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Research Article

Numerical Simulation of Urban Waterlogging Based on FloodArea Model

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Assessment of urban water logging risk depth is mainly based on extreme value of rainstorm and its occurrence frequency as disaster causing factor. Regional waterlogging disaster risk assessment can be determined through regional geographic spatial information coupling calculation; the fundamental reason lies in the lack of an effective method for numerical simulation of waterlogging risk depth. Based on the hydrodynamic principle, FloodArea model realizes the numerical simulation of regional waterlogging depth by hydrologic calculating of runoff generation and runoff concentration of waterlogging. Taking risk assessment in Nanchang city as an example, spatial distribution of urban waterlogging depth was simulated by using FloodArea model in return period of 5 years, 10 years, 50 years, and 100 years. Research results show that FloodArea model can simulate urban waterlogging forming process and spatial distribution qualitatively.

1. Preface

Urban waterlogging refers to the phenomenon when there is rainstorm or short time heavy rain, which surpasses the capacity of the urban drainage system, and then waterlogging disaster happens. Urban waterlogging numerical model realizes numerical simulation of waterlogging depth based on hydrology and hydrodynamic mathematical models, combined with GIS technology.

There are hundreds of different kinds of urban rainstorm models aiming at different purposes in the world. Several models are famous, such as MIKE series developed by Danish Hydraulic Research Institute in the early 1970s [1]; the Surface Water Modeling System developed by the United States Army Corps of Engineers, Waterways Experiment Station, and the United States Federal Highway Administration in 1971; STORM (Storage Treatment Overflow Runoff Model) developed by Hydrology Center of the US Army Corps in 1977 [2]; SWMM (Storm Water Management Model) developed by United States Environmental Protection Agency during 1971–1988. SWMM model is one of the most commonly used rain flood models at present [3]. Besides, there are also France's CAREPAS, Russia's RATIONAL, and other storm water runoff models. Looper and Vieux used distributed hydrologic model (PBD) to simulate flash flood in Austin, Texas, and achieved accurate hydrologic prediction during a flash flood event [4]. Grimaldi et al. used consequent hydrological data and constructed hydrodynamic model (WFIUH) to identify regional flood risk [5]. Chinese scholars studied and optimized these models and then established several models applicable to certain specific regions with the consideration of actual situation in China. Yin et al. took meticulous precipitation monitoring as driving conditions to establish waterlogging numerical model of Beijing city (BUW) based on hydrodynamic process [6]. Combined with the characteristics of Suzhou city, Dai et al. established a flood drainage mathematical model with flood control and drainage in the center of Suzhou city [7].

Previous models are based on hydrology or hydraulics. Hydrology model is based on watershed hydrology, taking city as a small and medium scale basin and dividing it into several subbasins that are catchments. Computational methods of catchments runoff generation and concentration are equal to basins. Water transfer from subbasins to city outlet is done by drainage network. Hydrological model is a black box model. In the simulation of urban waterlogging, it only contains the input of rainfall and the output of results and cannot present the loss of the flow and transport process. Waterlogging models based on hydrodynamics have certain physical meaning and can reflect the waterlogging performing progress in detail, but the solving process is complicated and it is also difficult to consider various factors during the process. These models are not well combined with the increasing development of urban GIS and urban geographical spatial data has not been effectively utilized, so data processing of simulation based on these models is complex and the simulated result are not practical.

FloodArea model, a hydrological model for flood risk analysis, is receiving more attention during recent years. The model is based on the hydrodynamics principles and combined with GIS technology; the influences of underlying surface, elevation, and other factors are considered in the waterlogging process. FloodArea model realizes waterlogging depth numerical simulation by simulating the progress of water generation and concentration. Simulation results are layers of a certain time step of waterlogging area and waterlogging depth. It can both express waterlogging area visually and also can analyze the waterlogging influence quantitatively. Taking urban waterlogging numerical simulation of Nanchang city as an example, technical method of urban waterlogging numerical simulation based on FloodArea model is discussed in this paper.

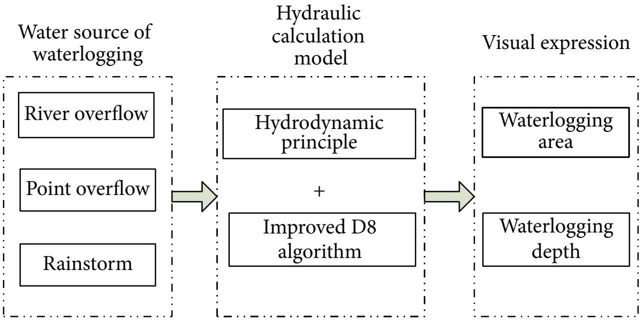

Figure 1: FloodArea model framework concluded by authors.

