Physics and Chemistry of the Earth 125 (2022) 103075

Contents lists available at ScienceDirect

Physics and Chemistry of the Earth

journal homepage: www.elsevier.com/locate/pce

Research and application of the mathematical model for extreme weather event in coastal urban areas

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ARTICLE INFO

Keywords:
Extreme weather events
Flood and waterlogging
Mathematical model
Flood risk analysis
Pudong flood protection area

ABSTRACT

Extreme weather event simulation in coastal urban areas is more complex and difficult due to their special geography and climate characteristics, different kinds of land uses, close-packed buildings, and large amounts of flood control works and drainage systems. Urban Flood Simulation Model (UFSM) was integrated in this study to simulate the extreme weather events in the Pudong flood protection area (Shanghai, China). The model is established based on two-dimensional unsteady flow theory and nonstructural and irregular mesh technique. A method based on one-dimensional unsteady flow theory is proposed to deal with small-scale river and road. The calculation of the pumping stations, the water gates is indicated based on the real scheduling discipline. The extreme weather event scenarios (typhoon+rainstorm+ astronomical high tide + upstream flood) are simulated. The results show that the flood risk is higher in the coastal area and the upstream of the Huangpu Rive, and UFSM is a suitable method for simulating the flood inundation of coastal urban areas.

1. Introduction

The potential increases in extreme events due to climate change come on top of alarming rises in vulnerability (Aalst, 2006). Observations since 1950 indicate increases in some forms of extreme weather events as well as the disaster damage (Banholzer et al., 2014). Climate change, although a natural phenomenon, is accelerated by human activities. Extreme weather event is more frequent and costly in coastal areas than that in inland areas due to their special geography, climate and social characteristics. For flood hazard-affected bodies themselves, the subjective reasons for frequent occurrence of flooding and waterlogging disasters are analyzed as follows. (1) Cities expand in high flood hazard areas. (2) Impervious areas increase. (3) The large population and property density result in the increase of flood vulnerability in urban areas. Typhoon, rainstorm, astronomical high tide and upstream flood may affect coastal areas individually or in combination, where human activity is more concentrated than interior areas. Flood risk assessment methods generally contain three types: mathematical statistics methods, index system methods, and dynamic risk evaluation methods based on integrated model. With the development of hydrological model, hydrodynamics model and GIS technology, the integrated models have been widely used. Urban pluvial flood scenario modeling based on high resolution topographic data is developing continuously. Flood inundation information and social economy information are analyzed by spatial overlay analysis (Li et al., 2016). Flood inundation simulation (different frequency or return period) is an important basis for flood damage assessment, flood risk assessment, emergency plan, and risk management. The complexity of surface cover and underground drainage systems in urban areas brings great difficulties to the simulation of extreme weather events. There are three kinds of method for flood inundation simulation (Xu et al., 2003): (1) Hydro-hydraulics coupling method. It is used to simulate the movement of surface runoff, river channel and pipe network (Hsu et al., 2000; Dushmanta et al., 2007). The calculation unit is the water-collecting area, and the calculation results can merely reflect the water flow process of the key location or river cross-section within the simulated basin. (2) Hydrodynamic method (Venkatesh et al., 2008). The process of surface runoff is calculated by solving the Saint-Venants equations. Therefore, the

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https://doi.org/10.1016/j.pce.2021.103075
Received 7 January 2020; Received in revised form 2 September 2021; Accepted 4 October 2021

