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A two-dimensional hydrodynamic urban flood model based on equivalent drainage of manholes

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ABSTRACT

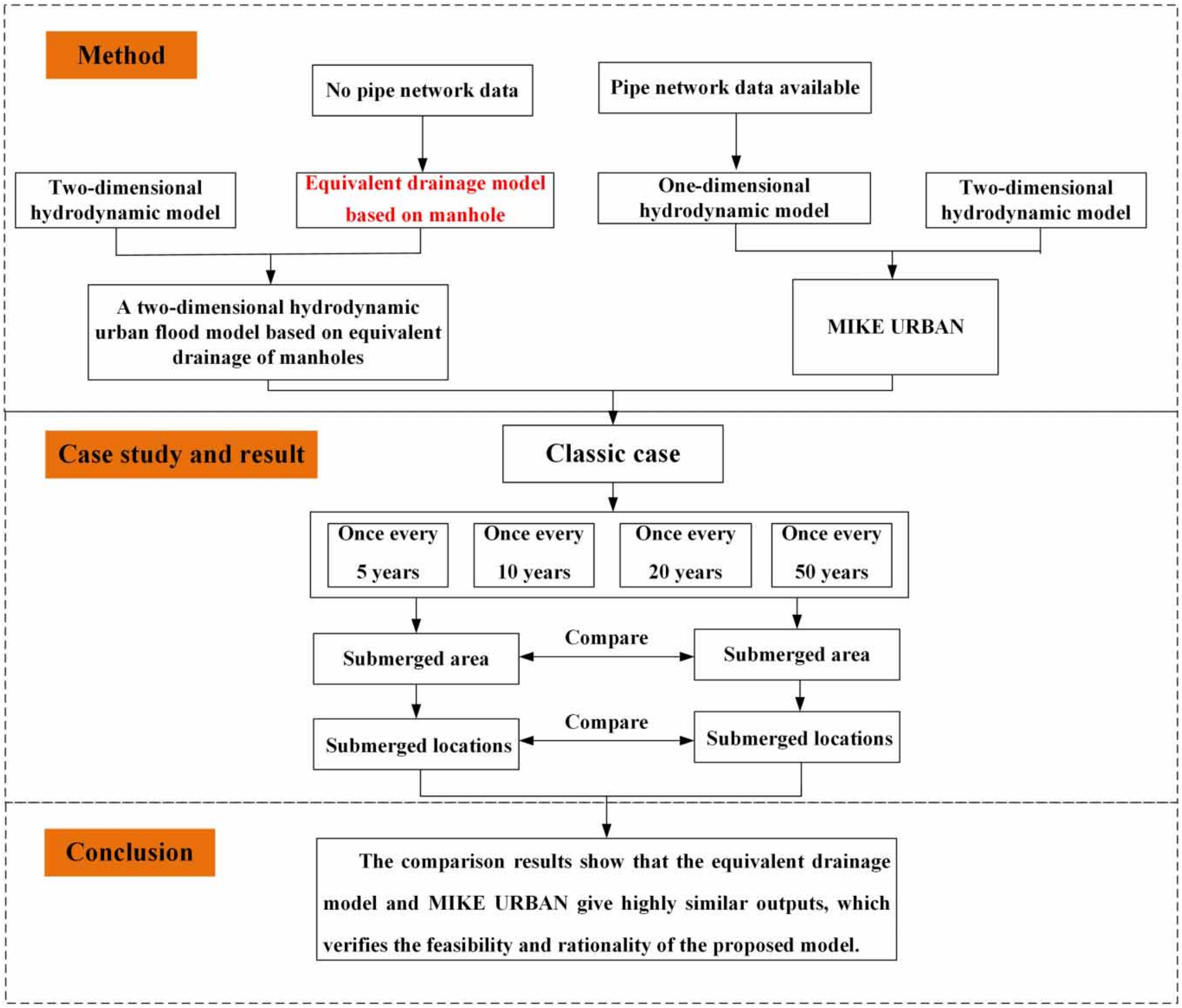
Numerical simulations of urban flood events are of great significance in flood control and disaster reduction. An important part of these numerical investigations concerns drainage, which is crucial to the accuracy of the simulation results. To overcome the difficulty of obtaining underground pipe network data and improve the traditional equivalent drainage simulation method, an equivalent drainage model based on manholes is proposed, to simulate urban flooding based on a two-dimensional hydrodynamic model. The new model is applied to a classic case and the simulation results are compared with those from the MIKE URBAN model to verify the simulation accuracy of the proposed formulation. The submerged areas given by the two models are compared under different rainfall conditions, with an average relative error of 6%. The differences in water depths at various nodes are statistically analyzed, and the average Nash–Sutcliffe efficiency and average root mean square error are found to be 96% and 0.03 m, respectively. The results of this research provide effective urban flood simulation in areas lacking pipe network data and have important significance for promoting the practical application of refined numerical simulations of urban flooding.

Key words: equivalent drainage method, manhole, MIKE URBAN, two-dimensional hydrodynamic model, urban flooding

HIGHLIGHTS

- The equivalent drainage model based on manholes was proposed.
- This overcomes the problem of missing pipe network data in urban flood simulation.
- An urban flood model based on two-dimensional hydrodynamic was coupling established.
- Compared with MIKE URBAN, the applicability of the equivalent drainage model was verified.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Global climate change and rapid urbanization are increasing the prevalence of extreme climate phenomena, and frequent urban flood disasters cause huge economic losses and serious casualties (Ma *et al.* 2018; Xu *et al.* 2020a; Agonafir *et al.* 2023). At present, numerical simulations are vital in studying urban flooding, and accurate reproductions of the development of urban flooding based on numerical results are of great significance for urban construction and stormwater management (Wang *et al.* 2010; Moon *et al.* 2023). Insufficient drainage capacity is an important cause of urban flooding, and so drainage simulations are an indispensable part of the associated numerical simulations. Reasonable generalization and modeling of urban drainage is of great significance for improving the accuracy of urban flood simulations (Leitão *et al.* 2017).