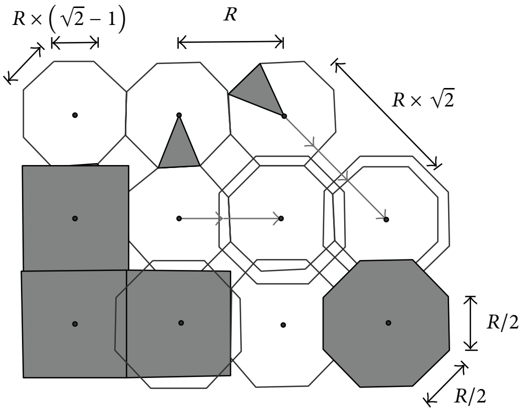

Figure 2: Schematic diagram of FloodArea model principle given by the FloodArea model user's manual [9].

2. Principle of FloodArea Model

2.1. Overview. FloodArea is a flood inundation model developed by Geomer Company in Germany. It can simulate both mountain flood and urban waterlogging caused by rainstorm. FloodArea model is a distributed hydrodynamic model. Its framework is shown in Figure 1. FloodArea model determines factors causing waterlogging and then calculates cell volume based on hydrodynamic principle and improved D8 algorithm [10] considering the underlying surface and elevation as influence factors. FloodArea model provides 3 methods to simulated runoff generation process: elevation model assumes that flooding is initialized by the entire drainage network; hydrograph model assumes that water enters through dam failure; rainstorm model assumes that flooding is produced by rainfall-runoff. Hydrograph model can be simultaneously used with elevation model or rainstorm model. Select the appropriate model according to the specific simulation scenarios. The convergence analysis is based on hydrodynamics principle and considers the influence of 8 cells around the center cell. Utilize underlying surface and elevation comprehensively and consider influence of surface features on convergence process, including block of flow barrier and mitigation effects of different land use types on runoff concentration; water increase caused by dam failure can get a result of waterlogging area and depth. Drainage is an important factor in urban waterlogging simulation. FloodArea model does not set drainage parameters alone, but drainage is not essential for flood in mountain area.

The model is embedded in ArcGIS platform, based on the principle of hydrodynamics and integration of the GIS hydrological calculation algorithm, that can realize the flood and inundation depth calculation; the model principle is shown in Figure 2 [9]. The discharge volume to the neighboring cells is calculated using the Manning-Strickler formula:

$$V = K_{\mathrm{St}} * r_{\mathrm{hy}}^{2/3} * I^{1/2}. \tag{1}$$

In (1), V is the discharge volume, K_{St} is the roughness values, r_{hy} is the hydraulic radius, and I is the gradient.

The flow depth during an iteration interval is taken from the difference between water level and maximum terrain elevation along the flow path:

$$f = w_A - \max(e_A, e_B). \tag{2}$$

In (2), f is the flow depth, w_A is the water level of point A, e_A is the terrain elevation of point A, and e_B is the terrain elevation of point B.

The inclination and the direction of the water table are recalculated in every iteration step and the steepest slope is used as the inclination in the Manning-Strickler formula:

$$s = \sqrt{\left(\frac{\partial z}{\partial x}\right)^2 + \left(\frac{\partial z}{\partial y}\right)^2},$$
$$a = 270 - \frac{360}{2\pi} * \alpha \tan 2\left[\frac{\partial z}{\partial y}, \frac{\partial z}{\partial x}\right]. \quad (3)$$

In (3), s is the gradient, a is the aspect, α is the slope, $\partial z/\partial y$ is the north-south direction elevation change rate, and $\partial z/\partial x$ is the east-west direction elevation change rate.

2.2. Processing Model of Rainfall. Processing model of rainfall data includes two parts: rainfall return period calculation and rainfall pattern calculation.

2.2.1. Calculation of Rainfall Return Period. The rainstorm return period is the average interval that rainstorm intensity is greater than or equal to some rainstorm intensity value, whose unit is year (a). Frequency distribution curve fitting of rainfall return period is based on the selected statistical samples, using empirical frequency curve or theoretical frequency curve to do trend fitting adjustment. Generally choice of theoretical frequency curves is Pearson Type III Distribution Frequency Curve or Gumbel Distribution Frequency Curve. In practical application, the fitting of multifrequency distribution function is usually selected from the years data of representative meteorological observation station.

2.2.2. Calculation of Rainfall Pattern. Rainfall pattern is the time distribution of rainfall density. Rainfall pattern is quite significant to urban waterlogging analysis. When simulating waterlogging, time distribution of the rainfall density has a serious impact on waterlogging degree calculation. Minute rainfall pattern and hour rainfall pattern both can be used in FloodArea model. Minute rainfall pattern can be determined by the method of Chicago rainfall pattern, according to rain peak type, rain peak position, and rainfall distribution (three aspects) [11]. The duration of hour rainfall pattern can be 1 hour, 3 hours, 6 hours, 12 hours, 24 hours, and 72 hours. Common methods of determining hour rainfall pattern are (1) same frequency analysis method: time series is determined based on most occurrence number in the same return period and calculates the mean value as the proportion of rainfall in each time period [12]. (2) Pilgrim and Cordery method takes the most probable position as rain peak position and takes rainfall proportion of rain peak as average proportion of rain peak in every rain process [13, 14].