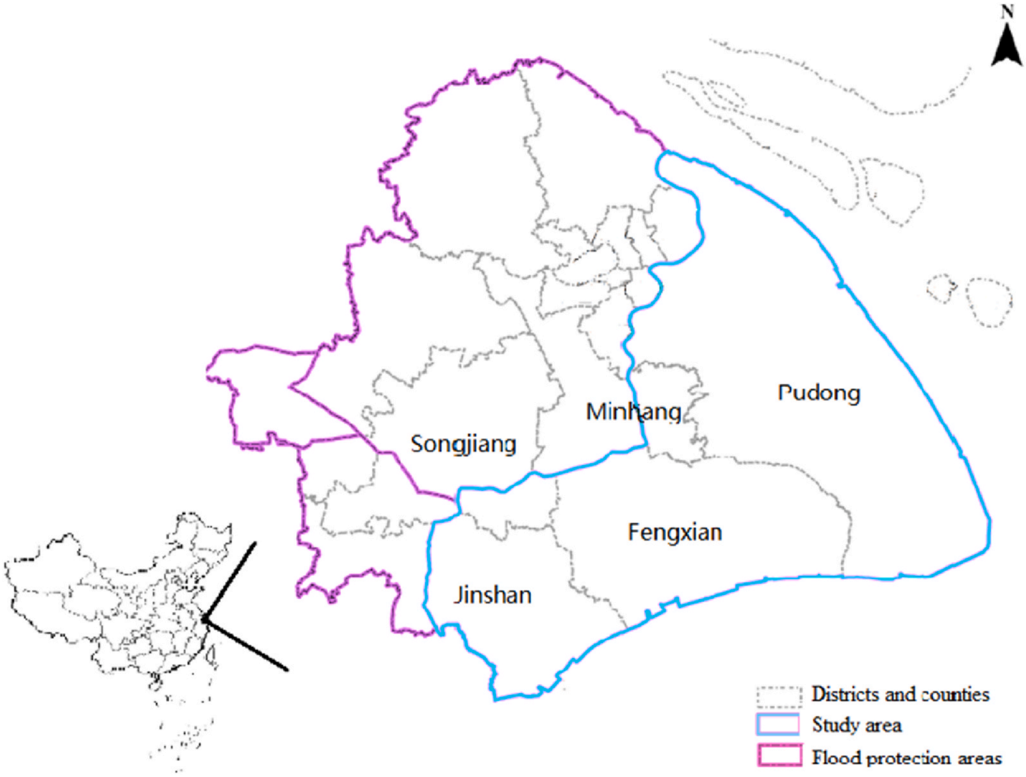

Fig. 1. The location of Pudong flood protection area.

catchment division does not limit the result, and the flow process of any grid or passage can be checked. (3) GIS technology method. The calculated result of this method is the final state of flood inundation, which may not reflect the movement process. (Huber et al., 1989). Mathematical model of urban storm water runoff and drainage was developed since the 1960s. The research results of urban flood simulation models have been highly applied, and the commonly used models include SWMM (Storm Water Management Model) (EPA, Environmental Protection Agency) (Gayer et al., 2010), DHI-MIKE (Denmark) (Roca and Davison, 2010), and InfoWorks CS(Wallingford) (Huber et al., 2005). Since 2010, SWMM(Zhao et al., 2009) model is widely used in China for flood risk assessment and underground pipe network design. Urban flood and waterlogging simulation based on SWMM has been carried out in Beijing, Tianjin, Wuhan, Shenzhen, Guangzhou and many other big cities (Niu et al., 2012; Feng and Xiao, 2011; Huang et al., 2011).

At present, in the process of numerical model establishment for flood and waterlogging risk analysis, the main difficulty is lack of sufficient measured data, including flood inundation range, inundation water depth and duration. The selection of appropriate mathematical model is more important since the model calibration and validation is limited to real data situation. In this study, a method was developed for urban flood and waterlogging simulation. A key element of this method is the ability to provide objective inundation information with the consideration of buildings, land uses, drainage systems, and other flood control works. The results can be used as scientific basis for flood risk assessment, for land use planning, for mapping evacuation egress routes, and for locating suitable emergency shelters (Li et al., 2018).

2. Study area

Pudong flood protection area is taken as a study area and hereinafter referred to as Pudong, which is part of Shanghai. Shanghai is an important centre for economy and finance with large population. The flood and waterlogging disaster may cost highly once it occurs. However, weather extremes appear occasionally due to rainstorm, typhoon, astronomical high tide and upstream flood. The average annual precipitation is 1, 191 mm, and the rainy season accounts for more than 60% of the annual rainfall. The average number of tropical typhoon affecting Shanghai is 2.6 per year, and the average number of storm surges is 1–2 per year. The geographical location of the research area is shown in Fig. 1. Pudong is located on the south bank of the Huangpu River, a total area of 2, 722 km^2 east to the China Eeast Sea, south to Hangzhou Bay, west to the Huangpu River as the boundary. Pudong is Yangtze river delta flood plain, which is relatively flat with average elevation of 3.87 m, The northwest part is lower than the southeast, the elevation generally ranges from 3.5 m to 4.5 m, and some low-lying areas is about 3.2 m.

In 2000, the urbanization rate of the Shanghai population was 88.3%, and in 2013, it was 89.3%, which only increased by one percentage point. However, since the new century, the urbanization of Shanghai suburbs has developed rapidly, and the urban built-up area of Shanghai has increased from 550 km^2 to 999 km^2, nearly doubling the area. The Gross Domestic Product (GDP) of Shanghai in 2020 is 3.87 trillion RMB, and a per capital GDP was155,605 RMB.

