ADVANCING RAINWATER HARVESTING SYSTEMS TO HELP MITIGATE THE URBAN FLOODING PROBLEMS IN CHINA

by

LI FU

(Under the Direction of Ronald B. Sawhill)

ABSTRACT

With the acceleration of urbanization in Nanjing, China, urban flooding problems are becoming more and more serious. In order to help mitigate the urban flooding problems, this thesis aims to identify a suitable and artful rainwater harvesting system for application in Nanjing, China. Successful contemporary rainwater harvesting systems in other countries are explored, as well as the historical rainwater harvesting systems used in China. The concept of an artful rainwater harvesting system is discussed, and a set of design principles from classical Suzhou gardens is proposed to guide the aesthetics of rainwater harvesting in Nanjing. Additionally, integrating Low Impact Development (LID) methods with the rainwater harvesting system to achieve maximum utility is explored. Lastly, a conceptual design for a residential area in Nanjing, China, offers examples which can be used to guide future designs.

INDEX WORDS: rainwater harvesting, artful rainwater design, LID methods, China, flood control, stormwater management

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BLA, Nanjing Forestry University, China, 2016

A Thesis Submitted to the Graduate Faculty of The University of Georgia in Partial Fulfillment of the Requirements for the Degree

MASTER OF LANDSCAPE ARCHITECTURE

ATHENS, GEORGIA

2018

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May 2018

DEDICATION

To my parents, for their unreserved support.

To my girlfriend, whose love and support helped me a lot.

To my friends, your support carried me through the tough times.

ACKNOWLEDGEMENTS

I would like to thank my major Professor, Ronald B. Sawhill, for his infinite patience and capacity for succinct explanation. His logical thinking and the experience I've had during the research have been invaluable. I would like to thank my committee chair, David Nichols, and my committee members, Michael Marshall, and Kevin Kirsche. I truly appreciate all the suggestions and help you have given me and thank you all for your time.

I would like to thank my classmates. Your friendship and support have made the two years a whole lot of fun. Finally, I would like to thank the entire faculty and staff at the College of Environment & Design for their kindness and enthusiasm.

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CHAPTER 1

INTRODUCTION

Since the 1990s, with the accelerated urbanization process in China, rainwater issues have become one of the major threats of cities. Urban flooding problems, which are caused by increased imperviousness in watersheds during rainstorms, are becoming more serious in Nanjing, China. Based on applying the rainwater harvesting systems used in other countries, this thesis attempts to design a rainwater harvesting system that can help mitigate urban flooding issues in Nanjing while incorporating traditional Chinese design aesthetics, and thereby can be more readily accepted by the local people.

The thesis attempts to answer the question: what constitutes a culturally suitable and artful rainwater harvesting system which has the ability to mitigate the urban flooding problems in Nanjing, China? One residential area is chosen to propose the design. The topic is important because it explores what an artful rainwater harvesting system looks like for Nanjing. The focus of this thesis looks at trying to mitigate the flooding problems in Nanjing specifically, which can help reduce runoff, and reduce pressure on the city's drainage system when storm events occur.

Chapters 1 & 2 of the thesis will explore the current development conditions and problems related to rainwater harvesting systems in China. Two examples of traditional Chinese rainwater harvesting systems in urban area will be discussed.

Chapter 3 will analyze the rainwater harvesting system in Japan and Germany from three aspects: legal, economic, and technical. Potential applications and issues related to China are considered.

Chapter 4 investigates four case studies: the first one is a rainwater harvesting system used in a residential area in Beijing, China. The second one demonstrates how a rainwater harvesting system can be combined with green roofs. The third one is an example to show how a rainwater harvesting system can be combined with bioretention devices. The last one is an example of an artful rainwater harvesting system.

Chapter 5 explores and establishes principles for application to culturally acceptable artful rainwater harvesting systems in Nanjing, China that have the ability to mitigate the flooding problem there. To achieve this result, this chapter will discuss it from the principles of Chinese aesthetics standpoints, and then this chapter will analyze how this rainwater harvesting system can be used effectively to help mitigate the flooding problem in Nanjing, China.

Chapter 6 explores the proposed applications of a rainwater harvesting system in a residential area in Nanjing, China. As a design thesis, the chapter will include a site-specific rainwater harvesting design for a residential area in Nanjing, China. This design will be evaluated by its before and after runoff volume to determine potential runoff mitigation and related flood reduction.

