Simulation Accuracy Analysis of HEC-HMS Distributed Hydrological Model under Different Objective Functions

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Abstract

The simulation effect of hydrological model is directly related to the selection of objective function, Different objective functions are very important for parameter determination. HEC - HMS hydrological models, for example, using the built-in Nelder-Mead algorithm for multi-parameter optimization of the model under four objective functions (SSR, sum of squares of residuals, PEPF, percent error in peak flow, PEV, percent error in volume flood volume errors, SAR, sum of absolute residuals absolute residuals), comparing model simulation optimization results, the influence of different objective functions on the simulation results is analyzed. Taking the upper reaches of Shouguang Basin in Shandong Province as the research area, the application of WMS and HEC - HMS hydrological model is set up, by setting up five kinds of objective function, from the error of the peak flow, the error of the actual, Nash coefficient and certainty factor four numerical indicators to evaluate simulation accuracy, comprehensive comparing the simulation result shows that in the sum of squared residuals (SSR) as the objective function is optimized simulation results on the overall effect is better.

Keywords

Hydrological simulation; Objective function; HEC-HMS model.

1. INTRODUCTION

With the development of computer technology, hydrological and hydrodynamic simulation software can be used to model and analyze flood accurately. With proper modeling, analysis, and management methods, its harmful effects can be minimized. These modeling and analysis techniques help in flood risk assessment, prediction of flood occurrence, emergency evacuation preparation and mitigation of flood impact damage. Due to the open source and simplicity of HEC-HMS/RAS, this paper adopts HEC-HMS/RAS as an exploratory hydro-hydraulic modeling research tool for flood simulation, and combines ArcGIS and Watershed Modeling System (WMS) to assist modeling. Hydrological model is a simplification and abstraction of the real world. The model contains parameters that are difficult to be measured directly. Therefore, it is necessary to calibrate the model parameters to obtain the values of these parameters indirectly [1] [2]. The accuracy of the model is usually determined by the structure and parameters of the model. At present, the value of some parameters cannot be directly calculated by the characteristics of the basin characteristics, and the parameters need to be optimized and calibrated in the actual simulation process. With the rapid development of computer technology and various mathematical algorithms, the automatic optimization of model parameters has been widely used, including the univariate-gradient search algorithm (Univariate-gradient), Markov chain Monte Carlo method (MCMC) and Nelder-Mead algorithm built into HEC -- HMS, as well as other

SCE-UA algorithms [3], particle swarm optimization algorithm [4], genetic algorithm [5] etc. In the process of parameter calibration of rainfall-runoff model, the selection of objective function directly affects the optimization results of model parameters, thus affecting the model accuracy [6] [7]. Oudin [8] et al. analyzed the influence of four different objective functions on the simulation optimization of the model in the case of different traffic levels. Zhangru-Qiang [9] et al. took the deformation form of Nash coefficient as the objective function to optimize the hydrological parameters in the upper reaches of Heihe River, so as to reveal the influence of each form on the overall simulation effect.

This study takes multiple floods in the Mi River Basin of Shandong Province, China as the research object, and uses the latest version of HEC-HMS 4.3 software and WMS Integrated Watershed Management Model to establish a comprehensive hydrological model for the basin. The model was optimized with multiple objective functions (SSR—sum of squared residuals, PEPF—percent error in peak flow, PEV—percent error in volume error, SAR—sum of absolute residuals) to compare the simulation performance of the whole body.

2. STUDY AREA AND DATA SOURCES

2.1. The Study Area

The study area-the Mi River Basin is located in the central part of Shandong Peninsula, China, with coordinates of 36°10’N~36°55’N and 118°20’E~118°50’E. It belongs to the continental climate of the warm temperate monsoon region, with annual average rainfall of 561.5mm, annual average evaporation of 1003.6mm, annual average temperature of 11.7 ~ 14.3°C, annual sunshine duration of 2450h, and southerly easterly winds prevailing most of the year. [10] The basin is composed of more than 150 rivers of different sizes, with a total length of 206km. The terrain is descending from southwest to northeast. The flow path is Linqu County, Qingzhou City and Shouguang City, with a total basin area of about 3863km^2 .Mi River has a large slope, rapid current and uneven width, with the widest point reaching 750m and the narrowest point only 25m.The average annual rainfall in this basin is 650.8mm, and the average annual water depth is 112.5mm. The Mi River is a mountain stream torrential flood channel, and its flow varies with the seasons. Heavy rain is concentrated in the flood season. Due to the direct influence of rainfall changes, the flood rises and falls sharply, and the flow is sometimes cut off in the dry season. [11].

In the history of the Mi River basin ten years of drought, in order to ensure that the downstream residents and livestock have a stable drinking water source, but also for Shouguang vegetable base to provide irrigation, in 1959, 1970, 1972, the Mi River upstream three control reservoirs: Yeyuan Reservoir, Songshan Reservoir and Black Hushan Reservoir. Among them, Yiyuan Reservoir has a control basin area of 786KM^2 , with a total storage capacity of 168.6 million m^3 , located in the main stream of the upper reaches of Mi River; Songshan Reservoir has a control basin area of 151km^2 , with a total storage capacity of 56.28 million m^3 , located in the upstream tributary; Heihushan Reservoir has a control basin of 190km^2 , with a total storage capacity of 536 million m^3 , located in another tributary of the upper reaches. Detailed reservoir data are shown in Table 1. In the downstream of Linqu County, the three reservoirs flow into the Mi River, jointly affecting the downstream Qingzhou City and Shouguang City. Mi River trunk flow through more highways, high-speed railway and other important traffic trunk lines. The map of Mi River Basin is shown in Figure 1, Figure 2.

