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# The Application of HEC-HMS in Mountain Torrents Simulation of Northern Small Watershed

Shanshan Zhang<sup>1,a</sup>, Jiangting Wang<sup>2,b</sup> and Zhenghe Xu<sup>1,\*</sup>

<sup>1</sup>School of Water Conservancy and Environment, University of Jinan, Jinan, China

<sup>2</sup>HuBei Jinhoseten Engineering Consulting Co., LTD, Wuhan, China

\*Corresponding author e-mail: xu4045@126.com, <sup>a</sup>zssylyx33@163.com,  
<sup>b</sup>214495375@qq.com

**Abstract.** In hilly areas of northern China, frequent mountain torrents have seriously threatened the security of people's lives and properties. For those flood-prone hilly areas lack of hydrological data, this paper took the Tongtian river small watershed as the research area, and used HEC-GeoHMS module to preprocess the DEM of 30m\*30m, then established the HEC-HMS model of the research area. By comparison and analysis of methods, this paper adopted respectively initial loss and steady seepage method, Snyder unit hydrograph method, exponential attenuation method, Muskingum method to simulate the calculations of runoff yield, direct runoff, base flow and river flood routing accordingly, then chose 7 floods to calibrate parameters and 3 floods to verify them. The results showed that the occurrence time of simulated flood peak was close to that of observed flood peak, and the error of flood peak flow calculation was within 10%. The good applicability of HEC-HMS model was demonstrated with the results of the simulation, and HEC-HMS model can be applied to the calculation and analysis of rainfall-flood process in the actual small hilly watershed. This research may provide the reference for the prevention and control of mountain torrents effectively.

## 1. Introduction

In small watersheds of northern China, the frequent mountain torrents, which could be caused by heavy rainfall, or other factors, have threaten the security of people's lives and properties seriously in those flood-prone hilly areas. Therefore, it is of great significance to clarify hydrological processes such as the relationship between water level and flow in those regions, so as to prevent mountain floods effectively and minimize losses.

HEC-HMS model was a distributed hydrological model, which was developed by the United States Army Corps of Engineers. It mainly had four calculation stages, namely, runoff yield, direct runoff, base flow and river flood routing. In each stage, a variety of calculation methods were provided with wide applicability. Zhang Jianjun et al. evaluated the applicability of HEC-HMS model by using the observed hydrological data in 2004 - 2006 from a Chinese National Ecosystem Observation and Research Station located in Jixian County of Shanxi province [1]; Li Yan et al. selected HEC-HMS model to simulate 10 floods in Zhongtang River basin of Henan Province, and the relative error of flood peak was within 20% [2]; Lu Bo et al. adopted HEC-HMS model to simulate 5 floods in



Wanjiabu River basin of Jiangxi Province, which had good applicability [3]; Given the above, HEC-HMS model was selected in this paper to simulate and analyze rainfall-flood processes in the research area.

## 2. Overview of the research area

In this paper, the Tongtian river basin, which was located at about 117 °23 ' ~ 117 °37'E, 36 °24 ' ~ 36 °33 'N in the northern mountainous area of Laiwu city, was chosen as the research area. The Tongtian River originated from Hongshaozi village in Xueye town, and flowed into Xueye reservoir. The total length of Tongtian River was 16.1 km, and its basin area was 98 km<sup>2</sup>. The rainfall in the research area varied greatly from year to year, with the precipitation from October to April accounting for about 1/4 of the whole year; it is a shell-shaped topography with three sides of east, west, and north high and south low. The surface was covered by bluestone weathered soil layer, which could be saturated easily and more likely to generate runoff when rainfall occurs. The research area was 126.91 km<sup>2</sup>, of which arable land accounted for 88.1%, while forest land, grassland and swamp land accounted for 8.32%, housing construction 3.2%, the land used for construction and water conservancy facilities 0.23%, and other land use 0.15%. The main soil types in this area were brown soil, coarse bone soil and cinnamon soil.

## 3. Research methods

### 3.1. Runoff yield

Comparison of methods: initial loss and steady seepage method is suitable for short-term rainfall-runoff process, which require few parameters and was easy to use; the CN value table in SCS curve method is derived from the data of small agricultural catchment area in the United States, which is still uncertain to other regions [4]; Green and Ampt method required many parameters, which are difficult to calibrate, and it has not been widely applied yet; the break-even constant method should be combined with the atmospheric model for evapotranspiration calculation; SMA method is suitable for long series continuous simulation calculation; Grid SCS curve method is to apply SCS curve method to independently calculate the runoff yield in each grid cell of the basin, and its principle is similar to SCS curve method; accordingly, Grid SMA method is similar to SMA method. To sum up, the initial loss and steady seepage method was selected for the calculation of runoff yield in this study.

