Study on the calculation methods to determine the scale of the sponge city facilities in residential area----- taking Shenzhen as an example

Jian Liu [1,2*], Min Dong [2], Yu-ting Han [1], Lingyi Wu [1,2]

[1] *Ecological Technology Institute of Construction Engineering, Shenzhen University, Shenzhen 518060, China;*
[2] *Colleges of Civil Engineering, Shenzhen University, Shenzhen 518060*
E-mail address: liujian@szu.edu.cn

Abstract: The sponge city construction is being carried out in China, and how to reasonably determine the scale of the sponge city facilities is a key point that the planners and designers should seriously solve. In this paper, taking determination of the sponge city facilities in a residential building in Shenzhen as an example, the layout and scales of the rainwater tanks, raingardens, ecological roofs and permeable pavements are decided by using the volumetric method and stormwater management model (SWMM). The calculated results by the two methods are compared and analyzed. The results show that the scales of the sponge city facilities determined by the two methods are almost the same, and it means that any method can be used to determine the scale of sponge city facilities. The volumetric method is relatively simple, and it is suggested to use to determine the scale of sponge city facilities during planning stage. While SWMM is more complex and requires a lot of input conditions, but it can provide the reduction effects of the sponge city facilities for rainfalls with different recurrence periods. Therefore, SWMM is recommended to use the calculation of the hydrological process of the sponge city facilities during the design stage.

Key words: residential area, sponge city, stormwater management model, volumetric method

1. INTRODUCTION

With the acceleration of urbanization process, the natural attributes of urban areas are weakened, and the original hydrological cycle process is disturbed, which result in frequent urban waterlogging and deterioration of urban water environment [1]. General Secretary of the Communist Party of China (CPC), Xi Jinping, pointed out in the *Central Urbanization Work Conference* in December 2013 that priority should be given to the limited rainwater storing on site in enhancing urban drainage system and drainage by use of natural forces, and natural retention and storage, natural infiltration and natural purification of the sponge city should be built [2]. In response to Xi's call, the central government began the pilot work of the sponge city construction in April 2015. According to the *guiding opinions on promoting the construction of the sponge city* issued by the General Office of the State Council in October 2015, the sponge city construction should give full play of vegetation and soil to infiltration of rainwater, and give full play of wetlands, water basins to natural purification of water quality for realizing the natural circulation of urban water. Giving full part to the natural ecological functions and artificial intervention, the implementation of source reduction, process control, system management, is conducive to restore urban water ecology, conservation of water resources, enhance the urban waterlogging control ability, expand effective investment of public goods, improve the quality of new urbanization and promote the harmonious development of human beings and nature. Through the sponge city construction, the comprehensive infiltration, detention, storage, purification, utilization, drainage measures are used to minimize the impact of urban development and construction on the ecological environment. By 2020, more than 20% of the urban built-up areas will meet the requirements that 70% rainfall will be consumed and utilized locally; and more than 80% of the urban built-up areas will meet the target requirements by 2030[3].

As one of the most advanced city in China's reform and development, Shenzhen's rapid urbanization has caused lot of environmental problems such as water shortage, frequent floods and serious pollution. Shenzhen was selected as one of the pilot cities of sponge city construction in April 2016. Since 2016, Shenzhen government has required that all new large infrastructure must be built according to the sponge city construction requirements. Therefore, how to determine the scale of sponge city facilities is a key issue to be solved by the planners and designers.

Technical guide for sponge city construction -- Construction of rainwater system with low impact development (Trial Implementation) issued by the Ministry of Housing and Urban-rural Development in October 2014 proposed that the scale of sponge city facilities could be determined by volumetric method and simulation model [4]. At present, the most widely used numerical model in China is stormwater management model (SWMM).

This paper discusses how to use the volumetric method and SWMM to determine the scale of sponge city facilities through the sponge city facility layout in a residential area in Futian District, Shenzhen, analyze advantages and disadvantages of the two methods, and give the application scope of two methods.