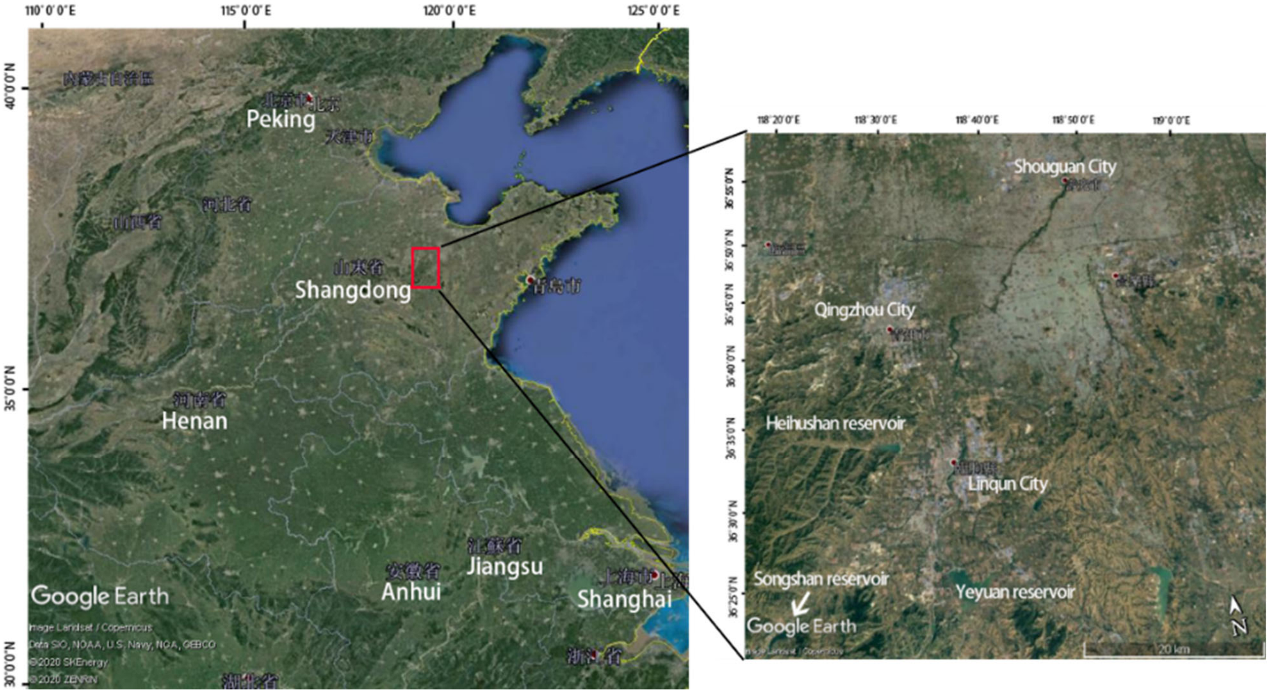


Figure 1. Location of the Study Area (1)

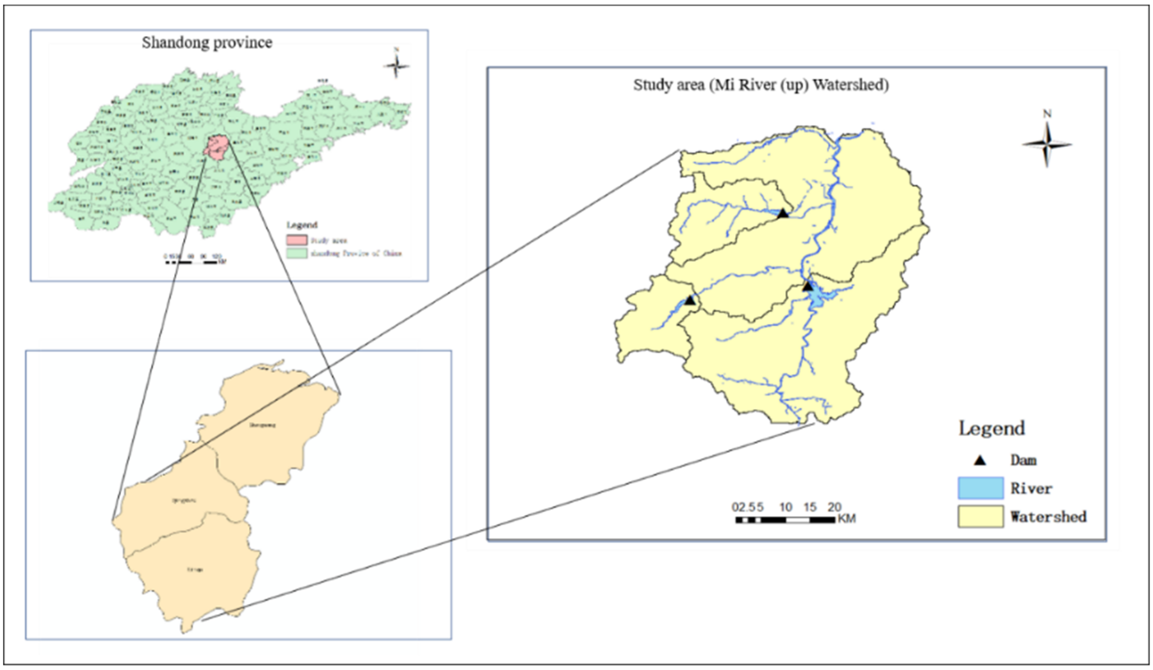


Figure 2. Location of the Study Area (2)

Table 1. Reservoir information

Reservoir Name	Total storage/1000 m^3	Controlled watershed area/Km^2	Normal reservoir level/m	Flood control level/m	Design flood level/m	Check flood level/m
Yeyuan	168600	786	137.25	137.72	138.76	141.18
Songshan	56280	151	—	289.0	289.77	292.10
Heihushan	53600	190	162.92	163.0	168.19	—

2.2. Data Source and Processing

DEM data is derived from geospatial data cloud (https://www.gscloud.cn/) with a resolution of 30m*30m, shown in Figure 3. The lower reaches of this region are the planting bases of greenhouse vegetables in China, while the upper reaches are mainly mixed crops, such as corn, various vegetables and soybeans. The upper mountain area is more, the main mountain to plant persimmon, peach fruit trees, but also a large amount of pepper trees. From China's state bureau of surveying and mapping (http://www.webmap.cn/mapDataAction.do?Method = GloballandCover) shows that the basin includes agricultural 49.75%, grassland herbaceous10.82%, forest 24.38%, urban 10.69%, water 1.14% and other land 3.2%.Soil type data from the United Nations food and agriculture organization (FAO), can be free from the network access (http://www.fao.org/home/en/),which accuracy is 1 km, shown in Figure.4.Rainfall and runoff data are provided by Shandong Provincial Hydrological Information Center. There are four rain-measuring stations (Yiyuan Station, Linqu Station, Qingzhou Station, Changle Station) and Tanjiafang Hydrological Station.

