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A methodology for simple 2-D inundation analysis in urban area using SWMM and GIS

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Abstract

Urban waterlogging occurred frequently in recent years, causing serious social harms and huge economic losses. Accurate waterlogging warning is important for disaster prevention and mitigation. Urban rainstorm waterlogging processing based on Geographic Information System (GIS) and Storm Water Management Model (SWMM) can provide prediction and management of flood situation, but the previous methods of catchments from a single aspect of hydrology or geometry cannot reflect the dual impact of pipe networks and terrain to drainage, and the available inundation algorithms achieved some unreasonable results due to the artificial boundaries. In this paper, a methodology for simple 2-D inundation analysis in urban area using SWMM and GIS is introduced, which need not edit SWMM's original code. Furthermore, a geometric method of catchments division and inundation algorithm are proposed to improve accuracy. The revised catchments division method provides a good result of supplementing the drainage of terrain, and the improved inundation algorithm can obtain a reasonable inundation distribution based on the principle of source diffusion and dynamic distribution without any boundary limit. The case study was performed in Longwen District of Zhangzhou, and good results are achieved: (1) The external outflow percentage of the revise method is always bigger than that of the geometric method, and the value of the revised method is 25.18%, while that of geometric method is only 19.56% at rainfall peak, and (2) the less the rainfall is, the less grids flooded in two algorithms there are with only 14.30% when the rainfall is 0.1 mm.

Keywords GIS · SWMM · Urban waterlogging process · Catchments division · Inundation algorithm

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1 Introduction

In the last years, frequent urban waterlogging caused traffic congestion and enormous loss of life and property. For example, there were 79 victims, 1.6 million of people affected by the flood and 1.7 billion dollars loss in property in '7.12' Beijing Rainstorm in 2012 (Sun et al. 2013). The rainstorm happened in July 2018 in Nanjing caused the water level of some areas over automobile tailpipes, and the vehicles were trapped in the water for a long time. So it is important to predict water floods as urban flood blocks the healthy development of cities (Bisht et al. 2016). Accurate prediction and risk assessment are the scientific references for disaster prevention and mitigation, which has a great social impact (Olugunorisa 2009). Daily rainfall forecast can only reveal the intensity of rainfall rather than the ability to respond of different cities affected by rainstorm. On the contrary, a hydrological model combined with GIS technology can convert the rainfall into flood depth and spatial distribution, which achieves the direct prediction of hazard factors. A 1-D (one-dimensional)/2-D (two-dimensional) coupled model is simple and fast enough to get the flood depth and spatial distribution during rainstorms, useful to predict water flood before their occurrence. SWMM is a well-known free open-source software, so many 1-D/2-D coupled models based on SWMM have been developed (Pathirana et al. 2008).

Geographic Information System (GIS) can design to capture, store, manipulate, analyze, manage and present spatial or geographic data. GIS tools allow users to create interactive queries (user-created searches), analyze spatial information, edit data in maps and present the results of all these operations. EPA's Storm Water Management Model (SWMM) is a dynamic hydrology–hydraulic water quality simulation model. It is used for single event or long-term (continuous) simulation of runoff quantity and quality from primarily urban areas. SWMM is one of the commonly used distributed models throughout the world for planning, analysis and design related to storm water runoff, combined and sanitary sewers and other drainage systems in urban areas (Li et al. 2014). One of the main applications of SWMM is to construct drainage models to simulate hydrological and hydraulic processes (Cipolla et al. 2016; Wang et al. 2018). Sensitivity analysis of model parameters provided a good modeling reference (Li et al. 2014; Rabori et al. 2017; Sharifan et al. 2010). Catchment is a vital parameter in SWMM, whose division methods can be divided into two categories: (1) hydrological analysis method based on DEM and (2) geometric method based on nodes. There are several shortcomings in both two division categories, so many researchers took some means to overcome the shortcomings for better results. For hydrological methods, catchments are divided with hydrological tools based on DEM and then some details are revised according to the priority (Mariza and Stephen 1994). The method has a poor applicability in plain areas. Many researchers have improved algorithms of catchments division with achieving some certain effect, but all the algorithms neglect the influence of urban drainage pipe network on the process of urban waterlogging. A hydrological method was implemented by combining other factors into DEM (digital elevation model) using known streets and pipes to adjust the local elevations (Gironás et al. 2010). For geometric methods, the nodes are determined according to research objectives firstly and then catchments are divided with Voronoi (Thiessen polygon) method based on nodes. The geometric method is a high-precision method but neglects surface fluctuation (Li and Zhang 2012). The geometric method was used to study the effect of node-type selection for catchment division, and the Voronoi-based algorithm was proposed to avoid irrelevant branches through labeling sample points to obtain a better catchment division (Karimipour and Ghandehari 2013). Most previous methods dealt with the problem from a single aspect of hydrology based on terrain or geometry computed on nodes, instead urban drainage is a combination of drainage system and terrain, so some researchers tried some means to solve this problem. A new GIS-based division approach was proposed to capture the characteristics of the spatial variability in topography and hydrogeological information of urban catchments, which reflects the hydrological features of the urban catchments but it is complex (Shen and Zhang 2015). Drainage of urban terrain has been considered, while the known streets and pipe networks are mainly considered (Gironás et al. 2010). However, most of the pipes in China are distributed along the streets and the drainage of streets is well revealed. In the high-precision division, the catchment area does not even cover the entire street, so in this case, there is no need to express the drainage of streets again. A revised geometric catchments division method supplementing the drainage of terrain is proposed in this paper, which has simple data processing.

As SWMM is an open-source software, many 2-D inundation analysis models coupled with GIS and SWMM are available. The SWMM computing engine is used to simulate and calculate automatically the model though a dynamic link library (DLL) (Leandro and Martins 2016), and then it parses the results to obtain the required information. Finally the inundation analysis is performed with an inundation algorithm (Azli and Rao 2010; Huang et al. 2011, 2015). The nodes flood was converted into grid flood to get the depth with GIS tools (Shi et al. 2014). Simple inundation analysis coupled with GIS and SWMM was done with a non-source diffusion algorithm to get urban inundation risk, and catchments are units of inundation analysis and inundation always starts from the lowest grids (Wang 2017). Seed spread method is one of mainly used source algorithm, and an algorithm on the principle of seed spread was proposed to search the flooded grids and calculate inundation depth (Qian 2015) and to solve spatial discontinuity of inundation within a catchment instead of between all catchments. There are also many inundation algorithms involved in those methodologies or models (Shi et al. 2014), but most of these algorithms have a defect that neither the source or non-source inundation algorithms can solve the limitation of catchment boundary. The flood is diffused in one catchment limited only by the boundaries in most algorithms. Catchments are used to collect water during rainfall–runoff process, but there is no real barrier in these boundaries during inundation analysis and the flood can go through more than one area. The boundaries make the inundation unreasonable, so the boundaries should be broken.

The paper aims to propose a methodology for simple 2-D inundation analysis in urban area using SWMM and GIS without the need for editing SWMM's original code. To achieve this goal, the data processing of 2-D inundation analysis using GIS and SWMM is presented in Sect. 2.2, and then a revised method of catchments division and a source dynamic diffusion inundation algorithm are proposed to improve accuracy. Results and analysis are presented in Sect. 3 as well as discussions in Sect. 4, and finally conclusion is given in Sect. 5.

2 Materials and methods

2.1 Studied area and data used

Longwen district is one of the main city areas in Zhangzhou, Fujian Province. Its annual averaged precipitation is 1450 mm. It suffers urban water flood frequently, as it has affected by typhoon. The studied area is the center of economic activity in Longwen district. The area is an optimum place to test the method as it is populous, it has intensive constructions, its water conservancy facilities are in good conditions, and its surface features are complex.

The visual remote sensing image was downloaded from the website of 'Map World' (http://www.tianditu.gov.cn), and its resolution is 0.3 m (Fig. 1). The DEM has been retrieved from the Survey Department of Zhangzhou City, and its resolution is 5 m. The sewer system data with information on shape and attributes were obtained from the Zhangzhou City Archive, which are drawn by real field measurements. The observation data of the station in studied area are used for rainfall data.

2.2 A methodology for simple 2-D inundation analysis in urban area using SWMM and GIS

This section starts with a detailed presentation of data processing of 2-D inundation analysis using GIS and SWMM. In the end of this section, a methodology for simple 2-D inundation analysis used in this paper is concluded.

Urban rainfall waterlogging processing based on GIS and SWMM can be divided into four parts: data preprocessing based on GIS, SWMM construction, flood volume acquisition and inundation analysis and visual presentation of results using GIS (Fig. 2). Land use data, DEM, drainage system and precipitation station data are collected as basic data, and these data are preprocessed to meet the requirement of SWMM construction.

After preprocessing, all the parameters are put into SWMM to construct the model of the studied area. The main parameters of SWMM are catchments, conduits, junctions and outfalls, and all the parameters have their attributes. Catchments are the basis of the distributed hydrological model and also important input parameters of SWMM. A revised catchments division method will be elaborated in Sect. 2.3. The infiltration model of SWMM is Horton model. The Horton equation is one of the most popular empirical models simulating infiltration of water into soils. The infiltration equation is a three-parameter equation which is commonly expressed as (Abulkadir et al. 2011):

$$f(t) = f_c + \left(f_o - f_c\right)e^{-kt} \tag{1}$$

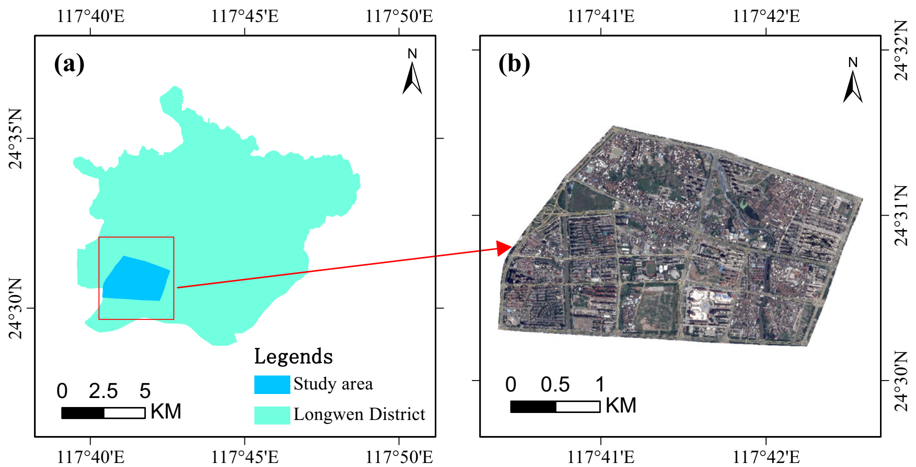

Fig. 1 Sketch map of study area: **a** the map of Longwen district boundary; **b** the remote sensing image of study area with 0.3 m resolution ratio

