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Abstract – **Urban waterlogging caused by rainstorm has occurred more frequently in many cities of China these years. In 2021, "July·20th" torrential rain hit Zhengzhou, the capital city of Henan province, resulting in a serious waterlogging disaster, causing heavy casualties and economic losses, and exposing the weaknesses of the design and construction of the city's drainage system in case of heavy rain.**

Detailed numerical simulation is a key technology for predicting and mitigating the urban waterlogging problems. On the basis of the city of Kaifeng, Henan province, as a case study, this work aims to analyse the spatiotemporal distribution of waterlogging and assess its risk for each district in the city. In this study, a waterlogging simulation model considering the city's digital elevation model (DEM), the non-uniform surface friction and infiltration, and the drainage system is proposed and tested to obtain the spatiotemporal distribution of the water depth and water velocity on the ground of the urban areas. The 2D hydrodynamics module TELEMAC-2D (of the open TELEMAC system) is used to simulate the surface water flow and is then coupled with SWMM (Storm Water Management Model) to simulate the flow in the underground water drainage system taking into account pumps, regulating sluice and so on.

A rainfall data from 2021.08.28 to 2021.08.29 is used to validate the model. The spatial distribution of high-risk areas obtained by the model is generally in agreement with the registered logs provided by the city's bureau of urban management.

Keywords: Urban Waterlogging, SWMM, TELEMAC-2D

I. INTRODUCTION

In 2021, the now sadly famous "July·20th" torrential rain hit Henan province. In the cities of Zhengzhou, Kaifeng, Xinxiang, Zhoukou and Jiaozuo (see Figure 1), ten national meteorological observation stations broke the historical extreme value of daily rainfall [1]. According to the data of Kaifeng meteorological station, from July 20th to 21st, the maximum accumulated precipitation in 48 hours was 354.7 mm, which has reached 56.5% of the annual average precipitation of 627.5mm in Kaifeng [2]. The heavy rain caused heavy casualties and economic losses [3], and exposed some weaknesses of the design and construction of the city's drainage system as well as the requirement to upgrade flood control schemes to face more and more unusual weather.

With now increasingly frequent extreme weather and weak drainage system capacity, urban waterlogging prevention is facing severe challenges. In order to meet the challenges, a numerical simulation method was used to predict the urban water distribution.

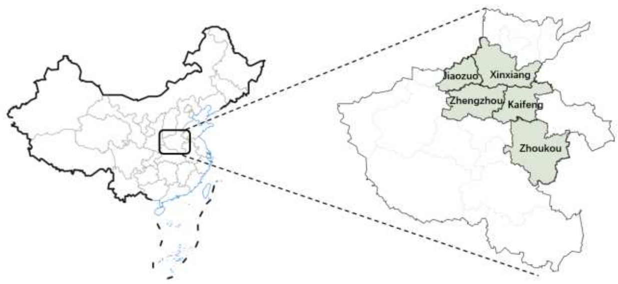

Figure 1. Position of Henan province in China

There are many software packages available commercially and non-commercially with varying degrees of complexity to simulate stormwater runoff quantities and qualities. Deepak Singh Bisht used Storm Water Management Mode (SWMM) and MIKE URBAN to simulate the flood inundation scenarios and provides an insight into the importance of 2D model to deal with location-specific flooding problems [4]. Guoru H proposed a 1D-2D coupled urban flood simulation model based on InfoWorks ICM to obtain disaster-causing factor data by simulating the flood process under the rainstorm return periods of 1 a, 5 a, and 50 a. SWMM is used to simulate the runoff and design of an efficient drainage system [5]. Since, SWMM is a 1D pipe flow model and does not simulate urban surface flood extent and inundation depth, a TELEMAC-2D model was used to complement SWMM's limitations.

This paper presents the TELEMAC-2D/SMWM coupled model specifically constructed for urban water logging simulation in Kaifeng urban district. Its aim is to build a model that can predict future waterlogging in real time.

Section II introduces the study area and presents the setup of the model, including precipitation data access and rainstorm design method, SWMM pipe flow model setup, TELEMAC-2D overland flow model setup and coupling mode of the two models. Section III presents the typical case verification results and highlights some error analysis. Section IV finally concludes this work with some further perspectives.

II. STUDY AREA AND METHODS

A. Study area

Kaifeng is in the hinterland of Central China, on the south bank of the Yellow River. The terrain is flat and relatively low compared to the Yellow River. Kaifeng has a monsoon climate of medium latitudes with four distinct seasons. The annual average precipitation is 627.5 mm, and the precipitation is mostly concentrated during the summer, more specifically in July and August [1].