3. Materials and method

3.1. Historical flood and waterlogging disasters

Pudong District is affected by typhoon, rainstorm, astronomical high tide and upstream flood. These four factors may occur singly or concomitantly. The rainstorms from June to September are mainly caused by plum rain, typhoon or thunderstorm, so urban flood and waterlogging disasters always appear during these times and cause plenty economic losses. The "two combinations" extreme weather event happens commonly during rainy season. The typical "three combinations" extreme weather event such as "9711" typhoon, "1999 plum rain", "2000 Pippian", and "2005 Maesha". "Fitow" is a "four combinations" extreme weather event which happened in 2013 and caused 953 million

Table 1
Historical Extreme weather events.

Year	Extreme weather events	Combination type	Direct economic loss (RMB)
1997	9711	Typhoon+Rainstorm+Astronomical high tide	635 million
1999	Plum Rain	Upstream flood+ Rainstorm+Astronomical high tide	871million
2000	Pippian	Typhoon+Rainstorm+Astronomical high tide	122 million
2005	Maesha	Typhoon+Rainstorm+Astronomical high tide	1.358 billion
2013	Fitow	Typhoon+upstream flood+Rainstorm+Astronomical high tide	953 million

RMB losses. Typhoon, Taihu Basin upstream flood, rainstorm, and astronomical high tide happened at the same time during "Fitow" typhoon (see Table 1).

3.2. Basic data

The data of administrative division, residential land, elevation, traffic systems, river networks and land use adopted in this paper are the surveying and mapping data and water resources census data in 2012. Water level data is based on the elevation of Shanghai Wusong (Sheshan).

Shanghai has formed "three lines of defense": seawall, riverbank, and drainage system. Such a flood control system has brought great benefits to disaster prevention. The Huangpu River flows through the whole Pudong District. There are 15163 rivers in the Pudong flood protection area, with a length of 12412.13 km and a total surface area of 209.57 km^2. The main municipal canals include the Dazhi River, Zhaojiagou, Chuanyang River, Pudong Canal, etc. The data of rainfalls and water levels during typhoon "Maesha" in 2005, typhoon "Haikui" in 2012, typhoon "Fitow" in 2013 was collected and used for model calibration and verification.

3.3. UFSM model

3.3.1. Basic concept

UFSM is developed by China Institute of Water resources and Hydropower Research. Based on self-developed GIS platform, coupling of urban drainage network with two-dimensional model can be realized. The successful application of UFMS in cities such as Shanghai, Jinan and Fuzhou shows that it has the ability to deal with complicated actual urban flood and waterlogging simulation.The river channels and main roads are treated as 1D networks, while floodplain is calculated as a 2D domain. UFSM model combines the finite volume method with the finite difference method, adopts the irregular quadrilateral grid without structure to discrete the study area, calculates the water depth at the centric of the grid, and calculates the flow rate at the channels around the grid (Wang et al., 2010). It can reveal the social and economic scenario, climate scenario and flood control system scenario, and simulate different types of risk sources and their combinations such as river flood, high tide level and rainstorm (Cheng, 2009).

Continuity equation:

$$H_i^{T+2DT} = H_i^T + \frac{2DT}{A_i}\sum_{k=1}^{K} Q_{ik}^{T+DT} L_{ik} + 2DTq^{T+DT} \tag{1}$$

Where H_i is water depth of the grid i; DT is half of time step; A_i is grid area; Q_{ik} is unit-width flow over passage k on grid i; L_{ik} is the length of the passage k in the grid i; q is source sink term which consists of effective rainfall intensity and regional drainage intensity.

Momentum equation:

$$Q_j^{T+DT} = Q_j^{T-DT} - 2DTgH_j^T\frac{Z_{j2}^T - Z_{j1}^T}{DL_j} - 2DTg\frac{n^2 Q_j^{T+DT}\left|Q_j^{T-DT}\right|}{\left(H_j^T\right)^{7/3}} \tag{2}$$

Where Q_j is discharge of passage j; g is gravitational acceleration; H_j water depth of the pessge j; Z_{j1}、Z_{j2} are the water levels of the grids on both sides of channel j; DL_j is spatial step, $DL_j = DC_{j1}+DC_{j2}$, DC_{j1}、DC_{j2} are the distances between the grid centroid on both sides of channel j and the midpoint of channel.

