Using the DEM-based Xin'anjiang hydrologic model to simulate hydrologic characteristics in SiheRiver Basin

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Abstract. In order to consider the spatial distribution of precipitation, the basin is generally divided by the Thiessen polygon method with the same concentration parameters in all divided units in Xin'anjiang hydrologic model, without considering the impact of terrain. The runoff concentration characteristics depend on the terrain condition to a great extent. Therefore, it is necessary to consider the impact of terrain condition in the model. The purpose of this article is to consider the impact of terrain condition to improve the Xin'anjiang hydrologic model. The basin is divided, and then the slopes of the divided sub-basins and the distances to the basin outlet are extracted based on the DEM. Two function relations between the terrain slope and the runoff concentration are established, and the application results of Sihe river basin show that the Xin'anjiang hydrologic model simulation precision is improved greatly based on the DEM, and it is more reasonable that the recession coefficient and the average gradient of the basin is an exponential relationship.

1. Introduction
Since the Xin'anjiang hydrologic model was developed, it has been widely used globally, especially in the humid and sub-humid lands of China[1]. Unfortunately, the modeler only considered the spatial distribution of rainfall without considering other distributions, especially the terrain factor. Also, the same runoff generation and concentration parameters are used in the model calculation units. In fact, the terrain features not only affect the runoff generation characteristics, but also bring impacts on the basin runoff concentration process [2, 3]. In addition, the computing units are divided by the Thiessen polygon method with multi-outlets of runoff in each unit; thus, the runoff generation processes are disrupted.

At present, the studies of the Xin'anjiang hydrologic model have focused on three aspects. One is the optimization method of parameter calibration[4], followed by the storage capacity curve line[5]. The third is how to add a new module so that the Xin'anjiang hydrologic model can be adapted to infiltration-excess runoff conditions [6]. The development of the computer, GIS technology, especially the DEM, provides technical support for the hydrologic model based on the topographic effects. There are many watershed hydrologic models that have been developed to adapt DEM data structure or directly are based on DEM structure, such as the SHE model [7, 8], TOPMODEL [9], and HMS model [10,11].

One of the main development methods for Xin'anjiang hydrologic model is to take full advantage of the new data sources to improve the accuracy of the simulation. The purpose of this article is to
divide the sub-basin and determine the flow recession coefficient to develop the Xin'anjiang hydrologic model based on the DEM and GIS.

2. The Xin'anjiang hydrologic model introduction

The Xin'anjiang hydrologic model is a kind of distributed model in which the basin is divided into many units and the runoff generation and concentration process are modelled for each unit [1]. For each unit area, the total runoff is determined with the saturation-excess runoff method. Then, the runoff is divided into surface runoff RS, interflow RI and underground runoff RG according to the storage capacity theory of the free water reservoir. Finally, the discharge hydrograph of the basin can be obtained by the channel flood routing based on the each unit export flow. To take into account the uneven distribution of rainfall rather than others, the Thiessen polygon method is used to divide the basin unit with a rainfall station as the general centre. In practical applications, there are other classification methods, such as the natural sub-basins division method [12] or the grid cell division method [13].

2.1. Model structure

The model structure can be divided into four parts, which are evapotranspiration calculation, runoff producing calculation, runoff division calculation and runoff concentration calculation. The model calculation process is shown in figure 1.

![Figure 1. Xin'anjiang hydrologic model structure.](image-url)

The internal variables outside the blocks are parameters, and all symbols inside the blocks are variables including inputs, outputs, and state variables. Model inputs include the measured rainfall process \( P(t) \) and pan evaporation process \( EM(t) \). Also, model outputs for the basin are the exit section flow process \( Q(t) \) and the actual evapotranspiration process \( E(t) \). The function, method and corresponding parameters of each level structure for the model are shown in table 1.
Table 1. Function, method and the corresponding parameters for Xin’anjiang hydrologic model.

| Level  | Function                  | Method                     | Parameters |
|--------|---------------------------|----------------------------|------------|
| Level 1| Evapotranspiration calculation | Three-layer model           | KC, UM, LM, C |
| Level 2| Runoff producing calculation | Saturation-excess runoff    | WM, B, IM   |
| Level 3| Runoff division calculation | Free water reservoir        | SM, EX, KG, KI |
| Level 4| Runoff concentration calculation | Slope flow concentration    | CS, CI, CG |
|        |                           | River flow concentration    | KE, XE      |

