Meteorological and Environmental Research 2025, 16(2): 41 – 44

Calculation of the Rainfall at the Flood-inducing Interface in Small and Medium-sized Basins by Three Hydrological Models

Zhiyuan YIN[1], Fang YANG[2*], Haixia QI[1], Yiheng XIANG[1]

1. China Meteorological Administration Basin Heavy Rainfall Key Laboratory/Hubei Key Laboratory for Heavy Rain Monitoring and Warning Research, Institute of Heavy Rain, China Meteorological Administration, Wuhan 430205, China; 2. Hubei Province Meteorological Information and Support Centre, Wuhan 430074, China

Abstract It is an important standard to judge the flood disaster in the basin whether the rainfall at the flood-inducing interface is reached. In this paper, the Xin'anjiang model, Topmodel model and SCS model were selected to calculate and compare the rainfall at the flood-inducing interface in the Zhanghe Reservoir basin in Hubei Province. The results showed that average relative error and average absolute error of Xin'anjiang model were −3.36% and -21.46×10^5 m^3, which were the minimum, followed by Topmodel model with 5.72% and 26.22×10^5 m^3, SCS model with 11.33% and 58.13×10^5 m^3. The minimum absolute error of the three hydrological models in calculating the rainfall at the critical interface was 3.26 mm, while the maximum was 49.24 mm. When the initial water level exceeded 120 m, the difference among the three models in calculating the rainfall at the critical interface became more and more obvious. When the reservoir water level was lower than 120 m, it mainly referred to the calculation results of Xin'anjiang model. When the reservoir water level was higher than 120 m, it mainly referred to the calculation results of Topmodel model. The research conclusion can provide reference for small and medium-sized basins selecting hydrological model to calculate the rainfall at the flood-inducing interface.

Key words Rainfall at the flood-inducing interface; Hydrological model; Small and medium-sized basins; Zhanghe Reservoir

DOI 10.19547/j.issn2152 – 3940.2025.02.009

Flood has always been one of the most serious natural disasters threatening human survival and development. With the continuous development of human society and economy, the economic losses caused by continuous flood disasters in the world are increasing day by day. Due to the impact of global climate change, the frequency of flood disasters continues to increase, and the loss of flood disasters continues to rise[1]. For example, affected by the El Nino phenomenon in 2016, the north of China continued to be sunny and warm, while the South suffered from rainstorm. The flood disaster affected 625 counties (cities, districts) in 10 provinces (cities) of the Yangtze River basin, including Hubei, Anhui, Hunan, Jiangxi, Chongqing, Sichuan, Guizhou, Jiangsu, Yunnan, Shaanxi, and so on, causing more than 49 million people affected, 222 people dead or missing, 110 000 houses collapsed, and direct economic losses of more than 100 billion yuan. At present, many hydrometeorological scholars have conducted extensive research on basin flood forecasting[2]. The rainfall at the flood-inducing interface is an important indicator to judge whether there is a flood disaster in the basin. Ye Jinyin *et al.*[3] used the ensemble forecasting method based on information matrix to forecast the areal rainfall of the basin, and the results showed that the ensemble forecasting had significantly improved the prediction of the magnitude below 24-hour heavy rain. Pan Yaying *et al.*[4] used HBV hydrological model to analyze the rainfall at the flood-inducing interface in the Fuchunjiang Reservoir Basin, and the calculation results can be used as the theoretical basis for scientific regulation of reservoir water level. Li Ming[5] established the meteorological statistical prediction equation for flood, which can accurately predict the possible flood level of small and medium-sized rivers. At present, most of the researches on the rainfall at the flood-inducing interface are based on a hydrological model, and there are few studies on the comparison of the calculation results by different models. Xin'anjiang model is one of the most widely used hydrological models in China. The model is relatively mature and has high prediction accuracy for floods in humid and semi humid areas in southern China. Topmodel is a hydrological model introduced from abroad and widely used in China. The model can effectively use the topographic information of the basin, and has fewer operation parameters and high portability. SCS model is developed by the Soil and Water Conservation Bureau of the United States Department of Agriculture. The most important feature of SCS model is that it can be used for flood forecasting in areas without data. Based on the consideration of the characteristics of different hydrological models, three hydrological models, Xin'anjiang model,

Received: February 9, 2025 Accepted: March 14, 2025

Supported by Open Project Fund of China Meteorological Administration Basin Heavy Rainfall Key Laboratory (2023BHR-Y26); Innovation Project Fund of Wuhan Metropolitan Area Meteorological Joint Science and Technology (WHCSQY202305); Innovation and Development Special Project of China Meteorological Administration (CXFZ2022J019); Project of Huanggang Meteorological Bureau's Scientific Research (2022Y02).