The formula for calculating net rain by initial loss and steady seepage method is as follows [4]:

$$P_{et} = \begin{cases} 0, & \sum P_i < I_a \\ P_t - f_c, & \sum P_i > I_a, P_i > f_c \\ 0, & \sum P_i > I_a, P_i < f_c \end{cases} \quad (1)$$

Where,  $P_{et}$  is the calculated net rainfall (mm);  $I_a$  is the antecedent influenced rainfall (mm);  $P_t$  is the cumulative rainfall for time  $t$  to  $t+\Delta t$  (mm);  $P_i$  is the cumulative rainfall (mm);  $f_c$  is the maximum soil infiltration capacity (mm).

### 3.2. Direct runoff

Comparison of methods: Synder unit hydrograph method associate a unit hydrograph characteristics (such as peak flow) with a catchment characteristics to form a synthetic unit hydrograph [4]; the unit hydrograph specified by the user is only suitable for rainstorm analysis with the same duration, and it could be difficult to obtain data; SCS unit hydrograph is derived from the small agricultural catchment areas in the United States with a large number of rainfall runoff records, and it assumes that the unit hydrograph of the basin had a single peak, which is uncertain to be applicable to the research area; Clark unit hydrograph and Modclark unit hydrograph only consider water storage in catchment area, and the latter is often combined with grid loss method; due to the numerical characteristics of the

algorithm, the dynamic wave model is only suitable for river basins whose area is less than 1 square mile. In conclusion, Snyder unit hydrograph was selected for direct runoff calculation in this study.

Snyder unit hydrograph took flood peak delay, flood peak flow and total rainfall time as the characteristic values of the unit hydrograph [5]. In the standard unit hydrograph, the relationship between flood peak delay  $t_p$  and rainfall duration  $t_r$  was as follows [6]:

$$t_p = 5.5t_r \quad (2)$$

If there is a big difference between the rainfall duration of the unit hydrograph and the standard unit hydrograph in the actual research area, then:

$$t_{pr} = t_p - \frac{t_r - t_{rr}}{4} \quad (3)$$

Where,  $t_{pr}$  is the flood peak delay time of unit hydrograph in the research area;  $t_{rr}$  is the duration of unit hydrograph required in the research area.

At this point, the relationship between the flood peak delay time  $t_{pr}$  and the flood peak  $U_{pr}$  of the unit hydrograph in the research area was as follows:

$$\frac{U_{pr}}{A} = C \frac{C_p}{t_{pr}} \quad (4)$$

Where,  $C_p$  is the peak coefficient;  $C$  is the conversion constant, which is equal to 0.75 in the international system of units;  $A$  is the area of the study region.

### 3.3. Base flow

Comparison of methods: exponential attenuation method has fewer parameters; linear reservoir method is often used in conjunction with SMA method; the monthly constant flow method assumes that the monthly base flow is constant, and the initial value needs to be determined based on the multi-year runoff data of the basin [6]. In conclusion, exponential attenuation method was selected to calculate the basic flow in this study.

Exponential attenuation method involves some parameters such as initial base flow  $Q_0$ , attenuation constant  $K$  and threshold flow. Suppose the relationship between base flow  $Q_t$  and initial base flow  $Q_0$  at any time is [7]:

$$Q_t = Q_0 K^t \quad (5)$$

### 3.4. River flood routing

Comparison of methods: Muskingum method has fewer parameters and is easy to calibrate; dynamic wave method needs to collect many parameters information such as river section shape; modified puls method assumes no lateral inflow [4]; delay method is the simplest, and it only sets the lag time as a parameter, but assumes that the inflow is equal to the outflow, and the shape of the process line remains unchanged; Muskingum-Cunge method recalculates parameters at each time step and distance step, and section size, roughness, energy gradient and section length need to be specified. To sum up, Muskingum method was adopted for the calculation of river flood routing in this study.

