A study of urban stormwater runoff and water quality control based on system coupling simulations

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Abstract. This study constructed a coupling model of an urban drainage (rainwater) flooding prevention system. Multifactor measures such as the internal source control, drainage pipe network, flooding prevention, and drainage of the system are coupled, the entire process from rainfall to urban rainwater drainage is simulated, and the control and improvement effects of low-impact development (LID) measures on urban stormwater runoff and water quality under different rainfall conditions are discussed. The results showed the following: (1) The constructed coupling model of the urban drainage (rainwater) flooding prevention system has good applicability and can accurately simulate the process and characteristics of urban stormwater runoff and water quality. (2) After LID measures are added, the runoff process is delayed, and the duration of runoff increases. The peak outlet flow of the study area under rainfall with a return period of 2, 3, 10, and 20 years decreases by 66.5%, 57.2%, 51.0%, and 48.2%, respectively. The peak pollutant concentrations decrease, the peaks are delayed, and the minimum removal rate of pollutants under rainfall with a return period of 1, 3, and 5 years is 51.1%, 49.7%, and 37.6%, respectively. (3) The LID measures play a role in improving the runoff flooding in the study area.

1. Introduction
Large-scale urban construction has severely changed the natural geographic characteristics of watersheds. Impermeable surfaces such as buildings, roads, and plazas in residential areas have replaced permeable underlying surfaces such as grasslands and woodlands. The impermeability of large urban surfaces leads to a greater runoff coefficient and an increase in runoff [1], affecting the runoff characteristics and drainage pattern of the watershed and increasing the urban stormwater risk [2,3]. Frequent flood events have caused enormous losses of life and wealth [4–6]. Urban downtown areas often have old drainage networks, and their drainage capacities are generally low. When heavy or continuous rainfall occurs in the flood season, flood-relief channels such as rivers outside the city or artificial open channels also need to withstand the pressure from the upstream river. Once the river level is higher than the water level at the drainage outlet of the urban drainage pipe network, the backwater effect of the river level will occur, so that the urban surface runoff cannot be discharged in time, causing serious stormwater runoff. Frequent rainstorms also cause more serious combined sewer overflow of urban drainage systems, which changes the accumulation and erosion patterns of nonpoint source pollution [7] and often results in poor water quality in stormwater runoff [8]. The nonpoint source pollution generated by rainfall runoff, along with domestic sewage and industrial wastewater, pollutes receiving waterbodies in urban areas [9–12].
Low-impact development (LID), best management practices, water-sensitive urban design, and sustainable drainage systems are among the measures that are widely applied for urban stormwater management and water governance. LID technology is a new concept of rainwater management that can effectively solve urban stormwater runoff and water pollution problems. LID technology controls the runoff and pollution generated by rainfall through many decentralized, small-scale source control measures (e.g., green roofs, plant storage ponds (rain gardens), permeable pavement, vegetative swales, and detention tanks) [13–16]. Both individual and combined LID measures can reduce surface rainfall runoff and pollutants to different degrees [17–20], lower the impact of urban construction on urban hydrological characteristics and the environment [21–23], and restore the hydrological cycle [24,25].

The urban stormwater model is an important technical means to assist urban stormwater disaster prevention and control [26]. By using numerical simulation techniques to simulate the urban water cycle process, the key states and characteristics of the urban stormwater process can be obtained, and the effects of different stormwater management measures can be simulated and predicted. These are key for urban stormwater management and utilization. SWMM, STORM, InfoWorks ICM, and MIKE series software can all be used to simulate urban stormwater floods, design drainage pipe network systems, estimate urban nonpoint source loads, and assess stormwater risks [27,28].

Existing studies often only simulate and calculate some of the links in the urban hydrological cycle, such as rainfall, runoff, lake systems, and urban rainwater drainage networks, or focus on the use of urban stormwater models to investigate the effects of LID measures on the runoff characteristics of drainage pipe networks [29–33]. However, they fail to reflect the complete process from rainstorm to urban rainwater drainage and pay less attention to the impact of LID measures on urban stormwater runoff by comprehensively considering all links in the hydrological cycle, especially the impact of LID measures on the degree of urban stormwater runoff flooding.

