Study of Hydrological Simulation on the Basis of Digitized Basin

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Abstract: On the basis of geographic information systems, indices of basin terrains and some other characteristics were extracted. Drainage networks were created by different mesh sizes of digital elevation model (DEM) in the basin with different kinds of terrain. These drainage networks were analyzed and the indices of the length and slope of the flow routine were derived. According to the basic principle and the mechanism of rainfall-runoff production, the definition and physical meaning of the parameters of the Xinanjiang hydrological model, relevant relationships between several sensitive parameters, and the indices were studied. The relationships were adopted to determine the parameters and the influence was studied with different kinds of mesh sizes of DEM in the basins with different terrains. In this way, the model parameters studied derived from the relationships can be used in an ungauged basin. The results extracted in this paper can then be adopted as the theoretical foundation for the study of the digital hydrological model.

DOI: 10.1061/(ASCE)1084-0699(2008)13:5(317)

CE Database subject headings: Hydrological models; Simulation; Digital techniques; Geographic information systems; Drainage systems.

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Introduction

Flood forecasting is a key component in flood control. In the era of "digital globe" with rapid developments in computer and information technology, the unprecedented change of hydrological modeling has also been witnessed. Quantitative expressions of basin terrains, distributions of vegetation and soil, watershed lines, river networks, and subbasins can be actualized by digitized technology (Ma 2003). These quantitative expressions can be adopted to the quantitative study and determination of hydrological model parameters, especially in ungauged basins. The drainage network is the best way to express the basin terrain and to express flow confluence route quantitatively. Beven and Kirkby (1979), and Wharton (1994) have given its definition. Beven and Kirkby (1979) extracted the index of the basin terrain and the index was used in the hydrodynamic equations for modeling of the flow confluence in TOPMODEL. But it was only applied to the test basins and only the basin terrain was studied. There is no evidence that this model is sufficiently robust to be used for real hydrological modeling in a relative large basin. Zhang et al. (2000) studied the methodology of deriving the drainage network and also calculated the characteristics of the basin terrain. Jing et al. (2004) tested it for hydrological modeling in the Three Gorges interbasin.

On the basis of the work of Jing et al. (2004), the difference in extracting the drainage network in different methods is compared in this study. The inference of the mesh size of the digital elevation model (DEM) to the availability of the drainage network was studied in basins with different kinds of terrain. The indices of topography, vegetation, and geology were calculated. The relationships between indices and parameters of the Xinanjiang model (Zhang et al. 2000) were established. The relationships were studied in some gauged basins and its availability was proved in the Three Gorges interbasin.

Characteristics of Basin Terrain

Comprehensive Analysis of Drainage Network

Topography plays a main part in flow concentration in the basin. The drainage network is the best way to describe the flow route and can be derived by the use of DEM of the square grid (Zhang et al. 2000). However, the drainage network is closely related to DEM. Only reliable and reasonable drainage networks can be used to perform the special analysis and to obtain reasonable characteristics of the basin terrain.

1. Comparison of drainage networks deduced by different kinds of software. There are some discrepancies among the drainage networks deduced by different kinds of software. One of the best ways to verify the rationality and reliability of a drainage network is to inspect the fitness of the modeling river network extracted from the drainage network to the real river network. The software ARC/INFO and River Tools are studied in this paper. The discrepancies of drainage networks are shaped because of different methods of the depression filling and calculation of the grid direction in two software. The characteristics of basin terrain may not be kept after depression filling. In this case the grid direction is relatively

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Note. Discussion open until October 1, 2008. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on November 13, 2006; approved on May 22, 2007. This paper is part of the ***Journal of Hydrologic Engineering***, Vol. 13, No. 5, May 1, 2008. ©ASCE, ISSN 1084-0699/2008/5-317–320/$25.00.

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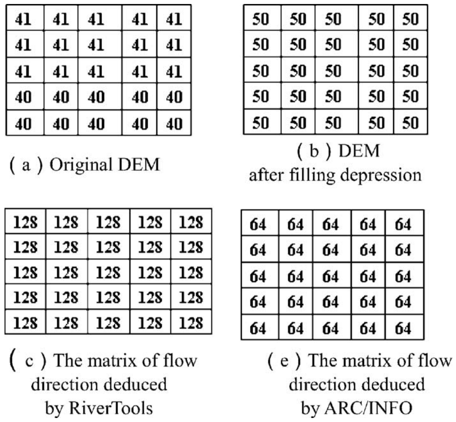

Fig. 1. Comparison of DEM and flow direction between two software in part of area of Yaogu basin

subjective. This subjectivity often causes the discrepancies mentioned above.