Muskingum method is a method of river flood routing calculation, which is based on tank storage equation and water balance equation. The equation of river flow is [8, 9]:

$$Q_2 = C_0 I_2 + C_1 I_1 + C_2 Q_1 \quad (6)$$

$$\begin{cases} C_0 = \frac{0.5\Delta t - Kx}{K - Kx + 0.5\Delta t} \\ C_1 = \frac{0.5\Delta t + Kx}{K - Kx + 0.5\Delta t} \\ C_2 = \frac{K - Kx - 0.5\Delta t}{K - Kx + 0.5\Delta t} \end{cases} \quad (7)$$

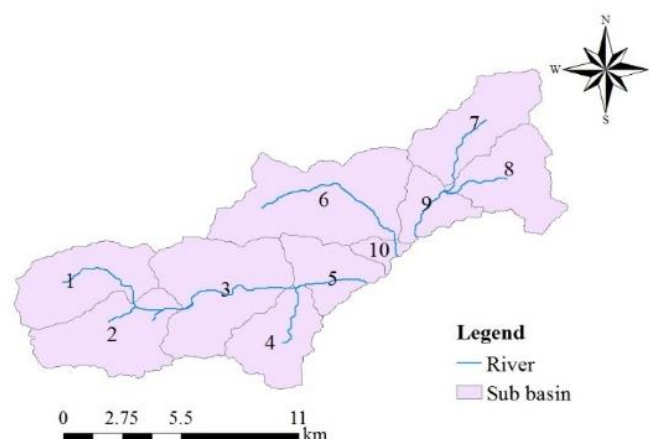
$$C_0 + C_1 + C_2 = 1 \quad (8)$$

Where,  $I_1$  and  $I_2$  are respectively the inlet flow of the upstream section at the beginning and end of the channel ( $\text{m}^3/\text{s}$ );  $Q_1$  and  $Q_2$  are respectively the outflow of the downstream section at the beginning and end of the channel ( $\text{m}^3/\text{s}$ );  $\Delta t$  is the calculating time (h);  $K$  is the propagation time of the reach under steady flow;  $x$  is the flow proportion factor.

#### 4. The application of HEC-HMS model

##### 4.1. River flood routing

**4.1.1. Data preprocessing.** HEC-GeoHMS module was used to fill in 30 m\*30 m DEM, and D8 method was applied to clear the flow direction. When the threshold value was 4500 by trial and error method, the river network, which was extracted by the flow confluence with the HEC-GeoHMS module Stream Definition tool, was more practical. Divided the river into sections according to the junction point of the river, and generated Stream Link through HEC-GeoHMS module, then obtained the node diagram of the river network. Based on junction diagram of river network and flow direction diagram, Catchment Grid Delineation tool was used to grade each section of the river to obtain the sub basins of each section, then used Drain Line Processing tool to vectorize the Grid Catchment diagram. Selected the water outlet on the basin map, and the sub basins were automatically divided according to the water outlet by HEC-GeoHMS module, so as to generate the digital water system map in the research area. See figure 1 for 10 sub basins in the research area.



**Figure 1.** River network and sub basins in the research area.

**4.1.2. HEC-HMS model building in the research area.** Watershed module. Through the analysis of HEC-GeoHMS module, the basin structure diagram was generated. Through HMS-Schematic function,

the watershed module building was imported into the HEC-HMS model. Based on the results of module calculation, the model automatically generated the watershed model in the research area.

Meteorological module. 7 floods, which were in 1960 - 2010 from the upstream rainfall station in the research area, were selected for parameters calibration. Rainfall-runoff data were imported into the HEC-HMS model through HEC-DSS module. 3 rainfall data in 2010 - 2016 were selected for verification. The simulation time step was set as 15 min, and the cumulative rainfall and observed flow data series of 15 min for each rainfall were obtained by interpolation.

The process of model building was mainly the establishment of Watershed module and meteorological module, while the control module and time series module were mainly set up in the process of model simulation.

#### 4.2. Parameter calibration and validation

*4.2.1. Parameter calibration method.* Manual parameter tuning will not make parameters deviate from the actual physical meaning, but it takes much time and effort. The objective function optimization method is simple and convenient to search by function, but it may ignore the actual physical meaning of parameters. Therefore, this paper combined the two methods to adjust the model parameters.

*4.2.2. Calibration and validation results.* According to the 'mountain flood disaster analysis and evaluation report of Laicheng district', the initial soil loss of rainfall in the research area was 10 mm, and the stable infiltration rate was 1.56-3.66 mm/h. The basic values of parameters were shown in table 1. Based on HEC-HMS model, 7 rainfall-flood processes were simulated, and Nardes optimization method and peak weighted mean square root objective function were used to optimize parameters, and the results were shown in table 2. The simulation results of 10 floods in the research area (the first 7 floods were calibrated and the last 3 floods were used for verification) were shown in table 3.