2.2. Model parameters

In the Xin’anjiang hydrologic model, each parameter has a definite physical meaning, in principle, so that most of them can be directly determined. However, due to the lack of measurement and experimentation, in reality some parameters can only be determined with system identification methods based on measured outflow. According to the classification of the model parameters, the model physical parameters are measured directly, generally without calibration. For process parameters, the initial value or range are determined according to the hydrological and hydraulic characteristics of the basin. Then, the optimal parameter values are calibrated by the trial and error method or the automatic optimization method. In actual work, model parameter calibration usually is executed with the manual trial and error method combined with the automatic optimization method, which was used in this research[1]. In the model, KC is the ratio of potential evapotranspiration to the pan evaporation; generally, KC <1.0. UM is the tension water capacity of the upper layer, which is about 10-20mm, and LM is the tension water capacity of the lower layer, generally 60-90mm. C represents the evapotranspiration coefficient of the deeper layer, which is about 0.15-0.20 in the humid southern region and 0.09-0.12 in the north sub-humid region, depending on the deep root plant coverage area. WM is the areal mean tension water capacity, generally 120mm. B is the exponential of the distribution of the tension water capacity, which is determined by the uneven distribution of tension water capacity. In the hilly area, it is generally 0.1 for a small watershed, 0.2-0.3 for a slightly larger watershed, and 0.3-0.4 for an large basin. IM is the ratio of impervious area to the total area of the basin, which is determined according to the specific circumstances. SM is the free water storage capacity, generally about 10-30mm. SM determines the surface runoff, so it is important for the calibration parameters. EX is the exponential of distribution water capacity, which is generally about 1.0-1.5mm, as determined by the inhomogeneity conditions of the surface free water capacity. KG and KI are the outflow coefficients of the free water storage to the groundwater flow and the interflow respectively, with KG+KI=0.7~0.8. CS is the recession constant of the lower interflow storage, which is generally about 0.2 depending on the river geomorphology. CI and CG are the recession constant of the groundwater storage and the channel network storage respectively, and the corresponding values are 0.6-0.9 and 0.99-0.998. KE and XE are the Muskingum coefficients, which were calculated according to the hydraulic characteristics of the river. The significance and range of the parameters are shown in table 2.

2.3. Flow concentration calculation

As this research focused on the impact of topography on the flow concentration, the theory of flow concentration was mainly introduced. In the Xin’anjiang hydrologic model, the runoff concentration calculation consists of two stages: the slope flow concentration and the river flow concentration[1].

- Slope flow concentration calculation

Through the runoff generation calculation, the surface runoff (QS) is acquired and flows into the river directly. All the surface runoff becomes the total inflow of the surface runoff on the river network (RS). After the soil water reservoir subsides (regression coefficient CI), the subsurface runoff
(QI) of all units flows into the river network as the total subsurface runoff (RI). Similarly, through the underground reservoir regulation, the underground runoff (QG) of all units flows into the river network as the total groundwater runoff (RG). The calculation formulas are as equation (1),(2),(3),(4):

\[ RS(t) = QS(t) \times U \]  
\[ RI(t) = RI(t-1) \times CI + QI(t) \times (1 - CI) \times U \]  
\[ RG(t) = RG(t-1) \times CG + QG(t) \times (1 - CG) \times U \]  
\[ TR(t) = RS(t) + RI(t) + RG(t) \]

where U is a unit conversion factor.

- River flow concentration calculation

In the model, the division-unit water entering the river to the unit export is simulated by the dimensionless unit hydrograph[1]. A basin with certain hydrological data and similar area to the studied sub-basin can be selected to analyze the unit hydrograph of the surface runoff in the studied basin or the adjacent basin.

Table 2. The significance and range of the parameters.

| Type | Notation | Parameter meaning | Value range |
|------|----------|-------------------|-------------|
| Evapotranspiration parameters | KC | Ratio of potential evapotranspiration to the pan evaporation | Generally KC <1.0 |
| | UM | Tension water capacity of upperlayer | About 10-20mm |
| | LM | Tension water capacity of lowerlayer | About 60-90mm |
| | C | Evapotranspiration coefficient of deeperlayer | About 0.15-0.20 in the humid southern region and 0.09-0.12 in the north sub-humid region |
| Runoff producing parameters | WM | Areal mean tension water capacity | About 120mm |
| | B | Exponential of the distribution of tension water capacity | Generally 0.1 for a small watershed, 0.2-0.3 for a slightly larger watershed, 0.3-0.4 for the large basin |
| | IM | Ratio of impervious area to the total area of the basin | Determined according to the specific circumstances |
| Runoff separation parameters | SM | Free water storage capacity | Generally about 10-30mm |
| | EX | Exponential of distribution water capacity | Generally about 1.0-1.5mm |
| | KG | Out flow coefficient of free water storage to the groundwater flow | KG+KI=0.7~0.8 |
| | KI | Out flow coefficient of free water storage to the interflow | KG+KI=0.7~0.8 |
| Runoff concentration parameters | CS | Recession constant of lower interflow storage | generally CS=0.2 |
| | CI | Recession constant of groundwater storage | About 0.6-0.9 |
| | CG | Recession constant of channel network storage | About 0.99-0.998 |
| Muskingum coefficients | KE | Geometry factor | Calculated according to the hydraulic characteristics of the river |
| | XE | Residence time of water | Calculated according to the hydraulic characteristics of the river |
In practical applications, a larger basin should be divided into many units, and it is unrealistic to analyze the surface runoff unit hydrograph for each unit. Therefore, the routing calculation is simplified. Through the regression process, the soil water and groundwater flow away from the unit. Also, the surface runoff is regulated by the surface water reservoir (regression coefficient CS) as the Unit export flow. Formula (1) can be rewritten as equation (5).

