Diagnostic analysis of waterlogging in Zhenjiang City by using PCSWMM

Q Q Yang1,4, Z D Bao1, Y Fu2, N She1,3 and Z Y Deng1

1China Machinery International Engineering Design and Research Institute Co. Ltd., Changsha 410007, China
2Jiangsu Manjiangchun Urban Planning Design and Research Institute Co. Ltd., Zhenjiang 212001, China
3Tsinghua University Innovation Center in Zhuhai, Zhuhai 519000, China
E-mail: sophiayang0103@foxmail.com

Abstract. Urban flood becomes a more and more serious problem in China now resulting from the urbanization. Compared with traditional methods, numerical model simulation is a better approach to analyse and evaluate the urban flood risk, waterlogging area and flooding depth. Taking a historical flooding area in Zhenjiang as an example, this paper analysed the operational causes of the waterlogging in an observed 4-day precipitation event by PCSWMM. The results showed that the waterlogging area was reduced up to 77% when the drainage pump was operated appropriately. With the pump turned on, the discharge rate increased from 0.2 to 2.04 m³/s and maximum water depth in flood area dropped from 0.9 m to 0.66 m. It indicated that the severe waterlogging in the study area was primarily resulted from the improper pump operation in the 4-day event. However, simulation resulted that even with appropriate pump operation; there was still 0.5 hectares of waterlogging area. In addition, the effectiveness of the drainage pipe system on the waterlogging reduction was evaluated with existing and planned conditions. The results showed that updated pipe system with a diameter of 1000-2800 mm could hold a discharge flow rate up to 3.5 m³/s. The study imply that combined of appropriate pump operation and pipe system updating may effectively improve the drainage capacity of the whole pipe system and reduce the waterlogging risk around crossroads.

1. Introduction
With the fast urbanization, more and more natural landscapes have been converted to commercial, residential and industrial land uses, which leads to a significantly change of the hydrologic regime feature. Typically, the hydrologic changes are indicated by the alternation of natural water characteristics, such as increasing of temperature, increasing of runoff, decreasing of infiltration, which leads to the water quality degradation, and increasing of flood risks [1]. All of those hydrologic changes will have a seriously inverse effect on the resident safety and the city development. Especially, the urban flooding problem gradually becomes a highlighted social concern. The flood prevention and storm-water management play an important role to guarantee the citizen’s living and urban infrastructure’s safety.

The rational method has been broadly used to calculate the runoff peak values which are applied to guide the city plan and the construction design. However, due to the change of runoff convergence, the traditional method could not precisely describe the characteristics of the storm water runoff and urban flood. It is necessary to evaluate the cause, the impact range and the water depth of waterlogging in
order to prevent the water-related urban issue with the helpful tool of numerical models [2].

According to the published peer-reviewed studies [3-5], PCSWMM is a good option to be applied to simulate the waterlogging area, water depth and flood risk in heavy rainfall events. PCSWMM is developed by Computational Hydraulics International in Canada based on EPA SWMM. It is combined with ArcGIS functions, which create a convenient interface and operation. Additionally, 2D flooding analysis is also added in the model. In this paper, we conducted a case study in Zhenjiang to demonstrate the PCSWMM application in flood analysis and diagnosis.

A continuous rainfall lasted in Zhenjiang City, China from Oct 25th to 28th in 2016. This rainfall leads to a serious waterlogging above ground around the intersection of Shangde Road and Gucheng Road. Although it was a historical flooding hotspot, the waterlogging reached the historical record with similar rainfall intensity and volume. In this paper, we addressed two objectives, include (1) to elucidate the most contributed reason for the at-site waterlogging by the hydrologic simulation, and (2) to evaluate the effectiveness of planned pipe system update to reduce the flooding risk in this area.

