Analysis of Runoff Reduction Effect of Sponge Reconstruction in Old Urban Area Based on SWMM

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Abstract. In order to study the application and reconstruction effect of low impact development storm water management measures for old urban areas, Maiji District of Tianshui in Gansu Province as the typical sample, SWMM model was established to analyze the reduction effect of rainwater runoff after sponge reconstruction under different return periods. The results show that the total runoff control rate under each return period after reconstruction has significantly increased and is more than 50%. The decrease of runoff peak value and lag maximum value reached 59.06% and 12 min respectively. The maximum growth rate of infiltration is 48.83%, the growth rate of water storage gradually increased and finally stabilizes at about 73%. The reduction rate of drainage is all above 25% of the original, and the reduction rate of accumulation reaches 71.4% when the return period is 1 year. The research results can provide guidance for the reconstruction of the old urban areas with the low return period rainstorm.

Keywords: low impact development · sponge city · old urban area · numerical calculation

1 Introduction

The sponge city concept was proposed in China in 2012, and it provides a new type of urban stormwater management to improve efficiency of rainfall utilization and urban flood control with low impact development (LID) technology as the main core [1]. A large number of studies showed that sponge city construction has significant effects on alleviating urban flooding. Huang M S et al. [2] analyzed the effect of flooding reduction in Guyuan before and after sponge construction by simulating the waterlogging accumulation under a typical design rainfall process; Tan Y R et al. [3] studied the pilot area of Xinglong in Jinan using SWMM model and found that the construction of sponge city can control the rainwater runoff and improve the surface runoff water quality. In recent years, rapid urbanization has led to the development of economics in China, while a series of water safety problems have emerged, which are particularly prominent in old urban areas with inadequate design and aging infrastructure, and seriously affected the daily lives of urban residents [4, 5].

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In this study, a typical old urban area in Maiji District of Tianshui is taken as the study area, and a SWMM model is constructed to calculate and analyze the runoff reduction effect of the old urban area based on data of different return periods after reconstruction, to provide theoretical support and experience promotion for the practice of sponge reconstruction in old urban areas. The study area is located in the eastern part belonging to a temperate semi-humid semi-arid zone, in which a multi-year annual average precipitation is 501.9 mm, obvious seasonal changes in precipitation, precipitation in summer and autumn mostly in the form of heavy rainfall. The area is developed to a large extent and has a mixed layout, whose buildings are dense and mostly old. The drainage capacity of the pipe network is poor, and the rainfall is discharged into the river by the combined rain and sewage pipes nearby, causing water pollution, and the road surface is very easy to form stagnant water. The main types of land in the study area are residential, road plaza, public buildings, parking lots and green areas, with a total area of 0.871 km^2.

2 Storm Water Management Model (SWMM)

2.1 Model Generalization

The stormwater management model (SWMM) is a dynamic precipitation-runoff simulation model, having the advantages of easy-to-understand operating interface and simple modeling [6], mainly used to simulate a single precipitation event in cities, and is widely used to simulate the evaluation of sponge construction. SWMM provides three calculation methods for pipe network confluence: the steady flow method, the kinematic wave method and the dynamic wave method. Because of the non-constant flow situation in the surface runoff process [7], the dynamic wave method is applied in our study. The infiltration process of the permeable area is significant, which has three main infiltration models: Horton, SCS-CN, and Green-Ampt respectively. The Horton model is more suitable for this simulation because the study area is located in an urban area and the simulation does not involve soil storage during rainfall [8]. The SWMM model of the study area consists of 31 subcatchments, 27 nodes, 27 links and 1 outlets, as shown in Fig. 1.

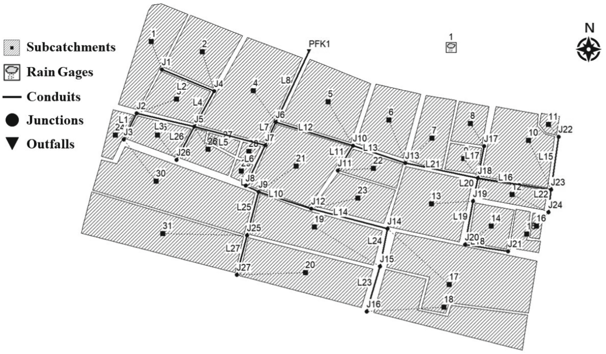

Fig. 1. The SWMM model of the study area

Table 1. Calibration process of model parameters based on runoff coefficient.