The urban district of Kaifeng City is considered as the study area in this paper. As shown in Figure 2, the area was defined according to the density of population and it is centred on Kaifeng ancient City Wall, reaching Lian-Huo Expressway in the north, Jinming Avenue in the west, Huaxia Avenue in the south, and Qingshui River in the east. The total area is about 77.4 km^2.

The 2D mesh is made of 310,671 nodes and 612,177 triangular elements, refined in built-up areas and river. The elements sizes vary from 20 m for the largest elements to 5 m for the smallest ones.

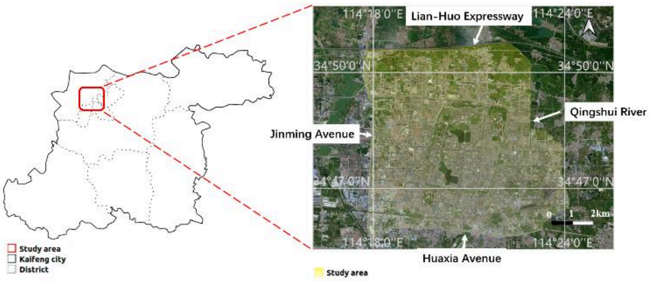

Figure 2. Study area

A. Data resources

The data resources used for the simulation were from reliable and authoritative public data or from Kaifeng City Administration Bureau.

Topographic data includes Digital Elevation Model (DEM) and building contour data. The DEM data were collected by the Advanced Land Observing Satellite (ALOS) launched from Japan on January 24, 2006. Phased Array L-band Synthetic Aperture Radar (PALSAR) data was used by the Satellite to receive the reflection from the ground to acquire elevation information. The horizontal and vertical accuracy of the data can reach 12.5 m, and the data is public data [6]. The building contour data was obtained from Open Street Map [7]. The data includes the position coordinates and height of the building.

Land use data was obtained from Map World on National Platform for Common Geospatial Information Services [8]. The data was used to distinguish different areas such as water system, green land, roads and buildings.

Pipe network data was obtained from Kaifeng City Administration Bureau. The data consists of spatial position, dimensions and elevations of manholes, pipelines and outlets.

Historical meteorological data was selected from daily observation precipitation dataset of Chinese national meteorological stations released by China Meteorological Administration [9].

Positions prone to waterlogging, water depth data caused by the historical rainfall, as well as underpass data consist of spatial position, width, length and depth were obtained from Kaifeng City Administration Bureau.

B. Precipitation and Rainstorm data

The precipitation data is a dynamic input for the simulation and can be directly used as input to the simulation in the form of a precipitation data file. We can generate the rain file in the following two ways: precipitation data access and rainstorm design.

- *Precipitation data access*: the calculation access to the real-time rainfall forecast data API, and the precision of the precipitation data file is determined according to the weather forecast precision. Usually, the rainfall forecast precision is hourly for the next 24 hours and daily for the next seven days.

- *Rainstorm design*: was based on the rainfall return period, e.g., 50 years, 100 years, and so on. Heavy rainstorms have long return periods, while light rain events have short return periods. The storm intensity equation was used to simulate rainfall of different intensities. The storm intensity equation was derived based on local rainfall records for many years:

$$q = \frac{5075(1 + 0.61 lgP)}{(t + 19)^{0.92}} \quad (1)$$

where q is rainfall intensity in L/s·ha2, P is the return period in years and t is rainfall duration in minutes.

The most used definition of rainstorm intensity is the average rainfall of a continuous rainfall period, which can be computed using the following formula:

$$i = \frac{h}{t} \quad (2)$$

where i is the rainfall intensity (mm/min), t is the duration of the rainfall event (min), and h is the total rainfall (mm).

Therefore, the unit conversion of q based on the definition of i is:

$$q = \frac{L}{s \cdot ha} = \frac{10^6 mm^3}{\frac{1}{60} \cdot min \cdot 10^4 m^2} = 0.006 \cdot i \quad (3)$$

and:

$$i = \frac{847525(1+0.61 lgP)}{(t+19)^{0.92}} \quad (4)$$

We simulated a rainfall series with an accuracy of one minute using the Chicago hyetograph based on the storm intensity formula [10] .

$$i(t)=\begin{cases}\dfrac{847525(1+0.61\lg P)\left[\dfrac{(1-0.92)t}{r}+19\right]}{\left(\dfrac{t}{r}+19\right)^{0.92+1}} & \text{if } t<t_{peak}\\[2ex] \dfrac{847525(1+0.61\lg P)\left[\dfrac{(1-0.92)t}{1-r}+19\right]}{\left(\dfrac{t}{1-r}+19\right)^{0.92+1}} & \text{if } t\geq t_{peak}\end{cases} \quad (5)$$

where i is the rainfall intensity in mm/min, P is the return period in years and r is proportion coefficient of the rain peak.