Fig. 1 is an example for indicating the discrepancies. Fig. 1(a) shows the distribution of grid elevations in a research area. Although DEMs have the same elevation value after filling the depression, the grid directions are different owing to different calculations of the direction. The value 64 means the right direction and the value 128 means the up-right direction. This situation occurs around the Yaogu hydrometric station in a test basin and breaks occur in the mainstream of the modeling river network. The cause of this error is similar in some other basins, such as the Guanliang basin of Xijiang, and the Yangjiafang and Maiyuan basins of the Longyan area. When a break occurs at a branch, the grid direction at the break can be re-endued and the drainage network can be connected into an integrity network in RiverTools. Since ARC/INFO cannot handle this problem, RiverTools is more advantageous in deducing the river network in the plain area. However, ARC/INFO is better than RiverTools in mountainous and hilly areas.

2. DEM contrast analysis with the different mesh size. The simulation precision of the drainage network is directly influenced by the mesh size for the grid DEM. The influence was studied in small basins with various landscapes. The influence on the river networks is analyzed and its validity is estimated in actual application. The modeling river networks produced by ARC/INFO were analyzed with real networks. The threshold value of the water collection area (Zhang et al. 2000, Wharton 1994) used here is 10 km^2 for the extraction of the modeling river network.

Table 1. Characteristic Values of Terrain in Test Areas

Basin	Average elevation	Index of terrain gurgitation	Average slope	Threshold (m)
A	1,636.57	4.1442	0.6645	≤600
B	294.2	3.9646	0.3744	≤200
C	1,011.94	2.9634	0.3991	≤600
D	124.32	2.7774	0.295	≤50
E	220.1	1.0118	0.0921	≤200
F	493.65	0.8948	0.1191	≤300
G	546.97	0.7699	0.2239	≤300
H	577.9	0.6987	0.2146	≤200
I	502.55	0.5983	0.2388	≤400
J	30.38	0.2918	0.3709	≤20
K	96.49	0.2863	0.2603	≤50

Compared with the real river network, the modeling network produced by 20 m DEM has the highest precision. The precision descends when the mesh size enlarges because of the accuracy of the descending DEM. However, there is an approximate threshold of the mesh size for the validity of the drainage network (Table 1). The index of terrain gurgitation ($R_{i,j}$) is calculated by Eq. (1), where $z_{i+1,j+1}$, $z_{i,j}$, $z_{i,j+1}$, and $z_{i+1,j}$=elevation values at four corners of a grid

$$R_{i,j} = \frac{1}{2}\left|z_{i+1,j+1} + z_{i,j} - z_{i,j+1} - z_{i+1,j}\right| \qquad (1)$$

The thresholds are closely related to the index of the terrain gurgitation and the average slope of the grids. The precision will increase very slowly when the mesh size is smaller than the threshold. If the mesh size is the same, the precision increases with that of the average slope and the terrain gurgitation. In other words, precision is higher in hilly areas than in campagna areas and is lower than in mountainous areas. That means the requirement for the mesh size is different for different terrains.

Division of Element Area

The Thiessen polygon method is traditionally adopted for division of the element area in the Xinganjiang model. The probable problem is that the element area strides over the dividing ridge in this way so there will be shortages in two aspects. The first one is the estimation of the area precipitation, which is calculated according to the gauged point value at the precipitation station. The influence of terrain is ignored in the estimation. The precipitation station located at one side of the dividing ridge might be adopted as the representative station of the subarea on the other side and then will cause an estimation error. The second one is the calculation of the characteristic values of terrain, such as the average slope

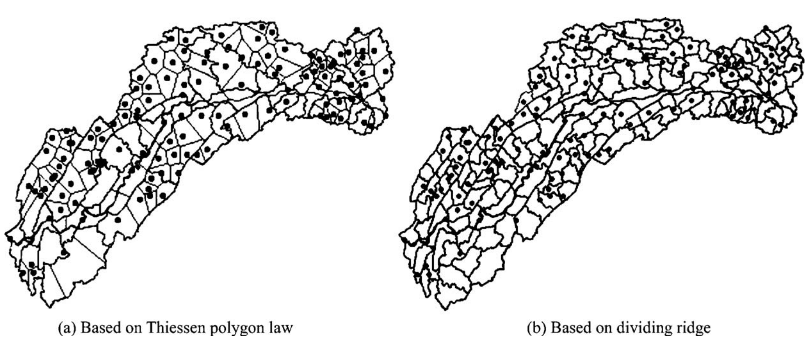

Fig. 2. Distribution maps of element areas in Three Gorge interbasin (dots represent precipitation stations)

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Table 2. Average Length (km) with Different Mesh Size in Three Small Test Basins

	Mesh size (m)					
Basin	50	100	200	400	800	1,600
Longhe	32.06	29.22	29.59	29.30	28.86	24.87
Modaoxi	77.26	76.90	77.13	70.86	64.85	61.00
Luodingjiang	53.46	52.99	52.43	50.21	48.6	45.99

(S), the average gradient slope of river (J), and the average length of the route of flow concentration (L) of an element, etc. These values cannot be calculated owing to the fact that the drainage network is broken by the dividing ridge in the element area. The runoff yielded on one side might be concentrated into the other side. In order to avoid these problems, the natural dividing ridge was adopted for division of the element area in this paper. It can be made automatically on the basis of the drainage network. The distribution of element areas in the two methods is contrasted in Fig. 2 in the Three Gorge interbasin.

