Simulation Study on the Effect of Rainfall-runoff Control in Sponge Transformation Quarter in Northwest China

Liu Yang[1,2,*], Bing Wang[1,2], Bo Ma[3], Shuhong Xue[3], Xiao Yang[3] and Shili Wei[3]

[1]*State Key Laboratory of Eco-hydraulics in Northwest Arid Region of China, Xi'an University of Technology, Xi'an, China*
[2]*Research Center of Eco-hydraulics and Sustainable Development, The New Style Think Tank of Shaanxi Universities, Xi'an, China*
[3]*Power China Northwest Engineering Corporation Limited, Xi'an, China*

Keywords: Sponge transformation quarter, Rainfall-runoff, Control effect, Northwest China

Abstract: To cope with urban flooding, water pollution, and water shortage, China has proposed and continuously promoted sponge city construction. The quarter-scale site is the main carrier for the centralized deployment of small scattered sponge facilities, which is an important part of the urban stormwater system and an essential link to realize the source reduction of rainfall-runoff. The diversification of sponge facility types and structures and its combined applications have greatly changed the ecological background and hydrological characteristics of a quarter, and the nonlinear relationship of rainfall-runoff has become more complex. It is of great practical and guiding significance to study the role and effect of small community sponge transformation on the control of rainfall-runoff. Therefore, this study takes a sponge transformation quarter in northwest China as an example, based on the storm water management model, constructs a quarter rainfall model before and after spongy transformation, and carries out the process and effect analysis of rainfall-runoff control. The main research results show that: 1) During the monitoring period, after sponge transformation in the study area, the runoff control rate in response to 1.0 mm-45.5 mm rainfall event reached 83.49%-99.07%, with a better reduction effect on the peak flow and its occurrence time. 2) For the heavy rain event on August 3, 2019, the peak reduction rate was 69.7%, and the runoff control rate increased from 50.09% to 85.25% before the sponge transformation, and for the heavy rain event on June 27, 2019, the peak reduction rate was 58.79%, and the runoff control rate improved from 48.89% to 83.49% before the sponge transformation. 3) After the sponge transformation of the study area, the storage facilities played a better role in the storage, and the water depth of the standing water node was lower than before. For the storm event on June 27, 2019, the water depth in the rainwater discharge wells on the east side of the study area decreased by 0.05 m compared with that before the transformation, and the rainwater runoff control effect was apparent.

1 INTRODUCTION

China's urbanization rate exceeded 60% in 2019 (National Bureau of Statistics, 2020). The Urban Blue Book: China Urban Development Report No. 12 predicts that this rate in China will reach 70% by 2030 and about 80% by 2050, and urbanization still has more room and potential for development (Jiang et al., 2018). While enjoying the dividends of urbanization, the urban water ecosystem has revealed three core challenges that are becoming increasingly serious: water pollution, water shortage, and urban flooding. Due to both climate change and urbanization development, urban flooding disasters are frequent within many cities in China. An average of more than 100 cities in China have been threatened by urban flooding every year Since 2010 (Wang et al., 2018). Under the talk of urban sea watching, there is more helplessness and better expectations for urban construction and urban water systems. On December 12, 2013, the Chinese President emphasized in his speech at the Central Urbanization Work Conference that "in upgrading urban drainage systems, priority should be given to keeping rainwater in, to making more use of natural forces for drainage, and to building cities with natural storage, natural infiltration, and natural purification." The sponge city has entered the public view, providing a new direction and idea for China's urban development and comprehensive response to urban water problems. China attaches great importance and supports it with

