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Scenario-based inundation analysis of metro systems: a case study in Shanghai

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Abstract. Catastrophic urban floods result in severe inundation of underground facilities in recent years. This paper presents an integrated approach in which an algorithm is proposed to integrate the storm water management model (SWMM) into the geographical information system (GIS) to evaluate the inundation risk. The proposed algorithm simulates the flood inundation of overland flow and metro station for each schemed scenario. It involves *i*) determination of the grid location and spreading coefficient and *ii*) iterative calculation of the spreading process. Furthermore, to evaluate the potential inundation risks of metro systems, an equation to qualitatively calculate the inundation depth around a metro station is proposed. This equation considered the drainage capacity and characteristics of each metro station. The proposed method is applied to simulate the inundation risks of the metro system in the urban centre of Shanghai under 50-year, 100-year, and 500-year scenarios. Both the inundation extent and depth are derived. The proposed method is validated by verifying from the records of historical floods. The results demonstrate that in case of the 500-year-rainfall scenario, for an inundation depth of over 300 mm, the inundated area is up to 5.16 km^2, which is 4.3% of the studied area and that there are four metro stations inundated to a depth of over 300 mm.

Keywords: urban inundation, scenario analysis, metro system, algorithm for overland flow, SWMM, GIS

1. Introduction

With rapid urbanization, numerous urban constructions (e.g., underground metro system, malls, infrastructural systems, and parks) have been built (Peng and Peng, 2018). The disturbance caused by underground constructions (Shen et al. 2014, 2017; Tan et al. 2017) makes the geological environment susceptible to natural hazards, e.g., floods, tornados, and typhoons (Chang et al. 2010; Lyu et al. 2016, 2017). In recent years, climate change has resulted in various rainstorm events in China (Zhou et al. 2012; Yin et al. 2018). Many metropolitan areas have frequently suffered from inundation due to urban flooding. Urban flooding is one of the most severe hazards which causes catastrophic submerging of the ground surface and severe inundation of underground facilities. Numerous metro lines were inundated during the flood season (May to September) in 2016 in China (Lyu et al. 2018a, b; Xu et al. 2018). Thus, prevent metro systems from inundation is an urgent challenge which needs to be solved during urban planning (Huong and Pathirana 2013). Thus, the prediction of the inundation of a metro system is of critical importance.

There are generally four methods for predicting the inundation risk: (1) statistical analysis based on historical disaster records (Nott 2006), (2) geographical information system and remote sensing (GIS-RS) techniques (Sampson et al. 2012; Meesuk et al. 2015), (3) multi-criteria index analysis (Jiang et al. 2009; Kazakis 2015), and (4) scenario inundation analysis (Willems 2013; Naulin et al. 2013). Although the assessment results based on historical disaster records can predict the risk of an area, the method needs large numbers of data (Nott 2006). GIS-RS can provide the technological support for inundation risk evaluation (Sampson et al. 2012; Meesuk et al. 2015); however, GIS-RS technologies require high investments and high-resolution data sources. Multi-criteria index analysis has a few limitations in the determination of subjective indices (Jiang et al. 2009; Kazakis 2015). Scenario-based inundation analysis presents inundation risk under different scenarios (Willems 2013; Naulin et al. 2013), which requires the topographical, land-use, and urban drainage system data. Owing to the complex interaction between the drainage system and overland surface in urban regions, scenario-based models can only simulate inundation over a small range, e.g., less than 3 km^2 (Wu et al. 2017), which limits their application. Thus, the application of scenario-based model needs to be extended to the problem of overland flow over a large scale.

Numerical simulation is a useful tool to analyse urban flooding. Xia et al. (2011) developed a numerical model which integrated an algorithm into a two-dimensional (2D) hydrodynamic model to assess flood risk. Szydlowski et al. (2013) proposed a numerical flood modelling in which a mathematical model was incorporated into a 2D hydrological model to estimate inundation risks. Chen et al. (2015) used numerical simulation to predict the inundation risk in a flood-prone coastal zone. Morales-Hernandez et al. (2016) presented a one-dimensional model coupled with a two-dimensional model (1D-2D model) for application in the fast computation of large-river flooding. However, these numerical models have the following shortcomings: i) it is difficult to consider the characteristics of the landform, and ii) numerical simulation is typically used to estimate the inundation risk in a small area, whereas flooding hazards often occur on a regional scale. Thus, most of these models can only simulate inundation in a small range (Horritt and Bates 2002; Han et al. 2014). Moreover, the existing numerical studies cannot identify the boundary, resulting in a large error because the boundary is in extreme vicinity of the area centre. Therefore, a new tool, e.g., GIS, is required to consider the characteristics of a landform, and an integrated method should be proposed to simulate regional-scale flooding and satisfy the boundary conditions.

The storm water management model (SWMM) is a dynamic hydrological model, which is widely used for the simulation of the rainfall–runoff process in an urban catchment (Hsu et al. 2000; Shen and Zhang 2015). However, till date, the SWMM has achieved this for only a small region of several square kilometres. For example, Zhu et al. (2016) used the SWMM and a multi-index system to evaluate the inundation risks in southwest Guangzhou, China, in an area of 0.43 km^2. Feng et al. (2016) selected the SWMM as the modelling platform to simulate the inundation risks in a campus of the Salt Lake City, Utah, U.S, in an area of 0.11 km^2. Wu et al. (2017) applied the SWMM in combination with Lisflood-FP to simulate the urban inundation in Dongguan city, China, within an area of 2 km^2. It is challenging to predict the potential inundation risks on a regional scale using the SWMM because it is difficult to determine the spreading process and flow direction of the runoff on a large scale. Thus, a new method needs to be proposed which can the predict inundation risk on a regional scale using the SWMM.

Till date, there are a few published research studies, which focused on the inundation risk of metro systems. Yanai (2000) and Hashimoto (2013) analysed the flood event in Fukuoka city in 1999, which led to the serious inundation of the metro station. Based on previous research, Aoki (2016) put forward anti-inundation measures to prevent inundation for the stations of the Tokyo metro. Herath and Dutta (2004) attempted to create a model of urban flooding including underground space. Suarez et al. (2005) undertook a risk assessment of flooding for the Boston metro area. Ishigaki et al. (2009) presented a method for the safety assessment of a Japanese metro. Therefore, the research on the investigation of the inundation risk of metro systems is insufficient.

The objectives of this study are to: *i*) propose a method for predicting the potential inundation risk on a regional scale by using an new algorithm to integrate the SWMM into the GIS to simulate the overland flow, *ii*) propose a method for evaluating the potential inundation risk of a metro system, and iii) apply the proposed method to simulate the scenarios of urban inundation and inundation depth for the Shanghai metro system in case of 50-year, 100-year, and 500-year-rainstorm events. The proposed method assumes that the runoff on the surface flows from one subcatchment to another, within the range serviced by the drainage station.

