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Early warning index of flash flood disaster: a case study of Shuyuan watershed in Qufu City

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ABSTRACT

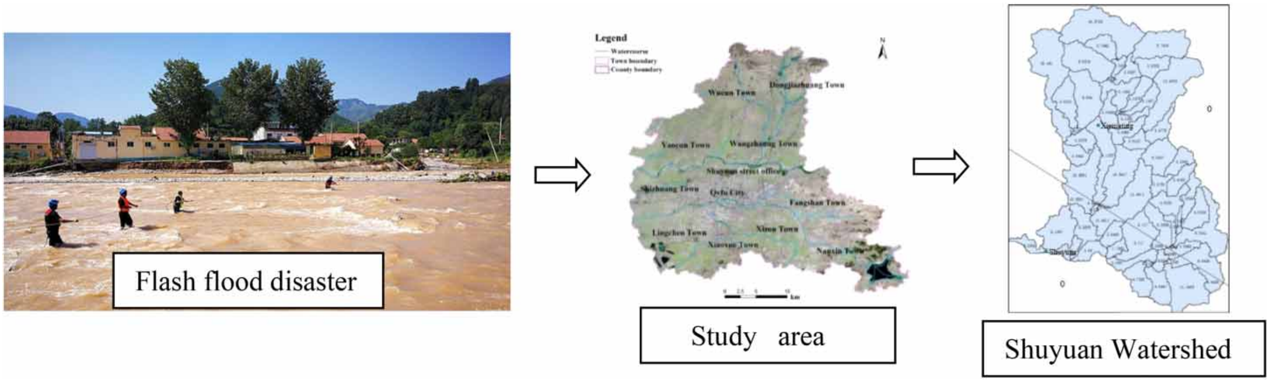
Flash flood disaster is one of the important natural disasters, bringing harm to human life and causing serious economic losses, so it is urgent to improve the accuracy of flash flood warning. To determine the critical rainfall and early warning indicators of disaster prevention objects, the Shuyuan Watershed of Qufu City Shandong Province was selected as the research object, the key disaster prevention objects were screened and finally, Hengmiao Village and Gaolou Village were selected as typical disaster prevention objects. Empirical analysis method, Storm analysis method, and model analysis method were used to calculate the critical rainfall at different times under different soil water content conditions, compare and analyze the rationality and existing problems of these three methods, and comprehensively determine the indicators of typical disaster prevention objects under different circumstances. The results show that the value of the index calculated by the storm analysis method is small and calculated by the model analysis method is large. This paper can improve the accuracy of flash flood warning, select the critical rainfall calculation method according to local conditions, accurately calculate the parameter values, and deal with the problem of effective early warning in the region as a whole.

Key words: early warning indicators, empirical analysis method, flash flood disaster, model analysis method, Shuyuan watershed, storm analysis method

HIGHLIGHT

- In this paper, the accuracy of flash flood warning can be improved, the critical rainfall calculation method can be selected according to local conditions, the parameter value can be calculated accurately, the regional overall effective early warning problem can be dealt with, and the early warning index of disaster prevention object can be comprehensively determined by different methods.

GRAPHICAL ABSTRACT



1. INTRODUCTION

China's geological and hydrological conditions are relatively complex. Due to the relative lack of hydrological and meteorological data and underlying surface factors in small watersheds, the research on flash flood disasters is relatively slow, and the early warning technology for flash flood disasters is relatively weak. Since the implementation of the ''National Flash Flood Disaster Prevention and Control Plan'', many scholars and experts have begun to explore and analyze the causes of disasters in various places (Zhao *et al.* 2016). Li & Guo (2013) and Ren (2015) have combed various calculation methods of early warning indicators and elaborated on the deep principles of the methods. Based on practical experience, Liu *et al.* (2014) used statistics and hydrological-related calculation methods to analyze the critical rainfall value, which is of great promotion value to establish a defense mechanism for flash flood disasters in data-poor areas. Based on the existing data collected by the hydrological department, Chen & Yuan (2005) used the statistical induction method to calculate the rainfall warning index and proved the feasibility of the method through the analysis of typical regional examples. Taking Yunnan Province as an example, Zhang *et al.* (2007) used spatial variation theory and different interpolation analysis methods to verify the versatility and operability of the Kriging spatial interpolation analysis method and also responded well in reflecting the change of law. Yang *et al.* (2020) study found that the traditional water level and flow back method has low early warning accuracy. It can organically combine the set cumulative rainfall threshold with the flood rise rate to improve the early warning accuracy of flash flood disasters.

In terms of the application of the model for monitoring and forecasting, Liu *et al.* (2010) proposed the application of the distributed hydrological model in the early warning and prevention of flash flood disasters, which has important guiding significance for hydrological monitoring in flood-prone areas. Ye *et al.* (2014) proposed a new method of dynamic early warning-Xinanjiang model, which laid a solid foundation for calculating dynamic critical rainfall. On this basis, the accuracy of the results was further improved by using the hyperbolic tangent model and the confluence model of the unit line watershed to simulate the measured rainstorm and flood and then determined the critical rainfall at different flow levels. In some provinces and cities, provincial water resources departments have studied and explored the HEC-HMS hydrological model, which has opened up a new way to calculate early warning indicators. Based on this model, Zhang *et al.* (2019) calculated the threshold of rainfall early warning index comprehensively considering different early conditions and verified its rationality with frequency interval and deviation degree as indicators, which provided the effective theoretical reference for mountain flood control in small watersheds lacking data. Sun *et al.* (2020) adjusted the hydrological model based on the actual rainstorm data and positioned the areas with weak flood control by establishing the flood surface line and building an elevation determination model along the line to better provide a convenient basis for application in real life. Various influencing factors were analyzed, and an index estimation model was established. The prediction range was proved to be reasonable and reliable after verification (Yuan *et al.* 2020).

In terms of the analysis of flash flood early warning indicators, a series of management projects related to flood monitoring and early warnings, such as hydrological and flash flood forecasting, were carried out in many countries under the support of the World Meteorological Organization with the 1990s. The FFG (Flash Flood Guidance) system was developed by the Hydrological Research Center of the United States (Villarini *et al.* 2010). The reverse calculation of runoff processes mainly calculates rainfall in different periods. This model has relatively high data and platform support requirements, but it can well realize dynamic early warning and has broad application prospects. With the support of this system, experts and scholars used ArcGIS to estimate the runoff threshold and verify its accuracy (Carpenter *et al.* 1999). In addition, under different previous conditions, such as rainfall threshold and soil moisture, the model's reliability under different scale and data scenarios was improved by analyzing the accuracy of the results when conditions changed (Norbiato *et al.* 2008). In view of the theoretical interpretation of the model, some scholars elucidated the characteristics of short-term surface runoff prediction and mountain flood forecast evaluation under heavy rainfall conditions, which provided significant theoretical guidance for the real-time calculation of mountain floods (Georgakakos 2005; Seo *et al.* 2013). Italian research centers are also constantly developing new flood forecasting systems, improving the original model, and adjusting the calculation module to make the distributed watershed hydrological model more complete, and the simulation results more satisfactory (Liu 2004; Liu *et al.* 2005). It is difficult to determine the hydrological coefficient when a flash flood accident comes. The HEC-HMS distributed model provides a reference for selecting the flash flood warning index (Hu 2019).

