Simulation of Urban Rainstorm Waterlogging and Pipeline Network Drainage Process Based on SWMM

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Abstract: Urban flood has already become weaknesses of flood control system in China. Flood and pipeline drainage calculation based on hydraulics model plays a key role in flood monitoring, warning and control management. On the basis of the topographic maps (high-precision DEM), underground drainage networks, land use and rainfall data in Enshi City, a SWMM-based urban flood model is constructed, which is applied to calculating rainstorm waterlogging and pipeline drainage process under the designed storm probability of 0.01, 0.02 and 0.05, and the designed storm period of 1 hour and 3 hours. The pipeline drainage peak flow of different pipeline type is also retrieved. And results suggest that SWMM is a reliable urban storm water model, which is suitable for urban storm flood simulation and pipeline network drainage analysis.

1. Introduction

With the continuous intensification of urbanization in China, the rapid development of city has led to significant changes in the underlying surface environment, which directly affects the process of runoff generation and changes the regional water supply, utilization, consumption and drainage conditions. Affected by global climate change, the number of urban flood disasters in China is increasing and the damage degree is increasing.\textsuperscript{[1]} The office of the State Flood Control and Drought Relief Headquarters pointed out that more than 100 cities in China have been threatened by flooding every year for the past five years. The frequent occurrence of urban rainstorm, flood and waterlogging not only affects the normal development of economy, but also poses a serious threat to lives and property.\textsuperscript{[2]}.

According to the requirements of urban storm flood prevention, the urban rainwater runoff model came into being. It is drawn from the watershed runoff model and adapted to the urban area after improvement. In the middle of the 20th century, domestic and international research on urban rainwater models has already begun. By simulating the migration and transformation of urban surface confluence, underground pipeline runoff and pollutants into water bodies, the pipeline network design and rainwater control schemes are evaluated to achieve the goals of flood control and drainage and rainwater runoff pollution control.\textsuperscript{[3-4]} At present, there are dozens of urban rainwater models widely used abroad, including DR3M-QUAL, FRQ, HEC-HMS, HSPF, InfoWorks CS, MIKE, MOUSE, P8-UCM, SCS, SLAMM, UNEMMIKURBAN, Stanford, SCS, SWMM, SITEMAP, GWLF, P8-UCM, STORM, etc.\textsuperscript{[5]} Although there are many models of urban rainfall and runoff, these physical models based on statistics, experience or hydraulics at different time and space scales can only be applied to some application scenarios, and there are no models applicable to all situations.\textsuperscript{[6]} In the middle and the late 20th century, some studies on urban rainwater models were carried out in China\textsuperscript{[7-8]}, but there are still some problems such as lack of the pre-processing and post-processing of data, poor visualization.
and operability of models. [7-9] Among them, SWMM model is the earliest and most widely used urban rainwater runoff model, which has been approved by domestic and international academic circles.

Enshi City is located in the valley basin formed by the scouring of high mountain rivers. The central city is low in topography, with many rivers, complex river systems, narrow downstream exit sections, poor urban drainage, and frequent urban waterlogging caused by torrential rains and torrents. Enshi City is representative in the analysis of urban waterlogging caused by torrential rains in mountain cities. Therefore, this paper selects Enshi city as the research area, combines the basic geographic information of the city, underground drainage pipe network, rainfall and other data, and constructs SWMM model to simulate the urban flood waterlogging and pipe network drainage under different rainstorm conditions, which provides an example for better planning the urban flood control and waterlogging elimination plan and urban underground pipe network planning. In order to simplify the analysis of drainage process of storm network, the SWMM model is mainly used for surface runoff concentration, network drainage and other modules.

2. Research area and data
The study area is located in Wuyangba Street Office in Enshi City, Hubei Province, with relatively flat terrain. The land types are mainly houses, roads, grasslands and so on, less green area, more residential buildings above 15-20m high floors, and the underground pipe network has realized the diversion of rain and sewage.

With the support of Enshi Flood Control and Drought Relief Headquarters Office, the city terrain, high-resolution remote sensing images, hydrometeorology, drainage pipe network and other data were systematically collected. Among them, urban terrain and hydrology data come from Enshi Hydrographic Bureau, high-resolution remote sensing image data comes from World View image, meteorological data comes from Enshi Meteorological Bureau, and drainage pipe network data comes from Enshi Housing and Urban-Rural Construction Bureau.

2.1. Delineation of Sub-catchment Areas
According to the spatial distribution of underground pipelines in the study area, the whole rainwater catchment is divided into 12 sub-catchment areas (as shown in fig. 1). Among them, the maximum one is 23800 square meters and the minimum is 5000 square meters.