2. Materials

2.1 Study area

Shanghai locates between latitudes 31°20′ and 31°00′N at longitude 121°20′ to 121°31′E, with a region of more than 6340 km^2. Fig. 1 shows the administrative region of Shanghai. As illustrated in Fig. 1, the Shanghai metropolis is surrounded by the Yangtze River in the northeast, Hangzhou bay in the southeast, Zhejiang province in the west, and Jiangsu province in the northwest (Shen and Xu 2011). The average elevation is ranged from 2 m to 5 m above the sea level in Shanghai (Xu et al. 2016). The urban centre with area of 120 km^2 includes the districts of Jingan, Huangpu, Luwan, Xunhui, Changning, Putuo, Zhabei, Hongkou, and Yangpu. Metro line no. 1 was constructed in Shanghai between 1990 and 1995. The first metro line from Xujiahui station to Jinjiang Park station was opened for operation on 28 May, 1993. At present, there are 14 metro lines under operation (data from Planning of Shanghai Metro Line, 2016) and another eight metro lines are currently under construction. As shown in Fig. 1, the urban centre with a dense distribution of metro lines. Moreover, the urban centre is near the Huangpu River, which passes through Shanghai city. There are also several metro lines passing through the Huangpu River. The rising tide in the Huangpu River increases the risk of floods, particularly during the flood season (from June to July). As significant underground infrastructures, metro lines play important roles at the traffic junctions in mega-cities. During flooding disasters, metro lines will be crippled, resulting in severe impacts such as traffic paralysis.

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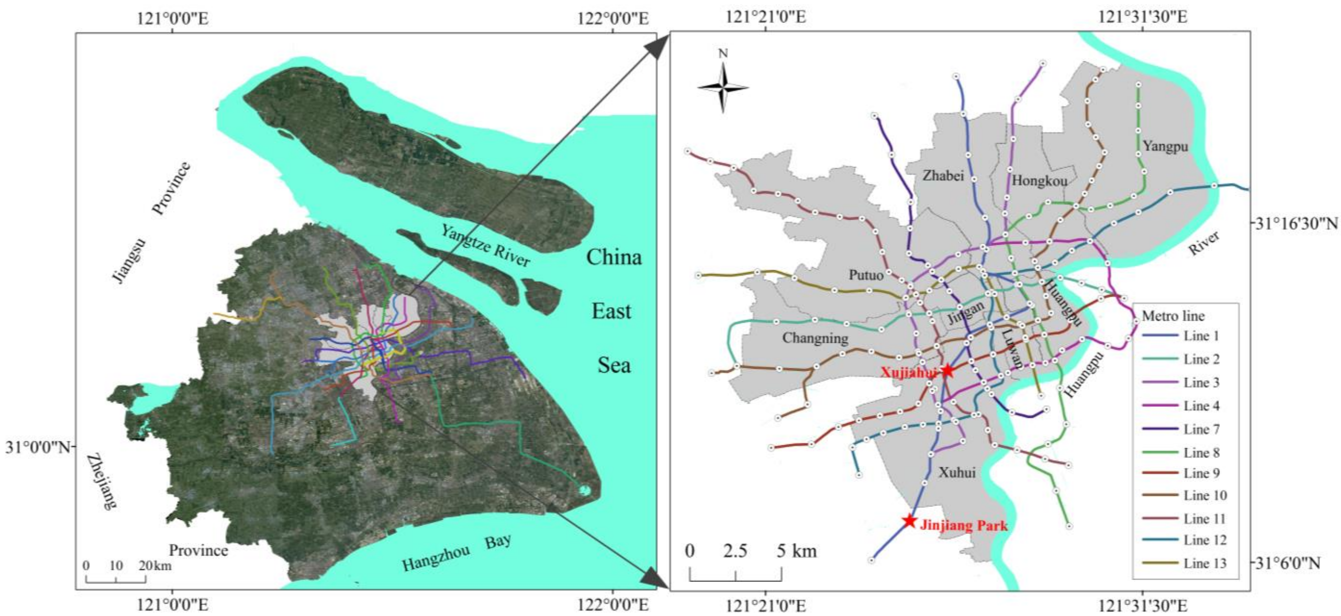

Figure 1: Distribution of metro line in the study area of Shanghai

2.2 Precipitation data and processing

Precipitation is the external driving force inducing flooding disasters. The Chicago design storm (Yin et al. 2016a, b) is widely applied to produce precipitation, which is used to calibrate the peak intensity and precipitation before and after the peak, within different return periods of the rainfall. The equations for the Chicago design storm can be expressed as follows:

$$i_a = \frac{a \times \left[\frac{(1-c)\times t_a}{1-r} + b\right]}{\left(\frac{t_a}{1-r} + b\right)^{c+1}} \tag{1}$$

$$i_b = \frac{a \times \left[\frac{(1-c)\times t_b}{r} + b\right]}{\left(\frac{t_b}{r} + b\right)^{c+1}} \tag{2}$$

where, i_a and i_b are the precipitation intensities after and before the peak value (mm/min); t_a and t_b are the times after and before the peak value (min); *a*, *b* and *c* are specific values related to the local municipal rainstorm models of the intensity-duration-frequency (IDF) type.

Based on documentary investigation, the IDF of the Shanghai municipal rainstorm can be expressed as follows (Jiang et al., 2015):

$$i = \frac{9.581(1 + 0.846\lg T)}{(t + 70)^{0.656}} \tag{3}$$

where i is the precipitation intensity (mm/min), T is the return period of precipitation (year), and t is the duration of the precipitation (min).

To consider the temporal variations, parameter r (e.g., the ratio of the time for the peak to the total event duration) is fixed as 0.45. The rainfall intensity for a duration of 2 h and return periods of the scenarios for 50 years, 100 years, and 500 years are designed to model the probable inundation. The drainage capacity of the metro line is designed to be 90 mm/h (the period of a 50-year-flooding event).

2.3 Topographical data and drainage station

The digital elevation model (DEM) of the study region was available with a 30-m-resolution, which was obtained from the geospatial data cloud. To replicate the reality of the study area, the DEM was further modified in the region with buildings based on field surveys and documents (Yin et al. 2016a). The heights of the buildings were rebuilt in the DEM to reproduce the blockage effects on the surface flows. The distribution of the drainage stations was obtained from the Shanghai Municipal Sewerage Management Branch (Quan et al. 2011).

3. Methodology

The proposed approach to predicting the inundation risk of metro system includes three phases. The first, a simulated rainfall runoff volume is obtained using SWMM model. The second, the calibrated runoff volume is distributed using the proposed spreading procedure algorithm, which integrates SWMM into GIS to determine the surface inundation depth. The third phase, the inundation depth around a metro station was obtained using a suggested equation and GIS tools.

3.1 SWMM calibration

The SWMM model is widely used to simulate the runoff quantity produced in each subcatchment in a simulated period. The results obtained by SWMM model were closer to measured value, and which can indicate the runoff reached a peak in the shortest time (Lee et al. 2010). The previous researches show that the SWMM is one of the best hydrologic models (Tan et al., 2008; Cherqui et al., et al., 2015). In this study, the SWMM is used to calibrate the runoff volumes from each subcatchment. It is supposed that, under extreme rainfall scenarios, runoff concentrates at the outlet point of each catchment and ignore the function of the drainage network. In this case, the overland flow is more likely to move in multiple directions rather than through the predefined flow paths and outlets. Therefore, a coefficient in the spreading process algorithm was used to determine the flow paths on surface. The spreading coefficient is used for moving runoff between neighbor subcatchments. The detailed information about the algorithm was introduced in section 3.2.

