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# Flooding prediction for a rainy,dense-population river basin of central China

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**Abstract**: Watershed runoff forecasting has been a research focus on hydrological model and flooding prediction. In China, Xinanjiang (XAJ) model is a widely used for flood forecasting, which is of significance to areas with booming economy, dense population, and high flooding risks, such as those located in central China. The Fu River basin located in Jiangxi Province is a rainy area with abundant precipitation (average annual rainfall is 1 761 mm). A lumped hydrological model, three-source XAJ model based on excess storage runoff generation, was established to simulate 18 rainstorms and floods in Fu River basin from 1981 to 1995. Muskingen's piecewise continuous algorithm was used to calculate river flood routing and the flow process line. The processes of the flow and flood were determined by linear superposition of all the flow processes. Parameters were calibrated by daily data and frequency data. Results showed that the average deterministic coefficient of the model in the field flood simulation was 0. 911, the average error of runoff depth for model calibration was 4. 73%, and the average error of runoff depth for validation was 8. 21%. Therefore, the three-source XAJ model could be used as a useful forecasting model in the flood forecasting system of Fu River basin. The useful references were provided for flood forecasting research in the rainy central China.

**Key words**: watershed hydrological forecast; three-source XAJ model; excess storage runoff; parameters of the calibrated

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## 1　Introduction

Flood is a natural disaster of increasing concerns across the world. It has features of high frequency, wide distribution and severe losses[1]. Particularly in China, frequent floods and associated waterlogging problems are recorded every year[2]. It has caused significant property and life losses for

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this country, affecting survival and development of the country[3]. Roughly, it is subject to frequent threat of flooding that are roughly, over 2/3 of its total areas, 5% of its total population, 30% of its cultivated land, and 70% of its industrial and agricultural outputs[4]. In 2010, the annual economic losses caused by floods have accounted for approximately 3.5% of the total national economic output value[5]. In certain period, there may be basin-scale flooding leading to significant losses. For example, the direct economic losses were 77.94、179.65 billion、228.04 billion and 255.09 billion yuan in 1991、1994、1996 and 1998, respectively[6]. Averagely, China suffers major floods every two years. Thus, it is of great significance to explore the mechanism of flooding for the prevention of disasters and the arrangement of disaster relief measures. However, generation and evolution of flooding are complicated. Understanding the mechanism of flood occurrence can effectively reduce and forecast the flood, thus reducing the risk of flood occurrence. Particularly in many areas of central China, due to highly dense population and good developed economy, losses of flooding are significantly enormous[7]. The inherent mechanism of flood is explored and analyzed in such area. Therefore, an effective measure for managing flood resources is to understand the generation of flood mechanisms and to use a physical model to describe the process of flood.

The 5th edition of the river forecasting system, which was continuously updated by the US weather service, officially opened the prelude of the modern flood forecasting system[8]. The Swedish National Hydrological Bureau further simplified the forecasting operation and established the HBV hydrological forecasting system[9]. Aiming at the difficult problem of rainstorm and flood forecasting in small watersheds, some researchers used flash flood modul simulation system (FFMS) model and hydrologic engineering center hydrological model system (HEC-HMS) model to hilly areas, including Luanchuan watershed and Hancheng watershed in Henan Province and Lipiyu watershed and Haojiadian watershed in Liaoning Province[10]. In order to conduct the flood forecasting research of small watershed in the control basin of Lengkou hydrological station based on Double-excess Model[11]. Chinese flood forecasting system based on the early development of a large number of foreign systems summarizes the technical experience. For example the telemetry system based on Sac model of Luhun basin and land water basin is first Chinese batch of flood forecasting system and the beginning of Chinese flood forecasting system. With the wide application of database and the emergence of network technology, a large number of flood forecasting systems have emerged , such as the decision support system for flood control dispatching of the Yellow River, the flood forecasting system for the Three Gorges Reservoir Input Station, and the flood control dispatching system of Biliuhe Reservoir in Liaoning Province based on WebGIS technology[12].

However, due to the vast territory of China, the flood forecasting system doesn't cover all the complete basins, such as the Qingshitan basin in Guilin, Guangxi Province, which relies on inefficient artificial forecasting[14]. In order to resist flood disasters, on the one hand, a large number of flood control projects have been built, on the other hand, various flood forecasting methods have been bred to take defensive measures.

Originally, flood forecasting system came out in 1950s. In the initial stage, when the experts did not understand the hydrological process and the interaction between the variable processes. It mainly uses mathematical statistics methods to predict hydrological, meteorological and climatic variables, that is, according to the changing laws of climate variables, namely, periodicity, transitionally and sustainability, and then predict the future state of the variables. This method can often obtain better prediction results of hydrological and meteorological variables with more periodicity and greater persistence, such as the total amount of seasonal runoff. For example, Linear methods include multiple regression models, cluster analysis[14], canonical correlation analysis[15], singular value decomposition, Empirical orthogonal function, Markov model[16], projection tracking model[17] and so on. Non-linear models include neural networks, Filtering techniques and some hybrid methods such as wavelet neural network[18], neuro-fuzzy model[19] and so on. Wu et al[20] proposed a Markov model for predicting the anomalies of East Asian monsoon rainfall. Cross Validation results to indicate that this model has a higher score of East Asian winter monsoon precipitation, but a lower score of East Asian summer monsoon precipitation. Wu et al[21] established a linear regression prediction model for East Asian summer monsoon precipitation using the previous North Atlantic Oscillation (NAO) indexed and two ENSO indices. At the same time, researchers generalized all linear reflux curves into dynamic curve clusters, and established a transfer model on the concept of Muskingan method. On this basis, the method of calculating unit line was verified[22]. Secondly, the non-linear function of the quadratic method is used to calculate the non-linear confluence: simplifying the Saint-Venant equation by hydrodynamic force[23]. Nonlinear reservoir parameters are transformed into non-linear unit hydrographs[24]. However, it is usually poor that the prediction effect of the discontinuous process with large randomness such as quarterly precipitation, and once the change law of the factors changes, it is impossible to make effective prediction. Statistical models are generally based on a large amount of data. Too much data will lead to cumbersome calculation and statistical deviation. The application of relatively accurate function fitting also has some challenges to accuracy. Although the mathematical statistics method is simple, it lacks physical meaning and it is difficult to express the nonlinear relationship between factors.