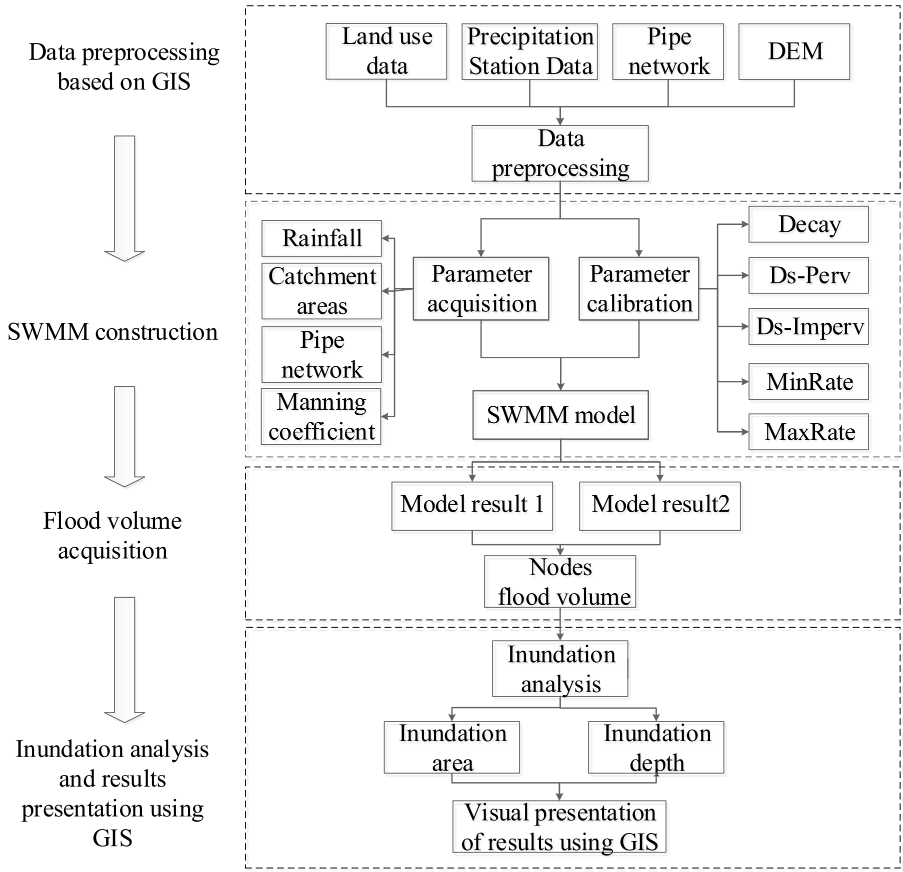

Fig. 2 Flowchart of basic data processing of 2-D inundation analysis using GIS and SWMM

where f = infiltration rate at time t, mm/hr; f_o = initial infiltration rate, mm/hr; f_c = final infiltration rate, mm/hr; t = time from beginning of storm, s; and k = rate constant in dimension of frequency, 1/s.

This equation describes the familiar exponential decay of infiltration capacity evident during heavy storms. In SWMM application, the area and width of catchments can be obtained directly through measurement, and the remaining seven attributes need to be calibrated: N-Imperv, Imperv, Ds-Imperv, Ds-Perv, MaxRate, MinRate and decay. Each catchment is composed of different land use types, and the land use type determines the land's permeability and its Manning coefficient. N-Imperv means the mean Manning coefficient of impermeable area of each catchment, and Imperv means the mean Manning coefficient of permeable area. The Manning coefficient of each land use type is determined according to the value given in the SWMM model reference manual, and nine features' Manning coefficient is given in Table 1. Ds-Imperv means water storage in depressions of impermeable area, and Ds-Perv means water storage in depressions of permeable area. MaxRate means the max infiltration rate of catchments, and MinRate means the steady infiltration rate of catchments. Decay means the Infiltration attenuation coefficient of catchments. After catchments division, N-Imperv and Imperv of each catchment are determined by the

Table 1 Manning coefficient of different land use types

Land use types	Reference class	Manning coefficient
Farmlands	Cultivated soil with residual coverage < 20%	0.06
Constructions	Cement mortar, brick	0.014
Woodlands	Dense shrub	0.8
Green space	Light shrub	0.4
Rivers	Small rivers with regular section	0.05
Lakes	Ponds with irregular sections	0.07
Meadows	Plain weeds	0.15
Roads	Smooth asphalt	0.011
Impermeable land	Smooth concrete	0.012

principle of area weighting. The remaining five attributes cannot be obtained directly by measurement and need to be calibrated.

$$N\text{ - Imperv} = \frac{\sum_{i=1}^{n} N\text{area}_i * M_i}{\sum_{j=1}^{n} N\text{area}_j} \tag{2}$$

$$\text{Imperv} = \frac{\sum_{\text{i}=1}^{\text{m}} \text{area}_\text{i} * \text{M}_\text{i}}{\sum_{\text{j}=1}^{\text{m}} \text{area}_\text{j}} \tag{3}$$

where n is the number of land use types of impermeable area in the catchment, $N\text{area}_i$ is the land use area of case i in impermeable area—its unit is m^2, M_i is the Manning coefficient of land use of case i, m is the number of land use types of permeable area in the catchment and area_i is the land use area of case i in permeable area—its unit is m^2.

SWMM provides results in two file formats: RPT and OUT. The RPT file is a text file that stores the results summary. The information of 'Total Flood Volume' in the part of 'Node flooding summary' shows the total flood volume during the whole simulation process, there is no matter to use the information to simulate the possibly most serious flood of the whole process, but it is inaccurate to use the information to reveal the flood of each instant and it exaggerates the flood. The OUT file is a binary file that stores the detailed information of all elements at each instant and is used to get the flood volume at each instant in this paper.

Next is the vital step for inundation analysis. Flood volume will transform into inundation extent and depth with DEM and a diffusion algorithm, which is the waterlogging expression, also known as inundation analysis. Fundamentals of inundation analysis and flow direction are two key points in waterlogging expression. The detailed information will be elaborated in Sect. 2.5.

The methodology for simple 2-D inundation analysis can be described in Fig. 3. First, basic data processing is to construct a SWMM model for the study area through SWMM 5.0 and then get the INP file. There is no need to run the SWMM desktop software to get results and edit SWMM's original code, automatic operation on INP file through a DLL generates RPT files and OUT files. The version of INP files must consistent with the version of the SWMM DLL, or it will lead to a failure. The version of SWMM DLL used in

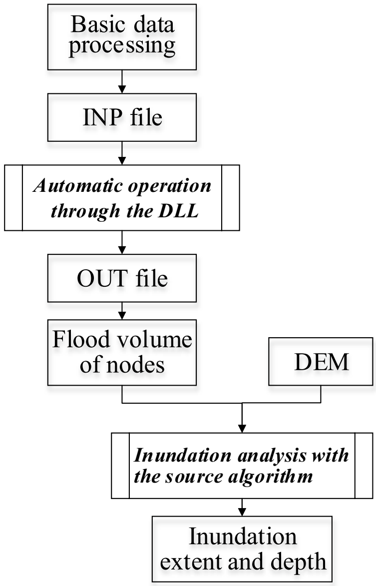

Fig. 3 Flowchart of the methodology for simple 2-D inundation analysis in urban area using SWMM and GIS used in this paper

this paper is 5.0, so the version of INP files should be 5.0.x. Steps from basic data processing to get OUT files are related to SWMM, but the remaining steps are independent of SWMM, they concern with file parse technology and grid map processing techniques. Flood volumes of all nodes at each instant are extracted from OUT files. With known flood volumes and DEM, inundation analysis using the source dynamic diffusion algorithm results in inundation extent and depth. Steps after INP files generation are processed by a program developed in C#, and GDAL (Geospatial Data Abstraction Library) is mainly used to process grid map in the program.

2.3 Methods of catchments division

A catchment is an area where water is collected by the natural landscape. It is essential to do catchments division on the basis of feature characteristics because the underlying surface is complex and different surface features show different characteristics during rainfall–runoff process. The accuracy of catchments division has a great influence on final results (Mazion and Yen 1994). The research about the influence of precision of catchments division on the result accuracy shows that a high-precision division should be taken when it simulates waterlogging during a single rainfall considering that the terrain of studied area slopes gently (Qin et al. 2016). Urban flood usually happens during a high intensity rainstorm with a short duration, and the terrain slopes gently in most cities except some 'mountain cities' with an abrupt terrain, so a high-precision division should be taken in urban waterlogging simulation of most of the cities.

For hydrological methods, catchments are divided with hydrological tools based on DEM. The method has a poor applicability in plain areas. One of the keys to deriving hydrological characteristics about a surface is the ability to determine the direction of flow from every cell in the raster. In method D8, pixels are centered on the DEM grid points, and each pixel discharges, or 'spills,' into one of its eight neighbors: the one in the direction of steepest descent. The total contributing area of a pixel is the number of pixels

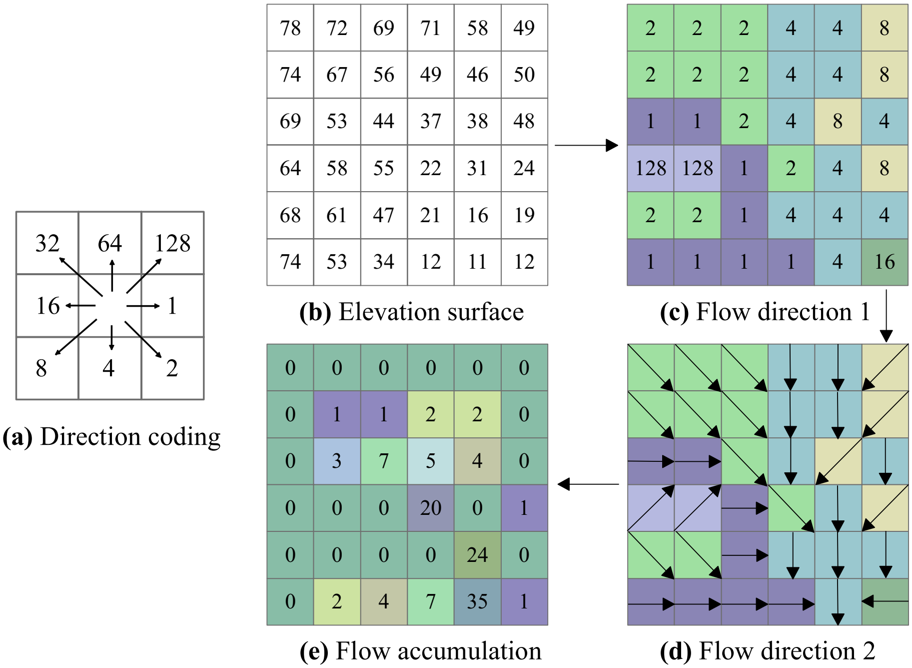

Fig. 4 Sketch map of D8 algorithm: **a** direction coding of D8 algorithm; **b** sample elevation surface; **c** flow direction in number of sample data; **d** flow direction in row of sample data; **e** flow accumulation of sample data

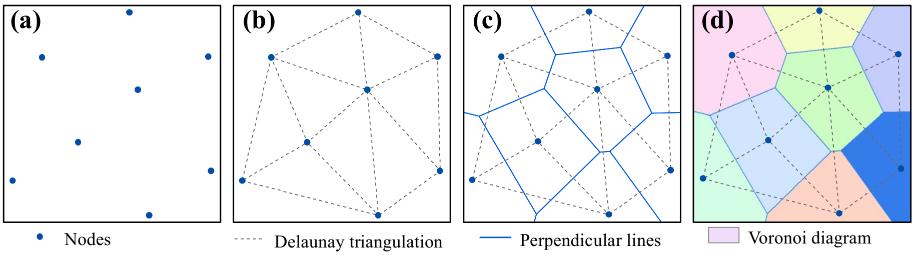

Fig. 5 Sketch map of Voronoi diagram: **a** nodes; **b** Delaunay triangulation of nodes; **c** create perpendicular lines of Delaunay triangulation; **d** Thiessen polygons of each nodes

whose flow reaches the pixel of interest following a path of steepest descents, multiplied by one pixel area (Mazion and Yen 1994). Basins are created according to grids' flow direction. A stream network can be obtained by calculating the number of upslope cells flowing to a location, which is used to extract natural flow paths in this case. Figure 4 (http://resources.arcgis.com/en/help/) shows the basis of D8 algorithm.

