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A novel seed spread algorithm–based approach for the simulation of rainstorm water logging in urban area

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ABSTRACT

Rainstorm water logging simulation is an important support for the flood disaster losses assessment and flood control in urban area. In this paper, according to the characteristics of urban rainstorm water logging, a novel seed spread–based calculation model for the simulation of rainstorm water logging in urban area is proposed. In this model, the urban area is firstly divided into many different calculation units on the basis of digital elevation model data, and the hydrological parameters of all these units are collected and stored in the form of spatial and attribute data with the help of geographical information system (GIS). The internal rainstorm water logging of each unit is simulated by simplifying the irregular topography of the calculation unit as a cone. In order to simulate the water spread between different calculation units, a new seed spread algorithm, which is based on the classical Direction 8 (D8) model, is adopted as well. Finally, with the supports of GIS, the improved urban rainstorm water logging simulation approach is implemented and applied to the city of Wuhan, China. It is shown that the proposed novel seed spread–based approach can provide more precise and more efficient simulation for the rainstorm water logging in urban area.

Keywords: Rainstorm; Water logging; Seed spread algorithm; Urban area; Simulation; Calculation unit; DEM; GIS

1. Introduction

Under the circumstance of global climate change, extreme weather such as rainstorm is more and more frequent in recent years. With the rainfall increasing, the flow rate at each outlet in urban area may exceed the maximum capacity of the corresponding drainage system. As a result, the rainstorm water cannot enter into drainage system in time but detain over the ground, and some of them may even overflow from the gullies to the surface of the city, which thereby leads to the rainstorm water logging in urban area. It has been shown that the water logging is one of the most important loss sources of urban rainstorm [1]. A large scale of deep water logging will not only seriously affect the traffic, commerce, production, government agencies, and education institutions of city, but also gravely damage the security of people's lives and properties [2]. The simulation of water logging is very useful to describe the hydrological process of urban rainstorm event, which not only can provide references for the emergency measurement of rainstorm flood disaster, but also is quite significant to guide the planning and designing of water resources system in urban area.

The rainstorm water logging can be divided into two different cases in general, the "non-source flood" and "source

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flood" [3,4]. For the non-source flood that has the flood levels as the given values, the water logging simulation is simple: all the points with elevations below the flood level in the entire basin should be included in the range of water logging. In the source flood case, the circulating area of water resources must be considered. Circulating area is the place where the water from the source flows and reaches, because the water can be obstructed by high lands in the basin, the low-lying regions may not be included in the circulating area of the water resources, and thus not be submerged in water.

With the rapid development of geographical information system (GIS) technology, digital elevation model (DEM) data are always applied to describe the irregular topography [5]. In order to simulate the water logging for the source flood, the seed spread algorithm which is based on the grid DEM data is being widely used in the existing traditional models. According to the special location of the flood source, a representative pixel of DEM is firstly selected as a seed, and then all the pixels, which are contiguous to it and whose elevations are smaller than the flood level, become seeds as well. For each new seed generated in the algorithm, contiguous pixels to them will be examined in the same way. This process repeats until there is not any new seed in the flood region, and the circulating area of flood source can be achieved by aggregating all the seed pixels, that is also the range of the water logging. The water logging depth of each pixel in the circulating area is the difference value between its elevation and the flood level.

So far, the seed spread algorithm mentioned above has been widely applied for the source flood simulation in general river basin, and almost all of the existing methods for the rainstorm water logging simulation in urban area are also based on its principle [6,7]. However, the actual water logging simulation results in urban area are always not as good as those in general river basin. The main reason is that there are many special characteristics for the urban area compared with the general natural watershed. In this paper, with the consideration of the characteristics of urban area, we improve the traditional seed spread method and try to propose a novel rainstorm water logging simulation approach which is more appropriate for the urban area.

2. Methodology

2.1. The characteristics of urban rainstorm water logging

Because of the human activities, the rainstorm water logging in urban area is quite different from that in general river basin.

(1) The urban rainstorm water logging is a multisource flood process. The capacity of urban drainage network is unable to cope with the rainstorm water in the extreme weather, which leads to the rainstorm water overflow from the gullies. Every overflow gully can be considered as a flood source. In the rainstorm with long return period, the number of overflow gully in the urban area is always more than one, so all these overflow gullies could form a multisource flood process, as shown in Fig.1.

(2) The water level is an unknown parameter in the simulation of urban rainstorm water logging. The simulation of the urban rainstorm water logging is, actually, a process to calculate the range and depth of rainstorm water according to the volume of overflow from the gullies. For each flood source, the water level cannot be acquired as an initial condition.

(3) The interinfluence between each flood source is conspicuous in urban rainstorm water logging. Due to the short distance between the gullies in urban drainage network as well as the flat topography in urban area, if the overflows occur in adjacent gullies, the flood could form several sources that may interact with each other through the surface runoff, which would make the rainstorm water logging area overlay each other, as shown in Fig.2.