Drainage simulations in hydrodynamic numerical models of urban flooding can be mainly divided into two categories. One approach is to directly simulate the runoff in the drainage pipeline network by solving the one-dimensional Saint–Venant equation, representing the surface inundation according to the overflow from the pipeline, or to accurately reflect the surface flood flow state by coupling with a two-dimensional algorithm (Cong *et al.* 2006; Fan *et al.* 2017). The second approach involves formulating an equivalent drainage scheme that does not require modeling of the pipe network system, with the drainage effect reflected through other generalized forms (Chen *et al.* 2015; Wang *et al.* 2018a; Luan *et al.* 2021). The Storm water management model (SWMM) and MIKE URBAN models include one-dimensional pipe network calculation modules that simplify or completely solve the Saint–Venant equations. This allows the runoff process of the drainage pipe network system to be calculated before simulating the surface water in combination with the surface hydrological module (runoff generation and confluence) (Li *et al.* 2018). Zhao *et al.* (2009) built a rainwater pipe network model based on real surveying and mapping data and used SWMM to simulate and analyze the service performance of regional rainwater drainage systems. One- and two-dimensional coupled hydrodynamic models involve complex hydrodynamic processes with strong physical support for both the surface confluence (two-dimensional) and underground pipe network (one-dimensional), resulting in highly accurate urban flood models (Xu *et al.* 2020b; Luo *et al.* 2022). Li *et al.* (2017) used the MIKE FLOOD software to couple one- and two-dimensional models in simulating the water depth of waterlogged and inundated areas under different rainfall recurrence periods based on pipe network information and topographic data. Leandro & Martins (2016) proposed a method of linking a two-dimensional surface flow model with the SWMM 5 stormwater channel model, enabling simulations of the two-way interaction between the two models, and verified the algorithm using a real case study.

Hydrodynamic models of pipe networks require significant amounts of pipe network data. Unfortunately, such data are often difficult to obtain. Moreover, the computational efficiency of one- and two-dimensional coupled models is low, and urban extreme rainstorms are generally short-duration events. Thus, researchers face the dual problems of data loss and low simulation efficiency of coupled models for large-scale urban area simulations. Therefore, when simulating urban flooding, the one-dimensional model is often replaced by an equivalent drainage mode in the two-dimensional hydrodynamic model to achieve a similar water loss effect to that of drainage via the pipe network (Bradbrook 2006). For example, in many studies, the discharge of the urban pipe network is distributed throughout the simulation area, and the water quantity is directly deducted from each calculation unit (Yu & Coulthard 2015; Yin *et al.* 2016). Alternatively, the method of deducting rainfall or continuous infiltration can be adopted to realize the water loss in the model, with the decrease in rainfall or increase in soil infiltration regarded as the pipe network displacement (Wang *et al.* 2018b). These two methods deviate from the actual operation mechanism of pipeline drainage; specifically, they only consider the displacement of the pipe network system and average deduction of surface water, while ignoring the location of drainage points and changes in displacement. In the actual situation, the pipeline and the ground are connected by manholes, and the accumulated water on the ground flows into the manholes and enters the pipeline to be discharged (Chang *et al.* 2018). In the one- and two-dimensional coupled model, the manholes are typically used as interaction points between the one- and two-dimensional models for water exchange. Xing *et al.* (2022) simulated drainage loss in a hydrodynamic model by deducting a constant inflow from inlets and manholes. However, in the actual situation, the displacement of inlets and manholes is not constant but is related to the confluence of the ground and the water accumulation in the underground pipeline. Therefore, the previous equivalent drainage model is either too simple, only considering the water loss; or the more advanced equivalent drainage model also only focuses on the location of drainage, but ignores that displacement is a dynamic process affected by flood conditions.

Aiming at the difficulty of obtaining underground pipe network data and the low computational efficiency of one- and two-dimensional coupled models in urban flood simulation, an equivalent drainage model based on a manhole is proposed in this paper. The model corrects the problem of insufficient consideration of drainage location and drainage process in traditional equivalent drainage simulation, so as to improve simulation accuracy and computational efficiency. The equivalent drainage model based on a manhole takes the manhole as the location of drainage and uses the displacement formula to calculate the displacement volume, to simulate the actual drainage mechanism, which has a certain physical basis. The calculation principle is simple and the calculation efficiency is improved. Compared with the simulation results of the classical one- and two-dimensional coupled models, the rationality of the equivalent drainage model proposed in this paper is verified.

2. METHOD

In this study, the runoff curve method is used to calculate the flow-producing process of rainfall on the surface. The two-dimensional shallow water equation is used as the control equation for simulating the confluence process of surface runoff, and the displacement of a manhole is used as the source term of the two-dimensional hydrodynamic equation for drainage calculations. The displacement of the manhole is determined using the combined formula for weir flow and orifice flow and the drainage capacity of the pipe network system.

2.1. Flow production calculation

The runoff calculation adopts the runoff curve method (Zhang *et al.* 2022). The runoff curve method makes two assumptions: (1) the ratio of direct surface runoff to potential maximum surface runoff is equal to the ratio of infiltration to potential maximum retention and (2) the initial loss is proportional to the potential maximum retention. The water balance equation of the rainfall process is

$$\begin{aligned} &P = I_a + F + Q \\ &\frac{Q}{P - I_a} = F/S \\ &I_a = \lambda S \end{aligned} \tag{1}$$

where P is the total rainfall, mm; I_a is the initial loss before the runoff, mm; F is the total loss during the infiltration period, mm; Q is the surface runoff, mm; S is the potential maximum retention, mm; and λ is the initial loss rate.

Mockus (1949) deduced that $I_a = 0.2S$ based on a large set of measured data, and converted Equation (1) into a rainfall–runoff relationship requiring only one parameter, written as

$$Q = \begin{cases} \dfrac{(P - 0.2\,S)^2}{P + 0.8\,S} & P \geq 0.2S \\ 0 & P \leq 0.2S \end{cases} \tag{2}$$

where S is the curve number, represented by the dimensionless coefficient CN according to Ponce & Hawkins (1996)

$$S = \frac{25,400}{\mathrm{CN}} - 254 \quad 0 \leq \mathrm{CN} \leq 100 \tag{3}$$

The CN value is determined according to the rainfall–runoff relationship diagram derived from the annual maximum rainfall and the resulting runoff. Thus, different land use types correspond to different CN values. According to the upper, lower, and median values of CN in Part IV Hydrology (NEH-4) of the 'National Engineering Handbook', the proposed model uses an empirical value of CN that regulates underground potential retention (Soil Conservation Service, U.S. Department of Agriculture (USDA-SCS) 1971).