Yang, L., Wang, B., Ma, B., Xue, S., Yang, X. and Wei, S.
Simulation Study on the Effect of Rainfall-runoff Control in Sponge Transformation Quarter in Northwest China.
In *Proceedings of the 7th International Conference on Water Resource and Environment (WRE 2021)*, pages 467-474
ISBN: 978-989-758-560-9; ISSN: 1755-1315

issued a series of policy documents and measures and has given great support in terms of funds. In 2015 and 2016, China's Ministry of Finance, Housing and Urban-Rural Development, and Water Resource jointly launched 30 pilot sponge cities. In March 2017, the construction of sponge cities was included for the first time in the "Government Work Report" of China's two sessions, calling for the coordination of urban construction above and below ground and the promotion of sponge city so that cities have both a "face" and a "face". In March 2018, the United Nations launched the "International Decade of Action for Water" plan, which aims to better cope with water shortage pressure and climate change through measures such as changes in water resources management. China's "sponge city" project has become one of the focus of the United Nations and has high hopes for it.

The construction of sponge cities has increased the variety of underlying surfaces to some extent, making the urban hydrological characteristics change once again and the rainfall-runoff nonlinear relationship more complex (Xiang et al., 2017). The effect of sponge cities on the control of rainfall-runoff has also gradually become a research hotspot. Dreelin et al. discovered that the permeable pavement had better runoff control at lower precipitation levels, with runoff reduction rates of up to 93% (Dreelin et al., 2006). By analyzing the effects of permeable paving and low elevation greenbelt in a region of Beijing, Jin Cuntian et al. found that low elevation greenbelt is more effective in controlling runoff and permeable paving is more effective when the intensity of precipitation is low (Jin et al., 2010). Wan chenghui et al. conducted a study on the effects of low-impact development using the storm water management model in Ping xiang City as an example. Results showed that this effect of combined low-impact development facilities on surface runoff hydrology and water quality control could effectively improve the regional pollution abatement and flood resistance when comparing the status quo (Wan et al., 2019). Xu Duo studied the runoff control effect of sponge campus LID facilities (Xu, 2019). The study showed that the total annual runoff control category reached 75% after the campus was transformed by sponging, and the contribution ranking of the three LID facilities to runoff abatement is permeable pavement > sunken tree pond > low elevation greenbelt. The research results have been mainly focused on the single LID and sponge facilities themselves in terms of structure, effect, impact research, etc., lack of research on the comprehensive role of a variety of facilities, and the monitoring and evaluation of the actual operation effects of the sponge transformation of old quarters.

Therefore, this paper takes a spongy transformation quarter in northwest China as the research object, obtains multiple rainfalls and flow data of the experimental site in the research area through monitoring, and simulates and analyzes the flow process of the discharge outlet and the distribution of water accumulation points before and after the spongy transformation of the quarter with the help of storm water management model, identifies the influencing factors, analyzes and evaluates the role and effect of the spongy transformation on the control of rainwater runoff, with a view to providing practical guidance for the spongy transformation of the future building quarters.

2 OVERVIEW OF THE STUDY AREA AND DATA SOURCES

2.1 Study Area Overview

The area of the study area is about 28855 m^2, the current building occupies about 8106 m^2, the green area occupies about 7940 m^2, the green area ratio is 27.52%, the rest are hardened pavement and square, the permeable area before renovation accounts for about 38%. The study area divides into two regions: office and living. The office area concentrates on the north side of the site, where the hardened pavement is mostly. The office area is less green but has a higher integrated surface runoff coefficient, which makes it easy to form local road ponding when the rainwater is discharged only by surface runoff organization under rainfall weather. Most of the living areas are residential buildings built at the beginning of this century, with the limited green area, aging road surface, limited scope of rainwater pipe network laying, and rainwater flowing on the road surface on rainy days. The terrain of the study area divides into 10s catchment areas with high south and low north and high west and low east trends roughly. There have no foreign water enters, the incoming water is mainly rainfall, and there are two rainwater outfalls connected to municipal pipes. The main types and scales of low-impact development facilities after the sponge transformation are as follows: 5429.63 m^2 of low elevation greenbelt, 1199.60 m^2 of the rain garden, 10350.95 m^2 of overall permeable pavement, 540.05 m^2 of permeable tile pavement, 399.28 m^2 of grass planting ditch, etc. The storage volume of 1# regulating pond is 60 m^3, the storage volume of 2#

regulating pond is 100 m^3, and the storage depth is about 4.3 m, accounting for 1.2% of the total area of the study area. The study area's percentage of the previous area after sponge transformation is about 73%. The process of rainwater runoff control is shown in Figure 1.