However, looking at the current situation of flood prevention and the application of early warning indicators, there are still serious technical problems, and the choice of critical rainfall calculation methods cannot be adapted to local conditions, so this paper focuses on how to calculate early warning indicators, and by using different methods, the early warning indicators for typical disaster prevention objects are determined comprehensively after comparison and analysis. Based on the standard of 'technical requirements for analysis and evaluation of flash flood disasters', this paper calculates the early warning indicators of typical disaster prevention objects in the Shuyuan basin. Generally speaking, the early warning indicators include water level and rainfall. However, according to field investigation and analysis, it does not have the conditions for water level early warning, so all the early warning indicators sought in this paper are rainfall early warning indicators. This chapter intends to use different methods to calculate the critical rainfall of each period under different soil water conditions, analyze each method's rationality and existing problems, and comprehensively determine the early warning indicators of typical disaster prevention objects under different conditions.

2. METHODOLOGY

2.1. Empirical analysis method

The empirical analysis method involves using the empirical method of local rainfall–runoff to calculate the early warning index. The three techniques that are most frequently utilized are statistical induction, comparison, and interpolation. The empirical analysis method merely determines the early warning index in accordance with the principle of the similarity of geographical environment and the correlation of occurrences, not by using an obvious physical derivation.

(1) Statistical inductive method

The statistical inductive method mainly analyzes the critical rainfall value according to the specific rainfall situation during the historical flash flood disaster, the local rainstorm and topographic and geological conditions, and the previous rainfall. The statistical inductive method is mainly selected under the condition of collecting relatively rich measured rainfall data. It needs to comb and compile the extreme and mean rainfall values of each flash flood, each rainfall measuring station, and multiple periods and analyze the initial critical rainfall values of a single station and the whole region. In addition, the threshold value should be adjusted accordingly. The method of determining the early warning index is very feasible for the area with data, and a series of valuable results have been obtained in the flash flood control pilot work in Shandong Province.

(2) Comparison method

The benchmark of the comparison method is that when the watershed characteristics such as meteorological conditions, geological conditions, and hydrological conditions have high similarity with typical small watershed, the critical rainfall value of the watershed can be used to determine the early warning index of mountain flood disaster in the study area. The comparison method is suitable because there are no data in the target study area, but the situation is similar to that of the typical study area. However, no two study areas can be without deviation. As for the error adjustment, it should be decided according to the actual situation of the study area.

(3) Interpolation method

The calculation criterion is that the distribution of rainfall shows a continuous distribution in time from the perspective of climate. Therefore, the determination of critical rainfall is related to meteorological and geological conditions, but under the condition that the early warning period has been determined, the hypothesis that the critical rainfall also shows a continuous distribution in the specified watershed can be tentatively proposed. The early warning index of the disaster prevention object whose critical rainfall value has not been determined in the analyzed small watershed can be obtained. GIS spatial interpolation method is generally used. The interpolation method assumes the uniformity of rainfall and the unity of underlying surface conditions, but there are some limitations.

2.2. Storm analysis method

The storm analysis method is widely used. The main advantages of this method are fewer data requirements, a simple calculation method, and a reasonable research basis for the process of production and confluence. Combined with the actual situation of the small watershed in Qufu City, Shandong Province, this section adopts the same frequency backpropagation method to deduce the early warning index, and the main calculation process is shown in Figure 1.

The basic principle of the Same frequency backpropagation method is that under the premise of assuming the same frequency of flood and rainfall, the specific early warning period of the disaster prevention object is determined by the

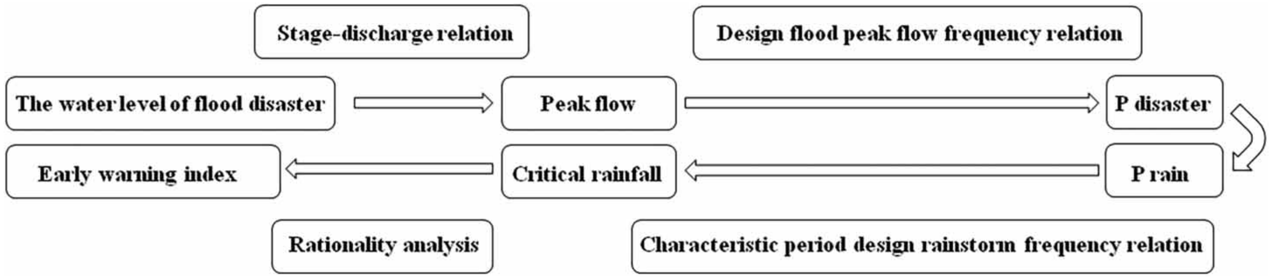


Figure 1 | Main derivation process of same frequency backpropagation method.

analysis of runoff generation and confluence, the design flood and rainstorm are calculated, the rainstorm-frequency curve and the design flood peak–frequency curve are established, and the corresponding frequency is obtained by field investigation and the critical flow of the control section calculated by Manning formula, to determine the critical rainfall in different periods.

(1) Design storms

For some areas with abundant measured rainfall data, it is recommended to adopt the P-III frequency fitness line method. After first calculating the empirical frequency P value, the deviation coefficient C_s value is first determined, and the rainfall curves under different frequency cases are plotted. By continuously adjusting the deviation coefficient C_v until the curve fitness rate reaches the maximum, generally above 98%, at which time the curve-related characteristic value is the desired one, from which the design storms volume can be further calculated.

For some areas where there is no actual measured flood data, the characteristic values are found using the Hydrological Atlas of Shandong Province as the standard, so as to analyze and calculate the design storms amount under different frequency conditions, but in the actual calculation, the 24 h design storms are generally converted into each short calendar design storms through the storms formula, and finally the point and surface conversion are carried out according to the relevant standards and the specific actual situation of typical disaster prevention objects.

(2) Storm time allocation

The design rain pattern for Qufu City can be determined by consulting the Hydrological Atlas of Shandong Province and verified by fitting with the actual basin rainfall data collected. Given that the confluence time of each sub-basin is lower than the 24 h storm calendar time in the storm atlas, the actual storm time allocation is generally calculated by the following methods.

The first is the time period deflation method, that is, when the confluence time is 4 h, the design rain type under investigation can be divided into four time periods, namely 1–6 h, 7–12 h, 13–18 h, and 19–24 h, and the results of the 4 h storm time allocation can be determined in accordance with the allocation ratio synthesis. The second method is to take the maximum value method. In other words, the time period with the maximum design rain pattern of 24 h is taken as the starting time, and the rainfall distribution values are selected on the left and right, respectively, and the ending time is taken as the time when the number of the last taken time periods agrees with the number of rainstorm ephemeral stages, and then the storm time allocation is completed by the integrated determined design rain pattern.

(3) Net rainfall process

The net rainfall calculation is also an essential step in the production and confluence process of a small catchment, which directly affects the accuracy of the design flooding results. The main methods used for net rainfall analysis are the rainfall-runoff correlation diagram method, the infiltration curve method, and the deductive loss method. The rainfall–runoff correlation method is based on the P_c–P_a–R correlation curve, which is based on rainfall P_c, runoff R, and the initial soil water content P_a, to directly find out the net rainfall value under different conditions; The infiltration curve method is based on subtracting the actual storm intensity from the losses in the infiltration process to obtain the net rainfall process, but in practice, the factors affecting infiltration are complex, so the accuracy of this method has yet to be verified; There are four simple deductive loss methods. The initial loss method can be used when losses occur only in the initial stages of rainfall, or the actual loss process of the infiltration curve method can be streamlined into two different stages of initial loss and subsequent loss, i.e. the initial loss and subsequent loss method, and the average distribution of lost rainfall over the entire rainfall process is known as the average loss rate method, but in the case of sudden flooding in a full storage basin, the amount of losses formed during the entire rainfall process is stable infiltration, i.e. the stable infiltration rate method. Different methods are based on different principles, and this paper determines the use of rainfall–runoff correlation diagram method based on the actual situation of the study area.

