Flood simulation and parameter calibration of small watershed in hilly area based on HEC-HMS model

Ying Wang¹, Guoqing Sang¹*, Cuiling Jiao², Yinghua Xu³ and Heng Zheng¹

¹School of Water Conservancy and Environmental, Jinan University, Jinan, China
² East Part of South to North Water Diversion in Shandong CO. LTD, Jinan, China
³ Weifang Water Conservancy Bureau, Weifang, China

*Corresponding author e-mail: sangguoqing@163.com

Abstract. The rivers in the hill area have a larger drop, and heavy rains are liable to form mountain floods. Flood calculation in small watershed is a key link in the prevention of flash floods. Taking the Xueye Lake basin in Laicheng District as the research object, HEC-HMS was used to establish the semi-distributed hydrological model of the hill basin to calculate the rainfall-runoff and flood routing process. Based on the historical flood elevations of three typical floods, the sub-basin parameters were calibrated using the trial-and-error method. According to the flow data of the basin outlet, the peak-weighted RMS error function was selected as the objective function, and the Nelder-Mead optimization algorithm was used to estimate the overall watershed parameters. Rainfall and flow data for two floods were used to verify model accuracy. The results show that the relative errors between peak discharge and runoff depth are less than 20%. The model has good applicability to the flood simulation of the Xueye Lake Basin and can play an actual role in the mountain flood warning forecast. The proposed lumped parameter calibration and modeling method can provide reference for flood simulation in other small basins.

1. Introduction

In recent years, due to various factors such as complex geological and topographic conditions, climatic factors, dense population distribution, and human activities, flash floods caused by extremely heavy rainfall in our country are frequent. Because of heavy rainfall and large descent of the ditch, small river floods in hilly areas have features such as short duration, strong rainfall, large drop, steep rise and steep drop. They are very different from floods in large river basins [1]. For flood prevention nodes along important river courses, calculating peak discharges and flooding processes at different levels of heavy rainstorms can provide technical support for the prevention of flood disasters.

According to the current major documents and applications, flood calculations in small basins mainly include runoff yield and confluence calculations. The methods for calculating runoff include rainfall-runoff empirical correlation method, initial loss method, infiltration curve method, index method, etc. Confluence calculation mainly includes reasoning formula method, unit hydrograph method and model method [2]. Li Lei et al. used the reasoning formula to calculate the design flood in the small watershed of Turkey. The results show that the improved reasoning formula method can combine the design rainfall and runoff yield rules of Turkey [3]. For the distributed hydrological
model, the U.S. Hydrology R&D Center studied the flood guidance system and determined the critical flow based on section topography and underlying surface conditions. Based on real-time rainfall or forecasted rainfall information, the rainwater runoff process was used to infer the rainfall over different time periods [4]. The TOPKAPI model achieves full integration of distributed hydrological models and GIS. Liu Gang et al. performed HEC-HMS simulation operation on the data-free areas in Sichuan Province. The calculation results are indistinguishable from the calculation results of the reasoning formula and the unit hydrograph, which proves that the HEC-HMS model can be applied to the calculation of floods in data-free areas [5].

Taking the Xueye Lake Basin in Laicheng District as the research object, the HEC-HMS was used to establish the simulation model of runoff flow concentration in the hilly area in this paper. The hydro-meteorological data of 5 typical floods were used to calibrate the model and verify the accuracy of the model. On this basis, the analysis of flood laws can play an actual role in the flash flood warning and forecast.

2. profile of research area

The Xueye Lake Basin is located at the eastern foot of Mount Tai, with a drainage area of 438 km². It is a warm temperate continental monsoon climate zone with a mean annual temperature of 13.6°C and an average annual rainfall of 709.3 mm. There are 1 hydrological station and 3 rainfall stations for hydrological data in the Basin (Figure 1). The main river in the basin is the Wenying River, with a total length of 39.4 km. Most of the basins are mountainous and hilly areas. The mountainous area accounts for 50% of the total area, the hilly area accounts for 22%, and the plain area accounts for 18%. The vast majority of the topography of the basin is sandy loam. There are many terraced fields in the valley, and the main crops are wheat, corn, and peanuts.

![Figure 1. Profile of Xueye Lake Watershed.](image)

The structural traces in the basin are dominated by faults, followed by folds. The underlying bedrock is mainly limestone and gneiss. Due to the topography and geology of the Xueye Lake Basin, heavy rainfall can easily cause flood disasters in the basin.