Parameters	Initial Values	Adjustment Values				
		First	Second	Third	Fourth	Fifth
N-Imperv	0.013	0.013	0.012	0.012	0.011	0.011
N-Perv	0.27	0.27	0.27	0.26	0.26	0.26
Dstore-Imperv/mm	2.3	2.3	2.2	2.2	1.8	1.8
Dstore-Perv/mm	6	5.9	5.7	5.6	5.5	5.5
Max. Infil. Rate/($\text{mm}\cdot\text{h}^{-1}$)	127	120	104	95	88	76
Min. Infil. Rate/($\text{mm}\cdot\text{h}^{-1}$)	14.3	13.5	10.9	8.6	6.6	4.7
Decay Constant/h^{-1}	11.2	11.2	11.2	10.4	10.4	10.4
Runoff Coefficient	0.364	0.398	0.434	0.479	0.567	0.590

2.2 Parameter Calibration

The parameters required in SWMM model are mainly divided into hydrological parameters, hydraulic parameters and quality parameters, among which hydrological parameters are more complex, including deterministic parameters obtained from measurements and empirical parameters. In this paper, the initial parameters are summarized from relevant references and the manual of SWMM [9, 10], and the runoff coefficient method is used to calibrate the accuracy of the parameters by comparing the runoff coefficients of the actual area with the total runoff coefficients of the catchment obtained from the SWMM model simulation, which can calibrate and verify the model parameters. According to the land use of the study area, it is determined that the study area is a densely built residential area with a comprehensive runoff coefficient of 0.5–0.7. Referring to the runoff coefficients for various types of surfaces in the specification [10, 11], and the weighted average of various types of subsurface areas to obtain the overall average regional runoff coefficient of 0.598. The model parameters were calibrated five times as shown in Table 1. The runoff coefficient increased continuously with parameter adjustment, and the fifth set of parameters calibration having the smallest relative error was finally determined as the calibrated model parameters [12].

2.3 Design Rainfall

According to the Technical guide for the construction of sponge city, Tianshui belongs to the total annual runoff control I zone, and the corresponding total annual runoff control rate is $85\% \leq \alpha \leq 90\%$. Taking into account the surface type, soil nature and topography, the total annual runoff control rate is set to 85%. The corresponding design rainfall is 18.8 mm from the statistical results of the multi-year average rainfall.

When the SWMM model is only used to evaluate the local drainage situation, if measured rainfall data is unavailable, the local urban design rainfall formula can be used to obtain the design rainfall process by combining the Chicago hyetograph or other rain patterns and substituting into the model for calculation [13]. The Chicago hyetograph

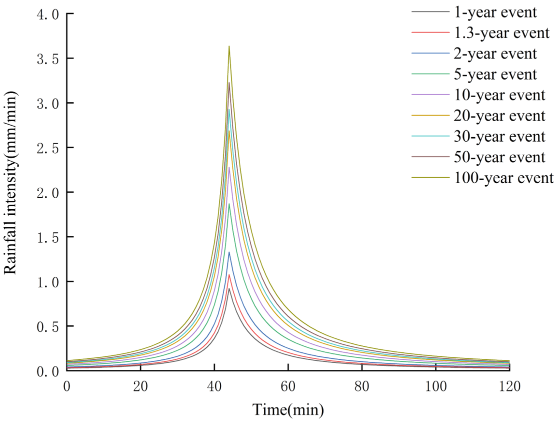

Fig. 2. Curves of 120 min rainfall process in different return periods in Tianshui

method is a typical rainfall process designed on the basis of the storm intensity formula. This method describes the moment of peak rainfall occurrence by introducing the rain peak location coefficient r, which can reflect the commonality of most rainfall and is consistent with the characteristics of short-duration rainstorms [14]. The Chicago hyetograph method was chosen to generate the relevant return period rainfall process for this simulation. According to the reference [15], the following storm intensity equation was used to calculate the design rainfall data in the study area:

$$i = \frac{10.3834 + 15.2967 \lg T}{(t + 15.3599)^{0.8867}} \tag{1}$$

Where: i is the storm intensity, mm/min; T is the return period of design rainfall, a; t is the rainfall duration, min.

In order to simulate the runoff generated by rainfall before and after sponge reconstruction in the study area using SWMM, rainfall with a return period of 1-year event, 1.3-year event (average design rainfall of 18.8 mm), 2-year event, 5-year event, 10-year event, 20-year event, 30-year event, 50-year event, and 100-year event were selected within 120 min. The distribution of LID in catchment areas. The usage of Chicago hyetograph generator to generate 120 min rainfall processes with different return periods, as shown in Fig. 2.

