Analysis and Comparison on the Flood Simulation in Typical Hilly & Semi-mountainous Region

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Abstract. Water-logging and flood are both serious in hilly and semi-mountainous cities of China, but the related research is rare. Lincheng Economic Development Zone (EDZ) in Hebei Province as the typical city was selected and storm water management model (SWMM) was applied for flood simulation in this study. The regional model was constructed through calibrating and verifying the runoff coefficient of different flood processes. Different designed runoff processes in five-year, ten-year and twenty-year return periods in basic scenario and in the low impact development (LID) scenario, respectively, were simulated and compared. The result shows that: LID measures have effect on peak reduction in the study area, but the effectiveness is not significant; the effectiveness of lagging peak time is poor. These simulation results provide decision support for the rational construction of LID in the study area, and provide the references for regional rain flood management.

1. Introduction

Recently, the regional underlying surface changed greatly with the acceleration of urbanization and short-duration storm resulted by the climate change in China. These changes have resulted in frequent waterlogging in Chinese cities and caused the large casualties and property losses. Therefore, runoff peak and discharge reduction, peak time lagging and accurate flood forecast is meaningful and crucial to the urban flood prediction, warning and management.

Lots of countries have implemented measures from the source to control the peak discharge and runoff quantity; and the evaluation on the control effect is a hot topic of urban hydrology [1-2]. In all the measures, LID is a commonly used one; and it is a rain management system proposed by the United States. In the LID system, through the distributed interception, bio-retention and other measures, impervious area can be reduced, runoff path can be extended and the runoff duration can be increased; and then, the storage and infiltration of runoff, the recharge of groundwater and reduction of runoff discharge can be achieved; at last, the utilization of storm and protection of river environment can be realized [3]. In the aspect of urban flood warning, an important method is to establish the urban flood forecasting model. Since the 1990s, the rapid development of computer and “3S” technology has promoted the continuous optimization of the urban flood model, and lots of urban flood models...
integrated with the GIS and dynamic monitoring have emerged at the right moment; at present, the widely used models include SWMM, MIKE21, STORM, ILLUDAS, DR3M-UQAL, UCURM, HSP, WALLINGFORD, TRRL, etc.\cite{4-5}. In these models, SWMM is the most typical one released by the Environmental Protection Agency (EPA), and it has been widely used by scholars in the world about the urban storm flood simulation, design of drainage pipe network and waterlogging risk assessment process, etc.\cite{6-7}.

Although the application of SWMM and LID in plain urban areas of China is widely used\cite{8}, there are still relatively few studies on the mountainous region and semi-mountainous region. This study is evaluated the LID effectiveness of controlling the storm runoff with different return periods in the typical hilly and semi-mountainous region on peak reduction and peak time lagging, based on the SWMM, so as to further promote the applicability of SWMM in different regions and enrich related contents of urban hydrology.

2. Data Collection

2.1 Study Region
This study area is Lincheng EDZ located in the middle east of Lincheng County, Hebei Province, China; it is mainly divided into the eastern and western areas, with a total planning area of 100km$^2$; it belongs to the hilly area in semi-mountainous region, and its geographical location is shown in the Figure 1. Lincheng EDZ locates in a warm, semi-humid zone of the East Asia monsoon region, with annual average temperature of 13.5°C and annual average precipitation of 605mm; and the precipitation in this area mainly concentrates from June to August. Lincheng EDZ is characterized by steep terrain, so it is easy to cause large slope runoff and regional flood in this region. On the basis of investigation, survey and research of the underlying surface, the digitization of Lingcheng EDZ was completed, totally consisting of 159 sub-catchments, 117 drainage pipes, 117 sub-catchment nodes and 3 water outlets, as shown in the Figure 2. The main drainage path is along the road, which means the main runoff form is surface flow. This above property of runoff in the study region influences the daily lives and transportation of local residents. Therefore selecting this region is significant to manage the flood warning and waterlogging control in the hilly areas.

2.2 Rainfall Process
In this study, the designed rainfall with different return periods and the typical rainfall on July 19, 2016 (for short "7.19" storm) were chosen as the model inputs. The "7.19" storm belongs to the heavy storm process and it is the third largest storm in the region, so it is typical and representative. The designed rainfall process was coupled with the local rainfall handbook and empirical Chicago pattern; the characteristics of the designed rainfall processes with the return period of 1, 5, 10 and 20 years and "7.19" storm are shown in the table 1. The "7.19" rainfall process is used for calibration, while the designed rainfall with one-year return period is used for model validation.