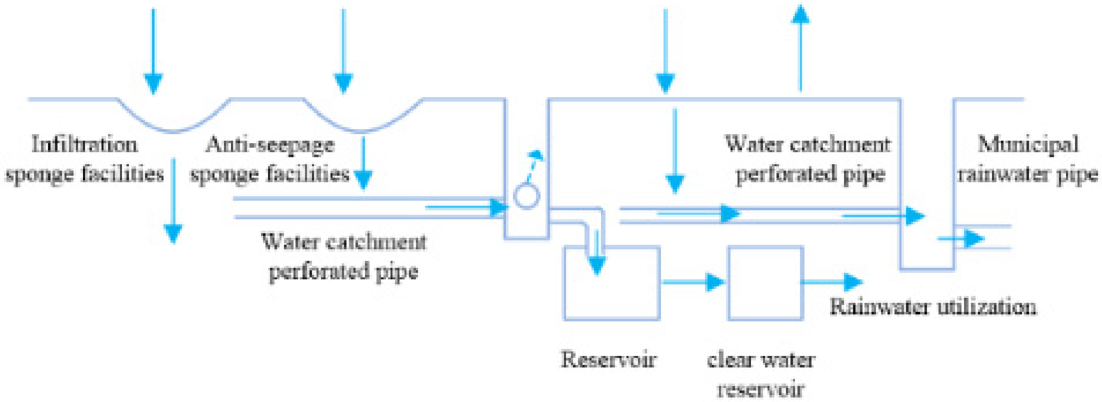


Figure 1: Diagram of the process of rainwater runoff control in the sponge transformation community.

2.2 Data Sources

The fundamental data required for this modeling collection mainly includes data on the subgrade conditions before and after the transformation of the study area, topographic maps, the number, length, diameter, and elevation of stormwater pipes, and the number and height of rainwater wells. In addition, the monitoring and collection of rainfall process data from July 25, 2018, to August 30, 2019, during the operation period after sponging in the study area, as well as the flow process data from the 1# transfer pond (60 m^3) inlet, can provide efficient data support for model construction, validation, and rate determination and conducting simulation analysis.

3 MODEL BUILDING

SWMM (Storm water Management Model) is an urban storm water management model proposed by the U.S. Environmental Protection Agency to cope with the increasingly severe urban water problems. After continuous improvement and upgrading of the model functions and interface, it has been added the setting of low impact development module after version 5.0, which can achieve field and long series continuous simulation of water quantity and quality, and is widely used in the areas of drainage network planning and design, evaluation of the effect of low impact development facilities and flood risk analysis, providing better environment and conditions for the simulation of rainfall and flood runoff process after sponge city construction. Therefore, this paper selects the storm water management model to construct the urban rainfall model of the study area and carries out the simulation and analysis of the rainfall-runoff process and inundation distribution before and after the sponge transformation of the study area.

3.1 Calculation Principle

The storm water management model is mainly used to deal with the hydrological processes generated by regional runoff. 1) The infiltration process, which exists in permeable areas, is calculated in this study using Horton Equation for infiltration. 2) The surface runoff includes flow production of the previous ground, Low-lying impervious surface, and Impervious floor without depression. In general, except for evaporation, rainfall on impervious surfaces is converted into a runoff, the amount of water produced by the Low-lying impervious surface is the amount of rainfall minus the initial loss of puddle filling, permeable surface flow rate is rainfall minus evaporation, ponding, and infiltration. 3) Surface confluence, treating each sub-catchment as a reservoir, is calculated using a nonlinear reservoir model coupled with the Manning equation and the continuity equation. 4) The pipe network converges, and the dynamic wave method is used to establish a complete set of St. Venant's equations to describe the flow variation process in the pipe channel with continuous momentum conservation equations and mass conservation at the nodes of the pipe channel.