C. The SWMM pipe flow model

SWMM simulates the runoff quantity generated from a sub-catchment during simulation period along with the discharge of the closed pipes. Developed primarily for urban areas, the model is able to simulate water volume and quality from a single event or a long-term continuous simulation through the catchment [11]. In this study, SWMM is used to simulate the drainage process by the underground pipe network.

In order to account for the infiltration losses, SWMM has three different schemes to choose from, i.e., Horton Model, Green–Ampt model and curve number scheme, while the flow routing can be carried out using steady wave routing, kinematic wave routing and dynamic wave routing [11]. In the present study, curve number scheme for infiltration losses and dynamic wave routing for flow routing were used.

In SWMM, the manhole was set as the junction and the pipeline was set as the conduit. The sub-catchment is the hydrologic unit of the land. In the overland part, the runoff is computed by using the curve number scheme infiltration model. The sub-catchment is connected to a junction to deliver the runoff to the underground pipe network, and the junction is connected by the link to deliver the water to another junction or outlet.

1) Junction properties

Junction properties consist of elevation of junction invert depth from ground to invert elevation, and pond area.

- *Elevation and depth*: the value is directly obtained from the pipe network data.
- *Pond area*: The ALLOW_PONDING analysis option needs to be turned on. The purpose is that the overflow water from the manhole can be temporarily stored in pond, so as to ensure the conservation of the total flow volume. The pond area is set as the area of the corresponding sub-catchment area.

2) Conduits properties

Conduit properties consist of upstream node, downstream node, conduit length, offset of conduit, roughness parameter in Manning's equation.

- Upstream node, downstream node, conduit length, offset of conduit: their value is obtained from the pipe network data.
- Roughness parameter in Manning's equation: The friction coefficient is determined according to the engineering manual [12], and the specific value is shown in the following table:

Table I Roughness parameter of different conduit material

Conduit material	***Concrete***	***Brick***	***PVC***	***GRP***
Roughness parameter	0.014	0.001	0.009	0.0084

3) Sub-catchment properties

Properties associated with a sub-catchment in SWMM are rain gage, outlet, area, width, slope, percent of land area which is impervious, roughness parameter in Manning's equation for impervious area and for pervious area.

- *Rain gage*: Precipitation time series generated in part C was set as rain gage input.
- *Area*: According to the position of junction and Theissen polygon principle, the shape of sub-catchment area is automatically generated. Then, the obviously unreasonable shape of the sub-catchment shape was manually adjusted according to the satellite map, and the area of the shape was counted as the area in SWMM.
- *Outlet*: The sub-catchment shape is generated according to the position of each junction. Therefore, the sub-catchment forms a one-to-one correspondence with the junction, and we can use the corresponding junction as an outlet.
- *Width*: In the SWMM simulation, the time and process curves of overland runoff production depend on the width of the sub-catchment, which is the ratio of the area to the length of the overland flow. Since the length of overland flow is difficult to determine accurately, in this study, the width of the sub-catchment is taken as the square root of the sub-catchment area.
- *Slope*: The slope can affect the rate of overland water flowing into the pipe network system in SWMM. The average slope of sub-catchment area can be obtained according to the DEM data.
- *Percent of land area which is impervious*: To be consistent with the TELEMAC-2D setup, we consider the entire study area to be pervious, so this parameter is set to 0% for all sub-catchment area.
- *Roughness parameter in Manning's equation for pervious area*: According to the land use data, we determined whether the features of each sub-catchment was road and building, green land or water system. Then set the Manning friction coefficient of the corresponding area according to relevant engineering manuals or relevant literature. In this study, the specific coefficients are consistent with the settings in TELEMAC-2D. The

roughness parameter is subjected to change during the calibration process.

- *CN number*: Similarly to the roughness parameter, we first determined the land properties of the sub-catchment and then set the corresponding CN value according to relevant engineering manuals or literature.

4) Outlet properties

The outlet is an outfall node which is final downstream boundary of the drainage system. The corresponding water stage elevation is set according to the value from the pipe network data.