With the rise of computer industry, modern flood forecasting system based on hydrological model began to rise[25]. In the 1950s, hydrological models focused on a single aspect of research[26]. With the emergence of digital watersheds, the research of watershed hydrological model has been developed step by step, and some famous models have been formed, such as Stanford IV model in the United States[27]. At this stage, the hydrological model was used to quantitatively analyze the flow process of the river basin entrance and exit sections, but the study at this stage did not go deep into the actual state of hydrological variables. Tank model, represented by Japan in the 1980s, has been able to simulate the relationship between water storage and outflow, greatly simplifying the process of rainfall runoff[28]. The subsequent SHE model can generalize the spatial characteristics of the basin in detail, and can describe the hydrological process of momentum conservation partial differential equation[29]. Facing complex geographical conditions, many Chinese scientific researchers have made the following achievements, including the XAJ model with full runoff storage and runoff yield forms initiated a new situation of hydrological forecasting in China and was widely used in humid and semi-humid areas[30]. The XAJ model is a rainfall-runoff model, which has been widely used in humid, semi-humid and semi-arid regions of China in flood forecasting and water resources assessment with good simulation accuracy[31]. At this stage, the distributed hydrological models based on XAJ model have been widely used and made outstanding contributions to the cause of flood mitigation for China's national defense.

Therefore, the objective of this research is firstly the selection of the study area. The Fu River basin is the second largest river in Jiangxi Province, China, and the main source of drinking water in the city center and river counties (districts). The area is also an important grain production base of the middle and lower reaches of the Yangtze River in Jiangxi. However, because the terrain in the area is mostly low hills and plains, the area is located in the middle and lower reaches of the Yangtze River and the eastern monsoon region of China. The warm and humid air currents from the Pacific Ocean in summer and autumn have a great impact on the precipitation in the area. These have led to frequent flooding with the region. Applying a hydrological model with physical significance of this area is of great significance to prevent droughts and floods with the area and to protect the lives and property of local people.

## 2 Overview of the studying watershed

The Fu River basin locates in the southeastern part of Jiangxi Province, spanning the east longitude from 115°30′E to 117°10′E and the north latitude from 26°30′N to 28°37′N. River length is 344 km. The Fu River, with a drainage area of 15.811 km$^2$ (above the hydrological station of Lijiadu)[32]. The main tributaries are Xujiang River, Lizhao River, Linshui River, Dongxiangshui River and Lijiadu hydrological station is a control station of Fu River. The elevation is from 20 meters to 1 800 meters. Mountains account for 27%, hills for 63% and plains for 10%. Fu River is divided into upper, middle and lower reaches. The upstream reach from Heyuan to Nancheng is a mountainous river with fine sand bed[33]. The width of the river is about 300 m. At the same time, the drop is large and the river course is crooked. Nancheng to Linchuan is the middle reaches of the river, which belongs to hilly and plain rivers. The river is flat, wide and shallow with a width of 400-500 m. Linchuan is a vast alluvial plain in the lower reaches of the river. Its elevation is generally below 50 m, and the width of the river is from 400 meters to 800 meters. According to the gentle terrain the flow is concentrated[34]. Fu River basin belongs to the middle subtropical monsoon humid climate area, with distinct seasons and abundant rainfall. The average annual rainfall is 1 761.0 mm. The maximum annual rainfall is 2 985.4 mm (1998 Goushu station) and the minimum annual rainfall is 905.5 mm (1963 Nancheng station). Fu River is a rain-flood type river. Most of the catchment floods occur to the first ten days of April to July. In some years, the typhoon affects the river from August to September, and if the rainfall is concentrated in March on the next year, the catchment floods will also occur. The flood process of Fu River mostly presents complex peaks. In a flood process, the upstream station usually lasts 3 to 5 days, the downstream station lasts 6 to 8 days, while the upstream station lasts 7 to 8 days and the downstream station lasts 10 to 15 days[35].

This area is an important grain production base of Jiangxi and even in the middle and lower reaches of the Yangtze River. However, because this area is located in the middle and lower reaches of the Yangtze River and in the eastern monsoon region of China, the warm and wet air flow from the Pacific Ocean in summer and autumn has a great impact on the precipitation in this area. In addition, the topography of this area is mostly low hills and plains, which causes frequent flooding disasters in this area. A series of problems caused by this have a great impact on the production and life of the local people. Therefore, the research is of great significance of the prevention of drought and flood disasters in this area and to the protection of the safety of local people′s lives and property[20].

