Master's Thesis

Multi-objective Optimization of Micro-catchment Rainwater Management to Improve the Sponge City Project in China

다목적 빗물 관리를 통한 스폰지 시티 프로젝트의 발전을 위한 설계 방법

August 2019

Graduate School of Civil and Environmental Engineering
Seoul National University
Environmental Engineering

Zhenrong Tian

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Advised by Mooyoung Han

Submitting a master's thesis of Public Administration

08 2019

Graduate School of Engineering
Seoul National University
Environmental Engineering

Confirming the master's thesis written by
Zhenrong Tian

08 2019

Chair ____Yongju Choi____(Seal)
Vice Chair ____Jongkwon Cho____(Seal)
Examiner ____Mooyoung Han____(Seal)

Abstract

Urban flood is a serious problem in many China's cities as a result of unfettered urbanization. The Chinese government proposed Sponge City project (SPC) in 2014 to address the problem as well as promote a sustainable water management. However, some barriers of SPC, such as limited green space and fund shortage, make the preliminary results unsatisfactory. Rainwater harvesting system (RWHS) has the potential ability to reduce the urban runoff, relieving the pressure on municipal sewer system. In addition, rainwater could be an alternative water source as solution of water scarcity.

Yet RWHS has not got much attention in China and there is only limited literature. In this study the different rainfall sequences (design rainfall, average daily rainfall and real daily rainfall) are used to investigate the performance of flood mitigation based on water balance simulation, besides the shortage of data selection in current research is discussed quantitatively and the appropriate input data sets are chosen for further evaluation. The flooding mitigation water saving effectiveness of SPC is estimated by using short and intensified design storm , as well as the real daily rainfall respectively, while the proper tank size is defined and applied in selected 31 cities, for evaluating the possibly enhanced efficiency after the construction of RHWS.

It is seen that the both of flood mitigation and water saving performances are positively affected by adding rainwater tanks all over the country. Then economic factor is included in the optimization analysis to search the optimal solutions for the design of SPC and RWHS, and the established method would be a good tool to give some suggestions for future construction of rainwater facilities.

Keyword : Sponge City project, Rainwater harvesting system, time reliability, stormwater control efficiency, optimization

Student Number : 2017-28879

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Chapter 1. Introduction

1.1. Background

1.1.1. Water challenges in China

Flooding is one of the most common environmental hazards around the world. In China, urban flood inundation caused by extreme storm has been a major issue for the recent decades due to rapid urbanization and climate change (Yutao Wang et al. 2017), and it is reported that around 200 cities suffered from flood each year, which resulted in enormous casualty and property loss, meanwhile, about 45% and 17% of China's cities are subject to insufficient water supply and severe water shortage, respectively (Jiang Y., 2009). Traditionally, Gray infrastructure is regarded as the main approach to mitigate urban flood (Jiaqing Xie et al., 2017), so cities that face these problems handle them by enlarging drainage system and adding large-scale retention facilities (Youngjin Kim et al., 2015). However, reconstruction becomes more difficult nowadays because of complicated urban composition and the high cost. Under this circumstance, Sponge City Project (SPC) was proposed in 2014 for alleviating urban flood and water shortage sustainably (MHURD, 2014 a, b).

Figure 1.1 Water challenges in China

1.1.2. Sponge City Project

The concept of SPC is basically the same as Low Impact Development (LID) in United State of America (Faith Ka Shun Chan et al., 2018; Pyke et al., 2011), and it is designed to integrate natural waters in drainage system while providing additional artificial water retention facilities and green space for versatile targets with the assistance of some computer modeling tools like Strom Water Management Model (Mariana L.R. et al., 2018). The conceptual figure of Sponge City Project is showing like Fig 1.2 since the main technologies using in China are green space and permeable pavement. 30 pilot cities were selected during 2015 and 2016 to apply the SPC (Yong Jiang et al., 2017) as shown in Fig 1.3, with 180 to 270 million dollars' investment per cities from the central government. Although huge human and material resources are invested, the current results are not satisfactory because 2/3 of these pilot cities still suffer from the urban flood in 2016 after the SPC construction (Ye-Shuang Xu et al., 2018), which reveal some disadvantages of SPC.

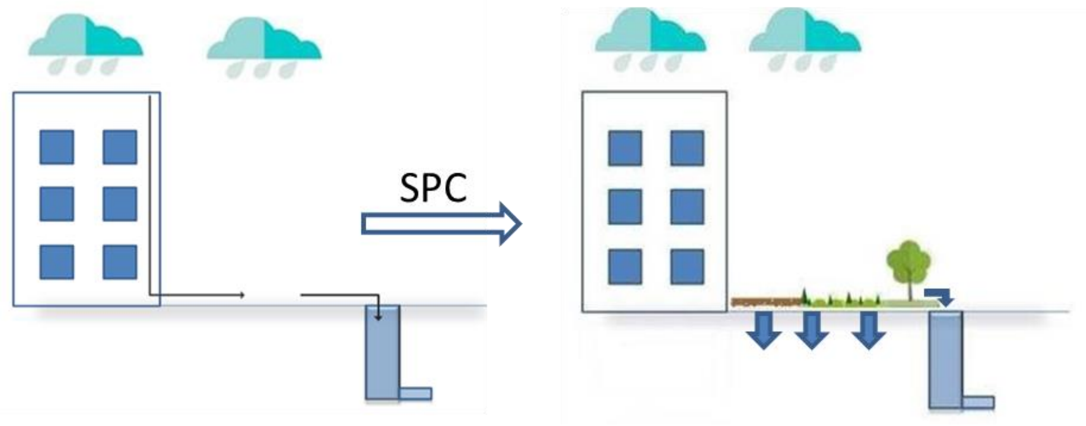

Figure 1.2 Conceptual construction of SPC

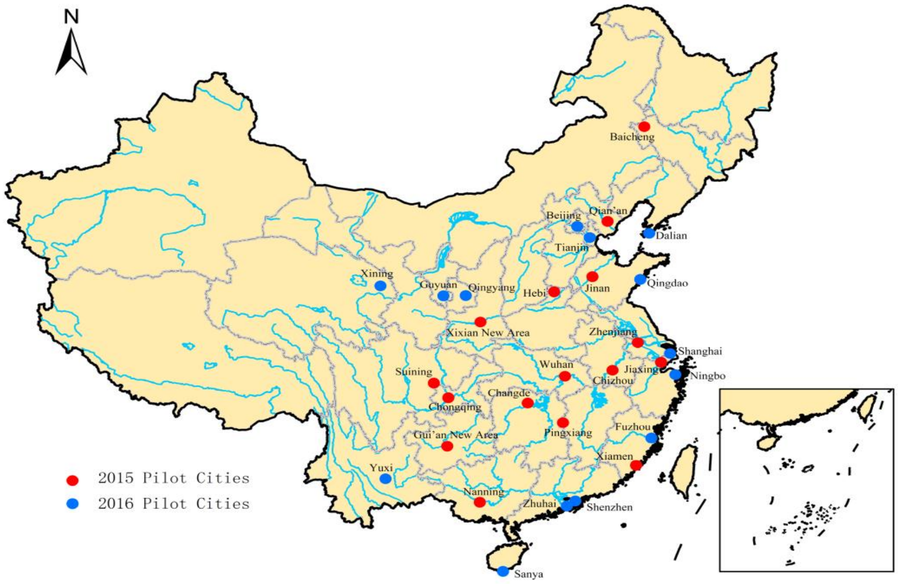

Figure 1.3 Location of pilot cities (adopted from Hui Li,2017)

First, the effectiveness of SPC could be not sufficient to withstand the frequent extreme storm in recent decades. Since the main approach to reduce surface runoff is increasing infiltration of the precipitation by improving the permeable area in cities, the limited reconfigurable area and permeability would be the obstacles for SPC to achieve an ideal mitigation. Although green roof has several merits to in urban design, such as the ability to retain and detain rainwater, as well as its esthetic appeal (Ju Youn g Lee et al., 2015), the relative high cost and complicated technology in China cause a very low ratio of green roof application. As a result, even though after construction of SPC, the rooftop of buildings is still the impermeable area which account for a large proportion of urban area and where the huge amount of runoff would produce leading to the unsatisfactory flood control effectiveness.

Finance is also a challenge of SPC in China. It is estimated t hat 1.2 billion to 1.8 billion RMB needed to be invested over a three -year period, and Public-private partnerships (PPP) are encouraged as a financial source of SPC (Xiaoning Li et al., 2016). Yet there are so me concerns that reduce the investment interest of social capital, like the high costs of design, construction and maintenance but with a lon g return periods and low returns (Zhang C, et al., 2011), so that a lo w cost effectiveness method is necessary for implementation of SPC.

1.1.3. Motivation

Rainwater harvesting system (RHWS) might be the most ancient method to deal with the water scarcity. It is also seen as an effective alternative solution for the some water issues today and could be an auxiliary method to make up these disadvantages about SPC mentioned above (Alberto Campisano et al., 2017). Harvested rainwater has been most commonly used to meet the non-potable water demands, like lawn irrigation and toilet flushing (Anna Petit-Boix et al., 2017; David J. and Jia Liu, 2014). The research and practice about RHWS are being promoted in developing countries (Tulinave B and Han, 2015; Nguyen et al., 2013), and are common in developed countries like Australia and Japan (Monzur Alam et al., 2011). Despite these efforts around the world, RHWS has not been drawn much attentions for utilization in China (Xinqi Zhang et al., 2012). Only limited research and almost none of empirical cases are conducted, amid which, the average daily data is commonly used in current research of China for estimation of both flood mitigation and water conservation. Whereas an intensified rainstorm with short duration is the major cause of the urban flood, and the average daily rainfall could not reflect the variation of rainfall in the real life for evaluation of water saving.

The micro-catchment rainwater harvesting system is designed by M.Y Han and D.C. Nguyen. As shown in Fig 1.3, two hydrological design systems of this rainwater management are Rainfall-Storage-Discharge (RSD) and Rainfall-Storage-Utilization-Discharge (RSUD), in which, RSUD is able to achieve both of two benefits, so it is selected as the improved method for current SPC.

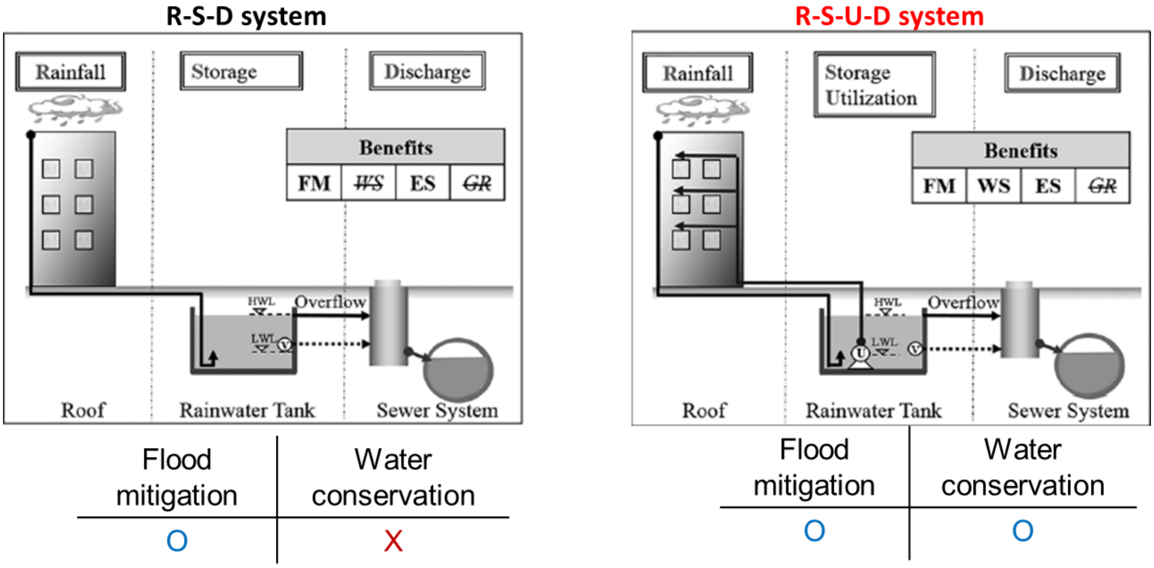

Figure 1.4 Two design of micro-catchment rainwater management system

1.2. Objectives

This study sets up a new configuration combining the concept of SPC and RHWS to estimate the maximum capacity of urban flood mitigation and water saving. The rainfall input is the significant step for final design decision, so the paper presents the difference of rainwater tank designs generated from the different data sets for the purposes of flood mitigation and water saving respectively. Then the design storm and daily rainfall of real sequence will be selected as rainfall input for assessment of the current SPC, and the combined system (SPC and RHWS), evaluating the potential capacity that the RWHS could enhance on the basis of SPC by comparison of the two systems (sole SPC and combined one). Finally, economic analysis will be included for seeking the optimal designs of the new configuration by adopting non-domination genetic algorithm (NSGA-ii) under the environment of MATLAB, which could provide some suggestions for the future construction of SPC in selected cities and the whole country.