In the present study, hole links of the urban hydrological system are comprehensively considered, and the MIKE FLOOD platform is used to construct a coupling model for an urban drainage (rainwater) flooding prevention system. The entire process of rainfall → surface runoff → drainage pipe network → flooding → rainwater drainage is simulated to investigate the impacts of LID measures on urban runoff and water quality, and the effects of LID measures on the improvement of urban stormwater runoff flooding under different rainfall conditions are discussed.

2. Materials and Methods

2.1 Overview of the study area

The study area (Fig. 1) is located between the Second Ring Road and the Third Ring Road in Xi’an, China, with a total area of 25.54 km². The study area has a continental monsoon climate, with an average annual precipitation of 583.7 mm and an uneven distribution of rainfall during the year. Extreme precipitation occurs frequently during summer, and most of the rainfall during rainstorms comes within a very short time [34]. The study area can be divided into the old town area (where impervious surfaces account for a large portion, and there are old drainage pipe networks designed with low standards), the new urban area (where commercial residential areas with good greening account for a large portion), and the wetland park area. The underlying surface of the study area is complex, and the short duration of heavy rainfall tends to produce a complex hydrological process on the urban surface.
2.2 Design rainfall of the study area
A long-duration rainfall pattern is used to simulate the stormwater runoff process in the study area. Return periods of 2, 3, 5, 10, and 20 years are set, and a time interval of 5 min is used. Design rainfalls with a duration of 24 h are used in the analysis and calculation (Fig. 2). The pollution caused by the initial scour is the main portion of surface runoff pollution, and the shorter the duration of a given amount of heavy rainfall, the more serious the initial scour. Therefore, when calculating runoff pollution, 2-h rainfalls with return periods of 1, 3, and 5 years are considered, and the latest rainstorm intensity formula for Xi’an is used to calculate the design rainstorm. The rainfall pattern of the study area has a unimodal pattern distributed in the middle stage of the rainfall [35,36]. Based on an analysis of recorded data, the integrated rainfall peak coefficient is determined to be $r = 0.35$ (Fig. 3).

The total rainstorm intensity formula for Xi’an is

$$q = \frac{2210.87 \times (1 + 2.915 \times \text{LgP})}{(t + 21.933)^{0.974}}$$

(1)

where $q$ is the design rainstorm intensity (L/haꞏs), $t$ is the duration of the design rainfall (min), and $P$ is the return period (years).
2.3 Construction of the urban rainstorm model

We use the MIKE FLOOD coupling platform to construct an urban stormwater runoff system, which includes a drainage pipe network model and an overland flow model, to simulate the overall hydrological cycle of the study area, including rainfall, surface runoff, drainage pipe network, drainage system, rivers and lakes, poor drainage, and overflow of the drainage pipe network due to the backwater effect of the rising river level and surface overflow in low-lying areas. The entire process of pollutant generation, transport, degradation, and output is simulated.

The process by which rainfall generates runoff on the surface is mainly affected by the underlying surface. The land use types of the underlying surface of the study area are analyzed (Fig. 4).

The drainage pipe network data of the study area were collected, and the drainage pipe network was generalized. There are a total of 14 drainage outlets, 1,093 inspection wells, and 1,101 drainage pipe networks, with a total length of 115.8 km. Using each inspection well as a center, the study area is divided into a total of 886 subcatchments with an average area of 3.14 ha, according to the geometric principle of Thiessen polygons. According to the computer-aided design data of the study area at a scale of 1:50,000, a digital elevation model was constructed with a grid size of 5 m × 5 m, resulting in a cumulative grid total of $1870 \times 934 = 1,746,850$. 

Figure 2. Long-duration design rainstorm process line

Figure 3. Short-duration design rainstorm process line

Figure 4. Land use type in the study area
To accurately and comprehensively present the rainstorm flooding process in the study area, we coupled the one-dimensional drainage pipe network and the two-dimensional surface and lake reservoirs (Fig. 5). The manholes between the one-dimensional drainage pipe network and the two-dimensional overland flow model are used as the connections. The drainage pipe network drains the urban water body through drainage systems such as drainage outlets, pumping stations, and weirs. In this study, the LID measures (Fig. 6) include sunken green space, six underground storage ponds, and two drainage pumping stations.