2.2. Pipe network data
The drainage pipe network in the study area is mainly laid along the main road (fig. 2), and the pipeline in the area eventually flows out to the periphery without considering the inflow of the peripheral pipeline.
As shown in Table 1, there are 31 pipes in the area, including 30 round pipes and 1 square pipe.

### Table 1: Pipeline information in the study area

| Number | Pipe type       | Width (m) | Height (m) | Number | Pipe type       | Width (m) | Height (m) |
|--------|-----------------|-----------|------------|--------|-----------------|-----------|------------|
| 1      | Round pipe      | 0.237     | 0.237      | 17     | Square pipe     | 0.120     | 0.150      |
| 2      | Round pipe      | 0.375     | 0.375      | 18     | Round pipe      | 0.462     | 0.462      |
| 3      | Round pipe      | 0.237     | 0.237      | 19     | Round pipe      | 0.375     | 0.375      |
| 4      | Round pipe      | 0.237     | 0.237      | 20     | Round pipe      | 0.225     | 0.225      |
| 5      | Round pipe      | 0.305     | 0.305      | 21     | Round pipe      | 0.300     | 0.300      |
| 6      | Round pipe      | 0.305     | 0.305      | 22     | Round pipe      | 0.305     | 0.305      |
| 7      | Round pipe      | 0.375     | 0.375      | 23     | Round pipe      | 0.237     | 0.237      |
| 8      | Round pipe      | 0.237     | 0.237      | 24     | Round pipe      | 0.915     | 0.915      |
| 9      | Round pipe      | 0.237     | 0.237      | 25     | Round pipe      | 0.915     | 0.915      |
| 10     | Round pipe      | 0.375     | 0.375      | 26     | Round pipe      | 0.915     | 0.915      |
| 11     | Round pipe      | 0.534     | 0.534      | 27     | Round pipe      | 0.915     | 0.915      |
| 12     | Round pipe      | 0.534     | 0.534      | 28     | Round pipe      | 0.915     | 0.915      |
| 13     | Round pipe      | 0.534     | 0.534      | 29     | Round pipe      | 0.915     | 0.915      |
| 14     | Round pipe      | 0.305     | 0.305      | 30     | Round pipe      | 0.762     | 0.762      |
| 15     | Round pipe      | 0.375     | 0.375      | 31     | Round pipe      | 0.915     | 0.915      |
| 16     | Round pipe      | 0.305     | 0.305      |        |                 |           |            |

According to the photos taken during the field investigation and referring to the hydraulics calculation manual [10], the roughness coefficient is selected as 0.03 - 0.035 for river courses, 0.15 for houses, 0.07 for villages, 0.065 for woods, 0.05 for paddy fields, 0.035 for open spaces and 0.012 for pipe networks. The import loss coefficient of the drainage pipe network is 0.5 and the export loss coefficient is 1.

### 2.3. Rainfall data

According to the hydrometeorological data of Enshi City, rainfall data are selected. Under the condition of 1h and 3h rainstorm duration, there are 3 rainstorm orders once every 20 years, 50 years and 100 years, and the specific data are shown in tables 2 and 3.

### 3. SWMM Modeling

#### 3.1. Surface runoff generation module
The study area is divided into 12 sub-catchments, and the runoff process is simulated according to the hydro-hydraulic characteristics of each sub-catchment. The surface runoff consists of three parts: the runoff in permeable areas, the runoff in impermeable areas with storage capacity and the runoff in impermeable areas without storage capacity. Among them, the flow rate in the permeable area is equal to the amount of rainfall minus the amount of depression and the amount of loss caused by infiltration. The flow rate in impermeable area with depression storage is equal to rainfall minus depression storage. The flow rate in impermeable area without depression storage is equal to rainfall. Horton model was used to calculate the infiltration amount. Horton's model has few fixed parameters and has a good effect on simulating rainfall and runoff in small urban areas, and has also been widely used in various calculations at home and abroad [11].