The primary objectives of this paper are: 1) to analyze the effect of rainfall patterns on the design of rainwater tanks; 2) to estimate the enhanced capacity of RHWS compared to SPC all over China; 3) to seek the optimal configurations of rainwater facilities by multi-objective optimization.

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Chapter 2. Hydrologic factor

2.1. Introduction

The average rainfall is widely used in design of current Sponge City Project or rainwater harvesting system in related Chinese research (Shouhong Zhang et al., 2019; Xueer Jing et al., 2018). However, the average daily might reshape the rainfall variation so that the rainfall patterns become even and well-distributed in a year. Even though the historical daily rainfall is more closed to real condition, the existing results from the average daily rainfall might give some incorrect information about the real function and performance of rainwater harvesting system. Monzur Alam Imteaz optimize the tank design from large roofs in Melbourne, Australia, by using different Calendar years of dry year, wet year and average year for estimation of water saving and flood control, however the tank design of the method has serious options which make the decision making hard; Chao Mei assessed the integrated green infrastructure for flood mitigation by design storm but there was no function of water saving in this research.

From the previous literature we can see that the effect of the processed data on the design of rainwater tank is not well investigated and yet there is little related research in China, in this part, the objectives is to analysis the possible results difference between real daily rainfall sets and average daily rainfall data. To achieve the objective, 6 cities located in different climate zone will be selected to represent the general condition in China. The long real daily rainfall sequence will be operated and present in a statistical way, which could make the comparison more visualized.

2.2. Study sites and data compilation

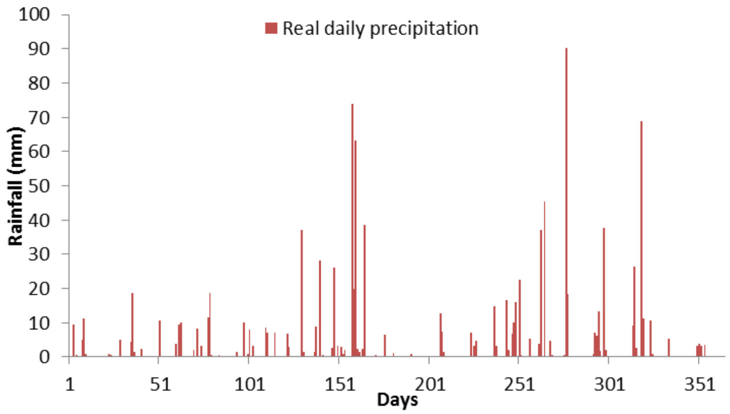
Xueer Jing (2017) assessed the vitality of RHWs in some China's cities which was classified as 4 different climate regions based on annual rainfall, where the humid zones are larger than 800mm, semi-humid zones are from 400mm to 800mm, semi-arid zones are from 200mm to 400mm, and arid zones are less than 200mm. To be in line with the previous research, 6 cities located in these climate regions (Fig 2.1) are selected to estimate the difference of water saving performance between real daily rainfall and average daily rainfall, and the cities are: Shanghai and Guangzhou (humid zones), Beijing and Jinan (semi-humid zones), Urumchi and Yinchuan (semi-arid and arid zones). There are only 4 capital cities with an annual rainfall less than 400mm, among which only 1 city can present the arid zones, so semi-arid zones and arid zones Daily rainfall data was obtained from National Climatic Center (CNN).

Figure 2.1 Location of study cities of Chapter 2

As shown in Tab 2.1, the average length of these study cities is around 60 years. The prepared average daily rainfall data and real daily rainfall data of Shanghai city with the same annual rainfall amount is shown in Fig 2.2, other study cities would repeat the same procedure to compile daily rainfall.

Table 2.1 Information of daily rainfall in study cites

Station name	Station number	data length	Annual rainfall (mm)
Guangzhou	59287	1951.01-2016.12	1789.81
Shanghai	58362	1959.01-2016.12	1122.12
Jinan	54823	1951.01-2016.12	692.1
Beijing	54511	1951.01-2016.12	589.7
Urumchi	51463	1951.01-2016.12	277.13
Ningxia	53614	1951.01-2016.12	196.04



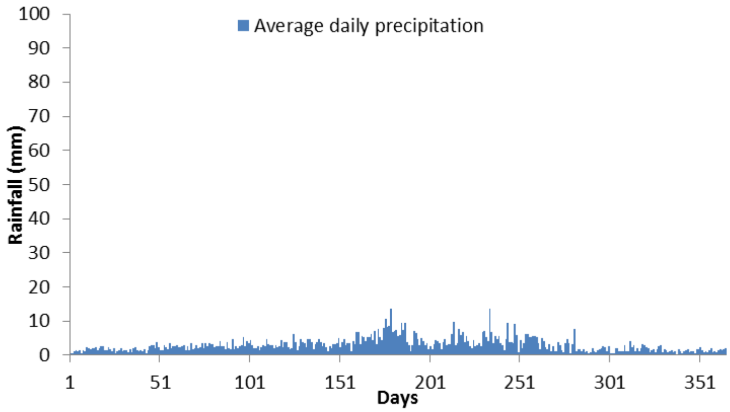


Figure 2.2 Variation of average daily rainfall and real daily rainfall in Shanghai

In this study, the roof area of the building is 100 m^2 and it serves 10 habitants for toilet flushing only. The water demands in different cities have some sight difference, whereas daily toilet flushing was estimated as 0.32 m^3/day, which is the average demand around the country. Other non-potable water usage (like laundry) was not included here.

2.3. Methodology

2.3.1. Water balance simulation

Several behavioral models have been developed and widely used to investigate the performance of RWH. In this study, water balance model that was set up by (Han) was adopted, and expressed as

$$V_t = V_{t-1} + Q_{in,t}\Delta t - Q_{sup,t}\Delta t - Q_{out,t}\Delta t$$

$$Q_{sup,t}\Delta t = \begin{cases} 0, & V_t \le 0 \\ V_{t-1} + Q_{in,t}\Delta t, & V_{t-1} + Q_{in,t}\Delta t < D\Delta t \\ D\Delta t, & V_{t-i} + Q_{in,t}\Delta t \ge D\Delta t \end{cases}$$

$$Q_{out,t}\Delta t = \begin{cases} 0, & V_t \le V \\ V_{t-1} - V + Q_{in,t}\Delta t - Q_{sup,t}\Delta t, & V_t > V \end{cases}$$

where V_t (m^3) is the cumulative water stored in rainwater tank at time t; V_{t-1}(m^3) is the cumulative water stored in rainwater tank at time t-1; Δt is the time step, which, as well as the following parameters about flow rate, would be adjusted according to different simulation process (10 minutes for flood mitigation and 24 hours for water saving); $Q_{in,t}$ (m^3/10 min or m^3/day) is the inflow rate of rainwater tank at time t; $Q_{sup,t}$ is the water supply rate to building from the rainwater tank; $Q_{out,t}$ is the outflow rate from rainwater tank; D is the water demand. The water demand was neglected when simulating flood mitigation since the time interval (10 minutes) is too short to be considered as a reasonable period of water consumption, in another word, there is no supplied water during a rainstorm event.

All the runoff generated from rooftop is assumed collectable and no loss. Therefore, $Q_{in,t}$ could be calculated by using Rational Method as:

$$Q_{in,t} = CP_t A$$

where C is the runoff coefficient; P_t (mm) is the rainfall depth; A (m^2) is the catchment area. C is set as 0.9 here to be consistent with other research. The computing process is shown in Fig 2.3.

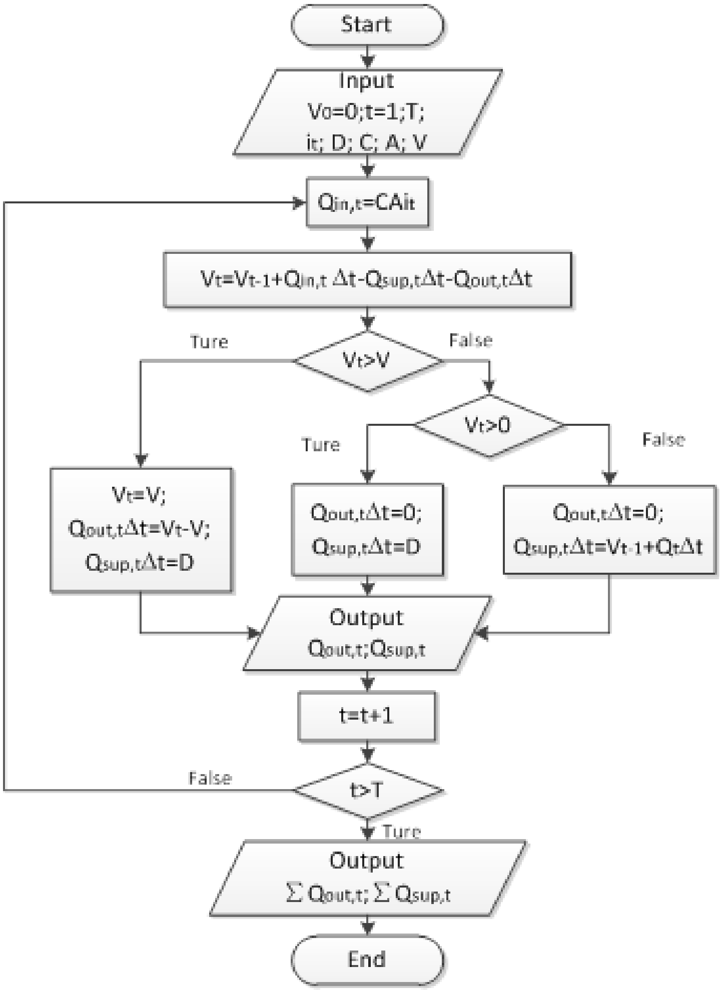


Figure 2.3 Flow chart of water balance for simulation of RSUD

2.3.2. Indicators for estimation

The water saving performance of RWH system is estimated by water saving efficiency and time reliability, as used in Xueer Jing, 2017 and Shouhong Zhang, 2018. Water saving efficiency is expressed as,

$$\omega = \frac{\sum Q_{sup}}{\sum D}$$

where Q_{sup} (m3) is the supplied water volume from rainwater tank; D (m3) is the water demand.

Time reliability can be calculated as,

$$g = \frac{N-U}{N}$$

where U is the number of days that RHW is unable to meet the water demand, and N is the total days of simulation period.

The Qsup could be attained directly from the flow chart, while the a selection statement is needed here to get the values of N and U according to the water demands (0.32 m^3/day).

2.4. Results

All the 60 years' real daily rainfall of selected cities were operated and presented box-whisker figure that includes statistic meaning, while the blue line is the result from average daily rainfall. As shown in Fig 2.4, in the humid zones, the water saving efficiency generated from average daily rainfall is higher than that from most historical years, since it is evident from the results that the water saving performance of average daily rainfall is even better than that of the 75% wet year. In another word, the RWHs could achieve an all-right water saving performance by using average daily rainfall with a certain tank size, however, if there is a specific target in a humid zone, using the average daily would overestimate the efficiency of a rainwater tank resulting in an insufficient design. For example, if we assume that the goal of water saving efficiency in Shanghai is 80%, this can be achieved by installing a tank sized 6 m3 when using average daily rainfall, but only 63%-73% demand would be met in the real rainfall conditions based on the historical data. A similar situation can be seen from the semi-humid zones, even though the results of average rainfall and of real one have overlapped parts. The results of both cities in semi-arid and arid zones show a different trend, where the efficiency of average daily rainfall is below that of median real one basically and almost in the same level as the 25% dry years. Thus it is concluded that the RHWs would have a better performance than that expected by using average daily rainfall.