For geometric methods, the nodes are determined according to research objectives firstly and then catchments are divided with Voronoi (Thiessen polygon) method based on nodes. The Voronoi diagram is also known as Thiessen polygon and dual to the Delaunay triangulation (Guth and Klingel 2012), which is shown in Fig. 5. The Voronoi diagram is based on a set of nodes and defines one area for each node with every point within the area being closer to the originating node of the area than to any other node. They represent the catchment areas of the nodes (Shen and Zhang 2015).

For a high-precision division, catchments of nodes based on Voronoi diagram are the first choice, because there are numerous junctions among streets so that selecting key junctions to be nodes and creating their Thiessen polygons are feasible. To reveal the effect of urban terrain to drainage, extraction of the stream network with D8 algorithm is used to revise pipe networks. So, the urban pipe network model is firstly constructed by selection and process with some rule of real drainage networks, the first part of junctions and conduits are obtained. Then, a stream network is extracted based on DEM with D8 algorithm, and it can be done with the hydrological analysis tools ArcGIS. The stream network may contain flow paths such as rivers or roads and so on, but the terrain-derived flow paths are only needed, so the stream network should be further processed. All the flow paths and their nodes, including start points, end points and intersection points, are analyzed and compared to the actual drainage network, the nodes that overlap with the actual pipe network will be removed, and the nodes that play a complementary role in regional drainage will be kept. The pipe network at these nodes is supplied after analyzing the flow direction. The two parts of the nodes constitute all the nodes of the final model, and the same is true for pipe network. The modified nodes and pipe network demonstrate drainage characteristics caused by terrain, which can make up for the shortage that there is no actual pipe but actual flow paths in some areas.

The revised method is an optimization of geometric methods by revealing the drainage function both of urban terrain and drainage pipe network. The direct differences between two methods are drainage, then consequent area of catchments and flow length, and these will result in different runoff and outflow in SWMM models. Assessing the two methods is similar with sensitivity analysis about the two parameters. Extensive sensitivity analysis results can be consulted in previous researches, which all concluded that a slight change in any of these input parameters will significantly change the simulated runoff, but had inconsistency in parameters. Akdogan and Goven (2016) revealed that area of subcatchments, precipitation and conduit depth are the most significant parameters in SWMM affecting runoff production and percent imperviousness and percent slope are the least significant parameters. Chow et al. (2012) studied on SWMM runoff quantity modeling, his conclusion was that catchment width had a strong influence on peak flow but relatively weak on runoff depth. The inconsistency of conclusions may be due to differences in applicable scenarios, but this doesn't matter it can conclude that the two catchments division methods will result in different runoff. The specific effect of two methods will be elaborated in latter case study.

2.4 The SWMM model for the study area

There are nine land use types in study area: rivers, lakes, farmlands, constructions, woodlands, green space, meadows, roads and impermeable land, and Fig. 6 shows the map of their Manning coefficient distribution.

Drainage system data are collected, and drainage networks model is constructed according to actual data. The drainage networks distribution map is shown in Fig. 7c with 167 nodes and 137 conduits. The study area is divided into some catchments with the revised catchments division method proposed above. Pipe networks have been obtained in the last step, and natural flow paths in region are extracted (Fig. 7b). All the flow paths and their nodes are analyzed and compared to the actual drainage network,

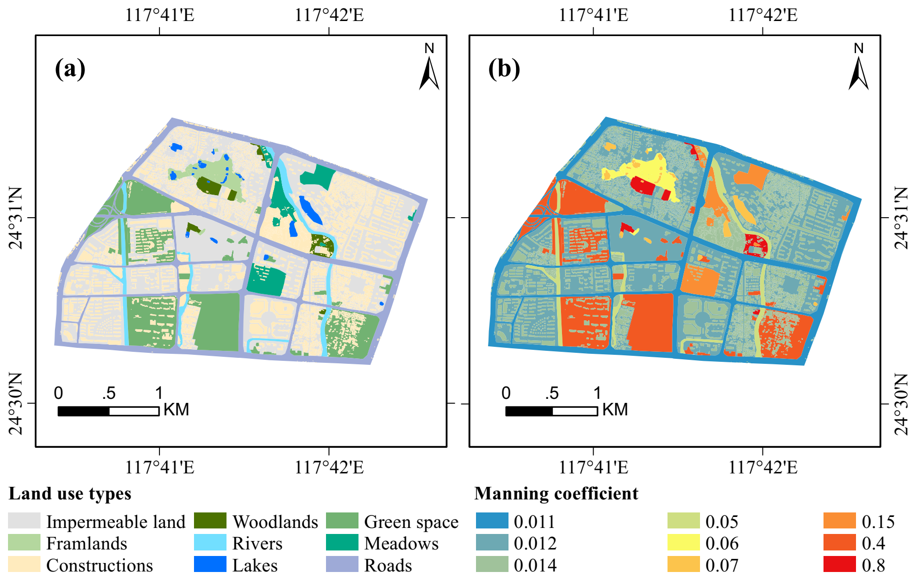

Fig. 6 Distribution map of land use types and Manning coefficient: **a** the distribution map of land use types in study area; **b** the distribution map of Manning coefficient in study area

nodes that overlap with the actual pipe network are removed, and nodes that play a complementary role in regional drainage are extracted. There are 198 nodes including 177 junctions and 21 outlets in the final (Fig. 7d). The directions and starting points of the flow paths are analyzed, and drainage networks at these nodes are replenished. There are 166 conduits in the final (Fig. 7d). The catchments are divided based on nodes with Voronoi method, and there are 198 catchments (Fig. 7d).

After catchments division is done, and the area and width of catchments are automatically acquired, and the average slope of the catchments based on DEM is calculated. The N-Imperv and N-Perv of each catchment with area weighting principle are calculated. First, the study area is split into permeable zone (Fig. 8b) and impermeable zone (Fig. 8a), and the two layers are exported separately. The space overlay analysis is carried out between the two layers and the catchments layer. Taking the catchments layer as the target layer and the permeable layer as the auxiliary layer, Clip operation is done, which can obtain permeable zone distribution map of each areas. The same operation is done to impermeable layer. The intersect operation is done between the permeable zone layer of each catchments and the Manning coefficient distribution layer. Dissolve operation is done to the result layer. The polygons are dissolved according to catchments name, and Manning coefficient of permeable zone is calculated in each catchment with area weighting principle, so that we can obtain Imperv of each catchments (Fig. 8c), the same as to the N-Imperv of each catchment (Fig. 8d). The remaining five parameters are calibrated and tested by the automatic method (Barco et al. 2008). Comparing the simulated discharge hydrograph and the actual discharge hydrograph of junction 'YS2698608' on September 14, 2016, and on October 23, 2016, respectively, the simulated discharge hydrograph is consistent with the actual discharge hydrograph generally, and the error percent of peak value and total discharge is shown in Table 2, and the

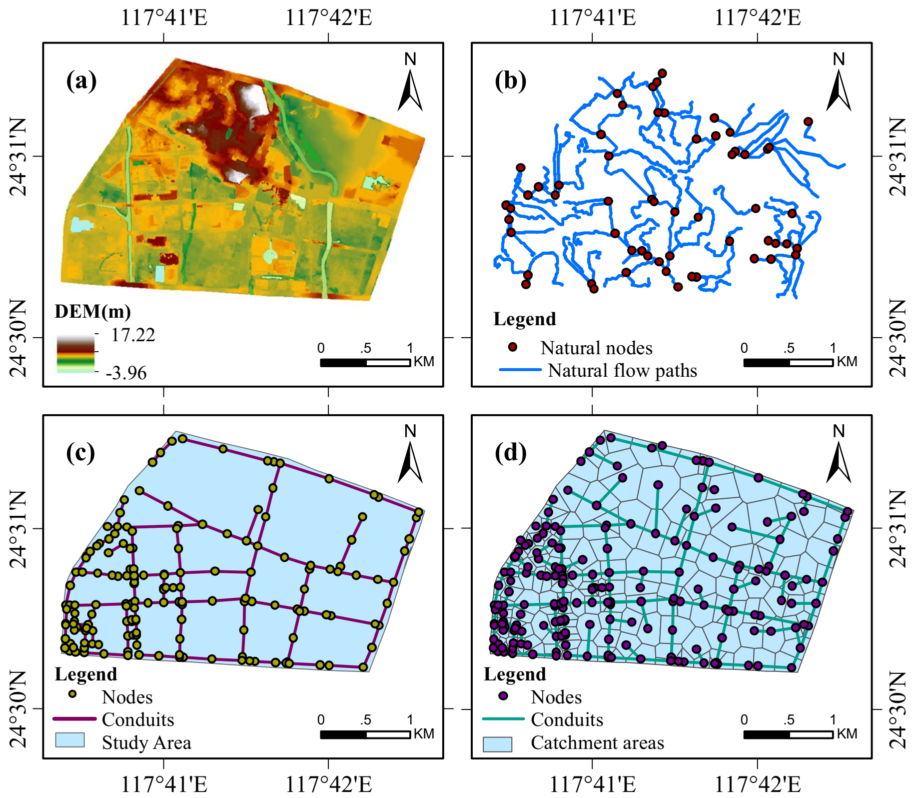

Fig. 7 Model of nodes and conduits: **a** DEM of study area with 5 m resolution ratio; **b** natural nodes and flow paths; **c** preliminary model of actual nodes and conduits; **d** final model of synthetic nodes and conduits

optimal combination of parameters is that: Ds-Imperv shall be 1.92 mm, Ds-Perv shall be 3.7 mm, MaxRate shall be 74.3 mm/h, and MinRate shall be 2.4 mm/h.

The catchments, conduits, junctions, outlets are inputted into SWMM model. The rainfall process is on June 18, 2016. The rainfall data details are shown in Table 3. The rainfall process is directly input through the time series editor of the rainfall module. The infiltration model is Horton and routing model is Kinematic wave. The initial condition for catchments and sewer over flow situation is that of initially dry. SWMM model construction was done by the desktop software of SWMM 5.0, and the version of generated INP is 5.0.022.

