Effectiveness evaluation of LIDs through SWMM: A case study of typical urban unit in Handan, China

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Abstract. LIDs are frequently utilized measures in urban waterlogging management in the world and the evaluation of their effectiveness through model gets a lot of attention in urban hydrological research. In this study, a typical urban unit of Handan, China was selected, and regional SWMM model was calibrated and validated through measured maximum waterlogging depths (MWD) of typical positions; the LIDs effectiveness on runoff process in different return period events were evaluated through the SWMM. The results show that LIDs have an effect on decreasing total runoff quantity and peak discharge and the effectiveness is more significant when the return period is small. The research provides a technical support to the scientific management of local flood and waterlogging and supplies a reference to local Sponge City planning.

1. Introduction
Recently, the frequency of extreme rainstorms has increased due to global climate change [1]. In addition, the accelerated urbanization has changed urban underlying surface, and the impervious proportion areas have increased, resulting in lots of serious urban water problems [2]. Urban waterlogging not only affects social and economic development, but also brings great inconvenience to residents living, and even injures the lives [3]. In the late 1990s, low impact development (LID) as a new conception was proposed in order to solve stormwater problem [4]. LIDs could control runoff from the source through infiltration, filtration, evapotranspiration and other natural hydrological processes, aiming to the reduction of runoff quantity and pollution, and the protection of the receiving water, which is different from traditional stormwater management [5].

In recent years, with the implementation of the sponge city construction policy in China [6], LIDs researches have been the focus in China. Many experts in the world had studied the effects of LIDs. The effectiveness of concave greenbelt and permeable pavement were evaluated [7], and these related results propose that the proportion of concave greenbelt area in the community area is at least 30%, and the proportion of permeable pavement area in whole road area is at least 20%. The research
indicates that rain barrel/cistern and porous pavement are effectiveness on the total runoff reduction, and 50 percent of rain barrel/cistern, 50 percent of porous pavement and 25 percent of rain barrel/cistern combined with 25 percent of porous pavement are more effective in the research watersheds of 70 km$^2$ and 40 km$^2$ near Indianapolis, Indiana [8]. The comprehensive effectiveness and benefits of LIDs (i.e. bio-retention, concave greenbelt, permeable pavement, vegetative swales, and green roofs) also had been studied [9],[10].

Model simulation is an important means to study and analyze the effect of LIDs, such as SWAT [11], MIKE SHE [12], MIKE URBAN [13] and SWMM [14],[15]. SWMM is a dynamic precipitation - runoff simulation model developed by the Environmental Protection Agency (EPA), which is mainly used for single event or long-term (continuous) simulation of runoff quantity and quality from primarily urban areas. Through SWMM, the generated runoff quantity or quality in each sub-catchment can be tracked, and the discharge, water depth and water quality in each pipe and channel in any time step during any period can be simulated [16]. Due to these above properties, SWMM was selected in this study.

Recently, the application frequency of LIDs increase greatly for waterlogging management in China, however the cities in humid urban areas were more selected in the case studies [17] and few cases were be focus on urban areas of semi-humid and semi-arid areas. In this research, a closed urban unit in Handan was selected and different two scenarios (present with no LIDs and LIDs) in series of rainfall events of different return periods were designed. Furthermore, different runoff processes in different scenarios were simulated and compared through SWMM. This study can improve the applicability of SWMM, also supply the reference to LIDs application in semi-humid and semi-arid regions.

2. Study area and data collection

2.1. Study area

![Figure 1. Study area location and the distribution of calibration position.](image)
Handan city is located in the south of Hebei province and the east of Tai-hang Mountains (figure 1), China, of which the climate is semi-humid and semi-arid continental with warm temperate. The average annual rainfall is 502.7 mm, and it is mostly concentrated on the period from June to August. The study area is located in the main metropolis of Handan City and bounded by North Ring road in the north, by Zhizhang River in the south, by Hanlin Channel in the east and by Fuyang River in the west, with an area of 29.67 km². The underlying surface consists of residential and commercial land, road and green land, of which the area is 24.65 km², 4.38 km² and 0.66 km² respectively and the corresponding percentage is 83.1%, 14.7% and 2.2% respectively.