3.1.1 Subcatchment division and flow direction

A subcatchment is the basic calculation cell in the SWMM. There are two types of subcatchment divisions (Shen and Zhang 2015): i) based on the subcatchment partition and ii) based on the drainage system. In this study, a subcatchment was initially divided using the Thiessen polygon method based on the spatial distribution of the drainage stations (Shen and Zhang 2015; Zhu et al. 2016). The drainage capacity of each subcatchment was determined by the service range of the drainage stations. The boundary was a fixed boundary, i.e., the water level at the boundary is not considered to spread because the attention point is sufficiently far from the boundary. Fig. 2 shows the characteristics of subcatchment and grid in SWMM and GIS. The study area was classified into different subcatchment based on the drainage capacity of the pumping station service (Fig. 2a). Each subcatchment was classified into grid with 20 m×20 m (Fig. 2b), and each grid has its own information to reflect the different characteristic. To realistically mimic the effect of the natural hydrology features of a subcatchment, the topographical characteristics of the catchment was paid attention in the process of subcatchment division. The flow direction of each subcatchment was determined based on the DEM. Following this procedure, the average elevation and slope of each subcatchment was extracted by GIS tools. To reproduce the obstacles from the buildings in the flow of the surface runoff, the elevation included the height of the building and the building location in the model. Therefore, the average slope of a subcatchment will be reflective of the obstacle imposed by a building in the flow of the rainwater.

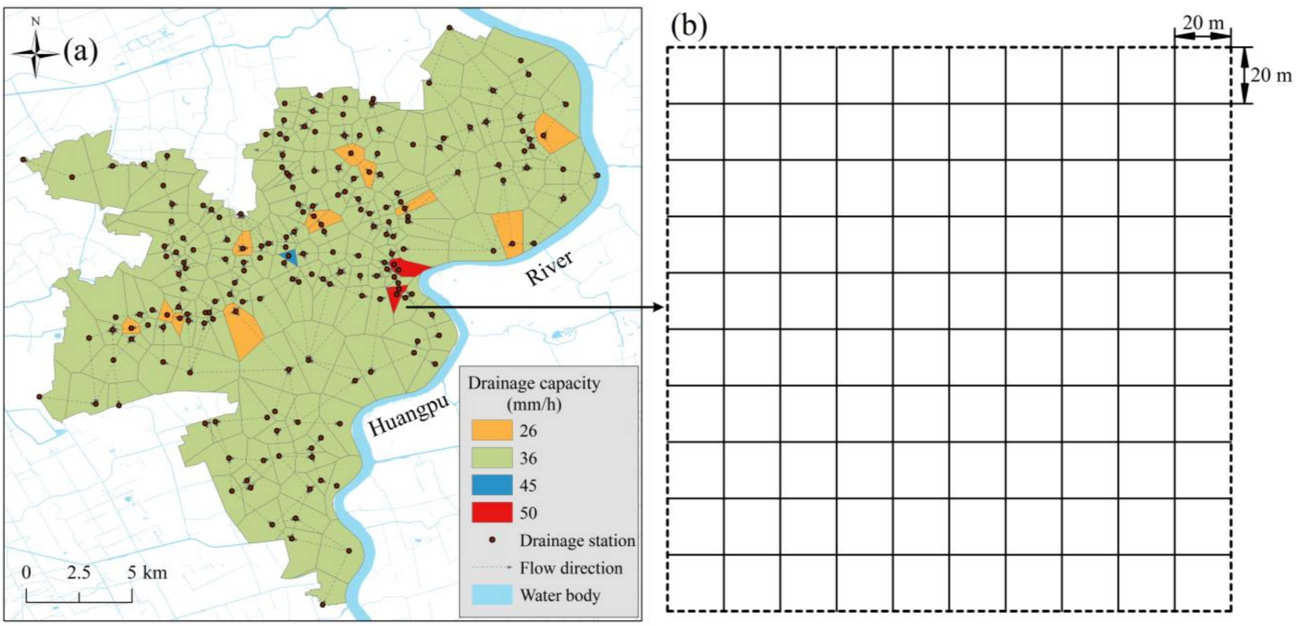

Figure 2: Calculated subcatchment and grid in SWMM and GIS: (a) drainage capacity and flow direction of each subcatchment; (b) calculated grid of each subcatchment

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3.1.2 Model input and determination of parameters

Based on the aforementioned method of subcatchment division, each subcatchment was assigned with its own topographical characteristics. The model included 195 subcatchments and 204 junctions. Each subcatchment in the SWMM model included the parameters of width, area, and permeability. The width and area can be calculated by GIS tools. The impervious parameter was determined based on the types of land use. A set of optimal parameters generated a good prediction with a designated flood scenario. Table 1 tabulates the parameters of the subcatchments in the SWMM. Thus, the largest subcatchment is 10.38 km^2 and the smallest is 0.16 km^2. The largest and smallest widths of the subcatchments are 5283.83 m and 432.45 m, respectively. The impervious parameter ranges from 55% to 65%. The slope of each subcatchment ranges from 0.3 to 5.5. In addition, the parameters to reflect the permeability characteristics of the local soils are also listed in Table 1.

Table 1 Parameters of the subcatchments in the SWMM

Parameter	Meaning	Value
Area (km^2)	Area of each subcatchment	10.38–0.16
Width (m)	Width of each subcatchment	5283.83–432.45
Impervious (%)	Percentage of the impervious area	55–70
Slope (°)	Average slope of each subcatchment	0.3–5.5
Destore-impervious (mm)	Depression storage depth in the impervious area	1.5
Destore-pervious (mm)	Depression storage depth in the previous area	5
N-impervious	Manning's coefficient in the impervious area	0.1
N-pervious	Manning's coefficient in the previous area	0.24
MaxRate (mm/h)	Maximum infiltration rate	76
MinRate (mm/h)	Minimum infiltration rate	3.3
Decay (h^{-1})	Decay constant	4
Dry (d)	Drying time	2

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3.2 Data conversion between GIS and SWMM

Following the calibration of runoff volume of each subcatchment, the next step is to determine the spreading procedure of the calibrated runoff. The spreading procedure algorithm is used to integrate the data between GIS and SWMM. Fig. 3 shows the description of the spreading procedure of runoff. First, grids are created with 20×20 m meshes across the study area using GIS fishnet tools; second, the calculated average inundation depth is extracted from each grid. The study area includes 113810 grids. As shown in Fig. 3, the spreading procedure includes four steps. The detailed steps are described as follows:

Step 1: The grid location (*GL*) and spreading coefficient (*f*) are determined (see Fig. 3a). Assuming that each grid h_I is surrounded by h_{Ij} grids (j = 1, 2,…8), if $h_I + \Delta x = h_{Ij}$ or $h_I + \Delta y = h_{Ij}$, then the location of grids h_{Ij} are determined as GL = 1 and spreading coefficient f = 1. However, if $h_I + \Delta x = h_{Ij}$ and $h_I + \Delta y = h_{Ij}$, then the location of grids h_{Ij} is determined as GL = -1 and spreading coefficient f = 0.569.

Step 2: The spreading grid is ranked. In this process, the rank of a spreading grid is based on the value of the possible water quantity of target grid h_I from surrounding grids h_{Ij}, and it can be described by Eq. (4). It is assumed that the grid with the maximum quantity is the first spreading grid.

$$Q_{target} = \sum_{j=1}^{n} h_{Ij} \cdot a_j \cdot f \quad (n = 1, 2, \cdots, 8) \tag{4}$$

in which, Q_{target} is the runoff of the target j grid; h_{Ij} means there are j grids surrounding with the h_I grid; a_j is the area of j grid (in this study a_j=400 m^2); f is the spreading coefficient.