2. Materials and methods

2.1. Study area

Jiangbin Area locate in the northwest region of Jingkou District, Zhenjiang. It goes north to Binshui Road, south to Jiangnan School, west to Beigushan Park and east to Wojiashanshui neighbourhood. Totally, this area covers about 206 hectares, consisted of mostly old and high-density residential communities. The drainage system in this area is a combined sewer system which is the typical characteristic of old communities. Jiangbin pump station is set in the north part of the area, which directly drains the excess storm water to Jinshan Lake to prevent from flooding. According to the historical flood record, a historical flooding hotspot locates near the intersection of Shangde and Gucheng Road and the intersection of Shangde and Zhongxin Road, where the elevation is slight lower than the surround area. The study area and the location of historical flooding area are shown in figure 1.

![Figure 1. Location of Jiangbin Area and the historical flooding area.](image)

2.2. Cases simulation

In the study, the reason of waterlogging in the historical flooding area was diagnosed and on the purpose to reveal potential solution to address the waterlogging issue. Therefore, three scenario cases were simulated, include: (1) the existing drainage condition with the existing pipe system when Jiangbin pump station was off, (2) the existing drainage condition with the existing pipe system when Jiangbin pump station was on, and (3) the planned drainage condition with planned pipe system when Jiangbin pump station was operated.
2.3. Planned pipe systems
Due to the flooding history in the crossroads, the pipe system update was planned through replacing the existing pipes to bigger size pipes with a diameter of 1000-2800 mm to improve the discharge capacity. The pipe system update was planned in Mengxi Road and Shangde Road, as shown in figure 2.

![Figure 2. Location of the planned pipe system updating.](image)

2.4. Precipitation
The rainfall intensity from Oct 25th to 28th in 2016 was recorded at a local station and was used in our study to simulate the risk of waterlogging in Jiangbin Area. Total precipitation was 149.5 mm in the event. Figure 3 showed the 5-min interval time series of the rainfall.

![Figure 3. Time series of observed rainfall.](image)

2.5. Catchment surface analysis
The impervious percentage and slope affect the runoff volume on a catchment surface. High impervious rate and steep terrain usually lead to enhanced surface runoff generation. Therefore, the precise and accurate of the two parameters guarantee the hydrologic model results.

From a high resolution satellite map of Jiangbin Area, the impervious surface in this area was extracted through traditional interpretation [6] and elevations were used to interpolate the surface slope in this area using ArcGIS 10.5 (Geographic Information System) software. After the impervious
rate and slope of the whole area obtained, the weighted values were calculated for individual subcatchment by equations (1) and (2). The distribution of impervious percentage and slope of each subcatchment are shown in figure 4.

\[
W_{\text{slope}} = \frac{\sum A_i \times S_i}{\sum A_i}
\]

(1)

\[
W_{\text{impervious}} = \frac{\sum A_i \times \text{IMP}_i}{\sum A_i}
\]

(2)

where \(A\) refers to unit area, ha; \(S\) refers to slope, %; and \(\text{IMP}\) refers to impervious percentage, %.

![Figure 4](image-url)

Figure 4. Slope and impervious percentage distribution in the subcatchments.

2.6. Waterlogging standard

According to the code for design of outdoor wastewater engineering [7], a waterlogging may be identified when the maximum water depth is over 0.15 m. The value of 0.15 m was used as a criterion to evaluate the risk of waterlogging.

2.7. Model set-up

Among the branch of numerical models simulating the urban drainage system, EPA SWMM (Storm Water Management Model) is a top used one. However, SWMM is a one-dimension model and lack of the feature to simulate a two-dimension waterlogging evolution process. Computational Hydraulics International in Canada further developed a hydrologic and dynamic model on the basis of SWMM, named PCSWMM. It has the capability to couple one-dimension drainage pipes and two-dimension land surface together to simulate the flooding process and evaluate the effectiveness of drainage designs [4]. In this paper, PCSWMM was used to run the simulation of the waterlogging in the study area.

Based on the CAD drawing of the subcatchments and the pipe system, a one-dimension model was set up by PCSWMM, with totally 209 subcatchments and 333 pipes involved. The model interfaces for two scenarios are shown in figure 5. The scenarios were conducted to evaluate the performance of planned pipes on waterlogging reduction. The left panel shows the existing drainage condition with the current pipe size, while the right panel shows the design conditions with planned pipes. The impervious percentage and the slope of the subcatchments were calculated by equations mentioned above. Based on the land surface coverage characteristics, manning’s \(n\) for impervious and pervious areas were set as 0.2 and 0.5, respectively. The manning’s \(n\) value of pipes was set as 0.013-0.015 depending on the materials.