(4) Design floods

There are various methods for calculating design floods, for Shandong Province, the four main ones commonly used are inferred formula, instantaneous unit line, integrated unit line, and empirical formula method, but because the principle of inferred formula method is simple and easy to understand, the calculation involves relatively few parameters and does not require high accuracy of rainfall data, it is used as an important means to calculate design floods in this paper, and combined with the Code of Practice for Calculating Design Floods of Water Conservancy and Hydropower Engineering (SL44-2006), etc., based on the net rainfall during the rainfall ephemeris, the flood flow is calculated by assuming the confluence time, and the confluence time is calculated according to the flood flow, through several trial calculations until the two confluence times are infinitely close to each other, at which time the input value is the requested value.

2.3. Model analysis method

The model analysis method has a relatively wide range of applications, a sound physical mechanism, and can achieve dynamic early warning. Several sub-watershed models were constructed, and the rainfall in different periods was deduced based on the flooding process and disaster discharge. The HEC-HMS hydrological model is selected as a semi-distributed rainfall–runoff model. Considering the climate characteristics, rainfall distribution, and underlying surface conditions in the application process, the rainfall–runoff process model of the whole study area can be obtained by setting the runoff parameters of different sub-watersheds.

HEC-HMS hydrological model is mainly divided into two modules: input and calculation. The input module is divided into the watershed, meteorology, time series, and control operation. By sorting out different calculation methods, the runoff model of the study area is generalized, the hydrological and meteorological conditions in the study area are determined, the collected rainfall data are imported in order, and the time step and start and end time of the model simulation are set up, to complete the input module. The calculation module mainly includes runoff, runoff, base flow, and confluence, and each module calculation method is varied.

(1) Productive flow model

In this paper, the SCS curve method is chosen for the flow production analysis. Under the assumption of equal proportions, the water balance equation is used according to the relationship between the initial loss of rainfall and the maximum retention potential, and the net rainfall is mainly related to the soil cover and the pre-humidity, which can be estimated as a function related to it. When the accumulated rainfall is less than the initial loss of rainfall, both rainfall and runoff are considered to be zero at this time, and therefore the increase in water production after time t is equal to the amount of flow produced during this interval. The relationship between the maximum soil storage and the characteristics of a small watershed can be constructed by using the C_N value to determine the watershed yield.

(2) Confluence model

The HEC-HMS offers two types of optional conversion models. Empirical models are mainly used to establish runoff-net rainfall correlations without considering runoff details, and the parameters involved in the models are selected by fitting and continuous optimization methods and retrograde, typical of conceptual models using the motion wave method for Simulation. In this paper, the 10 typical flood scenes selected to produce multiple peaks during a single rainstorm also have a small proportion of the information available for calibration and parameter estimation as well as the basic assumptions of the various algorithms, so the SCS unit line method is used for confluence analysis.

(3) Base flow model

Base flow refers to the part of the runoff in the river channel due to the previous rainfall or the current rainfall delay, in the calculation process, it is necessary to consider in detail the impact of the maximum water storage and groundwater movement, the size of the base flow is related to the geographical conditions in the study area, comprehensively considering the specific conditions of the study area, the base flow calculation in this paper mainly uses the linear reservoir method, the basic principle is to simulate the groundwater movement and storage as the movement of water in the reservoir, in the calculation process, the time step is expressed as a function of the average water storage capacity, in general, The base flow is the sum of the outflows from all linear reservoirs in the study area.

(4) River confluence model

The river confluence model, also known as the evolutionary model, is based on the upstream calculation of the downstream hydrological process line and the evolution is achieved by solving the continuous and kinematic equations. Based on the absence of measured hydrological process data for calibration in the study area, the presence of significant backwater affecting the flow process line and the specific value of the channel slope, the kinematic wave method is chosen for the river confluence calculation in this paper, which is based on the finite difference approximation of the continuous and momentum equations, involving parameters that can be obtained from the previous field measurements and working base maps and can be directly invoked during the application of the model.

3. CASE STUDY OF QUFU CITY

3.1. Overview of the study area

Qufu City is located in the southwest of Shandong Province, with a total land area of 895.95 km^2, of which the hilly area is 275 km^2, the plain area is 620.95 km^2, and the average altitude of the area is about 60 m. Qufu City is a temperate monsoon continental climate. The average annual precipitation distribution is uneven, mostly concentrated in the flood season, that is, from June to September. The annual precipitation is 666.3 mm. A total of 14 rivers, including large and small rivers in Qufu City, mainly include the Dang River, Liao River, and Si River, especially the two main rivers of Si River and Yi River, which run through the city from east to west. The total length of the river is 245.9 km, the average annual runoff depth is 201.4 mm, the average annual runoff is 180.44 million m^3, the city has 270 large and small water storage dams, the total storage capacity is 155.16 million m^3, the actual available water resources is about 230.87 million m^3, the hydrographic chart is shown in Figure 2.

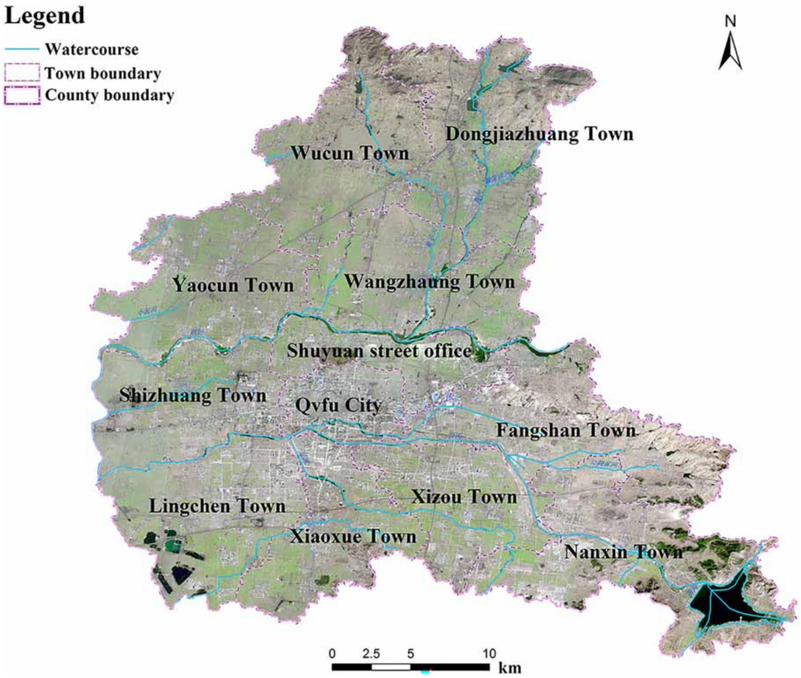


Figure 2 | Hydrographic chart of Qufu small watershed.

3.2. Storm analysis to determine early warning indicators

(1) Design rainstorm

There is a rain measuring station in the upper reaches of the academy basin – Xiemating Station. Therefore, the design rainstorm of Hengmiao Village and Gaolou Village uses the measured rainfall data to calculate the annual maximum 24-h rainfall at each frequency. According to the maximum 24-h rainfall measured by the Xiemating rainfall station for 40 consecutive years, the curve is obtained after multiple adjustments to the maximum fitting degree by the frequency fitting method. As shown in Figure 3, the average annual maximum 24-h rainfall in the Shuyuan basin is $H_{24} = 99.2$ mm, and the coefficient of variation is $C_v = 0.6$. The multi-year average maximum 24 h rainfall H_{24} is determined to be 100 mm, and the results of the frequency fitting method are reasonable. The calculation of 24 h design point rainfall under different frequency conditions is shown in Table 1.