Step 3: Spreading and updating of the water level in each grid is started. It is assumed that the water level difference in each spreading step is Δh (Δh can be fixed as a specific or flexible value). The amount of water quantity in each spreading step can be described by Eq. (5). To ensure the convergence of the

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calculation process, the value of Δh can be fixed as some small value in the initial stage and then allowed to increase with time. In this algorithm, initial value Δh is fixed as 0.01.

$$Q_{spreading} = \sum_{j=1}^{n} (h_I - h_{Ij}) \cdot a_j \quad (n=1,2,\cdots,8) \tag{5}$$

in which, $Q_{spreading}$ is the runoff of surrounding grids.

Step 4: Cessation of the spreading is estimated. When the water level difference between target grid h_{I} and surrounding grid h_{Ij} is less than 0.01, the spreading process is stopped. The pseudo-code for this algorithm is described in the Appendix.

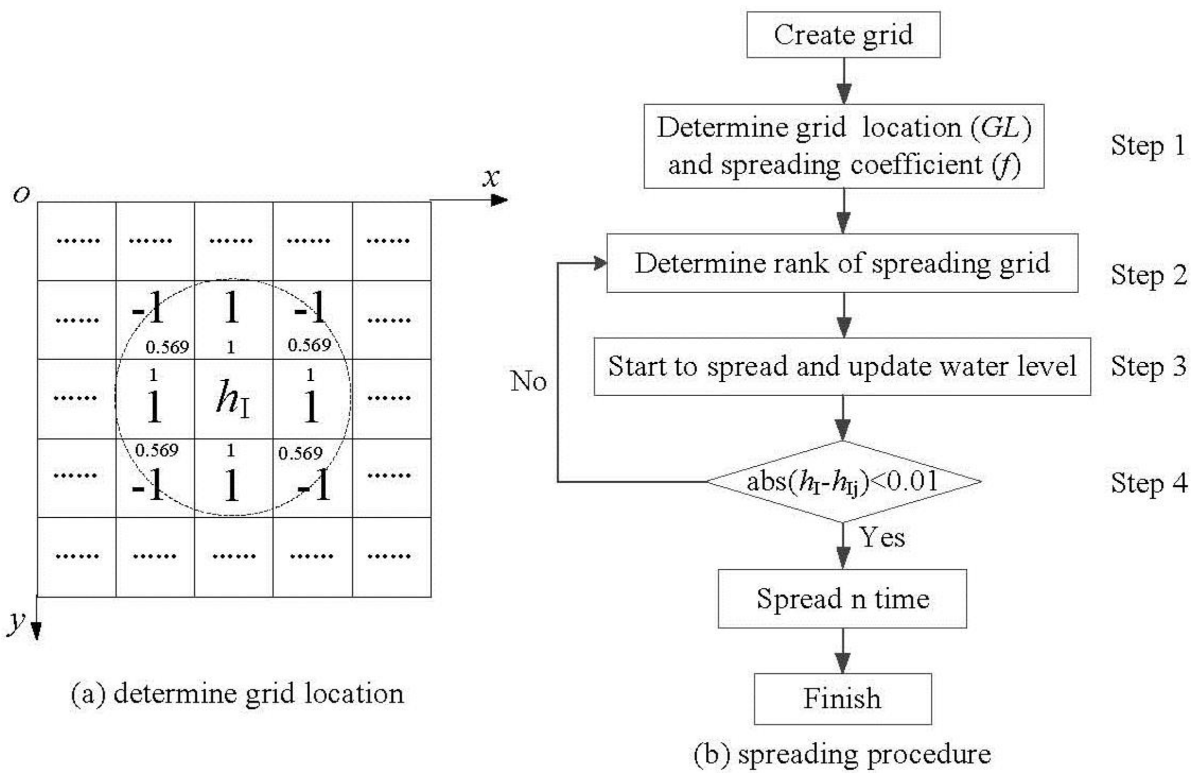

Figure 3: Description of the spreading process: a) determination of the grid location and spreading coefficient and b) iterative calculation of the spreading process

The inundation depth around a metro station is used to evaluate the inundation risk of metro lines. Eq. (6)

is proposed to qualitatively calculate the inundation depth around a metro station.

$$h_{t(station)} = (h_i - p) \times t - h_{0(station)} \tag{6}$$

where, $h_{t(\text{station})}$ is the inundation depth around the metro station, h_i is the inundation depth over the ground surface, p is the drainage capacity of the metro station, and $h_{0(\text{station})}$ is the step height of the metro station, (based on the standard of the design of a metro system, $h_{0(\text{station})} = 0.2$ m). When $h_{t(\text{station})} > 0$, the metro station will become inundated.

3.3 Model calibration and visualization

During the establishment of the storm water model in the SWMM, the rainfall intensity is set as the return period of 50 years, 100 years, and 500 years. The simulation time period is set as 2 h. The runoff quantities of each subcatchment can be computed in the SWMM. Based on the obtained runoff volume, the inundation depth can be computed using the proposed algorithm. The inundation depth is used to evaluate the flood risks of the study area. Using the inundation depth of the ground surface, the inundation depth around a metro station can be yielded using Eq. (6). The spatial distribution of the inundation depth can be visualized by the GIS.

4. Results and analysis

4.1 Runoff volume

Fig. 4 shows the runoff volume of each subcatchment at different rainfall intensities. It can be seen that the runoff increasing with the increased rainfall intensity. Fig. 4 also depicts the area of each subcatchment. Most of the subcatchments cover approximately 2 km^2. The area of each subcatchment is used to calculate the average inundation depth. Then the average inundation depth is used to simulate the spreading process by employing the proposed algorithm. The computed results are incorporated GIS into SWMM to yield the map of the inundation distribution. Because the average inundation depth is related to the runoff

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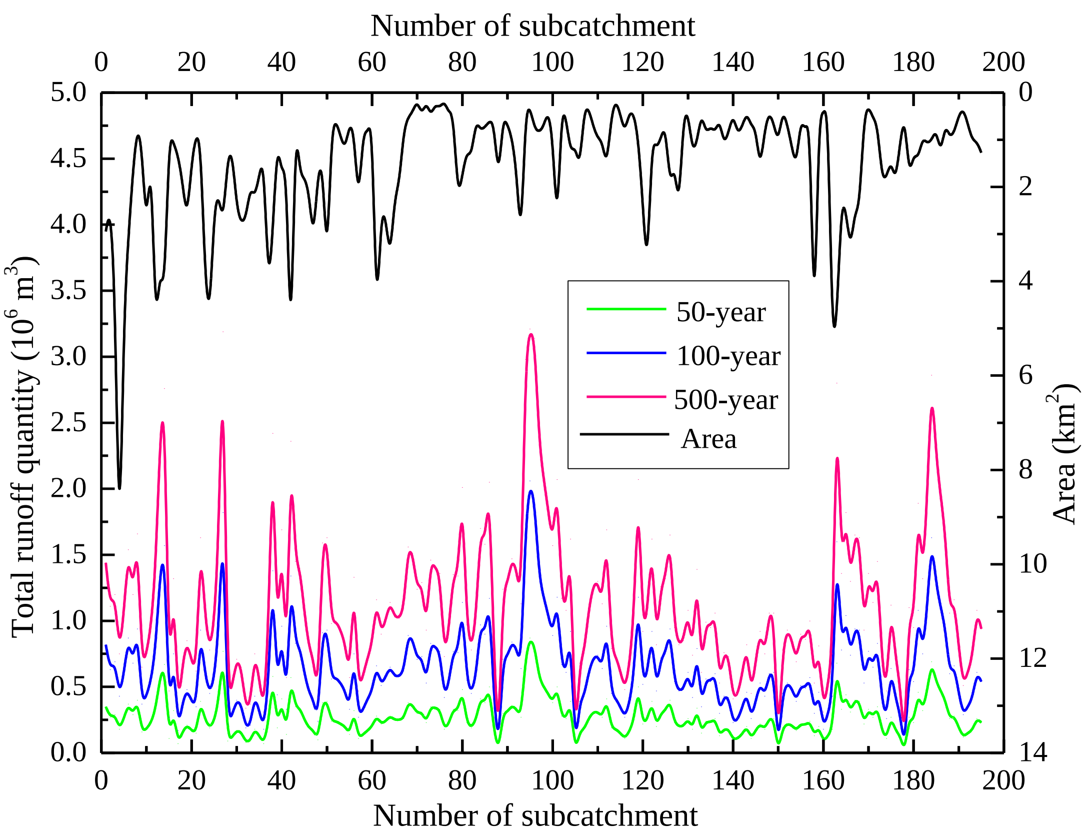
volume and area of the subcatchment, the simulated results are able to reflect the surface runoff and overland flow of the study area. The algorithm plays an important role in analysing the spreading processes of the surface runoff volumes.