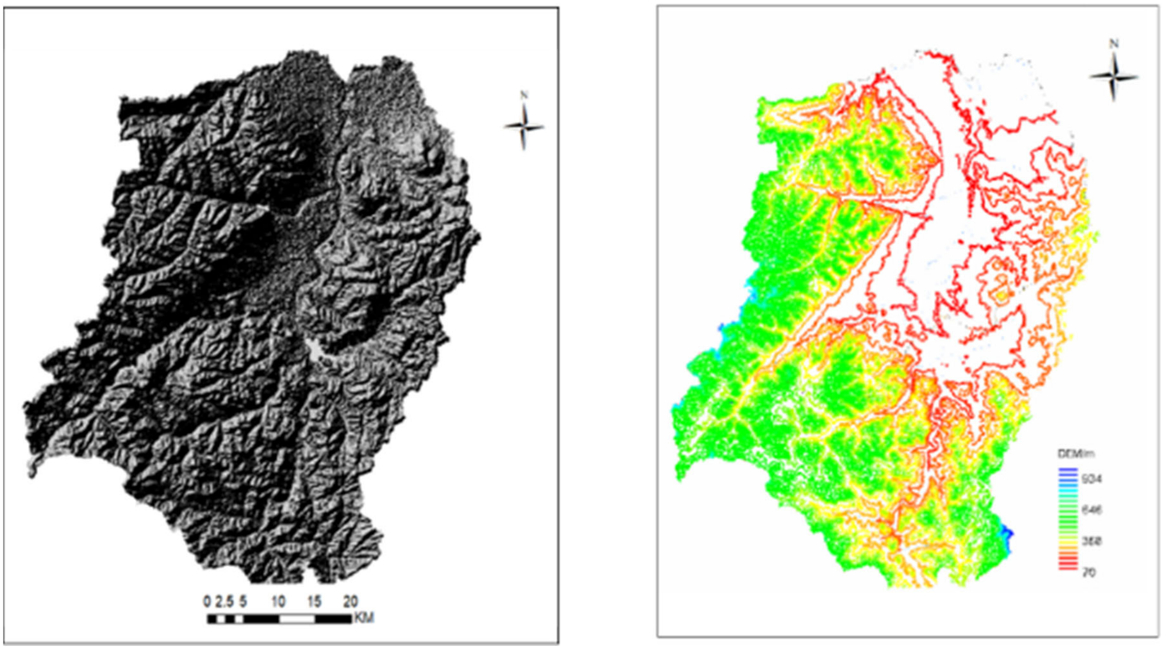


Figure 3. Watershed digital elevation DEM

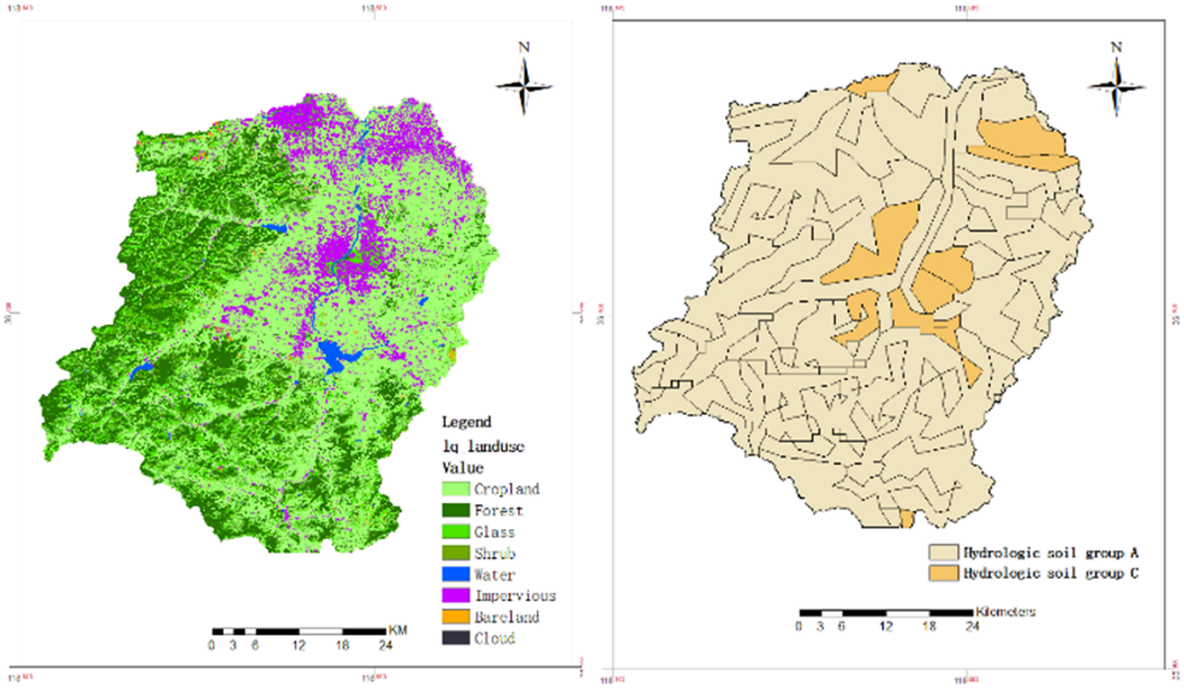


Figure 4. Landuse and soiltypes

The DEM in the study area was processed by ArcGIS10.2 and WMS10.1 (Watershed Modeling System) software. TOPAZ algorithm can automatically carry out processing steps such as depression filling, calculation of flow direction, calculation of confluence cumulant, river channel extraction, boundary extraction, sub-basin division, etc., so as to obtain the topographic features and river characteristic parameters of the basin, etc. [12]. As shown in the figure below, the basin is divided into four sub-basins and three main channels, namely 1B, 2B, 3B, 4B and 7R, 8R, 9R. The characteristic parameters are shown in the table.2.Finally, the HEC format can be derived from WMS and the watershed model can be established. According to the distribution of each rainfall station, the Tyson polygon is constructed, and the area weight of the Tyson polygon in each sub-basin is calculated. Finally, the rainfall is distributed to each sub-basin by area weight. The calculation formula is as follows:

$$\overline{P_J} = \frac{1}{A}\sum_{i=1}^{n} a_i p_i \tag{1}$$

Where, $\overline{P_J}$ is average surface rainfall for sub basin; a_i is the i-th a precipitation station in the j-th sub-basin; p_i is precipitation station rainfall; A is the area of A sub-basin.