The basin area above the control section of the typical disaster prevention object is checked, and the conversion is carried out according to the design rainstorm point-surface conversion coefficient table. The area of Hengmiao village is 17.26 km^2, and the conversion coefficient $\alpha_{24} = 0.98$, while the area of Gaolou village is 6.592 km^2, without point-surface conversion. $n_1 = 0.5$, $n_2 = 0.78$ in Qufu City, as shown in the Hydrological Atlas of Shandong Province. According to the short-duration rainstorm conversion formula, the design rainstorm results of 0.5, 1, 2, 3, 4, 6, 12, and 24 h can be calculated, as shown in Tables 2 and 3.

(2) Design rain pattern analysis

The rainfall pattern in the south of Taiyi Mountain provided in the hydrological guidance document of Shandong Province is adopted in the small watershed of the academy, as shown in Table 4 and Figure 4. However, the designed rainfall pattern is 24 h duration, which exceeds the confluence time of typical disaster prevention objects, so the maximum value method is used to allocate the designed rainfall pattern.

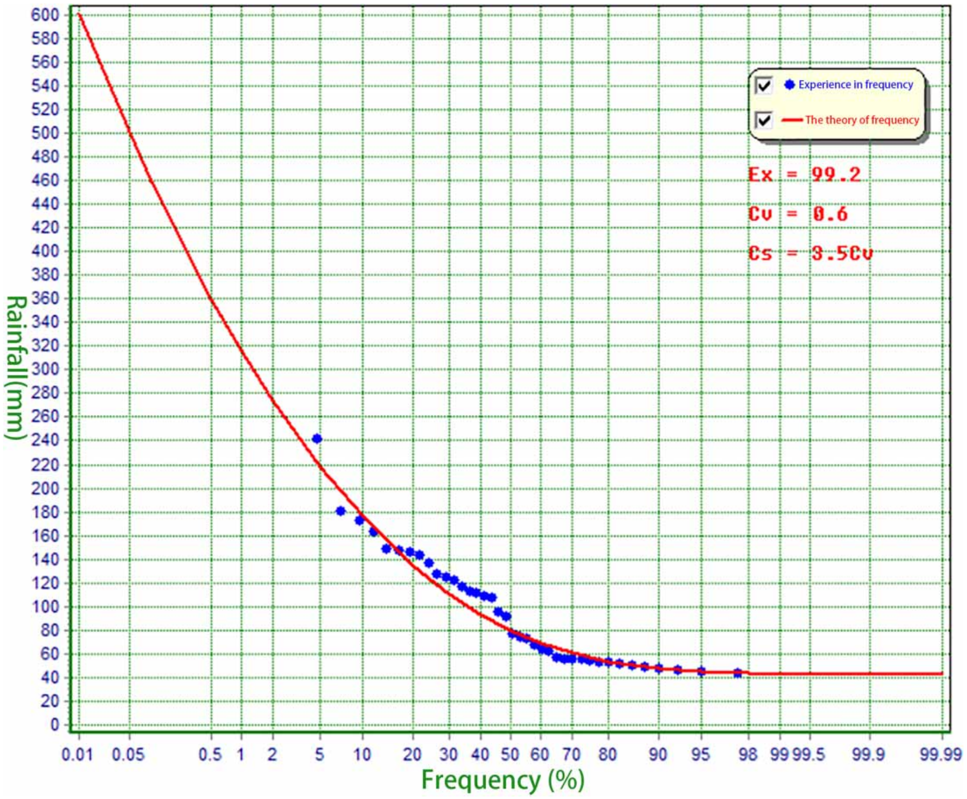


Figure 3 | Frequency line fitting results of small watershed in Shuyuan.

Table 1 | Table of 24 h rainstorm at design points under different frequencies

Frequency %	$P = 0.01\%$	$P = 0.1\%$	$P = 0.5\%$	$P = 1\%$	$P = 2\%$	$P = 5\%$
Point rainfall	601.1	458.3	359.1	317.4	273.8	218.2
Frequency %	$P = 10\%$	$P = 20\%$	$P = 50\%$	$P = 75\%$	$P = 95\%$	$P = 99\%$
Point rainfall	175.6	133.9	80.4	56.5	47.6	42.7

Unit: mm.

Table 2 | Hengmiao village control small watershed different frequency design surface rainfall results table

	Design period							
Frequency	$T = 0.5$ **h**	$T = 1$ **h**	$T = 2$ **h**	$T = 3$ **h**	$T = 4$ **h**	$T = 6$ **h**	$T = 12$ **h**	$T = 24$ **h**
Average	79.35	112.21	130.70	142.89	152.23	166.43	193.85	225.78
$P = 0.01\%$	207.04	292.80	341.03	372.85	397.21	434.27	505.81	589.13
$P = 0.10\%$	157.84	223.22	259.99	284.25	302.82	331.08	385.61	449.14
$P = 0.50\%$	123.68	174.90	203.72	222.72	237.28	259.41	302.15	351.92
$P = 1.00\%$	109.33	154.61	180.08	196.88	209.75	229.32	267.09	311.09
$P = 2.00\%$	94.29	133.35	155.32	169.81	180.91	197.79	230.37	268.32
$P = 5.00\%$	75.16	106.30	123.81	135.36	144.20	157.65	183.63	213.88
$P = 10.00\%$	60.47	85.52	99.61	108.90	116.02	126.84	147.74	172.07
$P = 20.00\%$	46.12	65.23	75.97	83.06	88.49	96.74	112.68	131.24
$P = 50.00\%$	27.67	39.14	45.58	49.84	53.09	58.05	67.61	78.74
$P = 75.00\%$	19.47	27.54	32.08	35.07	37.36	40.85	47.58	55.41
$P = 95.00\%$	16.40	23.19	27.01	29.53	31.46	34.40	40.06	46.66
$P = 99.99\%$	14.69	20.78	24.20	26.46	28.18	30.81	35.89	41.80

Table 3 | Gaolou village control small watershed different frequency design surface rainfall results table

	Design period							
Frequency	$T = 0.5$ **h**	$T = 1$ **h**	$T = 2$ **h**	$T = 3$ **h**	$T = 4$ **h**	$T = 6$ **h**	$T = 12$ **h**	$T = 24$ **h**
Average	80.97	114.50	133.37	145.81	155.34	169.83	197.81	230.39
$P = 0.01\%$	211.26	298.77	347.99	380.46	405.31	443.13	516.13	601.15
$P = 0.10\%$	161.06	227.78	265.30	290.05	309.00	337.83	393.48	458.30
$P = 0.50\%$	126.20	178.47	207.87	227.27	242.12	264.71	308.31	359.10
$P = 1.00\%$	111.56	157.77	183.76	200.90	214.03	234.00	272.54	317.44
$P = 2.00\%$	96.22	136.07	158.49	173.28	184.60	201.82	235.07	273.79
$P = 5.00\%$	76.70	108.46	126.33	138.12	147.14	160.87	187.37	218.24
$P = 10.00\%$	61.71	87.26	101.64	111.12	118.38	129.43	150.75	175.58
$P = 20.00\%$	47.06	66.56	77.52	84.76	90.29	98.72	114.98	133.92
$P = 50.00\%$	28.24	39.93	46.51	50.85	54.18	59.23	68.99	80.35
$P = 75.00\%$	19.87	28.10	32.73	35.79	38.12	41.68	48.55	56.54
$P = 95.00\%$	16.73	23.66	27.56	30.14	32.10	35.10	40.88	47.62
$P = 99.99\%$	14.99	21.20	24.69	27.00	28.76	31.44	36.62	42.66