2.4 LID Setting

According to the guiding ideology and technical requirements of sponge city construction [16], as most of the old urban areas have large impervious areas, high buildings' density, limited green areas and open space areas, etc., applicable means with less cumbersome structure, simple and easy design and construction, less engineering impact, the shorter engineering cycle and higher functional benefits should be selected as far as possible in the reconstruction. Based on the planning and construction, topography and geology, rainfall and other regional characteristics of the study area, the reconstruction measures

Table 2. LID Measure Parameter Value.

Layer	Parameters	Permeable Pavement	Bio-Retention Cell	Green Roof
Surface	Berm Height/mm	15	150	200
	Vegetation Volume Fraction	0.2	0.7	0.15
	Surface Roughness	0.27	0.24	0.15
Soil	Thickness/mm	40	600	150
	Porosity	0.5	0.5	0.4
	Conductivity/(mm·h^{-1})	17	150	18
	Suction Head/mm	3.5	3.4	3
Storage	Thickness/mm	500	350	—
	Void Ratio	0.27	0.7	—

Fig. 3. The distribution of LID in sub catchments

are permeable pavement, bio-retention cell and green roofs [17, 18]. The specific LID parameters are shown in Table 2. The LID layout of the reconstruction is shown in Fig. 3.

3 Study Area Sponge Reconstruction Runoff Reduction Analysis

The SWMM model was used to simulate the rainfall control effect under the design storm with different return periods and time of 120 min before and after the sponge reconstruction in the study area. The total duration of simulation is 4 h, the time step is 1 min, and the dynamic wave model is selected for the pipeline transmission calculation.

Table 3. Calculation results of runoff control rate before and after LID reconstruction in the study area under different return periods.

Return Period/a	Total Precipitation/mm	Total Precipitation Volume/10^3 m^3	Before		After	
			Total Runoff/ 10^3 m^3	Runoff Control Rate/%	Total Runoff/ 10^3 m^3	Runoff Control Rate/%
1	16.12	14.04	7.60	45.87	1.62	88.46
1.3	18.82	16.39	9.24	43.63	2.23	86.39
2	23.27	20.26	11.95	41.05	3.51	82.69
5	32.71	28.48	17.69	37.89	7.66	73.10
10	39.86	34.71	22.15	36.19	11.55	66.73
20	47.01	40.94	26.73	34.71	15.79	61.43
30	51.19	44.58	29.46	33.92	18.29	58.96
50	56.46	49.17	32.94	33.00	21.48	56.32
100	63.60	55.38	37.79	31.76	25.85	53.33

3.1 Effect of Total Runoff Control

The runoff control rate could be calculated and shown in Table 3. The highest rate before the reconstruction within the return period of 1 year is 45.87%. In terms of overall trend, the higher return period, the larger total amount of runoff, while the smaller runoff control rate, such as 31.76% of the runoff control rate matching the 100-year event. The runoff control rate after the reconstruction increased significantly comparing with that before the reconstruction. After the reconstruction, the growth rate of the runoff control rate of rainfall in the low return period is higher than that in the high return period. If the design rainfall is 18.8mm, the return period is 1.3 years, the total runoff control rate is 86.39%, which meets the requirement of 85% of the total annual runoff control rate of Tianshui.

3.2 Peak Runoff Reduction Effect

The results of peak runoff calculation for different return periods of design rainfall are shown in Table 4. Sponge reconstruction obviously effects the reduction and lagging of peak runoff. The peak runoff is 3.20 m^3/s and the peak time is 68 min when the return period is 1 year before the reconstruction, with the increase of return period, the peak runoff increases to 19.61 m^3/s and the peak time reduces to 56 min within the 100-year return period; the peak runoff reduction and peak lag time both reach the maximum value of 59.06% and 12 min when the return period is 1 year after the reconstruction, but gradually decline afterwards, indicating that the sponge reconstruction has a greater impact on the peak runoff under the high frequency of small and medium rainfall comparing to the low frequency of large rainfall events.

Table 4. Calculation results of peak runoff before and after LID reconstruction in the study area under different return periods.