3.2 Model Generalization

The probabilistic models of the study area have been constructed separately before and after the sponge transformation. Due to limited space, the probabilistic model construction process of the study area after sponging renovation is illustrated here as an example. Based on various influencing factors such as topography, elevation, pipes, rainwater wells, land use properties, and field observation and research during rainfall, the study area was divided into 232 sub-catchment divisions, as shown in Figure 2.

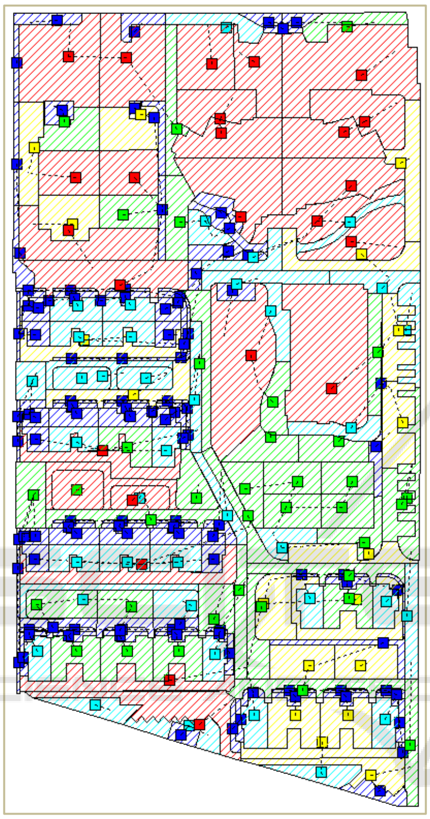


Figure 2: Generalized map of sub-catchments in the study area.

The rainwater pipe network system in the rainwater wells, storage facilities, outfalls is generalized as nodes. The pipe network, weirs, orifices are generalized as pipe sections. In this way, the rainwater pipe network system can summarize into a system composed of nodes and pipe sections. According to the study area, sponge transformation project of pipe plan layout and vertical elevation drawing data, rainwater pipe network system can be generalized as 100 pipe sections, 2s outfalls, 105 rainwater wells, and 2s storage facilities.

3.3 Parameter Calibration

Considering the rainfall ephemeris, intensity, and flow process continuity, the rainfall data of the study area on August 9, 2019, and the flow process data of the inlet of the storage pond were selected to rate the model. The measured flow process at the inlet of the storage pond and the model simulated flow process data are shown in Table 1. The rainfall lasted 145 mins, the outflow occurred at the 40th min after the rainfall started, and the flow process lasted until the 220th min. The simulation results are consistent with the measured flow process, and the peak occurrence time-matched and the relative error between the simulated and measured values are between -5.27% and 7.50%, which is within the allowable error range. After simulation analysis and rate determination, the main parameter settings in the model are shown in Table 2.

Table 1: Model calibration results.

Time (mins)	Observed values ($\times10^{-3}m^3/s$)	Simulated values ($\times10^{-3}m^3/s$)	Relative error
40	0.31	0.33	5.60%
50	0.96	1.01	5.73%
60	1.51	1.50	-0.50%
70	2.54	2.47	-2.80%
80	2.98	3.02	1.39%
90	2.94	2.90	-1.42%
100	2.40	2.43	1.13%
110	4.71	4.68	-0.69%
120	3.93	3.83	-2.55%
130	2.78	2.63	-5.27%
140	2.58	2.60	0.95%
150	1.71	1.80	5.09%
160	1.02	0.99	-3.54%
170	0.65	0.60	-7.50%
180	0.58	0.58	-0.35%
190	0.37	0.37	-1.30%
200	0.27	0.25	-6.22%
210	0.19	0.19	0.88%
220	0.04	0.05	4.81%

Table 2: The calibration setting of main parameters.