\[ RS(t) = RS(t-1) \times CS + QS(t) \times (1-\text{CS}) \times U \]  

In equations (1) to (5), the parameters CS, CI and CG are determined by the parameter calibration in the Xin’anjiang model, and are used in all units.

3. Methodology

3.1. Unit division
In order to keep the integrity of the runoff generation and the operability of the method, the divided unit should be kept consistent with the watershed boundary as far as possible. Additionally, the distribution of the precipitation stations should be taken into account to ensure that there is a station within each divided unit.

3.2. Analysis of runoff concentration characteristics
As the Watershed topography characteristics determine its convergence characteristics, the terrain characteristics are expressed by using the average slope, which is calculated by the grid DEM and GIS. The slope of each grid is extracted by the GIS, and the arithmetic mean slopes of all grids represent the runoff concentration characteristics.

3.3. Runoff concentration calculation improvement
In the improved model, the evapotranspiration calculation, runoff producing calculation, and runoff division calculation still use the original model calculation method, only to improve the surface runoff concentration. For simplicity, the surface runoff concentration is taken as the example to demonstrate the runoff concentration improvement. The average slope determines the runoff concentration characteristics with the same recession coefficients. The larger the basin mean slope, the higher the runoff concentration speed, and the lower the recession coefficients. The relationship between the recession coefficient and the average gradient of the basin is the key factor to reflect the influence of different gradients on the runoff concentration. Based on the relationship between the recession coefficient and the average gradient, it is assumed that the recession coefficient and average gradient of the basin is an exponential relationship and an inverse proportion function relationship. The performance of the model under two cases was analysed.

- Case 1: Assume that the recession coefficient and average gradient of the basin is an exponential relationship.

\[ CS = CS_0 \times e^{-(g^{-1})} \]  

where, CS_0 is the regression coefficient when the slope is 1 and PD is the mean speed.

The soil runoff and underground runoff are expressed using the same relationship. Then, the runoff concentration calculation formula can be improved as equation (7), (8), (9), (10).

\[ RS(t) = RS(t-1) \times CS_0 \times e^{-(g^{-1})} + QS(t) \times (1-CS_0 \times e^{-(g^{-1})}) \times U \]  

\[ RI(t) = RI(t-1) \times CI_0 \times e^{-(g^{-1})} + QR(t) \times (1-\text{CI}_0 \times e^{-(g^{-1})}) \times U \]  

\[ RG(t) = RG(t-1) \times CG_0 \times e^{-(g^{-1})} + QG(t) \times (1-\text{CG}_0 \times e^{-(g^{-1})}) \times U \]  

\[ TR(t) = RS(t) + RI(t) + RG(t) \]  

where the parameters of CS_0, CI_0 and CG_0 should be calibrated.

- Case 2: Assume that the recession coefficient and the average gradient of the basin is an inverse proportion function relationship.

\[ CS = CS_0 \times g^{-1} \]  

where CS_0 is the regression coefficient when the slope is 1 and PD is the mean speed.
where CS0 is the regression coefficient when the slope is 1 and g is the mean speed.

The soil runoff and underground runoff are expressured the same relationship. Then, the runoff concentration calculation formula can be improved as equation (12),(13),(14),(15).

\[
RS(t) = RS(t-1) \times CS_0 \times g^{-1} + QS(t) \times (1 - CS_0 \times g^{-1}) \times U
\]

(12)  
\[
RI(t) = RI(t-1) \times CI_0 \times g^{-1} + QR(t) \times (1 - CI_0 \times g^{-1}) \times U
\]

(13)  
\[
RG(t) = RG(t-1) \times CG_0 \times g^{-1} + QG(t) \times (1 - CG_0 \times g^{-1}) \times U
\]

(14)  
\[
TR(t) = RS(t) + RI(t) + RG(t)
\]

(15)  

where the parameters CS0, CI0, and CG0 should be calibrated.