2. OUTLINE OF RESIDENTIAL AREA AND CONSTRUCTION GOALS OF SPONGE CITY FACILITIES

2.1. Outline of residential area

The case study project located in Futian District, Shenzhen is one of the urban renewal projects in Shenzhen. The land area is 20519.2m^2, in which, the commercial and residential buildings account for 1/2 and roads, green space and green belts account for 1/2 (see Table 1). The annual rainfall is 1754mm in the project site, where is classified as the western rain area. The soil type is loam and the permeability is large.

Table 1. Land type in the project site

Item	**Area (m^2)**
Public buildings	5191.3
Residential buildings	4608
Green belts and space	5129.8
Asphalt road	736.8
Pavement	4853.3
Total	20519.2

2.2. Construction goals of the sponge city facilities

The s*pecial plan and implementation scheme of sponge city construction in Shenzhen* and the *planning key points and detailed review of Shenzhen sponge city* stipulated that the goals of the sponge city construction and the runoff control index for different use lands in each district, Shenzhen [5, 6]. According to the stipulations of the two documents, the annual runoff control rate in the project site is set as 70%, and corresponding design rainfall is 31.3 mm.

The sponge city facilities include rainwater tanks, rain gardens, ecoroofs which do not irrigate and fertilize permeable pavements. Part of roof rainwater is collected for irrigation, car wash and landscape. Figure 1 shows the layout of the sponge city facilities. The layout scale and quantities are shown in Table 2.

According to the *planning key points and detailed review of Shenzhen sponge city*, the retention water of ecoroofs and permeable pavements, which have smaller storage capacity than other facilities, are not included in the total storage volume during computing the storage capacity of the sponge city facilities. Storage capacity of rain gardens and rainwater tanks are 344m^3; it can keep the runoff created by design rainfall of 31.3mm equal to zero, and it means that annual runoff control rate reaches 70%.

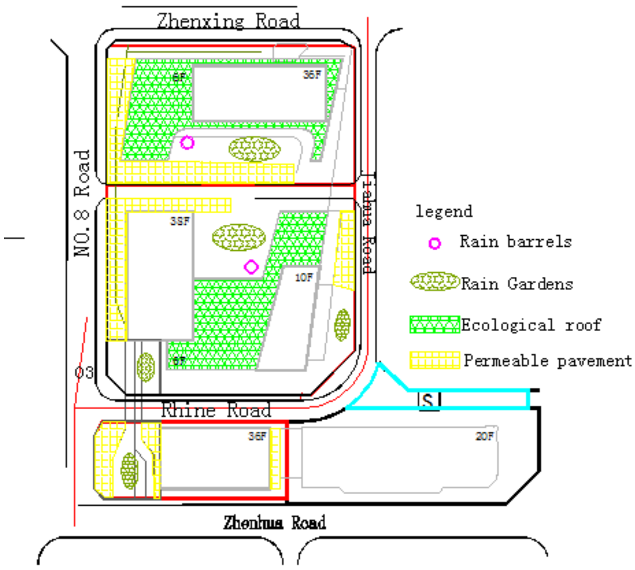

Fig.1. Layout of the sponge city facilities

Table 2. Areas and volumes of the sponge city facilities

Facility type	**Area /m^2**	**Storage volume /m^3**
Raingardens	850	340
Rainwater tanks	--	4
Permeable pavements	3882.64	233
Ecoroofs	1557.39	77.9
Total (without Permeable pavements and ecoroofs)		344

3. CALCULATION METHODS

3.1. Volumetric method

The sponge city facilities are designed as controlling the runoff and pollution. The storage capacity of the sponge city facilities can be calculated by the following formula [4].

$$V = 10H\varphi F \quad (3\text{-}1)$$

Where, V is the designed storage capacity (m^3), H is rainfall (mm), φ is runoff coefficient, and F is the catchment area (hm^2).