2.5 Inundation algorithms

Inundation analysis fundamentals are non-source inundation and source inundation (Zhang et al. 2009). Non-source inundation algorithm is simple and assumes that the inundation has nothing to do with geographic location but only the surface elevation. Non-source algorithm spreads flood from the ground to the high, so all grids in study area are traversed, inundation analysis is conducted until the elevations of all unflooded area are higher than flood elevation. (Flood elevation means the elevation plus its flood depth in each flood grid.) Source inundation algorithm is complex for considering region convexity and terrain

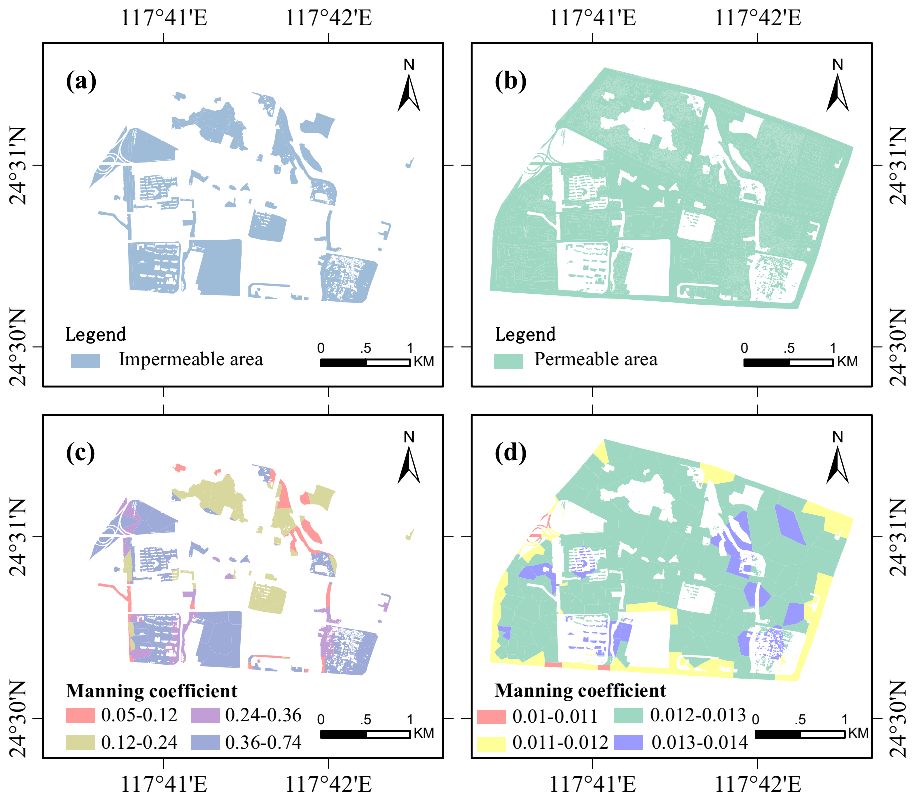

Fig. 8 Map of Imperv and N-Imperv of each catchment: **a** the map of impermeable area; **b** the map of permeable area; **c** the map of Manning coefficient of impermeable area of each catchment; **d** the map of Manning coefficient of permeable area of each catchment

Table 2 Error percent of peak value and total discharge

	20160914		20161023	
	Peak value	Total discharge	Peak value	Total discharge
Simulated discharged (m^3/s)	0.062	8.466	0.063	5.106
Actual discharge (m^3/s)	0.058	7.981	0.060	4.868
Error percent (%)	6.90	6.49	5.00	4.89

hindrance, so the algorithm is more close to the actual situation. The flow direction fundamentals are single-flow-direction algorithm and multiple-flow-direction algorithm. Single-flow-direction algorithm is simple with few factors considered, but it is not completely consistent with the actual flow process. Multiple-flow-direction algorithms are complex with much factors considered, but it is more consistent with the actual flow process. Many researchers (Li et al. 2016; Qin et al. 2006) chose numerous factors to improve multiple from different aspects, but it has an effect on solving specific issues in the choice of factors.

Table 3 Rainfall time series on June 18, 2016

Time	Rainfall (mm)
13:00	13.3
13:30	33.9
14:00	1.2
14:30	0.4
15:00	0.2
15:30	0.1

An algorithm with source inundation and multiple flow directions is proposed. The diffusion sources are nodes. The water spreads around on the basis of terrain with trial method and water balance principle. The result rationality is judged after each round of diffusion. If the current flood elevation is higher than the elevations of grids neighboring, the diffusion area is expanded to a circle bigger than before; otherwise, it will diffuse again in the new area, until the flood elevation is lower than elevations of grids neighboring all flooded grids. After all nodes diffusions are completed, it judges whether the grids are involved in two or more nodes diffusion process. If there are some nodes whose diffusion areas are intersected, the node is made as a new one and the nodes' volume is merged as the new node's volume, and then it diffuses again with the basic idea. It realizes water dynamic allocation and flood dynamic diffusion by judging rationality of flood depth and area constantly during the diffusion process. The flow direction depends on the difference of grids' elevations without any human intervention, and the flood can flow into any grid around it. There is no boundary in algorithm, and the inundation end depends on terrain and flood volume, which is tallied with the actual situation.
Specific steps of the algorithm are given in the following passage and Fig. 10:

(1) Read the DEM to get each grid's elevations;
(2) Read all nodes information, including nodes' number, volume and location.
(3) Diffuse the flood from the first node, assume that the flood volume of current node is **V**, the flood elevation is H, and A is the area of each grid.
(4) Diffuse the flood from the center (source) grid to outside, write diffusion area of round n as Rn, $R1$ is the diffusion area in the first round, just shown as the area masked with $r1$ in Fig. 9, $R2$ is not area masked with $r2$ in Fig. 9 but $r1 + r2$, so Rn should be $r1 + r2 + \ldots + rn$, while the current H is that:

$$H = \frac{V}{A} \tag{4}$$

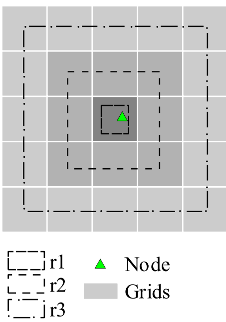

Fig. 9 Auxiliary graph of the source algorithm

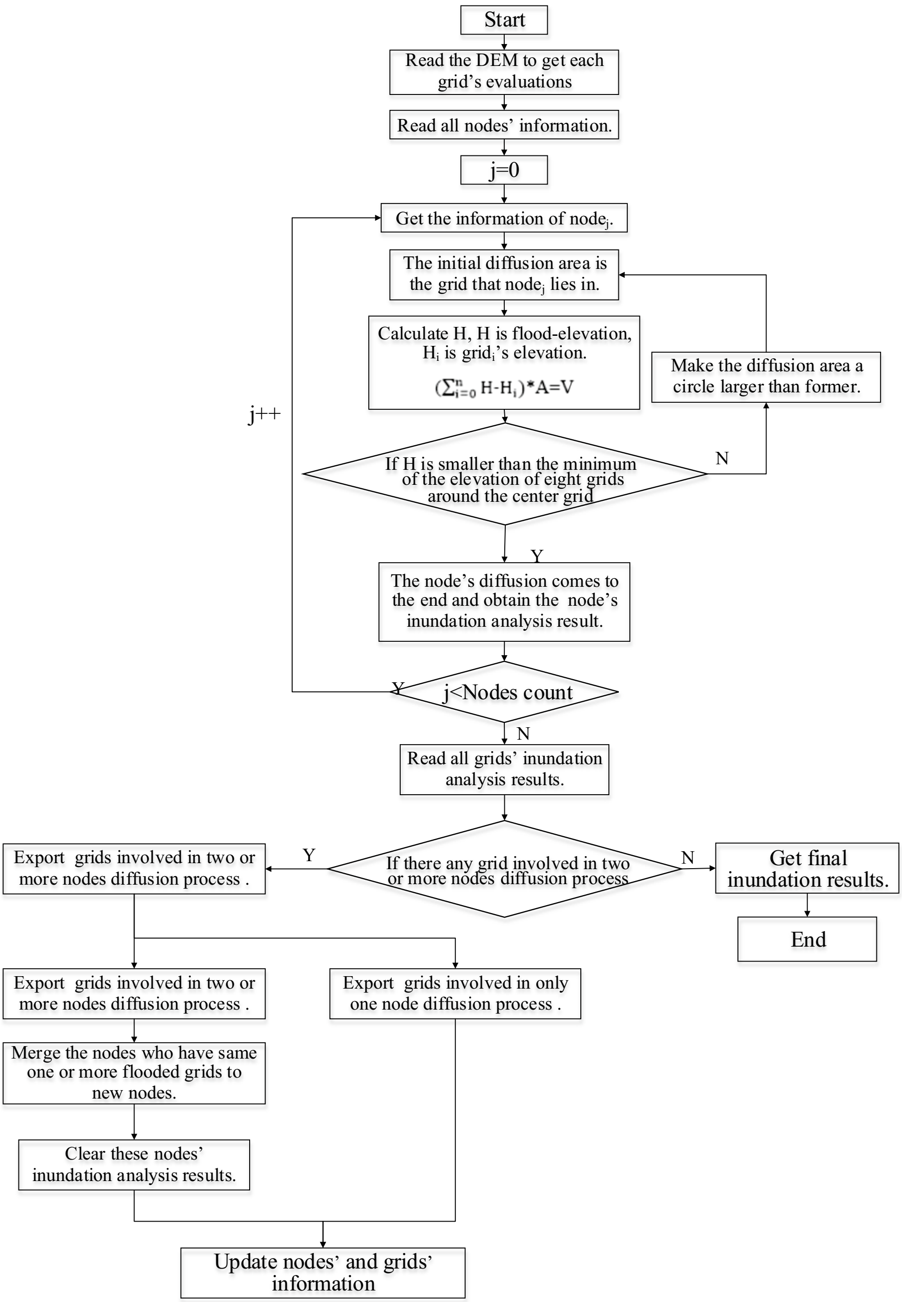

Fig. 10 Flowchart of the source algorithm

where the unit of H is m, the unit of V is m^3 and the unit of A is m^2.

The H should be compared with the elevation of grids outside around the diffusion area, which is written as compare area. If H is smaller than the minimum of the elevation of compare area, the node's diffusion comes to the end, else comes to the step (5). After all nodes diffusion has been done, it comes to step (6).

(5) Make the diffusion area a circle larger than former, and diffuse the flood among the new area. Assume there n grids are flooded and their elevations are $H1$, $H2$,…, Hn. H with trial method and the principle of water balance can be calculated as:

$$\sum_{i=0}^{n}(H - H_i) \times A = V \tag{5}$$

where the unit of H and H_i are m, the unit of V is m^3 and the unit of A is m^2.

If H is smaller than the minimum of the elevations of all grids surrounding the diffusion area, the node's diffusion comes to the end, else repeat the step. After all nodes diffusion has been done, it comes to step (5).

(6) Judge whether there is any grid involved in two or more nodes diffusion process. If there is no, the flood inundation is finished and returned the result. If yes, it makes the modes a new one and merges the nodes' volumes as the new node's volume with repeating the step (4).