![Figure 5. Results of model coupling](image)

2.4 Calibration and validation of model parameters
The runoff yield and concentration parameters (such as average surface confluence velocity, impervious surface coverage of the underlying surface, and initial loss) of the catchment areas in the study area refer to the recommended values in the user manual of the MIKE URBAN software. Other sensitive parameters (such as the Manning coefficient, pipeline roughness, and characteristic parameters of pollutants) of the pervious and impervious areas need to be calibrated.

In the present study, we selected the rainfall data of the study area measured on June 23, 2016 and June 26, 2018 to calibrate the parameters of the model. The precipitation process was measured using
the HOBO RG3-M automatic rain gauge (USA), recorded once every 30 s with a measurement accuracy of 0.2 mm. The sampling points for surface runoff were drainage outlets in the study area, with sampling intervals of 0, 5, 10, 20, 30, 60, 90, and 120 min. The measured water quality indicators include total nitrogen (TN), total phosphorus (TP), total suspended solids (TSS), ammonia nitrogen (NH3-N), and chemical oxygen demand (COD). After repeated calibration and optimization, the parameters (Tables 1 to 3) were used for model simulation calculations.

Table 1. Initial pollutant concentrations under different land uses (unit: mg/L)

| Land use type | TP   | TSS  | TN   | NH3-N | COD  |
|---------------|------|------|------|-------|------|
| Grassland     | 0.21 | 22.80| 2.10 | 1.25  | 19.86|
| Road          | 0.18 | 63.20| 2.01 | 1.15  | 6.77 |
| Bare land     | 0.26 | 572.50| 0.59 | 0.52  | 5.96 |
| Roof          | 0.03 | 34.80| 1.03 | 0.66  | 0.26 |
| Others        | 0.17 | 173.33| 1.43 | 0.90  | 5.96 |
| Sunken green space | 0.11 | 11.40| 1.05 | 0.63  | 9.93 |

Table 2. Pollutant attenuation coefficients

| Pollutant type | TP   | TSS  | TN   | NH3-N | COD  |
|----------------|------|------|------|-------|------|
| Attenuation coefficient (/h) | 0.416| 0.612| 1.028| 0.1   | 0.2  |

Table 3. Roughness coefficients of different underlying surfaces

| Underlying surface | Building | Grassland | Water body | Others |
|--------------------|----------|-----------|------------|--------|
| Roughness          | 0.0455   | 0.016     | 0          | 0.031  |

The water quality and depth data at the six flooding points in the rainfall data of July 24, 2016 and July 2, 2018 were used to validate the model. The accuracy and applicability of the model were evaluated by the Nash–Sutcliffe efficiency coefficient (NSE),

\[
NSE = 1 - \frac{\sum (Y_i - Y_0^i)^2}{\sum (Y_i - \bar{Y}^0)^2}
\]

where \( Y_i \) is the simulated output, \( Y_0^i \) is the measured output, and \( \bar{Y}^0 \) is the average of the measured output.

NSE is insensitive to peak values, while the mean relative deviation BIAS is relatively sensitive to the peak values and expressed as

\[
BIAS = 1 - \frac{\sum |Y_i - Y_0^i|}{\sum Y_i}
\]

The fitting results of the measured and simulated water quality parameters (including SS, COD, TN, and TP) (Fig. 7) show that the NSE values of COD, TP, and TN all exceed 0.5, with a TP of 0.7 and a TN of 0.69, and the BIAS values all exceed 0.8. The relative errors between the simulated results (Table 4) and the measured data are all within 10%, indicating that the model can accurately simulate the distribution characteristics and water quality variation in the storm flooding in the study area.
3. Results and discussion

3.1. Stormwater runoff simulation

The influences of LID measures on runoff are studied using rainfalls with different return periods as inputs. In the simulation process, rainfalls with a return period of 2 or 3 years are used to represent medium-sized rainfall events, and rainfalls with a return period of 10 or 20 years are used to represent heavy rainfall events and above. The influences of LID measures on the surface runoff yield and concentration as well as the nonpoint source pollution control under rainfalls with different return periods are evaluated using the following three indicators: runoff duration (the time from the start to the end of runoff, which can characterize the overall ability of the study area to absorb and store rainwater), source reduction rate (the ratio of runoff before to runoff after the addition of LID measures, which can reflect the in situ capacity of the sunken green land to absorb rainwater under rainfalls with different return periods), the process control rate (the percent change of flow in the study area after the addition of LID measures, which can reflect the effects of LID measures on runoff reduction and delay under rainfalls with different return periods).