Table 4 | Rainfall pattern of 24 h table of southern Taiyi Mountain

	Time allocation (calculation period is 1 h, time allocation is %)																							
Applicable rainfall (mm)	**1.0**	**2.0**	**3.0**	**4.0**	**5.0**	**6.0**	**7.0**	**8.0**	**9.0**	**10.0**	**11.0**	**12.0**	**13.0**	**14.0**	**15.0**	**16.0**	**17.0**	**18.0**	**19.0**	**20.0**	**21.0**	**22.0**	**23.0**	**24.0**
100	0.8	1.1	0.7	1.4	2.8	0.9	1.1	0.5	1.7	1.2	1.9	2.2	2.8	10.6	43.8	7.2	5.9	4.8	4.2	1.2	1.1	0.7	0.6	0.8
200	0.9	1.2	0.8	1.5	3.1	1.0	1.2	0.5	1.9	1.3	2.0	2.4	3.0	11.4	37.7	8.7	6.1	5.7	4.9	1.2	1.2	0.8	0.6	0.9
300	0.9	1.3	0.8	1.6	3.2	1.0	1.3	0.5	1.9	1.4	2.1	2.4	3.1	11.6	34.7	8.6	7.1	6.0	5.6	1.2	1.3	0.8	0.7	0.9
400	1.0	1.3	0.8	1.7	3.3	1.0	1.3	0.5	2.0	1.4	2.2	2.5	3.2	11.8	32.6	8.9	7.3	6.5	5.6	1.3	1.4	0.8	0.7	0.9
500	1.0	1.4	0.8	1.7	3.4	1.1	1.4	0.5	2.0	1.5	2.2	2.6	3.3	11.9	30.6	9.0	7.7	6.6	6.1	1.4	1.4	0.8	0.7	0.9
600	1.0	1.4	0.9	1.7	3.5	1.1	1.4	0.6	2.0	1.5	2.3	2.6	3.3	12.0	29.2	9.3	7.8	6.8	6.3	1.4	1.4	0.9	0.7	0.9

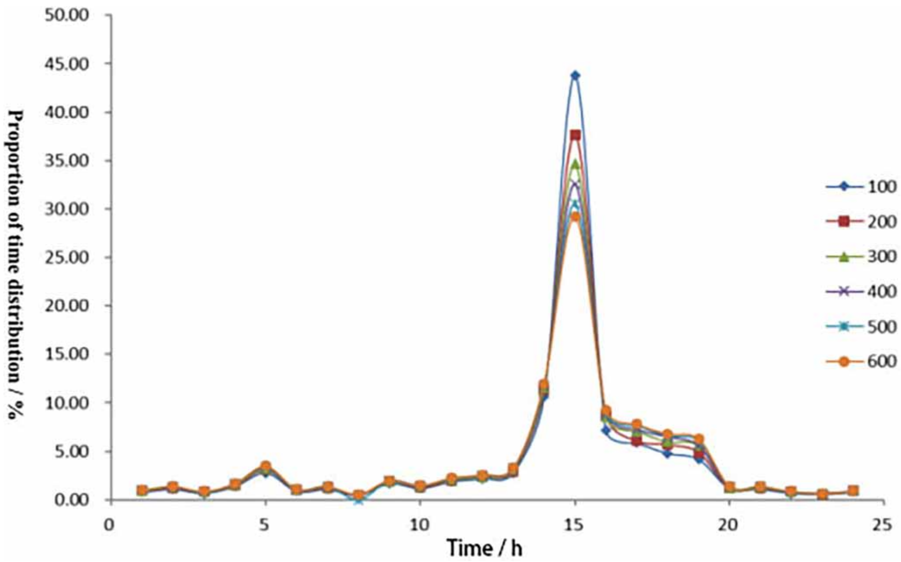


Figure 4 | Temporal distribution of 24 h rainstorm in southern Taiyi Mountain District.

(3) Designed net rain

The calculation of design net rain is particularly critical in the analysis of runoff generation and confluence and directly impacts the accuracy of design flood results. Because the rainfall–runoff correlation diagram method is more convenient and efficient in the analysis, this paper calculates the design net rain through the rainfall–runoff relationship line 4 (Table 5), and the maximum soil water storage in Qufu City is 65 mm. This paper considers a variety of working conditions and takes three typical critical values of $P_a = 13$ mm (0.2 Wm), 40 mm (general situation required by the hydrological atlas), and 52 mm (0.8 Wm) for early warning index analysis. The design net rainfall results of Hengmiao Village and Gaolou Village are shown in Tables 6 and 7.

Table 5 | Relationship between rainfall and runoff line 4

$P+P_a$	**50**	**60**	**70**	**80**	**90**	**100**	**110**	**120**	**130**	**140**	**150**	**160**	**170**
Net rain	4	8	13	18	24	33	40	48	57	65	74	83	92
$P+P_a$	**180**	**190**	**200**	**210**	**220**	**230**	**240**	**250**	**260**	**270**	**280**	**290**	**300**
Net rain	101	111	120	130	139	148	157	167	177	186	196	205	214
$P+P_a$	**310**	**320**	**330**	**340**	**350**	**360**	**370**	**380**	**390**	**400**	**500**	**600**	**700**
Net rain	224	233	243	252	262	271	281	290	299	308	404	500	596

Unit: mm.

Table 6 | Design net rainfall table of 5 h for small watershed controlled by Hengmiao village

	Soil water content (mm)		
Frequency	$P_a = 13$	$P_a = 40$	$P_a = 52$
$P = 0.01\%$	309.81	311.43	312.15
$P = 0.10\%$	244.42	269.25	281.05
$P = 0.50\%$	178.99	204.29	215.21
$P = 1.00\%$	150.97	177.27	188.30
$P = 2.00\%$	123.01	148.01	159.01
$P = 5.00\%$	87.01	112.31	123.46
$P = 10.00\%$	60.88	84.67	95.47
$P = 20.00\%$	37.16	59.35	69.45
$P = 50.00\%$	12.38	29.19	38.43
$P = 75.00\%$	4.90	17.62	25.12
$P = 95.00\%$	3.25	14.52	21.03
$P = 99.99\%$	2.89	12.80	18.96

Table 7 | Design net rainfall table of 3 h for small watershed controlled by Gaolou village

	Soil water content (mm)		
Frequency	$P_a = 13$	$P_a = 40$	$P_a = 52$
$P = 0.01\%$	310.32	311.94	312.67
$P = 0.10\%$	249.79	275.55	286.89
$P = 0.50\%$	183.57	208.87	220.30
$P = 1.00\%$	155.02	181.32	183.80
$P = 2.00\%$	126.89	151.50	162.89
$P = 5.00\%$	89.79	115.09	126.55
$P = 10.00\%$	62.87	86.91	97.71
$P = 20.00\%$	38.49	60.87	71.15
$P = 50.00\%$	12.95	30.21	39.23
$P = 75.00\%$	5.22	18.03	25.84
$P = 95.00\%$	3.85	14.86	21.48
$P = 99.99\%$	3.12	13.10	19.32

(4) Design flood

The inference formula method is used to calculate the design flood. The value of net rain is shown in Tables 6 and 7. In addition, the basin area, the longest confluence path length, and the gradient are obtained according to the data acquisition terminal of flash flood disaster investigation and evaluation. The design flood calculation results of each disaster prevention object are shown in Tables 8 and 9.

(5) Determination of early warning indicators

According to the calculation results, the rainfall–frequency curve and the design flood peak–frequency curve are established, as shown in Figures 5 and 6.