* Corresponding author.

Topmodel model and SCS model, were selected to simulate and calculate the rainfall at the flood-inducing interface in the same basin, and the differences in the calculation of rainfall at the critical interface by different models were analyzed and compared.

1 Research object and data

The research object is the Zhanghe Reservoir located in the middle of Hubei Province, which is 18 km away from the urban area of Jingmen City in the east. The reservoir controls a drainage area of 2 212 km^2, accounting for 74.5% of the Zhanghe River basin. The flood limit water level of the reservoir is 122 m, and the total storage capacity is 2.035 billion m^3. The Zhanghe Reservoir is located in a subtropical monsoon climate zone, with an average annual precipitation of 1 074 mm for many years, concentrated in April – September, accounting for about 80% of the annual precipitation. The research data include: ① hourly rainfall data in the basin from 2008 to 2011; ② data of four hourly inflow processes of the Zhanghe Reservoir from 2008 to 2011; ③ water level – capacity curve of the Zhanghe Reservoir.

Fig. 1 Schematic diagram of the Zhanghe Reservoir basin

2 Research methods

2.1 Xin'anjiang model The Xin'anjiang model was proposed by Professor Zhao Renjun, Department of Hydrology, Hohai University, in 1973 when forecasting the inflow of the Xin'anjiang Reservoir. It is a distributed conceptual rainfall runoff model for the basin. It has been widely used in humid and semi-humid areas in China for many years, and developed into the Xin'anjiang model with three water sources in the mid-1980s[6].

The saturation excess runoff model of the basin is adopted, and the water storage capacity curve is mostly B-order parabola. The ordinate A corresponding to the basin water storage W is:

$$A = W'_{mm}\left[1 - \left(1 - \frac{W}{W_m}\right)^{\frac{1}{1+B}}\right] \qquad (1)$$

where W'_{mm} is the maximum point storage capacity in the basin; W_m is average water storage capacity of the basin, which is composed of the water storage capacity of each soil layer in the basin, represents the drought situation of the basin and is a climatic factor; B represents the heterogeneity of water storage capacity in the basin, which is determined by geological and topographic conditions.

2.2 Topmodel model Topmodel is a semi distributed hydrological model based on topography, which was proposed by Beven and Kirky in 1979[7-8]. This model uses the topographic index $\ln(\alpha/\tan\beta)$ to reflect the hydrological phenomenon of the basin, and simulates the concept of variable contributing area generated by runoff. The core equation of Topmodel is shown as the following:

$$D_i = \overline{D} + m\left[\lambda - \ln\left(\frac{\alpha}{\tan\beta}\right)\right] \qquad (2)$$

where D_i is soil moisture deficiency at grid point in the basin; $\overline{D}$ is average moisture deficiency in the basin; m is effective depth of soil profile; α is catchment area per unit contour; $\tan\beta$ is local slope angle; $\ln\left(\frac{\alpha}{\tan\beta}\right)$ is topographic index; $\lambda = \frac{1}{n}\sum_i A_i \ln\left(\frac{\alpha}{\tan\beta}\right)$ is mean for spatial distribution of topographic index in the basin.