parameter	Manning coefficient in impermeable zone	Manning coefficient of permeable zone	Manning coefficient of rainwater pipeline	Sinkage storage in impervious area /mm	Sinkage storage in permeable area /mm	Maximal infiltration rate/$mm\cdot h^{-1}$	Minimum infiltration rate /$mm\cdot h^{-1}$	attenuation constant/h^{-1}
the value	0.012	0.1	0.013	5.75	1.25	103.81	11.44	6.2

3.4 Model Validation

The model was validated using the rainfall and flow data on August 26, 2019, as shown in Figure 3. It can be seen that the simulated flow process is consistent with the measured flow process, and the relative errors between the simulated and measured values range from -7.23% to 9.30%, and the peak occurrence times match, indicating that the storm water management model of the built study area can simulate the actual process of rainfall-runoff in the study area more realistically, and can be used for the simulation of the flow process of the discharge outlet and the effect of rainfall-runoff control before and after the sponge transformation of the study area Analysis.

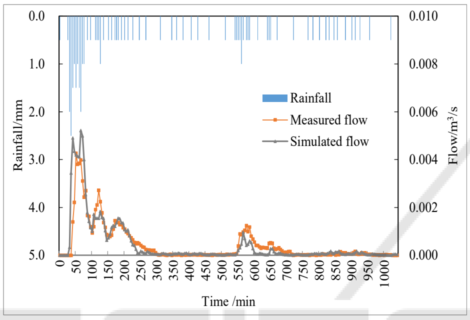


Figure 3: Flow process diagram for model validation fitting.

4 RESULTS AND ANALYSIS

4.1 Analysis of Rainfall Characteristics During the Monitoring Period

When the sponging of the study area is completed, the rainfall data from July 25, 2018, to August 30, 2019, were monitored and collected. And a total of 61 rainfall events were monitored. The data collected in the study area were compared and verified by using the real-time public rainfall events, duration, and rainfall data information on the website of Xi'an Meteorological Bureau. The rainfall data collected by the rainfall station in the study area and the public data have a slight fluctuation. However, the characteristics of rainfall events and duration are the same, indicating that the rainfall station monitoring data in the study area have certain reliability. The daily rainfall distribution during the monitoring period is shown in Figure 4.

Combined with the process data of the inlet flow of the1# storage tank, it is found that 34 light rain events have not occurred during the monitoring period. There are eight rain events and two outflow events. There are 18 heavy rain events, including 15 outflows. There are two heavy rainfall events, of which the 12-hour rainfall on 27 June 2019 is 36.5 mm and the 12-hour rainfall on 26 August 2019 is 37 mm.

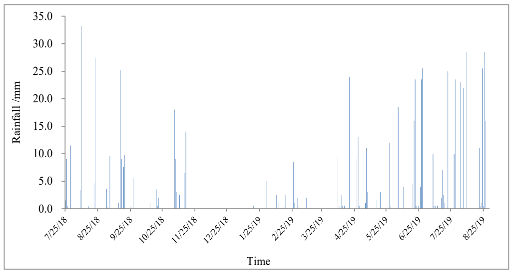


Figure 4: Daily rainfall distribution during monitoring period.