As known, the simulation range, resolution and simulation time step contribute to the model running speed, and the simulation efficiency and accuracy [4]. In order to balance the simulation...
accuracy and efficiency, the significant area near the historical flooding point was set for two-dimension simulation. Its elevations were collected and utilized to generate the DEM (Digital Elevation Model) by ArcGIS. As shown in figure 6, the red squares represent the buildings. The elevations in the two-dimension range are from 3.9 to 9.0 m which are lower than the nearby areas. Two-dimension meshes were generated with the hexagonal style and spatial resolution of 5 m. The manning’s $n$ value was set as 0.033. Totally, 29840 meshes were generated with areas varied from 6.5 to 28 m$^2$.

![Figure 6. DEM for the two-dimension simulation area.](image)

Afterwards, the one-dimension pipe system was connected with the two-dimension model through bottom orifices, which formed the coupling model.

3. Results and discussion

3.1. Precipitation analysis

It is indicated in figure 3 that the observed rainfall was very little in the initial stage, which was almost zero. Multiple rainfall peaks appeared during the rainfall process with the highest in the late stage. The total rainfall was 149.5 mm, with an average intensity of 1.6 mm/hr and a peak intensity of 34 mm/hr.

As shown in equation (3), a new generation rainfall intensity formula in Zhenjiang was developed by annual maximum value method based on the precipitation data from 1980 to 2010 in Zhenjiang [8]. The precipitation was calculated regarding different return periods as shown in table 1.
rainfall monitored in the event was equivalent to a 5-year return period design rainfall. However, the precipitation duration in the design rainfall was much shorter than the observed rainfall event, indicating a small peak intensity observed in the rainfall event.

\[
i = \frac{12.5596 + 14.6953 \log(P)}{(t + 10.6421)^{0.7436}}
\]

where \( i \) refers to rainfall intensity, mm/min; \( P \) refers to return period, year; and \( t \) refers to rainfall duration, min.

| Table 1. The design rainfall in Zhenjiang. |
|------------------------------------------|
| Return period (year) | 3 | 5 | 10 |
| Duration (hrs) | 24 | 24 | 24 |
| Rainfall volume (mm) | 125.6 | 146.6 | 175.0 |
| Peak intensity (mm/hr) | 142.4 | 166.2 | 198.4 |

3.2. Waterlogging analysis for the 1st case

In the first case, it was assumed that Jiangbin pump station was off operation in the 4-day precipitation due to unknown reasons. The final waterlogging distribution is shown in figure 7. It was noticed that the waterlogging (the maximum water depth was over 0.15 m) occurred mainly in three regions, as the intersection between Shangde Road and Gucheng Road, and its northwestern and eastern residential areas, respectively. The total area of 2.24 hectares were observed waterlogged, with the water depth peaked at 0.9 m. The simulated waterlogging range was coincident with the local flood records, indicating the simulation was reasonable and reliable.

![Figure 7. Waterlogging distribution for the 1st case.](image)

The waterlogging primarily was caused by the weak discharge capacity of the drainage system and relative lower elevations in this area. In old communities, the size of the branch pipes in the waterlogging area is very small, with diameters varied from 200-400 mm. The small size of drain pipes can’t convey the excess storm water efficiently into the main drainage system in heavy rain events. The discharged rainwater from small pipes were merged into a main pipe with a diameter of 1200 mm. The main pipe could transport water flow with a flow rate up to 0.2 m³/s during the rainfall. In addition, these areas site in the local lower point which would be easy to be waterlogged.