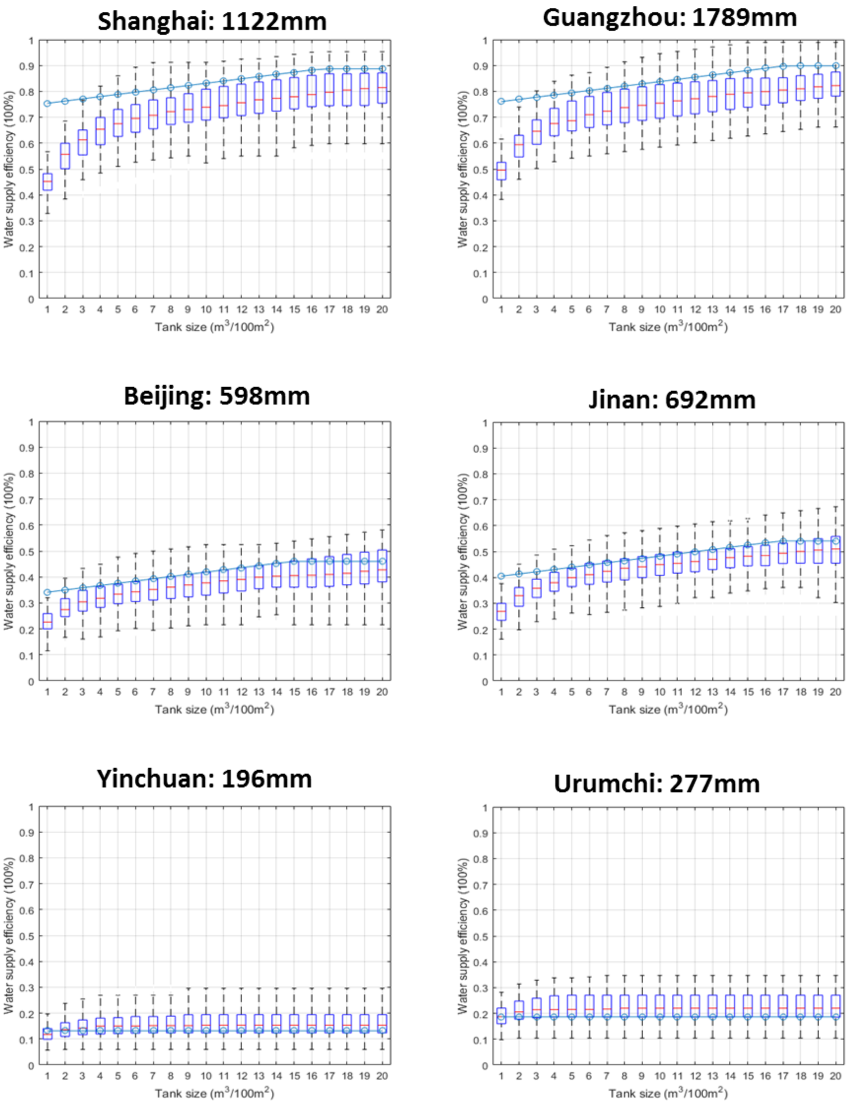


Figure 2.4 Comparison of water saving efficiency in different climate zone

As for time reliability, the difference of performances generated from two sets rainfall is not obviously linked to annual rainfall in humid and semi-humid zones. It can be observed that time reliability calculated from average data in Shanghai city is lower than that from real data, keeping in

70% with a tank sized 17 m^3 or larger, while in Guangzhou city, average and median real daily rainfall have almost the same variation as the tank size increases and reached to the highest reliability (80%) with 17 m^3s tank. The similar conclusion can be draw from Beijing and Jinan city, so difference of time reliability could be attributed to the rainfall patterns during a year, instead of total volume or depth, in these areas with abundant rainfall. From the last climate group we can see that in the semi-arid and arid zones, RHWS is not possible to meet the water demand during the whole year if using the average daily rainfall to design the system in both of cities, whereas the time reliability is up to 30% in the real rainfall condition. To some extent, the simulated results of RWHS from average data cannot reflect the situations in the real conditions, so it seems plausible to use the real daily rainfall data to design a RHWS.

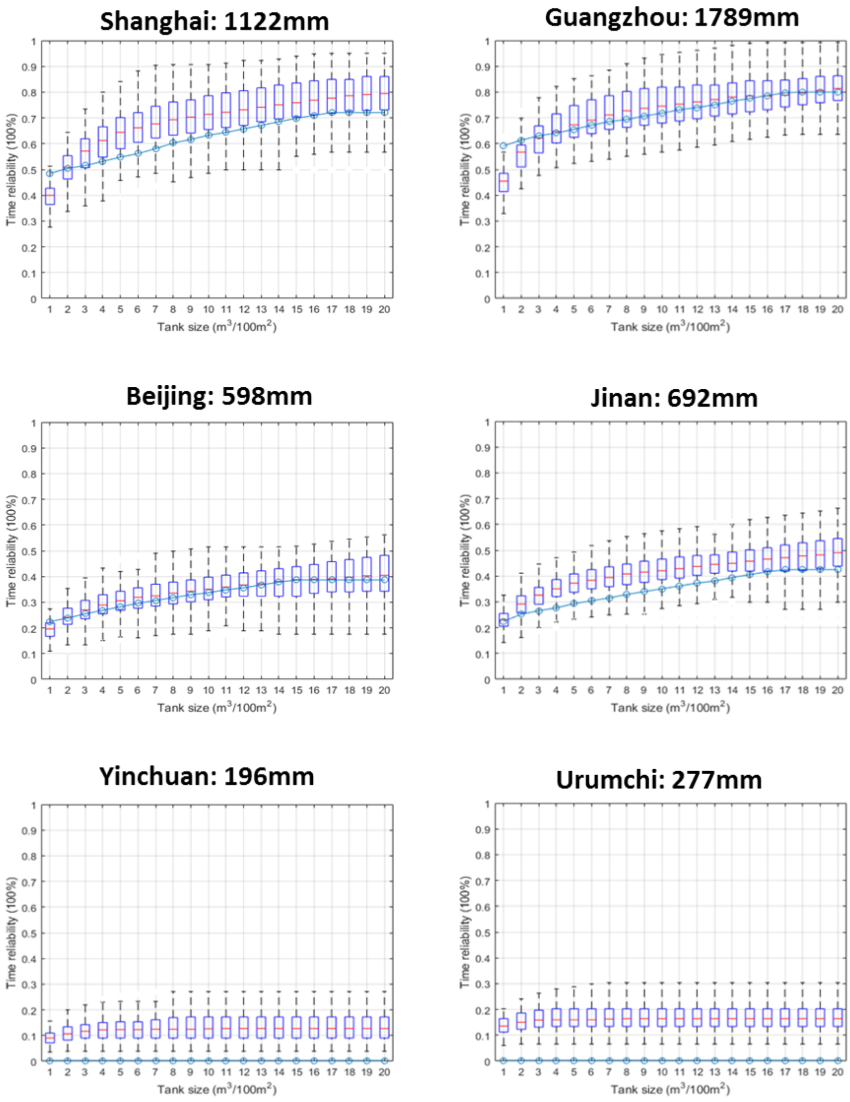


Figure 2.5 Comparison of time reliability in different climate zones

2.5. Discussion

Water conversation is needed most in semi area and arid zones where the annual rainfall is quite low and the temporal distribution is uneven. The results from the average daily stated that the RHWS have no function in term of reliability, which means that there is no day in a year could have sufficient water supply, and this incorrect estimation might be one of the reasons why people and government in China hesitate to develop the rainwater harvesting system in these arid zones. However, from the results of the Chapter, the rainwater tank could keep a safe water supply for at 30% of a year (more than 90%), and the water saving function of rainwater harvesting system is noticeably underestimated. In addition, the rainwater harvesting system could get the best performance when the tank size is still small (around 3 m^3/100 m^2) and do not improve with the increasing tank size, so applying this system is also economically viable.

For the sake of more accurate design of rainwater tank, the real daily rainfall data will be used for the further assessment in this research and also is high recommended as the input rainfall for other related research.

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Chapter 3. Improved method

3.1. Introduction

3.1.1. Chicago model

Design storm is defined for the design of hydrologic system, and it is derived from Intensity-Duration-Frequency (IDF) curve (Eugene A, Stallings., 1987). IDF curves is one of the most important tools in water related engineering and planning, could be developed by using historical storm events data and frequency analysis based on mathematical and statistical methods (Ashish Shrestha et al, 2017; Hongxiang Yan et al., 2019). Van thanh Van built a decision support tool (SMEwRain) to identify the most accurate distribution of certain extreme storm events to provide a reliable rainfall estimation and prediction.

Several methods were developed to generate the design storm (like Huff method, Uniform distribution and Alternating block method). While some research about Huff method was done (S.Q. Yin et al, 2016; Cuilin Pan et al., 2017), Chicago model is still the most commonly used methods and is widely adopted by Chinese scholars. And the relevant compilation work was completed in hydrographic department of each province.

The basic formula of Chicago model is:

$$\mathrm{i} = \frac{A \times (1 + c\lg P)}{167 \times (t + b)^{n}}$$

where the i is the storm rainfall intensity (mm/min); t is the duration of this storm (min); P is the return period; A is the strength parameter, the design rainfall depth when the return period is 1 year and duration is 1 minute; C is the variation of rain force (dimensionless); b is the duration correction parameter; n is the damped exponential, which is related to the return period (Chen yang et al, 2017).

In addition, to generate a design rainstorm, the position of peak rain is needed, which express as,

$$r_i = \frac{t_i}{T_i}$$

where the ri is the parameter of rain peak position; ti is peak rainfall time; Ti is the duration of rainfall; i is the specific year. This procedure should be: first, average the rain peak position coefficient of the sample of the same maximum annual precipitation process over the same period; the next step is weighted average of the peak rain position parameters based on different duration. The final value of peak rain position will be calculated (Youxue dai, et al., 2017).

Based on related regulation and guideline, the peak rainfall in China is around 0.25-0.5 (Technical Guidelines for establishment of Intensity-Duration-Frequency Curve and Design Rainstorm Profile). In the chapter, the value of 0.3 will be used as the peak rain position for all the selected cities.

3.1.2. SCS CN method

SCS runoff curve number is established by the United Stated Department of Agriculture Soil Conservation Service (SCS), and is a method to evaluate the runoff of different covered ground from rainfall. SCS CN is one of the most common methods to calculate urban and rural runoff in China, meanwhile some research based on the local condition of China is also in progress (Feng lei 2013; G.Y. Gao et al., 2012; Zhi-Hua Shi et al, 2009). So in the study, SCS CN method is used for calculated the runoff from developed urban surface (impervious space) and the ground after the construction of Sponge City Project, by adopting different CN values.

According to the National Engineering Hand book of US (2004), the soil was divided into 4 hydrologic group (A, B, C, D) based on their infiltration rates (Group A soil has highest infiltration rate). The urban soil in China is generally classified into Group B (Bo xiao et al., 2011). To be in line with previous study, CN values in Group will be selected in this research. Specifically, the impervious ground space and rooftop space in cities are classified as the “Paved parking lot, roofs, driveways, etc. (excluding right of way)” with a CN value of 98; green space of SPC is classified as the “Open space (lawns, parks, golf courses, cemeteries, etc.) with a CN value of 69; permeable pavement is classified as the “Gravel (including right of way)” with a CN value of 85.

3.2. Study sites and data

3.2.1. Study sites and rainfall data

In this chapter, all the 31 capital cities of China are selected as study areas to represent the climatic conditions of their corresponding provinces, except Macao, Hong Kong and Taiwan (Fig 3.1).

Figure 3.1 Location of study cities in Chapter 3

To meet the objectives, design rainstorm formulas and historical daily rainfall of the studied cities were collected for the estimation of flood mitigation and water conservation, respectively. Daily rainfall data was still obtained from National Climatic Center (CNN). The mean annual rainfalls are from 200 mm to 2000 mm and the average length of years is about 60 years. Besides both of the sources and the parameters of design rainstorm formulas in different cities are presented in Table S1. Particularly, Shanghai, Beijing and some other cities are chosen as case study to make the computational process clear. As mentioned before, real daily rainfall is used as input daily rainfall for the estimation of water saving performance in this chapter, while design rainstorms are generated from Chicago Model for flood mitigation by applying these collected parameters into Eq. Taking Shanghai and Beijing city as an example, the calculated rainstorms with 720 minutes' during and 50-year return period are shown in Figure 3.2.