The outflow simulation results show that the flow processes under rainfalls with different return periods have similar trends; that is, the flow increases to a peak and then gradually decreases, with fluctuation, until the end of the rainfall process. The trend of the outlet flow hygrograph after the addition
of LID measures is similar to that before the addition, though the peak value is significantly reduced (Fig. 8). Specifically, the peak values of the outlet flow under rainfalls with return periods of 2, 3, 10, and 20 years decrease by 66.5%, 57.2%, 51.0%, and 48.2%, respectively. As the rainfall return period increases, the peak reduction ratio of the outlet flow in the runoff process gradually decreases. After the addition of LID measures, the runoff duration increases significantly, and the runoff delay time gradually decreases as the return period increases, and the runoff delay time under small and medium rainfalls is significantly greater than that under heavy rainfall. The runoff delay times under rainfalls with the four different return periods are 7.02 h, 6.28 h, 4.62 h, and 3.98 h, respectively (Fig. 9).

As the rainfall return period increases, both precipitation and runoff increase, but the source reduction rate decreases, and in particular, the source reduction rate of small and medium rainfalls is significantly higher than that of heavy rainfalls. The source reduction rates under the four rainfall return periods are 56.8%, 52.8%, 50.8%, and 50.9%, respectively (Fig. 10). As the rainfall return period increases, the outlet flow increases, as does the process control rate, showing values of 3.6%, 11.1%, 17.4%, and 20.4%, respectively, under the four rainfall return periods (Fig. 11).

3.2. Water quality simulation
Urban surface runoff pollution generally reaches the peak pollutant concentrations at the initial stage of rainfall. Therefore, this study selects the 2-h rainfall process with return periods of 1, 3, and 5 years to investigate the runoff pollution process and total pollution load under short-duration heavy rainfall with different return periods.
Under the rainfall return period of 1 year, the removal rate of TN is 51.1%, but the removal rates of all other pollutants are above 80%. Under a rainfall return period of 3 years, the removal rates of pollution loads TN, TP, TSS, NH3-N, and COD are 49.7%, 58.9%, 56.7%, 67.2%, and 63.1%, respectively. Under a rainfall return period of 5 years, the removal rates of TN, TP, TSS, NH3-N, and COD are 37.6%, 39.8%, 40%, 40.8%, and 40.5%, respectively (Fig. 12). As the rainfall return period increases, the pollution load of each pollutant gradually increases, but the pollution load removal rate gradually decreases.

![Figure 12. Pollution loads and removal rates](image)

After adding LID measures, the peak pollutant concentrations decrease (Table 5). Under each condition, the peak reduction effects on TN, TSS, and NH3-N are the most significant, indicating that the three pollutants are more retained during the initial stage of rainfall; that is, the peak reduction effects of LID measures on the three pollutants are relatively good. In addition, after the LID measures are added, the peak pollutant concentrations are all delayed. Under the rainfall return periods of 1, 3, and 5 years, the peak pollutant concentrations are delayed on average by 9 to 10 min, 2 to 3 min, and 2 to 5 min, respectively (Table 6). Therefore, the small and medium rainfalls are more sensitive to the peak pollutant concentration.

**Table 5. Peak pollutant concentration at drainage outlets (unit: mg/L)**

| Return period | Condition | TN  | TP  | TSS | NH3-N | COD   |
|---------------|-----------|-----|-----|-----|-------|-------|
| 1A            | w/o LID   | 1.45| 0.16| 34.31| 1.45  | 12.59 |
|               | with LID  | 1.22| 0.15| 29.65| 1.22  | 11.71 |
|               | Peak reduction (%) | 15.8 | 9.4 | 13.6 | 15.8 | 7.0   |
| 3A            | w/o LID   | 1.81| 0.18| 42.87| 1.35  | 13.75 |
|               | with LID  | 1.74| 0.18| 41.22| 1.32  | 13.48 |
|               | Peak reduction (%) | 4.2 | -   | 3.9  | 2.2  | 1.9   |
| 5A            | w/o LID   | 1.84| 0.18| 44.78| 1.36  | 13.79 |
|               | with LID  | 1.34| 0.18| 42.95| 1.34  | 13.64 |
|               | Peak reduction (%) | 27.1 | -   | 4.1  | 1.5  | 1.1   |