4.2 Analysis of Rainwater Runoff Effect Control

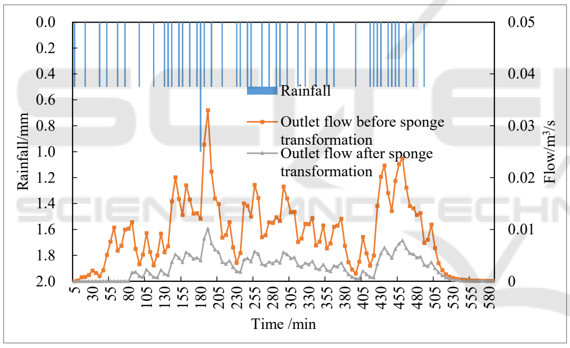
The rainfall events with 12 - hour rainfall exceeding 5 mm during the monitoring period are simulated, and the control effect of sponge transformation on rainwater runoff in the study area is analyzed and calculated. The results show that there is no outflow at the outlet of rainwater in 33 light rain events and eight moderate rain events, and the runoff control rate was 100%. In 18 heavy rain events and two rainstorm events, there are 12 outflows of rainwater outlets in the residential area, and the runoff control rate is 83.49%-99.07%. The characteristics of rainfall events and the outflow of rainwater discharge outlets in the sponge transformation area are detailed in Table 3. It is found that rainfall intensity, early drought days, and rainfall are the main factors affecting the control effect of rainwater runoff in the sponge transformation area, among which rainfall intensity has a greater impact. With the increase of rainfall intensity, the rainwater pipe flows out earlier. Rainfall events with small rainfall intensity and uniform distribution have less outlet flow and a gentle flow process. The rainfall intensity and occurrence time also have a great influence on the occurrence of peak flow. The greater the drought days in the early stage, the better the reduction effect of rainwater runoff.

4.3 Process Analysis of Rainwater Discharge

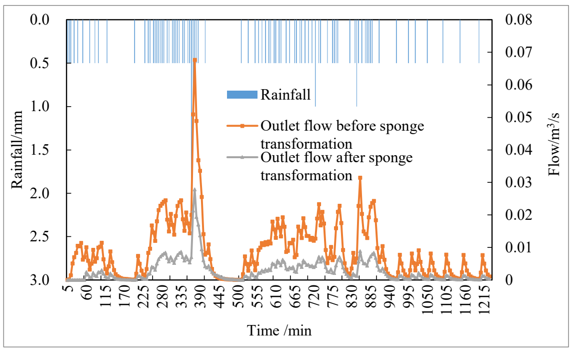
Limited by space, the measured rainfall data of the heavy rain event on August 3, 2019, and the rainstorm event on June 27, 2019, are selected as input files to simulate and analyze the rainwater discharge process of the residential area before and after the sponge transformation in the study area, as shown in Figure 5. It can be seen that the changing trend of the rainwater discharge process before and after the sponge transformation in the study area is basically the same, and the occurrence of peak flow is closely related to the occurrence time of maximum rainfall intensity.

Table 3: Characteristics of rainfall events and runoff control rate.

Order number	Time	Rainfall duration/ min	Previous drought day / d	Rainfall/ mm	Maximum rainfall intensity / mm/5min	Rainfall scale	The start time of outflow / min	Runoff control rate
1	2018/07/30	15	2	11.5	7.0	heavy rain	10	99.07%
2	2019/06/05	550	7	18.5	1.0	heavy rain	260	96.53%
3	2019/06/20	280	0	15.5	1.0	heavy rain	115	94.77%
4	2019/06/21	465	0	14.5	1.0	heavy rain	180	97.32%
5	2019/07/22	270	3	24.5	1.5	heavy rain	60	89.98%
6	2019/07/29	255	0	22.0	4.0	heavy rain	42	85.07%
7	2019/08/03	485	4	23.0	1.0	heavy rain	85	85.25%
8	2019/08/06	440	2	21.5	1.0	heavy rain	73	84.12%
9	2019/08/09	145	2	27.5	3.5	heavy rain	40	91.06%
10	2019/08/24	65	2	25.5	5.5	heavy rain	34	93.57%
11	2019/6/27	1200	5	45.5	2.0	rainstorm	55	83.49%
12	2019/8/26	1020	1	43.5	2.5	rainstorm	42	84.91%