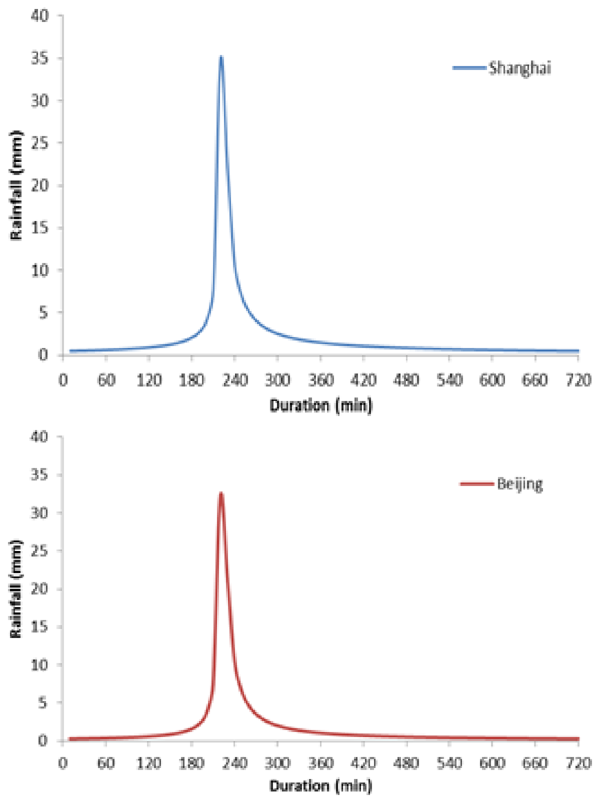

Figure 3.2 Design storm patterns of Beijing and Shanghai City with a 50-year return period and a duration of 720 minutes

3.2.2. Establishment of calculation model

The real urban surface conditions are quite complicated. In order to simply the calculation process as well as adopt the micro-catchment theory, the micro system was established as the calculation unit, based on the real regional surface conditions. The calculation unit is consisted of one building with a 100 m2's rooftop and its surrounding road and ground space. The area of all kinds of urban surface utilizations of study cities were collected from the Year Book of each province. In general, residential and commercial area were regarded as the building area with flat rooftop that could the catchment of rainwater harvesting system; urban trunk road was regarded as road area; the rest of the part (subtracted the existing green belt and part area) are impermeable area. Tab 3.1 shows the data conversion of Beijing and Shanghai City.

Table 3.1 Total impervious area of Beijing and Shanghai City

City		Shanghai	Beijing
Urban surface area	rooftop (km^2)	1106.85	534.07
	Ground (km^2)	1536.25	594.34
	Road (km^2)	272.9	260.74
Micro-scale surface area	rooftop (m^2)	100	100
	Ground (m^2)	138.79	111.28
	Road (m^2)	24.65	48.82

Besides, The official construction guideline (Engineering technical code for utilization in building and sub-district, GB 50400-2006) states that the construction area of permeable pavement should be less than 30% of the urban trunk road; the construction area of green space should be less than parking lot area and other unchangeable area, which is roughly considered as 40%. So the physical constrains could be shown numerically as Tab 3.2. Since it is difficult to compare construction areas directly among these cities due to different covers, the ratio of each space was used here.

Table 3.2 Physical constrains of calculation unit

Item	**Rainwater harvesting (RWHS)**	**Green Space (GS)**	**Permeable pavement (PP)**
Construction ratio (η)	0,1	<0.4	<0.3
Curve number (CN)	×	69	85

3.3. Methodology

3.3.1. Runoff calculation

As stated, one building with a 100 m^2's rooftop and its surrounding road and ground space would be a calculation unit for each cities based on local conditions. As shown in Fig 3.3, the simulation is consisted of two parts: catchment 1 (rooftop), where the rainwater is harvested into tank and the overflow goes to the outfall of the system; catchment 2 (road and ground), where the rainwater is infiltrated through green space and pavement area, the overflow goes to the same outfall. As SPC focuses on increasing the urban permeable area to reduce surface runoff with the intention of alleviating urban flood, we can generally regard this project as changing the impermeable urban ground to green space, hard road to permeable pavement as much as possible. Thus the runoff from all kinds of surfaces, no matter it has converted or not, could be calculated simply by choosing an appropriate CN value as mentioned before. The performance of this combined system could be estimated by comparison of the runoff amount of outfall before and after installing rainwater tank.

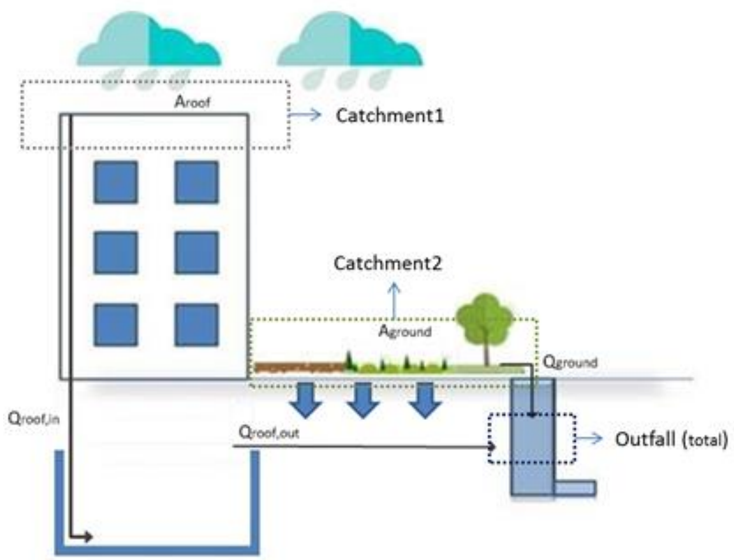

Figure 3.3 Illustration of combined system

As mentioned before, SCS (Soil Conservation Service) CN (Curve Number) is one of the most common methods using to calculate runoff in China, so it was applied here to estimate the possible runoff from various urban surfaces of Sponge City Project as:

$$Q = \begin{cases} 0, & P \le I_a \\ \dfrac{(P - I_a)^2}{P - I_a + S}, & P > I_a \end{cases}$$

where Q (mm) is the runoff depth; P (mm) is the rainfall; I_a is the initial abstraction; S is the potential maximum soil moisture retention after runoff begins. I_a and S have a relationship as,

$$I_a = 0.05S$$

besides, S can be calculated from CN by the equation,

$$S = \frac{1000}{CN} - 10$$

The computing process of SCS curve number for estimation of SPC is shown as Fig 3.4. Output Qspc would be used to evaluate the performance of SPC as well as the improved system.

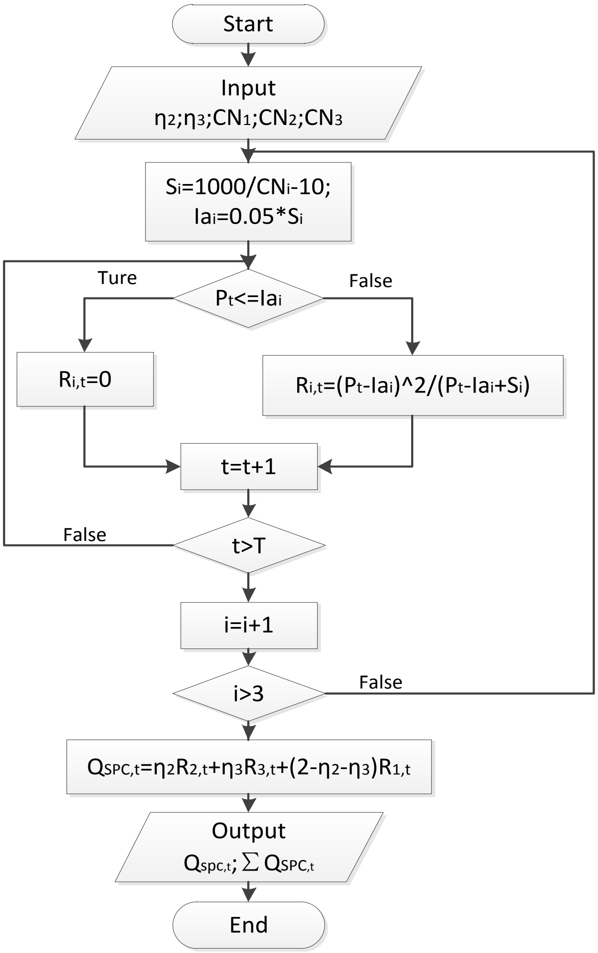

Fig 3.4 Flow chart of SCS CN method for SPC

The runoff from rooftop (catchmet 1) still used water balance simulation as metioned in Fig 2.2.1. Then the sum and sequence of outflow form the two catchments will be attained and used for further analysis.

3.3.2. Indicators of flood mitigation and water saving

Stormwater control ratio refers to the proportion of reduced stormwater in total initial runoff during a certain storm event, and is employed here to evaluate the performance of flood mitigation. Because both of RWHs and SPC have the function of alleviating storm, in this study, it is formulated as,

$$\mathrm{r} = 1 - \frac{\sum Q_{out} + \sum Q_{SPC}}{W}$$

where Q_{out} (m^3) is the outflow from rooftop of a building; Q_{SPC} (m^3) is the outflow from its surrounding ground and road area; W (m^3) is the total runoff of the entire area. In this case, the r represents the control ratio of the whole system and the place where the runoff collected is outfall in Fig 3.3.

Besides, the runoff depth is the total runoff amount of outfall from the combined system. Runoff depth could provide a more straightforward way to get the reduction of RHWS in a city, and it is expressed as,

$$\text{runoff depth} = \frac{\sum Q_{out}}{A}$$

where Qout (m^3) is the outflow form rooftop; A (m^2) is the area of rooftop.

The indicators using to estimate the performance of water saving are the same as that mentioned in Chapter 2 (water saving efficiency and time reliability).

3.4. Results

3.4.1. Performance of flood mitigation

Design rainstorms have the return periods of 20, 50 years with duration of 720 minutes. The flood mitigation performance in Shanghai and Beijing city can be increased dramatically by installing rainwater tank, as shown in Fig 3.5. For instance, the red circled points are where the runoffs of 50-year storm are reduced into that of 2-year event (around 80 mm) of these two cities respectively, corresponding to the tank sizes of 10 m^3 and 8 m^3. If we define the tank size that approaches the runoff to a constant value is the proper tank size, the proper tank sizes for Beijing city is 8 m^3 while the proper tank size for Shanghai city is 10 m^3.

In addition, the 0 m^3 tank size means only SPC is applied in that city. The runoff depths of sole SPC in the two cities are around 120 mm. After installing the proper rainwater tanks, the runoff depth of these two cities reduced by 40 mm (Shanghai) and 37 mm (Beijing), and the decreased runoffs are below the drainage capacity of the municipal sewer system so that the overflow would not occur.

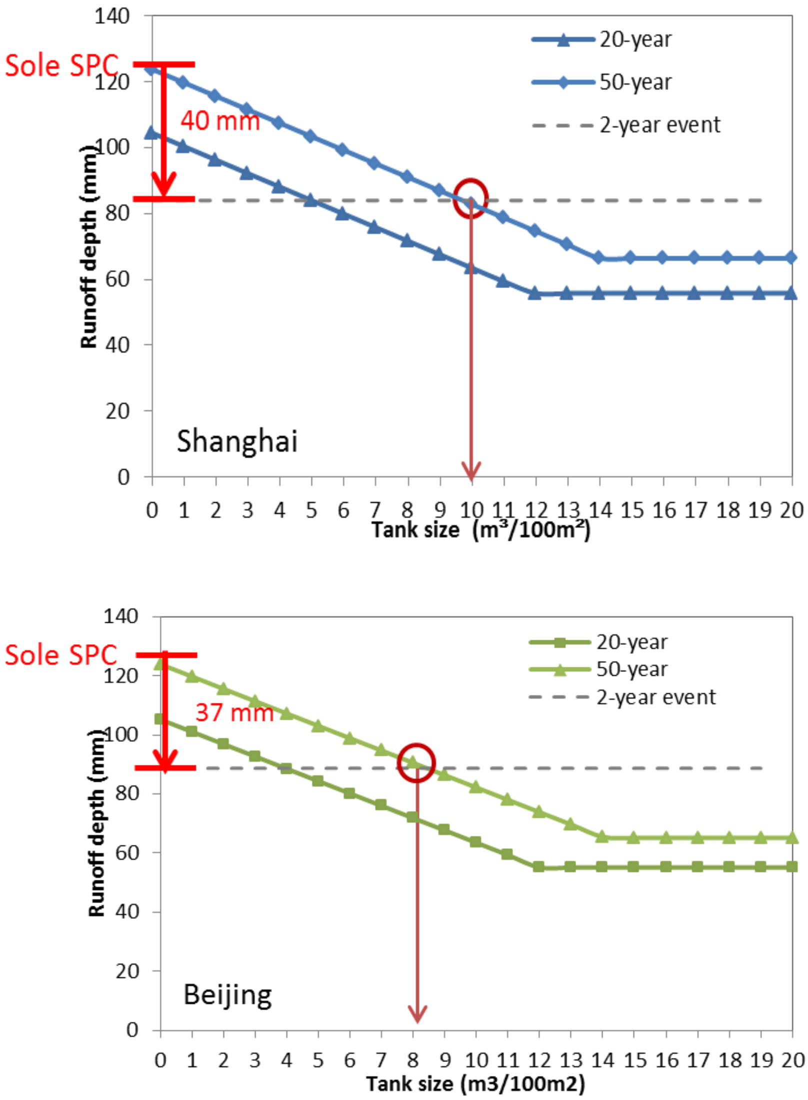

Figure 3.5 Runoff depth-tank size curves of Shanghai and Beijing City

Fig 3.6 presents the variation of cumulative runoff during 50-year rainstorm with tank sizes of 9 m3 and 14 m3, and the gaps at the end of these curves are the total alleviated runoff depth at the end of the storm. To be clear, by installing a tank sized 9 m3, the total runoff can be dropped from 134 mm to 100 mm. Besides, it is noticeable that accumulated runoff is reduced considerably when the precipitation reaches its peak.

