean slope for whole catchment (°)	Mean slope for river channel (°)
Maduwang	17.01	8.17
Banqiao	14.85	8.87
Zhidan	15.72	4.53

CONCLUSION

In this study, the influence of precipitation and topographic conditions on the model simulation results were tested on

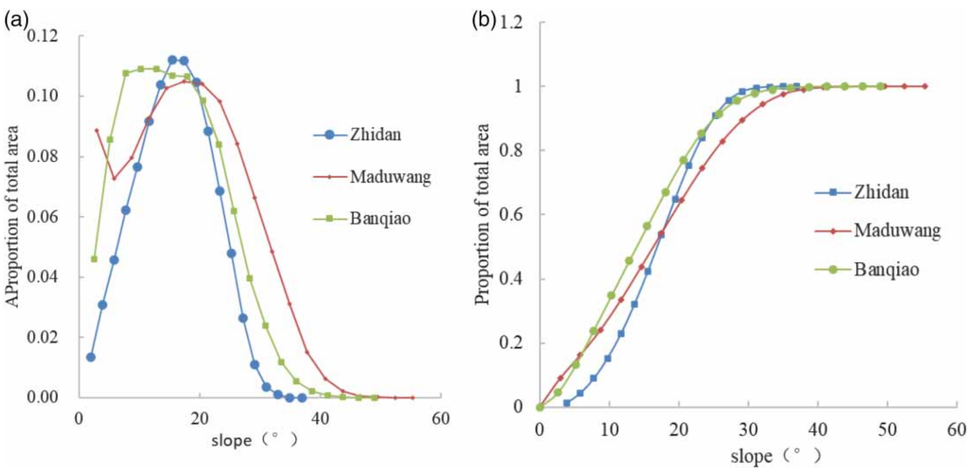

Figure 7 | Distribution of slope (a) and the cumulative distribution curve of slope (b) for the three catchments.

three catchments using six different models. The results show that for the region where the runoff generation mechanism was dominated by the infiltration-excess runoff, the model that incorporated infiltration-excess runoff mechanism could obviously lead to better model performance than if only the saturation-excess runoff had been considered. In the semi-humid region, most of the traditional model could not perform reasonably because of the low capability in simulating the infiltration-excess runoff process. The model with flexible structure, such as the first Infiltration-Excess then Saturation-Excess runoff model and the combination of Xin'anjiang with Infiltration-Excess runoff model, shows some advantages in the model simulation for the place that both runoff generation mechanisms exist.

Results indicate the topographic characteristics and climate conditions of a catchment strongly affect the rainfall-runoff process. Floods are relatively similar and easier to be simulated in the region with well-developed vegetation and simple terrains. The influence of slope for a river channel is higher than that mean slope for the whole catchment. It has been detected from this work that for a particular catchment, the higher the topographic index is, the greater the possibility of saturation-excess runoff generation is.

It can be found for the study catchments that model simulation results are impacted by several factors. Not only the structure of the model, but also the accuracy of the observations and the underlying conditions could affect the model performance. Therefore, for flood simulation in semi-humid or semi-arid regions, sufficient analysis has to be taken before determining whether the model is applicable. Moreover, when the existing models could not adapt to the complex runoff generation process, adjusting the model structure by adding some corresponding modules to accommodate all possibilities could be a good choice for flood simulation in mixed runoff generation regions.

DATA AVAILABILITY

The precipitation and discharge data used to support the findings of this study were supplied by Shaanxi Hydrology Bureau under license and so cannot be made freely available. Requests for access to these data should be made to Long Sun (sunlongmwr@163.com).

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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