To more deeply assess the effect of the source dynamic diffusion inundation algorithm, the differences between source and non-source algorithm are compared. The biggest difference between these two algorithms is the way to search the inundated grid, while the way to calculate the flood elevation has no natural difference. The simulation results of the two algorithms and their differences are elaborated in Sects. 3 and 4.2.

A non-source algorithm in lecture (Wang 2017) is elaborated, whose steps are shown in Fig. 11. The flood volume of each catchment is the total volume of all nodes in the area. Diffusing the flood around the surface, the inundation starts in the grid whose elevation is the lowest. If the flood elevation is lower than the elevations of all the grids not inundated in this catchment, inundation of the catchment comes to the end, else adds the grid, whose elevation is secondary low. A new flood elevation is calculated for the inundation area without consideration of spatial adjacency until the flood elevation is lower than the elevation of all the grids not inundated. The flood elevation of non-source 'H' can be calculated by the formula:

$$\sum_{i=0}^{n}(H - H_i) \times A = \sum_{j=0}^{k} V_j \tag{6}$$

where k is the number of nodes in the area, V_j is the flood volume of nodes j and its unit is m^3, n is the number of inundated grids and H_i is the elevation of grid i and its unit is m.

The differences between two inundation algorithms can be directly perceived through decision boxes in Figs. 10 and 11. There are three decision boxes in Fig. 10 and two in Fig. 11. The second decision boxes in Figs. 10 and 11 represent start of algorithms; the first decision boxes represent the end of diffusion. With the four boxes, the non-source algorithm proceeds from catchments so the diffusion is governed by catchments and end in the compare between flood elevation and elevations of unflooded grids in each catchment with no consideration of spatial locations, while the source algorithm proceeds from nodes so the diffusion happens overall and ends in the compare between flood elevation and elevations of grids around flooded area. The source algorithm has one more decision box which revises effect between nodes.

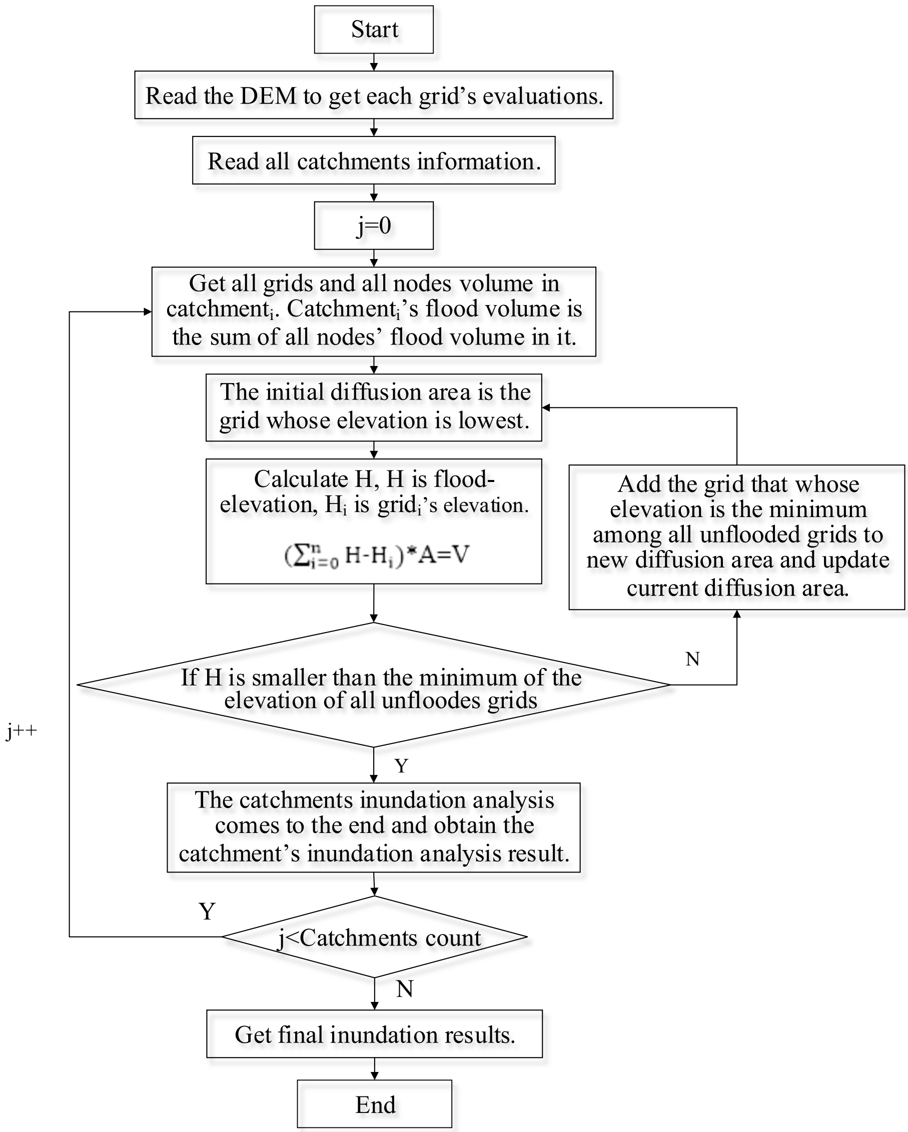

Fig. 11 Flowchart of the non-source algorithm

3 Results and analysis

3.1 Results of source algorithm

OUT files are generated after automatic operation on INP files through the DLL, and flood volumes were extracted from OUT files. Table 4 shows some nodes' flood volume at some instant. The water volume unit is m^3/s, which is a unit of speed, so the amount of water accumulated at each time needs to be multiplied by time.

Table 4 Nodes flood volume time series on June 18, 2016

Time	J1 (m^3/s)	J2 (m^3/s)	YS3103604 (m^3/s)	YS3103702 (m^3/s)	YS3103904 (m^3/s)
13:00	0	0	0.059	0.006	0.003
13:30	0	0	0.823	0.864	0.209
14:00	0.510	0.088	1.307	2.081	0.478
14:30	0	0	0.710	0.494	0.124
15:00	0	0	0.630	0.215	0.097
15:30	0	0	0.458	0.136	0.082

Taking 30 min as the time interval, flood at each instant is obtained by inundation analysis using the source algorithm and DEM (Fig. 7a). From Fig. 12, it can be found that:

(1) The trend of waterlogging is consistent with the process of rainfall, and the flood peak and the rainfall peak both happened at 13:30. As the rainfall decreased, the flood receded.
(2) The flood in the northwest and southeast was discretely distributed and heavier, and the flood in the northeast and southwest was continuously distributed and easier.
(3) Summarizing the simulation results of the whole rainfall process, the inundated area can be summed up into three categories which are masked with circles, rectangles and triangles shown in Fig. 12f. The areas masked with circles tend to be inundated, because the flood in these areas came from the beginning of the rainfall when the rainfall is not heavy and retreated completely more than 3 h after the rainfall peak or even longer, so the main reason of flood in these areas is the poor drainage capacity. The inundation depth in areas masked with triangles seems to be the most deepest, but the rainfall that makes these areas to start to be inundated is heavier than that in area masked with circles, so these areas are used to be inundated under the heavier rainfall and are with a better drainage capacity that can make the flood retreat fast. The area masked with rectangles was inundated with a large and even distribution, because the areas are residential areas with flat but impermeable surface, so its drainage is slow in short intense rainfall. The six areas masked in Fig. 12f are consistent with the waterlogging points by the field surveying, also as well the characteristics of waterlogging in these points.

3.2 Results of the not revised catchment division

To evaluate the effect of the revised method, a new SWMM model of the study area with all natural flow paths and removed nodes is constructed with 167 nodes and 137 conduits (Fig. 13a). Based on the source diffusion algorithm, simulation results are shown in Fig. 14. It is found that the trend of waterlogging is consistent with the progress of rainfall and the global distribution characteristic is consistent with the results of the revised method or it seems to be a little lighter, but the conclusion should be proved by data so the compare will be elaborated in Sect. 4.1.

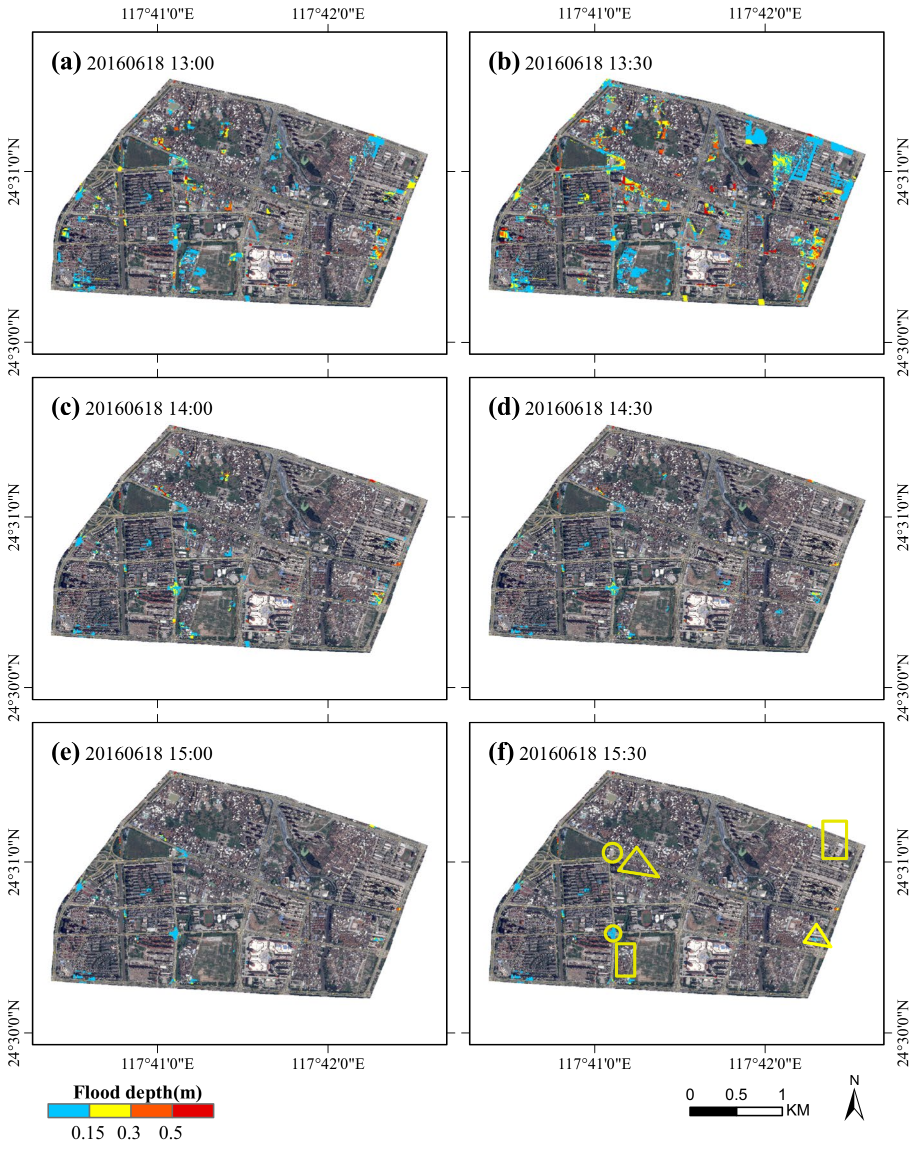

Fig. 12 Simulation results of source algorithm

3.3 Results of the non-source algorithm

Similarly taking 30 min as the time interval, the simulation results with the non-source inundation algorithm are achieved and shown in Fig. 15. The catchments division method is the revised method; just the diffusion algorithm is changed to get the simulation results. The trend of waterlogging is also consistent with the rainfall progress.