5 **Figure 4:** Runoff volume of each subcatchment in the corresponding area under different scenarios

4.2 Inundation extent and depth

The inundation depth across the study area can be computed using the proposed algorithm (see Fig. 3). Fig. 5 displays the distribution of the inundation extent and depth under the aforementioned rainfall scenarios. For all the three scenarios, the floodwater profiles are similar; however, the inundation depth and areal extent exacerbate with increasing rainfall intensity. Figs. 5a and 5b exhibit the similarities in both the inundation depth and extent for the different scenarios. Fig. 5c depicts the maximum inundation depth and extent for the 500-year-rainfall intensity. The largest depth in each scenario first occurs in some places in the Changning, Huangpu, and Yangpu districts. The maximum inundation depth exceeds 400 mm.

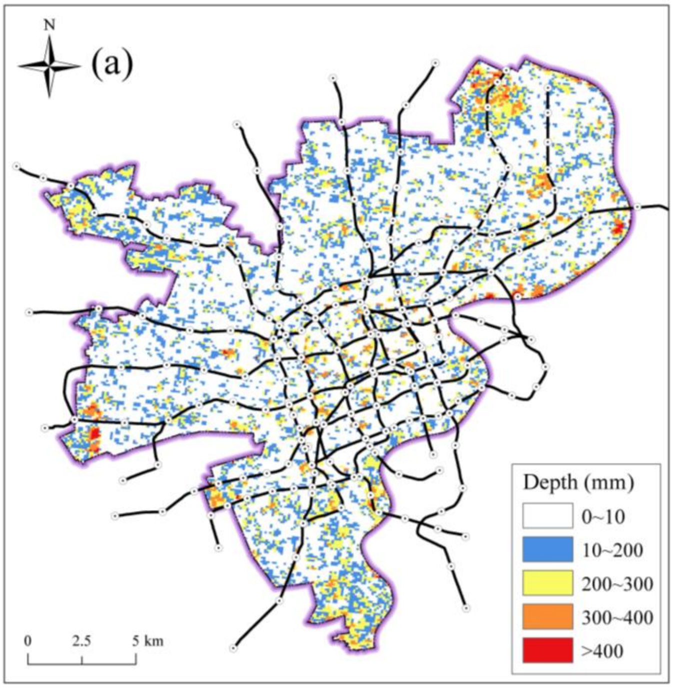
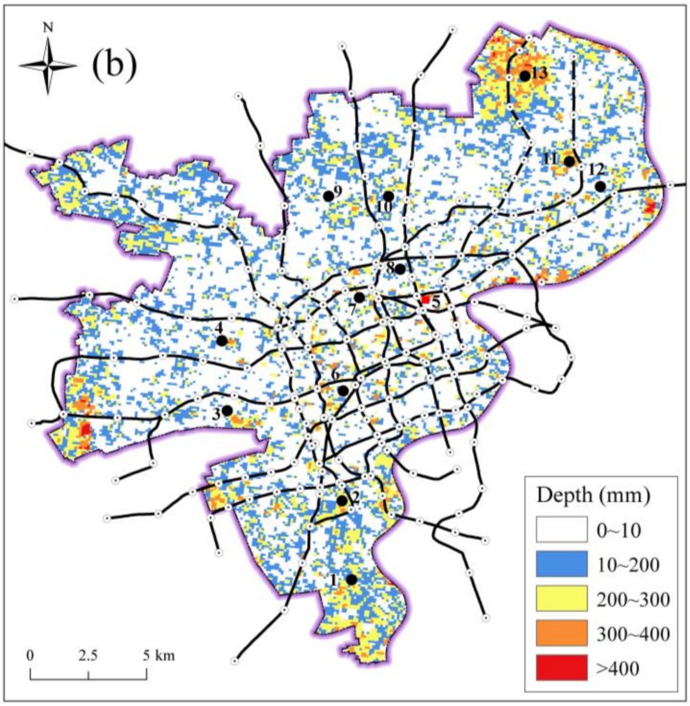


Figure 5: Distribution of the potential inundation extent and depth under different rainfall scenarios: (a) 50-year, (b) 100-year, and (c) 500-year-rainfall intensity (continuing)



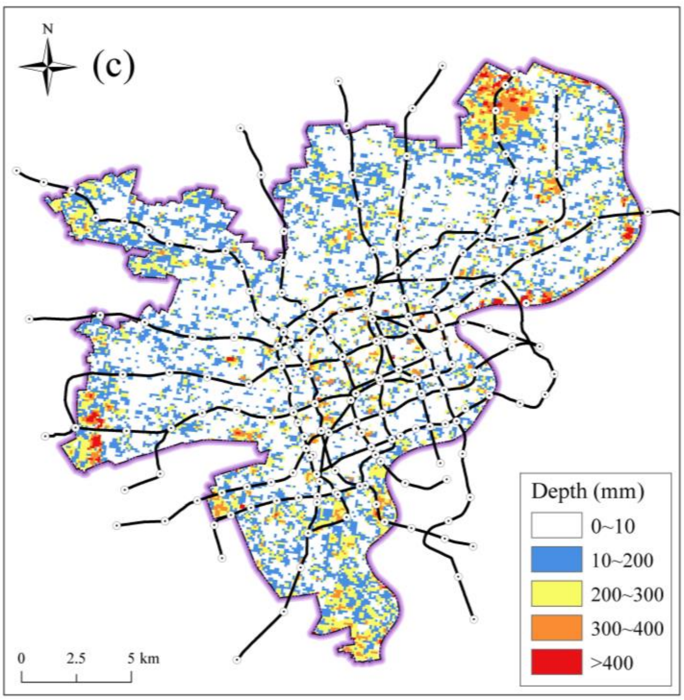


Figure 5: Distribution of the potential inundation extent and depth under different rainfall scenarios: (a) 50-year, (b) 100-year, and (c) 500-year-rainfall intensity (continued)