(a) August 3, 2019



(b) June 27, 2019

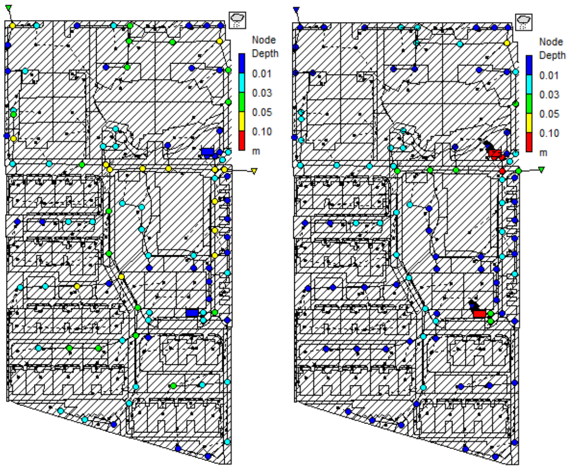
Figure 5: Rainwater discharge process before and after sponge transformation in the study area.

During the rainfall process on August 3, 2019, before the sponge transformation of the study area, the rainwater outlet of the study area outflowed in the fifth minute after the rainfall began. After the sponge transformation, the outflow time of rainwater drainage in the residential area is delayed by about 80 minutes. The maximum peak flow is 0.033 m^3/s before the sponge transformation, and the maximum peak flow is reduced to 0.01 m^3/s after the sponge transformation, and the peak reduction rate is 69.7%. The runoff control rate also increased from 50.09% before sponge transformation to 85.25%.

During the rainfall process on June 27, 2019, before the sponge transformation of the study area, the rainwater discharge outlet of the residential area occurred 5 minutes after the rainfall began. After the sponge transformation, the outflow time of rainwater drainage in the residential area was delayed by about 50 minutes. The maximum peak flow was 0.068 m^3/s before and 0.028 m^3/s after the sponge transformation, and the peak reduction rate was 58.79%. The runoff control rate also increased from 48.89% before sponge transformation to 83.49%.

4.4 Distribution and Analysis of Water Accumulation Points

The simulated analysis was carried out using the measured rainfall process data on August 3, 2019, with a rainfall of 23 mm. The water depth distribution of nodes before and after the sponge transformation in the study area is shown in Figure 6.



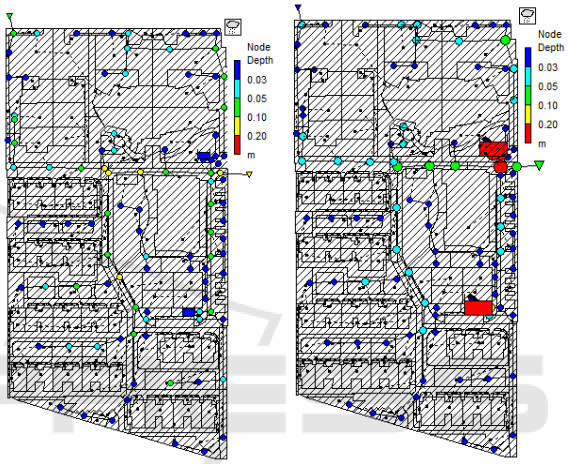
(a) Before sponge reconstruction

(b) After sponge transformation

Figure 6: Distribution of simulated node water depth during rainfall process on August 3, 2019 (the maximum water occurred at 3:10).

The results show that after the sponge transformation in the study area, the node with ponding has the maximum water depth at 3:10. At the same time, there are 14 nodes with a water depth of 0.05 m -0.1m and 35 nodes with a water depth of 0.01 m -0.03 m before the sponge transformation. There is only one node with a water depth of 0.05-0.1 m and 32 nodes with a water depth of 0.01 m -0.03 m after sponge transformation. The water depth in the well of the municipal pipe network in the north of the study area is 0.04 m, and that in the east is 0.08 m. After the sponge transformation, the two storage tanks in the study area played a good role in regulating and storing. The storage tank on the north side was fuller than that on the south side. Compared with before the sponge transformation, the node water depth decreased. There was no water in the drainage well on the north side, and the water depth in the drainage well on the east side was 0.05m, which decreased by 0.03m.