## 3 Materials and methods

### 3.1 Flood disaster situation in Fu River basin

Flood disasters occur frequently to the Fu River basin, with different degrees of floods occurring every year. Generally, a large flood occurs to two to three years, and causes serious disasters. For example, from June 13rd to 17th, 2002, the upstream of the Fu River experienced continuous rainstorms and extremely heavy rainstorms. The rainfall at Shuinan station in Guangchang County reached 601 mm. As a result of continuous rainfalls, there were huge floods of the upper and middle reaches, and once in a century and once in 50 years at Shaziling and Nancheng stations. The Fu River basin floods occurred in 1 774 villages in 205 townships and counties of 11 counties and cities in 1998. The affected population was 23.664 4 million, houses were destroyed, 53 dikes of 1 000 mu (1 mu=667 m$^2$) overtopped by floods, and economic losses amounted to 4.049 billion yuan. Flood disaster has caused huge economic losses and seriously restricted the development of social economy.

The River prediction stations in the Fu River basin include Shaziling, Nanfeng, Nancheng, Liaojiawan, Taopo, Chongren, Loujiacun and so on. Many researchers[36] showed that Tyson polygon method is an accurate method of calculating surface rainfall. It is suitable for the case of uneven distribution of precipitation or rainfall stations in the basin. In this research, the rainfall data onto the stations was transformed into surface data based on Tyson polygon method, which was used for the long-term analysis of the precipitation in the Fu River basin. The Tyson polygon method based on ArcGIS platform is used to calculate the regional average rainfall, which solves the problem of traditional method to calculate the area weight coefficient and improve the accuracy of regional average rainfall. According to the characteristics of the Fu River basin, the basic information about the corresponding sub-basins is shown in Tab. 1. The rainfall stations and weights of each sub-basin are shown in Tab. 2.

Tab. 1  Subbasins of Fu River basin and their intervals

| Name of subbasin | River name | Direction of inflow | Control station name and information | Drainage area/km$^2$ |
|---|---|---|---|---|
| Shaziling | Xujiang | Fu River | Shaziling (Flow, Water level) | 1 225 |
| Nanfeng | Xujiang | Fu River | Nanfeng (Water level) | 2 935 |
| Nancheng | Xujiang | Fu River | Nancheng (Flow, Water level) | 4 159 |
| Hongmen reservoir | Litan River | Fu River | Hongmen reservoir (Flow, Water level) | 2 376 |
| Liaojiawan | Fu River | Poyang Lake | Liaojiawan (Flow, Water level) | 6 347 |
| Taopo | Suitable yellow water | Linshui | Taopo (Flow, Water level) | 1 611 |
| Chongren | Yanrenshui | Linshui | Chongren(Water level) | 1 671 |
| Loujiacun | Linshui | Fu River | Loujiacun (Flow, Water level) | 4 969 |
| Liaojiawan+Loujiacun+Lijiadu section | Fu River | Poyang Lake | Nothing | 2 119 |
| Lijiadu | Fu River | Poyang Lake | Lijiadu (Flow, Water level) | 15 811 |

Tab. 2  Weight table of rainfall stations in Fuhe River basin

| Rainfall station | Chishui | Shuinan | Shaziling | Changpo | Baishe | Fufang | Shuangtian | Nanfeng | Lita | Shangtang | Nancheng |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Weight | 0.132 | 0.110 | 0.110 | 0.079 | 0.085 | 0.065 | 0.065 | 0.067 | 0.074 | 0.070 | 0.065 |

## 3.2 Modeling of XAJ

Generally, XAJ model is widely used in reservoir flood forecasting in China. It was proposed by Professor Zhao Renjun in 1973 and established through the study of XAJ reservoir. The following is the structure of XAJ model with three water sources in Fig. 1[37].