2.3. Simulation Process of Runoff Generation and Runoff Concentration. FloodArea model is the theories integration of runoff generation and runoff concentration, including two main parts: one part deals with water balance and rainfall loss treatment, including evapotranspiration, infiltration, and vegetation interception, which determines the size of total runoff volume and runoff generation. The other part is the storage part of total runoff; it deals with runoff redistribution process and realizes calculation of runoff.

Table 1: Runoff coefficient of different land use features determined according to outdoor drainage design norm of China (GB50014-2006) [8].

Features	Woodland	Paddy field	Greenland	Water systems	Road & building
Runoff coefficient	0.1	1	0.1	1	0.85

2.3.1. Simulation Process of Runoff Generation. FloodArea model provides 3 methods to simulated runoff generation process. The difference lies in the way in which rainfall enters the model: (1) elevation model assumes that flooding is initialized by the entire drainage network and digital elevation data of drainage network with water level is needed. (2) Hydrograph model assumes that water enters through dam failure. A hydrograph data file at one or more locations is needed. (3) Rainstorm model assumes that flooding is produced by rainfall-runoff. It requires a raster layer of hydrograph data representing weighted input and rainfall pattern data. The second model is similar to the third model; the most important difference is the input data forms; the input data form of the former is a dot file and the latter is a raster layer. The third model is usually used to simulate urban waterlogging.

Once the rainfall intensity exceeds the infiltration, the redundant water may be temporarily left on the surface; when the storage reaches a certain limit, it flows to the lower place, becoming surface water and importing to the regional drainage system. The process is called surface runoff. The amount of water in the process is called the quantity of surface runoff. Runoff coefficient is used to represent the relationship between runoff volume and runoff yield. Runoff coefficient is the ratio of total runoff (mm) and rainfall (mm) within a certain catchment area; it is also the ratio of runoff depth (Y) and the rainfall depth (X) causing the runoff in any interval. When simulating urban waterlogging by FloodArea model, the runoff coefficient in raster form is used to represent the weight of the rainfall. Some features' runoff coefficients are shown in Table 1.

2.3.2. Simulation Process of Runoff Concentration. Convergence process refers to the concentration of runoff in a certain area. Surface convergence involves a variety of underlying surfaces, buildings, roads, rivers, and so forth, which divide the city into several subbasins. After the rain, a small amount of rainfall directly flows into the natural water body along with surface fluctuation; most of the rain enters the drainage system through the urban drainage pipe network.

Hydraulic roughness is roughness of fluid dynamics. It is a comprehensive index to measure influence of rivers, irregularity of surface shape, and fluctuation. Different land cover types with different surface roughness have different resistivity during urban waterlogging concentration process.

Table 2: The empirical value of roughness of different land use types given by the FloodArea model user's manual [9].

Features	Woodland	Paddy field	Greenland	Water systems	Road & building
Manning coefficient	18	33	40	50	25

When simulating waterlogging by FloodArea model, different roughness values are given to different land use types. Its value is related to Manning coefficient, as shown in

$$K_{\mathrm{St}} = \frac{1}{n}. \tag{4}$$

In (4), K_{St} is the roughness and n is the Manning coefficient.

Some features' empirical roughness is shown in Table 2.

2.3.3. Simulation of Drainage Process. Drainage is an important factor in urban waterlogging simulation. FloodArea model does not set drainage parameters alone. In the calculation process, some parameters are adjusted to reflect the drainage process, so that the whole simulation process is consistent with the actual flooding process. Usually, in the same rainfall process, urban underlying surface factors do not change; that is, the city's land use types do not change, so the influence of hydraulic roughness and runoff coefficient determined by land use types and water resistance of building and railway to flood process is explicit; the drainage conditions cannot be simulated by adjusting the type of ground objects; that is to say, the drainage conditions cannot be simulated by adjusting the runoff coefficient and the roughness of the model. The degree of urban waterlogging is determined by the rainfall, urban drainage capacity is fixed, and therefore subtracting the amount of water in the rainfall to simulate drainage treatment is proposed in this paper; that is to say, the influence of drainage condition on the process of flood and waterlogging is reflected by adjusting the rainfall parameters. The basic idea is to estimate the average displacement of a city, the catchment area is used as the unit, adjusting the drainage capacity of each catchment according to the number of the region networks, rivers, and so forth, and the average displacement of each area is obtained, in terms of daily rainfall subtracted from the drainage volume after the hour rainfall of the catchment area.

3. Numerical Simulation of Urban Waterlogging Based on FloodArea in Nanchang City

3.1. Study Area. Nanchang city is located in the north central part of Jiangxi Province, which lies between 115.45 and 116.58 degrees east longitude and 28.17 and 29.18 degrees north latitude; its sketch map is shown in Figure 3. Its annual rainfall is 1600–1700 mm. As the drainage pipe network in old city is backward, frequent flooding has a greater impact on urban life. Under the background of global warming, the intensity of precipitation in Nanchang city is increasing and the risk of flood disaster is also increasing. As research shows, annual rainy days of Nanchang city are decreasing in the past 50 years; lightly rainy days showed a downward trend, but the heavily rainy and rainstorm days showed an increasing trend. Waterlogging disasters of Nanchang city mainly occurred in May and June each year, but other months have varying degrees of occurrence [15].