Comparison and Analysis of Characteristic Value of Terrain

Topographical factors are the key issues in the hydrologic model. In the three research basins, indices of R, L, S, and J of a basin under different mesh sizes of DEM were calculated separately (Zhang et al. 2000).

1. Analyzing the average length of the route of flow concentration (L). The flow concentration route (L) of a basin is closely related to the topography. The average length from each grid to the outlet of the basin can be calculated according to the drainage network. But precision is related to the mesh size and decreases with the enlargement of the mesh size (Table 2). So, the average length calculated from the drainage network is only a relative value. But it can be used as an index in the hydrological modeling. As mentioned earlier, a threshold of the mesh size should not be exceeded in order to guarantee the precision of the drainage network. The L extracted in this case can be accepted as a standard value in hydrological modeling.
2. Analyzing the average slope of a basin (S). On the basis of the drainage network, the average slope (S) of a basin can be calculated according to the grid slopes (Zhang et al. 2000). But its precision also decreases with the enlargement of the mesh size. This is because some characteristics of microtopography are neglected and the topography is evened when the mesh size is enlarged. When the mesh size is 1,000 m the average slope is more than twice its value when it is 20 m. The average slope changes notably, especially when the mesh size is larger than 100 m (Fig. 3). So the mesh size should not be larger than 100 m when S is accepted in hydrological modeling no matter what kind of terrain it is. The average gradient slope of the river (J) is similar to that of S.

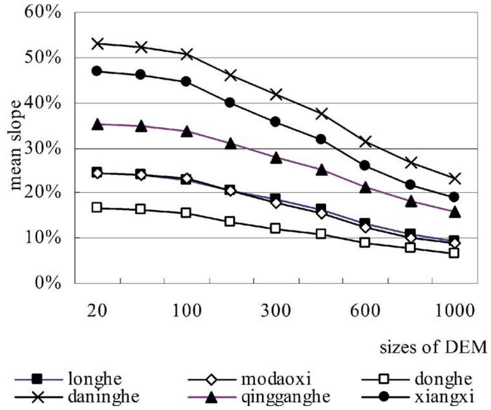

Fig. 3. Average slopes with different mesh sizes in some test basins

Comprehensive Characteristics of Hillside

The comprehensive characteristics of the hillside, such as the spatial distribution of vegetation, soil, and rock, etc., are also the key issues to dominate the mechanism of runoff yield (Zhuang and Lin 1986). The rate of forest cover (P) and the geological characteristic index (M) in an element area can be calculated according to the corresponding spatial distribution maps on the basis of geographic information systems (GIS) (Jing et al. 2004).

Characteristics of Basin and Hydrological Modeling

In this paper, the relationships of some parameters of the Xinanjiang model with the characteristics of the basin mentioned above were established in several test basins mentioned in Table 2 by the use of regression analysis.

Index P with Free Water Storage Capacity of Basin SM

When vegetation flourishes and humus is thick, the soil pore is larger near the root. Infiltration of the topsoil layer is also large, the surface runoff is only small, and the free water storage capacity (SM) becomes larger. The curve of the flood process becomes fat in this kind of basin. The parameter SM is affected by the rate of forest cover. Therefore the relationship between P and SM is established, $SM=38.582^{*}P-7.2497$. The mean square deviation (σ) is 7.01 correspondingly.

Table 3. Simulation Result with Different Mesh Size in Three Basins

	Flood 780622 in Longhe basin				Flood 850807 in Modaoxi basin				Flood 910703 in Luodingjiang basin			
Mesh size (m)	DC	CE1 (%)	CE2 (%)	ΔT (h)	DC	CE1 (%)	CE2 (%)	ΔT (h)	DC	CE1 (%)	CE2 (%)	ΔT (h)
50	0.93	1.75	4.17	−2	0.90	−2.18	−22.8	−3	0.87	2.25	7.25	−3
100	0.94	1.84	−0.46	−2	0.91	−1.94	−23.8	−3	0.92	2.30	−2.96	−2
200	0.94	1.97	−6.02	−2	0.92	−1.05	−27.0	−5	0.93	2.38	−16.23	−2
400	0.89	2.68	−28.5	−2	0.89	−2.51	−26.1	−6	0.6	2.66	−58.7	0
800	0.56	6.17	−64.0	−4	0.48	28.54	−73.9	−14	−0.08	−45.41	—	—
1,600	−0.06	−47.43	—	—	−0.26	62.54	—	—	−0.21	2.08	—	—