2.2. Data collection
The data in this study includes information of regional drainage pipe network, information of typical rainfall processes and the corresponding measured MWDs of typical positions.

The information of drainage pipeline network includes 273 nodes, 272 pipelines and 196 subcatchments and the corresponding spatial distributions, which provided by the drainage department of Handan city Administration Bureau. As the study area is bounded by river, total twenty one outlets marked red in the figure 1 exist, of which twenty are utilized for discharging runoff into the river directly, and one is utilized for discharging the sewage into the treatment plant (figure 1).

Because the study area is small, there is no gauge in the area and only two rainfall gauges (Mubi and Shangbi) are nearby. Furthermore, the rainfall difference between these two gauges is little, so the arithmetic mean method i.e. the average of these two gauges, was used to calculate the regional rainfall in this study. Two typical processes rained on June 21, 2017("6.21") and May 19, 2018 ("5.19") were selected, of which the time step is five-minute.

Due to the absence of observed discharge data, the MWDs on different waterlogging positions of two typical storm-runoff processes was selected, investigated and measured. The relative error between the simulated MWD value and measured MWD value was calculated for model calibration and validation. Total four typical waterlogging positions were selected in this case, according to the waterlogging situations of several storms.

3. Methodology

3.1. Model construction

3.1.1. Setting of parameter values. Subcatchment width, N-Imperv, N-Perv, Dstore-Imperv, Dstore-Perv and others are the main parameters required for the simulation in this research. The Horton infiltration model was adopted to simulate the infiltration process in the study area, and Max. Infil. Rate, Min. Infil. Rate, Drying time, Decay constant was the parameters involved.

The above parameters were based on the values in the SWMM user manual [16] and then calibrated. The subcatchment width is related to the subcatchment area. Because the subcatchment area of the study area has a more regular shape, and refers to the SWMM user manual [16], the method was selected to calculate the subcatchment width following equation (1). Therefore, the empirical coefficient K value needed to be determined.

$$W = K \times \sqrt{a}$$

(1)

Where $W$ is subcatchment width; $K$ is empirical coefficient; $a$ is sub-catchment area.

3.1.2. Parameter calibration and model validation. Due to the limited measured data, only the “5.19” rainfall event was selected to calibration and MWD was used as indicator to determine the parameters. Firstly, "5.19" process was simulated through the SWMM. Then, the nodes corresponding to the four measured points were found in the model, and the maximum depths of the corresponding nodes were derived, and finally checked with MWD.

After adjusting the parameters several times, the error range of all verification points (table 1) were
controlled within -20%~20%, which meets the requirements of the corresponding standard [18]. The parameter calibration results are shown in table 2, and rainfall and discharge process of this event is shown in figure 2(a).

Table 1. MWD comparison between measured and simulated value during the calibration process.

| Position No. | Measured Value (m) | Simulated value (m) | relative error (%) |
|--------------|--------------------|---------------------|-------------------|
| (1)          | 0.06               | 0.06                | 0                 |
| (2)          | 0.07               | 0.07                | 0                 |
| (3)          | 0.09               | 0.08                | 11.1              |
| (4)          | 0.07               | 0.07                | 0                 |

Table 2. Initial and calibrated parameters.

| Parameter          | Initial value | Calibrated value |
|--------------------|---------------|------------------|
| K                  | /             | 2.1              |
| N-Imperv           | 0.01          | 0.012            |
| N-Perv             | 0.1           | 0.2              |
| Dstore-Imperv      | 1.27mm        | 5mm              |
| Dstore-Perv        | 1.27mm        | 1.27mm           |
| Conduit roughness  | 0.01          | 0.01             |
| Max. Infil. Rate   | 76mm/h        | 76mm/h           |
| Min. Infil. Rate   | 12.7mm/h      | 12.7mm/h         |
| Drying time        | 7h            | 7h               |
| Decay constant     | 4             | 4                |

Figure 2. Rainfall and discharge process: (a) parameter calibration, (b) verification.