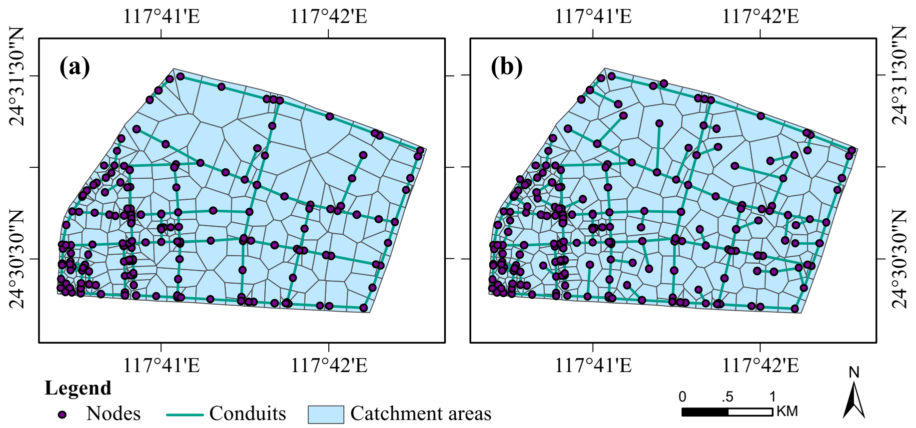

Fig. 13 Catchments with different methods: **a** catchments divided by the geometric method without consideration of terrain; **b** catchments divided by the revised geometric method with consideration of terrain

4 Discussions

To assess effect of the revised method and the improved algorithm, we calculate difference between results of different methods or algorithms. We made subtraction of results, taking the result of the revised catchments division and the source algorithm as the minuend and the result of the geometric catchments division and the source algorithm or the result.

4.1 Assessment of the revised catchments division method

From Sect. 2.3, it is known that different catchment divisions cause different runoff, and the revised method is proposed to reveal terrain-derived drainage well, so Table 5 are given to show these in detail. From Table 5, the total inflow of revised method is a little heavier than that of geometric method at the first two instant and lighter at the next four instant, but the external outflow percent of revise method is always bigger than that of geometric method, which indicates that revised method has a better effect on drainage than geometric method. Inundation analysis results with source algorithm are obtained for further assessment on two catchments division methods; Table 6 and Fig. 16 show the results. The flooded grids of geometric are less than the grids of revised method but their mean depth is deeper when the rainfall is heavy, indicating that the nodes flood volume is greater when the nodes number is less, so the flood in some regions is not well expressed, especially the regions with no pipe networks; so, not only the pipe network plays a part in urban drainage in a rainstorm but also the terrain, and the revised method is reasonable to taking the drainage of terrain into account.

4.2 Assessment between non-source and source algorithms

To study the limit of boundaries of the catchments in non-source, some comparisons are made in Fig. 17. Figure 17a–c shows the original DEM of the study area. Take the same

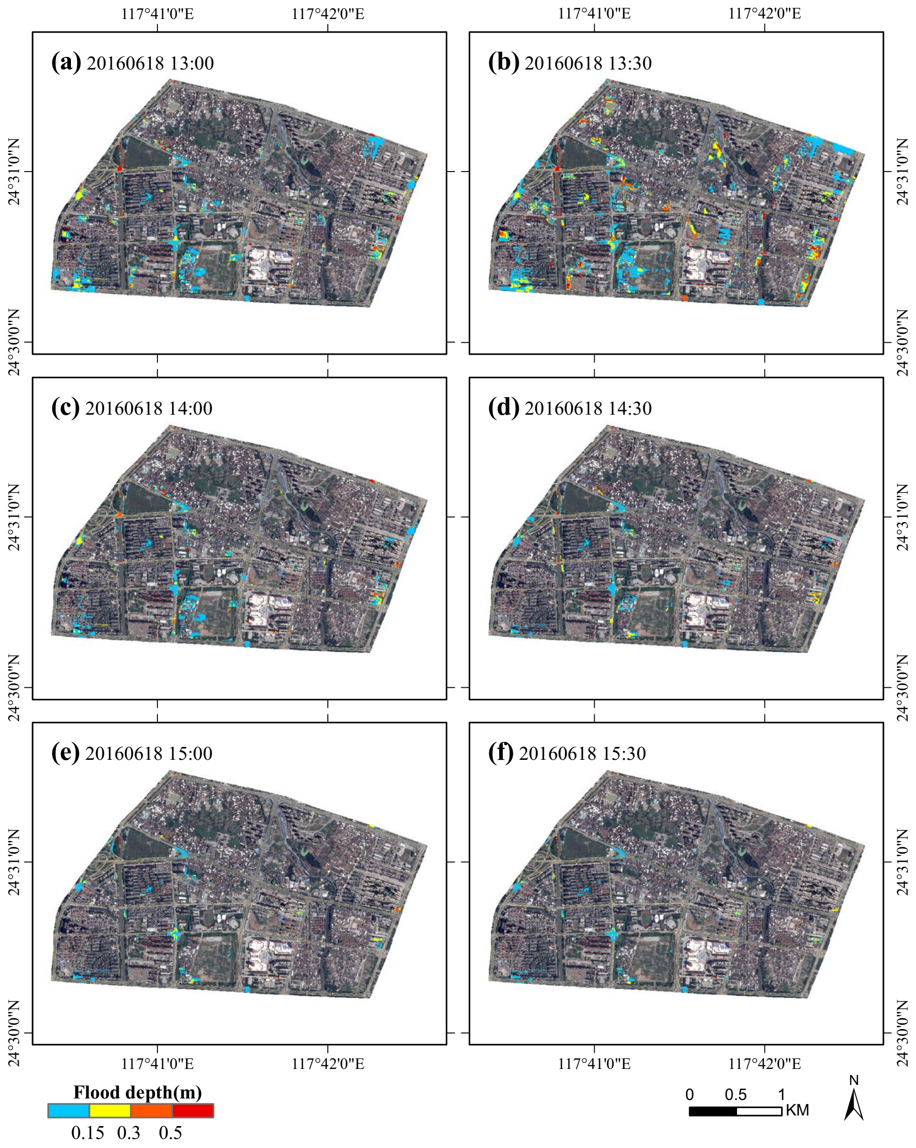

Fig. 14 Simulation results of the geometric catchments

standard to display the flood elevation of flood grids; Fig. 17d–f shows DEM and flood elevation, which replaces the DEM with flood elevation if the grid is flooded. From Fig. 17b, c, e, f, many grids elevations are higher than the elevations of its unflooded neighboring grids, which is unreasonable in terms of actual situation. Figure 17g–i shows the flood elevation of flooded areas. Some grids flood elevations are different with the flood elevation of its neighboring grids, which also goes against the nature. From above analysis, the boundaries of catchments have a great impact on inundation results or the non-source algorithm needs an accurate division method of catchments.

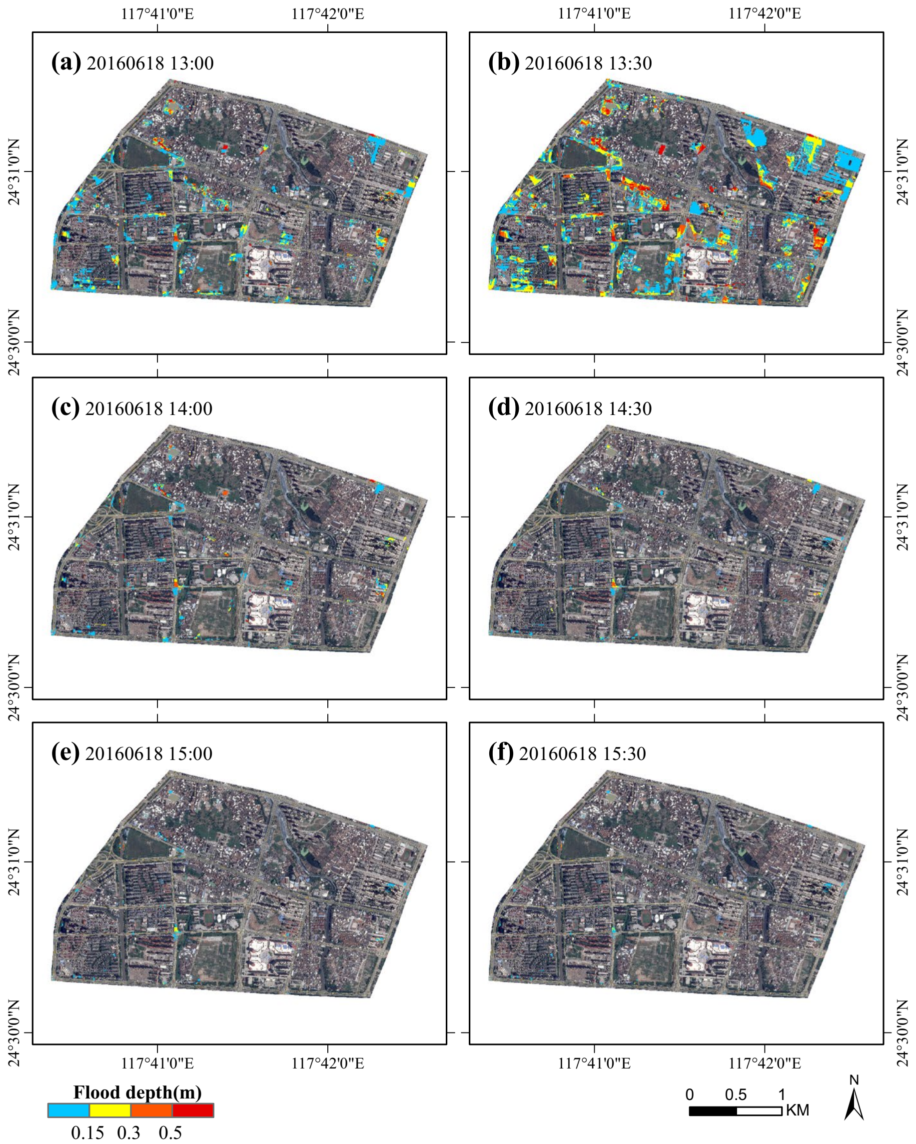

Fig. 15 Simulation results of non-source algorithm

The differences between two algorithms are diffusion patterns and boundaries; these mainly cause different inundation analysis results: firstly locations of flooded grids, and consequently count and depth of flooded grids. So differences of spatial distribution of inundation analysis results ought to be the most important to assess the differences between two algorithms. From Table 7, percent of grids flooded in both two algorithms are completely consistent with the rainfall trend. It shows that when the rainfall is small, the flooded grids are less and inundation analysis results with two algorithms have large difference. As the rainfall increases, the flooded grids are great so probability that inundation

Table 5 Comparison between total inflow and external outflow of different catchment division methods on June 18, 2016