2.2. The limitation of seed spread algorithm for urban rainstorm water logging

Although the seed spread algorithm is very effective in the simulation of rainstorm water logging in general river basin, however, because of the characteristics of rainstorm water logging in urban area mentioned above, it is difficult for the traditional seed spread algorithm to get favorable application effects in the simulation of urban rainstorm water logging.

(1) The circulating area plays a key role in the seed spread algorithm, which needs to be determined firstly. However, as urban rainstorm water logging is actually a multisource

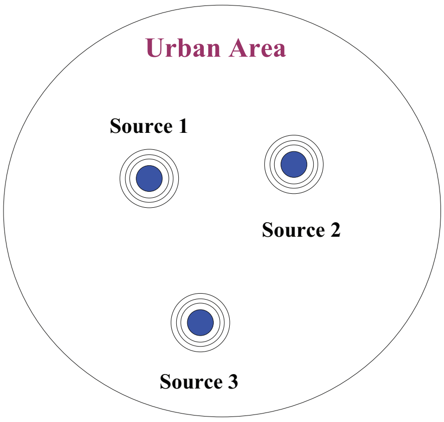

Fig. 1. Multisources in urban rainstorm water logging.

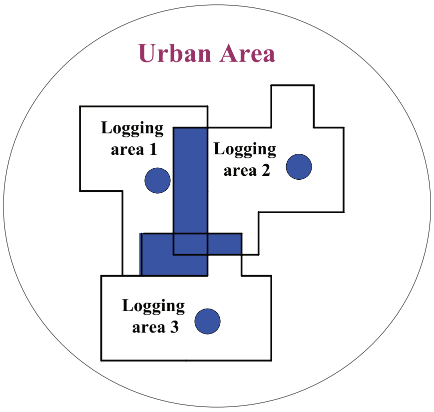

Fig. 2. Interinfluence between different sources.

flood, and flood sources may be close to each other, so there are inevitably overlaps between circulating areas of the flood sources. For the DEM pixels in the overlapping area, the flood levels from multiple flood sources need to be considered in the same time, which would obviously bring some sorts of difficulties to the acquisition of the circulating areas, and affect the feasibility of the seed spread algorithm.

(2) As the water level from each flood source is unknown, a successive approximation algorithm is always applied to deduce the actual water level according to the overflow amount from gully. This algorithm, with a high complexity of computation [8], must be repeated for every flood source, which seriously reduce the calculate efficiency. In a large-scale urban area, because there is a great number of DEM pixels that need to be considered in the circulating area, the efficiency of calculation model will be further reduced, which severely affects the timeliness of the urban rainstorm water logging simulation.

2.3. The improvement of seed spread algorithm for urban rainstorm water logging

Due to the above limitations that exist in the seed spread algorithm applied to urban rainstorm water logging simulation, how to calculate the rainstorm water logging from each flood source independently with unknown water level, and consider the water spreading between them, have become the key problem in the simulation of urban rainstorm water logging. In order to solve this problem, it is quite necessary to improve the traditional seed spread algorithm with the comprehensive consideration of the hydrological characteristics in urban area.

The improvements can be summarized as follows. Because it is difficult to determine the circulating areas of the flood sources in urban region, the drainage areas of gullies, which are actually the flood sources of urban rainstorm water logging, are introduced in this paper instead of the circulating areas as the calculation units. Comparing with the circulating areas, the drainage areas will not be affected by the actual flood level of the rainstorm water logging and can be easily extracted from the DEM of urban region. Moreover, in order to ensure the efficiency of the model in the case of large scale urban, the complex topography inside each drainage area is simplified as a regular spatial geometric figure, and then the rainstorm water logging inside each drainage area can be calculated by simply using water balance equations, which will obviously reduce the computational cost of the model. However, the inner calculations of drainage areas are not able to represent the influence scope of each flood source, so this paper also focuses on the water interaction between the drainage areas and proposes a novel D8-based algorithm for the simulation of surface runoff processes.

2.3.1. Construction of calculation unit

In urban area, the rainstorm water flows over the ground and finally enters into the drainage system through the gullies, which is the process of surface runoff. Thereby, each gully is actually an outlet, and the corresponding drainage area of the gully is the area where the rainstorm water will finally flow toward by surface runoff. Every drainage areas can be considered as a subcatchment, which has its own hydrological characteristics and independent rainfall-runoff process [9]. However, as each gully becomes a flood source, the urban rainstorm water logging is actually a reverse process of surface runoff. The overflow from each gully firstly floods the corresponding drainage area and then, when the current drainage area has been entirely flooded, spreads to adjacent drainage areas. In the urban rainstorm water logging model proposed in this paper, these subcatchments are considered as the calculation units. As a result, before the rainstorm water logging simulation, we must divide the urban area into several subcatchments (drainage areas) and then gather their corresponding hydrological information.