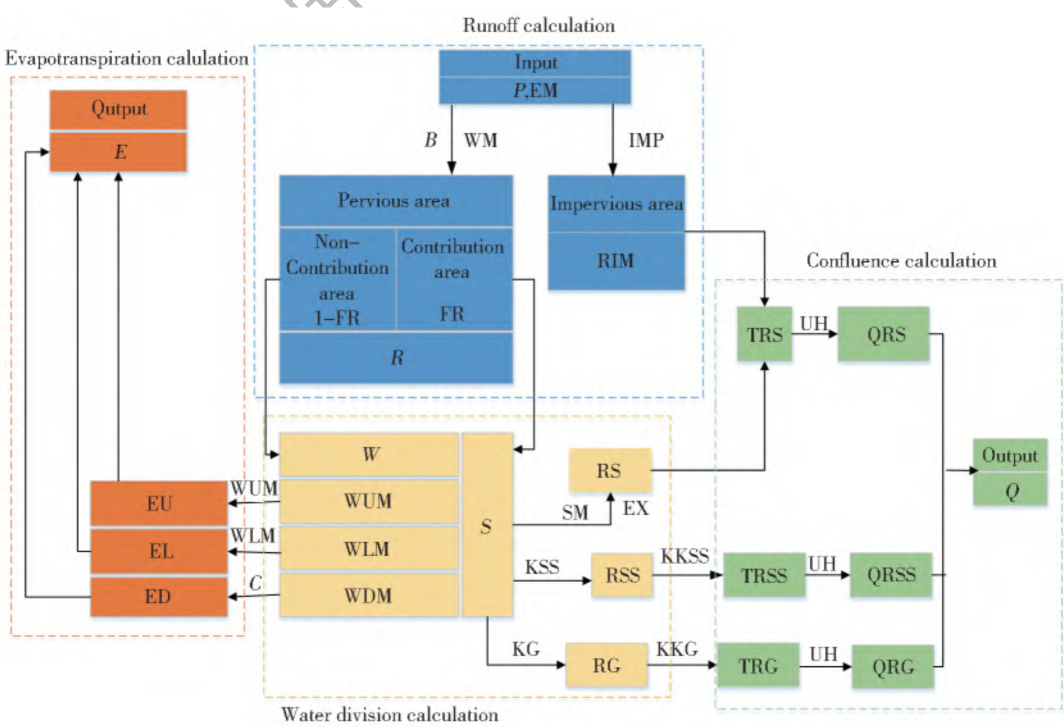


Fig. 1  Flowchart of the three-source XAJ model

XAJ model can be divided into evapotranspiration calculation, runoff generation calculation, water source division and confluence calculation. Among them, evapotranspiration calculation is responsible for calculating soil evaporation in the upper and lower layers, runoff generation calculation is based on full storage runoff generation model, and water source division divides free water into surface runoff, soil middle runoff and underground runoff. Unit line method and linear reservoir method are the approaches of confluence calculation. The former is generally used to calculate the surface runoff confluence of unit area, while the latter is generally used to calculate the confluence of soil water runoff and groundwater runoff. The Muskingum method of delay algorithm or piecewise continuous calculus is a common method for calculating river network confluence. The parameters of XAJ model are as shown in Tab. 3, the values of parameters and sensitivity in the above four levels. McCarthy proposed the Muskingum in 1938 and pioneered the hydrological method of flood calculus[23]. The equation of the flow calculation as

$$M_2 = C_0 I_2 + C_1 I_1 + C_2 M_1 \tag{1}$$

$$C_0 = \frac{-Kx + 0.5\Delta t}{K(1-x) + 0.5\Delta t} \tag{2}$$

$$C_1 = \frac{Kx + 0.5\Delta t}{K(1-x) + 0.5\Delta t} \tag{3}$$

$$C_2 = \frac{K(1-x) - 0.5\Delta t}{K(1-x) + 0.5\Delta t} \tag{4}$$

Where: $M_1$, $M_2$ are the river outflow at the beginning and end of the calculation period respectively; $I_1$, $I_2$ are the river inflow at the beginning and end of the calculation period respectively; $C_0$, $C_1$, $C_2$ are the coefficients of flow calculus; $K$ is the constant amount of storage; $x$ is the coefficient of the flow specific gravity; $\Delta t$ is the period of time.

Tab. 3 The structure and function of XAJ model, calculation method and corresponding parameters

| Arrangement | Parameter symbol | Parameter significance | Whether sensitive | Range of values |
|---|---|---|---|---|
| Evapotranspiration calculation | KC | Conversion coefficient of evapotranspiration | ✓ | |
| | UM | Upper tension water capacity/mm | × | 10～20 |
| | LM | Lower tension water capacity/mm | × | 60～90 |
| | $C$ | Deep evapotranspiration diffusion coefficient | × | 0.1～0.2 |
| | WM | Average tension water capacity of watershed/mm | × | 120～200 |
| Runoff yield calculation | $B$ | Curve equation of tension water storage capacity | × | 0.1～0.4 |
| | IM | The proportion of impervious area to the whole basin area | × | 0.01～0.04 |
| | SM | Surface free water storage capacity | ✓ | |
| Water source division | EX | Curve equation of surface free water storage capacity | × | 1.0～1.5 |
| | KG | Sunrise coefficient of groundwater in surface free water storage reservoir | ✓ | |
| | KI | Sunrise coefficient of surface free water storage reservoir to soil flow | ✓ | |
| | CI | Coefficient of subsidence of flow in soil | ✓ | |
| | CG | Coefficient of subsidence of groundwater | | |
| Confluence calculation | CS | Water storage and recession coefficient of river network | ✓ | |
| | $L$ | Time lag/h | ✓ | |
| | KE | Muskingan algorithm parameters/h | ✓ | KE=$\Delta t$ |
| | XE | Muskingan algorithm parameters | ✓ | 0～0.5 |

With the development of IT industry and the popularization of computer technology, human-computer interaction is developing day by day. The method of calibrating parameters is called human-computer interaction calibration method. The calibration is divided into two parts: daily model and hourly model.

The main goal of using the daily model is to determine all parameters of the first layer, the second layer, the third layer, and the convergence parameters of the fourth layer. The model parameters obtained by the daily model need to be calibrated. First set the parameters, then compare the total runoff for many years, compare the annual runoff depth, compare the annual difference between dry and wet seasons, and compare the underground runoff, especially in the dry season. The above parameters are used to calibrate the model parameters to achieve the purpose of improving the accuracy of the model. Parameters that are independent of the length of time in the hourly model can be directly applied to the model. Parameters related to the length of time need to be calibrated. The general calibration method is divided into the following three steps, the comparison of total flood runoff, the comparison of flood peaks, and the comparison of flood peak occurrence times.