2.3 SCS model The SCS model is based on a basic assumption, that is, the ratio of the actual infiltration to the actual runoff in the catchment area is equal to the ratio of the maximum possible infiltration to the maximum possible runoff before the rainfall, which is expressed as[9]:

$$\frac{F}{Q} = \frac{S}{Q_m} \qquad (3)$$

where F is actual infiltration; Q is actual runoff; S is the maximum possible infiltration; Q_m is the maximum possible runoff. After a series of derivation, the following formula for calculating the runoff can be obtained:

$$Q = \begin{cases} \dfrac{(P - 0.2S)^2}{P + 0.8S} & P > 0.2S \\ 0 & P \leqslant 0.2S \end{cases} \qquad (4)$$

$$S = \frac{25\ 400}{CN} - 254 \qquad (5)$$

where P is precipitation; CN is an empirical parameter that comprehensively reflects the characteristics of underlying surface in the basin before rainfall, and its value can be determined by referring to the CN look-up table[10].

2.4 Confluence calculation The instantaneous unit hydrograph of variable rainfall intensity is adopted for the calculation of surface runoff concentration[11], and the basic equation is:

$$Q_S(j) = \sum_{k=1}^{j} ncR_s^{2-1/n}(j - k + 1)V^{n-1}(1 - V^n)\Delta t \qquad (6)$$

where $Q_S(j)$ is surface outflow process; n and c are confluence parameters; R_S is net rain intensity; t is time; V is the function of $F(V, n) = \int_0^t \frac{1}{1 - V_n}$, called variable stream function.

2.5 Calculation of rainfall at critical interface The calculation of rainfall at critical interface is divided into three steps:

(1) The reservoir inflow can be obtained by integrating the time according to the warehousing flow.

$$V = \int_{t_1}^{t_2} Q_t dt \quad (7)$$

where V is reservoir inflow; Q_t is flow; t_1 is initial time of flow warehousing; t_2 is end time of flow warehousing; t is time.

(2) The storage capacity V_1 at the time t_1 can be calculated from the water level Z_1 at the time t_1 and the water level-storage capacity relationship curve, and then the storage capacity V_2 at the time t_2 can be calculated according to the following formula.

$$V_2 = V_1 + V \quad (8)$$

(3) According to the water level – storage capacity relationship curve and the storage capacity V_2 at the time t_2, the water level Z_2 at the time t_2 can be determined. When Z_2 is the flood limit water level of reservoir, the cumulative rainfall corresponding to the flow process is the rainfall at critical interface.

Since there is always difference between the inflow simulated by hydrological model and the measured value, in order to quantify this difference, it is necessary to first determine the average relative error between the measured inflow and the inflow calculated by hydrological model, and then retrieve the inflow calculated by hydrological model to reach the flood limit level according to the average relative error, so as to determine the rainfall at critical interface under different model simulations. The inversion formula is as follows:

$$V_{calculated} = V_{measured} \times (1 + \overline{R}) \quad (9)$$

where $V_{calculated}$ represents the inflow calculated by hydrological model to reach the flood limit water level; $V_{measured}$ represents the measured inflow when the flood limit water level is reached; $\overline{R}$ represents the average relative error of inflow calculated by hydrological model.

Since the flood limit water level of the Zhanghe Reservoir is 122 m[12], this paper takes 122 m as the critical flood level for relevant calculation.

3 Simulation calculation

As shown in Table 1, the average relative error and average absolute error of Xin'anjiang model were −3.36% and −21.46 $\times 10^5$ m^3, which were the minimum, followed by Topmodel with 5.72% and 26.22 $\times 10^5$ m^3, SCS with 11.33% and 58.13 $\times 10^5$ m^3. Among the four processes of Xin'anjiang simulation, the error of one process was larger, while the errors of three processes were smaller; Topmodel showed that the errors of four times were too large; SCS had a small error in the first time and a large error in the other processes. The simulation results by the three models had some differences, but in general, the prediction errors of two models were larger, and the prediction error of one model was smaller. It can be seen from Fig. 2 and Fig. 3 that the simulation errors of Xin'anjiang in the four processes were lower than those of the other two models. Although the simulation errors of SCS model in three processes were close to Topmodel, the simulation error in 20100724 suddenly increased, resulting in the increase of average error. It also showed that the stability of simulation calculation by this model was not as good as Xin'anjiang model and Topmodel.