3.3. Waterlogging analysis for the 2nd case

In the second case, it was assumed that Jiangbin pump station had been normally operated during the rainfall. As shown in figure 8, it noticed that the waterlogging range was much smaller compared to in
the first case, with total waterlogging area of 0.50 hectares and the maximum water depth of 0.66 m. The flow rate of the main pipe reached up to 2.04 m$^3$/s. As compared with the first scenario the waterlogging situation was reduced in both areas and depth, mainly attributed to the working pump station which drains the storm water effectively into the pipe system. Therefore, the waterlogging during the rainfall event was probably caused by the improper operation of the drain pump.

![Figure 8. Waterlogging distribution for the 2nd case.](image1)

![Figure 9. Waterlogging distribution for the 3rd case.](image2)

3.4. Waterlogging analysis for the 3rd case
As analyzed in the second scenario, the historical flooding area was still waterlogged even with the pumps appropriately operated. The residential waterlog may be resulted from the weak capacity of the drainage pipe system.

To address the problem, the local urban design institute proposed a solution that conveying pipes with diameters of 1000-2800 mm were planned in the objective area to against the large rainfall event. The planned pipes were added into the model instead of existing pipes to evaluate the effectiveness to reduce the waterlog. As shown in figure 9, there was almost no ponding in the eastern residential areas with the updated pipe system. The intersections appeared surface water ponding, but the maximum water depth was below 0.15 m, not considered as waterlogging [7]. In addition, the discharge flow rate of the pipes conveying the storm water from the objective area could be up to 3.5 m$^3$/s. It indicated that the drainage capacity of the pipe system was greatly improved with the planned pipes replaced. Therefore, the implementation of planned pipes may be helpful to solve the waterlogging problem efficiently.

4. Conclusions
The waterlogging diagnosis model, developed with the hydrologic model PCSWMM, was used to investigate the possible reason of waterlogging in one of the historical flooding areas in Zhenjiang. Additionally, the model was performed to evaluate the effectiveness of planned pipes on the waterlogging problem. The conclusions would be drawn as follows:

- During the observed 4-day rainfall, the waterlogging area near the crossroads was reduced by 77% if the pump was on. Furthermore, the drainage capacity could be increased if the pump was on. It was diagnosed that the severe waterlogging during that rainfall was caused by the improper pump operation.
- The planned pipes with diameters of 1000-2800 mm could help to improve the drainage capacity effectively and to prevent the serious waterlogging in the crossroads when the pump was operated timely.
Acknowledgments
The work was supported by the research incubation fund (GCCT-KJYF-01) and the project (SINOMAST-ZDZX-2017-07) from China Machinery Engineering Corporation.

References
[1] Ahiablame L and Shakya R 2016 Modeling flood reduction effects of low impact development at a watershed scale J. Environ. Manag. 171 81-91
[2] Liu Z and Huang W X 2016 The application of SWMM on the design of urban drainage and flood prevention Sichuan Cement 4 77 (in Chinese)
[3] Liu H J, Xue L J, Yu L et al 2016 Study on urban storm-flood simulation in Tianjin Southwest Airport Economic Zone based on PCSWMM South to North Water Trans. Water Sci. Technol. 14 4-8 (in Chinese)
[4] Wu H C and Huang G R 2016 Risk assessment of urban waterlogging based on PCSWMM model Water Resour. Prot. 32 11-6 (in Chinese)
[5] Lu Y, Zhao L, Ji Z H et al 2016 The application of double drainage system of rainwater drainage computing method base on PCSWMM in the flood defending ability assessment analysis of a nuclear facility site Nucl. Safety 15 30-7 (in Chinese)
[6] Zhu A L and Lv C W 2010 Advances in the methods of extracting urban impervious surface based on remote sensing J. Anhui Normal Univ. 33 485-9 (in Chinese)
[7] National Standards of People’s Republic of China 2016 Code for design of outdoor wastewater engineering (GB50014-2006) pp 20-5 (In Chinese)
[8] Shao Y M, Hu J, Shao D N Et Al 2014 Research and Application on Design of Rainfall Hyetograph in Zhenjiang pp 67-74 (Hangzhou, China: Hangzhou Smart Drainage Engineering Co.) (in Chinese)