Table 2. Characteristic parameters of watershed and channel

Basin	**Basin Area （km²）**	**maximun flow length （km）**	**basin length （km）**	**basin slope**	**maximun flow average slope**	**mean basin elevation （m）**
1B	962.26	68.06	48.10	0.10	0.0037	193.78
2B	223.39	17.68	21.21	0.25	0.0083	401.80
3B	777.53	44.62	31.30	0.15	0.0094	313.18
4B	165.29	13.81	19.36	0.24	0.0029	481.83

Reach code	**Reach length （km）**	**Energy slope (m/m)**	**Bottom width （m）**	**Side slope**	**n**
7R	35841.57	0.00242	200	0.5	0.035
8R	45926.36	0.00147	200	0.5	0.035
9R	68913.54	0.00288	200	0.5	0.035

3. METHODOLOGY

3.1. Construction of HEC-HMS Model

HEC-HMS is a physically-based semi-distributed hydrological model developed by the U.S. Army Corps of Engineers to simulate the hydrological response of catchments given hydrometeorological inputs, such as large river catchments and small urban or natural catchments. According to the obtained topographic and hydrometeorological data, ArcGIS and WMS software were used to set up reservoirs and outlet, divide molecular basins to extract river network water system, and the sub-basins and their confluence paths were generalized as shown in the figure 5. below.

HEC-HMS mainly includes four modules: watershed module, meteorological module, control module and time series data module. Among them, the watershed module is a generalization of rainfall-runoff model, including four parts: rainfall loss, direct runoff, base flow and river confluence, as well as engineering component structures such as reservoirs and dykes[20].Each part provides a variety of calculation methods, users can choose the most suitable scheme for runoff simulation according to the actual situation. According to the actual situation of Mi River Basin and the obtained basin data, the SCS-CN curve method, SCS-CN unit line method, exponential decay method and Masjingen-Chunge method are adopted in the four parts of this paper. As shown in Table 3 below.

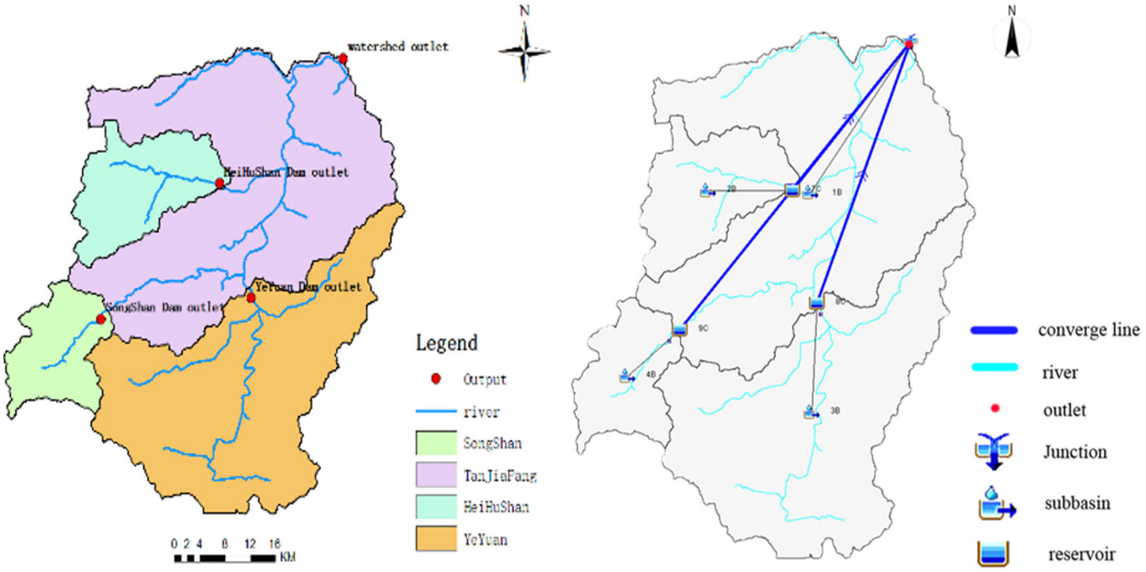


Figure 5. Generalized map of Mi River Basin

Table 3. Model method selection

Model	Loss method	Transform method	Baseflow method	Routing method
Method selection	SCS Curve Number Loss	SCS Unit Hydrograph Transform	Recession Baseflow	Muskingum-Cunge Routing

(1) SCS-CN curve method. As a method to determine hydrological loss, SCS-CN curve method has the advantages of simple parameters and easy data acquisition, and fully considers the different characteristics of the underlying surface, so it has been widely used in the calculation of rainfall runoff in the basin. The CN value is an index developed by the Natural Resources Conservation Service of the United States Department of Agriculture based on land use, soil type, and soil water content[13], ranging from 0 to 100. The higher the value, the greater the surface runoff. The SCS-CN method is suitable for catchment studies and has been used in many hydrological models. The SCS-CN model is given by Equation (2):

$$Q = \frac{(P-I_a)^2}{(P-I_a+S)} \tag{2}$$

Where, Q is runoff (mm); P is precipitation (mm); Ia is the initial loss (mm); S is the potential maximum water storage.