## 4 Result analysis

Fu River basin is a humid area with abundant groundwater and high groundwater level. The water storage under the aeration zone is often kept around the field capacity. Because of evaporation, especially in flood season, the water shortage will change to 20 mm to 30 mm, which is easy to replenish the water shortage. In addition, the vegetation of the Fu River basin is good, and the surface soil is not easy to penetrate. Therefore, a single rainfall can produce runoff in the seepage zone, which is called full storage runoff. The annual runoff coefficient of the Fu River basin is higher (generally over 0.5), because the water content of the aerated zone is at normal level when the runoff is full. The annual runoff coefficient of the Fu River basin is shown in the Tab. 4 below.

Tab. 4 Annual runoff depth in Fu River basin

| Years | Runoff depth/mm | Runoff coefficient | Years | Runoff depth/mm | Runoff coefficient |
|---|---|---|---|---|---|
| 1985 | 708 | 0.55 | 1993 | 871 | 0.63 |
| 1986 | 643 | 0.58 | 1994 | 1 479 | 0.80 |
| 1987 | 713 | 0.46 | 1995 | 1 240 | 0.87 |
| 1988 | 1 130 | 0.78 | 1996 | 981 | 0.70 |
| 1989 | 1 000 | 0.69 | 1997 | 1 612 | 0.72 |
| 1990 | 879 | 0.47 | 1998 | 1 734 | 0.89 |
| 1991 | 1 488 | 0.78 | 1999 | 1 230 | 0.75 |
| 1992 | 1 488 | 0.80 | | | |

According to the annual runoff process line, the following conclusions are drawn: the rapid rise and fall of flood engineering in Fu River basin, which is caused by the above-mentioned components of runoff, which are termed surface runoff, soil runoff and underground runoff. The runoff yield rate of surface runoff is the highest, that of soil runoff is the second, and that of underground runoff is the lowest. Because of the higher steady infiltration rate and the more components of the soil flow and underground runoff in the flood-falling section, most of them show a skewed pattern of rapid rise and fall. In conclusion, it is concluded that full storage runoff generation is the main runoff generation mode in the Fu River basin. There are 10 hydrology stations in the Fu River basin, such as Loujiacun and Shaziling. This paper will not list them one by one. The Loujiacun station is taken as the research object. The research method is to divide the unit area first. The whole river basin is divided according to the number of stations by the Tyson polygon method. Tab. 5 is the weight of each unit area calculated.

Tab. 5 Weight table of Loujiacun rainfall station in Fu River basin

| Serial number | Station name | Weight | Serial number | Station name | Weight |
|---|---|---|---|---|---|
| 1 | Huangpo | 0.094 | 7 | Shiqiao | 0.077 |
| 2 | Lanshui | 0.067 | 8 | Wutou | 0.082 |
| 3 | Shengang | 0.087 | 9 | Chongren | 0.092 |
| 4 | Daifang | 0.083 | 10 | Taopo | 0.158 |
| 5 | Matou | 0.101 | 11 | Loujiacun | 0.077 |
| 6 | Xinfeng | 0.082 | | | |

In order to get the flood process of Loujiacun reservoir, the unit area of each Loujiacun reservoir is calculated by three-source model. Next, river flood routing is needed. The method adopted is Muskingen's piecewise continuous algorithm. The purpose is to get the flow process line of the study area. In order to obtain the flow and flood process in the study area, the last step is to linearly superpose all the flow process lines obtained above one by one.

The parameters need to be initially determined and then calibrated according to the indicators. Firstly, the daily model calculation is carried out. The calculation data are based on the daily precipitation and daily evaporation in Loujiacun watershed from 1981 to 1995. Then, the data of the first ten years (1981 to 1990) are calibrated and the remaining five years (1991 to 1995) are used for final verification. At the same time, the sub-model calculation is also needed. The calculation data are based on 18 floods in Loujiacun from 1981 to 1995, followed by parameter calibration. The first twelve of the eighteen floods are used for parameter calibration, and the remaining six are used for flood parameter verification, such as Tab. 6 and Tab. 7.

Tab. 6 List of 18 floods at Loujiacun rainfall station

| Flood code | Start time |
|---|---|
| 810329 | 1981-3-29 20:00:00 |
| 820525 | 1982-5-25 20:00:00 |
| 820611 | 1982-6-11 14:00:00 |
| 830406 | 1983-4-06 04:00:00 |
| 830609 | 1983-6-09 16:00:00 |
| 840901 | 1984-9-01 00:00:00 |
| 850405 | 1985-4-05 12:00:00 |
| 850603 | 1985-6-03 16:00:00 |
| 850915 | 1985-9-15 14:00:00 |
| 860410 | 1986-4-10 16:00:00 |
| 880504 | 1988-5-04 14:00:00 |
| 890617 | 1989-6-17 14:00:00 |
| 900606 | 1990-6-06 14:00:00 |
| 910321 | 1991-3-21 04:00:00 |
| 930613 | 1993-6-13 12:00:00 |
| 940609 | 1994-6-09 12:00:00 |

Tab. 7 Daily model and hourly model parameters of Loujiacun rainfall station in Fu River basin

| Parameter | *K* | *C* | UM | LM | WM | *B* | IM | SM | EX | KG | KI | CI | CG | CS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Daily model | 0.95 | 0.15 | 20 | 80 | 130 | 0.3 | 0.01 | 25 | 1.5 | 0.4 | 0.3 | 0.985 | 0.995 | 0.3 |
| Hourly model | 1.00 | 0.15 | 20 | 80 | 130 | 0.3 | 0.01 | 60 | 1.5 | 0.4 | 0.3 | 0.950 | 0.999 | 0.8 |

According to Tab. 8 to 10 below, the runoff depth of the study area data used for model calibration is obtained. The absolute error is between 0.15% and 9.93%, the average error is about 5.00%, the maximum error is about 10%, less than 20%, which meets the criterion. The maximum error of runoff depth is about 11%, the absolute value is between 5% and 10%, and the average value is about 8%, which is in accordance with the standard. It is shown in Tab. 8.