Table 8 | Results of peak flood discharge control of small watershed in Hengmiao village

	Soil water content (mm)		
Frequency	$P_a = 13$	$P_a = 40$	$P_a = 52$
$P = 0.01\%$	364.38	372.15	390.52
$P = 0.10\%$	265.63	302.21	319.99
$P = 0.50\%$	175.34	209.14	224.17
$P = 1.00\%$	139.73	173.09	187.60
$P = 2.00\%$	106.33	136.08	149.73
$P = 5.00\%$	67.02	94.19	106.85
$P = 10.00\%$	41.63	64.62	75.84
$P = 20.00\%$	21.55	40.24	49.61
$P = 50.00\%$	4.98	15.62	22.55
$P = 75.00\%$	1.44	7.97	12.79
$P = 95.00\%$	0.84	4.28	5.64
$P = 99.99\%$	0.72	2.12	3.15

Table 9 | Results of flood peak flow control in small watershed of Gaolou village

	Soil water content (mm)		
Frequency	$P_a = 13$	$P_a = 40$	$P_a = 52$
$P = 0.01\%$	267.19	272.05	288.82
$P = 0.10\%$	200.07	228.04	240.64
$P = 0.50\%$	132.68	157.61	169.21
$P = 1.00\%$	105.90	130.51	132.90
$P = 2.00\%$	81.09	102.71	113.13
$P = 5.00\%$	51.14	71.20	80.80
$P = 10.00\%$	31.79	48.96	57.23
$P = 20.00\%$	16.52	30.45	37.50
$P = 50.00\%$	3.87	11.97	16.95
$P = 75.00\%$	1.15	6.01	9.71
$P = 95.00\%$	0.77	4.65	7.59
$P = 99.99\%$	0.58	3.93	6.59

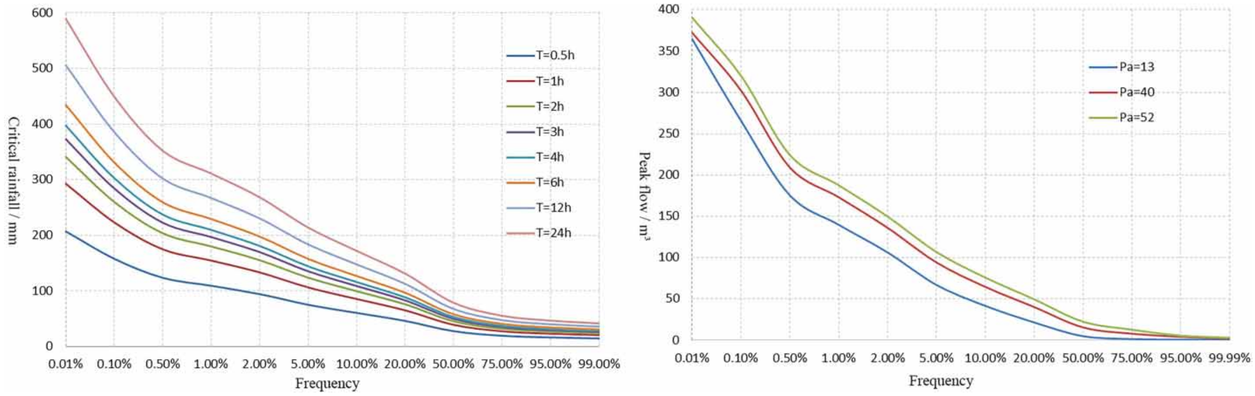


Figure 5 | Results of the rainstorm and flood design in Hengmiao village.

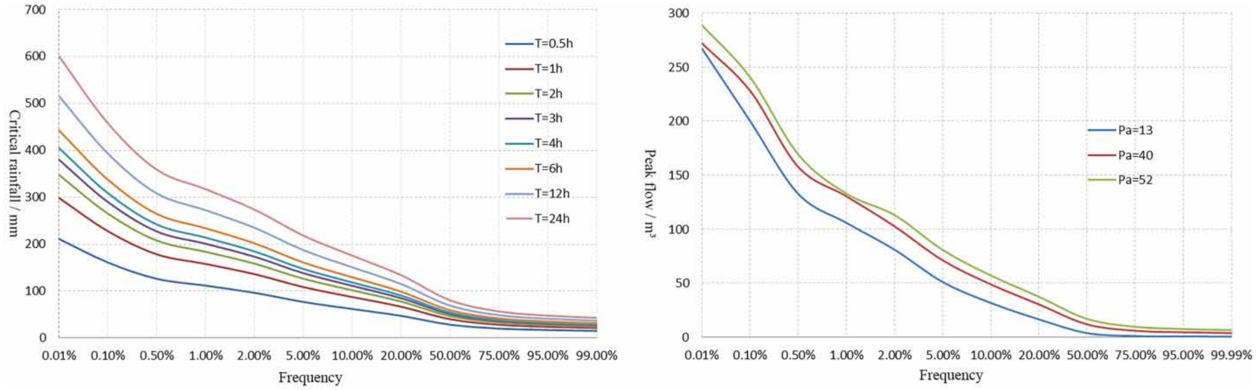


Figure 6 | Results of the rainstorm and flood design in Gaolou village.

According to the Manning formula and the critical flow obtained by the disaster-causing water level, the critical flow corresponding to the frequency *p* is found in the design flood curve. Assuming that the rainstorm flood has the same frequency, the design surface rainfall value can be found in the design rainstorm curve, which is the critical rainfall value in this period.

3.3. Model analysis to determine early warning indicators

(1) Establishment of the HEC-HMS model

The DEM of Shandong Province, with a resolution of 12.5 m, is selected as the working base map of the primary data. Firstly, the coordinate system is determined according to the latitude and longitude of the study area, and the boundary is divided by ArcGIS. The DEM data layer of the Shuyuan basin is obtained by cropping, as shown in Figure 7(a). The HEC-GeoHMS module is used to set the Shuyuan hydrological station as the basin outlet, and the water system of the Shuyuan basin is extracted. Then the basin parameters are processed, including specific factors such as river length and slope, and the basin model is generated, as shown in Figure 7(b).

(2) Establishment of the meteorological model

The meteorological module can add rainfall evaporation and other contents. There are two rainfall stations and Shuyuan hydrological stations in the Shuyuan basin. The collected data are all large rainfalls and floods within the excerpt length. According to the location of each sub-basin and rainfall station, the weight of the station is determined by the Thiessen polygon method. The specific station distribution and sub-basin area weight distribution are shown in Figure 8. In order to meet the needs of time series database calls, HEC-DSSVue software can be used to input the measured rainfall data into the meteorological module of the HEC-HMS model.

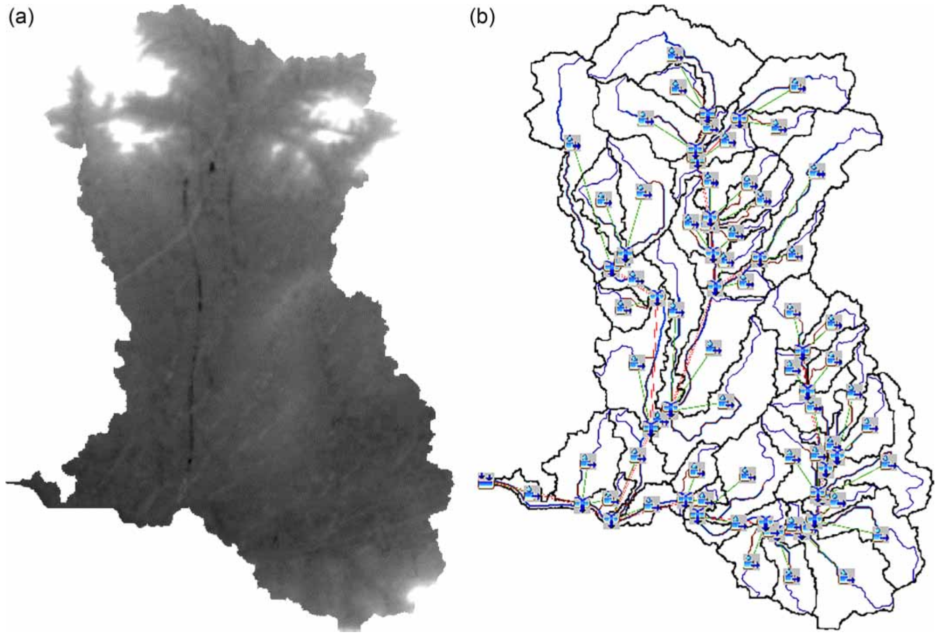


Figure 7 | ArcGIS processing map of Shuyuan watershed: (a) DEM preprocessing map, (b) Model structure diagram.