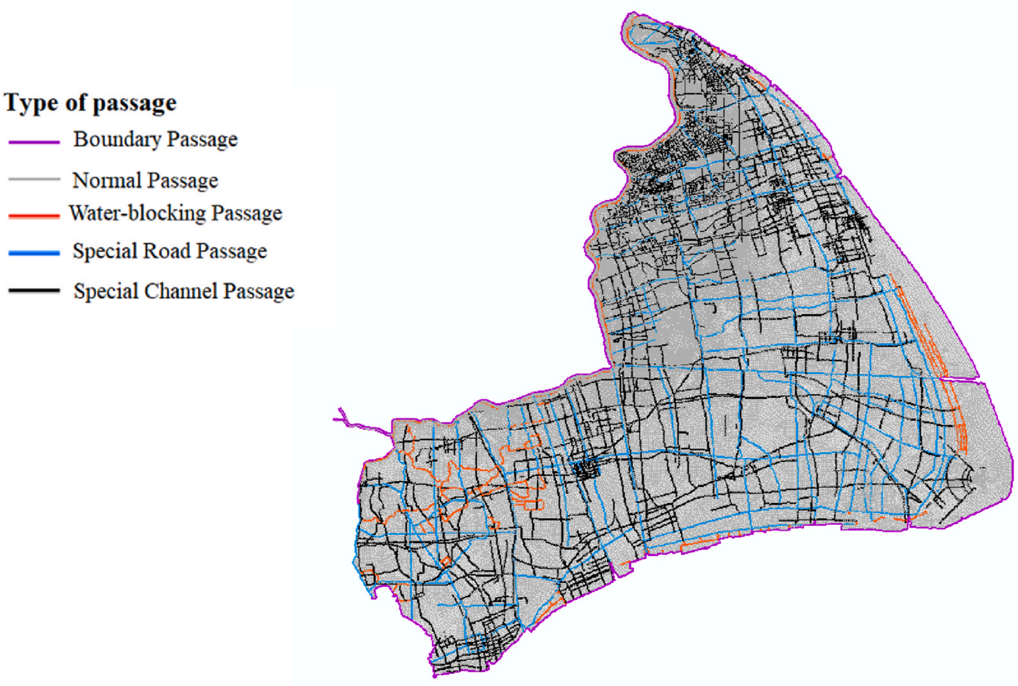

Fig. 2. Computing passage.

Table 2
Attribute assignments.

Object	Required attributes
Grid	Type, Elevation, Roughness, *AAR*
Water blocking passage	Elevation
Special river passage	Bottom Elevation and Width, Left &Right Bank elevation, Upper Width
Special road passage	Road elevation, road width, curb height
Sluice	Sluice type, Opening time, Opening water level, Closing water level, Width, Bottom elevation, Maximum drainage flow, opening ratio, etc
Pump station	Pump station type, Opening water level, Closing water level, Design drainage capacity, Operation ratio, etc

While the research scale is large, we may consider the computational efficiency and generate the mesh larger than a building area. Close-packed buildings affect the flow of water, thus, A new parameter-Adjusted Area Rate (*AAR*) is adopted, shown in Equation (3).

$$AAR = 1 - \frac{A_b}{A_m} \tag{3}$$

where A_b is the area of building within the mesh; and A_m is the area of the mesh.

The runoff coefficient of impervious area is about 0.9, while natural catchment is about 0.5. It can be calculated by linear interpolation according to the impervious area ratio. The impervious area ratio approximates to the *AAR*. Thus,

$$R = 0.5 + (0.9 - 0.5) * AAR \tag{4}$$

where, R is the runoff coefficient.

To reduce the impact of flooding and waterlogging disasters on cities, we built different kinds of flood control works, such as dikes, pumps, sluices, and pipe drainage networks. When the water level exceeds crest elevation or dike breaks, the weir formula is used to calculate the flow. The simplified method is adopted to calculate the impact of drainage systems. The study area is divided into several drainage zones, and each drainage zone is considered as a generalized "underground reservoir". According to the design drainage capacity of each drainage zone, an underground storage space is set for each grid within the zone to reflect the influence of drainage system on the surface inundation. Sluices and pumps are set according to the scheduling rules.

3.3.2. *Model establishment*

The main considered factors include rivers, dikes, railways, highways, and roads. The whole study area is divided into 127,453 irregular quadrilateral grids with an average area of 0.0215 km^2. The main rivers such as Huangpu River are divided into rive type grids. The other small rivers are taken as special channel passages. The railways, expressways and dikes are treated as water-blocking passages, and roads are treated as special road passages. The whole model contains 256,351 passages, including 7,055 special channel passages, 2,142 water-blocking passages, and 21,826 special road passages. The model passages are shown in Fig. 2.

Attribute assignment includes grid, water-blocking passage, special channel passage, special road passage, sluice and pump station. The

Fig. 3. Boundary conditions.