Table 1 Calculation error of reservoir inflow

Process	24-h cumulative rainfall//mm	Topmodel		Xin'anjiang		SCS	
		A//10^5 m^3	R//%	A//10^5 m^3	R//%	A//10^5 m^3	R//%
20080508	47.79	2.88	0.47	−45.50	−7.43	−23.31	−3.81
20090628	53.64	14.03	6.19	4.24	1.87	13.53	5.97
20100724	82.91	46.56	7.89	−33.36	−5.65	173.83	29.43
20110806	64.53	41.41	8.32	−11.21	−2.25	68.46	13.73
Mean	62.22	26.22	5.72	−21.46	−3.36	58.13	11.33

Note: A is absolute error; R is relative error.

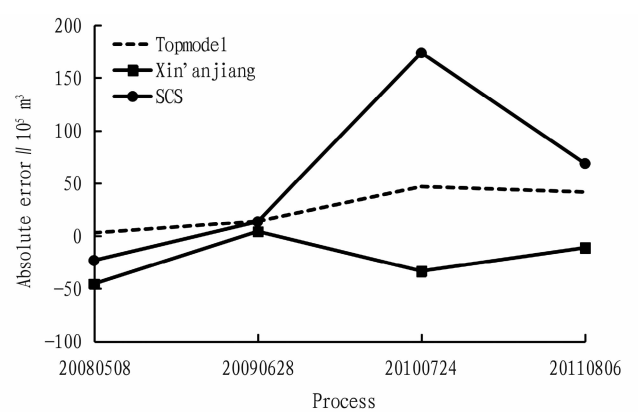

Fig. 2 Average absolute error simulated by three hydrological models

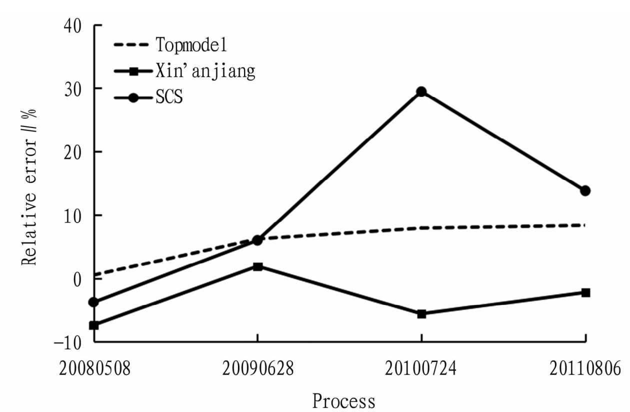

Fig. 3 Average relative error simulated by three hydrological models

After the average relative error of each model was determined, the rainfall at critical interface calculated by each model can be determined according to the equations (8) and (9), as shown in Table 2. The absolute error range of rainfall at the critical interface by Topmodel model was 3.26 – 24.86 mm, that of Xin'anjiang model was 1.92 – 14.6 mm, and that of SCS model was 6.47 – 49.24 mm. It can be seen that the lower the initial water level is, the greater the absolute error is. The maximum error can reach about 50 mm, which is equivalent to the accumulated rainfall in a rainstorm process. From Fig. 4, it can be seen more intuitively that when the initial water level exceeded 120 m, the difference between the three models in calculating the rainfall at the critical interface became more and more obvious. Further analysis found that the calculation results of Xin'anjiang model were lower than the measured values, so when the reservoir water level was lower than 120 m, the simulation results of Xin'anjiang model could be properly considered. When the reservoir water level was higher than 120 m, for safety reasons, the calculation values of Topmodel model with larger calculation results could be focused on.

Table 2 Calculation results of rainfall at critical interface mm

Water level//m	Measured	Topmodel	Xin'anjiang	SCS
122	0	0	0	0
121	57.08	60.34	55.16	63.54
120	111.32	117.69	107.58	123.94
119	164.44	173.85	158.92	183.08
118	215.30	227.62	208.07	239.70
117	264.47	279.59	255.58	294.43
116	311.37	329.18	300.91	346.65
115	355.45	375.78	343.50	395.72
114	396.13	418.79	382.82	441.02
113	434.56	459.42	419.96	483.80