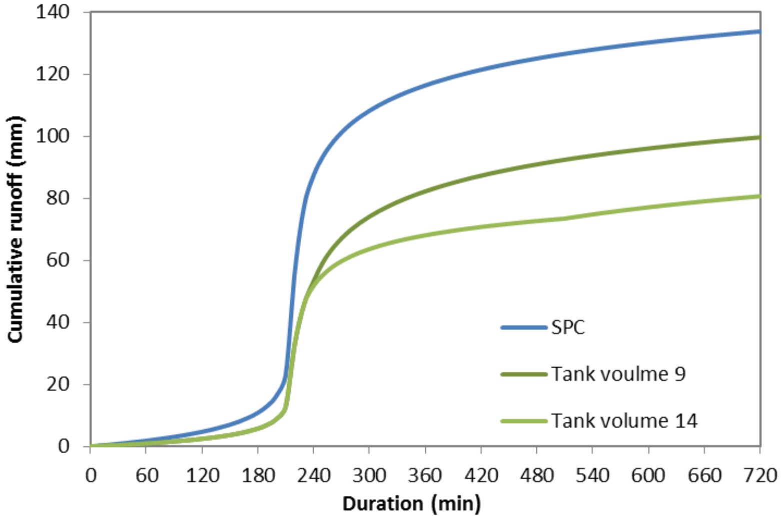

Figure 3.6 Cumulative runoff-duration curve of Shanghai city

Flood mitigation performance of all the other cities can be got by repeating the same procedure. Since the construction standard of municipal drainage system in most China's cities is to withstand 2-year rainstorm, here the tank sizes that reduce the runoff of 50-year event to 2-year event are chosen as proper sizes and applied in all the cities to calculate the stormwater control ratio. As shown in Fig 3.7, the stormwater control ratio can be increased markedly comparing to that of sole SPC (no rainwater tank), where the alleviated effect is up to 45%. Besides, the performance of flood mitigation in northern China is better than southern part, which could be due to the less intensified storm in northern China. More specific results are presented in Tabs. For instance, in Xi'an city, the RHWs attain the best effect of stormwater alleviation, where the control ratio is increased from

8.01% to 47.95% with the proper rainwater tank (10 m^3); biggest tank (18 m^3) is needed in Wuhan city to eliminate the flood.

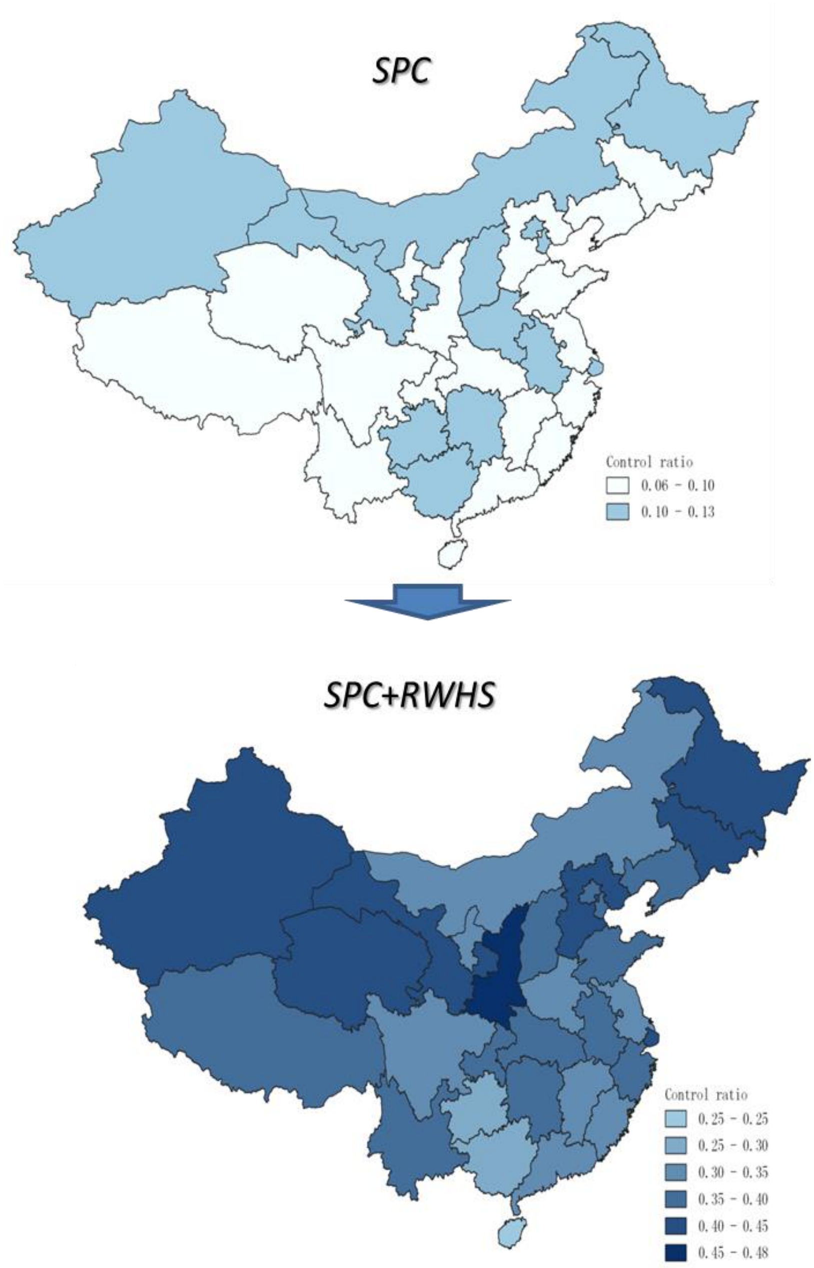

Figure 3.7 Stormwater control efficiency of SPC and Improved system

3.4.2. Performance of water saving

Here the optimal criterion is defined as the runoff depth approaches to a constant efficiency, as shown in Figure 3.8, the optimal tank sizes for water saving in Shanghai and Beijing City are 17 m^3 and 15 m^3, respectively.

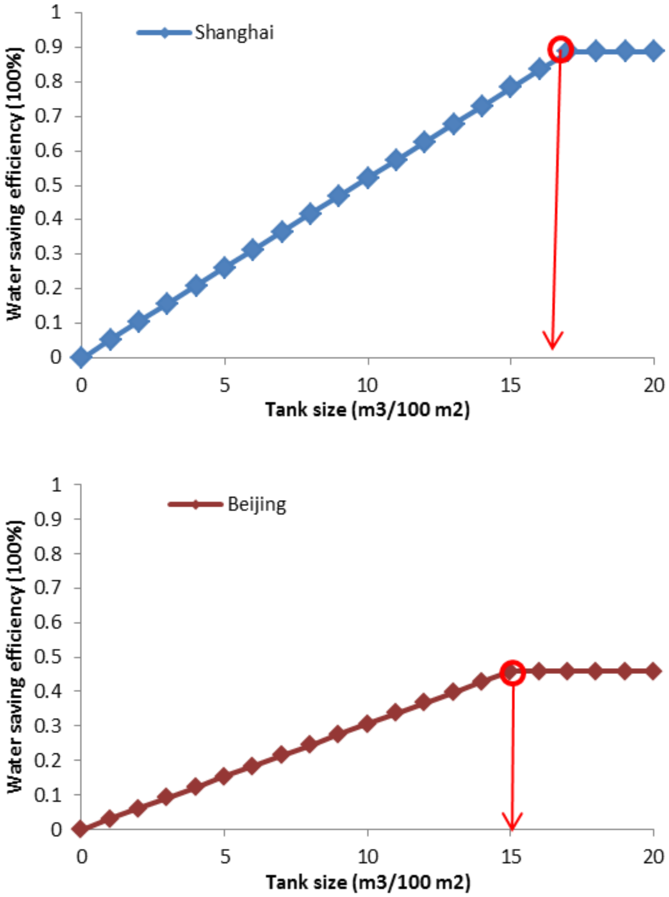

Figure 3.8 Water saving efficiency –tank size curves

As discussed previously, the water saving performance of average daily rainfall and real daily rainfall has certain difference. Thus, to ensure design system could be closer to the actual needs, real daily rainfall data would be used for the following calculation. Fig 3.9 shows the contribution of supplied rainwater and tap water in Beijing and Shanghai city, by using the real median year as the input rainfall data with best tank sizes of each cities. It appears that water demand can be met in most of days (276 days) in a year in Shanghai city, whereas in Beijing city, the rainwater tank is able to supply the sufficient water when there is plenty of rain in summer (164 days).

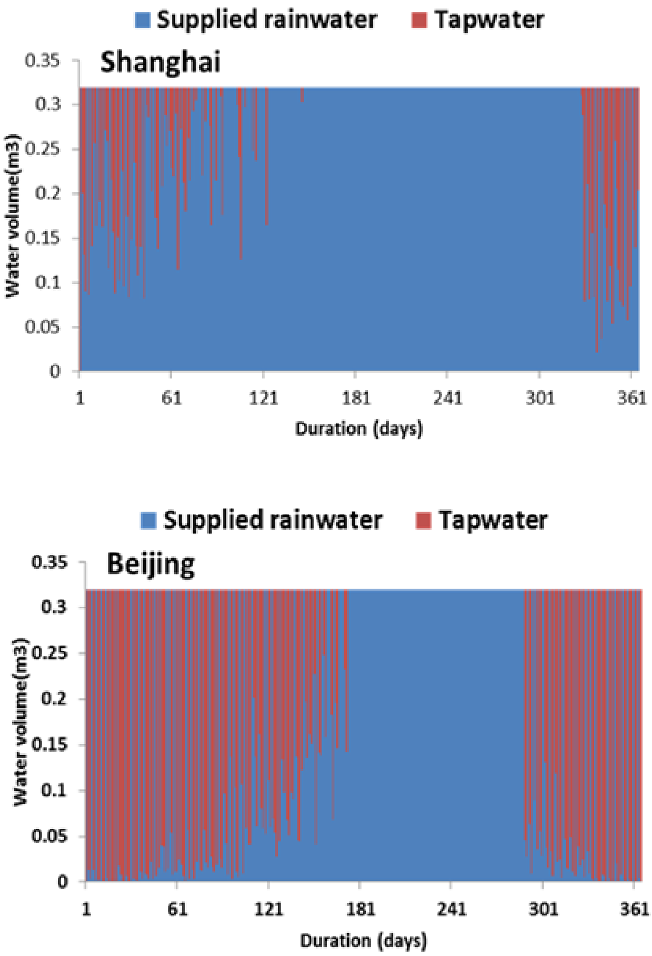

Figure 3.9 Daily contribution of rainwater and tap water during a year

Although current SPC is unable to achieve the function of water conservation, RHWS can appreciably improve the water saving efficiency with the best tank size in each city, as illustrated in Fig 3.10.