Tab. 8 Runoff depth error of daily model in Loujiacun rainfall station Unit: %

| Years | 1981 | 1982 | 1983 | 1984 | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| error | −9.93 | 1.23 | 5.15 | −8.63 | −1.61 | 2.49 | −3.62 | 0.15 | −6.89 | −7.56 | −10.28 | −4.77 | −7.57 | −8.05 | −10.38 |

Loujiacun sub-model simulation error statistics table is shown in Tab. 9. According to Tab. 9, it can be seen that the relative errors of peak discharge of regular rate floods are not up to 20% except 860 410 and 890 411 floods, and all other floods are in accordance with the stipulations of the Standard for Hydrological Information Forecasting. The relative errors of runoff depth and peak discharge of the six floods in the validation period also conform to the "Standard for Hydrological Information Forecasting". There are seven floods that meet the Class A standard within the regular rate period, and the remaining five floods all meet the Class B standard. During the validation period, four floods met Class A criteria and the remaining two reached Class B criteria. The relative error of runoff depth of hourly model is less than 10%, which accounts for 72.2% of the total. The relative error of peak discharge of hourly model is less than 10% and 13 times, which accounts for 72.2% of the total. Its certainty coefficient is 0.983, the minimum is 0.813 and the average is 0.911. The accuracy statistical structure shows that the calibrated parameters are basically reasonable according to the Tab. 10.

Tab. 9  Error of XAJ model in Loujiacun rainfall station

| Period | Flood code | Precipition/ mm | Measured runoff depth/mm | Calculating runoff depth/mm | Relative error of runoff depth/% | Flood peak flow measurement/ ($m^3 \cdot s^{-1}$) | Calculating peak discharg/ ($m^3 \cdot s^{-1}$) | Relative error of peak discharge/% | Coefficient of certainty |
|---|---|---|---|---|---|---|---|---|---|
| Parameter calibration | 810 329 | 488.3 | 335.74 | 347.4 | −3.46 | 2 560.0 | 2 296.4 | 10.30 | 0.985 |
| | 820 525 | 120.2 | 51.54 | 56.7 | −10.04 | 890.0 | 850.9 | 4.40 | 0.837 |
| | 820 611 | 521.7 | 405.67 | 386.1 | 4.82 | 3 860.0 | 4 059.4 | −5.20 | 0.963 |
| | 830 406 | 305.7 | 182.76 | 169.3 | 7.35 | 1 220.0 | 1 201.5 | 1.50 | 0.813 |
| | 830 609 | 390.0 | 265.57 | 238.4 | 10.23 | 2 480.0 | 2 516.4 | −1.50 | 0.923 |
| | 840 901 | 140.8 | 64.32 | 68.3 | −6.17 | 1 830.0 | 1 690.4 | 7.60 | 0.975 |
| | 850 405 | 120.0 | 77.48 | 75.5 | 2.52 | 864.0 | 799.5 | 7.50 | 0.938 |
| | 850 603 | 142.3 | 76.13 | 74.1 | 2.71 | 1 070.0 | 1 002.2 | 6.30 | 0.983 |
| | 850 915 | 151.8 | 59.44 | 59.8 | −0.59 | 964.0 | 921.7 | 4.40 | 0.862 |
| | 860 410 | 313.5 | 238.26 | 219.1 | 8.06 | 1 187.5 | 949.2 | 20.10 | 0.941 |
| | 880 504 | 299.9 | 238.32 | 208.7 | 12.42 | 2 440.0 | 2 554.9 | −4.70 | 0.859 |
| | 890 411 | 234.1 | 135.17 | 151.4 | 12.00 | 1030.0 | 1 262.4 | −22.60 | 0.859 |
| Parameter validation | 890 508 | 230.0 | 135.57 | 130.7 | 3.60 | 1 220.0 | 1 017.5 | 16.60 | 0.919 |
| | 890 617 | 325.4 | 257.24 | 213.9 | 16.85 | 2 670.0 | 2 612.6 | 2.10 | 0.923 |
| | 900 606 | 279.2 | 166.22 | 171.0 | −2.86 | 1 060.0 | 1 082.7 | −2.10 | 0.892 |
| | 910 321 | 397.9 | 268.93 | 256.3 | 4.70 | 1 010.0 | 940.4 | 6.90 | 0.88 |
| | 930 613 | 466.7 | 325.72 | 311.3 | 4.44 | 2 120.0 | 2 027.6 | 4.40 | 0.943 |
| | 940 690 | 422.8 | 310.53 | 280.3 | 9.73 | 2 430.0 | 2 106.4 | 13.30 | 0.932 |
| Average | | 297.4 | 199.7 | 189.9 | | 1 717.0 | 1 660.7 | | 0.911 |

Tab. 10  Precision classification of forecast items

| Accuracy grade | A | B | C |
|---|---|---|---|
| Pass rate/% | $P_r > 85.0$ | $85.0 \geq P_r \geq 70.0$ | $70.0 \geq P_r \geq 60.0$ |
| Coefficient of certainty | $C_c > 0.90$ | $0.90 \geq C_c \geq 0.70$ | $0.70 > C_c \geq 0.50$ |

Note: $P_r$ means the pass rate; $C_c$ means the coefficient of certainty.