Table 2 Storm duration of 1 hour (p=0.05,0.02,0.01)

| frequency | 1h rainstorm duration(interval 5min) | total |
|-----------|-------------------------------------|-------|
|           | 5 10 15 20 25 30 40 50 55 60      |       |
| 5%        | 1.27 2.28 5.46 3.90 7.54 3.28 2.89 1.85 1.56 1.01 0.85 |
| 2%        | 1.66 2.81 6.20 4.47 8.35 3.85 3.47 2.31 2.00 1.35 1.16 |
| 1%        | 1.87 3.17 6.99 5.03 9.42 4.34 3.91 2.60 2.26 1.52 1.30 |

Table 3 Storm duration of 3 hours (p=0.05,0.02,0.01)

| frequency | 3h Once in 20 Years (interval 15min) | total |
|-----------|-------------------------------------|-------|
|           | 15 30 45 60 75 90 105 120 135 150 |       |
| 5%        | 6.21 14.16 8.88 2.38 2.91 4.56 3.59 1.89 1.16 1.46 0.82 |
| 2%        | 6.97 14.18 9.43 3.46 3.98 5.45 4.63 2.99 2.17 2.46 1.70 |
| 1%        | 7.98 16.24 10.80 3.96 4.56 6.24 5.30 3.42 2.48 2.82 1.95 |

3.2. Surface confluence module
The convergence process of surface runoff refers to collecting the net rainfall of each drainage area to the outlet section. This paper uses the nonlinear reservoir model to simulate this process. By solving Manning's formula and continuous equation, the process of net rain in the basin is transformed into the process of outflow. The calculation formula is as follows.

Manning formula:

\[ Q = \frac{w^{1.49}}{n} \left( d - d_p \right)^{5/3} S^{1/2} \]  

Continuous equation:

\[ \frac{dv}{dt} = \frac{Adv}{dt} = At' - Q \]

Among them: \( W \)——inherent width of sub-basin, \( m \); \( S \)——slope; \( n \)——Manning roughness coefficient; \( d \)——water depth, \( m \); \( d_p \)——surface stagnant water storage depth, \( m \); \( V \)——surface water accumulation, \( m^3 \); \( A \)——catchment area, \( m^2 \); \( i' \)——net rainfall, \( m \); \( Q \)——output, \( m^3/s \).

3.3. Underground pipe network module
SWMM hydraulic module generalizes the drainage pipe network into a series of pipe sections and nodes, and provides simulation methods such as steady wave, dynamic wave and motion wave. Considering
the data situation and time step of the regional pipe network studied in this paper, the moving wave method is used to simulate the drainage system. The motion wave simulation method uses momentum equation and continuous equation to simulate the flow movement of each pipe section. The momentum equation assumes that the slope of the water surface line is consistent with the slope of the pipeline, and the maximum flow that the pipeline can transport is calculated by Manning's formula with full pipe. This method can choose whether to simulate the node storage, i.e. the amount of water exceeding the pipeline capacity is either stored on the storage node at the end of the pipeline or lost from the system. When there is capacity in the pipeline to transport, the water flows back into the pipeline. Generally, the calculation step size is 5~15m, thus ensuring the stability of numerical calculation. This method can be used for accurate and effective simulation calculation, especially for long-term simulation. [12]

4. Calculation of Rainstorm Waterlogging

4.1. Calculation Scheme
Under the conditions of 1h and 3h torrential rain duration, three torrential rain magnitudes are considered once every 20 years, 50 years and 100 years to form six torrential rain waterlogging calculation schemes, as shown in Table 4.

| number | Rainstorm duration | Rainstorm magnitude | number | Rainstorm duration | Rainstorm magnitude |
|--------|-------------------|---------------------|--------|-------------------|---------------------|
| 1      | 1h                | Once in 20 Years    | 4      | 3h                | Once in 20 Years    |
| 2      | 1h                | Once in 50 Years    | 5      | 3h                | Once in 50 Years    |
| 3      | 1h                | Once in 100 Years   | 6      | 3h                | Once in 100 Years   |

4.2. terrain correction processing
In ArcGIS, the depression is processed with the depression filling tool. The terrain of the building is raised to restore the water-resisting function of the building in the terrain, and the revised DEM comparison chart is shown in fig. 3.
4.3. Model Parameter Setting

The houses are impervious to water and roof rainwater is discharged quickly. In the calculation of rainstorm waterlogging, urban buildings are densely populated and therefore treated as impermeable layers. Some parameters of the sub-catchment area need to be verified and simulated by empirical rate determination, and the parameter rate determination involved in this model is shown in Table 5.