Time	Rainfall (mm)	Revised method			Geometric method		
		Total inflow ($10^3 m^3$)	External outflow ($10^3 m^3$)	External outflow percent (%)	Total inflow ($10^3 m^3$)	External outflow ($10^3 m^3$)	External outflow percent (%)
13:00	13.3	44.499	11.792	26.50	35.317	8.33	23.59
13:30	33.9	186.655	47	25.18	156.492	30.612	19.56
14:00	1.2	57.402	20.092	35.00	63.005	16.898	26.82
14:30	0.4	9.507	4.294	45.17	15.932	5.044	31.66
15:00	0.2	3.871	1.698	43.86	7.325	2.203	30.08
15:30	0.1	1.974	0.894	45.29	3.725	1.082	29.05

External outflow percent is the ratio of external outflow in total inflow

Table 6 Comparison between mean depth and grid count of different catchment division methods with source inundation algorithm on June 18, 2016

Time	Rainfall (mm)	Revised method		Geometric method	
		Mean depth (m)	Flooded area (km^2)	Mean depth (m)	Flooded area (km^2)
13:00	13.3	0.1508	0.272	0.1466	0.260
13:30	33.9	0.1696	0.610	0.178	0.457
14:00	1.2	0.1354	0.106	0.1417	0.163
14:30	0.4	0.1167	0.057	0.1409	0.096
15:00	0.2	0.104	0.046	0.1256	0.068
15:30	0.1	0.1091	0.034	0.116	0.052

with two algorithms covers the same grids with is getting larger. Differences of spatial distribution inevitably lead to differences in grid count and depth. Figure 18 shows the differences of inundation distribution and grid depths between two algorithms. As for grid depths and count, when the rainfall is small, the mean depth of non-source is lower than that of source algorithm and the grid count is the opposite. When the rainfall is heavy, the mean depth of non-source algorithm is deeper than that of source algorithm and the grid count is the opposite. Because inundation analysis always starts from the deepest grid, the deepest grid is flooded forever, especially when the elevation difference between the deepest grids and the second deepest grids is large. The depth in these deepest grids is huge shown as an abnormal value, which is avoided by the reasonable selection of nodes position in source algorithm.

Although the source inundation analysis algorithm shows a better result than the non-source algorithm, there are still two details of the algorithm to be improved, which are shown on Fig. 19. Firstly, there is an obvious boundary in the area circled with rectangle and its number is 1 in Fig. 19, because a diffusion radius has been set for the node. The elevation of the area is gradually decreasing from north to south so the flood area is even in the opposite of the lake in previous simulations, but it is unreasonable for the node locates on the northern road. Therefore, there may be some natural obstacle to be included to revise the diffusion boundary of each grid. Secondly, the depth is deep in area circled with rectangle and its number is 2, but it is obviously unreasonable because it locates by the river. Without inconsequence of algorithm and DEM, the DEM needs a fine preprocessing to eliminate river areas.

5 Conclusions

A methodology for simple 2-D inundation analysis in urban area using SWMM and GIS is proposed in this paper, which need not edit SWMM's original code. It also splits SWMM construction and inundation analysis. The two parts can be processed independently.

SWMM construction can be done after basic data processing by GIS tools. Automatic operation through the DLL can obtain model results, which provide flood volume for inundation analysis. A method to calculate N-Imperv and Imperv by GIS tools is proposed to simplify data processing. The revised method of catchments division can remedy the deficiency of the single method in drainage effect and makes the flood expression more

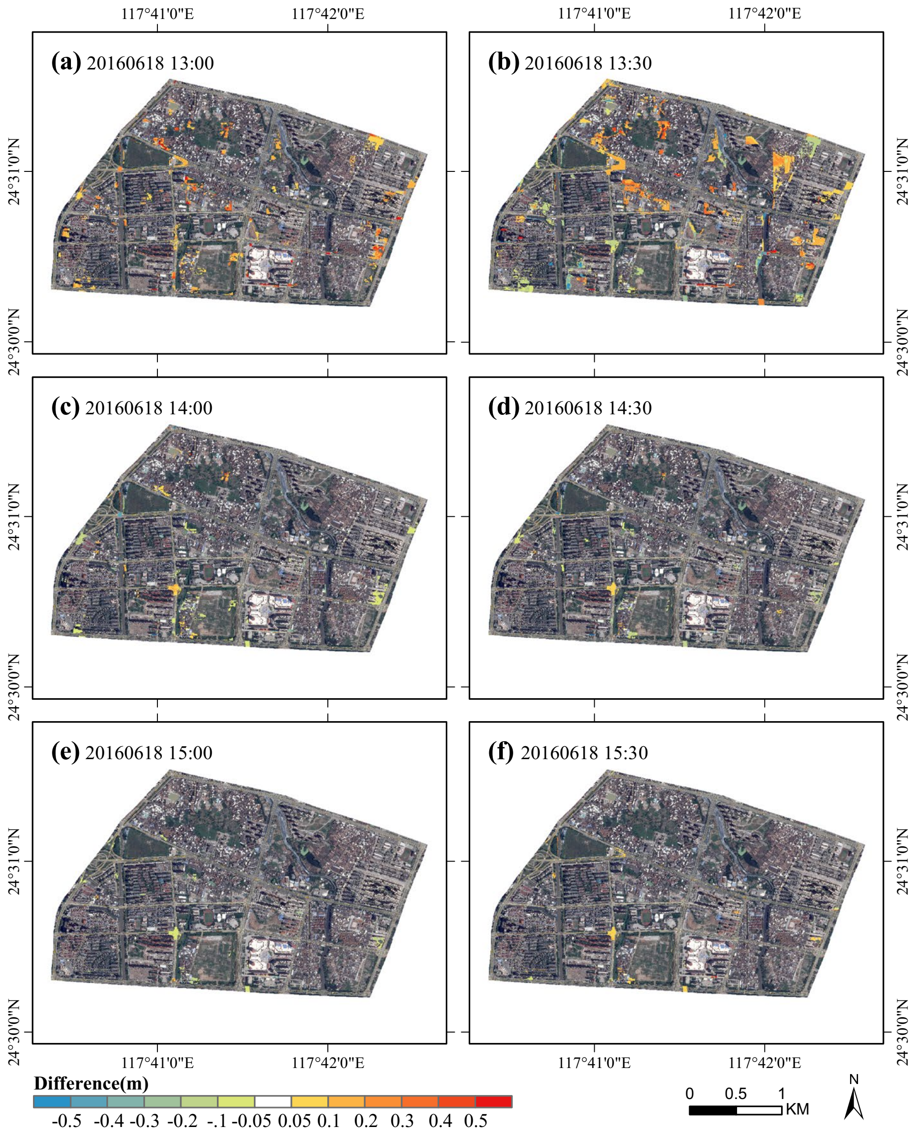

Fig. 16 Difference between different methods of catchments division. The inundation analysis results of the revised catchments division method with the source algorithm are minuends, and the inundation analysis results of the geometric catchments division method with the source algorithm are subtrahends

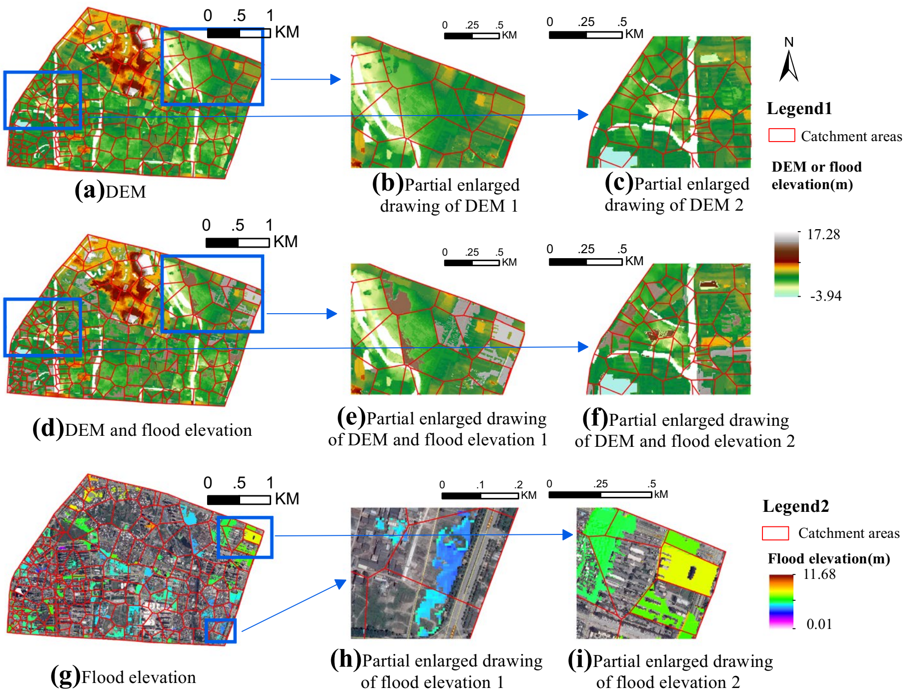

Fig. 17 Effect elevation of non-source algorithm: **a** the DEM of study area; **b** a partial enlarged drawing of DEM 1; **c** a partial enlarged drawing of DEM 2; **d** DEM of the study area and flood elevation of flooded area, the DEM and the flood elevation are shown with a same standard, so do (**e**) and (**f**); **e** a partial enlarged drawing of DEM and flood elevation 1; **f** a partial enlarged drawing of DEM and flood elevation 2; **g** the flood elevation of flooded area; **h** a partial enlarged drawing of flood elevation 1; **i** a partial enlarged drawing of flood elevation 2

meticulous. It is reasonable to take the drainage caused by the terrain into account, because the external outflow percentage of the revised method is always bigger than that of the geometric method.

Inundation analysis can be done once the flood volumes are known. The inundation analysis algorithm plays an important role in this part. Compared with previous non-source algorithm, the source dynamic diffusion inundation algorithm proposed in this paper has achieved a better result. This algorithm breaks the boundaries restrictions and can show spatial continuous distribution of waterlogging well with reasonable inundation depth and area, so it can improve the accuracy of inundation analysis.