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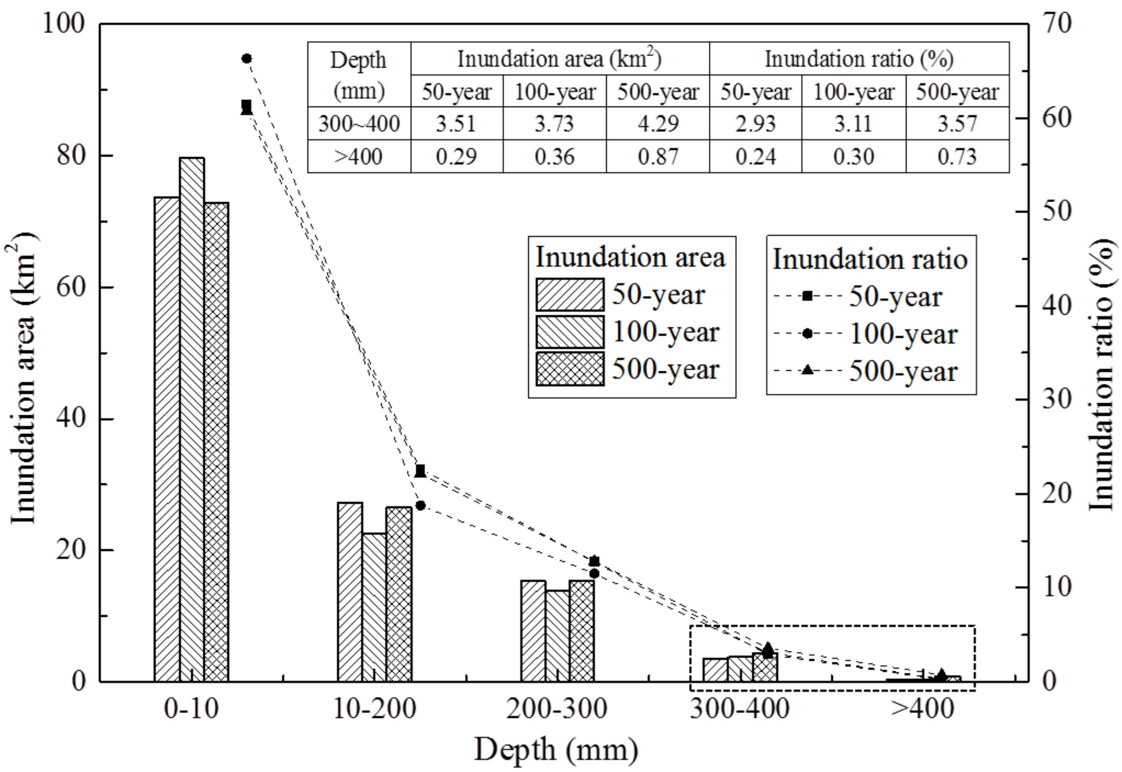
To analyse the inundation risk under different scenarios, the inundation area and inundated area ratios were accounted using the GIS. Fig. 6 presents the inundated area and ratio at different inundation depth ranges. As shown in Fig. 6, the inundated depth of 300 mm is a key point in the variation patterns under the three scenarios; specifically, when the inundated depth is over 300 mm, the inundated area increases with the increase in the rainfall scale, and when the inundated depth is less than 300 mm, the variation in the inundated area does not exhibit this pattern. To illustrate the variation in the inundated area and ratio for an inundation depth of over 300 mm, the detailed values of the inundation area and ratio in the depth range of 300–400 mm and over 400 mm are exhibited in Fig. 6. For the cases of inundation less than 300 mm, an irregular distributed pattern is formed for the inundated area, which may be due to the landform. The inundation area for an inundation depth of over 300 mm is up to 5.16 km^2 for the 500-year-rainfall intensity, which is 4.3% of the total studied area (120 km^2).



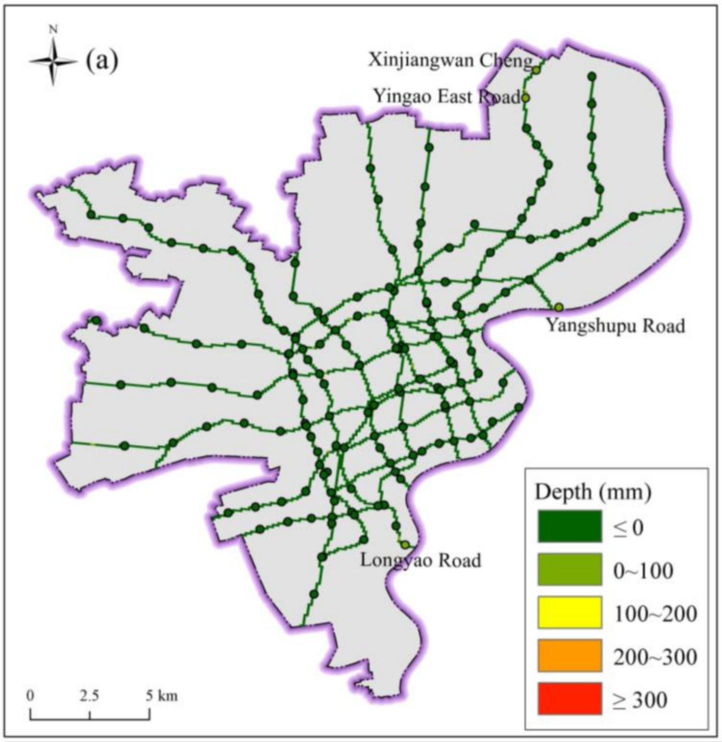
Depth (mm)	Inundation area (km^2)			Inundation ratio (%)		
	50-year	100-year	500-year	50-year	100-year	500-year
300~400	3.51	3.73	4.29	2.93	3.11	3.57
>400	0.29	0.36	0.87	0.24	0.30	0.73

Figure 6: Statistical inundation area with the corresponding ratio at different depths

4.3 Potential inundation depth around metro station

Following the spatial distribution of the inundation depth of a ground surface, the potential inundation depth around metro stations can be obtained by applying Eq. (6). Fig. 7 shows the potential inundation depth around the metro stations under the scenarios of 50-year-rainfall intensity (Fig. 7a), 100-year-rainfall intensity (Fig. 7b), and 500-year-rainfall intensity (Fig. 7c). The inundated metro stations major occurred in the region with a deeper flood depth. As shown in Fig. 7, the inundation depths and extents exacerbate with increasing rainfall intensity. For the 50-year-rainfall intensity, the Xinjiangwan Cheng station, Yingao east station, Yangshupu Road station, and Longyao Road station are predicted to be inundated at 0.1-m-depth. For the 100-year-rainfall intensity, the inundation depth of the four stations increased by 0.2 m–0.3 m, whereas the inundation extent exacerbated to other central regions. For the 500-year-rainfall intensity, the largest inundation depth exceeds 0.3 m, and other metro stations also undergo inundation with a depth of 0.1–0.3 m in the central region. For all the three scenarios, the inundation initially occurs in the metro stations of Xinjiangwan Cheng, Yingao east, Yangshupu Road, and Longyao Road, and the depths increasing with the increased rainfall intensity.

The number of inundated stations can also be accounted from Fig. 7. It is clearly seen that with the increase in the rainfall intensity, the number of inundated metro stations is increasing. For the 500-year-rainfall intensity, there are four metro stations inundated to a depth of over 300 mm.