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Index M with Effluent Coefficient of Underflow Runoff KI and That of Underground Runoff KG

The types and characteristics of rocks are important factors that influence the runoff yield in the basin and the vertical apportioning of runoff in the soil. Runoff is then divided into different kinds of runoff components, whose concentration in the soil behaves differently. Parameters KG and KI are adopted to apportion the runoff components. Since the basal rock is not composed of a single element, M is adopted to depict the lithology of the basal rock synthetically. The relationship between M and KG and that between M and KI are: $\mathrm{KI}=0.1389*M+0.407$ and $\mathrm{KG}=-0.1786*M+0.3271$. The mean square deviations (σ) are 0.0002 and 0.057, respectively.

Indices S and L with Flow Concentration Parameters CS and CI

The terrain characteristic and model parameters of flow concentration are closely related (Hu 1993). Indices S and L determine the speed of runoff on the hillside and then the processing of flow concentration. The relationships among the S, L, and the CS, CI, are $\mathrm{CS}=0.2640*S+0.0008*L+0.7189$ and $\mathrm{CI}=0.8483*S+0.0010*L+0.3163$. The mean square deviations (σ) are 0.0031 and 0.0230, respectively.

Index J and Parameter X of Muskingum Method

According to the physical significance of parameter X of the Muskingum method (Zhuang and Lin 1986), there is a close correlation between J and X. The relationship is $X=0.6298*J^{0.0915}$. The mean square deviations (σ) is 0.0130, correspondingly.

Hydrologic Simulation

The six parameters of the Xinanjing model and the Muskingum method, including SM, KI, KG, CS, CI, and X are calculated, while others are the calibrated values using a trial and error (TE) search procedure (Jing et al. 2004). Simulation in this case was compared, where all the parameters were calibrated by TE for both statistical and discharge curve precision.

The relationships for parameters CS, CI, and X are related to indices S, L, J. These parameters are dependent on the mesh size. Model parameters and the corresponding simulation precision of different mesh sizes were compared with each other and with that deducted from the calibrated values of TE. Statistical precision of flood simulation is shown in Table 3 for the three small basins. DC=deterministic coefficient, CE1=relative error of flood of the runoff value, CE2=relative error of flood peak, and Δt=time displacement of flood peak (+ means the simulated flood peak appears earlier than the observed one, while − means it appears later).

Generally, precision decreases with the enlargement of the mesh size. However the calculated parameters are approximated with the calibrated values of TE, when the mesh size is smaller than 400 m in the Modaoxi basin because it is located in a mountainous area. There are no distinct differences among model precisions (Table 3) but the mesh size should be smaller than 200 m in the Longhe basin and the Luodingjiang basin because they are located in hilly areas. Otherwise the hydrological modeling results become very poor and they cannot meet the actual request (Table 3). For these reasons different thresholds of the mesh sizes are introduced according to different terrains when model parameters are estimated by the relationships developed in this study.

Some parameters of the Xinanjing hydrological model can be determined according to the characteristics of a basin by the use of the above relationships. This strategy can be applied to an ungauged basin. The Three Gorges interbasin is located at the upper reaches of the reservoir dam. A great portion becomes the ungauged area because of the rise of the water level of the reservoir. This strategy has been applied to the real time flood forecasting for the Three Gorges reservoir. It is illustrated that the strategy is sufficiently reasonable for the real operation of flood forecasting. The strategy exceeds the method in which parameters for an ungauged area are taken from the gauged area directly for the modeling precision.

Conclusions

The availability of the drainage network is closely related the basin terrain and the mesh size of the DEM. Precision of the drainage network increases with the descending mesh size and the ascension of the average slope and the terrain gurgitation. There is a threshold of the mesh size for the availability in a basin. It is larger in the mountainous area than in the hilly area. The average slope (S), the average gradient slope of river (J), and the average length of the route of flow concentration (L) of an element can be calculated by use of the available drainage network. These terrain indices and some other indices of vegetation and geology can be adopted to establish the relationships between the indices and some parameters of the Xinanjiang model. The relationships can be used to determine the parameters in a basin, especially in an ungauged area. The relationships were studied for three research basins and their availability has been validated for real time flood forecasting in the Three Gorges interbasin.

Acknowledgments

This paper was funded by Specialized Research Fund for the Doctoral Program of Higher Education of China (Grant No. 20060294002).

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