## 5 Conclusions

In this paper, the XAJ model is applied to the Fu River basin, and its application effect is analyzed. It is concluded that the XAJ model based on the basis of full-storage runoff yield has high accuracy, accuracy requirements in the norms, and good applicability in the study basin. According to the above analysis, it can be concluded that the XAJ model can be used in flood forecasting in the Fu River basin. In other words, XAJ model can also be used as a basic forecasting model in the flood forecasting system of Fu River basin.

Because of the collected data, this paper only studies the Loujiacunzi watershed in the Fu River basin. The results have some limitations. Therefore, in the future research, we should collect the data of the whole watershed, and then further analyze and discuss its applicability in the whole watershed. The results are more convincing and universal. In practice, the uncertainties of the model are inevitable. For example, the measured value and the calculated value through the model are not identical in a certain range. The main reasons for this phenomenon is that the representative of the rainfall stations and so on. In order to solve the model uncertainty, the use of correction model can avoid this error. Various correction models are used to correct the errors. Finally, the most suitable and real-time correction method for Fu River basin research area is selected, and more convincing results are obtained through continuous correction.

**References:**

[1] BATES P, DEROO A. A simple raster-based model for flood inundation simulation[J]. Journal of Hydrology, 2000, 236: 54-77. DOI: 10.1016/s0022-1694(00)00278-x.

[2] ZHANG Y, WANG Y, CHEN Y, et al. Assessment of future flash flood inundations in coastal regions under climate change scenarios: A case study of Hadahe River basin in northeastern China[J]. Science of the Total Environment, 2019, 693: 1-11. DOI: 10.1016/j.scitotenv.2019.07.356.

[3] CHOU J, XIAN T, DONG W. et al. Regional temporal and spatial trends in drought and flood disasters in China and assessment of economic losses in recent years[J]. Sustainability, 2018. 11: 55-72. DOI: 10.3390/su11010055.

[4] SWANSON F, JOHNSON S, GREGORY S, et al. Flood disturbance in a forested mountain landscape-interactions of land use and floods[J]. Bioscience, 1998, 48: 681-689.

[5] CHEN H, LIANG Z, LIU Y, et al. Integrated remote sensing imagery and two-dimensional hydraulic modeling approach for impact evaluation of flood on crop yields [J]. Journal of Hydrology, 2017, 553: 262-275. DOI: 10.1016/j.jhydrol.2017.08.001.

[6] ZHANG M. Reconstruction of drought and flood sequence in 1470-1949 years and its social impact and countermeasures in Fuhe River basin[D]. Nanchang: Jiangxi Normal University, 2018.

[7] LI K, WU S, DAI E, et al. Flood loss analysis and quantitative risk assessment in China[J]. Natural Hazard, 2012, 63: 737-760. DOI: 10.1007/s11069-012-0180-y.

[8] ZHANG S. Study on the design and construction of national flood forecasting system [J]. Hydrology, 2002, 22: 32-34.

[9] OLSSON J, UVO B, YANG W. Technical note: initial assessment of a multi-method approach to spring-flood forecasting in Sweden[J]. Hydrology & Earth System Science, 2016, 20: 659-667. DOI: 10.5194/hess-20-659-2016.

[10] TIAN J H, FA S Q, WANG C, et al. Comparison of FFMS Model and HEC-HMS model in rainstorm and flood simulation [J]. Journal of Yangtze River Science Research Institute, 2021, 38: 1-8. (in Chinese)

[11] HU X, ZHANG Y, ZHU X. Research on flood forecasting based on double-excess model[J]. Pearl River, 2021, 42: 26-33. (in Chinese)

[12] ZHOU J, ZHANG H, ZHANG J, et al. WRF model for precipitation simulation and its application in real-time flood forecasting in the Jinshajiang River basin, China[J]. Meteorology and Atmospheric Physics, 2018, 130: 635-647. DOI: 10.1007/s00703-017-0542-9.

[13] X M. Design and implementation of flood forecasting system based on Xin'anjiang model[D]. Nanchang: Nanchang Hangkong University. 2018. (in Chinese)

[14] ZARE S, SHAMSI S, ABTAHI S. Weakly-coupled geostatistical mapping of soil salinity to stepwise multiple linear regression of MODIS spectral image products [J]. Journal of African earth sciences. 2019. 152. 101-114. DOI: 10.1016/j.jafrearsci.2019.01.008.

[15] HWANG S, SCHEM J, BARNSTON A. Long-lead seasonal forecast skill in far eastern Asia using canonical correlation analysis[J]. Journal of Climate, 2001, 14: 3005-3016. DOI: 10.1175/1520-0442(2001)014<3005:LLSFSI>2.0.CO;2.

[16] WU D, ZHAO X, CHEN J. Based on GIS technology flood disaster assessment study of Fuhe River basin [J]. Proceeding of SPIE, 2013, 2: 1-6. DOI: 10.1117/12.2051407.

[17] WELSER M, ACTON S. Projection model snakes for tracking using a Monte Carlo approach[J]. Journal of Electronic Imagin, 2004, 13: 384-398. DOI: 10.1117/1.1687732.

[18] KIM T, VALDES J. Nonlinear model for drought forecasting based on a conjunction of wavelet transforms and neural networks[J]. Journal of Hydrologic Engineering, 2003, 6: 319-328. DOI: 10.1061/(asce)1084-0699(2003)8:6(319).