Return Period/a	Before		After	
	Peak Runoff/$m^3 \cdot s^{-1}$	Peak Time/min	Peak Runoff/$m^3 \cdot s^{-1}$	Peak Time /min
1	3.20	68	1.31	80
1.3	4.02	66	1.68	77
2	5.38	64	2.42	73
5	8.41	61	4.39	69
10	10.83	60	6.25	67
20	13.37	59	8.62	65
30	14.91	58	10.02	63
50	16.88	57	11.76	60
100	19.61	56	14.65	58

3.3 Comprehensive Analysis of Reconstruction Effect

According to the technical methods of "infiltration, retention, storage, purification, reuse and drainage" of sponge city construction, the amount of infiltration, storage, drainage and water accumulation in the study area before and after the reconstruction are calculated under different return periods, and the results are shown in Fig. 4. Figure 4(a) and 4(b) show the comparison of the changes of infiltration and storage with the increase of return period before and after the reconstruction, and the results show that the infiltration and storage after the reconstruction have different degrees of growth under each return period. The growth rate of infiltration reaches the maximum of 48.83% when the return period is 2 years, and then the infiltration continues to grow in a more stable rate with the increasing of return period, which indicates that permeable modification of the underlying surface can effectively increase the infiltration; the growth rate of storage gradually increases to 73.3% and stabilizes at about 73%, indicating that the sponge reconstruction facilities have good storage capacity. From Fig. 4(c) and 4(d), the comparison of the changes of drainage and accumulation with the increase of return period before and after the reconstruction is shown, in which the drainage after the reconstruction is at least 25% lower than that before the reconstruction in each return period, indicating that the sponge reconstruction facilities can effectively retain and utilize rainwater through "infiltration, retention and storage"; after the reconstruction, the amount of accumulation reduces up to 71.4% when the return period is 1 year, and the reduction rate of accumulation after the reconstruction is not obvious in other return periods, but on the whole it is reduced, indicating that the sponge reconstruction facilities can alleviate the amount of water on the road.

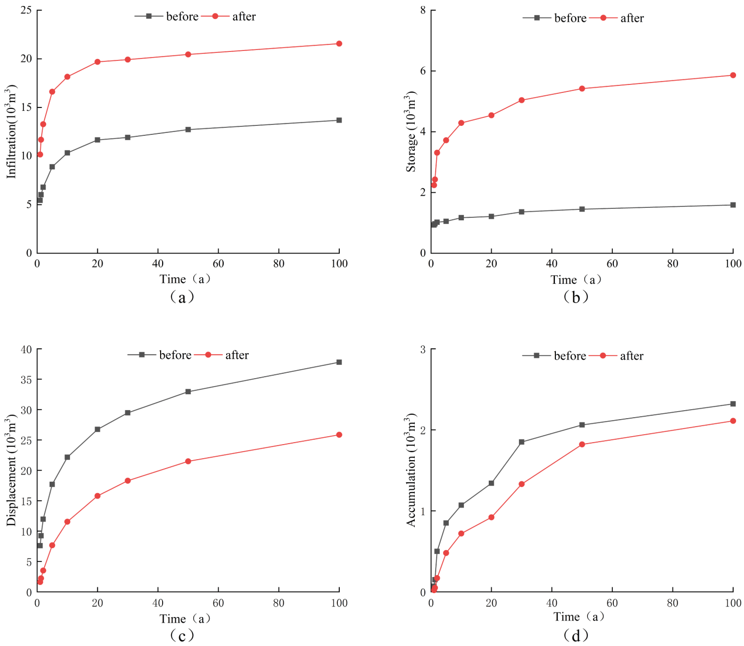

Fig. 4. Curves of infiltration, storage, drainage and accumulation of water before and after reconstruction under different return periods in the study area

4 Conclusions

In this paper, a SWMM model is established for a typical old urban area in Maiji District, Tianshui, and the optimization effects of total runoff, peak runoff, infiltration, storage, discharge and accumulation under different return periods of design rainfall before and after sponge reconstruction (combination of permeable pavement, bio-retention cell and green roof) were studied and analyzed. The conclusions obtained are as follows.

(1) The runoff control rate after the reconstruction increased significantly comparing with that before the reconstruction. If the design rainfall is 18.8mm (1.3 years), the total runoff control rate is 86.39%, which meets the requirement of 85% of the total annual runoff control rate of Tianshui.
(2) The peak runoff reduction and peak lag time both reach the maximum value of 59.06% and 12min when the return period is 1 year after the reconstruction.
(3) The growth rate of infiltration after the reconstruction reaches a maximum of 48.83% when the return period is 2 years, and the growth rate of storage gradually increases to 73.3% and stabilizes at about 73%; the drainage after the reconstruction is at least 25% lower than that before the reconstruction in each return period, and the accumulation reduces up to 71.4% when the return period is 1 year.

The above conclusions show that the sponge reconstruction combined with the study area’s own characteristics to select the corresponding reconstruction measures in the study area to get the better rainfall control effect, forming a more reasonable and feasible sponge reconstruction plan for the old city, which can provide guidance for similar areas in the sponge reconstruction.

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