2.2. Confluence calculation based on two-dimensional shallow water equation

The two-dimensional shallow water equation is used as the governing equation for calculating the surface confluence. As the core of the entire urban flood model, the two-dimensional shallow water equation integrates flow generation, confluence, and drainage into a single expression. The conservative format of the two-dimensional shallow water equation includes a continuity equation and momentum equation and can be expressed as

$$\frac{\partial U}{\partial t} + \frac{\partial E(U)}{\partial x} + \frac{\partial F(U)}{\partial y} = R + S \tag{4}$$

$$U = \begin{bmatrix} h \\ hu \\ hv \end{bmatrix},\ E(U) = \begin{bmatrix} hu \\ hu^2 + \dfrac{gh^2}{2} \\ huv \end{bmatrix}, F(U) = \begin{bmatrix} hv \\ huv \\ hv^2 + \dfrac{gh^2}{2} \end{bmatrix},\ S = \begin{bmatrix} 0 \\ gh(S_{ox} + S_{fx}) \\ gh(S_{oy} + S_{fy}) \end{bmatrix}$$

$$R = \begin{bmatrix} r - d \\ 0 \\ 0 \end{bmatrix}$$

$$S_{ox} = -\frac{\partial Z_b}{\partial x}, \quad S_{oy} = -\frac{\partial Z_b}{\partial y}, \quad S_{fx} = -\frac{n^2 u\sqrt{u^2 + v^2}}{h^{\frac{4}{3}}}, \quad S_{fy} = -\frac{n^2 v\sqrt{u^2 + v^2}}{h^{\frac{4}{3}}}$$

where U is the conservative vector, E is the flux in the x-direction, F is the flux in the y-direction, and S and R are the source term vectors. S_{ox} and S_{oy} are the source terms of the bottom slope in the x- and y-directions, and S_{fx} and S_{fy} are the friction gradient in the x- and y-directions, respectively. R is the source term representing runoff (r) and drainage (d); u and v are the average velocity components integrated along the water depth in the x- and y-directions, respectively, h is the water depth, g is the gravitational acceleration, Z_b is the underground elevation, and n is the Manning coefficient.

The element-centered method is chosen for the spatial discretization of the control body, and the explicit finite volume method is used to solve the problem. Given the Riemannian discontinuity on both sides of the element interface, the Roe scheme is used to solve the element normal flux. The source terms can be divided into two categories: for topographic conditions, the source term has components relating to the bottom slope and friction; for the water balance in the flood process, the source terms include flow production and drainage. The bottom slope feature decomposition method is used to deal with the bottom slope source term, and the interface flux is balanced using an upwind treatment. The discrete friction source term has an explicit formulation. The runoff source term comes from the surface runoff calculated by the runoff generation module, and the drainage source term is the displacement calculated according to the equivalent drainage method.

2.3. Equivalent drainage method based on manholes

Image data of the study area allow the locations of manholes to be identified. Thus, a grid containing the manholes can be determined on the corresponding two-dimensional grid. The grid is used to calculate the drainage source term, which is determined by the actual displacement of the manholes.

2.3.1. Displacement formula

The coupling between one- and two-dimensional models is usually performed by combining weir flow and orifice flow formulas (Russo *et al.* 2015; Jang *et al.* 2018). The weir flow formula is

$$Q = c_{\mathrm{w}} W_{\mathrm{p}} \sqrt{2g} H^{1.5} \tag{5}$$

where Q is the displacement, m³/s; c_{w} is the flow coefficient of weir flow; W_{p} is the wetted perimeter, m; g is the acceleration of gravity, m/s^2; H is the water head of the weir, where $H = h + \alpha v^2/2g$ and h is the water depth of the weir crest crossing section, m; v is the average flow velocity of the weir crest crossing section, m/s; and α is the kinetic energy correction factor. The orifice flow formula is given by

$$Q = c_{\mathrm{o}} A \sqrt{2gH_0} \tag{6}$$

where c_{o} is the flow coefficient of orifice flow; A is the section area of the orifice outflow, m^2; H_0 is the water head, where $H_0 = h_0 + \alpha_0 v_0^2/2g$ and h_0 is the elevation difference between the upper and lower water surfaces of the orifice flow, m; v_0 is the velocity of the upstream incoming flow, m/s; and α_0 is the correction factor.

The drainage process of surface water from a manhole mainly consists of weir flow and orifice flow. It is difficult to convert between the two flow modes, and the individual weir flow or orifice flow formula cannot adapt to the drainage process. However, the displacement formulas of the two flow modes have much in common and can be combined. According to the weir flow and orifice flow formulas, the displacement of both flow modes is mainly related to the velocity and water depth. Combining the information available in the two-dimensional water dynamic model, the unified displacement formula is written as

$$Q = c * u^a * A * (gh)^b \tag{7}$$

where c is the displacement coefficient; u is the flow velocity of the manhole flow, m/s; h is the depth of the manhole flow, m; A is the area of the manhole, m^2; and a, b are correction coefficients. The coefficients a, b, and c can be adjusted according to the actual situation.

2.3.2. Calculation of manhole displacement

The displacement capacity of a system is the maximum displacement of the urban pipe network system (Zhou *et al.* 2017). When the sum of the displacement through all manholes in the region is less than the drainage capacity of the system, the displacement of the manholes is not hindered. In this case, the displacement value of the manholes is calculated according to the displacement formula. When the sum of the displacement of all manholes in the region is greater than the drainage capacity of the system, the displacement of each manhole is limited and should be reduced according to the drainage capacity.

The actual displacement of a manhole is given by

$$q_{\mathrm{a}} = \begin{cases} q_{\mathrm{f}i} & Q_{\mathrm{all}} \le Q_{\max} \\ R_{\mathrm{f}} * q_{\mathrm{f}i} & Q_{\mathrm{all}} > Q_{\max} \end{cases} \tag{8}$$

$$Q_{\mathrm{all}} = \sum_{i=1}^{n} q_{\mathrm{f}i} \quad R_{\mathrm{f}} = \frac{Q_{\max}}{Q_{\mathrm{all}}}$$

where q_{a} is the actual displacement of the manhole, m³/s; $q_{\mathrm{f}i}$ is the value calculated by the manhole displacement formula, m³/s; and n is the total number of manholes in the study area. Q_{all} is the sum of the displacements of all manholes in the study area, m³/s; R_{f} is the reduction factor; and $Q_{\max}$ is the drainage capacity of the study area, m³/s.

2.4. Model verification

MIKE URBAN is a relatively mature urban flood model that has been widely used (Tong *et al.* 2019). This model is mainly applied to simulations of one-dimensional pipe network systems, providing accurate simulations of the flow inside the pipe network (Xu 2021). MIKE URBAN can invoke MIKE 21 to simulate the flow of the two-dimensional surface and is coupled with the one-dimensional MOUSE engine. This enables full one- and two-dimensional hydrodynamic simulations. Therefore, the results of MIKE URBAN for the two-dimensional surface are taken as the ground truth and used to verify the rationality of the equivalent drainage model based on manholes. MIKE URBAN uses pipe network data to construct a one-dimensional model in the drainage part, whereas the proposed equivalent drainage model uses an equivalent drainage algorithm. The two models are consistent in other parts of the flood simulation process, and so the rationality of replacing the one-dimensional model with the equivalent algorithm based on manholes can be verified by comparing their results.

