Coupling of SWMM With 2D Hydrodynamic Model for Simulation of Sponge City Construction Scheme

Yuyan Fan¹, Chengwen Wang ¹, *, Haijun Yu², Junhao Pan¹ and Zilu Ouyang¹

¹ School of Environment, Tsinghua University, Beijing 100084, China
² Research Center on Flood and Drought Disaster Reduction, China Institute of Water Resources and Hydropower Research, Beijing 100038, China
*Corresponding author’s e-mail: wangcw@tsinghua.edu.cn

Abstract. Sponge city is a new urban stormwater management concept proposed by China to solve the urban water environment and security problems. The stormwater management model (SWMM) is one of the most commonly used urban stormwater and sponge city simulation models. SWMM is coupled with a two-dimensional hydrodynamic model based on the finite volume method to establish a coupled 1D and 2D hydrodynamic model in this research. The coupled model can simulate the drainage pipe network, sponge measures and flood inundation at the same time. A predictor-corrector method with good stability was used in the coupled model to ensure the non-negativity of the water volume of the 2D model cell. The sponge city construction scheme for a community in Beijing was simulated and analyzed using several design rainstorm processes with different return periods based on the proposed model. It is proved that the coupling model can be applied to sponge city construction problems and sponge measures can reduce the flood inundation and the load of drainage network system by simulating the drainage conditions and ground waterlogging before and after the reconstruction of the drainage community.

1. Introduction
In recent years, China faces enormous challenges in terms of urban water security and water environment with the rapid development of socio-economic and continuous improvement of urbanization level. Sponge city, a new stormwater management concept, is proposed and designed to passively absorb, clean and use rainfall in an ecologically friendly way that reduces dangerous and polluted runoff. Urban rainstorm models are essential tools in the design, construction, management and evaluation of sponge cities. SWMM (Storm Water Management Model) model is the most widely used tool in stormwater management, drainage system design assessment, and low-impact development simulation analysis in different urban areas of the world, as well as in the construction of sponge cities in China. SWMM model is a one-dimensional model in hydrodynamic module, which cannot effectively simulate the surface waterlogging process. Therefore, coupling SWMM with a two-dimensional hydrodynamic model capable of simulating the surface flood inundation is a preferred technical route for many scholars to study the urban flooding simulation problem[1]. In this research, a two-dimensional surface hydrodynamic model is coupled with the SWMM model to more accurately simulate the urban rainstorm waterlogging and the flow interaction between surface and drainage system. The manhole (node) is assumed to function points of the flow exchange between the surface and subsurface systems. The overflow of the drainage system is adopting the value of node flooding computed by the SWMM model, while the surface back flow is computed by the weir formula. the SWMM model source code is
appropriately rewritten, so that the overflow from a node can consider the influence of surface water depth, and then SWMM model and the two-dimensional surface hydrodynamic model are coupled by a predictor-corrector method with good stability to ensure the non-negativity of the water volume of the 2D model cell. Based on the proposed model, a rainwater management model was constructed for a community in Beijing, and the sponge city construction scheme in the community was simulated and analyzed.

2. Methodology

2.1. 2D model
The 2D model for urban surface flood inundation simulation is based on two-dimensional shallow-water equations in a conservative form[2], which can be written as

\[ \begin{align*}
\frac{\partial U}{\partial t} + \frac{\partial E}{\partial x} + \frac{\partial G}{\partial y} &= S
\end{align*} \]

where \( t \) denotes time; \( x \) and \( y \) are the Cartesian coordinates; \( U \), \( E \), and \( G \) denote vectors of the conserved flow variables and fluxes in the \( x \)- and \( y \)-directions, respectively; and \( S \) is the source vector containing the bed slope source \( S_b \) and friction source \( S_f \). These vectors are expressed as