The empirical relationship between Ia and S obtained by the Soil Conservation Service (SCS) from a large number of experimental rainfall-runoff data is as follows: λ=0.2, that is, before the accumulated rainfall exceeds the initial infiltration amount, there will not be excessive precipitation resulting in runoff, so:

$$\mathrm{Q} = \frac{(\mathrm{P}-0.2\mathrm{S})^2}{\mathrm{P}+0.8\mathrm{S}} \quad , \qquad \mathrm{P} > 0.2\mathrm{S} \tag{3}$$

$$\mathrm{Q} = 0, \mathrm{P} \leq 0.2\mathrm{S} \tag{4}$$

There is a correlation between the potential maximum storage capacity (S) and the number of basin characteristic curves (CN). It can be seen from the SCS Hydrological Manual that the empirical conversion relationship between S and CN values is as follows:

$$\mathrm{S} = \frac{25400}{\mathrm{CN}} - 254 \tag{5}$$

$$CN = \frac{25400}{254+S} \tag{6}$$

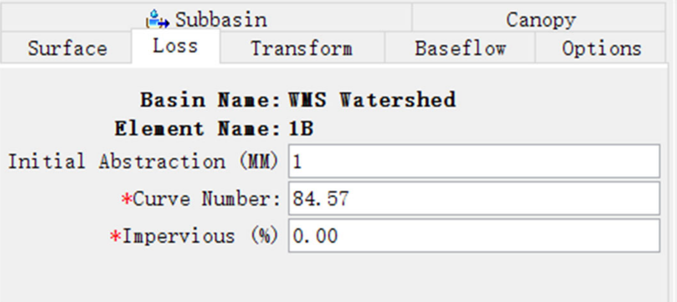
In the formula, CN value is a comprehensive parameter reflecting the characteristics of the basin, and is related to soil type, land use, soil moisture in the early stage, hydraulic conditions, topography and landform. In this study, the CN value was mainly calculated based on land use - soil type - hydrological soil group [20]. The larger the value of CN, the smaller the amount of infiltration before rainfall and the larger the runoff.CN value was calculated using the WMS hydrological modeling system.

a) By referring to the data of similar study areas and the HEC-HMS reference manual, the initial loss Ia of the sub-basin was estimated

b) The hydrological and soil group map, land use and other attribute data were superimposed in the hydrological module of WMS for calculation and processing, so as to obtain the CN value of each sub-basin.

c) The impervious rate of each sub-basin is estimated according to factors such as urbanization level and proportion of construction land, and the impervious rate is set as 20%, 10%, 10% and 10% respectively.

The loss model setting interface is as shown in Figure 6.



Basin Name: WMS Watershed
Element Name: 1B
Initial Abstraction (MM) 1
*Curve Number: 84.57
*Impervious (%) 0.00

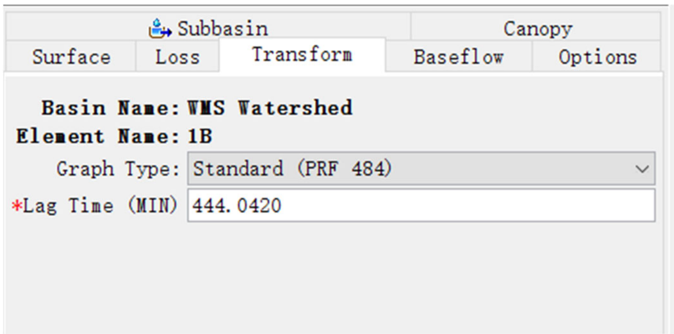
Figure 6. Parameter setting of Hec-hms loss model

(2) SCS Unit Hydrograph. The SCS unit line method was originally derived from the observed data collected from small agricultural basins. The calculation parameters only need to determine the lag time, which is defined as the time between the precipitation centroid and the peak flow of the hydrological process line [19]. Its value can be comprehensively calculated by WMS according to basin characteristic parameters. The calculation formula is as follows:

$$\mathrm{Lag} = \frac{\mathrm{L}^{0.8}(\mathrm{S}+1)^{0.7}}{1900 * \mathrm{Y}^{0.5}} \tag{7}$$

Where, Lag refers to the catchment Lag time (H); S is the potential maximum water storage; L is the length of river channel (m); Y is the average slope of the basin (%)

The transform model setting interface is as shown in Figure 7.



Basin Name: WMS Watershed
Element Name: 1B
Graph Type: Standard (PRF 484)
*Lag Time (MIN) 444.0420

Figure 7. Parameter setting of HEC-HMS direct runoff model

(3) Exponential recession. Basal flow is an important parameter in flood studies because it defines the maximum creek depth at which additional runoff accumulates. A model that ignores the base flow may underestimate the water level and therefore fail to identify the flooded reach.[14] Baseflow is modeled using an exponential decrease function, According to this model, the relationship between the base flow Qt(m3/s) at any time t and the initial value is:

$$Q_t = Q_0 * K^t \tag{8}$$

Where, Q_0 is the initial base flow, and the perennial runoff is selected, m^3/s; K is exponential decay constant

(4) Maskingen-Chunge method. The Maskingen-Chunge method is an evolutionary method based on the conservation of mass and momentum laws. In the evolution process of this method, the evolution parameters will be recalculated at each step according to the characteristics of river channel and water depth.

The initial parameters of each sub-basin and river channel are shown in the table 4 below.

Table 4. Initial parameters of each sub-basin and river channel

Sub-basin	Model Method	Canopy Simple Canopy		Surface Simpla Surface		Loss model SCS-CN			Transform SCS-UH	Baseflow Recession		
	Parameters	Initial Storage (%)	Max Storage (mm)	Initial Storage (%)	Max Storage (mm)	Abint (mm)	CN	Impervious (%)	Lag Time (min)	ID (m³/s)	Constant	Ration
1B		50	10	50	10	1	84.57	0	444.04	20	0.5	0.5
2B		50	10	50	10	1	86.8	0	140.62	5	0.5	0.5
3B		50	10	50	10	1	83.26	0	285.01	5	0.5	0.5
4B		50	10	50	10	1	83	0	116.08	5	0.5	0.5

Reach	Model Method	Routing Muskingum-Cunge			
	Parameters	ID (m³/s)	Manning’ n	Side Slope	Slope
7R		5	0.035	0.2	0.0024
8R		20	0.035	0.2	0.0015
9R		5	0.035	0.2	0.0029

3.2. Parameter Calibration Optimization

In the HEC-HMS hydrological model, each method has many kinds of parameters. Some parameters, such as slope, slope aspect, confluence network, watershed boundary, etc., can be determined according to the hydrological information of the basin, but some parameters are difficult to be determined or have no practical significance, such as canopy interception, surface area water, Manning coefficient N, CN value, watershed lag time L_t, Base-flow attenuation coefficient R_c, The CN value and watershed lag L_t is based on the whole watershed land use type, distribution and channel situation to calculate, but because of the dynamic error exists, it still need to these parameters using artificial method of combining the trial and error and optimization algorithms for parameter optimization rate. For manual parameter adjustment, researchers are required to have rich practical experience and rich and accurate measured data. The optimization algorithm can help us solve the global optimization problem of parameters quickly and easily. HEC-HMS provides three optimization algorithms and eight optimization objective functions [15]. In this paper, Nelder-Mead optimization algorithm [16] is adopted to optimize the parameters.