Different indexes are used to compare the results of the equivalent drainage model and MIKE URBAN. The submerged area and submerged location under different water depth thresholds are compared in terms of the relative error between the two models ($\mathrm{RE_a}$), given by Equation (9). The water depth difference at each node in the study area is compared in terms of the root-mean square error (RMSE_h) and Nash–Sutcliffe efficiency coefficient (NSE_h), as given by Equations (10) and (11), respectively (Yin *et al.* 2022; Cheng *et al.* 2023).

$$\mathrm{RE_a} = (\mathrm{Area_m} - \mathrm{Area_c})/\mathrm{Area_m} \tag{9}$$

where $\mathrm{Area_c}$ is the submerged area calculated by the equivalent drainage model and $\mathrm{Area_m}$ is the submerged area calculated by the MIKE URBAN model.

$$\mathrm{RMSE}_h = \sqrt{\frac{\sum_{i=1}^{n} (h_{\mathrm{m}i} - h_{\mathrm{c}i})^2}{n}} \tag{10}$$

where $h_{\mathrm{m}i}$ is the water depth of node i calculated by the MIKE URBAN model; $h_{\mathrm{c}i}$ is the water depth of node i calculated by the equivalent drainage mode algorithm based on manholes; and n is the total number of nodes in the study area.

$$\mathrm{NSE}_h = 1 - \frac{\sum_{i=1}^{n} (h_{\mathrm{m}i} - h_{\mathrm{c}i})^2}{\sum_{i=1}^{n} (h_{\mathrm{m}i} - h_{\mathrm{m}})^2} \tag{11}$$

where h_{m} is the average water depth of all nodes calculated by the MIKE URBAN model.

3. CASE STUDY

3.1. Study area and data

The case study is based on the 2D Overland Flow example available in the MIKE URBAN software. The modeling data mainly include a digital elevation model of the study area, pipe network data, and rainfall conditions. The pipe network data include the position and size of the manholes, the pipe layout, and the pipe diameters. The study area covers 36 ha of very undulating terrain over which the elevation ranges from 4 to 72 m, with an average elevation of 28 m. There are 133 manholes in the study area, a total of 133 pipes (pipe diameters of 0.15–1.2 m), and 1 drainage outlet. The terrain of the study area and the specific distribution of the pipe network are shown in Figure 1.

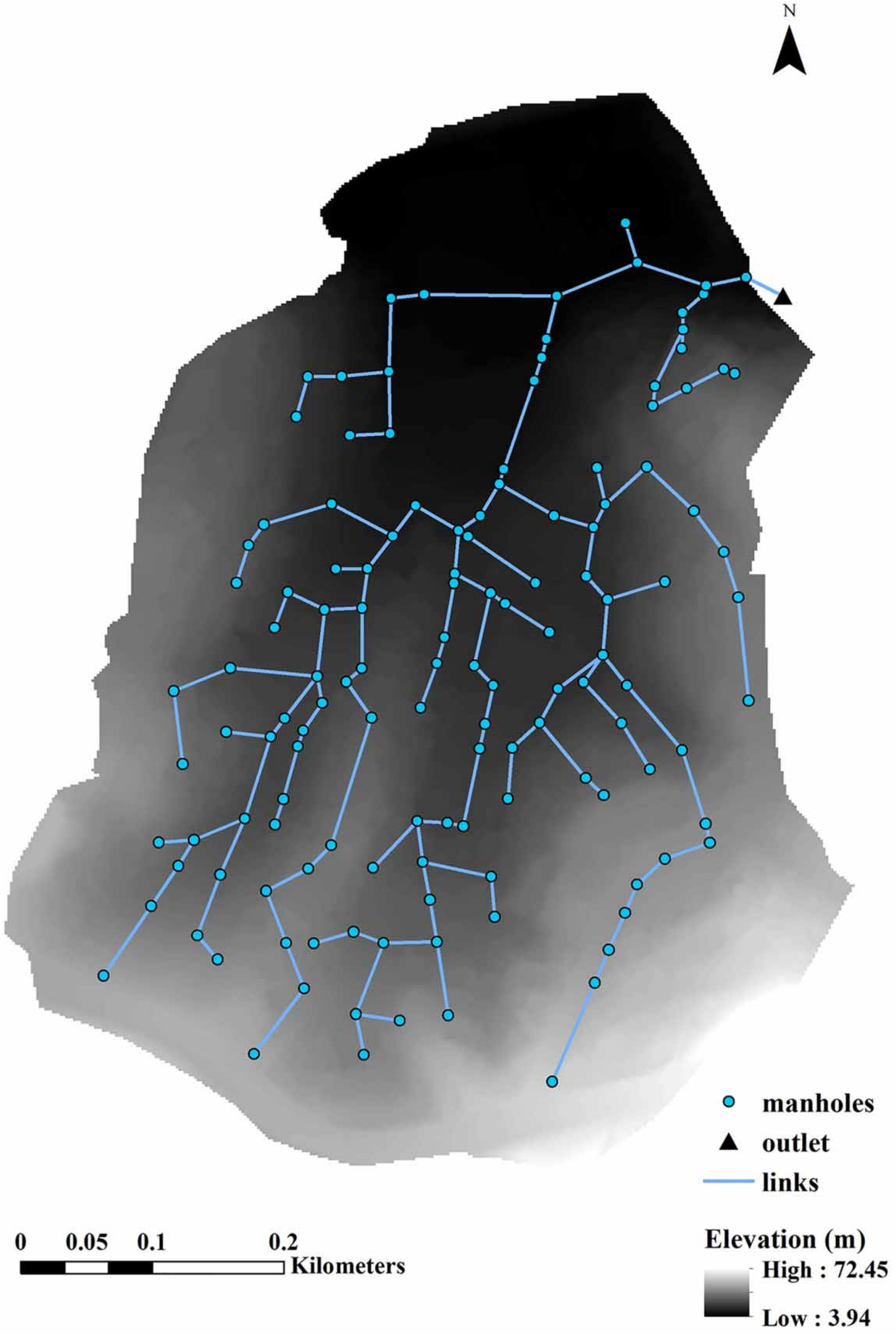


Figure 1 | Overview of the study area.