The model performance was analyzed to determine the merits of the improved model under the above two cases.

3.4. Model performance evaluation

The performances of model are analyzed by three evaluation indexes, including the relative error of the runoff, the relative error of the peak flow and the deterministic coefficient that is recommended by the World Meteorological Organization.

\[
RE = \frac{SR - MR}{SR} \times 100\%
\]

(16)  
\[
PFE = \frac{SPF - MPF}{SPF} \times 100\%
\]

(17)  
\[
DC = 1 - \frac{\sum_{i=1}^{n} (x_{0i} - \bar{x})^2}{\sum_{i=1}^{n} (x_{ci} - \bar{x})^2}
\]

(18)  

where \(RE\) is the relative error of the runoff, \(MR\) is the actual runoff, \(SR\) is the simulated runoff, \(PFE\) is the relative error of the peak flow, \(MPF\) is the actual peak flow, \(SPF\) is the simulated peak flow, \(DC\) is the deterministic coefficient (0 ≤ DC ≤ 1.0), \(x_{0i}\) is the actual daily runoff, \(x_{ci}\) is the simulated daily runoff, \(\bar{x}\) is the average data of \(x_{0i}\), and \(n\) is the length of the series. The smaller the absolute values of the relative errors are, the better the simulation results are. In contrast, the greater the deterministic coefficient is, the better the simulated results are.

4. Application

4.1. Unit division

The study basin is the upper catchment of Shuyuan hydrologic station on Siheriver in Shandong province of China with an area of 1542km². There are 10 precipitation stations in the basin. The extracted river network, the precipitation stations and the hydrologic stations are shown in figure 2. The DEM map and the basin division are given in figure 3. The slope of the basin is shown in figure 4.
Figure 2. The river network, precipitation stations and hydrologic stations of Sihe river basin.

Figure 3. The DEM and division units of Sihe river basin.

Figure 4. The slope of Sihe river basin.
4.2. Unit characteristics
Based on the DEM, the area, mean slope and distance to the basin outlet can be calculated by GIS (shown in table 3).

| Sub-basin | A | B | C | D | E | Total |
|-----------|---|---|---|---|---|-------|
| Area(km²) | 400.9 | 185.1 | 385.5 | 277.6 | 292.9 | 1542 |
| Weight    | 0.26 | 0.12 | 0.25 | 0.18 | 0.19 | 1     |
| Mean slope| 0.39 | 0.36 | 0.35 | 0.28 | 0.23 | (a)   |
| Distance to basin outlet of basin(km) | 58.8 | 49.3 | 29.4 | 15.1 | 0.5 | (b)   |

4.3. Parameter calibration
In order to compare the model performance based on DEM with original model performance without considering the terrain factors, the parameters $CS_0$, $CI_0$ and $CG_0$ are calibrated using natural meteorological and hydrological data of the 8 years from 1965 to 1972. The other parameters remain unchanged. The calibrated parameters of the original model and improved model are shown in table 4.

| Parameter | Original model | Improved model (Case 1) | Improved model (Case 2) | Parameter | Original model | Improved model (Case 1) | Improved model (Case 2) |
|-----------|----------------|------------------------|------------------------|-----------|----------------|------------------------|------------------------|
| K         | 0.55           | 0.55                   | 0.55                   | $KI$      | 0.3            | 0.3                    | 0.3                    |
| WM        | 120            | 120                    | 120                    | $KG$      | 0.4            | 0.4                    | 0.4                    |
| WUM       | 20             | 20                     | 20                     | $CS_0$    | 0.2            | 0.1                    | 0.13                   |
| WLM       | 70             | 70                     | 70                     | $Cl_0$    | 0.8            | 0.4                    | 0.2                    |
| B         | 0.3            | 0.3                    | 0.3                    | $CG_0$    | 0.99           | 0.8                    | 0.7                    |
| C         | 0.15           | 0.15                   | 0.15                   | $KE$      | 1              | 1                      | 1                      |
| SM        | 20             | 20                     | 20                     | $XE$      | 0.48           | 0.48                   | 0.48                   |
| EX        | 1.5            | 1.5                    | 1.5                    | L         | 1              | 1                      | 1                      |