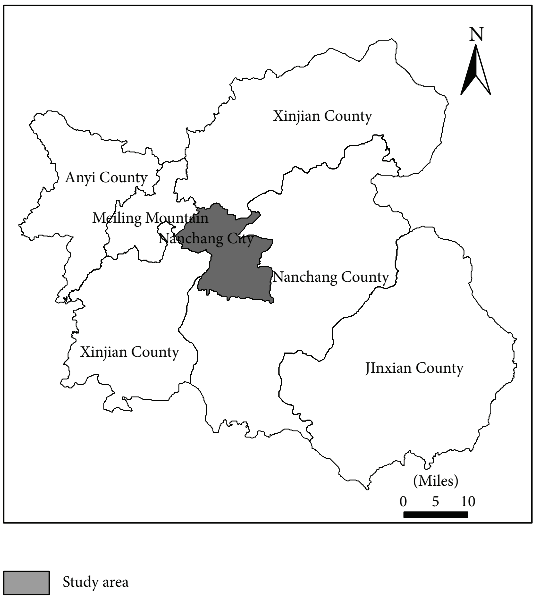

Figure 3: Sketch map of study area (the accurate administrative division data provided by Nanchang Meteorological Bureau).

Table 3: The table of recurrence interval and rainfall.

Return period (a)	5	10	50	100
Daily rainfall (mm)	151.9	177	246.4	282

3.2. Data Source and Data Preprocessing

3.2.1. Data Source. The hourly rainfall data from 21 p.m. to the next day 20 p.m. is achieved from Nanchang local base station for about 30 years from 1985 to 2014.

Digital elevation data is modeled as 30-meter resolution SRTM, as shown in Figure 4; remote sensing image comes from 2.5-meter resolution SPOT satellite photograph data, as shown in Figure 5.

3.2.2. Data Preprocessing. After sorting and calculating total daily rainfall data of 30 years, the 30 statistical samples were selected by using annual maximum method. The relationship between frequency and return period was simulated by Pearson III curve; the corresponding frequency and daily rainfall of each return period were obtained. Results are shown in Table 3. Calculate hourly rainfall of each return period. Taking the regional applicability into account, hourly rainfall pattern takes 24-hour hourly rainfall pattern recommended

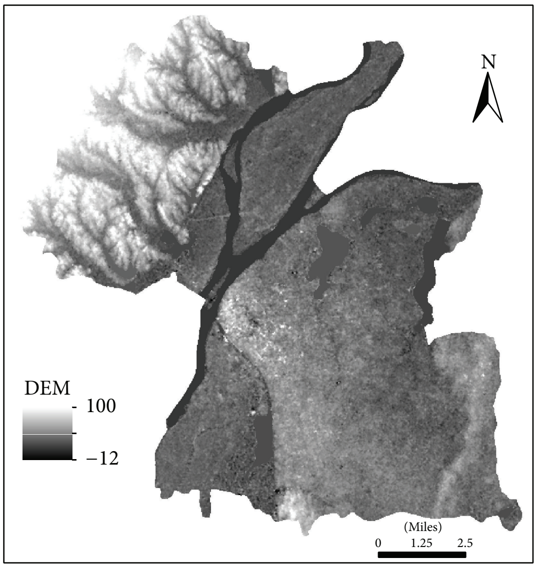

Figure 4: Digital elevation data modeled as 30-meter resolution SRTM.

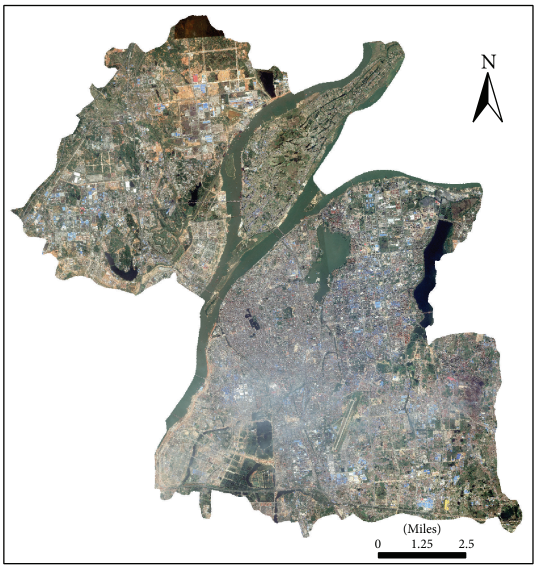

Figure 5: Remote sensing image coming from 2.5-meter resolution SPOT satellite photograph data.