Table 7 Comparison of these two algorithms on June 18, 2016

Time	Rainfall (mm)	Source algorithm		Non-source algorithm		Area flooded in both two algorithms (km^2)	Percent of area flooded in both two algorithms
		Mean depth (m)	Flooded area (km^2)	Mean depth (m)	Flooded area (km^2)		
13:00	13.3	0.1508	0.272	0.1483	0.277	0.139	50.56%
13:30	33.9	0.1696	0.610	0.1784	0.807	0.367	51.78%
14:00	1.2	0.1354	0.106	0.1406	0.066	0.026	30.51%
14:30	0.4	0.1167	0.057	0.1267	0.023	0.013	33.14%
15:00	0.2	0.104	0.046	0.0861	0.017	0.009	27.42%
15:30	0.1	0.1091	0.034	0.0865	0.008	0.003	14.30%

Count of grids flooded in both two algorithms means the number of grids that flooded in source inundation analysis results and non-source inundation analysis results although the depths may be not the same. Percent of grids flooded in both two algorithms means the ratio of aforementioned double grid count in the sum of grid count of two algorithms

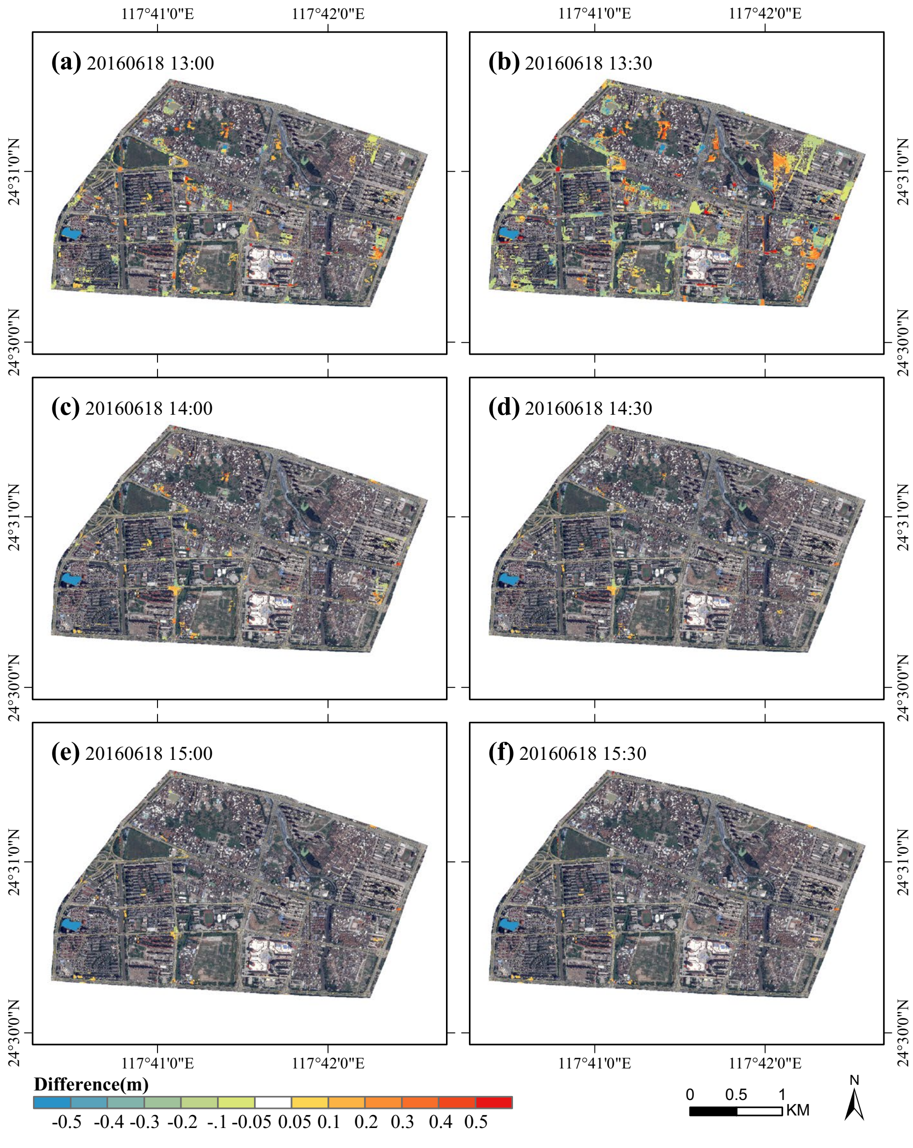

Fig. 18 Difference between these two algorithms. The inundation analysis results of the revised catchments division method with the source algorithm are minuends, and the inundation analysis results of the revised catchments division method with the non-source algorithm are subtrahends

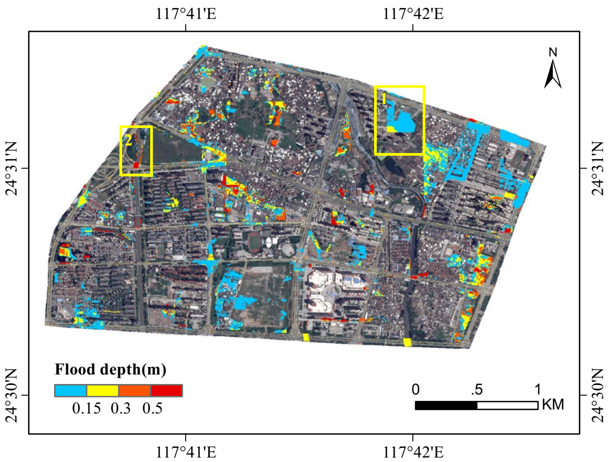

Fig. 19 A simulation result of source algorithm

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Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

References

Abulkadir A, Wuddivira MN, Abdu N et al (2011) Use of Horton infiltration model in estimating infiltration characteristics of an Alfisol in the Northern Guinea Savanna of Nigeria. J Agric Sci Technol 6:925–931

Akdogan Z, Guven B (2016) Assessing the sensitivity of SWMM to variations in hydrological and hydraulic parameters: a case study for the city of Istanbul. Glob NEST J 18(4):831–841

Azli M, Rao R (2010) Development of Huff curves for Peninsular Malaysia. J Hydrol 388:77–84. https://doi.org/10.1016/j.jhydrol.2010.04.030

Barco J, Wong KM, Stenstrom MK (2008) Automatic calibration of the U.S. EPA SWMM model for a large urban catchment. J Hydraul Eng 134(4):466–474. https://doi.org/10.1061/(asce)0733-9429(2008)134:4(466)

Bisht DS, Chatterjee C, Kalakoti S et al (2016) Modeling urban floods and drainage using SWMM and MIKE URBAN: a case study. Nat Hazards 84:749–776. https://doi.org/10.1007/s1106

Chow MF, Yusop Z, Toriman ME (2012) Modelling runoff quantity and quality in tropical urban catchments using storm water management model. Int J Environ Sci Technol 9:737–748. https://doi.org/10.1007/s13762-012-0092-0

Cipolla SS, Maglionico M, Stojkov I (2016) A long-term hydrological modelling of an extensive green roof by means of SWMM. Ecol Eng 95:876–887. https://doi.org/10.1016/j.ecoleng.2016.07.009

Gironás J, Niemann JD, Roesner LA (2010) Evaluation of methods for representing urban terrain in stormwater modeling. J Hydrol Eng 15(1):1–14

Guth N, Klingel P (2012) Demand allocation in water distribution network modelling—a GIS-based approach using Voronoi diagrams with constraints. In: Alam BM (ed) Application of geographic information systems. InTech, Rijeka. https://doi.org/10.5772/50014

Huang GR, Huang J, Yu HJ et al (2011) Secondary development of storm water management model SWMM based GIS. Water Resour Power 29:43–45

Huang GR, Huang W, Zhang LM et al (2015) Simulation of rainstorm waterlogging in urban areas based on GIS and SWMM model. J Water Resour Water Eng 26:1–6. https://doi.org/10.11705/j.issn.1672-643X.2015.04.01

Karimipour F, Ghandehari M (2013) Voronoi-based medial axis approximation from samples: issues and solutions. Springer, Berlin, pp 138–157. https://doi.org/10.1007/978-3-642-41905-8_9

Leandro J, Martins R (2016) A methodology for linking 2D overland flow models with the sewer network model SWMM 5.1 based on dynamic link libraries. Water Sci Technol 73(12):3017–3026. https://doi.org/10.2166/wst.2016.171

Li J, Zhang MH (2012) Division method of catchments of plain river network based on Voronoi map. J Zhejiang Agric Sci 05:761–763. https://doi.org/10.16178/j.issn.0528-9017.2012.05.002

Li C, Wang W, Xiong J et al (2014) Sensitivity analysis for urban drainage modeling using mutual information. Entropy 16(11):5738–5752. https://doi.org/10.3390/e16115738

Li ZM, Wei JW, Man W et al (2016) Extraction of river network based on D8 algorithm and Dinf algorithm. J Water Resour Water Eng 05:42–45. https://doi.org/10.11705/j.issn.1672-643X.2016.05.08

Mariza CC, Stephen JB (1994) Digital elevation model networks: a model of flow over hill slopes for computation of contributing and dispersal areas (DEMON). Water Resour Res 30:1681–1692

Mazion JE, Yen BC (1994) Computational discretization effect on rainfall-runoff simulation. J Water Resour Plan Manag 120(5):715–734. https://doi.org/10.1061/(ASCE)0733-9496(1994)120:5(715)

Olugunorisa TE (2009) Strategies for mitigation of flood risk in the Niger Delta, Nigeria. J Appl Sci Environ Manag 13(2):17–22. https://doi.org/10.4314/jasem.v13i2.55295

Pathirana A, Tsegaye S, Gersonius B et al (2008) A simple 2-D inundation model for incorporating flood damage in urban drainage planning. Hydrol Earth Syst Sci 5(6):3061–3097. https://doi.org/10.5194/hess-15-2747-2011

Qian L (2015) Study on simulation and analysis of urban storm waterlogging based on 3DGIS—a case study on Jiading town of Shanghai. Geography, Nanjing University of Information Science & Technology, Master Thesis

Qin CZ, Li BL, Zhu AX (2006) Multiple flow direction algorithm with flow partition scheme based on downslope gradient. Adv Water Sci 04:450–456

Qin P, Lei K, Qiao F et al (2016) Impact of sub-catchment size delineation on urban non-point source pollution simulation using SWMM. Environ Sci Technol 6:179–186

Rabori AM, Ghazavi R, Reveshty MA (2017) Sensitivity analysis of SWMM model parameters for urban runoff estimation in semi-arid area. J Biodivers Environ Sci 10(5):284–294

Sharifan RA, Roshan A, Aflatoni M et al (2010) Uncertainty and sensitivity analysis of SWMM model in computation of manhole water depth and subcatchment peak flood. Proc Soc Behav Sci 2:7739–7740

Shen ZJ, Zhang QW (2015) A GIS-based subcatchments division approach for SWMM. Open Civ Eng J 9:515–521. https://doi.org/10.2174/1874149501509010515

Shi YY, Wan DH, Chen L et al (2014) Simulation of rainstorm waterlogging and submergence in urban areas based on GIS and SWMM. J Water Resour Water Eng 32:57–60

Sun JH, Zhao SX, Fu SM et al (2013) Multi-scale characteristics of record heavy rainfall over Beijing area on July 21, 2012. Chin J Atmos Sci 27:705–718. https://doi.org/10.3878/j.issn.1006-9895.2013.12202

Wang W (2017) Research on simulation of urban waterlogging based on GIS and SWMM model. 3S Integration and Meteorological Application, Nanjing University of Information Science & Technology, Master Thesis

Wang J, Zhao L, Zhu C et al (2018) Review and optimization of carrying capacity of urban drainage system based on ArcGIS and SWMM model. Advances in Hydroinformatics. Springer, Singapore, pp 719–726. https://doi.org/10.1007/978-981-10-7218-5_51

Zhang DH, Lin R, Zhang YX et al (2009) The design and implement of a new algorithm to calculate source flood submerge area based on DEM. J East China Inst Technol 02:181–184. https://doi.org/10.3969/j.issn.1674-3504.2009.02.015