In order to extract the drainage areas for each gully, D8 algorithm, which is based on the DEM data, is adopted to determine the flow direction of each DEM pixel by finding the neighboring grid with the lowest elevation [10]. After the flow direction of every pixel is obtained, we can get the collection of all pixels that the flow direction finally point to, which forms the drainage areas of each gully. These drainage areas are usually irregular polygon shaped and can be organized in the vector format of spatial data by GIS, and their corresponding hydrological information are stored in an attribute data table with the structure as shown in Table 1 [11]. In Table 1, the first four fields are the known parameters needing to be input, while the remaining fields are the simulation results of urban rainstorm water logging which have to be calculated.

2.3.2. Simulation of urban rainstorm water logging inside a calculation unit

As each calculation unit is made up of several DEM pixels with independent elevations, it is difficult to describe the law of irregular topography inside each unit by a simple model. In order to reduce the computational complexity, the interior rainstorm water logging space of each unit can be simplified to a regular spatial geometric figure according to its physical parameters, and then the rainstorm water logging inside the unit can be calculated by geometry methods. Generally, the rainstorm water logging inside each unit is the process of level rising and range expanding of the overflow water, the logging range may reach the boundary of the unit if the volume of overflow is large, which will lead to the outward water spreading. As the outlet of each unit, the gully is always located in the low-lying region of the unit, so the water logging process starting from the gully is similar to the water logging of an upside-down circular cone from the bottom to the top. This paper assumes the interior space of each unit as an upside-down cone, which has the flood source (gully) of the unit as the vertex, the surface of each unit is approximated as a circle that can be considered as the bottom of the cone (Fig. 3(a)).

In Fig. 3(a), area is the area of the approximate bottom circle, ra is the radius of the approximate bottom circle, h is the height of the cone, α is the angle of the inclination of the cone. Let the mean slope of each unit be slope, then α satisfies Eq. (1).

$$\tan\alpha = \text{slope}/100 = \frac{h}{\text{ra}} \tag{1}$$

Table 1
The attribute data structure of calculation unit

Field	Description
ID	The unique identifier; primary key of the table
Area	The area of each calculation cell (m^2)
Mean elevation	The mean elevation of all DEM pixels in each calculation unit (m)
Mean slope	The mean slope of all DEM pixels in each calculation unit (%)
Flood volume	The overflow volume from the gully of each calculation unit; if there is no overflow from the gully, this value is zero (m^3)
Maximum submerged depth	The maximum water depth in each calculation unit; if there is no water logging in the unit, this value is zero (m)
Mean submerged depth	The mean water depth in each calculation unit; if there is no water logging in the unit, this value is zero (m)
Submerged range	The actual area of submerged region in each calculation unit; if there is no water logging in the unit, this value is zero (m^2)
Scope of water logging	The area of the region where has a high water depth and seriously affected by the rainstorm water logging (m^2)

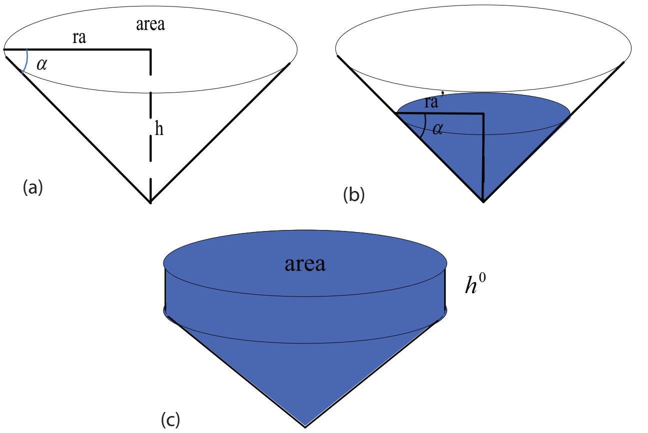

Fig. 3. Calculation unit construction: (a) the hypothetical cone of each unit; (b) the inner rainstorm water logging of each unit; and (c) the rainstorm water logging cylinder above the cone of calculation unit.

As the area and mean slope of each unit can be obtained from Table 1, slope and area are known parameters, and ra and h of the cone can be determined as Eqs. (2) and (3).

$$\text{ra} = \sqrt{\frac{\text{area}}{\pi}} \tag{2}$$

$$h = \text{ra} \cdot \text{slope} / 100 \tag{3}$$

The maximum submerged volume of each unit is the volume of the cone:

$$\frac{1}{3} \cdot \text{area} \cdot h = \text{ra}^2 \cdot \pi \cdot \frac{1}{3} \text{ra} \cdot \text{slope} / 100 \tag{4}$$

Let Q be the total volume of water logging inside each unit, it can be represented as Eq. (5).

$$Q = q + q' \tag{5}$$

where q is the flood volume in Table 1, q' is the volume of overflow spreading from the adjacent unit by the surface runoff, and its initial value is zero.