The final chapter of the thesis will review the design achievements and evaluate the success. Strengths and weaknesses of the process and the findings will be discussed. Applications to other regions of China will be considered and recommendations for rainwater harvesting system development and regulation will be suggested.

CHAPTER 2

RAINWATER HARVESTING SYSTEMS IN CHINA

2.1 THE CURRENT DEVELOPMENT CONDITION OF RAINWATER HARVESTING SYSTEMS IN CHINA

2.1.1 DEVELOPMENT PROCESS OF RAINWATER HARVESTING SYSTEMS AND RELATED REGULATIONS AND RESEARCH IN CHINA

Research on the utilization of rainwater in Chinese urban areas began in the 1990s. In 1996 a landmark event was held in Lanzhou: The First National Symposium on Rainwater Utilization. After the advent of research on this topic and the symposium, rainwater utilization developed quickly in the northwest region of China. A successful rainwater catchment irrigation project was carried out in Gansu called “121 Rainwater Collection and Irrigation Project.” This project built a rooftop rainwater harvesting system, two water cellars, and a vegetable field irrigated with collected rainwater. This project proposed to solve the problem of drinking water for 1.35 million people. In recent years, large and medium-size Chinese cities such as Beijing, Tianjin, Nanjing, Shenzhen, Qingdao, Xian, Harbin, and Zhengzhou, have become involved in the rapid development of rainwater utilization research (Figure 1).

Figure 1: Map of Chinese cities that have been involved in the rapid development of rainwater utilization research (produced by author)

In 2000 the Beijing Municipal Water Conservancy Bureau and the German University of Essen created a demonstration area for a cooperative rainwater utilization project. The same year, the city initiated an urban rain and flood control and utilization demonstration project (Qing, Guanglu, and Xiaolei 2009). In 2003 the Beijing Municipal Commission of Urban Planning issued the manual "Interim Regulations on Strengthening the Utilization of Rainwater Resources in Architecture Projects," which requires construction projects to collect, filter, store, and use rainwater on site (Qing, Guanglu, and Xiaolei 2009). After the completion of the project, the site did not increase the total discharge of rainwater.

In July 2003, the Water Science and Technology Building was constructed in Tianjin, and rainwater collected by the building is used as a non-potable water source. From 06/2003-10/2003, the building collected 260.4 m^3 of rainwater from the roof. After the success of this building, rainwater utilization technology was extended to Meijiang Elementary School. Two water reservoirs were built on the outer corner of the campus football field. Rainwater collected from the roof water was used to irrigate the turf of the football field (Qing, Guanglu, and Xiaolei 2009).

In 2006, experts in rainwater harvesting conducted a study on rainwater resource utilization in Shenzhen. They found that by 2020 the utilization rate of rainwater in Shenzhen would reach 4.9 billion m^3 per year, and the amount of usable harvested rainwater in the urban area would be 85 million m^3 per year (Qing, Guanglu, and Xiaolei 2009). Then in 2011 the city of Shenzhen issued the manual "Engineering Technical Code for Rain Utilization," which states that the drainage of construction land should not increase the rainwater peak flow. In addition, pollution after rainwater treatment—including chemical oxygen demand (COD), suspended solids (SS), and total phosphorus (TP) concentration—should be less than a specified value：COD < 40mg/L , SS < 40mg/L, TP < 0.2 mg/L, and rainwater should be collected and reused (Duan et al. 2011).

On April 1, 2007, the Ministry of Housing and Urban Rural Development of China, promulgated the manual "Engineering Technical Code for Rainwater Utilization in Building and Sub-District" (GB 50400-2006), which is the first national standard of rainwater utilization in China; the code puts forward detailed technical requirements for rainwater collection, rainwater infiltration, rainwater storage and reuse, water quality treatment, construction and installation, engineering acceptance, and operation and management.

During the last century, China's urban rainwater utilization has progressed significantly in terms of research, application, and policy formulation, but it still lags behind developed countries, and needs more attention and research.

2.1.2 RAINWATER HARVESTING SYSTEMS BUILT BY CHINESE RESIDENTS

Due to the rapid growth of urbanism, many environmental issues have arisen. The Chinese people have begun to realize the importance of protecting our environment, and now there are many civic organizations in China that focus on protecting the Chinese natural environment. For example, there is a non-government organization in Hangzhou, China, called "Hangzhou Ecological Culture Association" which is the first established in Zhejiang Province, China, but also the largest and most influential in all of China. This organization advocates a green lifestyle and spreads the concept of sustainable communities (Shao 2014).