3.2. Model setting and calculation

The rainfall conditions were designed according to the Beijing rainstorm formula (Yuan *et al.* 2020):

$$q = \frac{11.157*(1 + 0.906lg^{P})}{(t + 11.665)^{0.729}} \tag{12}$$

where q is rainfall intensity, mm/min; P is the recurrence period, a; and t is the duration of rainfall, min.

According to the rainstorm formula, four rainfall processes that can be expected to occur once every 5 years (5a), once every 10 years (10a), once every 20 years (20a), and once every 50 years (50a) were obtained. Each rainfall process lasts for 2 h. The rainfall process of each recurrence period is generated by the Chicago rainfall pattern. The accumulated rainfall per hour is obtained according to the rainfall process, and then the constant rainfall intensity of the first and second hours is obtained by equalization of the accumulated rainfall per hour, as shown in Figure 2.

The setup of the equivalent drainage model is consistent with that of the MIKE URBAN model. The boundary of the model is a fixed wall, and the rainfall is evenly distributed in space. The time step is 0.1 s, the simulation duration is 4 h (with rainfall only occurring in the first 2 h), and the roughness coefficient is 0.03. The drainage capacity in the equivalent drainage model is determined by the maximum displacement of the displacement port simulated by the MIKE URBAN model, which is 0.105 m^3/s.

Taking the calculation results given by MIKE URBAN in the 5a scenario as the standard, the coefficients in the manhole displacement formula were adjusted to determine suitable parameters for the study area. The validity of the model was verified for the three rainfall conditions of 10a, 20a, and 50a.

4. RESULTS

4.1. Comparison of submerged area

Taking water depths of 0.05, 0.1, 0.2, 0.5, and 1 m as the submersion thresholds, the submerged areas calculated by MIKE URBAN and the equivalent drainage model based on manholes at the four moments of 1, 2, 3, and 4 h are compared. Under the four recurrence periods, the differences in the submerged areas given by MIKE URBAN and the equivalent drainage model are shown in Figure 3. The relative errors between the two models are listed in Table 1.

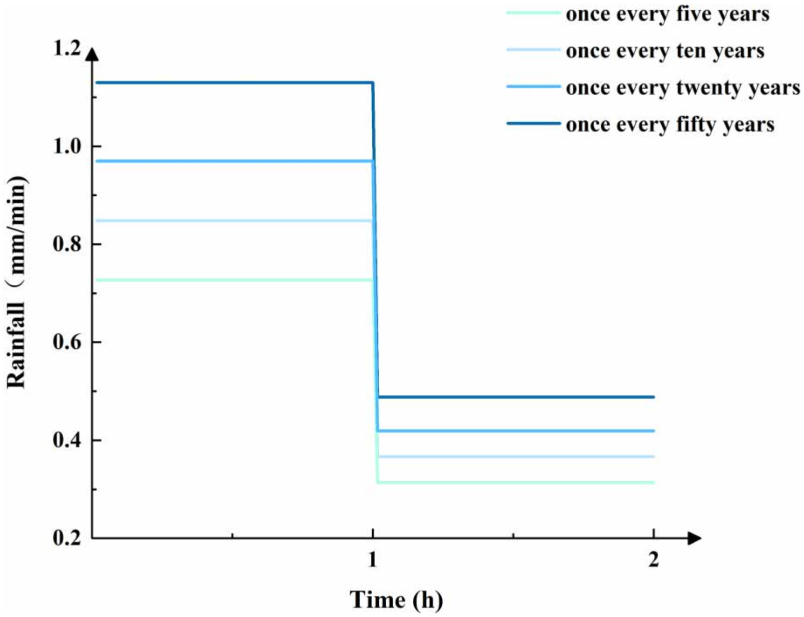


Figure 2 | Rainfall conditions in different recurrence periods.