According to the above definitions, the SWMM model obtained is shown in Figure 3.

Figure 3. SWMM model in ths study

Figure 4 is the water depth simulation result of a pipeline. In the figure, we see a longitudinal view of the pipe and manhole, with the light blue colour representing the water in the pipe and manhole and the dark blue line representing the water head. It can be seen that most of the water head is below the elevation of the manhole. But the head of manhole No. 1197 exceeded the top elevation, and the water would enter the pond to be stored. When there is a free volume in the manhole, the water flows back from the pond.

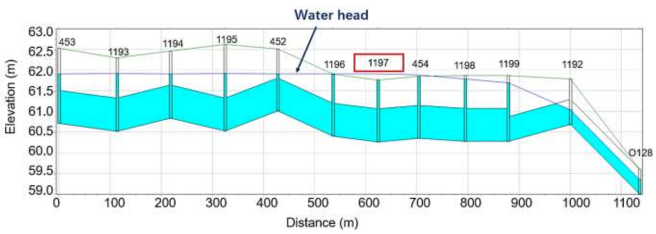

Figure 4. Water elevation profile of Node 453-O128

D. *TELEMAC-2D surface flow model*

The surface flow process was simulated using TELEMAC-2D. In surface flow simulation, it is necessary to consider the barrier effect of land elevation, the resistance due to friction, the absorption effect of the land, and the drainage process of the pipe network. For the drainage process, TELEMAC-2D and SWMM need to be coupled, and this will be described in detail in Part F. After considering all the factors above, TELEMAC-2D was used to solve the Saint-Venant shallow-water equations, to obtain the important variables e.g., water depth, velocity, and flowrate.

5) Elevation

In the simulation of urban waterlogging, elevation has an important effect on water flow. However, the accuracy of DEM data obtained is 12.5m*12.5m, which is not enough to describe the elevation of buildings. Therefore, we made fine adjustments to the DEM data, and modified the DEM data using the obtained information of building contour, location and subsidence depth of underpass, so as to reflect the overland characteristic.

Firstly, we performed low-pass smoothing on the DEM data. The "noise" band with higher frequency in the DEM raster is filtered out, which mainly contains the elevation information of buildings. The low-pass smoothing allowed us to create a DEM raster files that does not contain building elevations.

The building contour data which was obtained from Open Street Map includes the position and height information of the building. We modified the DEM raster file by using the building contour data which is a vector file that contains the building height attributes and position information. The elevation of the building part was changed to the height of the building plus the original ground elevation.

In addition, as shown in Figure 5, we found that the overpass elevation was recorded in the DEM instead of the ground elevation. The subsidence channel area is prone to waterlogging, so the deviation of elevation will have a great impact on the simulation results and risk prediction. We obtain the underpass data, which consists in spatial position, width, length and depth from Kaifeng City Administration Bureau. Based on these data, the DEM raster was further manually modified. The final DEM raster is shown in Figure 6.

Figure 5. An underpass in Kaifeng

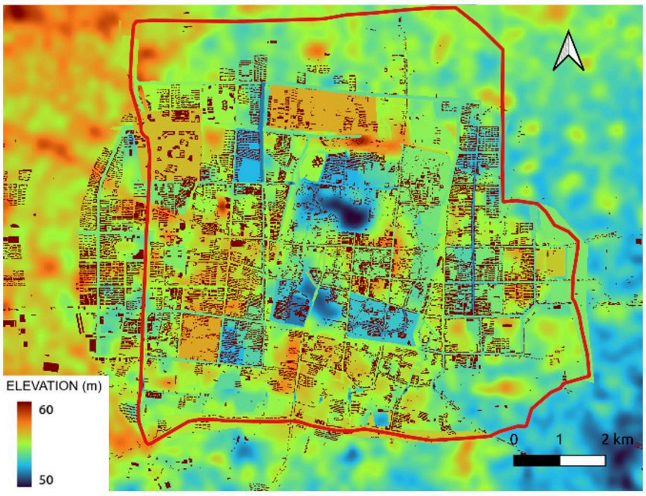

Figure 6. Modification of urban DEM

6) Bottom friction

Hydraulic roughness is roughness in fluid dynamics. Different land cover types with different surface roughness have different resistivity during urban waterlogging process. When simulating waterlogging in flood area model, different roughness values are given for different land use types. Its value can be related to the Manning coefficient, as shown in:

$$V=\frac{k}{n}R_h^{2/3}\cdot S^{1/2} \quad (6)$$

Where V is the velocity; K is the conversion constant and its value is 1 for the SI units; n is the Manning's n roughness coefficient, which reflects the influence of pipe and channel wall roughness on water flow, and we need to determine the value of the coefficient; R_h is the hydraulic radius and S is the slope.