Nelder-Mead optimization algorithm (Nelder-Mead), also known as the descending simplex method, is a numerical method applied to the heuristic search for the minimum or maximum value of the objective function in the multi-dimensional unconstrained problems. It is usually used to solve the multi-dimensional nonlinear optimization problems that may not know the derivative. The optimization process of model parameters is shown in the figure 8 below.

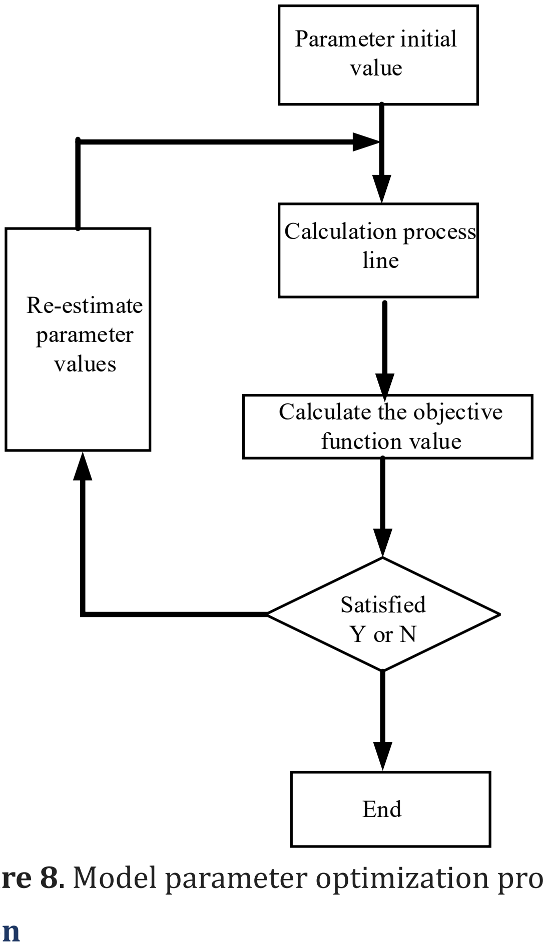


Figure 8. Model parameter optimization process

3.3. The Objective Function

The quantitative measure of the goodness-of-fit between the computed result from the model and the observed flow is called the objective function. The simulation effect of hydrological model is directly related to the selection of objective function[18].For the HEC-HMS rainfall-runoff model, the measured discharge at the drainage outlet section is generally adopted to calibrate the model, and the simulation effect of the model is evaluated by comparing the gap between the two. In this paper, four of the most widely used objective functions provided by HEC-HMS are selected [18].

(1) SSR—sum of squared residuals

$$SSR = \sum_{t=1}^{n}[Q_0(t) - Q_S(t)]^2 \tag{9}$$

Where, $Q_0(t), Q_S(t)$ are respectively measured outlet section flow and simulated flow at time t

(2) PEPF—percent error in peak flow

$$PEPF = \left|\frac{Q_0(peak)-Q_S(peak)}{Q_0(peak)}\right| \times 100\% \tag{10}$$

(3) PEV—percent error in volume

$$PEV = 100\% \times \left|\frac{V_0-V_S}{V_0}\right| \tag{11}$$

Where, V_0, V_S are measured flood volume and simulated flood volume respectively

(4) SAR—sum of absolute residuals

$$SAR = \sum_{t=1}^{n}|Q_0(t) - Q_S(t)| \tag{12}$$

Where, $Q_0(t), Q_S(t)$ are respectively measured outlet section flow and simulated flow at time t

3.4. Accuracy Evaluation

It is necessary to evaluate the reliability, accuracy and error of hydrological forecast scheme and its published forecast value. In this flood simulation, the flood forecast and forecast accuracy shall comply with the relevant provisions of the Hydrological Information and Forecast Specification (GB22482-2008). Four objective functions were set to evaluate the simulation accuracy from the following four indicators:

(1) Error of peak discharge

$$P = \frac{Q_0-Q_i}{Q_i} \times 100\% \tag{13}$$

$Q_i$is measured;$Q_0$is simulate values;$\bar{Q}$ as the measured average series; N is the point data number of the measured sequence

(2) The error of the actual

$$V = \frac{\sum_{i=1}^{n}(Q_0-Q_i)}{\sum_{i=1}^{n}Q_i} \tag{14}$$

(3) Nash coefficient

Nash coefficient (E) is the most widely used objective function in model calibration and also an important numerical index to evaluate the simulation effect. The calculation formula of Nash coefficient is as follows:

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Q_i - Q_0)^2}{\sum_{i=1}^{n}(Q_i - \bar{Q})^2} \tag{15}$$

(4) Coefficient of certainty

$$DC = 1 - \frac{\sum_{i=1}^{n}[Q_0 - Q_i]^2}{\sum_{i=1}^{n}[Q_i - \bar{Q}]^2} \tag{16}$$

4. RESULTS AND DISCUSSION

This paper from China's shandong province the basin hydrological information center for the decade four larger flood data in detail, the Numbers 20120802, 20130725, 20180817 and 20190808 respectively, through the data preprocessing, initial parameters setting, etc., using WMS software and HEC - HMS build the watershed hydrological models, and to simulate the four flood precipitation, runoff, and respectively by using the above four kinds of objective function parameters optimization and precision evaluation.

4.1. Determination of Initial Parameter Values

The canopy interception and surface water fractions in the rainfall loss model can refer to the recommended values given by the U.S. Army Corps of Engineers for such climate conditions[21].The Initial Discharge in the base flow model may vary before each rainstorm and is allocated according to the catchment area of each catchment, Recession Constant and Ratio were input into the model with the recommended values of 0.7~0.95 in the same latitude area. The CN value needed to be input by SCS curve method in the loss model can be calculated in WMS software according to the land use, soil type distribution and previous moisture table in the Mi River Basin. The initial parameter values are shown in the following table 5.