In 2013, this organization began a residential community retrofit project in Hangzhou, China. Goals of the project included creation of a sustainable community and engaging residents in the process to learn about the concept of a sustainable community. The name of this community is Modern City, located in Hangzhou, China. This community focuses on the following three parts to achieve the concept of a sustainable community:

1. In the part of water resources management, this community has established a rainwater harvesting system and uses it to irrigate the community farm.
2. In the part of green space, 200 households use their own balconies and common roofs to build community farms, which can not only beautify the community, but also provide food for residents (Figure 2).

3. In the part of waste management, 168 community residents use a “Kitchen Waste Compost Fermentation Bucket.” As long as the garbage in the kitchen goes into the compost bucket, it can be transformed into fertilizer.

Figure 2: Community farm

Source: http://js.qq.com/a/20140509/052541.htm#p=6

Residents can join the design process and give opinions to the designer. During the process of this project, residents were very enthusiastic and displayed their interest in sustainable community design, which can be a successful example for other cities in China (Figure 3).

Figure 3: Residents join the design process of a sustainable community

Source: http://js.qq.com/a/20140509/052541.htm#p=6

Another non-government organization is called "Friends of Nature" which is the oldest Chinese environmental non-government organization (Shao 2014). On March 31, 1994, the organization was officially registered under the name Green Culture Institute of the International Academy of Chinese Culture under the Ministry of Civil Affairs. This organization is focused on environmental education, family energy conservation, ecological communities, legal protection of rights, policy advocacy and other means to rebuild the link between humans and nature to protect the precious ecological environment, and to help people understand the concept of a sustainable community (Shao 2014).

This organization helped residents retrofit a yard in the Madian Huazhan International Apartment Community, Beijing, China. The area of this yard is 40 square meters, and there are over 600 people who joined the design and building process, which involved over 4,000 hours. In the design process, residents also voted for the final design (Figure 4).

Figure 4: Residents join the design process and an example of the residents' design draft

Source: http://blog.sina.com.cn/s/blog_8ebb4aed0102whyg.html

In agreement with the concept of a sustainable community, the residents recycled domestic waste as building materials, saving money and preventing domestic waste from polluting the environment. Also, they built a rainwater harvesting system to collect rainwater for irrigating plants and flushing toilets. This organization also conducted a course for residents to teach them about the rainwater harvesting system, to understand it and use it (Figure 5).

Figure 5: Rainwater harvesting system built in the yard

Source: http://blog.sina.com.cn/s/blog_8ebb4aed0102whyg.html

The residents were excited about this rainwater harvesting and helped build the system to save water and help reduce stormwater runoff (Figure 6).

Figure 6: Residents help build the rainwater harvesting system

Source: http://blog.sina.com.cn/s/blog_8ebb4aed0102whyg.html

In China, there are many other rainwater harvesting systems built by residents as a way for people to reduce water fees. A questionnaire and random interview were conducted in 2015, among residents of 16 different types of residential communities in Shanghai. The results showed that 81.2% of the respondents considered it necessary to utilize rainwater resources within the urban area of Shanghai to save water (Chunjie et al. 2009). This suggests people could be receptive to a rainwater harvesting system.

2.2 TRADITIONAL CHINESE RAINWATER HARVESTING SYSTEM DESIGN

Rainwater harvesting has a long history in China. The ancient Chinese had extensive experience in rainwater harvesting technology (Wei, Wang, and Ji 2017). By learning from ancient people, the rainwater harvesting system proposed for Nanjing, China, can fit into the cultural context. Generally, there were two types of rainwater harvesting systems in ancient China: those that caught rainwater from the roof, and those that caught it on the ground.

2.2.1 TRADITIONAL CHINESE ROOFTOP RAINWATER HARVESTING SYSTEM

The rainwater harvesting system that collects rainwater from rooftops is usually used in the southern part of China, which has humid climate zones. Residents use it to help improve the ecological climate inside the house. Traditional Chinese dwellings have focused on the collection and reuse of rainwater. The form of the roof, gutter, and trough are based on the use of rainwater. In the ancient village of Hongcun, which has many buildings from the Ming and Qing dynasties, most of the buildings have a space called tianjing (Figure 7), which is a small piece of open space surrounded by the houses. The special roof form of tianjing is designed to collect rainwater and then deliver it into the tianjing. When it is raining, rainwater falls into the trench below the roof, called si shui gui tang, which means “four directions of water go back to the yard.” In Fengshui, the term si shui gui tang means to collect fortune from four directions (Wei and Wang 2016).