Table 4: The table of percent of hourly rainfall recommended in the Handbook of Heavy Rain and Flood in Jiangxi Province (2010 Edition).

Time	1	2	3	4	5	6	7	8
Rainfall percent	1.65%	1.65%	1.65%	1.65%	1.65%	1.65%	0.00%	0.00%
Time	9	10	11	12	13	14	15	16
Rainfall percent	0.00%	3.42%	3.42%	3.36%	2.70%	5.40%	5.46%	9.35%
Time	17	18	19	20	21	22	23	24
Rainfall percent	37.00%	6.19%	3.23%	3.23%	2.83%	1.65%	1.65%	1.38%

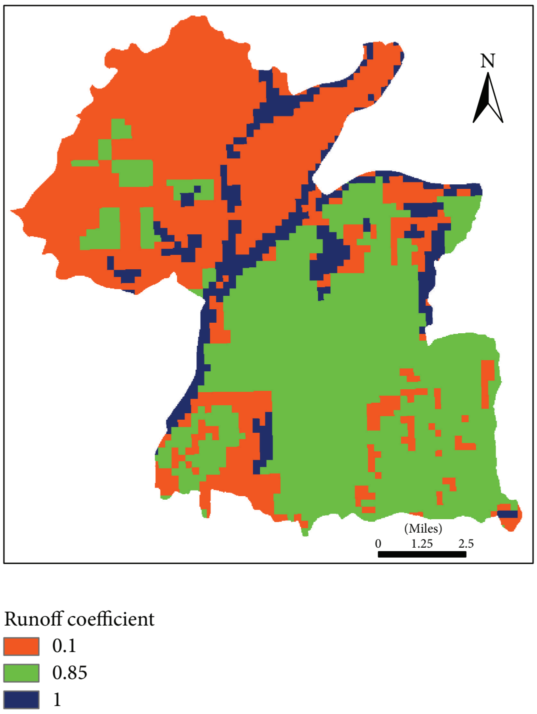

Figure 6: Distribution map of runoff coefficient determined according to Table 1.

in the Handbook of Heavy Rain and Flood in Jiangxi Province (2010 Edition), as shown in Table 4.

With the combination of daily rainfall and 24-hour rainfall percent table, 24 hours of hourly rainfall data of 5 return periods can be simulated.

After mosaicing, registering, correcting, and interpreting the remote sensing image data, divide Nanchang city into 30 M $*$ 30 M grids; land use types of research area are digitalized. According to the land use types, referring to FloodArea model parameter setting requirements, the runoff coefficient data (shown in Figure 6)and the roughness data (shown in Figure 7) are determined. The runoff data is the rainfall weight data in grid form needed by the model. The hydraulic roughness data is the roughness data in the model.

Collecting the network data is difficult, so the information is not perfect; only through historical hydrological data to estimate the amount of the old city of Nanchang city, the daily average volume of water is 30 mm; overall, the new city drainage performs more perfectly than the old city, so it is estimated that the new city section of the daily average drainage capacity is 35 mm. So, in the simulation, Nanchang city will be divided into the old city and the new city, distribution of hourly rainfall after subtracting the amount of water from the daily rainfall. The hourly rainfall amount minus the amount of water is the amount of rainfall that is entered in the simulation.

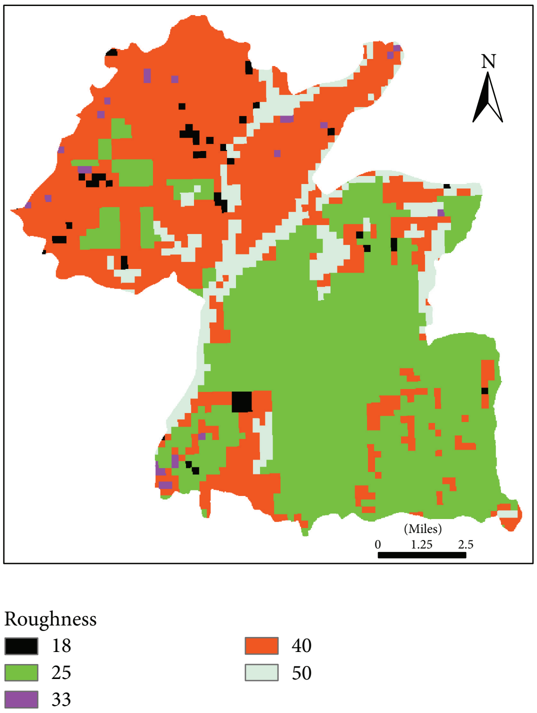

Figure 7: Distribution map of roughness determined according to Table 2.

Table 5: The rainfall data of June 28, 2013, coming from the observation data.

Time	1	2	3	4	5	6	7	8
Rainfall (mm)	0	0	3.6	2.8	0.1	0.3	1.6	21
Time	9	10	11	12	13	14	15	16
Rainfall (mm)	0.4	4.1	1	18.8	25.3	12.5	11.4	7.9
Time	17	18	19	20	21	22	23	24
Rainfall (mm)	3.4	4.7	6.5	9.2	4.2	0.8	0.2	0

Table 6: The contrast of actual waterlogging depth and simulated waterlogging depth.