For every calculation unit in the urban area, if $Q > 0$, there is rainstorm water logging in this unit, and the inner rainstorm water logging can be calculated by using the volume formula as shown in Fig. 3(b). The blue part in Fig. 3(b) is the space that has been submerged by the overflow, which is also a cone and similar to the cone of the calculation unit. Let ra′ be the radius of the approximate bottom circle of the submerged cone, h' be the height of the submerged cone, then the volume formulas are Eqs. (6) and (7), and ra′ and h' can be derived as Eqs. (8) and (9).

$$Q = \frac{1}{3} (\text{ra}')^2 \pi \cdot h' \tag{6}$$

$$\tan \alpha = \text{slope} / 100 = \frac{h'}{\text{ra}'} \tag{7}$$

$$\text{ra}' = \sqrt[3]{\frac{300Q}{\text{slope} \cdot \pi}} \tag{8}$$

$$h' = \text{ra}' \text{ slope/100} \tag{9}$$

If ra′ < ra, it indicates that the water logging range does not reach the boundary of the unit, and there is no water spreading to the other units. In this case, h' is the actual maximum submerged depth.

Generally, the water logging area with maximum depth less than 3 cm has little impact on the urban daily life, which can be ignored in the losses assessment. So the area with submerged depth more than 3 cm is defined as the actual submerged range in this paper, which can be calculated as Eq. (10).

$$\begin{cases} \left(\dfrac{(h'-0.03)*100}{\text{slope}}\right)^2 \pi, h' > 0.03 \\ 0, h' \le 0.03 \end{cases} \tag{10}$$

When the depth of water logging is more than 25 cm, the production and normal life of the urban region will be influenced seriously. So the area with submerged depth more than 25 cm is defined as the scope of rainstorm water logging, which can be calculated as Eq. (11).

$$\begin{cases} \left(\dfrac{(h'-0.25)*100}{\text{slope}}\right)^2 \pi, h' > 0.25 \\ 0, h' \le 0.25 \end{cases} \tag{11}$$

When ra′ > ra, it means that the current calculation unit has been entirely flooded, the residual water from the flood source will flow toward the neighborhood units. In order to simulate the spreading of residual water, the spreading direction calculation method is introduced in the next section.

2.3.3. Calculation of urban rainstorm water spreading direction

The flow direction of the residual water can be calculated by the idea of D8 algorithm. In the traditional D8 algorithm, the calculation grid is the DEM pixel and the flow direction of each pixel can be determined by finding the direction of maximum drop, which can be computed by the elevation from each pixel. However, in the simulation of urban rainstorm water spreading direction, the DEM pixels are replaced by the calculation units. This process can be summarized as follows:

Step 1:

Let e be mean elevation of the current calculation unit, and p is its centroid. For any adjacent unit of the current unit, let e' and p' be the mean elevation and centroid, respectively, and $(p.x, p.y)$ and $(p'.x, p'.y)$ are the coordinates of p and p', respectively, then the drop from the current unit to the adjacent unit can be computed with Eq. (12), and the geometric distance (d) between p and p' can be computed with Eq. (13).

$$(e - e')/d \tag{12}$$

$$d = \sqrt{(p.x - p'.x)^2 + (p.y + p'.y)^2} \tag{13}$$

Step 2:

For all of the adjacent units, calculate the drops from the current unit to them and find the adjacent unit which has the maximum drop as the spreading direction unit, and all the residual water from the current unit will spread to it.

Step 3:

For the current unit, if all the adjacent units satisfy $e–e' < 0$, it indicates that the current unit is a sink cell. When a sink cell has been entirely flooded, the residual water will not spread to the other units immediately, but accumulate above the sink cell until the water level is higher than the mean elevation of any neighborhood unit. For a sink cell, we can find the neighborhood unit which satisfies $\min([e' - e]/d)$ as the spreading direction unit, and define comp = $e'–e$ as the elevation compensation from the sink cell to its spread direction units, which means the maximum depth of water logging above the sink cell before it begins to spread to the other units.

Step 4:

For each calculation unit, find the spreading direction cell and record its ID and comp, if it is not a sink cell, the comp is set to 0.

2.3.4. Simulation of urban rainstorm water spread between calculation units

If the current calculation unit has been entirely flooded, the volume of residual water needs to be calculated first. Let q^0 be the volume of residual water, it can be given as Eq. (14).

$$q^0 = Q - V \tag{14}$$

where V is the maximum submerged volume of the current calculation unit, according to the above volume formulae, the volume of residual water can be expressed as Eq. (15).

$$q^o = Q - \frac{1}{3}(\text{ra})^2 \pi \cdot \text{ra} \cdot \text{slope} / 100 \tag{15}$$

If the current unit is not a sink cell, q^0 is the actual volume of spreading water. For the sink cell, because of the elevation compensation, the residual water will accumulate above the cone after it has been flooded. In this case, the water logging space above the sink cell is assumed as a cylinder, as shown in Fig. 3(c). The base area of the cylinder is the same with the cone of the calculation unit, h^0 is its height, and the volume of water logging can be written as Eq. (16):

$$h^0 \text{ area} = q^0 \Rightarrow h^0 = q^0/\text{area} \tag{16}$$

If h^0 < comp, there will be no water spreading from the current calculation unit due to the elevation compensation, as the residual water accumulate above the unit, the maximum submerged depth of the current unit becomes as follows:

$$h^0 + h = h^0 + \text{ra} \cdot \text{slope}/100 \tag{17}$$

As the unit has been entirely flooded, we can calculate the actual submerged range by subtracting the submerged area with depth less than 3 cm to the area of unit as Eq. (18).