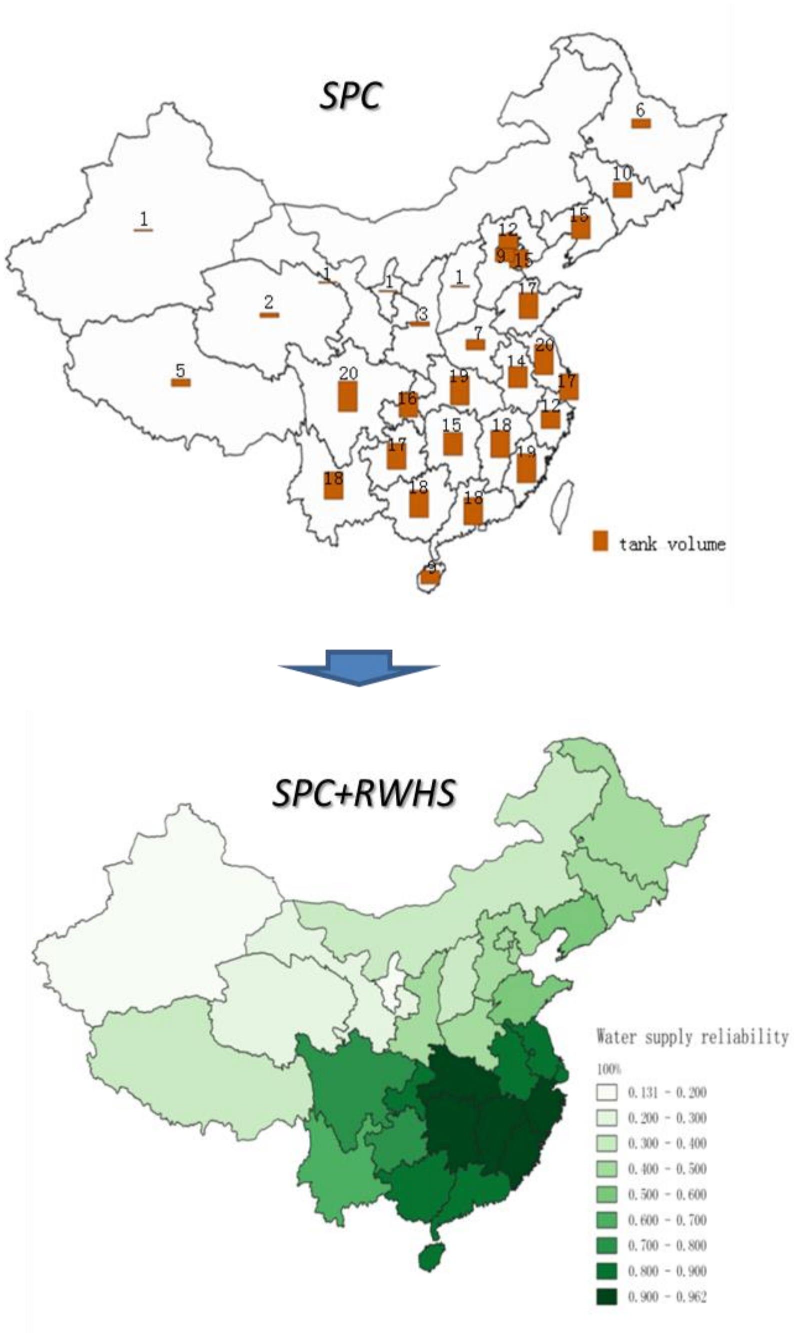

Figure 3.10 Water saving efficiency of SPC and Improved system

Climate and geographic position play an important role on the design of RWHS for water conservation, in particular, Southeastern China is where the highest water saving efficiency can be attained (generally more than 90%), while in northwest, only 13%-30% of water is supplied by rainwater tank. Accordingly, the smaller tank sizes (15-20 m3) are needed in northwestern China and the tank sizes needed in northwestern China are using less than 5 m3.

With considering the economy, the application of RHWS in Southern cities could benefit most, and the rainwater supplied from tanks is able to meet the water demands for toilet flushing. However, the construction fee of RHWS has a positively relationship with the rainwater tank sizes, which means a tank with 20 m^3 volume might have a great flood control and water saving performance but is not feasible economically. Thus, the economic factor will be included in the next chapter.

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Chapter 4. Optimization

4.1. Introduction

Economy is one of the most significant factors that determine the feasibility of RHWS and SPC. Yi Li investigated the best options for several combinations of green rooftops, porous pavements and green land and found the optimal configuration for the construction of SPC. However, in this research, it is proved that the viability to applying green roof is limited due to the high construction and maintenance fee as well as the high technical requirement. Furthermore, the rainwater tank was not considered as one option. So far, the investigations about the cost-effectiveness of RHWS and comparison between SPC and RWHS have not been attached enough attention in China.

Seeking the optimal solution for multi-objectives is difficult, especially when these objectives could not be unified to the same dimension. With the development of some evolutionary algorithms (like genetic algorithms and ant colony optimization), the multi-objective problem becomes solvable with a higher efficiency (J.P. Newman et al, 2013). Non – domination genetic algorithm (NSGA-ii) is an effective tool for solving multi-objective optimization problems, which is established in 2002 by Deb et al (Deb et al., 2002). In this chapter NSGA-ii is selected as the technique to solve optimization problems.

4.2. Methodology

4.2.1. Economic analysis

In this case, the construction cost is considered as an objective to be minimized, whose equations are different based on specific system. In terms of SPC,

$$E_c = EC_k A_k \times 10^{-3} + \sum_{t=1}^{m} \frac{Q_{kt}}{(1+i)^t}$$

where EC_k is the unit construction cost of SPC (green space and permeable pavement); O_{kt} is the operation and maintenance cost occurring in the year t of each SPC item; i is the discount rate, which is recommended as 8% according to National Development and Reform Commission of the People's Republic of China (2008); m is evaluation period (number of years), which is assumed as 20 years here, the same value as that used in other related research.

The cost of RWH can be described as,

$$\mathrm{PC} = \mathrm{I} + \mathrm{C} \times \frac{(1+i)^m - 1}{i(1+i)^m}$$

where PC is the present value of costs; C is the operation cost; i and m are the meanings and values mentioned above.

4.2.2. Objectives

Three objectives were set up here: minimizing the storm runoff depth; maximizing the water saving efficiency; minimizing the construction cost. In addition, two model scenarios were investigated, and each scenario was operated in case of SPC only, combined SPC and RHW as well. These are further expounded as:

Scenario A: considering flood mitigation and cost. 1) For SPC, two objectives are: Min$\frac{\sum Q_{SPC}+\sum Q_{rooftop}}{A}$ and MinE_c, where $Q_{rooftop}$ (m3) is the runoff volume from impermeable rooftop; A (m2) is the total area of simulated area. 2) For combined SPC and RWH, two objectives are: Min$\frac{\sum Q_{SPC}+\sum Q_{out}}{A}$ and Min$(E_c + PC)$.

Scenario B: comprehensively considering the three objectives. Since SPC is hardly able to achieve water saving, only combined case was operated here, which is: Min$\frac{\sum Q_{SPC}+\sum Q_{out}}{A}$, Min$(E_c + PC)$ and Maxω.

4.2.3. Method

As mentioned, NSGA-ii (Non-domination genetic algorithm) is chosen to deal with the multi-objective optimization problems. The process of NSGA-ii is shown as follows (Yi li et al, 2018):

Random initialization of population P (0) of size N;

Fast non-domination sorting on P (0);

For every generation t;

Select a parent population Pp (t) from P (t);

Create a child population Pc (t) from Pp (t) using crossover and mutation;

Combine P (t) and Pc (t) into an intermediate population Pi (t);

Fast non-domination sorting on Pi (t);

Place the best N individuals from Pi (t) to Pi (t+1);

End loop

Fig 4.1 presents the computing process of this algorithm, which is the foundation for program making.

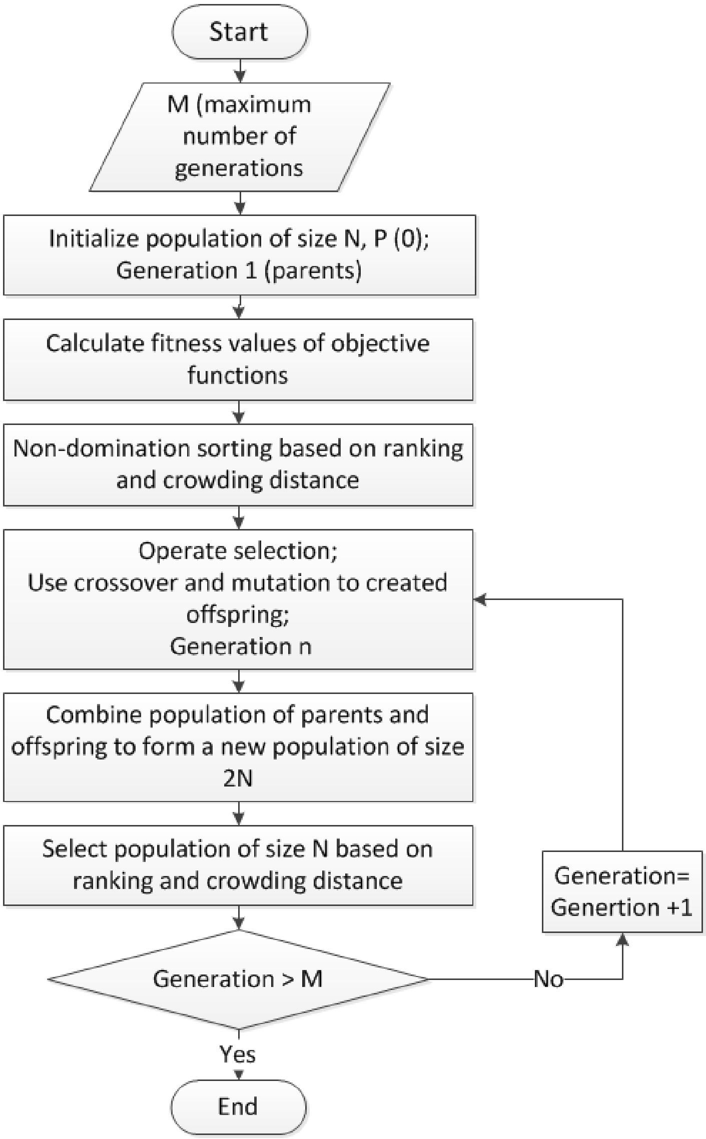

Figure 4.1 Flow chart of NSGA-ii (adopted from

Part of the source code was attained from Aravind 2001, and then it is modified according the set objectives in the study to search the matching optimal solutions.

4.2.4. Variations

The construction ratio of green space and permeable pavement, as well as the rainwater tank volume are chosen as the variations, as shown in Tab 4.1 to present the construction of SPC (GS and PP) and RHWS (tank volume), respectively. It is assumed that the construction ratio of rooftop area is 1 when installing the tank, which means the entire area of the building roof would be the catchment. The capacity of RWHS is adjusted by changing the tank volume merely.

Table 4.1 Variations of optimization problems

Configuration	η_{GS}	η_{PP}	$\eta_{rooftop}$	V_{tank}
SPC	√	√	0	0
SPC+RWHS	√	√	1	√

The sole SPC and improved system (RHWS included) are operated to get the optimal solution, and compare the effectiveness of this two methods as well.

Since these objectives have different dimensions, the output from this process will be a set of candidates, which called Pareto line (2 objectives) or Pareto surface (3 objectives. Each candidate has the same value and all of them are the optimal solutions for the optimizations problems. Further human decision-making is needed when choosing the scheme for a real project.

4.3. Results

4.3.1. Scenario A

All the numerical Pareto solutions for sole SPC, as well as the combination of SPC and RWHS, are presented in Table S2. Here only Shanghai city is shown due to page limitation.

Still taking Shanghai and Beijing City as examples (Fig 4.2), in Shanghai city, both of the Pareto lines are proportionate basically, showing that the cost and runoff depth are highly negatively correlated. Consequently, optimal configurations that have higher costs are likely to corresponding decreasing in runoff depth. This can be explained easily by that, the larger tank sizes would reduce more stormwater that is the cause of runoff, meanwhile, the larger the tank is, the more cost it needs.

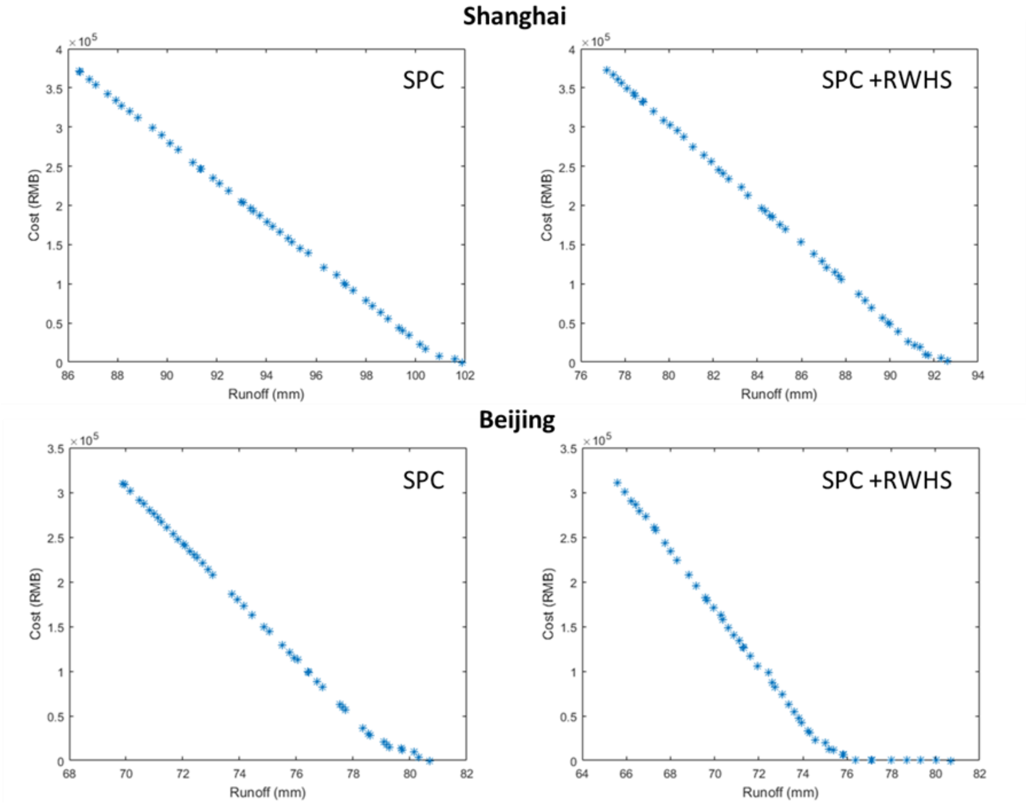

Figure 4.2 Pareto lines in Beijing and Shanghai City considering flood mitigation and cost

Besides, it appears that runoff of the combined system (86 mm-102 mm) is generally lower than that of sole SPC (76 mm-94 mm) when the costs are in the same range. To be more specific, one of the Pareto solutions with almost the same cost are shown in Table 4.2. The runoff of sole SPC is around 91.03 mm while the runoff the combination of SPC and RWHS is 81.92 mm, where an apparent runoff reduction can be seen with the similar cost (around 25,000 yuan), and optimal tank size in this case should be 7.36 m3/100 m2 to achieve the best effect of flood mitigation. The value of other variations seems to slightly decrease. In case of Shanghai city, the construction area of green space of the calculation unit should be reduced from 37.75 m^2 to 37.04 m^2, meanwhile the construction area of permeable pavement should be reduced from 7.34 m^2 to 7.24 m^2.