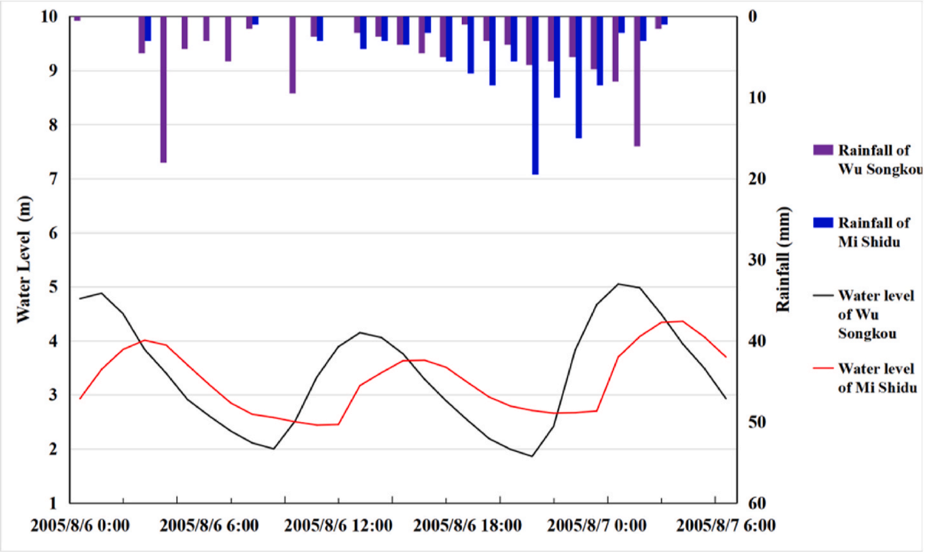

Fig. 4. The water level and rainfall of typical stations during typhoon "Maesha".

attributes required to assign values for different types are shown in Table 2. A total of 31 drainage zones, 44 sluices, and 262 pumping stations are simulated.

3.3.3. Boundary condition

The distribution of inflow boundary of the flood simulation model in the Pudong is shown in Fig. 3. The main water lever monitor stations along Huangpu River are Wu Songkou, Mi Shidu, and Huangpu Park. The other 8 boundary stations located in the estuary, where the water level is affected by the tide, are set as the measured tide level processes. The water level processes of Mi Shidu and Wu Songkou stations are adopted as the upper and lower boundary conditions of the Huangpu River respectively, and Huangpu Park station is selected as the verification station.

3.4. Simulation scenarios

In order to prove the rationality of model, it is necessary to calibrate and verify the established model. According to the comparison of simulated and measured river water level of monitoring stations, the model parameters should be adjusted to improve the reliability and simulation accuracy. The Pudong district is greatly affected by the water level of the Huangpu River. The typhoon "Maesha" in 2005 was selected for model calibration, and typhoon "Haikui" in 2012 was selected for model validation. Typhoon, Taihu Basin upstream flood, rainstorm, and astronomical high tide happened at the same time during typhoon "Fitow" in 2013, so it was selected as the extreme weather event scenario.

4. Results and discussion

4.1. Model calibration

4.1.1. Basic data

The rainfall data are measured data from 17 rainfall stations. The simulation duration is from 2005/08/06 0:00 to 2005/08/07 6:00. Fig. 4 shows the water level and rainfall of typical stations during typhoon "Maesha". Wu Songkou and Mi Shidu are selected as typical water level and rainfall stations.

4.1.2. Water level verification

The measured water level of Huangpu Park station is compared with the simulation results (Fig. 5). The comparison between the measured and simulated results is shown in Table 3. The relative error of the maximum water level in Huangpu Park is −1.23%, and the occurrence time of the maximum water level is 20 min later than the measured time. The relative error of the maximum water level of Mi Shidu station is −2.28%, and the occurrence time of the maximum water level is 5 min later than the measured time.

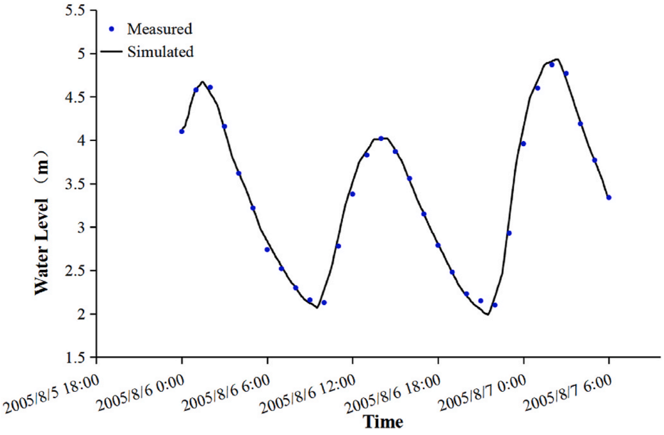

Fig. 5. Water level in Huangpu Park station during typhoon "Maesha".