Table 5 Calibrations of the parameter in the sub-catchment area

| Number | Parameter                                      | Calibration Result | Number | Parameter                                      | Calibration Result |
|--------|-----------------------------------------------|--------------------|--------|-----------------------------------------------|--------------------|
| 1      | Roughness Coefficient of Permeable Zone       | 0.25               | 4      | Water storage of depression in impervious area | 2mm                |
| 2      | Roughness coefficient of impervious zone      | 0.016              | 5      | Maximum infiltration rate                      | 75.0mm/h           |
|        | Water storage of depression in pervious area  | 8mm                | 6      | Minimum infiltration rate                      | 4.0mm/h            |

4.4. Model operation and result output

Model parameters are input into SWMM model for simulation (as shown in Figure 4). Among them, the model operation time of 1h designing rainstorm plan is 3h, and the model run for 6h designing rainstorm plan for 3h.
5. Results and analysis

5.1. 1h Design Rainstorm Calculation

1) design rainfall waterlogging and pipe network drainage calculation

Take 100-year period as an example. As shown in table 6, the larger the pipe diameter of the drainage pipe network, the larger the peak flow. The maximum pipe diameter is 0.915 m, and the corresponding maximum peak flow is 2.053 m$^3$/s; The square is the smallest, and the peak flow is the smallest, corresponding to 0.044 m$^3$/s.

| num ber | Pipe diameter (m) | peak flow (m$^3$/s) | num ber | Pipe diameter (m) | peak flow (m$^3$/s) | num ber | Pipe diameter (m) | peak flow (m$^3$/s) |
|---------|------------------|---------------------|---------|------------------|---------------------|---------|------------------|---------------------|
| 1       | 0.237            | 0.138               | 12      | 0.534            | 0.699               | 23      | 0.237            | 0.138               |
| 2       | 0.375            | 0.345               | 13      | 0.534            | 0.699               | 24      | 0.375            | 0.345               |
| 3       | 0.237            | 0.138               | 14      | 0.305            | 0.228               | 25      | 0.237            | 0.138               |
| 4       | 0.237            | 0.138               | 15      | 0.375            | 0.345               | 26      | 0.915            | 2.053               |
| 5       | 0.305            | 0.228               | 16      | 0.305            | 0.228               | 27      | 0.915            | 2.053               |
| 6       | 0.305            | 0.228               | 17      | 0.462            | 0.524               | 28      | 0.915            | 2.053               |
| 7       | 0.375            | 0.345               | 18      | 0.375            | 0.345               | 29      | 0.915            | 2.053               |
| 8       | 0.375            | 0.345               | 19      | 0.375            | 0.345               | 30      | 0.762            | 1.424               |
| 9       | 0.305            | 0.228               | 20      | 0.225            | 0.124               | 31      | 0.915            | 2.053               |
| 10      | 0.375            | 0.345               | 21      | 0.300            | 0.221               |         |                   |                     |
| 11      | 0.534            | 0.699               | 22      | 0.305            | 0.228               |         |                   |                     |

2) Comparison of drainage capacity of different types of pipe networks under different frequency rainfall waterlogging

Since there are 31 pipes in the study area, including 30 round pipes and 1 square pipe, and some round pipes have the same pipe diameter, the drainage pipes with different pipe diameters (10 pipes, 9 round pipes and 1 square pipe) were selected for comparative analysis.

As shown in the following table, for drainage pipes of the same pipe diameter, when the rainfall frequency changes from high to low, the peak flow of the pipes increases from small to large, i.e. when $p = 1\%$, the peak flow of the pipes is the largest; When $p = 2\%$, it is in the middle. When $p = 5\%$, it is minimum. Under the condition of rainfall of the same frequency, the larger the pipe diameter, the larger
the peak discharge will be.

Table 7 Comparison and analysis of typical frequency calculations of different pipe diameter drainage pipes (1h precipitation)

| number | pipe diameter (m) | peak flow (m³/s) | Pipe diameter (m) | peak flow (m³/s) |
|--------|------------------|------------------|------------------|------------------|
|        |                  | p=1% p=2% p=5%  |                  | p=1% p=2% p=5%  |
| 1      | 0.237            | 0.138 0.096 0.051 | 18               | 0.462           | 0.524 0.365 0.194 |
| 2      | 0.375            | 0.345 0.24 0.128 | 20               | 0.225           | 0.124 0.086 0.046 |
| 5      | 0.305            | 0.228 0.159 0.084 | 21               | 0.3             | 0.221 0.154 0.082 |
| 11     | 0.534            | 0.699 0.487 0.259 | 30               | 0.762           | 1.424 0.992 0.526 |
| 17     | 0.120/0.150      | 0.044 0.031 0.016 | 31               | 0.915           | 2.053 1.43 0.759 |

5.2. 3h Design Rainstorm Calculation

1) design rainfall waterlogging and pipe network drainage calculation

Take 100-year period as an example. The larger the pipe diameter of the drainage pipe network, the larger the peak flow. The maximum pipe diameter is 0.915 m, and the corresponding maximum peak flow is 3.175 m³/s; The square pipe diameter is the smallest, the width is 0.120 m, the height is 0.150 m, and the peak flow is the smallest, corresponding to 0.068 m³/s.