Table 4.2 One of the optimal solutions of SPC and improved SPC+RHWS (2 objetives)

Type	Tank volume (m3)	GS ratio	PP ratio	Cost (RMB)	Runoff (mm)
SPC	0	0.272	0.298	254868	91.03
SPC+RWHS	7.36	0.267	0.298	255397	81.92

A similar conclusion can be draw from Beijing city, though the cost seems to be lower than in Shanghai due to the relatively high proportion of roof area.

It should be noted that the Pareto line of the combined SPC and RWHS has a part with the almost constant cost where the runoff is still reducing, which shows that with a slight change in cost, the runoff depth could be reduced lot (from 82 mm to 76 mm). From Tab 4.3 we can see that in this part, the construction ratios of green space and permeable pavement are almost 0% and only RHWS was applied here. Thus it could be speculated that the RHWS has a high efficiency in flood mitigation in Beijing city.

Table 4.3 Special optimal solutions in Beijing City

Tank volume (m^3)	GS ratio	PP ration	Cost (RMB)	Runoff (mm)
0.180284	0	0	80.012	107.187
0.361222	0	0	79.31635	214.7628
0.526193	0	0	78.68209	312.845
0.700466	0	0.001278	78.00432	496.1029
0.928401	0	0	77.13574	551.9755
0.939942	0	0	77.09136	558.8372
1.158776	0	0.002731	76.38914	859.1446

4.3.2. Scenario B

Fig 11 is the three-dimensional representation of multi-objective Pareto solutions in these two cities, where water saving efficiency of SPC keeps in 0% since the SPC do not have the function of storing or recycling rainwater in this study. It is apparent that RHWS could achieve a better performance in Shanghai because of the higher annual rainfall. In addition, it can be seen that the runoff depth is also reduced distinctly from the distribution of these Pareto solutions.

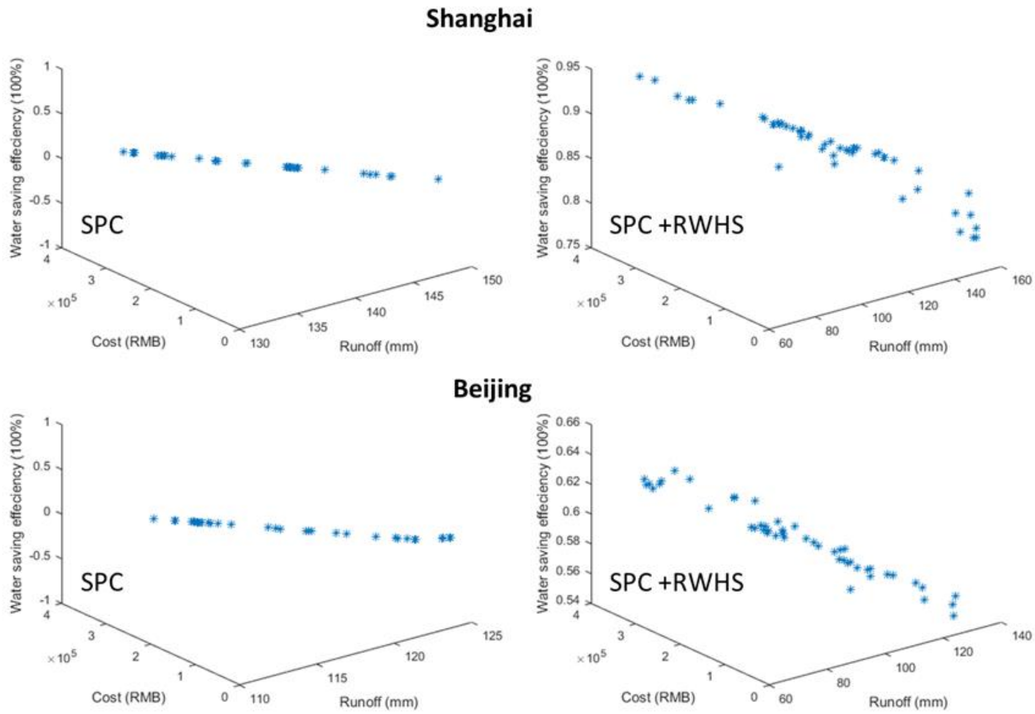

Figure 4.3 Pareto surface in Beijing and Shanghai city considering flood mitigation, water saving and cost.

As shown in Tab 4.4, with a cost of 25,000 RMB, around 58 percent of water consumption can be supplied from rainwater tanks, meanwhile the runoff depth would be decreased from 115.18 mm to 100.62 mm. According to this solution, the construction area of green space was increased slightly while the construction area of permeable pavement was decreased steeply.

Table 4.4 One of the optimal solutions of SPC and SPC+RWHS (3 objectives)

Type	Tank volume (m^3)	GS ratio	PP ratio	Cost (RMB)	Runoff (mm)	Water saving efficiency
SPC	0	0.318	0.299	250109	115.18	0
SPC+RWHS	4.11	0.342	0.006	250073	100.62	0.584

Since it is difficult to interpret the three-dimensional figures, the results of Pareto surface were illustrated in a two-dimensional way, It is seen in Fig 4.4. It is seen that there is little trade-off between runoff and water saving since the surface is narrow. Runoff seems to affect the cost in some extent, but the trend is not obvious (Fig 4.4 (a)), while the cost and runoff are in a negative correlation (Fig 4.4 (c)).

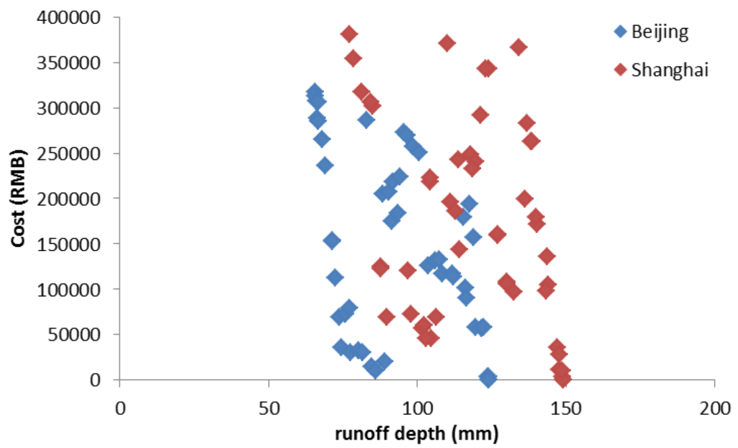

Figure 4.4 (a) Pareto solutions plotted with runoff depth and cost

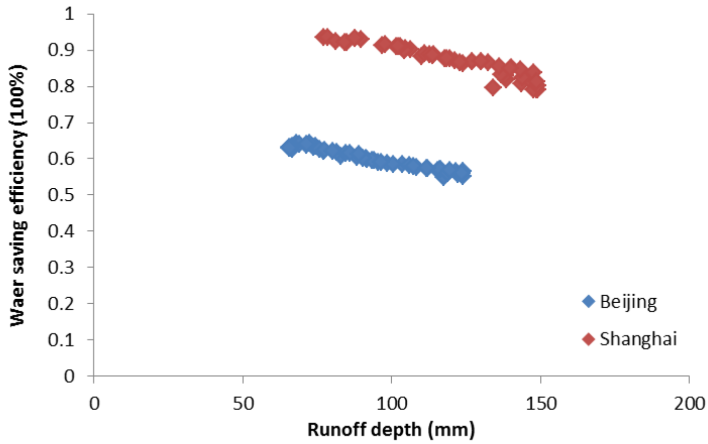

Figure 4.4 (b) Pareto solutions plotted with runoff depth and water saving efficiency

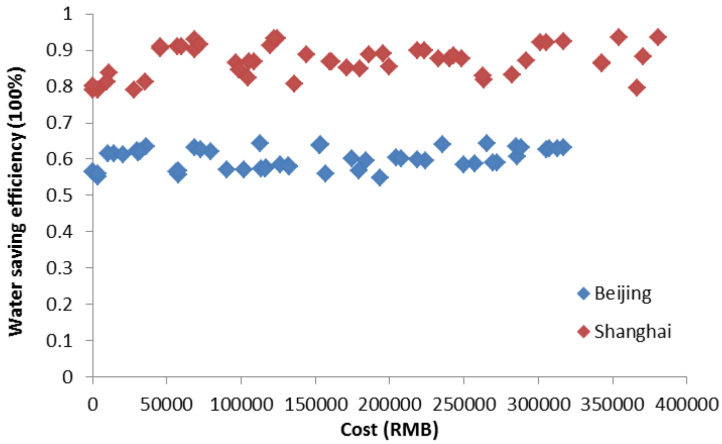

Figure 4.4 (c) Pareto solutions plotted with cost and water saving efficiency

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Chapter 5. Conclusions

The feasibility of RWHs and the enhancement of RHWs on SPC's foundation are estimated in terms of the performance of water saving and flood mitigation, as well as the consideration of cost. Two different sets (design storm and real daily rainfall) of precipitation data are used to make the evaluation as close to reality as possible. Indicators like stormwater control ratio and runoff volume (flood mitigation), time reliability and water saving efficiency (water conservation) are calculated to quantitatively assess the current SPC and with the assistance of RWHs, and are presented comparatively. Economic analysis is included in seeking the optimal configurations that combined SPC and RWHs. The optimization code established by () is used and the objectives are modified based on this study.

The selection of input precipitation data is important since different data sequence have a significant effect on the design of RHWs. In terms of flood mitigation, the unreasonably large tank sizes are needed to alleviate flood when using the daily rainfall as the input, and using the rainstorm design is more likely to get conceivable results because most of flood events could be intrigued by intensified short storm. In addition, by comparing the results of different daily rainfall (average daily rainfall and real daily rainfall), it can be identified water saving performances flexible with different rainfall sets, as well as under different climatic zones. Therefore, using average daily rainfall to design a RHWs is not always of practical significance, and the real daily rainfall should be chosen properly for specific location and condition.

Basically, the performances of both flood mitigation and water saving get better with the tank size increasing. The tank size that reduces a 50-year event to a 2-year event is defined as the proper size for flood control applying all over the country, and the behavior of sole SPC and combined SPC and RWHs are estimated to the enhancement that RHWs can achieve, as well as the ultimate impact of the combined systems. Generally speaking, the flood could be noticeably controlled by implementing RHWs where the alleviated ratio is up to 45% (from less than 10%). The rainwater tank gets a slightly better performance in the northern part than southern part, which could be due to the lower storm intensity in north than in south, however, the difference is not so obvious difference. On the other hand, spatial variability of annual rainfall contributes apparently to the water saving, that is, the southeastern part where there is abundant annual rainfall (humid and semi-humid areas) has the water saving efficiency as high as more than 70% in general, but the northwestern part with low annual rainfall present a poor performance. Besides, the tank size applied here is the best tank size which is the point that the tank size-efficiency line starts to approach a constant value (), and it is evident that the higher water saving efficiency means a larger tank volume in general.

The operation of optimization including economic analysis states that adding RHWS into current SPC improve the ability of both flood mitigation and water saving comparing to the sole construction of SPC and the optimal candidate solutions generated from the NSGA-II have been presented above which could provide a reference for the studied during the design of RHWs.