4.2. Determination of model parameters

After calibrating the model with the "Maesha" rainstorm and flood data in 2005, the model parameters were finally determined as follows:

(1) Grid roughness. According to the empirical value, corresponding roughness reference values of different underlying surface types is shown in Table 4.
(2) *AAR.* According to the method in Equation (3).
(3) Grid average elevation. Elevation value extracted from DEM data.
(4) Roughness of special river passage. Roughness of special river passage was 0.03.
(5) Pump station sluice parameters. It was set according to hydraulic census data and scheduling rules.

Table 3
The measured and simulated maximum water level and occurrence time.

Station Name	Maximum Water Level			Highest Water Level Occurrence Time		
	Measured	Simulated	Error	Measured	Simulated	Difference (min)
Huangpu Park	4.87	4.93	−1.23%	2005/8/7 2:00	2005/8/7 2:20	−20
Mi Shidu	4.38	4.48	−2.28%	2005/8/7 3:30	2005/8/7 3:35	−5

Table 4
The reference value of roughness.

Land Use	Thicket	Dry Farmland	Paddy Field	Open Space
Roughness	0.065	0.035	0.035	0.025–0.035

4.3. Verification

4.3.1. Basic data

The rainfall data is the measured data from the 27 stations. The simulation duration is from 2012/08/08 1:00 to 2012/08/9 6:00. The process of water level and rainfall of typical stations during "Haikui" typhoon is shown in Fig. 6.

4.3.2. Water level verification

The measured water level process of Huangpu Park station is compared with the simulation results. It can be seen from Fig. 7. The river level process simulated by the model is consistent with the measured process. According to Table 5, the comparison between the measured and calculated results show that the relative error of the maximum water level in Huangpu Park is −0.23%, and the maximum water level occurrence time is 5 min earlier than the measured time. The relative error of the maximum water level of Mi Shidu station was

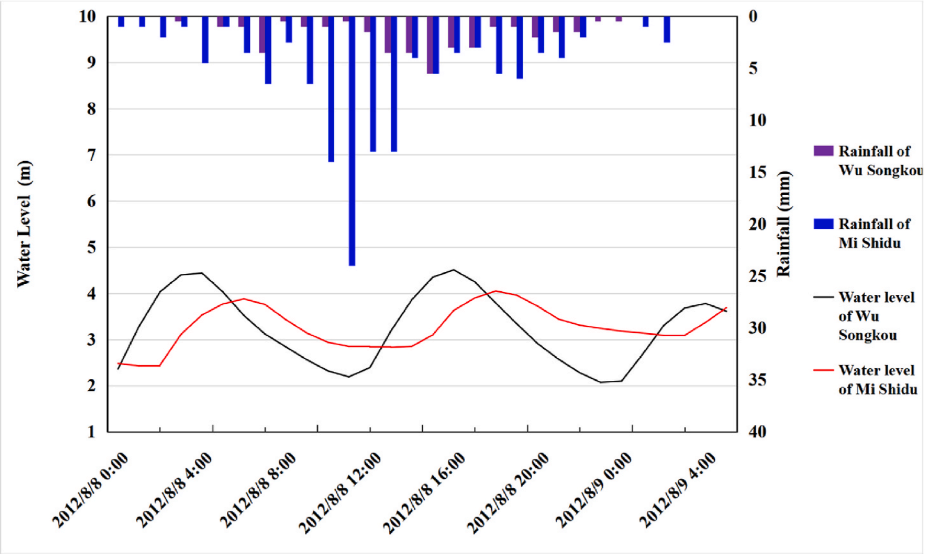

Fig. 6. The water level and rainfall of typical stations during typhoon "Haikui".