$$\begin{cases} \text{area}, h^0 > 0.03 \\ \left(\dfrac{\left(h+h^0-0.03\right)*100}{\text{slope}}\right)^2 \pi, h^0 < 0.03 < h+h^0 \\ 0, h+h^0 \le 0.03 \end{cases} \tag{18}$$

Similarly, the scope of rainstorm water logging can be calculated as follows:

$$\begin{cases} \text{area}, h^0 > 0.25 \\ \left(\dfrac{\left(h+h^0-0.25\right)*100}{\text{slope}}\right)^2 \pi, h^0 < 0.25 < h+h^0 \\ 0, h+h^0 \le 0.25 \end{cases} \tag{19}$$

If h^0 > comp, there will be still water spreading from the current unit, and the final volume of residual water is q^0 – comp × area. In this case, the maximum submerged depth of the current unit is comp + h.

For the current unit, when the actual submerged volume and range have been determined, the mean submerged depth can be calculated as Eq. (20):

$$D_a = Q^0/R_s \tag{20}$$

where D_a is the mean submerged depth, Q^0 is the actual volume of water logging inside the current unit, and R_s is the submerged range.

After the simulation of urban rainstorm water logging of the current unit is finished, the calculation results of the maximum submerged depth, the mean submerged depth, the submerged range, and the scope of water logging will be stored in the attribution data table. If there is water spreading from current unit, the volume of residual water will be added to the q' of the spreading direction unit.

2.3.5. New seed spread algorithm for urban rainstorm water logging simulation

In order to ensure that all of the overflow from every single flood source, no matter whether it is collected in the unit or spread to others, are considered in the simulation of urban rainstorm water logging, we design a new seed spread algorithm. In this algorithm, every calculation unit that has overflow from its gully is marketed as a seed. Elevations of every seed unit are sorted from highest to lowest to build a calculation queue, the water logging and spreading of each seed in this queue will be calculated in order (Fig. 4).

3. Application, result, and discussion

3.1. Study area

The study area is a university campus located in the city of Wuhan, China. The campus covers a total area of 3.88 km^2, whose land use types mainly include urban land, afforested cover, and shrub cover. According to the DEM data, the campus is generally flat with little gradient in the south, but hilly in the north, and the range of its elevation is between 24 and 147 m. The drainage facilities in the campus are complete but aging in a certain degree. In July 2013, a torrential rain caused serious storm water logging in the west of the campus, which severely threatened the safety and property of students. So it is representative to select this campus as the case study.

3.2. Design rainstorm

A rainstorm with parameters close to the heavy rainfall event in July 2013 is designed. According to the rainfall statistical data of the study area, the return period of the rainstorm in July 2013 is 5 years. On the basis of return period and rainstorm intensity formula, the rainfall curve with 120 min as rainfall duration and 5 min as sampling interval is determined as show in Fig. 5.

In the curve, the peak value of the rainfall intensity reaches 140.46 mm/h, which appears at 50 min after the rainfall starts, and the total rainfall depth in the 120 min duration is 75.25 mm. The intensity curve and time series of the rainfall are the main data input for the urban rainfall-runoff model, upon which the volume of each flood source of the rainstorm water logging can be simulated.

3.3. Calculation unit construction

By using D8 algorithm, the flow direction of the study area can be calculated based on GIS. All the gullies in the campus are merged into 67 major gullies, and therefore, 67 calculation units are formed according to the flow direction. The calculation units are organized in the form of polygon features in GIS, whose hydrological information are stored in the attribution data table. The calculation units' polygon layer of the study area is shown in Fig. 6, where each polygon represents a calculation unit. The statistical measures from the attribution data table of the 67 calculation units are given in Table 2.

In Table 2, it is shown that due to the flat area in the south of the study area, most calculation units have a little mean slope value except those in the north, and the calculation units with the maximum values of mean elevation and slope are both located at the hilly land of the study area. Moreover, there are nine sink cells in the 67 calculation units with the elevation compensation from 0.06 to 2.94 m, which will be considered especially in the water spreading simulation.

3.4. Calculation of the water volume overflowing from each source

The storm water management model (SWMM) has been widely used in the hydrological process simulation in urban region, and it is able to calculate the volume of overflows from gullies inside each calculation unit and store them in the attribution data table [12]. In order to obtain the overflow volume as the initial condition of the proposed approach for urban storm water logging simulation under the design rainstorm, the drainages and gullies data, the distribution of calculation units and hydrological parameters of the study area are collected, and an SWMM model is established. Table 3 shows the calculation results of water volumes for the design rainstorm in the study area.