**Table 6. Occurrence times of peak pollutant concentrations at drainage outlets (unit: min)**

| Return period | Condition | TN  | TP  | TSS | NH3-N | COD   |
|---------------|-----------|-----|-----|-----|-------|-------|
| 1A            | w/o LID   | 64  | 65  | 63  | 64    | 68    |
|               | with LID  | 73  | 75  | 72  | 73    | 78    |
|               | Delay (min) | 9   | 10  | 9   | 9     | 10    |
| 3A            | w/o LID   | 47  | 46  | 46  | 47    | 51    |
|               | with LID  | 50  | 49  | 49  | 50    | 53    |
|               | Delay (min) | 3   | 3   | 3   | 3     | 2     |
3.3. Urban flooding simulation

The flooding at the flooding points before and after adding LID measures under rainfalls with different return periods is analyzed. The boundary conditions are defined as the long-duration rainstorm processes with return periods of 2, 3, 5, 10, and 20 years. The entire process of flooding in the study area is simulated and calculated under a 24-h duration rainfall process with a time step of 5 min. The threshold of the flooding depth is set to 15 cm and 25 cm, considering that when the flooding depth exceeds 15 cm, the lanes may be completely interrupted due to vehicle stalls, and when the flooding depth exceeds 25 cm, the flooding problem becomes severe.

The simulation results show that under the rainfall conditions with return periods of 1, 3, and 5 years, there is no obvious flooding area; under the rainfall conditions with return periods of 10 and 20 years, there are a total of six relatively notable flooding points, labeled A to F in Figure 13.

| 5A | w/o LID | 45 | 47 | 67 | 45 | 48 |
|----|---------|----|----|----|----|----|
| w/ LID | 47 | 49 | 72 | 47 | 50 |
| Delay (min) | 2 | 2 | 5 | 2 | 2 |

3.3.1. Simulation of flooding characteristics

We extract the surface areas with flooding over 15 cm and 25 cm (Fig. 14), and the results show that for the areas with flooding depths above 15 cm, the depth rapidly reaches the maximum at the initial stage of rainfall, and then the increasing trend slows down until the end of the rainfall, so the peak waterlogged area usually occurs between the first rainfall peak and the end of the rainfall. In addition, the occurrence time of the maximum flooded area correlates with the rainfall intensity. The peak flooding area under rainfall with a return period of 20 years occurs at 88 min, but the maximum flooding areas under rainfalls with other return periods all occur at the end of the rainfall time (Fig. 15).
For the flooding depths of 25 cm or more, the depth rapidly reaches the peak value at the initial stage of rainfall, then decreases rapidly, and rebounds around the rainfall peak, after which it decreases slowly. When no LID measure is implemented, the initial peak is the maximum only under rainfalls with return periods of 10 and 20 years, both occurring at 77 min after the rainfall starts. After LID measures are added, the initial peak flooding area is the maximum only under rainfall with a return period of 20 years, occurring at 75 min, and the maximum values under other rainfall conditions all occur near the rainfall peak. Therefore, the maximum area of severe flooding (depth > 25 cm) often occurs in the early to middle stage of a rainfall event, while the maximum area where there is a flooding depth greater than 15 cm often occurs in the middle to late stages of a rainfall event.

After LID measures are added, the maximum flooded area with a flooding depth of over 15 cm under rainfalls with return periods of 2, 3, 5, 10, and 20 years decreases by 24.6%, 22.1%, 30.2%, 32.1%, and 29.3%, respectively, and the corresponding maximum flooded area with a depth of over 25 cm decreases by 13%, 19.8%, 39%, 51.7%, and 49.4%, respectively. Hence, the improvement effect of LID measures when there is a flooding depth of 25 cm is significantly better than that when the flooding depth is greater than 15 cm.