The simulated analysis was carried out using the measured rainfall process data on June 27, 2019, with a rainfall of 45.5 mm. The water depth distribution of nodes before and after sponge transformation in the study area is detailed in Figure 7. The results show that after the sponge transformation in the study area, the node with ponding has the maximum water depth at 6:15. Before the sponge transformation at the same time, there were five nodes with a water depth of 0.1-0.2 m, 19 nodes with a water depth of 0.05 m-0.1 m, and 19 nodes with a water depth of 0.03-0.05m. After sponge transformation, there is only one node with a water depth of 0.1 m -0.2 m, five nodes with a water depth of 0.05 m -0.1 m, and 24 nodes with a water depth of 0.03 m -0.05 m. The water depth in the well of the municipal pipe network in the north of the study area is 0.06 m, and that in the east is 0.12 m. After the sponge transformation, the two reservoirs in the study area have played a good role in regulating and storing. The northern reservoir is fuller than the southern reservoir. Compared with before the sponge transformation, the water depth of the node is decreased. The water depth in the northern drainage well is 0.02 m, which is decreased by 0.04 m. The water depth in the eastern drainage well is 0.07 m, which is decreased by 0.05 m. It has a good effect on the reduction of water-logging points in the study area.



(a) Before sponge reconstruction

(b) After sponge transformation

Figure 7: Water depth distribution of simulated nodes during rainfall on 27 June 2019 (the maximum water occurred at 6:15).

5 CONCLUSIONS

This paper takes a spongy transformation plot in northwest China as the research object, and obtains multiple rainfalls and flow data from the experimental site in the study area through monitoring. And with the help of storm water management model, we simulate and analyze the process of discharge flow and the distribution of water accumulation points before and after the spongy transformation of the district, identify the influencing factors, and analyze and evaluate the role and effect of spongy transformation on the control of rainwater runoff. The main research findings are as follows :

(1) During the monitoring period, the runoff control rate of rainfall events with rainfall of 1.0 mm − 45.5 mm reached 83.49% − 100% after the sponge

transformation in the study area. Among them, the runoff control rate of small and medium rainfall events reached 100%. The peak flow and the occurrence time of peak flow were well-reduced.

(2) After the sponge transformation of the study area, the low-impact development facilities played a better role in source reduction, and the storage tank played an important role in terminal storage. In response to the heavy rain event on August 3, 2019, the peak reduction rate was 69.7%. And the runoff control rate increased from 50.09% before the sponge transformation to 85.25%. In response to the heavy rain event on June 27, 2019, the peak reduction rate was 58.79%, and the runoff control rate increased from 48.89% before the sponge transformation to 83.49%. The effect of rainwater -runoff- control after the sponge transformation was significantly improved.

(3) After the sponge transformation in the study area, the regulation and storage facilities have played a better role in regulation and storage. In the heavy rain event on August 3, 2019, the time of outflow from the outlet was delayed by about 80 minutes, and on June 27, 2019, the time of outflow from the outlet was delayed by about 50 minutes. The water depth of the water accumulation node is decreased compared with that before the sponge transformation. Compared with the previous sponge renovation, the water depth in the two rainwater drainage wells in the study area decreased to 0.03 m-0.05 m. It effectively alleviates the problems of rainwater accumulation and heavy rain in front of the transformation road, and the sponge effect is prominent.

(4) The analysis found that rainfall intensity, early drought days, and rainfall are the main factors affecting the control effect of rainwater runoff in the sponge transformation area. Among them, the intensity of rainfall has a stronger impact. With the increase of rainfall intensity, the rainwater pipe flows out earlier. Rainfall events with small rainfall intensity and uniform distribution have less outlet flow and a gentle flow process. The rainfall intensity and occurrence time also have a great influence on the occurrence of peak flow. The greater the drought days in the early stage, the better the reduction effect of rainwater runoff.

ACKNOWLEDGEMENTS

This research was funded by Scientific Research Project Founded by Shaanxi Provincial Education Department (Program No.20JT052), Start up Fund Project for Teachers' Doctoral Research (Program No.107-451120003).

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