\[ \begin{align*}
U &= \begin{bmatrix} h \\ hu \\ hv \end{bmatrix}, \\
E &= \begin{bmatrix} hu \\ hu^2 + \frac{1}{2} g(h^2 - b^2) \\ hv \\ hv^2 + \frac{1}{2} g(h^2 - b^2) \end{bmatrix}, \\
G &= \begin{bmatrix} huv \\ huv \\ hv \\ hv^2 + \frac{1}{2} g(h^2 - b^2) \end{bmatrix}, \\
S &= S_h + S_f = \begin{bmatrix} 0 \\ g(h+b)S_{ox} - ghS_h \\ g(h+b)S_{oy} - ghS_f \end{bmatrix}
\end{align*} \]

where \( h \), \( u \), \( v \) and \( b \) are the water depth, depth-averaged velocity in the \( x \)- and \( y \)-directions, and bottom elevation, respectively; \( S_{ox} \) and \( S_{oy} \) are bed slopes in the \( x \)- and \( y \)-directions, respectively, which are given by

\[ S_{ax} = -\frac{\partial b}{\partial x}, \quad S_{ay} = -\frac{\partial b}{\partial y} \]

and \( S_{fx} \) and \( S_{fy} \) are friction slopes in the \( x \)- and \( y \)-directions, respectively, which are given by

\[ S_h = \frac{n^2 u \sqrt{u^2 + v^2}}{h^{4/3}}, \quad S_f = \frac{n^2 v \sqrt{u^2 + v^2}}{h^{4/3}} \]

where \( n \) is the Manning roughness coefficient.

A Godunov-type finite volume scheme with HLLC approximate Riemann solver is adopted to discretize two-dimensional shallow water equations on unstructured grid, while the MUSCL scheme[3] and two-step Runge-Kutta method[4] are applied to obtain second-order accuracy in both spatial and temporal.

2.2. SWMM model
SWMM[5] was developed by the US Environmental Protection Agency (EPA) in 1971. It is a dynamic rainfall-runoff simulation model used for single event or continuous simulation of runoff process from primarily urban areas. The newest version of the model, SWMM 5.1, is able to handle both water quantity and water quality problems. When applying the model, the study area is divided into a number of subcatchments, which are the basic objects representing a land area that collects rainwater and allows infiltration and drainage to a specific node or another subcatchment[6]. SWMM simulates surface runoff on the basis of two governing equations: the continuity equation and the Manning’s equation. Rainwater collected by the subcatchments finally drains to the network, and the flow routing in the network is calculated by solving the dynamic wave equation or its simplified form. The continuity and momentum equations of the 1D model is given by
\[
\frac{\partial Q}{\partial t} + \frac{\partial A}{\partial t} = 0
\]  

(5)

\[
gAQ \frac{\partial H}{\partial x} + \frac{\partial Q^2}{\partial x} + \frac{\partial Q}{\partial t} + gAS_f = 0
\]

(6)

where \( t \) denotes time; \( x \) is the Cartesian coordinates; \( Q \) is discharge; \( A \) is the wet cross-section area; \( H \) is the water level and water head for free surface flow and pressurised flow, respectively; \( g \) is gravity acceleration with a value of 9.81 m/s\(^2\); and the friction slope \( S_f \) is defined as:

\[
S_f = \frac{K}{gAR^{n+1}}Qp^l
\]

(7)

where \( K = gn^2 \), \( n \) is Manning coefficient; \( R \) is hydraulic radius, m; \( V \) is average flow velocity, m/s.

Based on the principle of water balance, the node equation of SWMM is given by

\[
\frac{\partial H}{\partial t} = \sum Q_i
\]

(8)

where \( H \) is node water level, m; \( Q_i \) is the inflow of each pipe, m\(^3\)/s; \( A_{ik} \) is the area of the node, m\(^2\).

2.3. Coupling strategies

In this study, the manhole function points of the flow exchange between the surface and subsurface systems. To ensure the stability of the pipe network model, the calculation of the overflow flow is determined by the drainage capacity of the pipe network, that is, the node flooding value in the SWMM model is directly used as the interaction flow, and the source code of the SWMM model is rewritten and improved to reflect the impact of surface water depth on the overflow. A predictor-corrector method with good stability was used to compute the the discharge of water flows from the ground’s surface into the sewer drainage systems in the coupled model to ensure the non-negativity of the water volume of the 2D model cell.