![Figure 1. Station of the study area.](image)
3. Regional SWMM

3.1 Initial Value of Model Parameters
The parameters of drainage pipe network, slope of sub-catchment, sub-catchment area and impervious percentage of sub-catchment were set according to the collected data and investigation results. Due to the flexibility of Horton formula, it is used to simulate and calculate the infiltration quantity of the catchment \(^9\). The characteristic width of sub-catchment is calculated by formula (1), in which, \(W\) indicates the characteristic width, \(K\) indicates the characteristic width coefficient which needs to be calibrated, and \(A\) indicates the sub-catchment area \(^{10-11}\). For the other parameters which need to be calibrated, their initial values shall be determined in accordance with the empirical range in the \(SWMM\) User Manual and the related references \(^{10-11}\).

\[
Width = K \times \sqrt{A} \quad (0.2 \leq K \leq 5)
\] (1)

3.2 Model Calibration and Validation
The empirical runoff coefficient method was applied in this study for model calibration and validation, in which, the "7.19" rainfall process for calibration and one-year designed rainfall process for validation due to the lack of the observed rainfall data. The calibration result of comprehensive runoff coefficient is 0.29 and the validation one is 0.17. These results are reasonable after referring to the related researches \(^{12-13}\), according to the properties of this hilly region and the magnitude of "7.19" storm.

4. Results and Analysis

4.1 Basic Scenario
The basic scenario refers to the scenario without LID measures. The drainage pipe network in the region is shown in Figure 2, and the rainfall inputs are the designed rainfall process with return period of 5, 10 and 20 years.

4.2 LID Scenario
The two LID measures (concave greenbelt and permeable pavement) were selected in this study, according to the application conditions of the related guideline \(^{14}\), the regional geomorphologic...
properties and local underlying surface characteristics; and the detail distribution is due to the functions and properties of the two measures \[14\] and the waterlogging situation of "7.19" storm in different sub-catchments in basic scenario. The rainfall runoff processes under different return period were simulated through SWMM in LID scenario and the related effectiveness of these two LID measures on runoff control was evaluated. The maximum waterlogging depth of eleven sub-catchments (No.21, No.28, No.32, No.44, No.46, No.52, No.58, No.107, No.112, No.125 and No.127) is much larger than that of the other sub-catchments, so the concave greenbelt is set here (Figure 3). The setting of permeable pavement is due to the waterlogging situation of the roads. In this study, permeable pavements are arranged on the municipal roads of fourteen sub-catchments (No.19, No.30, No.43, No.47, No.50, No.82, No.83, No.86, No.90, No.96, No.100, No.103, No.157 and No.159, shown in Figure 3).

Considering the project cost, based on the results of on-site investigation and related manual \[15\], the water storage depths of concave greenbelt and permeable pavement are both set as 200mm; and the storage area in each sub-catchment of concave greenbelt and permeable pavement is 50% and 40% respectively, in this study. The measures in LID scenario refer to the combination of concave greenbelts and permeable pavements according to the designed parameters and distributions. The rainfall processes are the same with that in the basic scenario, the designed rainfall process with return period of 5, 10 and 20 years were also selected in order to be convenient for comparison analysis.

![Figure 3. The distribution of the simulated peak discharge of the "7.19" storm.](image)

### 4.3 Results in Different Scenarios

The rainfall runoff processes in different scenarios with return period of 5, 10 and 20 years are shown in Figure 4 and the simulated peak time, peak runoff depth and runoff volume are listed in Table 2. The comparisons can be calculated and illustrated through Figure 4 and Table 2 that (1) the maximum runoff depth with five-year return period is reduced as 2.328mm after applying LID measures, with a reduction percentage of 21.33%, and its runoff volume is reduced as 0.94×10^5m^3 with a reduction percentage of 23.92%; (2) the maximum runoff depth with ten-year return period is reduced as 3.132mm after applying the LID measures, with a reduction percentage of 21.61%, and its runoff volume is reduced as 1.28×10^5m^3 with a reduction percentage of 23.88%; (3) the maximum runoff depth with twenty-year return period is reduced as 3.952mm after applying the LID measures, with a reduction percentage of 21.82%, and its runoff volume is reduced as 1.63×10^5m^3 with a reduction percentage of 23.56%.

These comparison results illuminate that the two LID measures have some effect on flood peak reduction and the peak reduction depth increases with the increase of the return period, but the decline of the reduction percentage is little. Although these LID measures have an effect on runoff reduction, their effectiveness on the reduction percentage can’t catch the runoff control target in related guideline \[14\]. The LID measures even have a negative effect on the peak time lagging because all the peak time of rainfall runoff emerges one minute ahead after applying the LID measures. In a word, the combination measures of concave greenbelt and permeable pavement do not play a fundamental role...
in runoff control in Lincheng EDZ in this study.

Figure 4. Runoff processes with different return periods (a) 5 years, (b) 10 years, (c) 20 years.