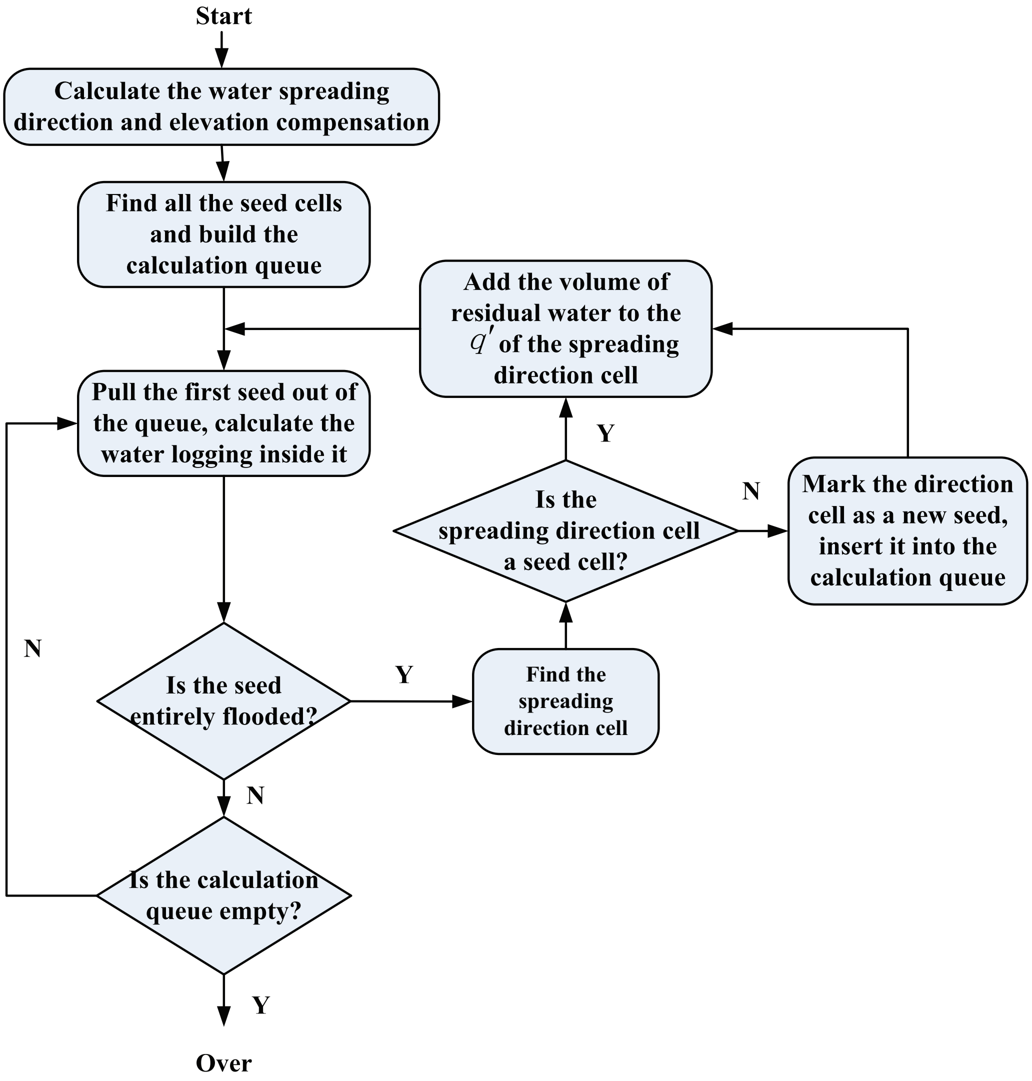

Fig. 4. The process of the new seed spread algorithm for urban rainstorm water logging simulation.

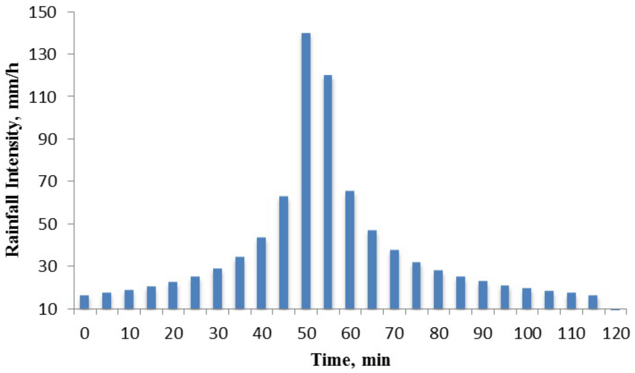

Fig. 5. The rainfall intensity curve of the design rainstorm.

It is shown that there are 20 calculation units which have overflow from their gullies, and therefore they constitute 20 flood sources in the study area. Out of these 20 calculation units, there are five sink cells with the ID of 9, 24, 29, 37, and 46. The ID of the calculation unit with the maximum water volume of 2,487 m^3 is 27. These calculation units are sorted by their mean elevations, which can form the calculation queue for the rainstorm water logging simulation in the study area.