Firstly, the discharge is estimated using the weir equation, which is given by

\[
Q_{\text{pro}}^\text{m} = \begin{cases} 
mcCh_{\text{m}} \sqrt{2gh_{\text{m}}} & \text{if } \frac{h_{\text{m}}}{h_{\text{sat}}} \leq \frac{2}{3} \\
mCh_{\text{m}} \sqrt{2g(h_{\text{sat}} - h_{\text{m}})} & \text{if } \frac{2}{3} \leq \frac{h_{\text{m}}}{h_{\text{sat}}} \leq 1
\end{cases}
\]

(9)

where \( m \) is the discharge coefficient; \( C \) is coefficients of side contract \( C \) is the perimeter of the node; \( h_{\text{sat}} \) and \( h_{\text{m}} \) are the water depth in the node and ground surface above the top of the node, respectively; and \( Q_{\text{pro}}^\text{m} \) is the exchange discharge without correction.

Then, the discharge is corrected based on the amount of water in the cell. The correction coefficient \( \gamma_i \) is given by

\[
\gamma_i = \min \left[ 1.0, \frac{Q_{\text{out}} \Delta t + A_i \cdot h_i}{Q_{\text{out}} \Delta t} \right]
\]

(10)

where \( A_i \) and \( h_i \) are the area and depth of the cell \( i \); \( \Delta t \) is the time step; \( Q_{\text{out}} \) is the sum of all the back flow computed by Equation 9; \( Q_{\text{out}} \) is the sum of all the over flow computed by SWMM.

The discharge of the exchange water flows is computed as

\[
Q_{\text{m}} = \min \left[ \gamma_i Q_{\text{pro}}^\text{m}, Q_{\text{m}} \right]
\]

(11)

where \( Q_{\text{m}} \) is the discharge after correction; \( Q_{\text{m}} \) is the maximum exchange discharge, which is determined based on the model stability.
3. Application and discussion

The drainage community in this study is located in Beijing, China, with a total area of 151,288 m². The overall impervious ratio of the community is 73%, and flooding occurs frequently in relation to the poor drainage of the community. The sponge city construction (SCC) design for the community adopts measures such as permeable pavement (42253 m²), rain garden (3660 m²), bioretention ponds (4406 m²) and water storage facility (WSF). The volume of the WSF is about 2700 m³. The effect of the SCC design was evaluated by using the proposed coupled 1D-2D hydrodynamic model in this research. The process of the rainfall-runoff and flows in drainage system are simulated by using SWMM while the flood depth caused by the overflow of the drainage system is calculated by using the two-dimensional hydrodynamic model. The whole computational area is divided into 29242 unstructured quadrilateral elements with a total of 60670 edges. Figure 1 illustrated drainage pipe distribution and the subcatchment division of the computational domain, and the overall and local enlarged meshes are shown in Figure 2. The average area of the mesh is 4 m².

![Computational domain](image1.png)

Figure 1. Computational domain: (a) drainage pipe distribution; (b) subcatchment division.

![Mesh and terrain](image2.png)

Figure 2. Mesh and terrain of the computational domain: (a) global view; (b) partial enlarged view.

Four rainstorms with different return periods were simulated to assess the drainage capacity and waterlogging risks of the community before and after SCC. Details of pipes reached full drainage
capacity (FDC) before and after SCC are presented in Table 1, and Figure 3 illustrated the discharge hydrographs of the outfall of two rainstorms with return periods of 3 and 10 years. From the Table 1, a significant reduction in the runoff coefficient can be observed as well as the number of FDC pipe and average time of FDC. As can be seen from Figure 3, the flood area and the flood depth are very small before SCC. However, with a return period of 10 years, almost all pipes were at an FDC state and there was greater flooding in the ground surface, thereby indicating an increased risk of flooding. Flooding areas are mainly distributed in the west entrance and the northwest side of the community, which is very consistent with the historical flood events.