| Year | Original model | Improved model (Case 1) | Improved model (Case 2) | Original model | Improved model (Case 1) | Improved model (Case 2) | Original model | Improved model (Case 1) | Improved model (Case 2) |
|------|----------------|------------------------|------------------------|----------------|------------------------|------------------------|----------------|------------------------|------------------------|
| 1965 | 9.72           | 6.52                   | 6.48                   | -16.56        | -12.35                 | -12.45                 | 0.822          | 0.877                  | 0.882                  |
| 1966 | 4.36           | 3.24                   | 3.54                   | -12.62        | -9.85                  | -10.04                 | 0.854          | 0.823                  | 0.814                  |
| 1967 | 5.45           | 3.56                   | 3.95                   | -15.87        | -5.74                  | -7.45                  | 0.795          | 0.815                  | 0.804                  |
| 1968 | 7.96           | 2.65                   | 2.3                    | -10.25        | -6.34                  | -7.32                  | 0.756          | 0.864                  | 0.813                  |
| 1969 | 2.31           | -1.26                  | 0.96                   | -7.89         | -5.12                  | -6.61                  | 0.825          | 0.912                  | 0.851                  |
| 1970 | 3.57           | 2.65                   | 2.84                   | -12.63        | -7.86                  | -8.98                  | 0.814          | 0.935                  | 0.864                  |
simulated results under the original model, improved Case 1 and improved Case 2, are showed in Table 6. The simulated and observed runoffs from 1975 to 1977 for three models are selected to show the performances.

In the calibration and validation period, the average relative error of annual runoff and peak flow for two improved models were smaller than those of the original model, and the deterministic coefficient was greater, which suggests that the model considering topographic effects has better performance, with better simulated runoff.

In addition, the average relative error of the annual runoff and peak flow for improved model Case 1 were smaller than those of improved model case 2, and the deterministic coefficient was greater, which demonstrates that the improved model case 1 had better performance, with better simulated runoff. In improved model case 1, the recession coefficient and average gradient of the basin was an exponential relationship. However, it is an inverse proportion function relationship in improved model case 2. The performance of the two improved models shows that it is more reasonable that the recession coefficient and the average slope of the basin is an exponential relationship. Why was this phenomenon produced? The recession coefficient variations under the two relationships are plotted in figure 5 and figure 6. As can be seen from the figure, when the recession coefficient and watershed average slope is an exponential relationship, the dot distribution is smoother with smaller gradients. Conversely, when the recession coefficient and the average slope of the basin are an inverse proportion function, the gradient is larger, especially between the first and the second point. This may be the reason for the better performance of the improved model case 1.

Table 6. Daily rainfall-runoff simulation results.

| Year | Relative error of runoff(%) | Relative error of peak flow(%) | Deterministic coefficient |
|------|-----------------------------|-------------------------------|--------------------------|
|      | Original model | Improved model (Case 1) | Improved model (Case 2) | Original model | Improved model (Case 1) | Improved model (Case 2) | Original model | Improved model (Case 1) | Improved model (Case 2) |
| 1971 | 1.21           | 0.56                         | 2.15                     | -8.96          | -5.21                      | -6.75                  | 0.754          | 0.871                      | 0.853                        |
| 1972 | 0.98           | 1.36                         | 1.26                     | -5.68          | 1.25                       | 1.13                  | 0.726          | 0.862                      | 0.757                        |
| Average | 4.45           | 2.47                         | 2.80                     | -9.10          | -6.20                      | -6.90                 | 0.777          | 0.863                      | 0.818                        |
Figure 5. Simulated and observed runoffs for three models.

Figure 6. Two function relationship lines between recession coefficient and gradient.
5. Conclusions
In the Xin'anjiang model, if the units are divided by the Thiessen polygons method, it is likely that the unit are segmented by the basin boundary, and there are multiple runoff outlets in one unit. Based on the utilization of DEM, the unit can be divided along the basin boundary, and it can be ensured that the there is one outlet on each divided unit with a clear physical concept.

The rainfall runoff formation process, in fact, is the temporal and spatial redistribution of the rainfall of the basin, so the runoff formation characteristics depend largely on the terrain characteristics of the watershed. Using the DEM of the basin, the slope of each sub-basin unit can be calculated. Through establishment of the quantitative relationship between the recession coefficient and the average gradient of the sub-basin, the impact of the spatial distribution of the terrain characteristics on the runoff concentration can be fully considered in the Xin'anjiang hydrologic model, which gave the DEM-based Xin'anjiang hydrologic model better performance.

The performance of the two improved models shows that it is more reasonable that the recession coefficient and the average gradient of the basin is an exponential relationship.

Whether there are other functional relationships between the recession coefficient and the average gradient of the sub-basin that could give the model better performance requires further study.

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