3.2. SWMM

SWMM is a dynamic precipitation-runoff model that is used to simulate a single precipitation event or a long-term runoff and water quality. The runoff module comprehensively deals with the precipitation, runoff and pollution load in each sub-basin. SWMM for the hydrological calculation of the LID facilities is its LID control module, which can simulate the hydrological process of the following 7 LID facilities: 1) Permeable pavement, 2)Rain gardens, 3) Green roofs, 4) Street planters, 5) Cisterns, 6) Infiltration trench and 7) Vegetative swales. The planners and designers can combine LID facilities with traditional drainage pipelines and sewage pipelines to calculate the efficiency of stormwater management and pollution removal [7].

4. CALCULATION RESULTS OF THE VOLUMETRIC METHOD

4.1. Catchment area and preliminary layout

Because the catchment area of 20519.2m^2 is relatively small, it is divided into two sub basins as shown on Fig. 2. The catchment areas of S1 and S2 are 12311.52 m^2 and 8207.68 m^2, respectively.

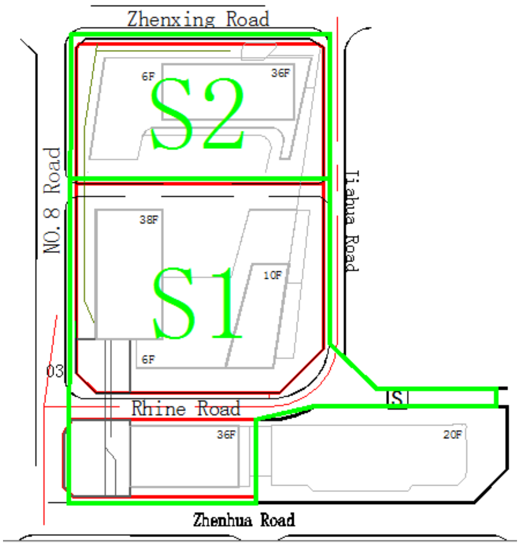

Fig.2. Division of subbasins

The sponge city facilities in Subbasins S1 and S2 are arranged as follows:

(1) 30% of the roofs of public buildings are designed as ecoroofs;

(2) 80% of the roads and traditional pavements are designed as permeable pavements.

The comprehensive runoff coefficients in two subbasins are calculated by the *Technical guide for sponge City Construction -- Construction of rainwater system with low impact development (Trial Implementation)*. The comprehensive runoff coefficients are 0.53 for two subbasins as shown in Table 3 and Table 4. The required storage volumes of S1 and S2 are 204.23m^3 and 136.16m^3 after the sponge city facilities are arranged, as listed in Table 5 and Table 6.

In order to store the runoff in S1, the storage volume of the sponge city facilities should be larger than 204.23m^3. The roofs are needed to control 141.8m^3, green space is needed to control 14.45m^3, asphalt roads are needed to control 11.76m^3, and the pavements are needed to control 37.36m^3. Without considering the storage functions of ecoroofs and permeable pavements, a rain barrel of 2 m^3 is installed to collect the roof runoff, and raingardens of 510 m^2 are arranged to collect the runoffs from the roads, roofs and pavement. The retention capacity of the raingardens is $510m^2*0.4m=204m^3$.

Table 3. Comprehensive runoff coefficient of Subbasin S1

Underlying surface type	Number	Area/m^2 A	Runoff coefficient B
Hardening roofs	1	4945.15	0.85
Ecoroofs	2	934.43	0.35
Green space	3	3077.88	0.15
Asphalt road	4	442.08	0.85
Impervious pavement	5	582.40	0.85
Permeable pavement	6	2329.58	0.3
Total		12311.52	
Runoff coefficient	=（A1*B1+A2*B2+…+A6*B6）/（A1+A2+…+A6）=0.53		

Table 4. Comprehensive runoff coefficient of Subbasin S2

Underlying surface type	Number	Area/m^2 A	Runoff coefficient B
Hardening roofs	1	3296.76	0.85
Ecoroofs	2	622.96	0.35
Green space	3	2051.92	0.15
Asphalt road	4	294.72	0.85
Impervious pavement	5	388.26	0.85
Permeable pavement	6	1553.06	0.3
Total		8207.68	
Runoff coefficient	=（A1*B1+…+A6*B6）/（A1+…+A6）=0.53		