Land use data was obtained from Map World on National Platform for Common Geospatial Information Services. The data was used to distinguish different areas such as water system, green land, road and building.

As shown in the Figure 7, we outline the study area, green land and water system area according to the satellite map. Since the study area is the urban district of Kaifeng City, it is considered that all the areas belong to the road and building area except the green land and water system. After determining the shape of each domain, we set the specific Manning friction coefficient according to the relevant literature [16], as shown in Table II. It should be noted that these values are not the final coefficients, and in future research, we will use the ADAO module of the SALOME platform, also linked to the TELEMAC system, to adjust the coefficients automatically [13].

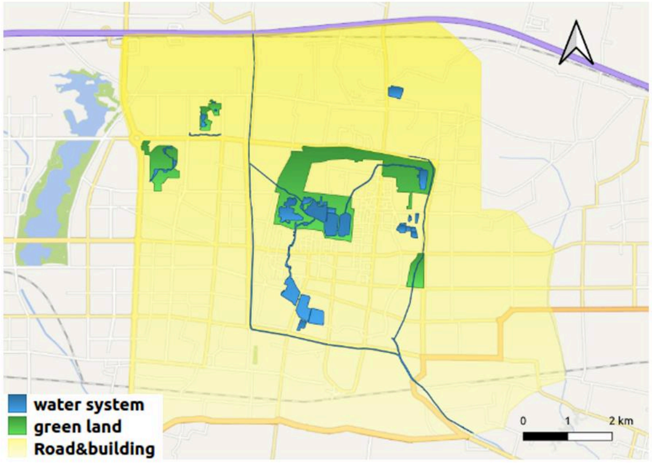

Figure 7. Shape of different feature land

Table II Friction coefficient of different features

Features	***Water system***	***Green land***	***Road & building***
Friction coefficient	0.015	0.5	0.06

7) Infiltration

In order to simulate the runoff process in the study area and take into account the inhomogeneity of land feature, a Soil Conservation Service Curve Number (SCS-CN) model was used in this study. The SCS-CN model is an empirical model developed by the Environmental Protection Agency (EPA) of the United States by analysing rainfall and runoff data of small watersheds in different regions. The model is mature and widely used [14][15]. It represents the natural law of rainfall and runoff and is very suitable for areas lacking data. The SCS-CN model has a simple structure, and the comprehensive parameter CN (Curve Number) value is used to represent the runoff production capacity of different land features. The CN is a dimensionless parameter, and the main influencing factors include soil type, land use, hydrological conditions and soil water content condition. Based on the principle of water balance and certain assumptions, the relationship between rainfall and runoff volume is:

$$Q=\frac{(P-\lambda S)^2}{P+(1-\lambda)S} \quad (7)$$

$$S=25.4\times(\frac{1000}{CN}-10) \quad (8)$$

where, P is the potential maximum runoff; S is the potential maximum retention after runoff begin.

Similarly to the way of setting the friction coefficient, as shown in Figure 7, we delimit different areas according to land properties. Then, we determined the specific CN value according to the literature [16] and engineering manual [6] shown in Table III, and used ADAO to calibrate the CN value.

Table III CN value of different land features

Features	***Water system***	***Greenland***	***Road & building***
CN value	98	61	95

E. Coupling

Based on urban GIS data, rainfall data, pipe network data, the SWMM pipe network model is constructed. The drainage flowrate of each manhole was obtained, and it was input into the TELEMAC-2D model. Similarly, the TELEMAC-2D model is established according to the urban geographic elevation data, land use data and rainfall data. Combined with the simulation results of the SWMM model, the water depth and water velocity over time are simulated by TELEMAC-2D. Figure 8 shows a schematic of the coupling data flow.

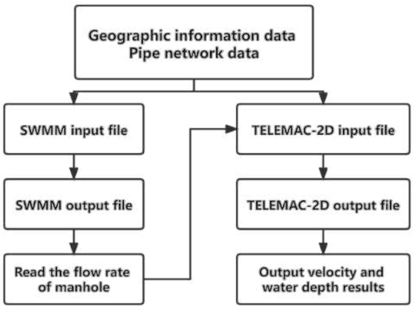

Figure 8. Schematic diagram of coupling data flow

8) Coupling by using TELEMAC-2D source term

For coupling the SWMM model and TELEMAC-2D model, the time-dependent drainage flowrate at each junction was computed and set as a source region in the TELEMAC-2D model as shown in Figure 9.