Appendix (Supplementary Table)

Table S1: Parameters of Chicago model of study cites

Station	Province	A	b	c	n
Harbin	Heilongjiang	4800	15	1	0.98
Urumchi	Xinjiang	195	7.8	0.82	0.63
Hohhot	Inner Mongolia	1663.32	5.4	0.985	0.85
Shijiazhuang	Hebei	1801.095	7.876	0.943533	0.741
Taiyuan	Shanxi	3385.09	12.745	0.84889	0.93
Changchun	Jilin	1064.959	4.367	0.893837	0.633
Shenyang	Liaoning	1924.174	8.196	0.811317	0.738
Beijing	Beijing	4203.39	14.941	0.792888	0.871
Tianjin	Tianjin	8280.862	25.334	0.803634	1.012
Jinan	Shandong	1869.916	11.0911	0.7573	0.6645
Lhasa	Tibet	700	0.1	0.75	0.596
Haikou	Hainan	2338	9	0.4	0.65
Nanning	Guangxi	5391.929	18.88	0.563509	0.851
Guangzhou	Guangdong	1864.221	5.033	0.59536	0.625
Fuzhou	Fujian	1029.054	1.774	0.629828	0.567
Nanchang	Jiangxi	1386	1.4	0.69	0.64
Hangzhou	Zhejiang	3360.04	11.945	0.031759	0.825
Baoshan	Shanghai	2974.604	10.472	0.82349	0.796
Hefei	Anhui	4162.809	17.008	0.81149	0.863
Nanjing	Jiangsu	2682.02	13.228	0.741843	0.775
Changsha	Hunan	4158.968	19.801	0.748153	0.863
Fengjie	Chongqing	1178.521	8.534	0.633	0.551
Wuhan	Hubei	894.953	2.824	0.745662	0.51
Zhengzhou	Henan	3073	15.1	0.892	0.824
Yan'an	Shaanxi	1008.847	14.72	1.475	0.704
Kunming	Yunnan	1489.306	10.247	0.693317	0.649
Suining	Sichuan	3365.718	18.768	0.663442	0.784
Guiyang	Guizhou	1144.451	5.168	0.174376	0.601
Yuzhong	Gansu	3049.42	8	1.03965	0.8
Xining	Qinghai	308	0.1	1.39	0.58
Yinchuan	Ningxia	242	0.1	0.83	0.477

Table S2 (a): Pareto solutions for Shanghai city (2 objectives)

Tank volume (m^3)	GS ratio	PP ratio	Runoff depth (mm)	cost (RMB)
2.459752	0	0	92.60547	1462.432
2.892841	0.4	0.3	77.19014	372788.6
8.42515	0.137228	0.299203	86.55408	138487.3
7.05108	0.233742	0.257337	83.27864	223608.7
3.458351	0.063963	0.296042	89.17633	69197.45
7.132294	0.303782	0.284559	80.67777	287834.9
3.373101	0.246793	0.285966	82.70244	234122.1
8.951704	0.153321	0.299012	85.98154	153343.4
3.53884	0.050086	0.298831	89.65982	56787.43
3.897107	0.340836	0.298982	79.30171	319865.3
3.641947	0.075485	0.263759	88.89132	78708.25
8.494775	0.12688	0.29865	86.92486	129155.8
7.377418	0.312468	0.285173	80.36594	295853.3
5.091341	0.180648	0.298985	85.00816	175753
2.90265	0.120719	0.3	87.13908	120303.7
2.480217	0.001651	0.055064	92.33264	4699.972
3.339719	0.259026	0.290387	82.24948	245300.8
7.505686	0.319488	0.299956	80.05841	302741.2
3.407487	0.290635	0.29815	81.09329	274162.1
3.544731	0.354023	0.3	78.828	331609.3
3.569517	0.011103	0.220395	91.35336	19094.75
8.132665	0.110758	0.299631	87.49537	114395.8
5.096495	0.190178	0.298948	84.6688	184371
3.569136	0	0.21845	91.75646	8994.928
2.873672	0.017308	0.299992	90.82299	26794.35
3.342518	0.253946	0.290557	82.42978	240715.3
3.088835	0.011734	0.274126	91.12207	21069.49
3.551172	0.363641	0.299963	78.48551	340307.7
3.51003	0.000466	0.247744	91.62601	10302.87
3.336843	0.381137	0.299677	77.86337	355988.5
5.082235	0.221466	0.298399	83.55636	212631.8
4.842202	0.175363	0.275389	85.28813	170084.5

7.362614	0.267255	0.298845	81.92348	255397.9
3.630162	0.366701	0.298185	78.3834	343065.5
8.386814	0.080406	0.299977	88.57526	87117.47
3.681247	0.392638	0.3	77.45241	366601.1
4.155566	0.327777	0.2984	79.76917	308194.4
7.445107	0.268058	0.2983	81.89699	256155.8
3.779628	0.029733	0.3	90.38031	38567
5.174674	0.278673	0.287349	81.56137	264058.9
3.55376	0.35526	0.3	78.78393	332733.3
5.124341	0.199082	0.298981	84.35148	192438.7
3.843021	0.043123	0.298702	89.90838	50668.86
5.091746	0.203047	0.3	84.20629	196035.4
5.047939	0.193614	0.29895	84.54639	187448.8
8.19867	0.105939	0.3	87.66562	110089.6
3.621887	0.105718	0.266467	87.80381	106114
3.780472	0.040443	0.299437	90.00099	48231.98
3.154922	0.374064	0.3	78.11408	349495.9
3.177277	0.386544	0.299664	77.67078	360782.3

Table S2 (b): Pareto solutions for Shanghai city (3 objectives)

Tank volume (m^3)	GS ratio	PP ratio	Runoff depth (mm)	cost (RMB)	Water saving efficiency (100%)
0	0	0.107829	148.8466	3738.082	0.790082
17.01838	0.4	0.3	77.19014	380866.4	0.934492
0	0.000396	0	149.2516	356.7399	0.790082
18.09704	0.375132	0.162257	78.61137	354329.6	0.934492
15.58225	0.061474	0.126822	89.92265	69041.09	0.929372
14.539	0.334783	0.199413	81.37551	317153.2	0.923076
12.55433	0.120422	0.116128	96.86916	119974.4	0.912769
10.47903	0.061137	0.219718	106.4562	68924.07	0.902144
6.396108	0.4	0.189567	110.0004	370722.6	0.88246
4.250875	0.315423	0.154156	121.2941	292026.7	0.8704
5.585281	0.265508	0.180318	117.9052	248759.9	0.877638
0.037952	0.148266	0.070801	143.5647	136045.9	0.80672
0.084832	0.290471	0.04208	138.4326	263186.1	0.819295
2.994796	0.371742	0.179359	123.9579	342889.5	0.862831
7.725747	0.149334	0.149851	114.0371	144319.2	0.888953
7.972519	0.205543	0.161862	111.0513	195519.1	0.890686
0.059578	0.030378	0.233327	147.0505	35491.1	0.811449
7.567248	0.195645	0.16112	112.9452	186335.7	0.888135
0.000673	0.027295	0.108344	147.8697	28345.69	0.790731
5.240596	0.256518	0.184305	119.5184	240594.6	0.875934
0.535696	0.187119	0.067486	140.3041	171228.3	0.851642
11.94296	0.048734	0.188722	101.4615	57545.67	0.910952
13.74479	0.318032	0.204484	84.96729	301766.6	0.920678
0.01089	0.4	0.181471	134.2697	366645.7	0.796171
3.448266	0.104582	0.015433	132.3908	96800.26	0.865935
16.2303	0.122659	0.127832	87.73912	124580.8	0.933163
9.590108	0.232239	0.103931	104.1852	218522.1	0.898499
11.21263	0.035047	0.223245	104.5872	45978.16	0.905767
13.89666	0.322344	0.203638	84.24051	305711.5	0.919986
0.119321	0.290256	0.041628	138.311	262997.4	0.829291
0.100042	0.10667	0.244195	144.1369	104620.4	0.823824

4.13926	0.171501	0.074146	127.1557	159531.2	0.869444
9.488045	0.237614	0.101494	104.3906	223219	0.897625
0.196081	0.008637	0.089822	147.8646	11011.44	0.838068
12.7711	0.067342	0.117748	97.9309	72341.57	0.914625
3.950934	0.117347	0.016378	130.0243	108631.4	0.868948
4.139725	0.173147	0.074158	127.0953	161015.3	0.869448
3.265105	0.371084	0.184845	122.9339	342647.7	0.865145
0.024562	0.000389	0	149.1586	364.6453	0.800383
0.065936	0.01087	0	148.6282	9831.477	0.813461
6.692629	0.258835	0.169511	113.9815	243032.6	0.884163
0.144835	0.305242	0.208095	137.0334	282283.2	0.832728
11.62319	0.034149	0.228773	103.0393	45605.08	0.90872
15.96929	0.120401	0.127771	87.81978	122389.6	0.931382
11.70932	0.051634	0.188912	102.2443	60026.27	0.909352
5.578901	0.248751	0.151318	118.6391	232654.9	0.877583
0.374413	0.0997	0.24562	143.3382	98553.99	0.84623
1.293	0.218226	0.065266	136.3299	199624.5	0.8538
3.927479	0.111149	0.08682	130.0603	105475.4	0.868748
0.503429	0.196676	0.066481	140.09	179783.8	0.849188

Abstract

(in Korean)

도시 홍수는 자유로운 도시화의 결과로 많은 중국의 도시에서 심각한 문제입니다. 중국 정부는 2014 년에 문제를 해결하고 지속 가능한 물 관리를 장려하기 위해 Sponge City 프로젝트 (SPC)를 제안했습니다. 그러나 제한된 녹지 및 자금 부족과 같은 SPC의 장벽으로 인해 예비 결과가 불만족 스럽습니다. 빗물 수확 시스템 (RWHS)은 도시 하수관을 줄일 수있는 잠재력을 지니고있어 하수도 시스템에 대한 압력을 덜어줍니다. 또한, 빗물은 물 부족의 해결책으로 대체 수원이 될 수 있습니다. 그러나 RWHS는 중국에서별로 주목을받지 못했으며 제한된 문헌 만 있습니다. 본 연구에서는 수자원 균형 시뮬레이션을 기반으로 한 홍수 완화 성능을 조사하기 위해 강수량 순서 (설계 강우량, 일일 평균 강우량 및 실제 일별 강우량)를 사용했으며, 현재 연구에서 데이터 선택 부족이 정량적으로 논의되고 적절한 입력 데이터 세트는 추가 평가를 위해 선택됩니다. SPC의 홍수 완화 효과는 유효 강수량뿐만 아니라 짧고 강화 된 설계 폭풍을 사용하여 추정되며, 선정 된 31 개 도시에서 적절한 탱크 크기가 정의되고 적용되어 건설 후 효율성이 향상 될 수 있는지 평가됩니다 RHWS. 홍수 완화 및 절수 성능은 모두 전국에 빗물 탱크를 추가함으로써 긍정적으로 영향을받는 것으로 나타났습니다. 그런 다음 SPC와

RWHS의 설계를위한 최적의 솔루션을 찾기위한 최적화 분석에 경제적 요소가 포함되며, 기존 방법은 향후 빗물 설비 건설에 대한 제안을하기위한 좋은 도구가 될 것입니다.

\

Acknowledgement

First of all, I would like to express the deepest appreciation to my advisor Professor Mooyoung Han, who has the attitude and the substance of a genius. He continually and convincingly conveyed a spirit of adventure in regard to research, and always keeps an excitement in regard to teaching. Besides, I'd like to thank my committee members, Professor Yongju Choi and Professor Jongkwon Choe, whose work demonstrated to me that the concern for environmental affairs, as well as the dedication to research and study. Without their guidance and persistent help my research and this dissertation would have not possible.

I must appreciate the help and encouragement I got from this lovely lab. Thanks to my lab members, the tedious studying time seems to be so light and pleasant. In particular, I get to express my gratitude to Canh, the Vietnamese senior who already graduated before my entrance but still gave me a lot of supports; Jooho just is like a "babysitter" for me, she is the one who always updated the news, noticed the compulsory course I need to take and prepare all kinds of forms; Gita is a positive and "restless" girl who brought me a lot of joy, and she still remembered my birthday even she was not her, which made me surprised and flattered; Thuy is the secondary mentor who taught the ways to communicate with Professor and gave me instructions about presentations and so on; And also for Malwina, Hakyung, Hayoon, Yunn and Esther, we just made such a great group to gossip, to joke, which was full of fun and means a lot to me.

Finally, I would like to give the most profound gratitude to my parents, who gave me the strongest spiritual and economic support. I felt so lucky and grateful that I am your child and receiving the unshared love from you.