Figure 7: Tianjing roof form

Source: http://www.yhachina.com/ls.php?action=pic&picID=20287&id=391&a=3

There are usually drainage channels surrounding the *Tianjing* to guide the water flow. Water outlets are installed at the four corners of the *Tianjing*, each covered with a perforated cap over a drainage hole (Figure 8). A drainage facility is commonly installed on the ground of *Tianjing*; the pool and water tank are placed in the center of a circular drainage channel (Figure 9). The ancient Chinese used this roof form to guide rainwater, which they then saved for fire protection and daily use, into the water tank. Surplus rainwater could be drained out through the circular drainage channel. In this way, rainwater could be collected, but the flooding caused by poor drainage during a rainstorm could be avoided (Wei and Wang 2016).

Figure 8: Picture of drainage hole in Tianjing (photo by author)

Figure 9: Drainage channel in the center of Tianjing (Wei and Wang 2016)

In southern China where it is humid, residents also used this technique to regulate the microenvironment in their home. The *Tianjing's* internal drainage method enables rainwater to flow off the roof and then drain out. The *Tianjing* uses the flowing water, along with the pool of collected water, to absorb heat and create heat exchange, lowering the surface temperature in the home. Since the ground is cooler than the air, the water in the pool absorbs the heat in the air, lowering the temperature of the home below the temperature outside. In winter, the temperature of the underground soil layer is higher than that of the ground; therefore, the water temperature of the pool and channel is higher than the air temperature, leading to heat exchange. As a medium of energy exchange, the water helps regulate the temperature and humidity (Wei and Wang 2016).

2.2.2 TRADITIONAL CHINESE GROUND RAINWATER HARVESTING SYSTEM

The rainwater harvesting system that collects water on the ground is usually used in the northern part of China, which has the most arid and semiarid climate zones. Ancient people used this system to help recharge the aquifer.

An outstanding example of this system is the Circular City (Jin Dynasty, 1115~1234 A.D.), located in Beihai Park in Beijing. This isolated enclosed area is 5,760 m^2 (Figure 10). Based on Beijing's average annual rainfall of 595 mm, the total runoff based on the area of Circular City is 3,427 m^3. The area has many old trees that require precipitation to grow, rather than depending on groundwater from the lake. To meet the needs of these trees, the ancient people designed inverted trapezoidal cyan bricks and underground culverts for the city (Li, Cao, and Meng 2003).