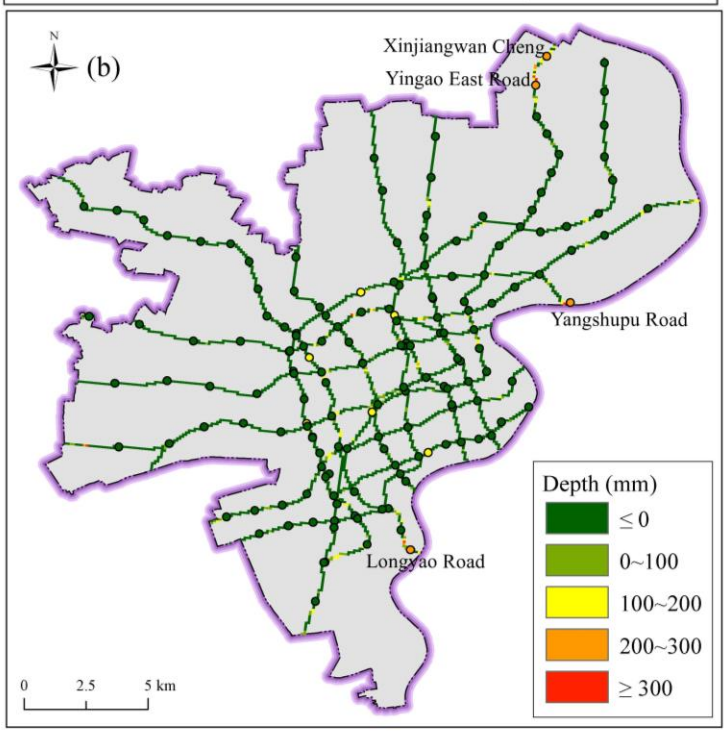


Figure 7: Potential inundation depth around the metro stations under different scenarios: (a) 50-year, (b) 100-year, and (c) 500-year-rainfall intensity (continuing)

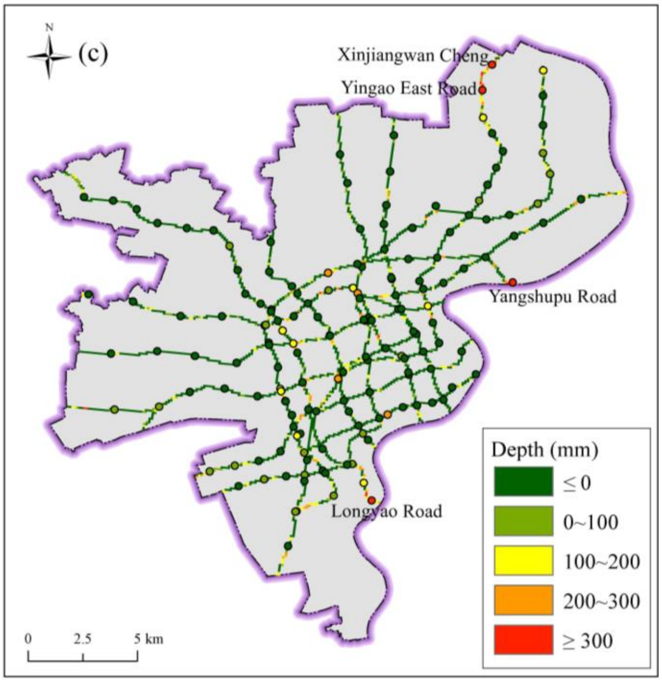


Figure 7: Potential inundation depth around the metro stations under different scenarios: (a) 50-year, (b) 100-year, and (c) 500-year-rainfall intensity (continued)

4.4 Model validation

For an effective validation of the proposed model, observed inundation maps from RS, such as aerial or satellite, and reliable field surveys must be compared with the calculated inundated areas. However, the observed inundation maps for historical flood events are not available for Shanghai. There are some historical recorded data of the inundated depth of several locations in Shanghai from public sources. Thus, the proposed model is validated by the comparison between the simulated data and these records of the historical floods. These records were collected from the following two sources: 1) flood incidents reported by public sources via websites (e.g., Google and Baidu), 2) publications (Huang et al. 2017; Yin et al. 2016b). The public sourced data provided enough information, which includes the location of the affected roads and buildings, with an estimate of the inundation depth. Fig. 8 depicts the location of the recorded flood. As presented in Fig. 8a, the records of the historical floods are located in the range with a deep inundation depth. Fig.8b shows the scene of the flooding of the Xujingdong road, which can be found online (http://www.miss-no1.com/file/2015/08/25/618466%40152054_1.htm). Fig. 8c shows the scene of the flooding of Yangshupu road, which can be accessed online (http://www.chexun.com/2013-10-09/102090984_2.html). The locations of these two flood incidents correspond with the simulated flood map (see Fig. 8a).

The other method for collecting the recorded flood data is the use of publications. The official records of the rainstorm which occurred with typhoon 'Matsa' in 2005 presented by Huang et al. (2017) are similar to the simulated 100-year-scenario, which caused serious inundation in the districts of Yangpu, Hongkou, Changning, Putuo, and Xuhui. In addition, Yin et al. (2016b) recorded the flood event which occurred on 12 August 2011, but this research analysed only an area of 3.25 km^2. Thus, only one validation point was extracted from Yin et al. (2016b). Finally, we collected 13 flooding locations as shown in Fig. 8a. In Fig. 8a, except for point 5, the points of the flood location were collected from the report of Huang et al. (2017). Point 5 is collected from the paper of Yin et al. (2016b). From the collection of these recorded data, the simulated results were compared with the records at 13 validation points. Fig. 9 shows the comparison of the inundation depth obtained from the simulated results and recorded data. For point 2 to point 12, the simulated data agrees well with the recorded data with a relative difference of less than 10%, whereas the simulated data at points 1 and 13 are much deeper than the records. One possible reason for the difference between the simulated data and recorded data for points 1 and 13 could be the fixed boundary effect because these two points are near the boundary. In addition, point 5 is the flood location in 2011, which is deeper than the simulated data. Overall, the calculated results can reflect the trends of the floodwater movement and depth.

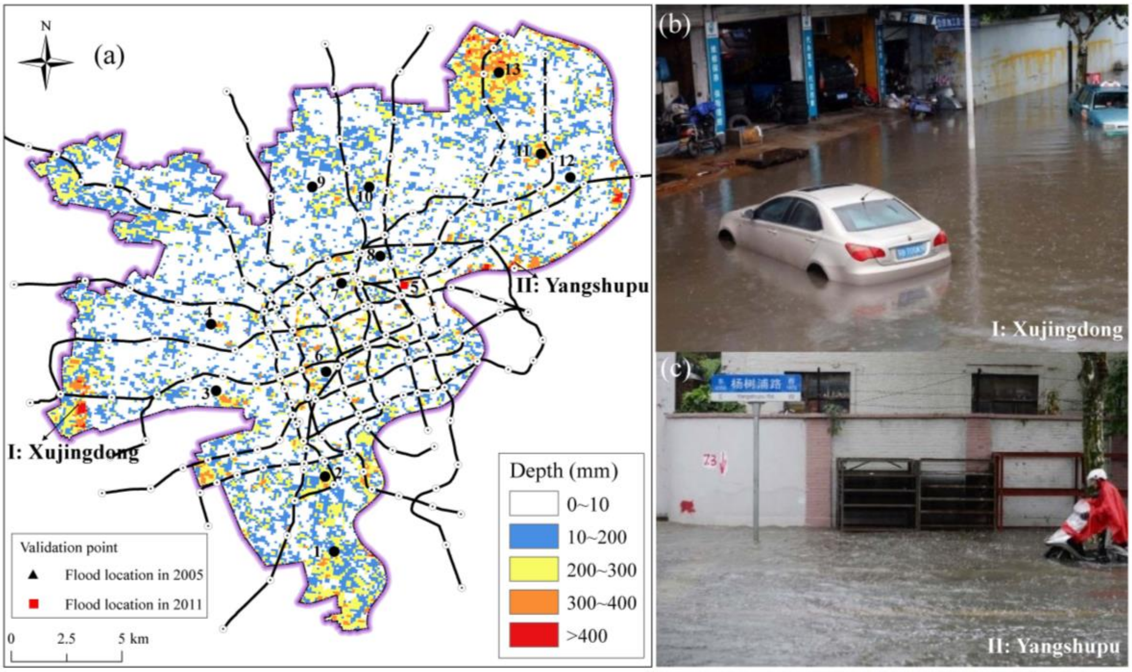


Figure 8: Distribution of the recorded flood locations: a) recorded flood locations, b) inundation of the Xujingdong road, and c) inundation of the Yangshupu road