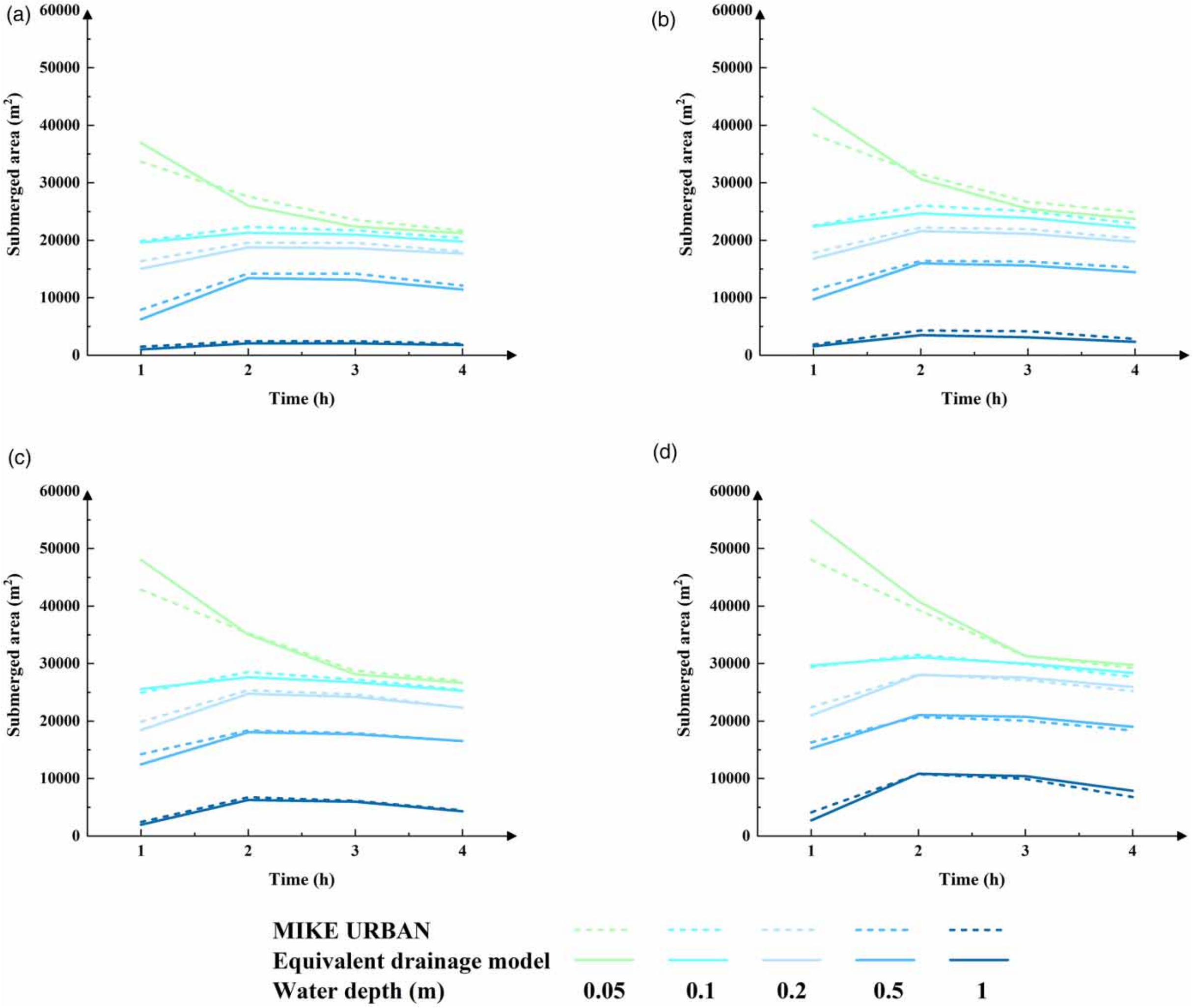


Figure 3 | Submerged area given by MIKE URBAN and equivalent drainage model: (a) once every 5 years; (b) once every 10 years; (c) once every 20 years; (d) once every 50 years.

Figure 3 shows that the two models are in good agreement regarding the submerged areas under different water depths for all four recurrence periods. In Table 1, RE_a for the different water depth thresholds is generally low, and the average relative error is 8% for 5a, 8% for 10a, 4% for 20a, and 6% for 50a. Analyzing the total relative errors in the submerged area under different recurrence periods, the simulation results for 20a are the closest to those of the MIKE URBAN model. This scenario gives the smallest overall average error and small relative errors for the different submersion depths. Additionally, the distribution of RE_a with different water depths exhibits the greatest level of consistency.

The submerged area above 0.05 m reaches the maximum at 1 h, when the absolute relative error is the largest, and the maximum relative error of −14% occurs in the 50a case. The areas submerged by water depths above 0.1, 0.2, 0.5, and 1 m reach the maximum when the rainfall ends at 2 h, and the maximum relative errors of each water depth at this time are 5% (10a), 4% (5a), 6% (5a), and 19% (10a). From the perspective of submerged water depth, the average RE_a values with water depths above 0.05, 0.1, 0.2, 0.5, and 1 m are 5, 2, 4, 6, and 15%, respectively. Considering the RE_a values across all recurrence periods, the smallest error occurs for a water depth of 0.1 m.

4.2. Comparison of submerged locations

The simulation results indicate that the maximum submersion range occurs at 1 h. The locations submerged by water at 1 h according to MIKE URBAN and the equivalent drainage model under the four recurrence periods are shown in Figure 4.

Table 1 | Relative error of submerged area between MIKE URBAN and equivalent drainage model

Water depth (m)/time(h)	0.05	0.1	0.2	0.5	1	The recurrence period
1:00	−0.0975	0.0113	0.0821	0.2141	0.3118	5a
2:00	0.0574	0.0444	0.0416	0.0552	0.1569	
3:00	0.0509	0.0353	0.0475	0.0744	0.1569	
4:00	0.0100	0.0299	0.0195	0.0555	0.0887	
Average value	0.0539	0.0302	0.0477	0.0998	0.1786	
1:00	−0.1192	0.0057	0.0574	0.1410	0.1638	10a
2:00	0.0294	0.0528	0.0281	0.0254	0.1933	
3:00	0.0456	0.0460	0.0365	0.0422	0.2529	
4:00	−0.0045	0.0314	0.0291	0.0514	0.1808	
Average value	0.0497	0.0340	0.0378	0.0650	0.1977	
1:00	−0.1214	−0.0244	0.0725	0.1249	0.1908	20a
2:00	0.0073	0.0314	0.0240	0.0166	0.0665	
3:00	0.0206	0.0176	0.0175	0.0089	0.0261	
4:00	−0.0268	0.0082	−0.0007	−0.0029	0.0357	
Average value	0.0440	0.0204	0.0287	0.0383	0.0798	
1:00	−0.1418	−0.0093	0.0629	0.0648	0.3424	50a
2:00	−0.0374	0.0137	0.0034	−0.0170	−0.0045	
3:00	0.0005	−0.0059	−0.0147	−0.0335	−0.0466	
4:00	−0.0524	−0.0249	−0.0273	−0.0357	−0.1631	
Average value	0.0580	0.0134	0.0271	0.0378	0.1392	

Taking the case of 10a as an example, the relationship between the submersion range and the location of the pipe network system at 1 h is shown in Figure 5. At 1 h, the equivalent drainage model is generally consistent with the submersion locations given by MIKE URBAN.

To further analyze the difference in submerged locations between the two models, the differences in water depth at various nodes are statistically analyzed. A total of 22,728 nodes are evenly distributed in the study area. The NSE_h and RMSE_h of the water depth results simulated by the two models at different times under the four rainfall conditions are listed in Table 2. The proposed model performs well in terms of both NSE_h and RMSE_h, with the average NSE_h exceeding 85% for all four recurrence periods. The lowest average NSE_h value of 88% occurs for scenario 5a, whereas the maximum of almost 99% is achieved in the case of 50a. The average RMSE_h is 0.055 m in scenario 5a and is less than 0.03 m in the other cases. The difference in the water depth distribution simulated by the two models is small, and the degree of fitting is high. NSE_h increases with increasing recurrence period. RMSE_h is largest for the 5a scenario, and there is little difference with other recurrence periods. In conclusion, a longer recurrence period produces a better agreement in the water depth distributions of the equivalent drainage model and MIKE URBAN.

5. DISCUSSION

5.1. The application of the model

The manhole information used in the proposed equivalent drainage model can be extracted from high-definition image data, which overcomes the difficulty of obtaining pipe network data. Even if sufficient pipe network data are available and a one-dimensional pipe network model can be established, the computational efficiency of coupling this to a two-dimensional model for large-scale urban flood simulations may be infeasible. At the same time, the construction of one- and two-dimensional coupled models covering large-scale areas is difficult, and the numerical simulations are prone to instability. Sometimes, one-dimensional models can be built to simulate urban flooding, but cannot simulate the movement of flood water on the surface, which is very important for the judgement of flood risk.