It is difficult to take all water grates into account in the SWMM model, and as a result, the total number of water collecting points in the model was less than that in reality. Therefore, in order to reduce the uneven drainage in space and truly reflect the drainage capacity of the pipe network, we set the sub-catchment area corresponding to each junction as the source region in the TELEMAC-2D model.

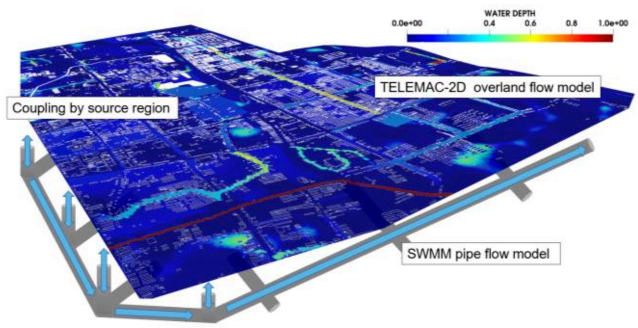

Figure 9. Schematic diagram of TELEMAC-2D coupling with SWMM

9) Definition of drainage flow value

In SWMM, the drainage flowrate at each junction cannot be read directly, so the existing variables need to be used to obtain the flowrate we need.

At time n, considering water conservation in SWMM, the drainage flowrate of each junction is:

$$Q^n_{\text{Source}} = Q^n_{\text{Rain}} + \frac{V^{n-1}_{\text{Pond}} - V^n_{\text{Pond}}}{\Delta t} = Q^n_{\text{Rain}} - \frac{\Delta V^n_{\text{Pond}}}{\Delta t} \quad (9)$$

where, Q_{source} is the drainage flowrate of each junction, Q_{rain} is the runoff flowrate produce by the corresponding subcatchment, ΔV_{pond} is the change of water volume in pond.

As shown in Figure 10 is the schematic diagram of the definition of drainage flowrate of each junction.

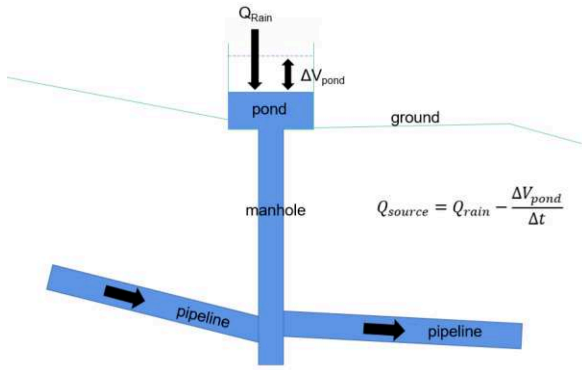

Figure 10. Schematic diagram of the definition of drainage flowrate

VI. RESULTS AND DISCUSSION

A. Typical case verification

The rainfall data for several heavy rains in 2021 and a batch of manually measured water depth data were obtained from the Kaifeng City Bureau of Urban Management. A rainfall with a large total rainfall and the largest amount of measured data last year from 2021.08.28 to 2021.08.29 is selected to verify the model. Figure 11 shows the 3-hour precision hyetograph for this rainfall. The rainfall peaks occurred at the 24th and 39th hour, and the data obtained by manual measurement mainly concentrated on the time period of the second rain peak.

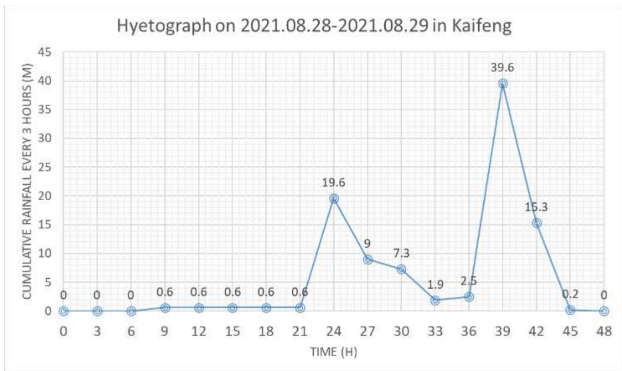

Figure 11. Hyetograph on 2021.08.28-2021.08.29 in Kaifeng

1) Spatial distribution verification

Waterlogging from 2021.08.28 to 2021.08.29 was simulated. The water depth simulation result of TELEMAC-2D is shown in Figure 12. According to the range of water depth, we divided the water depth into three levels as shown in Table IV, among which level 3 is the low risk level and it is only difficult for pedestrians to walk. Level 2 is medium risk level, bicycles and cars are difficult to drive. Level 1 is high risk and it will stop the traffic. The three different levels of danger are shown in light to dark blue.