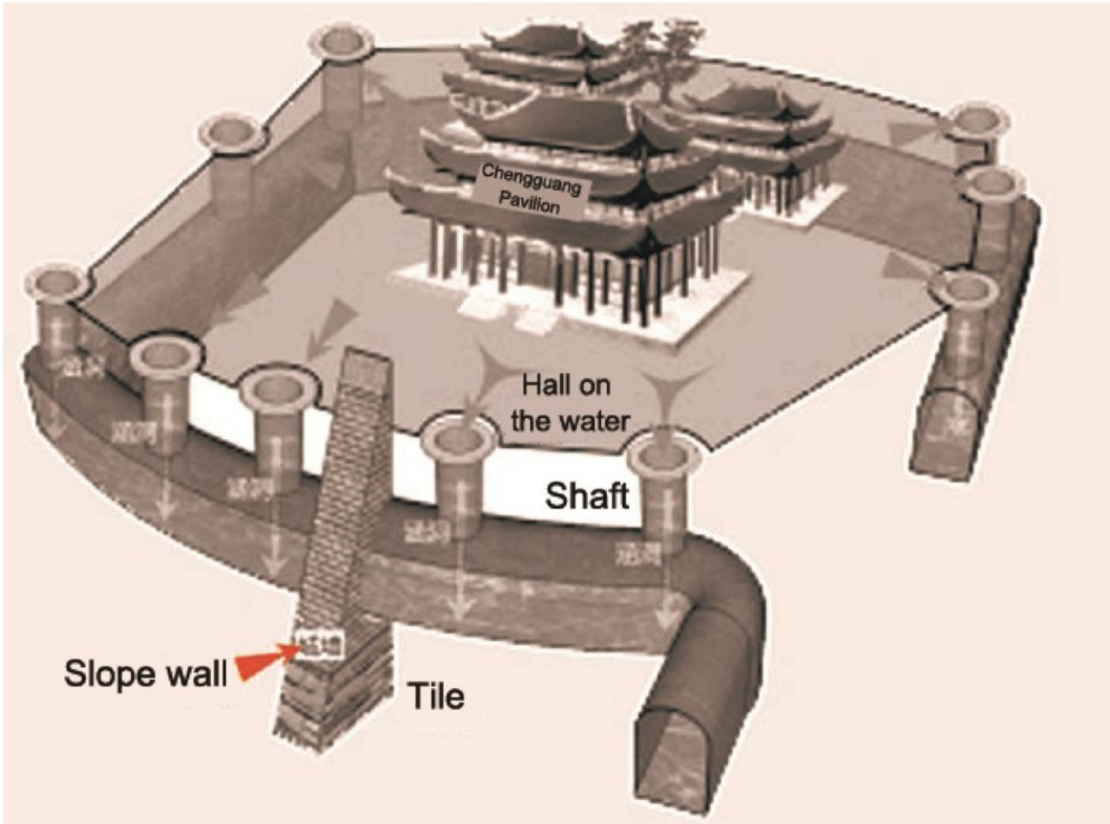


Figure 10: The construction of Circular City (Wei, Wang, and Ji 2017)

A pervious pavement infiltration practice was used by placing the bricks on the ground. Because the bricks provided more space at the bottom, water flowed easily into the sublayer of the ground (Figure 11). In addition, inlets on the ground that led to underground culverts captured extra water (Figure 12). The rainwater in the culverts could be used to recharge groundwater when the water table was low; when the water table was high, the system worked like a drain (Figure 13). The average depth of a culvert is H=1.46 m. According to the soil sample from this area, the percent of soil porosity is N=48%, and the maximum soil water storage capacity is Q= H*S*N= 4,037 m^3, while the local annual rainfall is only 3,427 m^3. This means that the design can absorb all the rainwater (Geiger 2015).

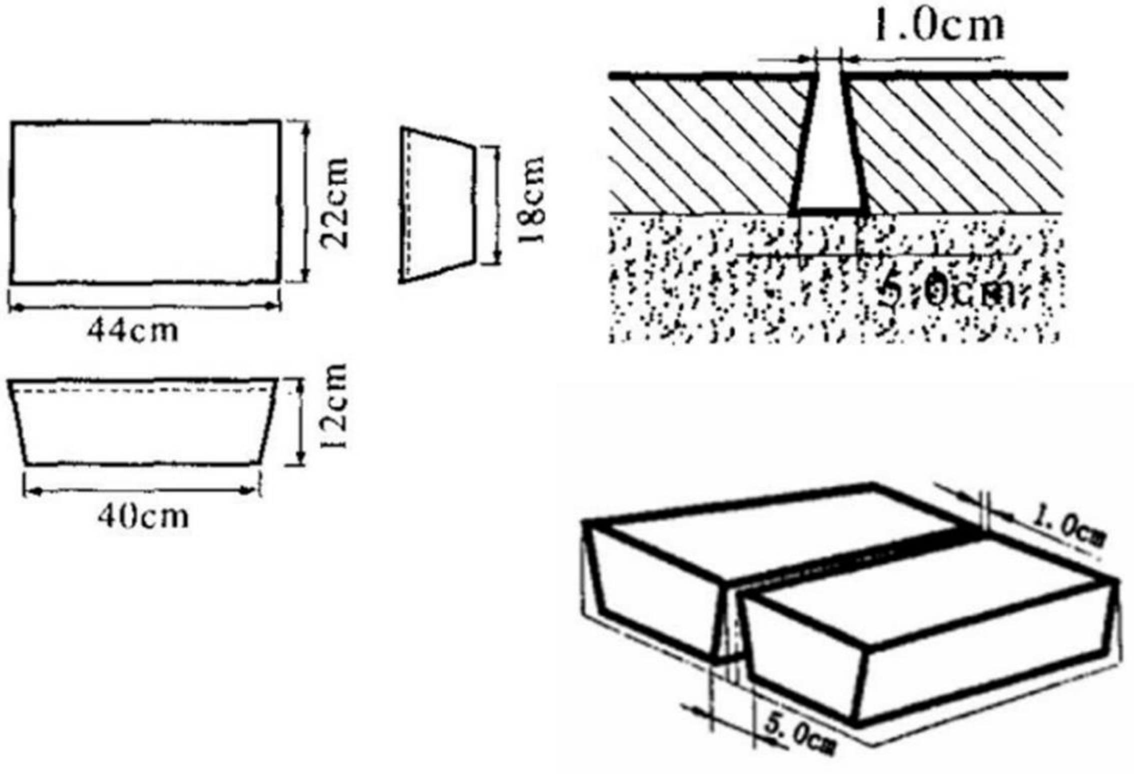


Figure 11: Section of inverted trapezoidal cyan brick (Li, Cao, and Meng 2003)