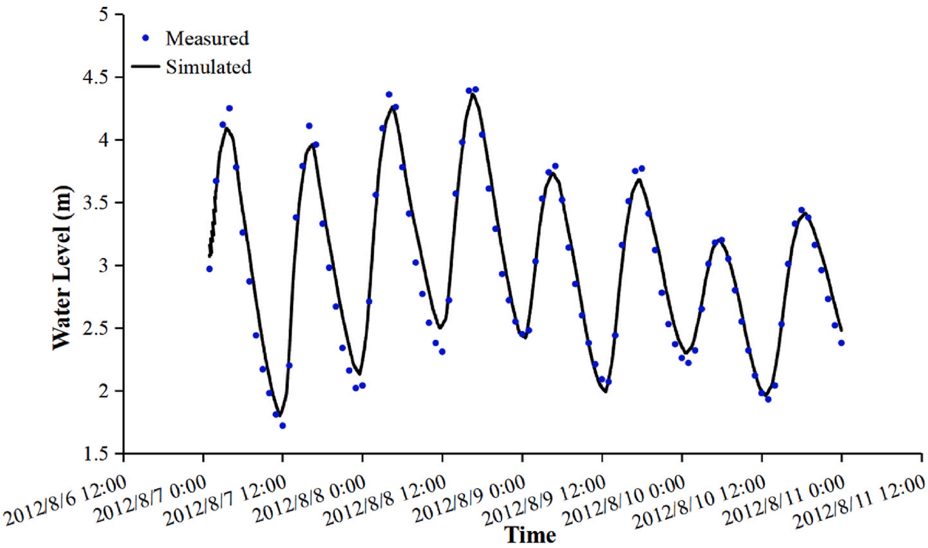

Fig. 7. Water level in Huangpu Park station during typhoon "Haikui".

Table 5
The measured and simulated maximum water level and occurrence Time.

Station Name	Maximum water level(m)			Maximum water level occurrence time		
	Measured;	Simulated	Error	Measured	Simulated	Difference (min)
Huangpu Park	4.40	4.41	−0.23%	2012/8/8 17:00	2012/8/8 16:55	5
Mi Shidu	4.05	4.08	−0.07%	2012/8/8 18:00	2012/8/8 17:58	2

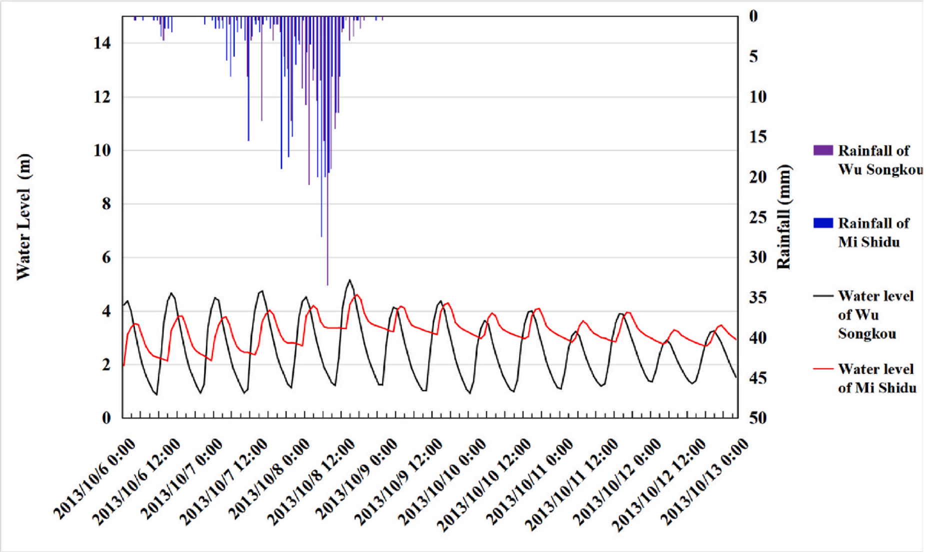

Fig. 8. The water level and rainfall of typical stations during typhoon "Fitow".

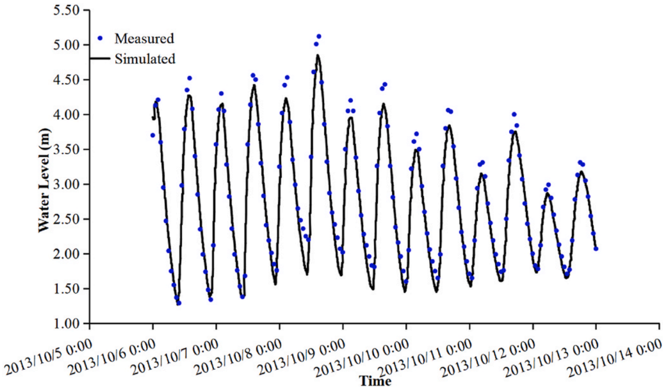

Fig. 9. Water level in Huangpu Park station during typhoon "Fitow".

−0.07%, and the maximum water level occurrence time was 2 min earlier than the measured time.

4.4. *Extreme weather event scenario*

4.4.1. *Basic data*

The rainfall data used in the simulation are from the 71 rainfall stations such as Wusongkou, Donggou, Gaoqiao, and Pudong Airport. The calculation period is set from 2013/10/06 0:00 to 2013/10/13 0:00, and the total simulation duration is 7 days. Fig. 8 shows the water level and rainfall process of typical stations during typhoon "Fitow".