Table 5. Design storage capacity of S1

Area /m^2	Runoff coef. before reform	Runoff coef. after reform	Annual runoff control rate	Design rainfall /mm	Design storage capacity /m^3
（1）	（2）	（3）	（4）	（5）	=10*（1）*（3）*（5）/10000
12311.52	0.68	0.53	70%	31.3	204.23

In order to store the runoff in S2, the storage volume of the sponge city facilities should be larger than $136.16m^3$. The roofs are needed to control $94.54m^3$, green space is needed to control $9.63m^3$, asphalt roads are needed to control $7.84m^3$, and pavements are needed to control $24.92m^3$. A rain barrel of 2 m^3 is installed to collect the roof runoff, and raingardens of 340 m^2 are arranged to collect the runoffs from the roads, roofs and pavement. The retention capacity of the raingardens is 340m ^{2}*0.4m=136 m ^{3}.

Table 6. Design storage capacity of S2

Area /m^2	Runoff coef. before reform	Runoff coef. after reform	Annual runoff control rate	Design rainfall /mm	Design storage capacity /m ^{3}
（1）	（2）	（3）	（4）	（5）	=10*（1）*（3）*（5）/10000
8307.68	0.68	0.53	70%	31.3	136.16

4.2. Calculation results

The sponge city facilities and their storage capacities in the whole project site are shown in Table 7. From the safety point of view, the storage capacities of the ecoroofs and permeable pavements are not included in the total storage capacity. The necessary and actual storage capacities in S1 and S2 are listed in Table 8. Without considering storage functions of the ecoroofs and permeable pavements, the actual storage volume of the cisterns and raingardens is 344m^3, which is larger than the design storage volume of 340.39m^3, it means that the sponge city facilities can meet the design goal of annual runoff control rate of 70%.

Table 7. Summary of areas and storage capacities of the sponge city facilities

Facilities type	Area /m^2	Storage depth/m	Storage volume /m ^{3}
Rain gardens	850	0.4	340
Rainwater barrels	--	--	4
Permeable pavements	3882.64	--	--
Ecological roofs	1557.39	--	--
Total			344

Table 8. Summary of design and actual storage capacities

Number	Catchment area/m^2	Design storage capacity/m^3	Actual storage capacity/m^3
1	12311.52	204.23	206
2	8207.68	136.16	138
Total	20519.2	340.39	344

5. CALCULATION RESULTS BY SWMM

5.1. Davison of subbasins and layout of the sponge city facilities

Similar to volumetric method, the project areas are divided into two subbasins. The sponge city facilities mainly focus on retention, purification and storage by raingardens, permeable pavements, ecoroofs and rainwater barrels. The runoff is drained to the municipal pipeline by one outlet as shown on Figure 3.

The catchment areas of S1 and S2 are 12311.52 m^2 and 8276.8 m^2. The raingardens of 850m^2, permeable pavements of 3882.64m^2 and ecoroofs of 1557.39m^2 are arranged. Each rain garden could be 50 m^2, 100 m^2 and 150 m^2.

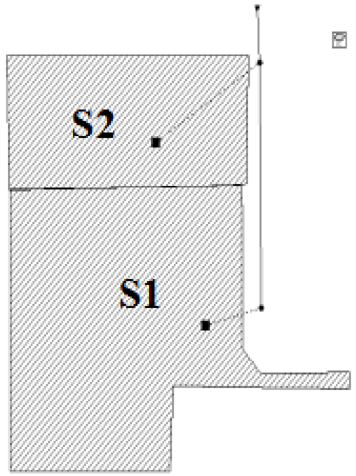

Fig.3. Division of subbasins for SWMM

5.2. Calculation results

Calculation results for design rainfall. The 10 minutes distribution of the design rainfall of 31.3mm was obtained by the 10 minutes distribution measured at the Shuiyuan Building on August 19-20, 2005. The storage capacities of the ecoroofs and permeable pavements are not considered during computation. Figure 4 shows the results calculated by SWMM. It can be found that the runoff is equal to zero for design rainfall of 31.3 mm, it means that the sponge city facilities can meet the design goal of 70% annual runoff control rate.