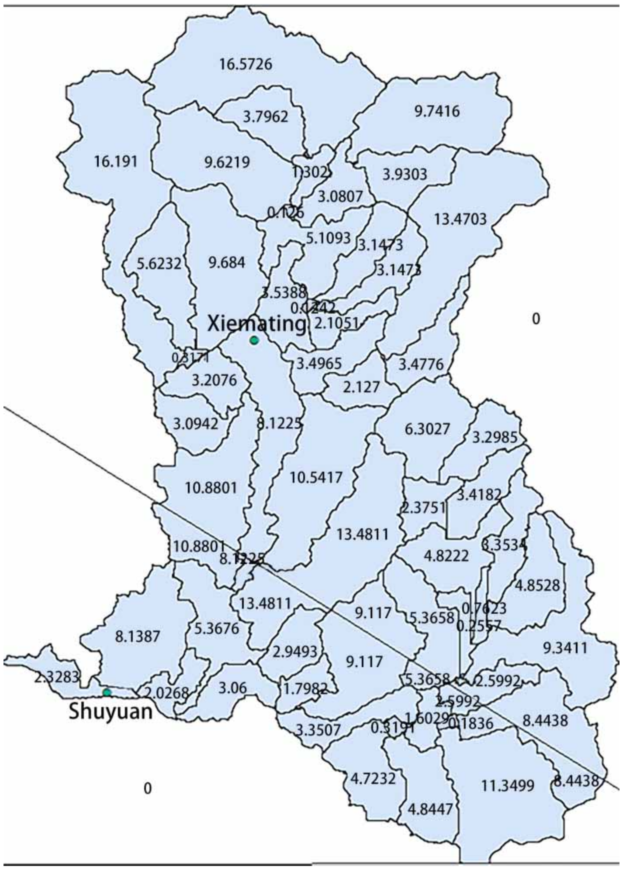


Figure 8 | Theissen polygon weight map of each rain measuring station in the Shuyuan Watershed.

For each sub-watershed inside the polygon, the areal rainfall is equal to the rainfall of the corresponding rainfall station, and for each sub-watershed across multiple polygons, it is necessary to calculate the areal rainfall with the polygon area as the weight.

(3) Parameter calibration

The objective function is generally selected in combination with the trial and error in model parameter calibration. The model rate timing optimization method mainly includes Nelder Mead and univariate gradient search. The optimization objective function method mainly includes seven kinds of weighted average and root mean square record error, which greatly improves the accuracy of the calibration.

This paper selects 10 rainstorm and flood data from 1955 to 2005. The parameter rate is mainly based on the actual measurement data, and the four floods of 1980.06.29, 1983.04.26, 1996.07.31, and 2005.09.19 are used for verification. The typical four flood simulation results are shown in Figure 9.

Based on the Hydrological Information Forecasting Specification (GB/T22482-2008), the applicability and accuracy of the model are evaluated by calculating the peak flow error and the contribution time difference. When the flow error is within 20%, it is considered that the forecast error is within the allowable range, and the forecast is qualified. In addition, the peak time difference is calibrated again. Generally speaking, when the peak time difference is greater than 0, the simulated flood peak appears earlier than the measured flood peak; otherwise, the occurrence time is late. When the peak time difference is 0,

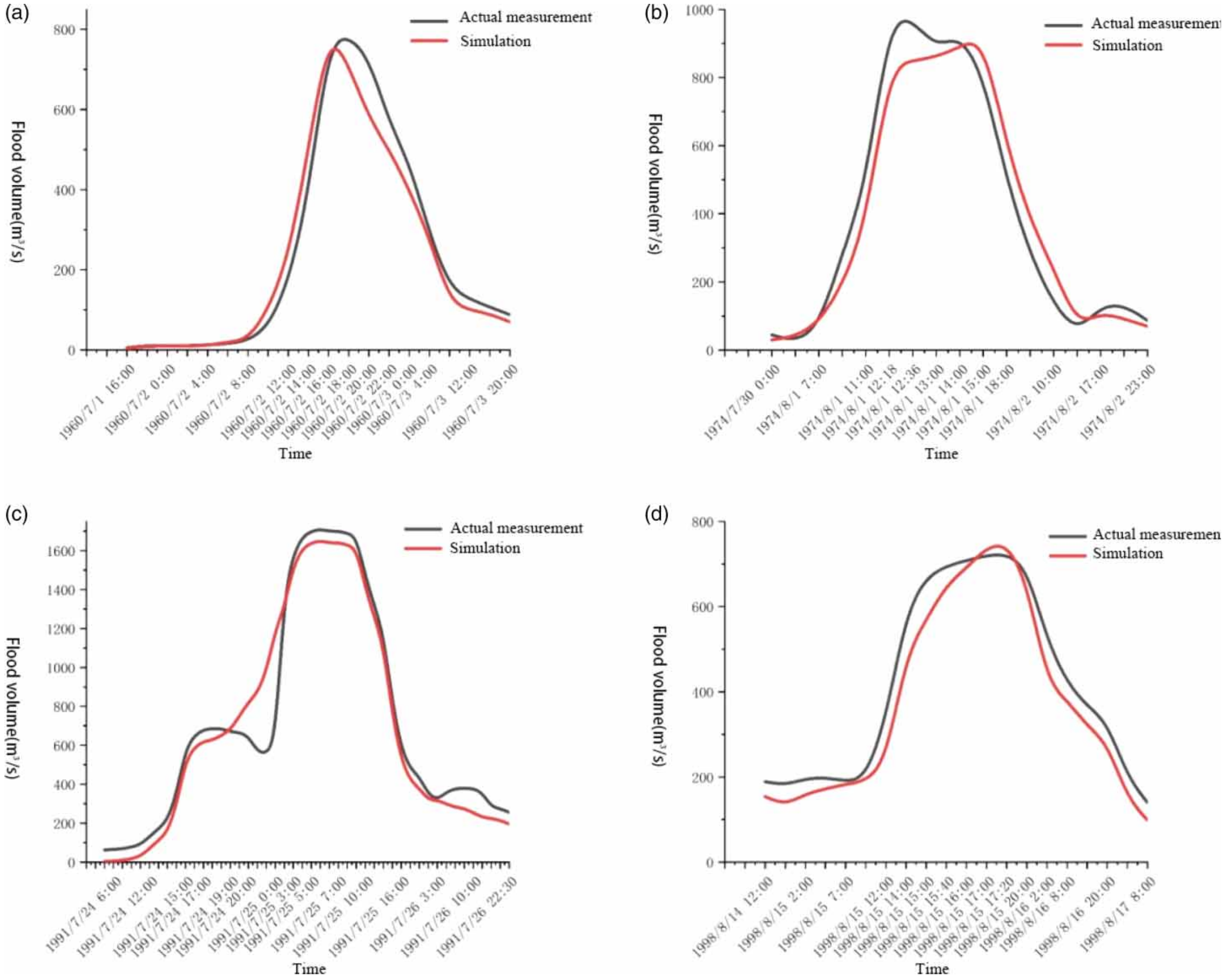


Figure 9 | Comparison of simulation results of typical field floods: (a) 19600702, (b) 19740801, (c) 19910725, (d) 19980815.

the simulated peak time is consistent, and the simulation effect is relatively good. The calculation table for the simulation of ten rainfall events is shown in Table 10.