3.3.2 Flooding improvement effect
The flooded areas with different flooding durations in the study area are statistically analyzed (Fig. 16). Under rainfalls with each return period, the areas with flooding depths over 15 cm and 25 cm both decrease as the duration of flooding increases, with more pronounced changes in the areas with depths over 25 cm. Under rainfalls with a return period of 20 years, before the addition of LID measures, the...
areas with a flooding depth over 15 cm and 25 cm and a flooding time of more than 90 min are 132 ha and 32 ha, respectively; after the addition of LID measures, the corresponding areas are reduced to 101 ha and 22 ha, respectively. As the rainfall return period decreases, the flooded area corresponding to each flooding depth decreases.

(a) Flooded surface area with waterlogging depth greater than 15 cm
(b) Flooded surface area with waterlogging depth greater than 25 cm.

(c) Improvement effect on surface flooded area with waterlogging depth greater than 15 cm
(d) Improvement effect on surface flooded area with waterlogging depth greater than 25 cm.

Figure 16. Flooded areas corresponding to different durations of flooding under rainfalls with different return periods

There are also certain patterns in the improvement effect of LID measures on the flooding areas with different durations of flooding. The improvement effect is more notable under rainfalls with relatively long return periods (e.g., 10 and 20 years). For a flooding depth of 15 cm or more, the improvement effect under rainfalls with a return period of 10 and 20 years is approximately 50% and 35%, respectively. For a flooding depth of 25 cm or more, the improvement effects under rainfall with a return period of 10 and 20 years are both approximately 23%. It can be clearly seen that the improvement effect of LID measures under rainfalls with each return period decreases slowly as the duration of flooding increases.

Under rainfalls with the same return period, the improvement effect of LID measures on the flooding area with different durations of flooding is also associated with the flooding depth. Under a rainfall with a return period of 20 years, when the flooding depth is more than 15 cm and 25 cm and the flooding duration is more than 10 min, the improvement effect is 50% and 24%, respectively. There are similar patterns under other rainfall conditions. That is, LID measures have a certain improvement effect on the flooding duration of areas with low flooding depths.
By comparing the flooding at the flooding points before and after the addition of LID measures, we find that before LID measures are added, the average maximum flooding depths under the two working conditions are 47.7 cm and 64.3 cm, respectively; after LID measures are added, the average maximum flooding depths are 16.8 cm and 23.8 cm, amounting to a decrease of 65% and 63%, respectively. In particular, the flooding at points D, C, and E is more severe; under a rainfall return period of 20 years, the maximum flooding depths at those three points are 93 cm, 86 cm, and 63 cm, respectively. After LID measures are added, the maximum flooding depths are 28 cm, 30 cm, and 26 cm, respectively.