Point number	Actual waterlogging depth (cm)	Simulated waterlogging depth (cm)
1	20	18.23
2	20	15.09
3	20	15.06
4	15	17.33

3.3. Model Verification. Waterlogging on June 28, 2013, was simulated. Its daily total rainfall was 139.8 mm; details are shown in Table 5. The amount of drainage water from rainfall was subtracted, and its waterlogging process was simulated.

Taking 4 waterlogging record points as sampling point, their locations are Xihu Road, Hongdu socks factory dormitory, intersection of Jingdong Da Dao and Huoju 2 Road, and intersection of Jingdong Da Dao and Changye Road as shown in Figure 8. The contrast of actual waterlogging depth and simulated waterlogging depth is shown in Table 6.

Table 7: The relationship between waterlogging depth and waterlogging risk level considering impact of water on traffic, vehicles, production, and residential life.

Waterlogging depth (m)	0.15~0.25	0.25~0.65	0.65~1	>1
Waterlogging level	4	3	2	1

Comparing the simulated results with the actual waterlogging depth, the maximum error is 5 cm. But because the actual waterlogging depth is estimated by China's meteorological department staff when it is measured with considering waterlogging area in order to reflect the accuracy evaluation of flood, that is to say, the final results are human judgment to approximate value, it can conclude that the results simulated by FloodArea are consistent with the actual results and the reliability is high.

3.4. Waterlogging Simulation. Waterlogging process of Nanchang city in return periods of 5 years, 10 years, 50 years, and 100 years was simulated by FloodArea model. Considering impact of water on traffic, vehicles, production, and residential life, waterlogging risk is divided into 4 levels, as shown in Table 7. Distribution maps of waterlogging are shown in Figures 9–12.

3.5. Evaluation of Waterlogging Effect. Analyze the simulated results and take the area of waterlogging depth less than 15 cm as unflooding area and get area ratio of each waterlogging depth level at each return period (area ratio is the proportion of each waterlogging depth level area in all waterlogging area), as is shown in Table 8.

In the simulation results, the population distribution data were collected and analyzed; the number of the affected population in each return period was obtained as shown in Table 9.

It can be found from Tables 8 and 9 that (1) as the return period is increasing, the waterlogging area and affected population are increasing too. Waterlogging areas in return period of 5 a, 10 a, 50 a, and 100 a are in order of 38.22 km^2, 45.29 km^2, 56.45 km^2, and 60.26 km^2, and the affected populations are 3685, 4363, 5456, and 5671 people. (2) As the return period is increasing, the area ratio of the same waterlogging depth level shows an increasing trend. The waterlogging depth of max area ratio in return period of 5 years, about 60%, is 15–25 cm. The waterlogging depth of max area ratio in return period of 10 years, 50 years, and 100 years is 15–25 cm, and the area ratio of waterlogging depth of 50 years and 100-year return period is about 60%. The area ratio of waterlogging depth of 10 years return period is about 48%, equal to the area ratio of 15 cm–25 cm.

4. Discussion and Conclusion

4.1. Discussion. FloodArea model does not set drainage parameters alone. A method is proposed to simulate the drainage condition of the rainfall data through several simulation experiments, which is easy to understand and deal