From the above simulation diagram and error calculation table, it can be seen that the simulated flood fields after parameter calibration are relatively good, and only 19910725 simulations of the four floods during the verification period are relatively poor. This is due to the use of HEC-HMS software. The SCS unit line method selected during the simulation is based on the calculation of single flood peak conditions, so only relatively large flood peaks are simulated during this flood simulation.

(4) Determine the critical rainfall

Based on the model calibration results, the trial algorithm can be used to solve the critical rainfall value. Firstly, the initial rainfall of the typical disaster prevention object is assumed as the original input value of the flood process simulation. When the difference between the simulated flood peak flow and the critical flow is within the allowable range, the input rainfall value at this time is the critical rainfall of the typical disaster prevention object.

4. RESULTS

By comparing the critical rainfall results of typical disaster prevention objects calculated by different methods, it is found that the calculated value of the HEC-HMS hydrological model is larger than that of the same frequency inverse method. This is because this method is based on the calibrated model of the study basin. The calculation and analysis of the specific comparison results are shown in Table 11.

According to the calculation results of the two methods, the critical rainfall is comprehensively determined. Combined with the experience of Shandong Province, the critical rainfall value is used as an early warning index for immediate transfer, and the early warning index for preparation for transfer is reduced by 15% based on critical rainfall. If the confluence time is less than or equal to 1 h, it is not necessary to calculate the early warning index for preparation for transfer because the time is too short. The results of Hengmiao Village and Gaolou Village are shown in Table 12 and Table 13.

Table 10 | Calculation table of Shuyuan watershed simulation

Serial number	Rainfall events	Measured flood peak (m^3/s)	Simulation of flood peak (m^3/s)	Flood peak flow error (%)	Measured flood peak time	Simulating flood peak time	Peak time difference (h)
Calibration period	19600702	787	800	−1.7	18:00	18:00	0
	19620714	800	820	−2.5	6:00	6:15	−0.25
	19650710	731	700	4.2	3:00	3:00	0
	19700806	1,190	1,230	−3.4	17:00	17:40	−0.67
	19740801	976	920	5.7	12:18	15:00	−2.7
	19900816	812	820	0.1	15:30	15:00	0.5
Validation period	19910725	1,710	1,650	3.5	6:00	6:00	0
	19950816	1,100	1,160	−5.4	11:30	11:30	0
	19980815	724	750	−3.6	17:00	17:20	−0.33
	20010804	916	886	3.2	17:00	16:40	0.33

Table 11 | Comparison of critical rainfall calculation results of typical disaster prevention objects

		13 mm		40 mm		52 mm	
Disaster prevention object	early warning period	Storm Analysis method	Model analysis method	Storm Analysis method	Model analysis method	Storm Analysis method	Model analysis method
Hengmiao village	1	–	–	140	158	135	145
	3	–	–	184	192	174	178
	5	–	–	209	215	205	219
Gaolou village	0.5	63	69	45	53	43	47
	1	92	96	64	76	61	69
	3	110	126	82	94	78	86

Table 12 | Calculation results of early warning index of Hengmiao village

		Soil water content		
Early warning period (h)	**Level**	$P_a = 13$ mm	$P_a = 40$ mm	$P_a = 52$ mm
1	Preparing transfer indicators	–	127	119
	Immediate transfer indicator	–	149	140
3	Preparing transfer indicators	–	160	150
	Immediate transfer indicator	–	188	176
5	Preparing transfer indicators	–	180	169
	Immediate transfer indicator	–	212	199

Table 13 | Calculation results of high-rise early warning index

		Soil water content		
Early warning period (h)	**Level**	$P_a = 13$ mm	$P_a = 40$ mm	$P_a = 52$ mm
0.5	Preparing transfer indicators	56	42	39
	Immediate transfer indicator	66	49	45
1	Preparing transfer indicators	80	59	55
	Immediate transfer indicator	94	70	65
3	Preparing transfer indicators	100	75	69
	Immediate transfer indicator	118	88	82

By calculating the early warning index of Hengmiao village under the condition of soil moisture $P_a = 13$ mm, it is found that the flood control capacity is greater than that of a hundred years in the case of 13 mm, so no early warning is needed.

5. DISCUSSION

Compared with other methods, the same frequency backpropagation method is also relatively low in terms of data requirements, and the calculation process is relatively simple, without the need for a special computing platform, the following conditions are generally required: (1) The basic data of each disaster prevention object can be obtained from the working base map collected by the previous flash flood disaster investigation and evaluation, so as to determine the parameter values such as convergence time; (2) The topography and cross-section of the river channel of each disaster prevention target can be obtained by field survey and measurement, so as to determine the parameter values such as characteristic water level and flow rate. (3) Hydrometeorological data of heavy rainfall can be obtained by the hydrometeorological department, if the data are relatively poor, the rainstorm data in the 'Hydrological Atlas of Shandong Province' can be used to calculate the rainfall–runoff in the small river basin. Moreover, according to the technical requirements of flash flood disaster analysis and evaluation, a small watershed in Sanya City, Hainan Province was used as a case to demonstrate the methods and processes of analyzing the characteristics of heavy rainfall and flooding in small watersheds by Zhao & Liao (2020), evaluating the current flood prevention capacity of villages along rivers, delineating hazard areas of different levels and determining early warning indicators. Compare the early warning threshold, issue an early warning signal, and distinguish the specific application scheme of batch evacuees according to very-high-risk areas, high-risk areas, and risk areas. It has a reference role in the early warning of flash floods in other small river basins. The results and objectives of the conclusions of this paper are basically the same.

The HEC-HMS model is widely used, and the model can achieve the purpose of increasing the application range of the model and simulating the generalization process of rainfall–runoff under different conditions by combining different methods of production and sink calculation, in addition, in terms of parameter rate determination, it is more efficient and convenient because it contains relatively many objectives and optimization functions. In the application process of HEC-HMS hydrological model, it can be found that the more detailed the demand data, the better the simulation effect, but it should also be noted that: (1) Whether the basic information including the topography and geomorphology of the watershed meets the basic requirements for establishing the model, such as whether the river section and remote sensing data are accurate; (2) Whether the hydrometeorological data meet the basic requirements of parameter rate determination and rationality analysis of simulation results, such as whether the measured rainwater data are complete and consistent; (3) Whether the calculation method selected according to the actual situation meets the requirements of local flash flood characteristics, such as whether the SCS unit line method is reasonable to simulate bimodal flooding.

Based on the actual situation of the study area, this paper chooses the frequency backpropagation method which requires less information. Although the results are compared and analyzed with the HEC-HMS model analysis method to determine the research results, there are still certain limitations, so the selection of the calculation method of early warning indicators for areas with more basic information should be based on the local climate, topography, and other conditions, and the application of hydrological models should be continuously optimized so as to improve the accuracy of early warning indicators.

6. CONCLUSIONS

In this paper, by using three different methods, the early warning indicators of typical disaster prevention targets are comprehensively determined after comparative analysis. Because of the lack of a physical mechanism and the difficulty of ensuring the accuracy of the results, the empirical analysis method is not used to analyze the early warning indicators. However, it can be used to verify the rationality of other methods. The critical rainfall index is calculated using the storm analysis methods and model analysis methods. To take Hengmiao Village and Gaolou Village as typical disaster prevention objects, the principle and applicable conditions of different early warning index calculation methods are clarified. Combined with the specific data of the study area, the same frequency backstepping method is selected to calculate the design rainstorm, rainstorm time distribution, design net rainfall, and design flood, and compared with the critical flow calculated above, the critical rainfall is deduced. Comparative analysis shows that the calculated value of the storm analysis method is too small, and the calculated value of the model analysis method is too large. Based on this, the critical rainfall and early warning indicators of typical disaster prevention objects are comprehensively determined, which lays a foundation for the subsequent regularity research of early warning indicators.

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DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

The authors declare there is no conflict.

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