4. Conclusion
Using Xi’an as the study area, a coupling model of the urban drainage (rainwater) flooding prevention system was constructed on the MIKE FLOOD platform, and the effects of LID measures on the control and improvement of urban stormwater runoff and water quality under different rainfall conditions were discussed. The results are as follows: (1) The constructed coupling model of the urban drainage (rainwater) flooding prevention system has good applicability and can accurately simulate the processes and characteristics of urban stormwater runoff and water quality. (2) As the rainfall return period increases, the process control rate increases, and the source reduction rate decreases. After LID measures are added, the runoff process is delayed, the peak value decreases, and the runoff duration increases. As the rainfall return period increases, both the peak outlet flow and pollution load of the pipe networks in the study area increase. After LID measures are added, the peak pollutant concentrations decrease and are delayed. The rates of peak flow reduction and pollution load removal by LID measures gradually decrease as the rainfall return period increases. (3) In this study, the maximum area of severe flooding (depth > 25 cm) occurs in the early to middle stage of a rainfall event, while the maximum area with a flooding depth greater than 15 cm occurs in the middle to late stages. After LID measures are added, both the flooding area and depth in the study area decrease, and the average maximum flooding depths at the flooding points under rainfall return periods of 10 and 20 years decrease by 65% and 63%, respectively. LID measures have certain improvement effects on the flooding depth and short-duration flooding in the study area.
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References
[1] Ahiablame, L.M.; Engel, B.A.; Chaubey, I. Effectiveness of low impact development practices: Literature review and suggestions for future research. Water. Air. Soil Pollut. 2012, doi:10.1007/s11270-012-1189-2.
[2] Xiaomeng, S.; Jianyun, Z.; Ruimin, H. Urban flood and waterlogging and causes analysis in Beijing. Adv. Water Sci. 2019, 30, 153–165.
[3] Hallegatte, S.; Green, C.; Nicholls, R.J.; Corfee-Morlot, J. Future flood losses in major coastal cities. Nat. Clim. Chang. 2013, doi:10.1038/nclimate1979.
[4] BAKER, J.A. Resolving Crustal and Mantle Contributions to Continental Flood Volcanism, Yemen; Constraints from Mineral Oxygen Isotope Data. J. Petrol. 2000, doi:10.1093/petrology/41.12.1805.
[5] Van Der Wiel, K.; Kapnick, S.B.; Jan Van Oldenborgh, G.; Whan, K.; Philip, S.; Vecchi, G.A.; Singh, R.K.; Arrighi, J.; Cullen, H. Rapid attribution of the August 2016 flood-inducing extreme precipitation in south Louisiana to climate change. Hydrol. Earth Syst. Sci. 2017, doi:10.5194/hess-21-897-2017.
[6] Chen, L.; Singh, V.P.; Shenglian, G.; Hao, Z.; Li, T. Flood Coincidence Risk Analysis Using Multivariate Copula Functions. J. Hydrol. Eng. 2012, doi:10.1061/(ASCE)HE.1943-5584.0000504.
[7] Guangnai, X.; Youpeng, xu; Hongliang, X. Advance in Hydrologic Process Response to Urbanization. J. Nat. Resour. 2010, 25, 2171–2178.
[8] McQueen, A.D.; Johnson, B.M.; Rodgers, J.H.; English, W.R. Campus parking lot stormwater runoff: Physicochemical analyses and toxicity tests using Ceriodaphnia dubia and Pimephales promelas. Chemosphere 2010, doi:10.1016/j.chemosphere.2010.02.004.
[9] Ana, E. V.; Bauwens, W. Modeling the structural deterioration of urban drainage pipes: The state-of-the-art in statistical methods. Urban Water J. 2010, doi:10.1080/15730620903447597.
[10] Lee, J.G.; Heaney, J.P.; Lai, F.H. Optimization of integrated urban wet-weather control strategies. J. Water Resour. Plan. Manag. 2005, doi:10.1061/(ASCE)0733-9496(2005)131:4(307).
[11] Grant, S.B.; Saphores, J.D.; Feldman, D.L.; Hamilton, A.J.; Fletcher, T.D.; Cook, P.L.M.; Stewardson, M.; Sanders, B.F.; Levin, L.A.; Ambrose, R.F.; et al. Taking the “waste” out of “wastewater” for human water security and ecosystem sustainability. Science (80-. ). 2012.
[12] Rose, S. The effects of urbanization on the hydrochemistry of base flow within the Chattahoochee River Basin (Georgia, USA). J. Hydrol. 2007, doi:10.1016/j.jhydrol.2007.04.019.
[13] Shuangcheng, T.; Wan, L.; Zhonghua, J.; Shan, L.; Yan, W.; Meng, Z. Effect of rain gardens on storm runoff reduction. Adv. Water Sci. 2015, 26, 787–794.
[14] Lee, J.Y.; Moon, H.J.; Kim, T.I.; Kim, H.W.; Han, M.Y. Quantitative analysis on the urban flood mitigation effect by the extensive green roof system. Environ. Pollut. 2013, doi:10.1016/j.envpol.2013.06.039.
[15] Drake, J.; Bradford, A.; Van Seters, T. Hydrologic Performance of Three Partial-Infiltration Permeable Pavements in a Cold Climate over Low Permeability Soil. J. Hydrol. Eng. 2014, doi:10.1061/(ASCE)HE.1943-5584.0000943.
[16] Deletic, A.; Fletcher, T.D. Performance of grass filters used for stormwater treatment - A field and modelling study. J. Hydrol. 2006, doi:10.1016/j.jhydrol.2005.05.021.
[17] Yanwei, S.; Xiaomei, W.; C A, P. Review of current research and future directions of low impact development practices for storm water. Adv. Water Sci. 2011, 22, 287–293.
[18] Yongxin, W.; Lihong, Z. Study on urban waterlogging numerical simulation base on low impact development. J. Water Resour. Water Eng. 2017, 28, 114–119.
[19] Li, J.; Zhang, B.; Li, Y.; Li, H. Simulation of rain garden effects in urbanized area based on miKE Flood. Water (Switzerland) 2018, doi:10.3390/w10070860.