Table 5. Initial parameter values of Mi River Basin (upper reaches)

Sub-basin	**Model**	**Canopy**		**Surface**		**Loss model**			**Transform**	**Baseflow**		
	Method	**Simple Canopy**		**Simpla Surface**		**SCS-CN**			**SCS-UH**	**Recession**		
	Parameters	**Initial Storage (%)**	**Max Storage (mm)**	**Initial Storage (%)**	**Max Storage (mm)**	**Ab_{int} (mm)**	**CN**	**Impervious (%)**	**Lag Time (min)**	**ID (m^3/s)**	**Constant**	**Ration**
1B		50	10	50	10	1	84.57	0	444.04	20	0.78	0.80
2B		50	10	50	10	1	83	0	140.62	5	0.80	0.80
3B		50	10	50	10	1	83.26	0	285.01	5	0.85	0.80
4B		50	10	50	10	1	83	0	116.08	5	0.88	0.80

4.2. Analysis of Model Application Results

By adopting four different objective functions, the Nelder-Mead algorithm of HEC-HMS model was used to conduct parameter optimization and calibration for the four floods, and the simulation results of the four floods were compared, as shown in Figure 9. below. The index error analysis of different objective functions is shown in Table 6. below.

Table 6. Error analysis of each index of different objective function

Flood number	Measured flood data		Initial parameter simulation results					
	Measured peak flow(m³/s)	Measured total flood(m³)	Initial simulated flood peak flow(m³/s)	Initial simulated flood volume(m³)	Flood peak flow error/%	Flood error/%	Coefficient of certainty/%	NSE
20120802	770	27776.9	1120	30264.9	45.45%	8.96%	0.62	0.60
20130726	259	14035	230	14348.8	-11.00%	2.24%	0.62	0.76
20180818	2250	65903.2	3280	101355.2	45.78%	53.79%	0.31	0.40
20190810	3550	70764	3780	90275.2	8.00%	27.57%	0.76	0.78
Average					22.05%	23.14%	0.57	0.60

Flood number	SSR						PEPF					
	SSR Simulated flood peak flow(m³/s)	SSR Simulated total flood(m³)	Flood peak flow error/%	Flood error/%	Coefficient of certainty/%	NSE	MSR Simulated flood peak flow(m³/s)	MSR Simulated total flood(m³)	Flood peak flow error/%	Flood error/%	Coefficient of certainty/%	NSE
20120802	1120	30264.9	6.49%	4.03%	0.96	0.90	890	31969.3	15.58%	15.09%	0.89	0.90
20130726	230	14348.8	-1.97%	0.01%	0.92	0.92	252.1	13500.5	-2.66%	-3.88%	0.91	0.91
20180818	3280	101355.2	0.01%	0.01%	0.95	0.95	2154.8	66910.9	-5.08%	1.86%	0.94	0.94
20190810	3593.3	72234.2	0.01%	0.01%	0.96	0.96	3180	70412.6	2.67%	2.08%	0.95	0.95
Average			2.12%	0.01%	0.95	0.93			6.50%	5.72%	0.92	0.92

Flood number	PEV						SAR					
	PEV Simulated flood peak flow(m³/s)	PEV Simulated total flood(m³)	Flood peak flow error/%	Flood error/%	Coefficient of certainty/%	NSE	SAR Simulated flood peak flow(m³/s)	SAR Simulated total flood(m³)	Flood peak flow error/%	Flood error/%	Coefficient of certainty/%	NSE
20120802	988.2	31352.6	28.34%	12.87%	0.76	0.78	975.7	32489.7	26.71%	16.97%	0.86	0.83
20130726	284.8	14003.7	9.96%	-3.81%	0.69	0.69	262.3	12606.2	1.27%	-0.22%	0.76	0.62
20180818	1763.7	59082.1	-4.23%	1.53%	0.85	0.84	2255.4	69116.5	-21.61%	-10.35%	0.94	0.94
20190810	3206.8	71337.7	-9.14%	-0.50%	0.95	0.95	3526.5	72418.2	-8.38%	0.81%	0.96	0.96
Average			12.91%	4.67%	0.81	0.80			14.50%	7.08%	0.88	0.83