4.4.2. *Water level verification*

The measured water level process of Huangpu Park station in the study area is compared with the simulation results. It can be seen from Fig. 9. The river level process simulated by the model is consistent with the measured process. According to Table 6, the comparison between the measured and calculated results shows that the relative error of the maximum water level in Huangpu Park is 5.27%, and the occurrence time of the maximum water level is 15 min earlier than the measured time. The relative error of the maximum water level of Mi Shidu station is 3.70%, and the occurrence time of the simulated maximum water level is 10 min earlier than the measured time.

Table 6
The measured and simulated maximum water level and occurrence Time.

Station Name	Maximum Water Level			Maximum water level occurrence time		
	Measured	Simulated	Error	Measured	Simulated	Difference (min)
Huangpu Park	5.12	4.85	5.27%	2013/10/8 14:00	2013/10/8 13:45	15
Mi Shidu	4.60	4.52	3.70%	2013/10/8 16:00	2013/10/8 15:50	10

According to the calculation results, inundation area such as Puxiao road in Minhang District, Baiqi road in Fengxian District, Guhua road and Huancheng east road has a water depth of more than 30 mm. In Songjiang District, parts of the riverbanks and tributaries of the Huangpu River, such as Zhangzetang, Yexietang and Nanmaojing are overflowed. The simulated inundation situation is consistent with the disaster investigation.

4.5. Discussion

The reasons for the model errors are analyzed as follows:

(1) The study area is very large, and the spatial distribution of rainfall is uneven. It can be seen from the rainfall data of typhoon "Maesha" and "Haikui" used in the calibration and verification that the rainfall in different stations has a large difference, so there is a certain error between the simulated and measured water depth and distribution.

(2) There are many sluices within the study area. The big sluices of the main rivers and channels are simulated, and some small sluices are ignored. Although all the pumping stations are included in the model, there are certain scheduling rules of the pumping and drainage systems. The process of dispatching according to the rules may be different from the actual operation process during the historical extreme weather events, which may cause the deviation of water level and inundation distribution between simulated and measured.

(3) The Huangpu River belongs to the tidal waterway, and the drainage pumps along the channel are generally opened during a low water level. The simulated water level of the Huangpu River is lower than the actual measured data, and the error is higher than the error at the high water level. It mainly because that the amount of water is neglected which are discharged into the Huangpu River at the low water level from the Puxi area.

(4) The data used in the model is the 2012 mapping data and water conservancy survey data, so the simulation result of the "Haikui" typhoon in 2012 is the smallest.

5. Conclusions

Extreme weather event simulation in coastal urban areas is more complex and difficult due to their special geography and climate characteristics. Different kinds of land uses, close-packed buildings, and large amounts of flood control works and drainage systems should be considered when we simulate the flood inundation. Pudong is taken as a study area where the extreme weather events (typhoon+rainstorm+ astronomical high tide + upstream flood) occur occasionally. The 2005 typhoon "Maesha" is simulated to determine the parameters of the extreme weather event model. The 2012 typhoon "Haikui" was used for model verification. The 2013 typhoon "Fitow" was chosen as the typical extreme weather event in the history. The research conclusions are as follows:

(1) It is reasonable for the model to generalize the research area. The UFSM model has the following advantages. The parameters such as grid elevation and *AAR* extracted from the basic terrain data can reflect the distribution characteristics of the underlying. The parameters such as grid and channel roughness, and runoff coefficient are reasonably set according to the specifications, literature or empirical values. The sluices and pumping stations are scheduled according to the rules.

(2) The simulated water level processes are consistent with the measured data. Comparing the measured and simulated results of Huangpu Park stations, the highest water level error is 1.23%, and the highest water level occurrence time error is 20 min. So the model can reasonably simulate the inundation distribution caused by extreme weather events.

(3) Scenario modeling of extreme weather events is a big challenge, particularly in urban coastal area. Detailed topographic data, hydrometeorological data, and inundation data are required for this study, thus the model is tested only for there extreme events. It is recommended that the model should also be tested and evaluated for more extreme events to enhance the reliability of the model outputs. The model can predict future flood risk and provide reference for urban disaster prevention planning if reasonable future scenario is given. However, how to set the most likely or most dangerous scenarios with the combination of different intensity of typhoon, rainstorm, astronomical high tide and upstream flood need further research.

Author statement

Under supervision by Miansong Huang, Chaochao Li performed model construction and data analysis. Juncang Tian and Jacqueline revised manuscript. All authors read and contributed to the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The work described in this publication was supported by National Natural Science Foundation of China (No. 51809143); First Class Discipline Construction Project of Ningxia(No. NXYLXK 2021A03); Key program for Primary Research & Development Plan of Ningxia (No. 2020BEG03045); The Fourth Batch of Ningxia Youth Talents (No. TJGC2019041).

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