Figure 3. Maximum water depth of rainstorm with different return periods before sponge city construction: (a) 3 years; (b) 10 years

| Return period (year) | Total rainfall (mm) | Runoff coefficient | Number of FDC pipe | Average time of FDC (min) | Proportion of FDC pipe (%) |
|---------------------|--------------------|--------------------|--------------------|-------------------------|---------------------------|
|                     | Before | After | Before | After | Before | After | Before | After |
| 1                   | 46.5   | 0.78  | 0.36   | 81    | 18    | 5.8   | 0.6    | 42.4  | 9.4   |
| 3                   | 64.5   | 0.84  | 0.40   | 157   | 65    | 10.6  | 2.57   | 82.2  | 34    |
| 5                   | 73.8   | 0.84  | 0.42   | 177   | 80    | 12.7  | 3.95   | 92.7  | 41.9  |
| 10                  | 84.2   | 0.87  | 0.44   | 186   | 125   | 15.7  | 7.43   | 97.4  | 65.4  |

Figure 4 illustrated the history of discharge change process at downstream outfall of when the community encountered the rainstorms with return periods of 3 and 10 years, respectively. The maximum flow is significantly reduced after SCC, and the discharges in the first hour were 0 due to the use of WSF, which can greatly reduce the total amount of water to the external pipes, thereby reducing the pressure of drainage system outside the community.
Figure 4. History of discharge change process at downstream outfall: (a) 3 years; (b) 10 years

The flood depth is very small when rains with return periods less than 10 years occurred after the SCC, thus the design rainstorm with return periods of 50 years was used to evaluate the effect of the SPC. Figure 5 illustrated the discharge hydrographs of the outfall and maximum water depth distribution. According to the statistical results, the water depth is less than 0.2 m in 72.2% of the submerged areas, and all the water depth is within 0.3 m except for very few low places. Generally speaking, the community after SPC can cope with the rainstorm with a return period of 50 years.

Figure 5. Results of rainstorm with a return period of 50 years: (a) history of discharge change process at downstream outfall; (b) maximum water depth

4. Conclusions
SWMM is coupled with a two-dimensional hydrodynamic model based on a predictor-corrector method with good stability. The following conclusions can be drawn.

1) The effect of sponge city construction was evaluated by using the proposed coupled 1D-2D hydrodynamic model, and the proposed model was found to be applicable in the evaluation of sponge city construction and the linking algorithm is reasonable and feasible.

2) Sponge measures at the community level can effectively reduce the pressure of the drainage network and the phenomenon of waterlogging, and the water storage facility can reduce the total amount of water to the external pipes, thereby reducing the pressure of drainage system outside the community.
Acknowledgments
The research reported herein was funded by National Key S & T Special Project (2018ZX07110-008) and the Beijing Natural Science Foundation (No. 8181001).

References
[1] LIANG D, FALCONER R A, LIN B. (2007) Linking one- and two-dimensional models for free surface flows. Proceedings of the Institution of Civil Engineers - Water Management, 160(3): 145-151.
[2] YU H J, HUANG G R, WU C H. (2015) Efficient Finite-Volume Model for Shallow-Water Flows Using an Implicit Dual Time-Stepping Method. Journal of Hydraulic Engineering, 141(6): 1-12.
[3] TORO E. (2001) Shock-capturing methods for free-surface shallow flows. John Wiley & Sons.
[4] VAN LEER B. (1979) Towards the ultimate conservative difference scheme V: A second order sequel to Godunov’s method. Journal of Computational Physics, 32(1): 101-136.
[5] ROSSMAN L A. (2010) Storm water management model user’s manual, version 5.0. US EPA.
[6] YU H J, HUANG G R, WU C H. (2014) Application of the stormwater management model to a piedmont city: a case study of Jinan City, China. Water Science and Technology, 70(5): 858-864.