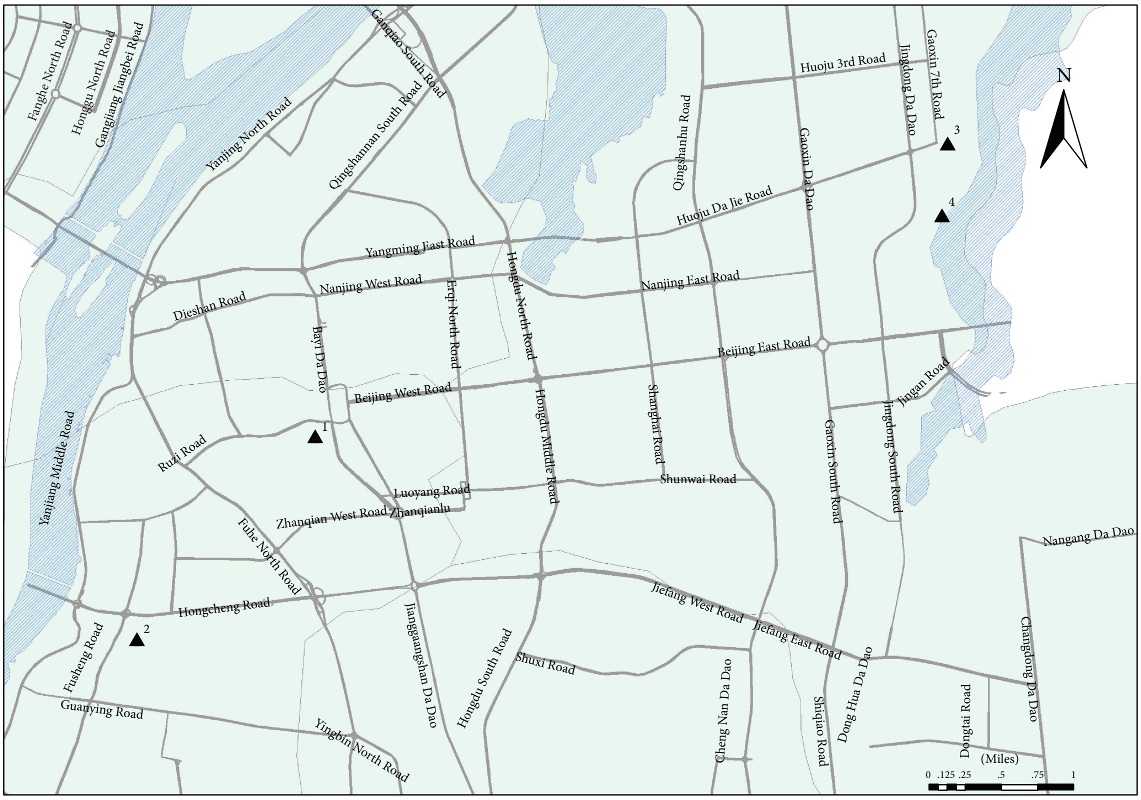

Figure 8: Distribution map of waterlogging sampling points. 1: Xihu Road; 2: Hongdu socks factory dormitory; 3: intersection of Jingdong Da Dao and Huoju 2 Road; 4: intersection of Jingdong Da Dao and Changye Road.

Table 8: The table of effect of waterlogging.

Return period	Waterlogging depth							
	15–25 cm		25–65 cm		65–100 cm		>100 cm	
	Area (km^2)	Area ratio	Area (km^2)	Area ratio	Area (km^2)	Area ratio	Area (km^2)	Area ratio
5 a	22.85	59.79%	14.31	37.44%	0.64	1.67%	0.42	1.10%
10 a	21.3	47.03%	21.78	48.09%	1.67	3.69%	0.54	1.19%
50 a	15.87	28.11%	33.78	59.84%	4.58	8.11%	2.22	3.93%
100 a	13.77	22.85%	37.66	62.50%	5.52	9.16%	3.31	5.49%

Table 9: The table of population affected by waterlogging.

Return period (a)	5	10	50	100
Affected area (km^2)	38.22	45.29	56.45	60.26
Affected population (per)	3685	4363	5456	5671

with. However, it is worth exploring whether the method of the drainage process can be better reflected by the appropriate adjustment of other parameters in the actual calculation process.

It is also worth exploring impact of rainfall pattern on urban waterlogging. Same rainfall and drainage and different rainfall distribution lead to different urban waterlogging.

4.2. Conclusion. Based on the principles of hydrodynamics, the model uses the underlying surface and elevation factors comprehensively in waterlogging process; it performs the whole process of city waterlogging formation in detail. The model framework is clear and its data collection and processing are simple. It realizes waterlogging depth numerical simulation by simulating the progress of waterlogging generation and waterlogging concentration. Its simulation results are waterlogging distribution and waterlogging depth maps of a certain time step. It can both express waterlogging distribution visually and also express waterlogging influence quantitatively.

FloodArea model is an existing commercial model in flood simulation. It needs some input parameters to do simulation, but the parameters are uncertain. We concluded its model framework and proposed the process of using easily available geospatial data to do simulation. In this paper, methods of various FloodArea model parameters processing are also proposed. The authors declared the specific process

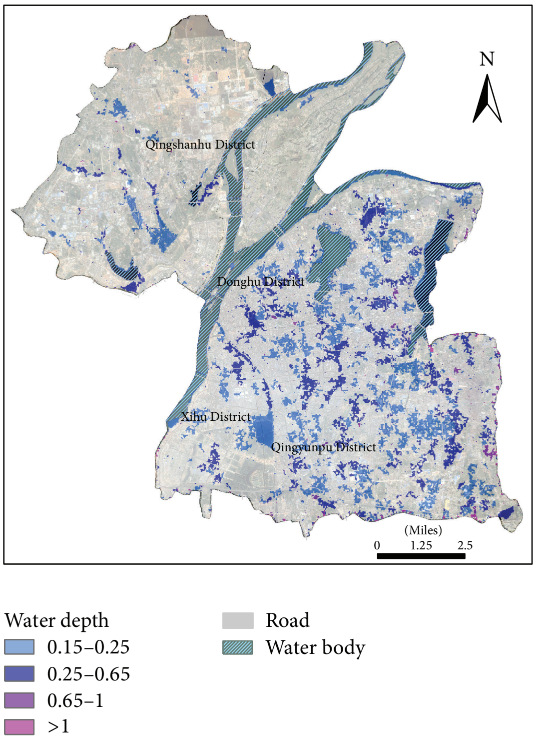

Figure 9: Distribution map of waterlogging in return period of 5 years of Nanchang.