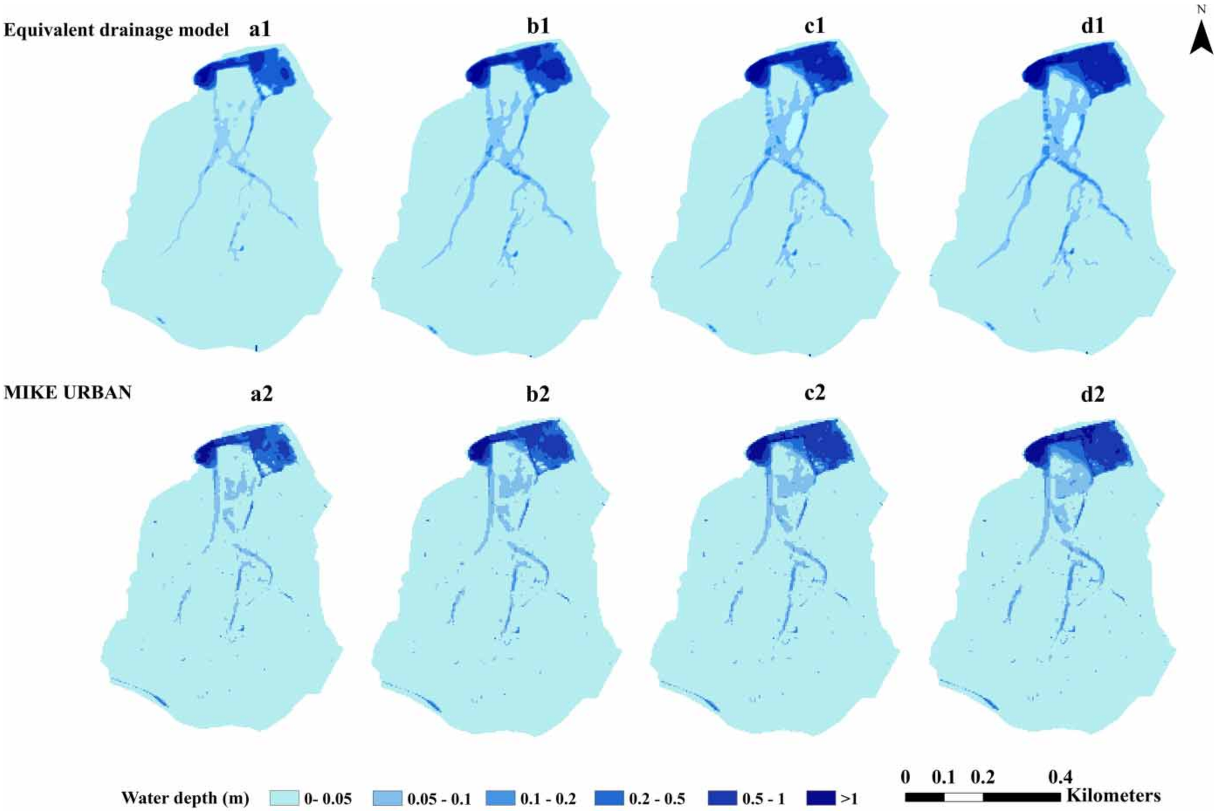


Figure 4 | Submersion locations at 1 h in equivalent drainage model: (a1) once every 5 years, (b1) once every 10 years, (c1) once every 20 years, (d1) once every 50 years; submersion locations at 1 h in MIKE URBAN: (a2) once every 5 years, (b2) once every 10 years, (c2) once every 20 years, (d2) once every 50 years.

The calculation method of the equivalent drainage model in this paper is simple, and Compute Unified Device Architecture (CUDA) parallel technology is used to greatly improve the calculation rate. Taking the 20a scheme in this paper as an example, it takes only 18 s to simulate 4 h (the first 2 h of rain) using the equivalent drainage model, and 13 min for the one- and two-dimensional coupled simulation using the MIKE URBAN model. Both models were simulated on the same device, a win11 system with a 13th Gen Intel(R) Core(TM) i7-13700 processor on the CPU and NVIDA GeForce RTX 4080 on the GPU. Unlike previous oversimplified equivalent drainage models, the proposed model broadly reflects the actual drainage mechanism. The model combines the two-dimensional hydrodynamic model and the drainage formula of manholes, thus having hydraulic support, and the comparison results against MIKE URBAN verify that the model achieves good simulation accuracy.

This paper tested other equivalent drainage methods, which did not use the displacement formula to calculate the displacement of the manhole, but directly gave each manhole a fixed displacement (drainage capacity divided by the total number of manholes). It is found that the accuracy of the simulation results is lower than that of the equivalent drainage model in this paper. Taking a case in 20a as an example, the average NSE_h and average RMSE_h of the node water depth between the other equivalent drainage algorithms and the MIKE URBAN model are 0.85 and 0.066, respectively, and the fitting degree is lower than the equivalent drainage model in this paper.

The equivalent drainage model based on manholes reflects that the surface flood discharge exceeds the bearing capacity of the pipeline system by reducing the displacement, and the actual displacement is less than the displacement calculated by the displacement formula. However, in actual life, when the drainage pressure of the pipeline system is too large, the phenomenon of water overflow from the pipeline to the ground may even occur. The one-dimensional pipeline model can simulate the overflow phenomenon, while the equivalent drainage model based on manholes cannot reflect the phenomenon due to the lack of hydraulic support of the underground pipeline.