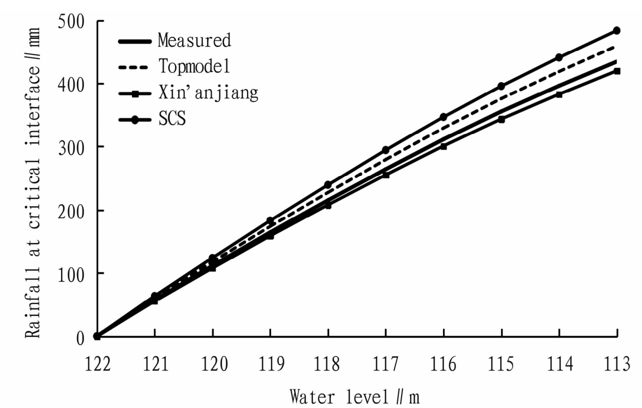

Fig. 4 Rainfall at critical interface calculated by three hydrological models

4 Conclusions

(1) The average absolute error and average relative error of three hydrological models in simulating inflow were compared and analyzed. The average relative error and average absolute error of Xin'anjiang model were −3.36% and -21.46×10^5 m^3, which were the minimum, followed by Topmodel with 5.72% and 26.22×10^5 m^3, SCS with 11.33% and 58.13×10^5 m^3. Moreover, The computational stability of Xin'anjiang model and Topmodel model was better than SCS model.

(2) The minimum absolute error of the three hydrological models in calculating the rainfall at critical interface was 3.26 mm, and the maximum was 49.24 mm. When the initial water level exceeded 120 m, the difference among the three models in calculating the rainfall at critical interface became more and more obvious. When the reservoir water level was lower than 120 m, it mainly referred to the calculation results of Xin'anjiang model. When the reservoir water level was higher than 120 m, it mainly referred to the calculation results of Topmodel model.

(3) Due to the small number of historical cases collected, the conclusions of this paper need to be further verified.

References

[1] National Comprehensive Research Group on Major Natural Disasters of the State Science and Technology Commission. Major natural disasters in China and countermeasures for disaster reduction (general)[M]. Beijing: Science Press, 1994.

[2] QIN W, LIN KP, HUANG Y, *et al.* A prediction scheme with genetic-neural network for area rainfall over power basin[J]. Journal of Catastrophology, 2015, 30(3): 33 – 37.

[3] YE JY, LIU J, LUO J, *et al.* Application of information matrix method to consensus forecast of areal rainfall[J]. Journal of Natural Disasters, 2014, 23(4): 127 – 133.

[4] PAN YY, MA DL, ZHANG Q, *et al.* Application of HBV model in determination of critical catastrophic surface rainfall in Fuchunjiang Reservoir basin[J]. Bulletin of Soil and Water Conservation, 2018, 38(6): 151 – 155.

[5] LI M. Statistical methods of meteorological forecasting for small- and medium-sized rivers flood and their applications in south part of Shaanxi Province[J]. Journal of Catastrophology, 2016, 31(3): 54 – 59, 65.

[6] ZHAO RJ. Hydrological simulation in watershed[M]. Beijing: Water Conservancy and Electric Power Press, 1984.

[7] BEVEN KJ, KIRKBY MJ. A physically based variable contributing area model of basin hydrology[J]. Hydrology Sci Bull, 1979, 24: 43 – 69.

[8] BEVEN KJ, KIRKBY MJ, SCHOFFIELD N, *et al.* Testing a physically-based flood forecasting model (TOPMODEL) for three UK catchments [J]. Journal of Hydrology, 1984, 69: 119 – 143.

[9] CAI WY, LIU XP, ZHANG JQ. The study of mountain flood disaster simulation based on distributed SCS model[J]. Journal of Catastrophology, 2016, 31(2): 15 – 18.

[10] VICTOR M. Estimation of direct runoff from storm rainfall[R]. National Engineering Handbook: Section 4 Hydrology, 1972.

[11] LI YJ, SONG XY, GE HF, *et al.* Research and application of flood forecast to Longwangshan Reservoir in Huai'an City[J]. Journal of China Three Gorges University: Natural Sciences, 2005, 27(3): 209 – 212.

[12] ZHAO JH, CHEN CD. Operation manual for the Zhanghe Reservoir [M]. Hubei Zhanghe Engineering Management Bureau, 2001.