The locations prone to waterlogging were obtained from Kaifeng City Administration Bureau: red dots indicate positions that have been prone to waterlogging over the years, brown dots indicate underpasses, and yellow-brown squares indicate neighbourhoods prone to waterlogging.

Among the 17 neighbourhoods prone to waterlogging, 5 were at medium risk and 4 were at low risk. All 10 overpasses are at high risk. Among the 27 waterlogging spots, 18 were at low risk, 3 were at medium risk and 6 were at high risk.

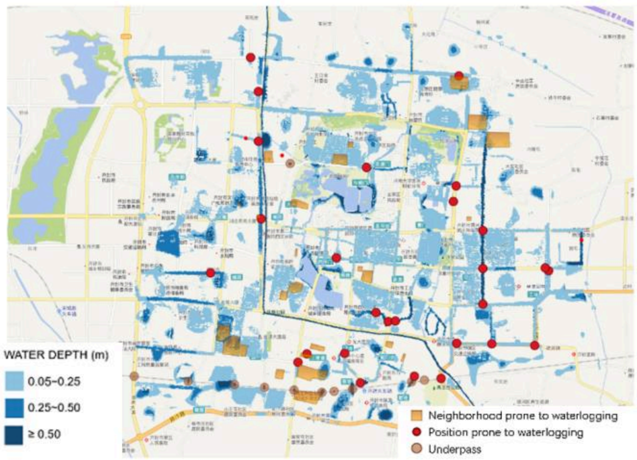

Figure 12. Water depth simulation results of TELEMAC-2D for the waterlogging from 2021.08.28 to 2021.08.29

Table IV Definition of waterloggoing level

Water depth (m)	*0.05~0.25*	*0.25~0. 50*	*≥ 0.50*
Waterlogging level	3	2	1

Comparison of 101 manually measured data with simulation results are shown in Figure 13. The spatial distribution trend of the simulation results is generally consistent with that of the measured data. It shows that the simulation results can reflect the trend of water spatial distribution in reality.

However, we found that 71% of the simulation results were lower compared with the measurement results, which may be caused by two reasons. One reason is that the setting of the CN value is small, which leads to the increase of infiltration rate and the decrease of runoff production, thus resulting in less surface water. Another reason is that after years of use, the drainage capacity of the pipe network system is lower than that of the new one. We can modify the parameters of SWMM in future work, such as the friction coefficient in the pipe, to reduce the drainage capacity of the pipe network.

2) Time distribution verification

We extracted three measurement points and verified the data in terms of time distribution. Figure 14 shows the time-varying water depth curves of Songmenguan Road, 17th middle school and Xihou Road respectively. It can be seen that in terms of time distribution, the simulation results have the same trend as the measured data, but similarly, the simulation results are lower than the measured results.

B. Error analysis and discussion

Based on the deviation between the simulation results and the measured data, we attempt to analyse here the causes of the error, and provide some practical experience for the future use of simulation model for urban waterlogging prevention.

1) Rainfall data

The accuracy of input data has a great impact on the accuracy of results. In order to improve the accuracy of rainfall data, we keep the precision of rainfall input file consistent with the precision of weather forecast. For example, in the waterlogging simulation for the next 24 hours, we use the hourly precipitation data as input. In addition, the more recent the forecast, the more accurate it is, so we feed new rainfall data from the API every three hours to achieve a real-time update of the simulation results.

2) Measurement data

The measurements that we obtained so far were taken manually by different people. Their readings can be off by 5 to 10 centimetres or more. Therefore, in the construction of a twin platform, one should invest in some water level meters and flowmeters, which can obtain more accurate data.

3) Parameters in model

There are many parameters in the model determined according to engineering manuals or relevant literature, such as infiltration rate and friction coefficient. These parameters do not reflect real urban conditions. We expect to calibrate these parameters using data assimilation (the ADAO module of the SALOME platform) after obtaining a sufficient number of measurements from the water level meter and flowmeter.

VII. CONCLUSION AND PERSPECTIVES

In this study, numerical simulations of urban waterlogging in the urban district of Kaifeng City were performed with coupling TELEMAC-2D model and SWMM model. More specifically, the establishment method and simplification principle of overland flow model and pipe network system model, as well as the coupling mode of TELEMAC model and SWMM model are put forward.