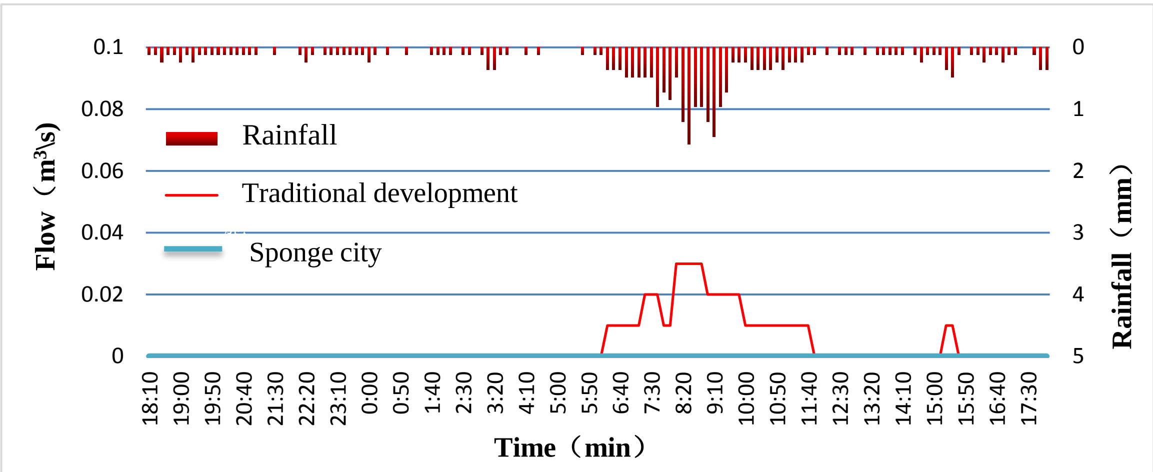

Fig. 4. Hydrographs for different development modes under design rainfall

Calculation results for rainfalls with different recurrence periods. Table 10 to Table 11 give the calculated runoffs and peak discharges of traditional pipeline development scheme and sponge city facility development scheme for the rainfalls with different return periods in Table 9. Fig. 5 shows the hydrographs of different development modes in the case of rainfall with 25-year return period. As compared with the traditional development, the runoff reduction rates of the sponge city facility scheme are 44.04%, 35.56%, 27.12%, 23.24% and 18.3% for 5, 10, 25, 50 and 100 year rainfall events; and the peak discharge reduction rates are 46.88%, 11.36%, 4.92%, 0.0% and 0.0%, respectively. The reduction rates of the runoffs and peak discharges decrease with the increase of the recurrence period of rainfall. This indicates that sponge city facilities are more effective for small probability rainfall events.

Table 9. Daily rainfalls with different recurrence periods

Recurrence periods	**5**	**10**	**25**	**50**	**100**
Rainfall (mm)	217.6	286	386.3	471.4	565.8

Table 10. Runoffs for the rainfalls with different recurrence periods

Recurrence period	**5**	**10**	**25**	**50**	**100**
Traditional development	3774	5088	7146	8856	10782
Sponge city	2112	3228	5208	6798	8808
Reduction rate	44.04%	36.56%	27.12%	23.24%	18.3%

Table 11. Peak discharges for the rainfalls with different recurrence periods

Peak discharge （m³/s）	**5**	**10**	**25**	**50**	**100**
Traditional development	0.32	0.44	0.61	0.75	0.91
Sponge city	0.17	0.39	0.58	0.75	0.91
Reduction rate	46.88%	11.36%	4.92%	0	0