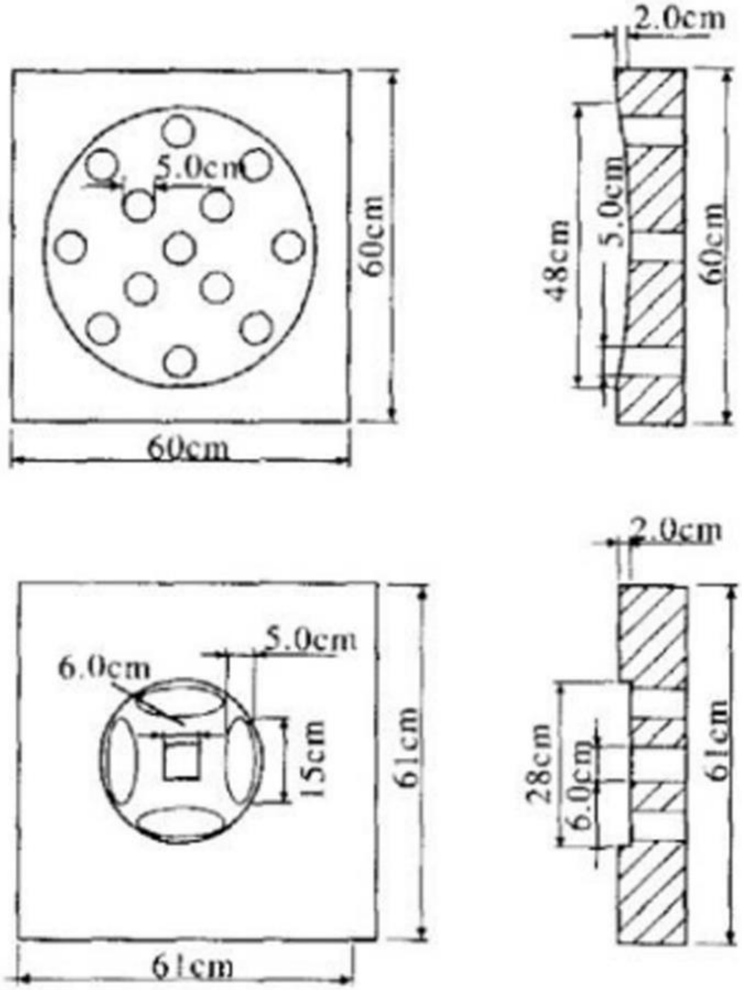


Figure 12: Plan and section of the rain inlet (Li, Cao, and Meng 2003)