[19] SRIVASTAVA G, PANDA S, MONDAL P. Forecasting of rainfall using ocean-atmospheric indices with a fuzzy neural technique [J]. Journal of Hydrology, 2010. 195. 190-198. DOI: 10.1016/j.jhydrol.2010.10.025.

[20] WU Q, YAN Y, CHEN D. A linear markov model for east Asian monsoon seasonal forecast[J]. Journal of Climate, 2013, 26: 5183-5195. DOI: 10.1175/jcli-d-12-00408.1.

[21] WU Z, WANG B, LI J, et al. An empirical seasonal prediction model of the east asian summer monsoon using ENSO and NAO [J]. Journal of Geophysical Research. 2009. 114. 1-13. DOI: 10.1029/2009jd011733.

[22] LIU J, SONG H, ZHANG X. Progress and discussion on theoretical research of Xin'anjiang model[J]. Hydrology, 2014, 34: 1-4.

[23] GUAN Z C, WU H L, GUI J, et al. A study on back mathematical calculation procedure of muskingum

method[J]. Journal of China Hydrology, 2006(26). 9-12. (in Chinese).
[24] PINAULT J L, PLAGNES V, AQUILINA L, et al. Inverse modeling of the hydrological and the hydrochemical behavior of hydrosystems: Characterization of karst system functioning[J]. Water Resources Research, 2001, 37(8): 2191-2204. DOI: 10.1029/2001wr900018.
[25] ARTINYAN E, VINCENDON B, KROUMOVA K, et al. Flood forecasting and alert system for Arda River basin[J]. Journal of Hydrology. 2016. 541. 457-470. doi: 10.1016/j.jhydrol.2016.02.059.
[26] ROSENFELD D, LOHMANN U, REGA G, et al. Flood or drought: How do aerosols affect precipitation? [J]. Science, 2008, 321, 5894: 1309-1313.
[27] ZHANG X. Brief introduction of flood control expert system[J]. Water Conservancy Informatization. 1990, 4: 19-21.
[28] CRAWFORD N H, LINSLEY R K. Digital simulation in hydrology[J]. Stanford Univ Tech Report, 1966.
[29] BIZZARRI A. Convergence properties of a modified Hopfield-Tank model [J]. Biological Cybernetics. 1991, 64: 293-300. DOI: 10.1007/bf00199592.
[30] BAO W, LI Q. Estimating selected parameters for the XAJ model under multicollinearity among watershed characteristics[J]. Journal of Hydrologic Engineering. 2012. 17(1), 118-128. DOI: 10.1061/(asce)he.1943-5584.0000415.
[31] SHI P, CHEN C, SRINIVASAN R, et al. Evaluating the SWAT model for hydrological modeling in the Xixian watershed and a comparison with the XAJ model[J]. Water Resources Management, 2011, 25(10), 2595-2612. DOI: 10.1007/s11269-011-9828-8.
[32] LU J, CUI X, CHEN X, et al. Evaluation of hydrological response to extreme climate variability using SWAT model: application to the Fuhe basin of Poyang Lake watershed, China [J]. Hydrology Research, 2016, 48(6): 1730-1744. doi: 10.2166/nh.2016.115.
[33] HU G, XU Z, DAI J, et al. Distribution of polybrominated diphenyl ethers and decabromodiphenylethane in surface sediments from Fuhe River and Baiyangdian Lake, north China[J]. 2010, 22: 1833-1839. DOI: 10.1016/s1001-0742(09)60328-4.
[34] ZHU A, LIU P, GONG Y, et al. Residual levels and risk assessment of tetrabromobisphenol A in Baiyang Lake and Fuhe River, China[J]. Ecotoxicology and Environmental Safety, 2020, 200: 1-6. DOI: 10.1016/j.ecoenv.2020.110770.
[35] TAO C, CHEN X, LU J, et al. Asswssing impacts of different land use scenarios on water budget of Fuhe River, China using SWAT model[J]. International Journal of Agricultural and Biological Engineering, 2015, 8: 95-109.
[36] MEN B, WU Z, LIU H, et al. Spatio-temporal analysis of precipitation and temperature: A case study over the Beijing-Tianjin-Hebei region, China[J]. Pure Appl Geophys, 2020, 177, 3527-3541.
[37] ZANG S H, LI Z J, YAO C, et al, A new runoff scheme for Xin'anjiang model and its routing parameters estimation based on geographical information[J]. Water, 2020, 12(12), 3429. 1-18.



# 华中多雨人口密集型流域洪水预报

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**摘要**:建立一个集总式水文模型,即基于蓄满产流的三水源新安江模型,模拟抚河流域1981—1995年的18次暴雨洪水过程;采用马斯京根分段连续算法计算河流洪水演算和水流过程线;然后将所有水流过程线线性叠加,确定水流和洪水过程;利用日尺度数据和洪水频率数据对模型进行参数率定。结果表明:该模型在现场洪水模拟中的平均确定系数为0.911,模型校准的平均径流深度误差为4.73%,验证的平均径流深度误差为8.21%,三水源新安江模型可以被应用于抚河流域的洪水预报工作中。该研究为我国中部多雨地区的洪水预报研究提供了有益的参考。

**关键词**:流域水文预报;三水源新安江模型;水资源规划管理;水资源持续利用;流域蓄水容量曲线