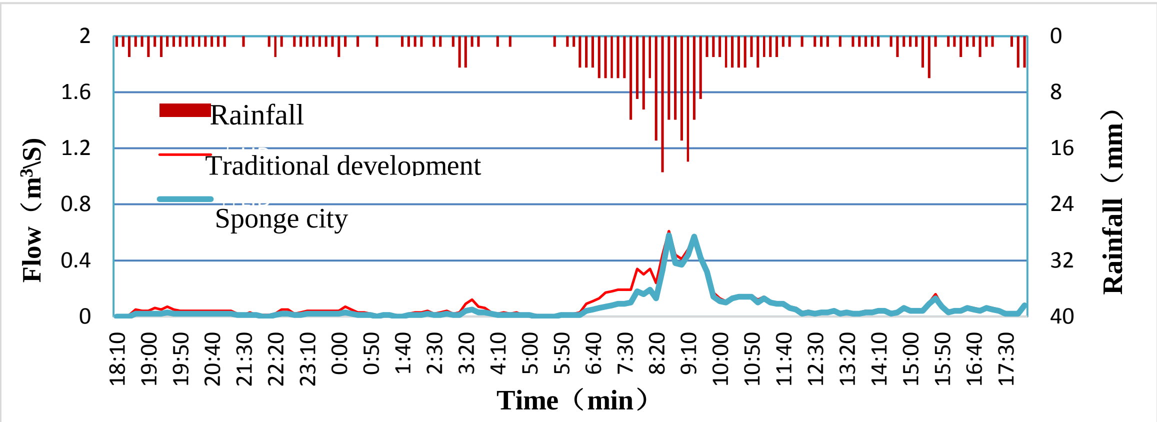

Fig. 5. Hydrographs for different development modes for 25 years rainfall

6. CONCLUSIONS

The sponge city facilities determined by both volumetric method and simulation model can meet the annual runoff control rate without considering the retention capacities of the ecoroofs and permeable pavement. Therefore, each method can be used to determine the scales of the sponge city facilities.

The volumetric method can only provide the storage capacity of sponge city facilities, and cannot give the reduction effects of the sponge city facilities for the rainfall with different return periods. Therefore, it is recommended that the volumetric method should be adopted during planning stage, and the simulation model should be used during design stage.

It should be noted that neglecting the retention functions of the ecoroofs and permeable pavements stipulated in the *Planning key points and detailed review of Shenzhen sponge city* is not rational for computing the storage capacity of sponge city facilities. According to the authors' work practice for many years, the gravel layer and mixed soil layer of the ecoroof and the gravel layer of permeable pavements can store 5-10cm deep runoff. Therefore, it is strongly suggested that the planner and designers consider the retention functions of the ecoroofs and permeable pavements when they design the similar sponge city facilities.

ACKNOWLEGEMENTS

The research was supported by the Natural Science Foundation of China (No. 51378312) under the title of mechanical performance of fiber-based ultra-high strength RC columns confined by high-strength stirrups under high axial compression creep and chlorine salt erosion.

REFERENCES

1. Liu J, Li SX, She N, Chen H and Wu LY, 2017. Case Study of Low Impact Development Facilities in Municipal Roads. *China Water and Wastewater*, 33(4):14-19.

2. Xi JP, 2014. *Xi Jinping talk about ecological civilization.* http://cpc.people.com.cn/n/2014/0829/c164113-25567379-3.html.

3. General Office of the State Council, 2015. *The guiding opinions on promoting the construction of the sponge City*. http://www.mohurd.gov.cn/zcfg/jsbwj_0/jsbwjcsjs/201411/t20141102_219465.html

4. Ministry of Housing and Urban-rural Development, 2014. *Technical guide for sponge City Construction -- Construction of rainwater system with low impact development (Trial Implementation)*. China Building Industry Press, Beijing, China.

5. Urban Planning, Land and Resources Commission of Shenzhen Municipality, 2016. *Planning key points and detailed review of Shenzhen sponge city*. http://www.sz.gov.cn/cn/xxgk/zfxxgj/tzgg/201703/t20170313_6066919.htm

6. Urban Planning, Land and Resources Commission of Shenzhen Municipality, 2017. *Special plan and implementation scheme of sponge city construction in Shenzhen*. http://www.szpl.gov.cn/xxgk/csgh/zxgh/201709/t20170921_440331.htm

7. U.S. Environmental Protection Agency, 2017. *Storm Water Management Model (SWMM) Version 5.1.012 with Low Impact Development (LID) Controls*. https://www.epa.gov/water-research/storm-water-management-model-swmm.