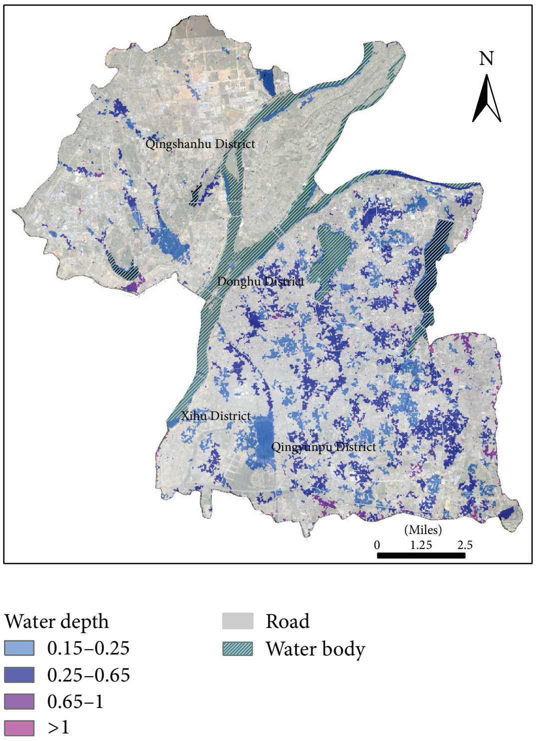

Figure 10: Distribution map of waterlogging in return period of 10 years of Nanchang.

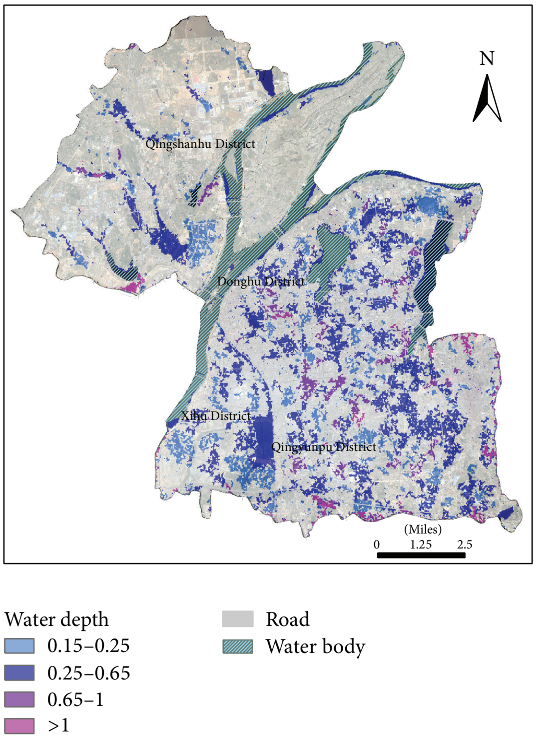

Figure 11: Distribution map of waterlogging in return period of 50 years of Nanchang.

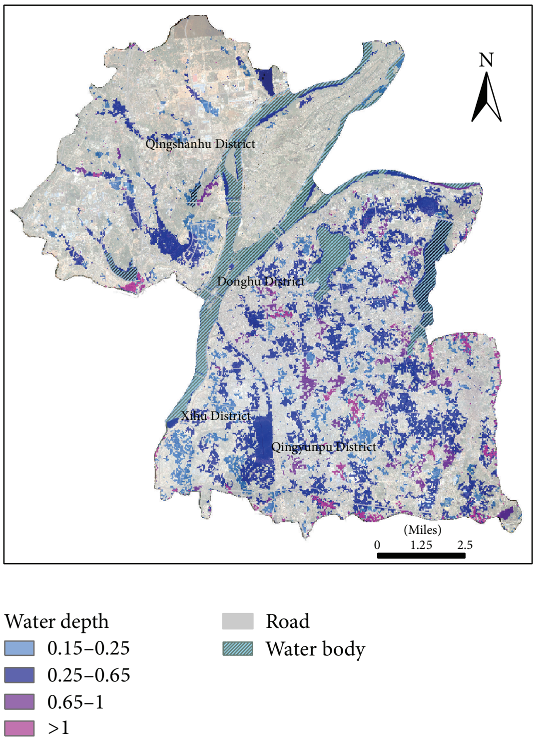

Figure 12: Distribution map of waterlogging in return period of 100 years of Nanchang.

to achieve land use type from remote sensing data and then calculate runoff coefficient and hydraulic roughness according to formulas. Concerning rainfall data processing, a variety of methods to simulate the frequency and return period from two aspects of return period and rainfall pattern are declared. Users can choose the appropriate method according to the climate characteristics. It increases the applicability of the model.

A method of drainage condition treatment is proposed. Calculate hourly rainfall after estimating the regional average drainage volume and reducing it from rainfall. It is an effective way to solve FloodArea's disadvantage without drainage parameter to make the simulation results more realistic and reliable.

Competing Interests

The authors declare that they have no competing interests.

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