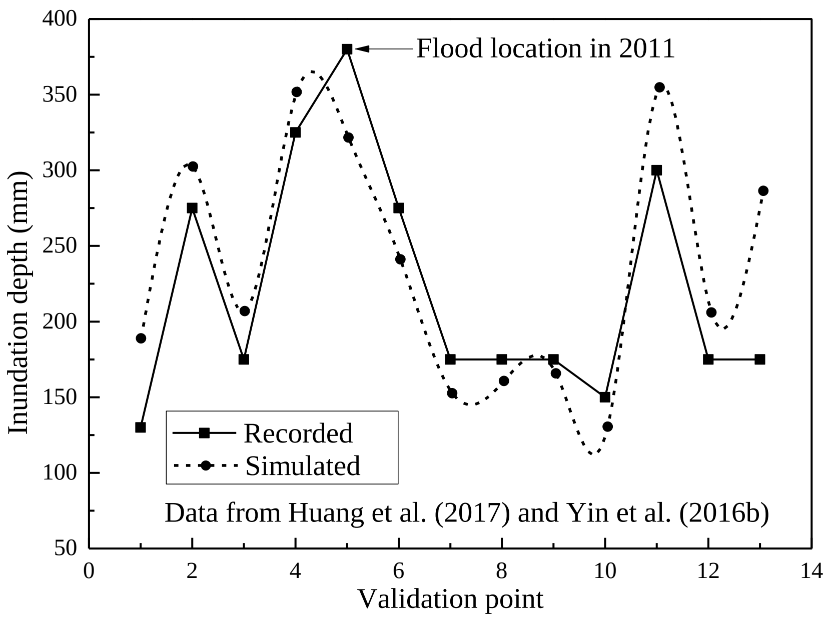


Figure 9: Comparison of the inundation depths obtained from the simulated results and recorded data

5. Discussion

5.1 Model evaluation and limitations

In this study, the open-source inundation model, SWMM, combines with the GIS is adopted to evaluate inundation risks. To improve the approach, a new algorithm is proposed to simulate the overland flow on the ground surface. The algorithm can integrate the SWMM into the GIS. The integrated approach can predict the inundation risks on a regional scale, whereas the existing methods can only evaluate a small area. Because of a lack of recorded data for the inundation depths of metro stations, only the inundation depth on the ground surface is validated by the comparison between the simulated results and the records of historical floods. The comparison reveals that the model can capture the surface flowing dynamics of rainwater. However, there are also some differences between the calculated inundation depth and validated results. This may be ascribed to the uncertainties from various assumptions of the parametric values, data quality, and modelling conditions. These uncertainties result in a larger inundation depth than the recorded data. Overall, the simulated result can provide a relatively safe prediction of inundation risks. Although there are various uncertainties in the simulated results, the deviation is acceptable and model is satisfactory for urban inundation predictions.

5.2 Flooding prevention measures

The simulated results show a spatiotemporal distribution of the inundation profiles. The inundation profiles are characterized by a consistency in the rainfall scenarios with larger inundation depths and extents corresponding to higher rainfall intensities. In the scenario of the 500-year-rainfall intensity, various regions within the study area are predicted to suffer catastrophic inundation, particularly those regions near the Huangpu River. This phenomenon may be due to the backwater effect, which is well known to be stronger and more apparent at riversides than that in inland regions. Therefore, there is a need to improve the drainage facilities (e.g., sewer system, manhole, and outlet) along the Huangpu River.

Inundation of the metro system primarily occurred in the regions with a deep inundation depth. To mitigate the damage caused by inundation in metro system, the drainage capacity of the ground surface around the metro station should be increased (Suarez et al. 2005; Aoki et al. 2016). In addition, the height of the step of the metro station with a high inundation risk should be increased. Drainage facilities within the metro station should also be allocated for the emergency of flooding. In the future, more flooding adaptation measures should be taken to mitigate the catastrophic damages caused by urban flooding.

6. Conclusions

This paper presented a method to evaluate potential inundation risks through the integration of a hydraulic model and GIS-based analysis via a proposed algorithm. The proposed approach was used to predict the inundation risk of metro system of Shanghai. The proposed approach could also be applied to other flood-prone areas. The results were verified by recorded flooding events. According to the results, major conclusions were drawn as follows:

(1) A new algorithm to simulate the overland flow was proposed to simulate the inundation extent and depth on the ground surface. This algorithm included two aspects: i) determination of the grid location and ii) an interactive calculation of the spreading process. With the proposed algorithm, the incorporated SWMM and GIS are adopted to yield a spatial-temporal distribution of the inundation risk on the ground surface.

(2) Based on the inundation depth on the ground surface, an equation to qualitatively calculate the inundation depth of the metro system was proposed. The proposed equation provided a quantitative evaluation of the metro system by considering the drainage capacity and characteristics of each metro station.

(3) The proposed approach was used to simulate the inundation risk of the metro stations in Shanghai under 50-year, 100-year, and 500-year-scenarios. The results showed that for an inundation depth of over 300 mm the inundation depth was up to 5.16 km^2 at 500-year-rainfall intensity, which was 4.3%

of the studied area. The inundation region with a depth of over 300 mm was predicted to primarily occur along the Huangpu River or at a location with inadequate drainage facilities. For the 500-year-rainfall intensity, four metro stations were predicted to be inundated to a depth of over 300 mm.

(4) The drainage facilities should be improved to decrease the damage induced by urban floods, especially for the regions with metro stations and high inundation risks. In addition, the height of the step for the metro stations with a high risk should be investigated in detail.

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Competing interests. The authors declare that they have no conflict of interest.

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Appendix: Pseudo-code of the algorithm for the spreading procedure

Algorithm: Algorithm for the spreading process of the runoff volume.

input: Arcgis.in € (A, E, h, x, y)

! *Data with area, elevation, average water depth, and X/Y coordinates from the arcgis database.*

output: Data.out € (A, h\`)

! *Water depth of each grid.*

Determine the relative location and spreading coefficient of each grid around the target grid.

Spreading process

Do i = 1, N

! *N is the iteration step of the spreading steps.*

Rank of spreading for each grid

$$Q_{target} = \sum_{i=1}^{link} h_i A_i$$

! *Based on the water quantity of each grid, select the target grid.*

Start spreading

Do n = 1, M

! *M is the total number of spreading grids. The maximum value of M=8.*

If ((**abs**(h_I-h_{Ij})>0.01) .and. Q_I>0) **Then**

$$Q_{diffuse} = \sum_{j=1}^{n} (h_I - h_{Ij}) \cdot A_j \quad (j=1,2,\cdots,n)$$

! *Based on the spreading coefficient, allocate the water quantity and update the water level of each grid around the target.*

End if

End do

End do

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