3.5. Results and discussion of the rainstorm water logging simulation

3.5.1. General situation of the rainstorm water logging

According to Table 4, the rainstorm water logging appears in 21 calculation units in the study area, and 17 of them with the maximum submerged depth over 25 mm. The ID of the calculation unit with the biggest submerged range is 27, which is located at the westernmost periphery of the study area, and the flooding area inside it reaches over 10,000 m^2. Moreover, the scope of water logging in this calculation unit is 4,362.5 m^2, which is also the biggest one among all the 67 units. Large range of water logging coupled with high submerged depth (maximum: 0.66, mean: 0.24) will obviously cause a great damage to the safety and property of students in this unit, which is coincident with the rainfall records in

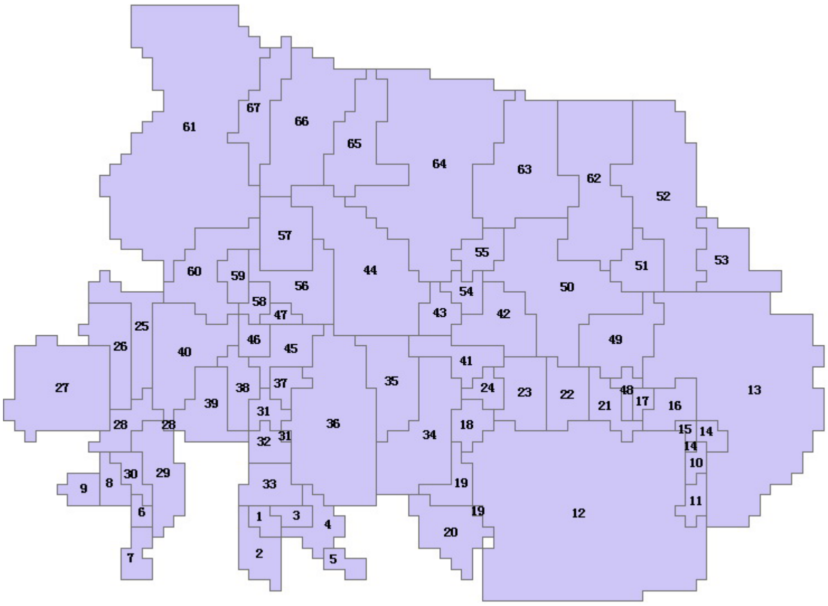

Fig. 6. The distribution map of calculation units in the study area.

Table 2
The statistical measures of 67 calculation units in the study area

Field	Value		
	Minimum	Mean	Maximum
Area	0.25	3.49	26.45
Mean elevation	36.81	50.50	77.79
Mean slope	0.2	2.27	14.2
Number of sink cells		9	
Elevation compensation	0.06	0.63	2.94

July 2013. The calculation unit with the deepest submerged water is ID 67, which is located at the northwest hill land in the study area. Due to the steep slopes in this unit, the flood overflowing from the gully will collect at the low-lying of the unit more easier, and thus cause high submerged depth (maximum: 0.66, mean: 0.24). However, as the flood is mostly concentrated within a small scope, the actual water logging situation in this unit is not very serious.

3.5.2. Water spreading in the study area

As the number of the submerged calculation units is bigger than the number of flood sources, it is evident that there is water spreading between the calculation units. The water spreading situation in the study area is represented in Table 5. There is no flood source in the calculation unit 58, but the unit 47, which is one of neighbor units of unit 58, has been entirely flooded, and the residual water from it would spread to the unit 58, thus cause the water logging inside this unit. Moreover, as the volume of residual water flowing to unit 58 reaches 1,114 m^3, this unit, which has flat surface and small size, has also been submerged. There are 508 m^3 of residual water from unit 58 and then flow to the unit 46, finally stuck at there. As the mean slope of unit 58 is very small, there is no deep water logging inside although it has been entirely submerged, and the scope of water logging in the unit 58 is only 54.9 m^2, which will not cause any serious flood disaster. In addition, another calculation unit with the ID of 24 has also been entirely flooded besides the unit 47 and 58. However, because this unit is a sink cell with 0.38 m as its elevation compensation, although the residual waters accumulate above the cell, and finally, as the depth of water logging does not reach 0.38 m, there is no water spreading from unit 24.

Table 3
The flood source (ID) and water volume in the study area

ID	Water volume
8	37
9	50
24	1,974
25	363
26	1,168
27	2,487
28	186
29	1,131
30	615
34	2,199
36	2,103
37	35
38	548
44	761
46	562
47	2,081
48	44
59	457
60	540
61	495