3. Modeling and parameter calibration for small watersheds

The HEC-HMS model is a semi-distributed rainfall runoff and flood routing process simulation system. The runoff process of the watershed in the model includes the main part of natural runoff processes such as rainfall, evapotranspiration, surface runoff, infiltration and base flow. The main idea
of modeling is to divide the basin into several sub-basins based on DEM basic data, calculate the runoff flow concentration of each sub-basin, and finally calculate it to the drainage section of the drainage basin.

3.1. Sub-basin classification and hydrology database
Taking the Xueye Lake basin in Laicheng District as the research object, based on the basin DEM data, ArcGis was used to extract the water system and the entire watershed was divided into 33 sub-basins. The structural model of the watershed model is shown in Figure 2, and the eigenvalue information of each sub-basin is shown in Table 1. The weights of the three rainfall stations were calculated using the Tyson polygon method, and a database of rainfall and flow in the basin was established using HEC-DSSVue.

![Figure 2. Sub-basin division and model construction.](image)

| Watershed | Area/km² | Gradient | Watershed | Area/km² | Gradient | Watershed | Area/km² | Gradient |
|-----------|----------|----------|-----------|----------|----------|-----------|----------|----------|
| 1         | 20.31    | 0.0169   | 12        | 15.81    | 0.0171   | 23        | 1.89     | 0.0187   |
| 2         | 13.72    | 0.0217   | 13        | 11.62    | 0.0147   | 24        | 14.44    | 0.0233   |
| 3         | 16.83    | 0.0195   | 14        | 16.25    | 0.0244   | 25        | 15.14    | 0.0357   |
| 4         | 10.66    | 0.028    | 15        | 23.59    | 0.0102   | 26        | 20.72    | 0.012    |
| 5         | 20.46    | 0.0176   | 16        | 13.35    | 0.0111   | 27        | 10.65    | 0.0298   |
| 6         | 0.85     | 0.0397   | 17        | 12.12    | 0.0111   | 28        | 8.1      | 0.0124   |
| 7         | 12.5     | 0.0171   | 18        | 6.44     | 0.0512   | 29        | 9.6      | 0.0439   |
| 8         | 2.62     | 0.0202   | 19        | 12.29    | 0.0261   | 30        | 59.63    | 0.087    |
| 9         | 16.62    | 0.0254   | 20        | 13.23    | 0.0233   | 31        | 0.04     | 0.0559   |
| 10        | 12.89    | 0.0252   | 21        | 6.12     | 0.0206   | 32        | 1.3      | 0.081    |
| 11        | 11.02    | 0.0153   | 22        | 24.33    | 0.0149   | 33        | 12.6     | 0.0722   |
3.2. Calculation of runoff flow concentration

According to the rainfall-runoff process, the HEC-HMS model is mainly divided into four calculation models: loss, transform, baseflow, and routing. Each calculation model contains a variety of available calculation methods [6]. Among them, the loss model includes: SCS curve number method, initial and constant method, and Green and Ampt method; Transform model includes: SCS unit Hydrograph, Clarke unit Hydrograph and Kinematic wave method; Baseflow model includes: recession method and linear reservoir method; Routing model includes Lag method, Muskingum method and modified Puls method.

3.2.1. Loss model-SCS Curve Number Method. The principle of the SCS curve number method is based on the water balance equation and the two basic hypotheses of hydrology: the assumption of proportional equality, and the calculation of runoff flow based on different conditions such as soil, cumulative rainfall, land use, and initial soil moisture content. Before the rainfall exceeds the initial loss, the excess precipitation and flow are equal to zero. The excess precipitation is calculated as follows.

\[ P_t = \frac{(P - I_a)^2}{P - I_a + S} \]  

Where: \( P_t \) is the accumulated excess precipitation corresponding to time \( t \) (mm); \( P \) is the cumulative rainfall depth corresponding to time \( t \) (mm); \( I_a \) is the initial amount of rainfall loss (mm); \( S \) is the maximum amount of soil storage (mm).

In order to establish the relationship between the maximum soil storage and the basin characteristics such as soil type and initial soil moisture content, it can be expressed by the parameter curve number \( CN \) value. See formula 2 for the calculation formula:

\[ S = \frac{25400 - 254CN}{CN} \]  

3.2.2. Transform model - SCS Unit Hydrograph. SCS Unit Hydrograph is a unit hydrograph model that is derived from rainfall and runoff data. Its principle is to calculate the relevant eigenvalues of the unit hydrograph through a set of equations in the unit hydrograph method, so as to obtain the unit hydrograph of the watershed that can be used. It proposes the relationship between the peak of the unit hydrograph \( U_p \) and the peak time of the unit hydrograph \( T_p \) as:

\[ U_p = C \frac{A}{T_p} \]  

Where, \( C \) is conversion constant, take 2.08; \( A \) is flow area (m²).