Table 2. Comparison of regional peak and runoff in different scenarios.

| Return Period | Different Scenarios | Peak Time | Peak depth(mm) | Peak Reduction (%) | Runoff Volume ($\times 10^5 m^3$) | Runoff Reduction (%) |
|---------------|---------------------|-----------|----------------|-------------------|-----------------------------------|----------------------|
| 5 years       | Basic               | 18:40     | 10.912         |                   | 3.93                              |                      |
|               | LID                 | 18:39     | 8.584          |                   | 21.33                             | 2.99                 |
| 10 years      | Basic               | 18:36     | 14.496         |                   |                                   | 5.36                 |
|               | LID                 | 18:35     | 11.364         |                   | 21.61                             | 4.08                 |
| 20 years      | Basic               | 18:35     | 18.116         |                   | 21.82                             | 5.29                 |
|               | LID                 | 18:34     | 14.164         |                   |                                   | 23.56                |

5. Conclusion and discussion

This study applied SWMM model and selected Lincheng EDZ as the typical hilly urban region to simulate and analyze the effectiveness of LID. The regional runoff coefficient was used to calibrate and verify the model with the typical observed storm "7.19" and the designed rainfall with one-year return period; according to distribution of the maximum waterlogging depth of "7.19" storm in different sub-catchments and roads, two LID measures (concave greenbelt and permeable pavement) were designed and the designed rainfall with return period of 5, 10 and 20 years were calculated and input. The result shows that: the peak reduction rate is 21.33%, 21.61% and 21.82% respectively, and the runoff reduction rate is 23.81%, 23.87% and 23.66% respectively under the different design rainfall with return period of 5, 10 and 20 years in the LID scenario, but the peak time emerges one minute ahead. In conclusion, LID measures have not significant effects on the peak and runoff reduction.

However, LID measures have obvious effects on the peak reduction and peak time lagging in other areas, especially in plain areas [16-17]; this is not similar with the results of this study. In the research area, the geomorphology slopes are steep, so the speed of flow is much faster and the runoff process is shorter than that in the plain areas in the natural condition; therefore, the detention storage is more difficult after rainfall and confluence, and it is also more difficult to play the role of LID. In future, vegetative swale or bio-retention measures would be designed in the high terrain area (upstream) according to the topography in order to buffer the flow velocity while the concave greenbelt and
permeable pavement would be designed in the low terrain area (downstream) to increase the runoff infiltration, and then their comprehensive effectiveness would be evaluated.

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References
[1] Jia H, Lu Y, Shaw L Y, et al. Planning of LID–BMPs for urban runoff control: The case of Beijing Olympic Village [J]. Separation & Purification Technology, 2012, 84(2): 112-119.
[2] Burszta-Adamiak E, Mrowiec M. Modelling of green roofs’ hydrologic performance using EPA’s SWMM [J]. Water Science & Technology, 2013, 68(1): 36-42.
[3] Dietz ME. Low impact development practices: A review of current research and recommendations for future directions [J]. Water, Air, Soil Pollut., 2007, 186(4): 351-364.
[4] Xiang Liu. Rainfall Runoff Analysis and Simulation in the Urban Areas [D]. Nanjing: Hohai University, 2005.
[5] Shoushan Chen. Study on the Simulation and Utilization of Storm Water in Urban Area [D]. Nanjing: Hohai University, 2007.
[6] Karamouz M, Hosseinpour A, Nazif S. Improvement of urban drainage system performance under climate change impact: Case study [J]. Journal of Hydrologic Engineering, 2011, 16(5): 395-412.
[7] Shon T S, Kim S D, Cho E Y, et al. Estimation of NPS pollutant properties based on SWMM modeling according to land use change in urban area [J]. Desalination and Water Treatment, 2012, 38(1-3): 267-275.
[8] Shuang he, Jun Liu, Jiaqi Zhu. Rainwater Control and Utilization Effect Assessment and Simulation of Low Impact Development Based on SWMM [J]. Water Resources and Power, 2013, 31(12): 42-45.
[9] Xingchao Zhang, Fanchen Meng, Shuhan Zhang et al. A rainfall-runoff process simulation in Beijing Fragrant hill area based on the SWMM model [J]. Beijing Water, 2014, (06): 5-9.
[10] Shengjie Zhang, Yongwei Gong, Junqi Li. Case Study of Hydrological Parameters Sensitivity Analysis Using SWMM [J]. Journal of Beijing University of Civil Engineering and Architecture, 2012, (1): 45-48.
[11] Chunlin Li, Yuanman Hu, Miao Liu et al. Local sensitivity analysis of parameters in Storm Water Management Model [J]. Chinese Journal of Ecology, 2014, (04): 1076-1081.
[12] Yingxue Liu. An Analysis of Surface Water Resources [J]. Groundwater, 2014, (04): 153-162.
[13] Wenxia Guo. Characteristics of Xingtai Hydrology and Water Resources [A]. Construction technology and management, 2016:2.
[14] Ministry of Housing and Urban-Rural Development of the People’s Republic of China. Technical guidelines for the construction of sponge cities [R/OL], 2014-10-22.
[15] Lewis A. Rossman. STORM WATER MANAGEMENT MODEL USER’S MANUAL Version 5.0. Water Supply and Water Resources Division, National Risk Management Research Laboratory Cincinnati, OH 45268.
[16] Yongwei Gong, Haijun Qi, Junqi Li et al. Retention and Reduction of Rainwater on Urban Roads Based on Low Impact Development [J]. China Water & Wastewater, 2014, 30(09): 151-154, 158.
[17] Zuopeng Hu, Zhiqiang Liu, Seng Peng et al. Simulation of storm water runoff control effect by low impact development (LID). Chinese Journal of Environmental Engineering, 2016, 10(07): 3956-3960.