Table 4
The simulation results of the rainstorm water logging in the study area

ID	Submerged range	Water logging scope	Maximum submerged depth	Mean submerged depth
8	352.2	0	0.24	0.11
9	579.7	0	0.18	0.08
24	8,200.0	2,582.2	0.62	0.24
25	2,051.3	500.0	0.46	0.17
26	5,251.0	1,990.7	0.60	0.22
27	10,300.1	4,362.5	0.66	0.24
28	1,597.0	20.5	0.28	0.12
29	4,270.2	2,009.6	0.73	0.26
30	4,898.9	204.5	0.31	0.12
34	7,248.4	3,869.6	0.85	0.30
36	6,784.3	3,685.6	0.87	0.31
37	395.6	0	0.19	0.09
38	3,938.1	377.8	0.35	0.14
44	4,997.9	749.7	0.39	0.15
46	5,159.3	1,750.6	0.56	0.21
47	4,416.4	1,637.5	0.59	0.22
48	473.8	0	0.20	0.09
58	5,238.9	54.9	0.28	0.12
59	2,133.9	763.5	0.58	0.21
60	1,973.6	959.9	0.76	0.27
61	1,342.7	823.0	1.04	0.37

Table 5
The simulation results of water spreading in the study area

ID	ID of water spreading direction	Water volume	Water volume from the adjacent unit
47	58	2,081	0
58	46	0	1,113
46	45	562	508

3.5.3. Spatial distribution of submerged unit

According to the spatial distribution characteristics of the calculation units in which there are different depth of rainstorm water logging, the layer of calculation units is rendered to show where and how the rainstorm water logging happened (Fig. 7).

In Fig. 7, the calculation units without rainstorm water logging inside are displayed by white color, and other units are submerged by the overflow from the flood sources. The redder the color is, the deeper the water is. As shown in Table 4 and Fig. 7, it is obvious that the water logging is mainly located at the west and middle of the study area, and the calculation units with large scopes of water logging are unit 26, 27, 29, 34, and 36, which constitute the heavy disaster area of the rainstorm water logging. According to the flood records of the rainstorm in July 2013, the simulation results are basically identical with the actual situation of the rainstorm water logging. The results above are quite encouraging and prove that the novel approach proposed in this paper can provide a fast and accurate simulation for rainstorm water logging in urban area.

3.5.4. Assumptions and limitations

In this paper, the inner topography space of each calculation unit is considered as a regular geometric figure so as to reduce the computational complexity. However, the actual topographic relief of each calculation unit is always irregular and uneven. As a result, the proposed approach is not able to describe the specific distribution of water logging inside each unit, but provides a general situation of the submerged results. This problem can be solved by subdividing each calculation unit into several subunits with smaller size, but the complexity will be increased at the same time.

4. Conclusion

This paper proposed a novel seed spread approach for the simulation of urban rainstorm water logging. In the improved model, the characteristics of urban rainstorm water logging have been fully taken into account, and the calculation units have been changed into the drainage area of the gully. As a result, the rainstorm water logging from multisources can be calculated independently inside the corresponding units, which can resolve the difficulties in circulating area calculation that commonly exist in the traditional methods. In addition, a D8-based seed spread algorithm is proposed as well to simulate the water spreading between several units. Finally, the proposed approach is applied to a case study. It is shown that as the hydrological characteristics of the urban rainstorm water logging are fully considered, the simulation results are more reliable and accurate. Even though there are some sorts of limitation existing in the approach proposed in this paper, the implementation of calculation model is still able to

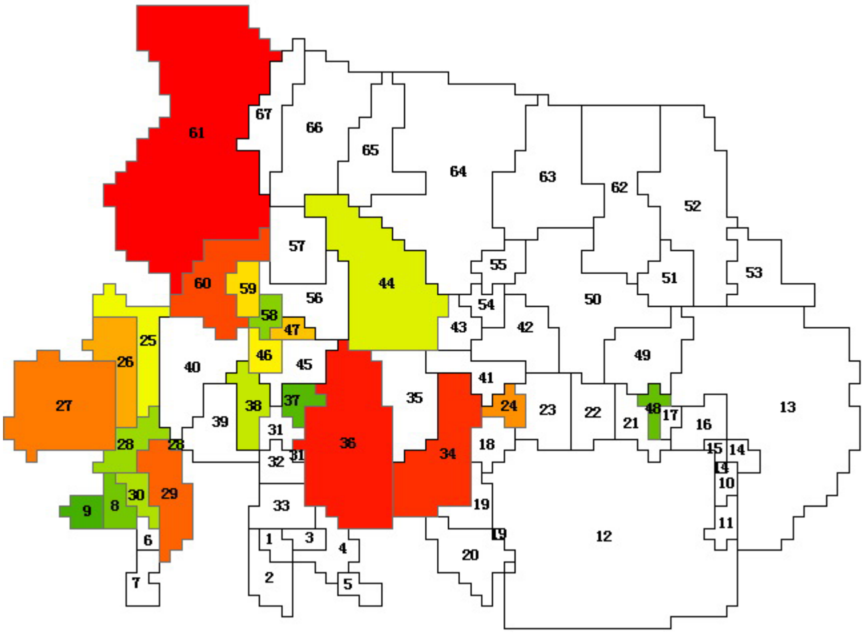

Fig. 7. The spatial distribution map of simulated rainstorm water logging in the study area.

afford a new idea to solve the problem of how to simulate the rainstorm water logging in urban area more accurately and efficiently, which can provide strong supports for the flood losses assessment and flood control in urban area.

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