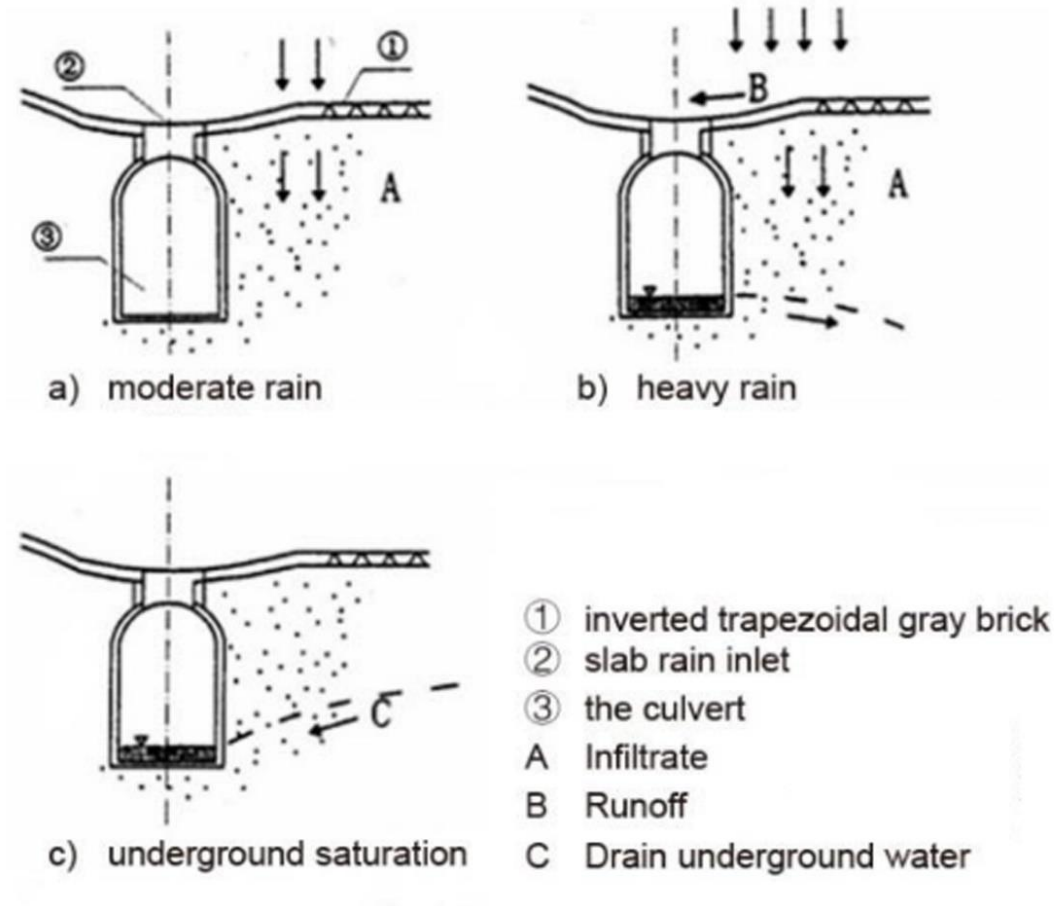


Figure 13: Infiltration and drain principle of the culverts (Li, Cao, and Meng 2003)

In ancient times, although they did not have the technologies we have today, ancient people used their wisdom to establish "guidance-storage-retention-drainage" rainwater utilization systems (Wei and Wang 2016). The rainwater is led into the tianjing through the roof, the accumulated rain water is used for daily life or as green irrigation; the excess part enters the drainage pipe or ditch and finally merges with the surrounding natural waterway (Wei, Wang, and Ji 2017).

The case of Hongcun shows how to use roof forms to collect rainwater, and how to store it so that it can be used by residents and also can be a landscape in the community. Finally, it shows that rainwater can help regulate the micro-environment.

The example of Circular City shows how our ancestors combined pervious pavement and a ground rainwater harvesting system to collect rainwater and how it can also serve as an efficient drainage system.

These two examples are the best-known examples of the Chinese ancient rainwater harvesting system. The first example of rainwater harvesting system in Hongcun is widely used in the traditional Chinese buildings in the southern part of China, which have direct connection to the thesis topic, because Nanjing is also in the southern part of China. The example of the rainwater harvesting system in Circular City is a typical example of the traditional Chinese rainwater harvesting system in the northern part of China. This case shows how our ancestors wisely used pervious pavement to collect rainwater in a dense, urban area, which can also serve as a valuable reference for the thesis topic.

Principles from these cases, could be applied to Nanjing's historical area without a negative impact to the function and historical context of the old city.

CHAPTER 3

RAINWATER HARVESTING SYSTEMS IN OTHER COUNTRIES

Currently Japan and Germany are the leading countries regarding the production, implementation, and research of contemporary rainwater harvesting (Ward 2010). After decades of development, they have gained much practical experience. They have developed a comprehensive system of laws and regulations in the use of rainwater resources. As shown in table 1, Japan and Germany have used economic and technical tools to develop a variety of rainwater utilization measures and to form a comprehensive management framework and a technical support system for the rainwater resources (Cheng et al. 2007).