Table 8 Pipeline drainage peak flow (p=0.01)

| number | Pipe diameter (m) | peak flow(m³/s) | number | Pipe diameter (m) | peak flow(m³/s) | number | Pipe diameter (m) | peak flow(m³/s) |
|--------|------------------|-----------------|--------|------------------|-----------------|--------|------------------|-----------------|
| 1      | 0.237            | 0.213           | 12     | 0.534            | 1.081           | 23     | 0.237            | 0.213           |
| 2      | 0.375            | 0.533           | 13     | 0.534            | 1.081           | 24     | 0.915            | 3.175           |
| 3      | 0.237            | 0.213           | 14     | 0.305            | 0.533           | 25     | 0.915            | 3.175           |
| 4      | 0.237            | 0.213           | 15     | 0.375            | 0.533           | 26     | 0.915            | 3.175           |
| 5      | 0.305            | 0.353           | 16     | 0.305            | 0.533           | 27     | 0.915            | 3.175           |
| 6      | 0.305            | 0.353           | 17     | 0.120/0.150      | 0.068           | 28     | 0.915            | 3.175           |
| 7      | 0.375            | 0.533           | 18     | 0.462            | 0.809           | 29     | 0.915            | 3.175           |
| 8      | 0.237            | 0.213           | 19     | 0.375            | 0.533           | 30     | 0.762            | 2.202           |
| 9      | 0.237            | 0.213           | 20     | 0.225            | 0.192           | 31     | 0.915            | 3.175           |
| 10     | 0.375            | 0.533           | 21     | 0.300            | 0.341           |        |                  |                 |
| 11     | 0.534            | 1.081           | 22     | 0.305            | 0.353           |        |                  |                 |

2) Comparison of drainage capacity of different types of pipe networks under different frequency rainfall waterlogging

Since there are 31 pipes in the study area, including 30 round pipes and 1 square pipe, and some round pipes have the same pipe diameter, the drainage pipes with different pipe diameters (10 pipes, 9 round pipes and 1 square pipe) were selected for comparative analysis.

As shown in the table below, for drainage pipes of the same pipe diameter, when the rainfall frequency changes from high to low, the peak flow of the pipeline increases from small to large, i.e. when p = 1%, the peak flow of the pipeline is the largest. When p=2%, it is in the middle. When p=5%, it is minimum. Under the condition of rainfall of the same frequency, the larger the pipe diameter, the
larger the peak discharge will be.

Table 9 Comparison and analysis of typical frequency calculations of different pipe diameter drainage pipes (3h precipitation)

| number | pipe diameter (m) | Peak flow (m³/s) | number | pipe diameter (m) | Peak flow (m³/s) |
|--------|-------------------|------------------|--------|-------------------|------------------|
|        |                   | p=1%  | p=2%  | p=5%  |                   | p=1%  | p=2%  | p=5%  |
| 1      | 0.237             | 0.213  | 0.146 | 0.076 | 18                | 0.462 | 0.809 | 0.555 | 0.289 |
| 2      | 0.375             | 0.533  | 0.366 | 0.19  | 20                | 0.225 | 0.192 | 0.132 | 0.068 |
| 5      | 0.305             | 0.353  | 0.242 | 0.126 | 21                | 0.3   | 0.341 | 0.234 | 0.122 |
| 11     | 0.534             | 1.081  | 0.741 | 0.386 | 30                | 0.762 | 2.202 | 1.509 | 0.786 |
| 17     | 0.120/0.150       | 0.068  | 0.047 | 0.024 | 31                | 0.915 | 3.175 | 2.176 | 1.133 |

6. Conclusion
1) SWMM model is a mature urban rainwater runoff model, which is suitable for urban stormwater waterlogging and pipe network drainage analysis.

2) This paper selects Enshi City as the research area, combines the basic geographic information of the city, underground drainage pipe network, rainfall and other data, constructs a SWMM model to simulate the drainage situation of 6 storm pipe networks once every 20 years, 50 years and 100 years, taking into account the 1h and 3h rainstorms. The result is basically consistent with the" Enshi City Flood Control Emergency Plan” issued by Enshi City Flood Control and Drought Relief Headquarters Office.

3) The roughness and parameter factors of the underlying surface need further optimizing. The SWMM model is used to analyze and calculate the rain and flood in a typical city, which requires a large amount of historical flood process data to determine the roughness of the underlying surface and adjust the parameter factors. At present, the historical flood process data of most cities are not enough, and with the rapid development of cities, several flood processes that are relatively close may cause completely different flood impacts and disaster losses to the same city, which poses certain obstacles to the popularization and application of the flood analysis model represented by SWMM.

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