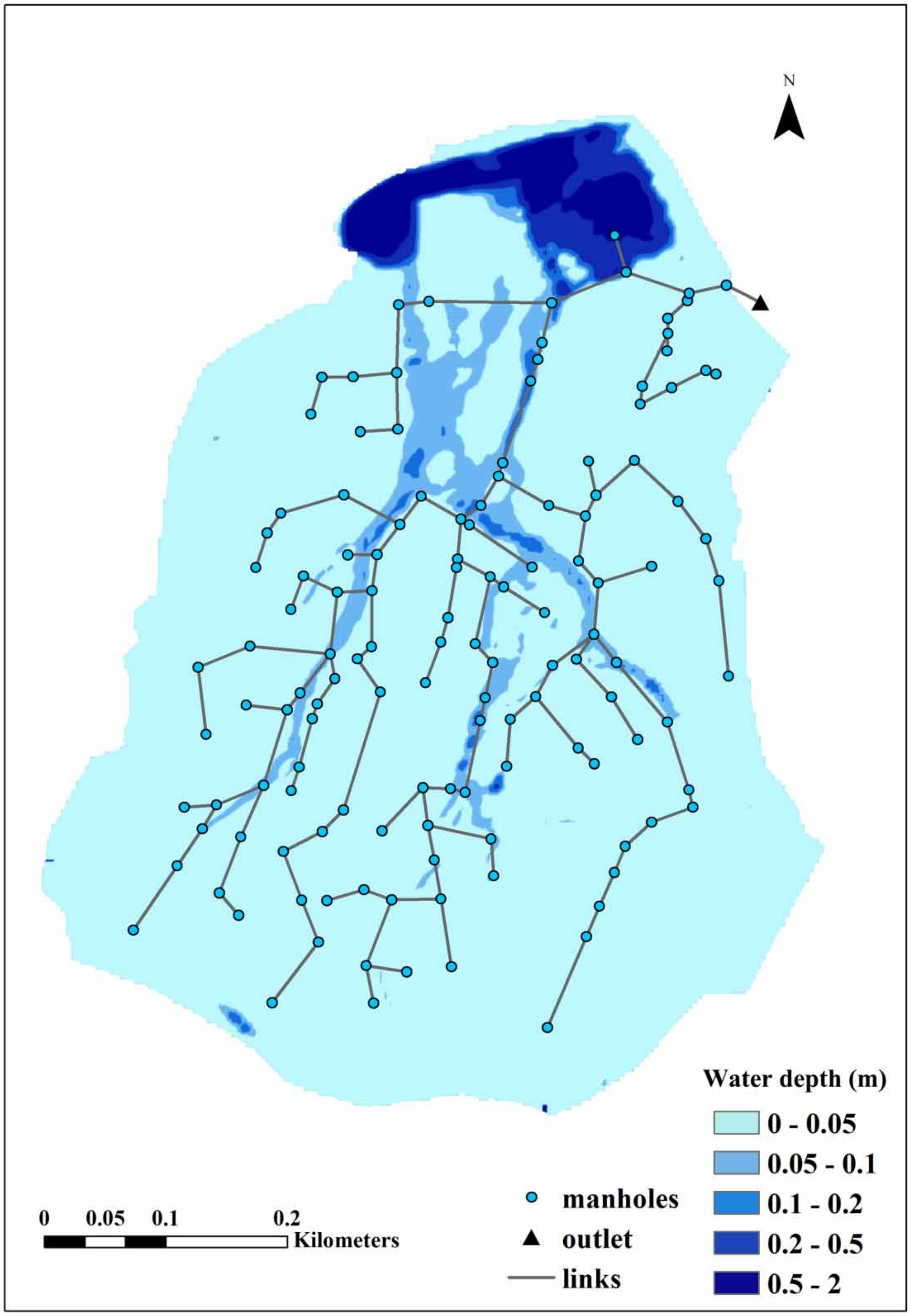


Figure 5 | The relationship between the submersion range and the location of the pipe network system at 1 h in the once-in-10-years case.

5.2. Future research direction

The displacement of the manhole is determined jointly by the drainage formula and the drainage capacity of the pipe network system. When the sum of displacement of all manholes in the study area exceeds the drainage capacity, the formula displacement of each manhole is multiplied by a common reduction coefficient (drainage capacity divided by the sum of displacement of manhole) to limit the displacement, so as to ensure that the displacement does not exceed the drainage capacity. Because when the displacement exceeds the drainage capacity, the underground drainage pipe network is in the overloaded pressure

Table 2 | Statistical analysis of water depth at nodes of MIKE URBAN model and equivalent drainage model

	5a		10a		20a		50a	
Time(h)	NSE_h	$RMSE_h$(m)	NSE_h	$RMSE_h$(m)	NSE_h	$RMSE_h$(m)	NSE_h	$RMSE_h$(m)
1:00	0.902	0.040	0.964	0.028	0.969	0.030	0.975	0.031
2:00	0.860	0.063	0.985	0.024	0.988	0.025	0.990	0.026
3:00	0.881	0.058	0.985	0.024	0.989	0.023	0.990	0.025
4:00	0.862	0.057	0.984	0.022	0.988	0.022	0.987	0.025
Average value	0.876	0.055	0.979	0.025	0.983	0.025	0.985	0.027

state, which will produce resistance to the displacement, and the manhole cannot discharge according to the displacement calculated by the formula. This resistance is represented by the reduction coefficient in the equivalent drainage model based on the manhole. The internal pressure of the underground pipeline system is related to the external discharge and internal confluence, and the external discharge is determined by the surface confluence, which is closely related to geographical information such as elevation and slope. Similarly, the underground pipe network system receives different external inflow, and the internal convergence is also different. Therefore, manhole resistance is affected by geographic information, and manholes in different geographical locations shall have different reduction coefficients according to geographical locations, and incorporating geographical factors into reduction coefficients is a direction that can be discussed in the future.

6. CONCLUSION

To overcome the difficulty of obtaining drainage network data for urban flood simulations, this paper has proposed an equivalent drainage model based on manholes. The design of this model was intended to improve the part of the existing equivalent drainage method that is quite different from the actual drainage mechanism. The feasibility of the proposed equivalent drainage algorithm and the rationality of the model were evaluated through comparisons with the simulation results provided by MIKE URBAN.

(1) According to the actual situation of urban drainage, manholes were considered as the key media, and an equivalent drainage model was constructed using easily available data such as manhole location information and the drainage capacity of the pipe network system. The equivalent drainage model is based on a two-dimensional hydrodynamic model and combines the weir flow and orifice flow formulas to fully reflect the two main flow modes of manhole discharge. The drainage capacity of the pipe network system was used to limit the displacement. Thus, the equivalent drainage model not only overcomes the difficulty of accessing pipe network data but also accelerates the calculation efficiency of the whole model for the simplicity of the algorithm. And the calculation mechanism accords with the actual situation of urban drainage, has a certain physical basis, and improves the accuracy of the simulation results. However, compared with the one-dimensional model, the equivalent drainage method in this paper cannot reflect the overflow situation of the pipeline. The study of incorporating geographical factors into the equivalent drainage model is a direction that can be continued in the future to further improve the accuracy of the model.

(2) The proposed equivalent drainage model and MIKE URBAN were used to calculate the same four scenarios of rainfall events occurring once every 5 years, once every 10 years, once every 20 years, and once every 50 years. The differences in the simulation results given by the two models were then compared from the perspectives of the submerged area and submerged location. The average relative error between the equivalent drainage model and MIKE URBAN was found to be only 6%. The differences in water depths between the two models were statistically analyzed at multiple nodes, and the average NSE_h and $RMSE_h$ were found to be 96% and 0.03 m, respectively. The comparison results show that the equivalent drainage model and MIKE URBAN give highly similar outputs, which verifies the feasibility and rationality of the proposed model.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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