After the end of parameter calibration, “6.21” rainfall event was used to verify the reliability of the model. The verify method was the same as the method of parameter calibration. The rainfall and discharge process of this event is shown in figure 2(b), and the simulation results are shown in table 3. According to the simulation results in table 3, the error of the four typical points were -16.7%, -12.5%, 0 and -16.7%, respectively. The error of (1) (2) (4) verification point were relatively high, mainly because the model derived data was only accurate to two decimal places, and more accurate data could not be given. According to the corresponding standard [18], the relative error range of the simulation results is -20%~20%, and all verification points meet the requirements. Therefore, it can be considered that the model has certain credibility of rain flood simulation in Handan area.
Table 3. Comparison on measured MWD and simulated MWD in validation.

| Position No. | Measured Value (m) | Simulated value (m) | Relative error (%) |
|--------------|--------------------|---------------------|--------------------|
| (1)          | 0.06               | 0.07                | -16.7              |
| (2)          | 0.08               | 0.09                | -12.5              |
| (3)          | 0.1                | 0.1                 | 0                  |
| (4)          | 0.06               | 0.07                | -16.7              |

3.2. Designed scenarios

Two scenarios were designed in this study. One was the current scenario, and the type of land use was described in 2.1. The other was to add LIDs. For these two scenarios, this research simulates the rainfall and discharge process at different return periods (2 years, 5 years, 10 years and 20 years).

3.2.1. Designed precipitation. Based on rainstorm intensity formula of Handan [19] (equation (2)), Chicago rain type generator was used to construct four designed precipitation with the return period of 2 years, 5 years, 10 years and 20 years, respectively. The rainfall lasted for 120 min and the peak coefficient was 0.4. The rainfall process of different design frequencies is shown in figure 3.

\[
i = \frac{7.802 + 7.51 \log P}{(t + 7.76)^{0.602}}
\]

(2)

Where \( i \) is storm intensity, mm/min; \( P \) is rainstorm return period, year; \( t \) is duration of rainfall, min.

3.2.2. LIDs selection and parameter setting. The LIDs include bio-retention cell, rain garden, green roof, infiltration trench, rain barrel and others of which green roof and infiltration trench were selected in this study. The main types of land use of study area are residential and commercial land, road and green land. The infiltration capacity of green land is large, and waterlogging is not easy to occur, so LIDs are not added in green land. Most of the impermeable land is residential and commercial land, so green roof were designed on the roof of residential and commercial buildings, about 30 percent of the total area. At present, all the surface of roads are impervious and the middle part is higher, thus, runoff mainly concentrates on the pavement on both sides of the roads. Due to this, the artificial roads were added with infiltration trench on both sides of the road, about 20 percent of the total area. The spatial distribution of the LIDs is shown in figure 4.

In this study, green roof is composed of drainage layer, filter layer, soil matrix layer and vegetation layer [20]. Refer to the results of others [21], combined with the regional situation, the parameters of the green roof are set as shown in table 4. In this study, the infiltration trench is a gravel shallow channel. According to the technical guide for sponge city construction [22], the parameters of
Infiltration trench are set in table 5.

![Infiltration trench setting map](image)

**Figure 4.** LID setting map: (a) present scenario without LIDs, (b) LID scenario with two LIDs.

| Parameter | Value   | Parameter | Value   |
|-----------|---------|-----------|---------|
| Berm height | 150mm  | Soil thickness | 150mm  |
| Surface roughness | 0.1 | Soil porosity | 0.5 |
| Drainage Thickness | 3mm | Field capacity | 0.2 |
| Void fraction | 0.5 | Wilting point | 0.1 |
| Drainage roughness | 0.1 | Conductivity | 12.7mm/h |

**Table 4.** Parameters of green roof.

| Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|
| Storage thickness | 300mm | Surface roughness | 0.1 |
| Void ratio | 0.75 | Flow exponent | 0.5 |
| Seepage rate | 0.5mm/h | Offset height | 6mm |
| Clogging factor | 0 | | |

**Table 5.** Parameters of infiltration trench.

4. Results and analysis

Analyse of discharge process throughout study area is the focus of this study. Due to the study area is bounded by the river, outlets are evenly distributed around, and the conflux time is not much different. Therefore, the conflux time of a certain outlet is not considered separately. The changes in peak discharge and runoff quantity of the overall system are analyzed at the two scenarios under different return periods (2 years, 5 years, 10 years and 20 years).