For the validation process, a rainfall data from 2021.08.28 to 2021.08.29 is used to validate the model. For the spatial distribution verification, among the 17 neighbourhoods prone to waterlogging, 5 were at medium risk and 4 were at low risk. All 10 overpasses are at high risk. Among the 27 waterlogging spots, 18 were at low risk, 3 were at medium risk and 6 were at high risk. The spatial distribution trend of the simulation results is generally consistent with that of the measured data. It shows that the simulation results can reflect the trend of water spatial distribution in reality. In terms of time distribution validation, the simulation results have the same trend as the measured data. However, 71% of the simulation results were lower compared with the measurement results. In view of this, we propose several reasons for the error of the results, including the error of rainfall data, measurement error, and the error caused by the model parameter settings that cannot reflect the real urban conditions.

In further improving this work, we will keep the precision of rainfall input file consistent with the precision of weather forecast and feed new rainfall data from the API every three hours to achieve a real-time update of simulation results in order to improve the accuracy of rainfall data. In setup of the simulation, we will invest into some water level meters and flowmeters, which can obtain more accurate measurement data. We will calibrate the setting parameters including friction coefficient and CN values by using data assimilation after obtaining a sufficient number of measurements from the water level meter and flowmeters.

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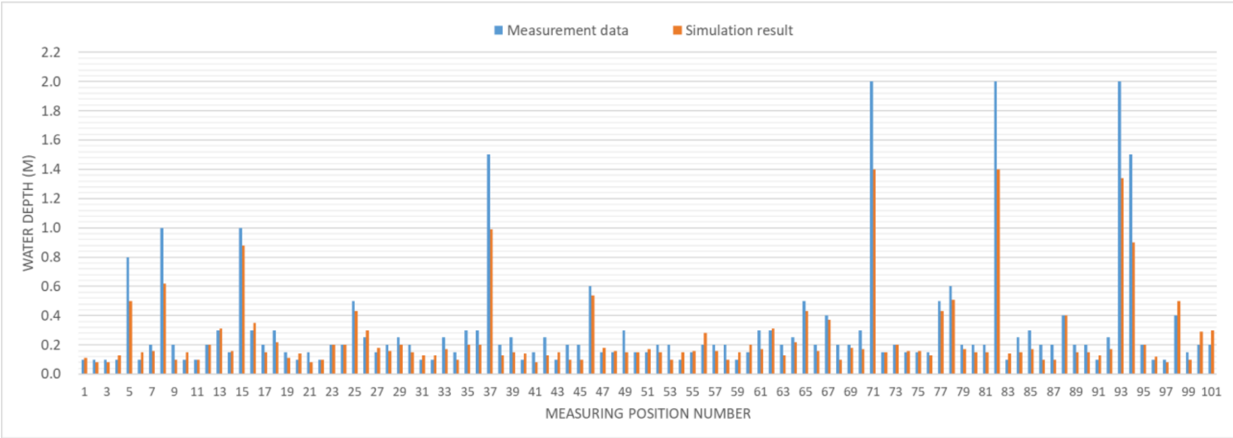

Figure 13. Comparison of 101 manually measured data with simulation results

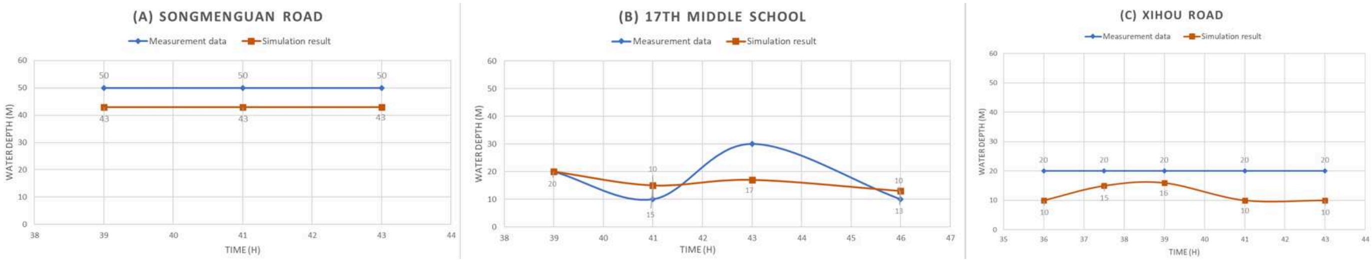

Figure 14. Comparison of 101 manually measured data with simulation results