[20] Ruiling, S.; Hua, W.; Ningjun, H.; Huaian, L.; Sheping, W.; Bin-ling, Z.; Ning, W.; Zhaoxian, D. Effect simulation and evaluation of low-impact development measures in new city. China Water & Wastewater 2016, 32, 141–146.

[21] Zuopeng, H.; Zhiqiang, L.; Sen, P.; Zhipeng, A. Simulation of storm water runoff control effect by low impact development (LID). Chinese J. Environ. Eng. 2016, 10, 3956–3960.

[22] Qiongni, C.; Zhihe, C.; Xing, C.; Xingzhen, C.; Danlong, Z. Simulation of control efficiency of low impact development measures for urban stormwater. Water Resour. Prot. 2017, 33, 31–36.

[23] Kwak, D.; Kim, H.; Han, M. Runoff Control Potential for Design Types of Low Impact Development in Small Developing Area Using XPSWMM. In Proceedings of the Procedia Engineering; 2016.

[24] Ahiablame, L.; Shakya, R. Modeling flood reduction effects of low impact development at a watershed scale. J. Environ. Manage. 2016, doi:10.1016/j.jenvman.2016.01.036.

[25] Elliott, A.H.; Trowsdale, S.A. A review of models for low impact urban stormwater drainage. Environ. Model. Softw. 2007, doi:10.1016/j.envsoft.2005.12.005.

[26] Zoppou, C. Review of urban storm water models. Environ. Model. Softw. 2001.

[27] Karamouz, M.; Hosseinpour, A.; Nazif, S. Improvement of urban drainage system performance under climate change impact: Case study. J. Hydrol. Eng. 2011, doi:10.1061/(ASCE)HE.1943-5584.0000317.

[28] Shon, T.S.; Kim, S.D.; Cho, E.Y.; Im, J.Y.; Min, K.S.; Shin, H.S. Estimation of NPS pollutant properties based on SWMM modeling according to land use change in urban area. Desalin. Water Treat. 2012, doi:10.1080/19443994.2012.664382.

[29] Chapman, C.; Horner, R.R. Performance Assessment of a Street-Drainage Bioretention System. Water Environ. Res. 2010, doi:10.2175/106143009x426112.

[30] Debusk, K.M.; Wynn, T.M. Storm-water bioretention for runoff quality and quantity mitigation. J. Environ. Eng. 2011, doi:10.1061/(ASCE)EE.1943-7870.0000388.

[31] Tao, C.; Zongxue, X.; Sulin, S. Rainfall-runoff simulations for Xinglong sponge city pilot area of Jinan. J. Hydroelecrr. Eng. 2017, 36, 1–11, doi:10.11660/slfzxb.20170601.

[32] Guan, M.; Sillanpää, N.; Koivusalo, H. Assessment of LID practices for restoring pre-development runoff regime in an urbanized catchment in Southern Finland. Water Sci. Technol. 2015, doi:10.2166/wst.2015.129.

[33] Lee, J.M.; Hyun, K.H.; Choi, J.S. Analysis of the impact of low impact development on runoff from a new district in Korea. Water Sci. Technol. 2013, doi:10.2166/wst.2013.346.

[34] Li, J.; Ma, M.; Li, Y.; Zhang, Z. Influence analysis of different design conditions on urban runoff and nonpoint source pollution. Water Environ. Res. 2019, doi:10.1002/wer.1154.

[35] Shuiqing, Y.; Yang, W.; Yun, X.; Anlin, L. Characteristics of intrastorm temporal pattern over China. Adv. Water Sci. 2014, 25, 617–624, doi:10.14042/j.cnki.32.1309.2014.05.001.

[36] Xu, B.; Long, C.; Dongsheng, Y. Analysis on Urban Rainstorm Pattern of Xi’an. J. Anhui Agric. Sci. 2015, 43, 295-297+325, doi:10.13989/j.cnki.0517-6611.2015.35.107.