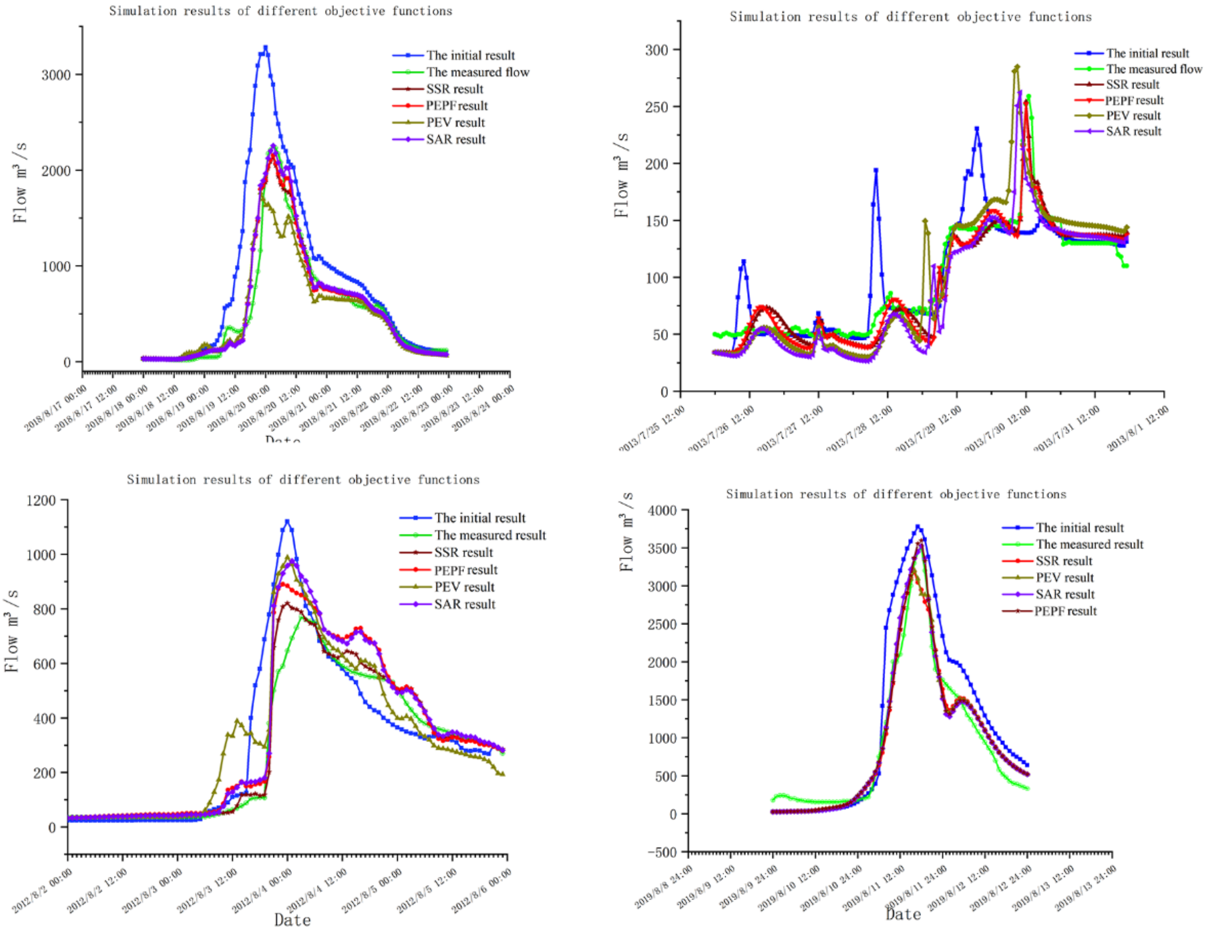


Figure 9. Simulation results of four flood processes

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REFERENCES

[1] Vrugt J A, Gupta H V, Bouten W, et al. A Shuffled Complex Evolution Metropolis algorithm for optimization and uncertainty assessment of hydrologic model parameters[J]. Water resources research, 2003, 39(8).

[2] Muleta M K. Model performance sensitivity to objective function during automated calibrations[J]. Journal of hydrologic engineering, 2012, 17(6): 756-767.

[3] Hapuarachchi H. A. P.,LI Zhijia, WANG Shouhui. Application of SCE-UA Method for Calibrating the Xinanjiang Watershed Model. J. Lake Sci.2001,13(4):304-314. DOI:10.18307/20010404

[4] Zhang Wenming, Dong Zengchuan, Zhu Chengtao, Qian Wei. Multi-objective optimization of hydrological model parameters based on particle swarm optimization [J]. Journal of Hydraulic Engineering,2008(05):528-534.

[5] Cheng C T, Zhao M Y, Chau K W, et al. Using genetic algorithm and TOPSIS for Xinanjiang model calibration with a single procedure[J]. Journal of Hydrology, 2006, 316(1-4): 129-140.

[6] Diskin M H, Simon E. A procedure for the selection of objective functions for hydrologic simulation models[J]. Journal of Hydrology, 1977, 34(1-2): 129-149.

[7] Servat E, Dezetter A. Rainfall-runoff modelling and water resources assessment in northwestern Ivory Coast. Tentative extension to ungauged catchments[J]. Journal of Hydrology, 1993, 148(1-4): 231-248.

[8] Oudin L, Andréassian V, Mathevet T, et al. Dynamic averaging of rainfall-runoff model simulations from complementary model parameterizations[J]. Water Resources Research, 2006, 42(7).

[9] Zhang Ruqiang, Gao Hongkai, Liu Junguo, et al.Study on the influence of different objective functions on the simulation effect of hydrological model [J]. China Rural Water and Hydropower,2017,4.

[10] Yang Yingjia, Zhang Danrong, Zhuang Huibo, Liu Jiang, Guan Yiqing, Shao Guangwen. Spatial-temporal variation of groundwater depth and its exploitability in the plain area of Mihe River Basin [J]. Journal of Water Resources and Water Engineering, 2019, 30(06): 102-108.

[11] Xiang Zheng, Du Zhande, Wang Haijun. Enlightenment from joint operation of reservoir groups in Mihe River Basin in Shandong Province in flood season in 2018 [J/OL]. Flood Control and Drought Relief in China: 1-4 [2020-04-04].https://doi.org/10.16867/J.ISSN.1673-9264.492899999896

[12] O'Callaghan J F, Mark D M. The extraction of drainage networks from digital elevation data[J]. Computer vision, graphics, and image processing, 1984, 28(3): 323-344.

[13] Mockus V. National engineering handbook[J]. US Soil Conservation Service: Washington, DC, USA, 1964, 4.

[14] Knebl M R, Yang Z L, Hutchison K, et al. Regional scale flood modeling using NEXRAD rainfall, GIS, and HEC-HMS/RAS: a case study for the San Antonio River Basin Summer 2002 storm event[J]. Journal of Environmental Management, 2005, 75(4): 325-336.

[15] Scharffenberg W, Ely P, Daly S, et al. Hydrologic modeling system (HEC-HMS): Physically-based simulation components[C]//2nd Joint Federal Interagency Conference, Las Vegas, NV. 2010.

[16] Bian Yida. Urban Rain and Flood Simulation Based on HEC-HMS and SWMM [D]. Shandong University, 2014

[17] Fu Z, Yin D, Zhao W, et al. Assemblies of Ti Active Sites Over HMS Supports Containing Surface's OH or NH 2 Groups[J]. Catalysis letters, 2003, 90(3): 205-212.

[18] Gan T Y, Dlamini E M, Biftu G F. Effects of model complexity and structure, data quality, and objective functions on hydrologic modeling[J]. Journal of hydrology, 1997, 192(1-4): 81-103.

[19] Peters J C. HEC-HMS Hydrologic Modeling System: User's Manual[M]. US Army Corps of Engineers, Hydrologic Engineering Center, 1998.

[20] USACE. Hydrologic Modeling System HEC-HMS User's Manual[M]. US: Hydrologic Engineering Center, CA, 2013.

[21] Legates D R, McCabe Jr G J. Evaluating the use of “goodness-of-fit” measures in hydrologic and hydroclimatic model validation[J]. Water resources research, 1999, 35(1): 233-241.