**Table 1.** Basic values of parameters for runoff yield calculation in the research area.

Sub basin number	Initial soil loss of rainfall/mm	Impervious area/%	Stable infiltration rate/mm h <sup>-1</sup>	Area/km <sup>2</sup>
1	10	2.3	2.24	14.44
2	10	3.2	3.51	15.14
3	10	7.6	2.26	20.72
4	10	1.3	3.66	10.65
5	10	8.9	1.88	8.1
6	10	5	2.5	24.33
7	10	1.8	2.6	13.23
8	10	0	3.3	12.29
9	10	3.1	3.34	6.12
10	10	1.2	1.56	1.89

**Table 2.** Calibration results of parameters in the research area.

Sub basin number	Synder unit hydrograph						Exponential decay method			Muskingum method	
	$T_p$ /h	$L$ /km	$L_c$ /km	$C$	$C_t$	$C_p$	Base flow $/m^3 s^{-1} km^{-2}$	Attenuation index	Rate of turning point of backwater	$K/h$	$x$
1	2.9	5.3	2.5	0.75	1.80	0.47	0.28	0.7	0.2	0.45	0.15
2	2.2	3.3	1.4	0.75	1.85	0.55	0.28	0.7	0.2	0.50	0.20
3	3.2	5.7	2.7	0.75	1.90	0.46	0.34	0.7	0.2	0.45	0.15
4	3.1	4	2.6	0.75	2.05	0.45	0.31	0.7	0.2	0.45	0.15
5	2.9	3.7	2.2	0.75	2.09	0.48	0.31	0.7	0.2	0.50	0.20
6	3.9	7.5	3.5	0.75	1.93	0.53	0.34	0.7	0.2	0.50	0.20
7	3.1	5.1	3.2	0.75	1.80	0.50	0.25	0.7	0.2	0.45	0.15
8	3.1	3.7	2.7	0.75	2.05	0.45	0.34	0.7	0.2	0.45	0.15
9	2.9	3.6	2.1	0.75	2.10	0.46	0.34	0.7	0.2	0.45	0.15
10	2.1	1.9	1.3	0.75	2.18	0.56	0.31	0.7	0.2	0.50	0.20

**Table 3.** Analysis of simulation results of 10 rainfall-flood processes in the research area.

No.	Rainfall events	Simulation of flood peak/ $m^3 s^{-1}$	Measured peak/ $m^3 s^{-1}$	Peak discharge error/%	Simulate flood peak time	Measured flood peak time	Difference of peak current/h
1	19660714	1141.2	1040.9	9.70	8:30	8:00	-0.5
2	19840809	453.2	445.2	1.80	3:00	3:00	0
3	19900816	510.3	500.0	2.06	8:45	10:00	1.25
4	19940629	858.8	920.4	-6.70	9:00	9:00	0
5	20030904	878.1	850.2	3.30	8:30	9:00	0.5
6	20040717	626.0	580.7	7.80	8:45	8:45	0
7	20070718	784.2	781.7	0.32	10:30	12:30	2
8	20110702	602.2	577.0	4.37	16:00	16:30	0.5
9	20120708	918.5	885.0	3.79	9:15	9:00	-0.25
10	20160722	494.2	493.2	0.20	9:00	9:00	0

## 5. Conclusion

The simulation results showed that: (1) the difference between the simulated and the observed peak time was relatively small, except that the simulated flood peak of rainfall in 19900816 and 20070718 showed an advance of 1.25 hours and 2 hours respectively, and the errors of others didn't exceed 0.5 hours; (2) the errors between the simulated and measured flood peak flow in 10 rainfall-flood processes were within 10%; (3) the simulation results were more and more close to the measured flood process line shape, and the simulation results tended to be stable, so the results were relatively reasonable and the simulation results were good; (4) The good applicability of HEC-HMS model was demonstrated with the results of the simulation, and HEC-HMS model can be applied to the calculation and analysis of rainfall-flood process in the actual small hilly watershed. The shortcomings of this paper were that the other rain measuring stations around the Tongtian river basin were far away from the basin. In this study, only the rainfall data from the upstream rain measuring station in the basin were adopted, which

was not representative enough. In other similar studies, more data should be applied to the model to further improve the simulation accuracy.

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