The relationship between the peak time and the unit excess precipitation duration is:

\[ T_p = \frac{\Delta t}{2} + t_{lag} \]  

Where, \( \Delta t \) is the time interval; \( t_{lag} \) is the lag time.

The lag time can be estimated using the following formula:

\[ t_{lag} = CC_t(\text{LL}_C)^{0.3} \]
Where, $L$ is the length of the main stream in the river basin; $L_c$ is the distance from the center of the river basin to the outlet of the river basin; $C$ is the conversion constant, taking 0.75; $C_t$ is the time delay coefficient of the river basin, taking 1.8 to 2.2.

3.2.3. Transform model - Recession method. The basic flow begins to decay at the initial value of the flow in an exponential manner. The relation between the baseflow $Q_t$ and the baseflow $Q_0$ at the initial time is:

$$Q_t = Q_0 e^{-kt}$$

(6)

Where: $Q_0$ is the initial base flow; $Q_t$ is the base flow at $t$; $K$ is the exponential decay constant.

3.2.4. Routing model - Muskingum method. The Muskingum method is a simplified continuous equation based on the Muskingum groove storage curve equation and the water balance equation. The flow calculation equation for the river flow is as follows.

$$Q_2 = C_0 I_2 + C_1 I_1 + C_2 Q_1$$

(7)

$$C_0 = \frac{0.5 \Delta t - Kx}{0.5 \Delta t + K - Kx}$$

$$C_1 = \frac{0.5 \Delta t + Kx}{0.5 \Delta t + K - Kx}$$

$$C_2 = \frac{-0.5 \Delta t + K - Kx}{0.5 \Delta t + K - Kx}$$

(8)

Where, $K$ is the time for the flood wave to pass through the river; $x$ is the flow specific gravity factor, the value range is 0 to 0.5; $I_1$ and $I_2$ are the initial and final flow rates of the upper section of the river channel; $Q_1$ and $Q_2$ are the initial and final flow rates of the lower section of the river channel.

3.3. Parameter calibration

The parameter calibration means that the error between the simulated value and the actual observed value is minimized by adjusting the parameter value based on the measured rainfall and flow data. A lumped parameter calibration method combining distributed sub-basin and integrated basin is adopted. First, the peak discharge is calculated based on the flood elevation at the outlet of the sub-basin. The trial and error method is used to calibrate the parameters of the sub-basin and determine the optimal parameters for each sub-basin. Then, basing on the discharge of the Xueye Reservoir Hydrometric Station at the outlet of the river basin, the overall basin parameters are calibrated to obtain the global optimal parameters.

The parameters that need to be calibrated in the model are initial loss $I_a$, CN value, watershed delay time $t_{lag}$, flow specific gravity factor $x$ and flow propagation time under steady flow conditions $K$ [7].

3.3.1. Sub-basin parameter calibration. According to the cross sections, the Manning formula was used to derive the water level and discharge curve. The peak discharge was calculated from the flood level at the outlet of the sub-basin (Figures 3 and 4). The parameters of the small watershed were calibrated by the trial-and-error method to determine the optimal parameters for each sub-basin. Taking the sub-basin above the control section of Jishan Village as the unit of calculation, the hydrological process simulation and parameter calibration were performed. The parameters are shown in table 2.
3.3.2. Parameter calibration of whole watershed. The overall watershed parameter is calibrated by the Nelder-Mead optimization algorithm. It uses the simplex method to directly search the parameters to reach the target value [8]. In the model, the optimal parameters obtained by timing the sub-basin rate are input. Based on the flow data of the Xueye Reservoir hydrological station, the peak-weighted RMS error function was selected as the objective function, and the Nelder-Mead optimal algorithm was used to calibrate the parameters in the calculation model to reach the optimal parameters. Table 3 shows the results of parameters of some river basins and river sections.
The objective function quantitatively describes the fitting degree between the calculated discharge and the measured discharge [9]. The peak-weighted RMS error function is a correction to the standard RMS error. When the peak value is higher than the average value, the weight is increased. Therefore, the measured peak value corresponds to the largest weight value, and the calculation formula is as follows:

$$Z_p = \left( \frac{1}{n} \sum_{i=1}^{n} \left( q_0(i) - q_s(i) \right)^2 \right)^{1/2} \left( \frac{\left( q_0(i) + q_{0,\text{mean}} \right)}{2q_{0,\text{mean}}} \right)$$  \hspace{1cm} (9)

Where, \( n \) is the number of hours; \( q_0(i) \) is the measured flow value; \( q_s(i) \) is the predicted flow value; \( q_{0,\text{mean}} \) is the average of the measured flow.