4.1. **Comparison of simulation results under different designed precipitation conditions**

Due to the large return rainfall, the end of the discharge time is longer, and the trend of dewatering is relatively stable. Therefore, only the first 6h of discharge process at different return periods (2, 5, 10, and 20 years) were analyzed (figure 5). It is illustrated that the trend of different return periods were similar, both gradually increasing and then gradually decreasing, and the runoff peaks were all concentrated in 1.9 h~2.1 h after the start of rainfall. The four designed rainfalls began to runoff yield.
was 0.86 h, 0.81 h, 0.76 h and 0.73 h after the start of rainfall, respectively. The time to start runoff yield is continuously advanced as the return period increases. The peak discharge was 18.1 L/s, 66.9 L/s, 164 L/s and 347.9 L/s, respectively. As the return period increases, the peak value increased rapidly. It can also be seen from figure 5 that the runoff quantity varies greatly under the four scenarios. Under the 2 years (“2 yrs” for short) return period rainfall, the rainwater can be emptied within 4 hours. In the case of a 5 yrs return period rainfall, rainwater evacuation requires 5.8 hours, and in 10 and 20 years it takes more than 6 hours to drain the rainwater. It can be seen that the greater the return period of the designed rainfall, the earlier the start of the flow, and the peak discharge and total runoff quantity are also significantly increased.

![Figure 5](image)

**Figure 5.** The first 6 hours of discharge processes in different return periods.

### 4.2. Comparison of simulation results under different scenarios

![Figure 6](image)

**Figure 6.** Simulated rainfall runoff process in different return periods in two scenarios: (a) two years, (b) five years, (c) ten years, (d) twenty years.
It can be seen from figure 6 that under different return periods, the LIDs group complete the discharge process first than present group. With the increase of the return period, the closer the two groups of discharge processes before the peak discharge occurs. It can be seen that the effect of LIDs weakens as the return period increases. The specific values are shown in table 6.

| Return period | Peak discharge(L/s) | Total runoff quantity(m$^3$) |
|---------------|---------------------|-----------------------------|
|               | Present LID Ratio   | Present LID Ratio           |
| 2 yrs         | 18.1                | 11 39.23%                   | 71.7 50.4 29.71% |
| 5 yrs         | 66.9                | 62.1 7.17%                  | 553 399 27.85%  |
| 10 yrs        | 164                 | 152.2 7.20%                 | 1940 1410 27.32% |
| 20 yrs        | 347.9               | 329.7 5.23%                 | 5180 3760 27.41% |

Based on the analysis of data in table 6, it is concluded that the peak discharge of the LID scenario under the design period of 2, 5, 10, and 20 years are relatively reduced by 39.23%, 7.17%, 7.20%, and 5.23%, respectively; the total runoff quantity are relatively reduced by 29.71%, 27.85%, 27.32% and 27.41%. It can be seen that the LIDs have a certain reduction effect on both peak discharge and total runoff quantity, and the effect is most obvious under the 2 yrs return period rainfall, and the reduction effect is continuously weakened as the return period increases.

The peak discharge reduction effect decreases rapidly under the 5 yrs return period. It can be seen that the peak clipping effect of the combined LIDs is weaker in the face of large return period rainfall. However, the weak of the total runoff quantity reduction effect is not obvious with the increase of the return period.

5. Conclusion and discussion
In this study, The SWMM were calibrated and validated through measured MWDs of "5.19" rainstorm and "6.21" rainstorm, respectively. Through SWMM, LIDs effectiveness in a closed urban unit of designed runoff process in different return period events were evaluated. The peak discharge and total runoff quantity in present scenario and LIDs scenario were analyzed and compared. The results show that the related values in LIDs scenario were both lower than that in present, and the reduction effects of LIDs decrease with the increase of the return period. The LIDs have best effect on two-year return period event: the corresponding decrease of the peak discharge and total runoff quantity is 39.23% and 29.71% respectively. This study indicates that LIDs can effectively release the waterlogging pressure. At the same time, the research provides a technical support to the scientific management of local flood and waterlogging and supplies a reference to local Sponge City planning.

Due to the absence of data, only two measured rainfall were used for calibration and verification. In the future, data collection of measured runoff and pipe flux should be increased to improve the reliability of the model. In addition, in this study only green roof and infiltration trench are involved, however different LIDs have different advantages. The method to combine and optimize sorts of LIDs needs to be carried out in further research.

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