### Table 3. Watershed model parameter calibration.

| Sub-basin | \( I_o/\text{mm} \) | CN | Percent imperviousness/\( \% \) | \( t_{\text{lag}}/\text{min} \) | k | Rate to peak | Reach | \( K/h \) | x |
|-----------|-----------------|----|-------------------------------|------------------|---|------------|--------|---------|---|
| 1         | 12              | 86 | 8                             | 289              | 0.9| 0.2        | reach1 | 0.51    | 0.3 |
| 2         | 12              | 89 | 10                            | 244              | 0.9| 0.2        | reach2 | 0.39    | 0.3 |
| 3         | 12              | 86 | 7                             | 233              | 0.9| 0.2        | reach3 | 0.46    | 0.3 |
| 4         | 12              | 86 | 7                             | 218              | 0.9| 0.2        | reach4 | 0.55    | 0.3 |
| 5         | 10              | 86 | 10                            | 288              | 0.9| 0.2        | reach5 | 0.37    | 0.3 |
| 6         | 12              | 86 | 8                             | 99               | 0.9| 0.2        | reach6 | 0.59    | 0.3 |
| 7         | 10              | 86 | 8                             | 239              | 0.9| 0.2        | reach7 | 0.97    | 0.3 |
| 8         | 12              | 86 | 7                             | 148              | 0.9| 0.2        | reach8 | 0.37    | 0.3 |
| 9         | 11              | 86 | 8                             | 216              | 0.9| 0.2        | reach9 | 0.95    | 0.3 |
| 10        | 11              | 89 | 8                             | 186              | 0.9| 0.2        | reach10| 0.89    | 0.3 |

### 3.4. Model validation

The five typical floods in the basin were selected to calibrate and validate the model parameters. The results are shown in Table 4. Figures 5 and 6 show the measured and simulated flow process. From the table, it can be seen that the relative errors between peak discharge and runoff depth are less than 20\%, and it can be seen from the figure that the simulated flood process is in line with the measured flood process.

### Table 4. Model calibration and verification results.

| Period of calibration | Floods       | Peak discharge | Runoff depth |
|-----------------------|--------------|----------------|--------------|
|                       | Simulated (/\( \text{m}^3/\text{s} \)) | Measured (/\( \text{m}^3/\text{s} \)) | Relative error/\( \% \) | Simulated / mm | Measured / mm | Relative error/\( \% \) |
| period of calibration | 940629       | 2109           | 2083         | 2             | 113.5          | 138.3        | -18 |
|                       | 960725       | 627            | 573          | 9             | 58.7           | 61.4         | -4  |
|                       | 30904        | 1393           | 1255         | 4             | 100.6          | 93.5         | 8   |
| period of validation  | 120708       | 1611           | 1560         | 3             | 99.5           | 106.3        | -6  |
|                       | 160720       | 890            | 817          | 8             | 79.7           | 72.5         | 10  |
4. Conclusion

(1) Based on the watershed DEM data, the semi-distributed hydrological model of the small watershed in the hilly area of the Xueye Lake Basin was established by referring to the distribution of soil types and vegetation data in the basin. Among them, the loss model uses the SCS curve number method, the transform model uses the SCS unit hydrograph method, the base flow model uses the recession method, and the routing model uses the Muskingum method.

(2) The model parameters were calibrated using a combination of distributed sub-basin and integrated basins. Based on the flood elevation in the sub-basin and the measured discharge at the outlet of the basin, the trial-and-error method and the Nelder-Mead algorithm were used to calibrate the parameters.

(3) The rainfall and flow data of 2 floods are used to verify the model. The results show that the relative errors of peak discharges and runoff depths are all less than 20%. This model has good applicability to the flood simulation of the mountain basins. On this basis, the analysis of flood laws can play an actual role in the flash flood warning and forecast.

(4) In this paper, the measured discharge at the outlet of the sub-basin is lacking in the model parameters calibration. The impact of small reservoirs on watershed simulations was not considered,
which affected the calculation accuracy of the model to some extent. In the later period, the reservoir unit needs to be added to the model to further improve the accuracy of the model.

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