Table 1: Management systems of rainwater utilization in foreign countries (Cheng et al. 2007)

Management system	Japan	Germany
Legal tool	Construction Department implemented rainwater storage and infiltration plan, and set up a "rainwater storage and infiltration technology association." The association has prepared a rainwater utilization guide	Federal water law, construction regulations and regional regulations require the sustainable use of water in the form of legal provisions or regulations, and federal water law is the basis for building regulations and state laws.
Technical tool	Japanese government built multi-functional rainwater storage facilities, both above ground and underground.	The rainwater harvesting system in Germany is mainly divided into roof rainwater harvesting system, green roof rainwater harvesting system, rainwater interception and infiltration system
Economic tool	Implementation of rainwater utilization subsidy system	The development of the rainwater discharge fee collection standards encourage people to implement rainwater harvesting systems to avoid rainwater discharge fees

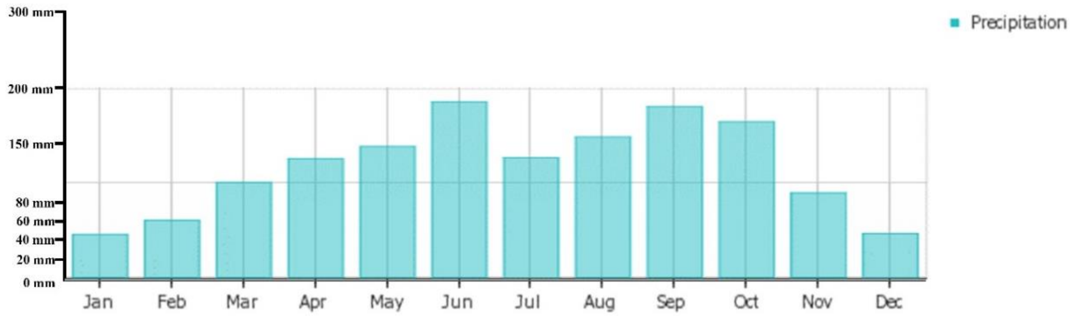


Figure 14: Average precipitation in Tokyo (reproduced by author)

Source: https://weather-and-climate.com/average-monthly-Rainfall-Temperature-Sunshine,Tokyo,Japan

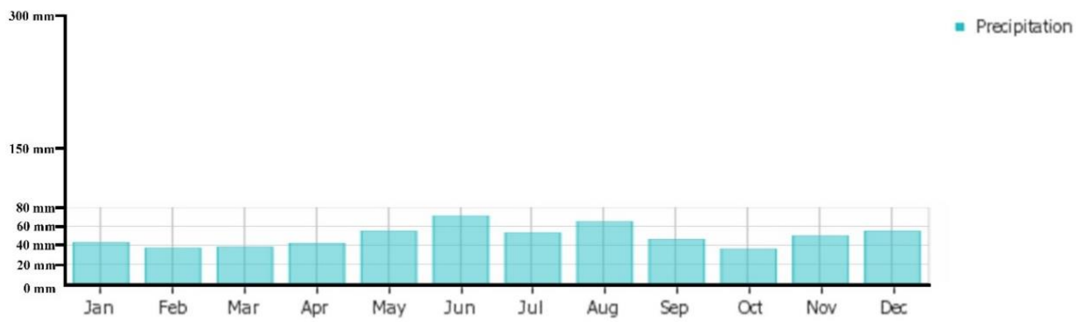


Figure 15: Average precipitation in Berlin (reproduced by author)

Source: https://weather-and-climate.com/average-monthly-Rainfall-Temperature-Sunshine,Berlin,Germany

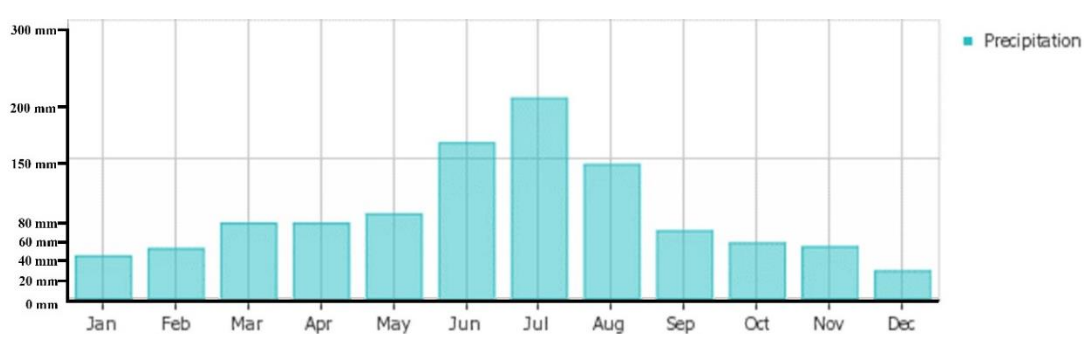


Figure 16: Average precipitation in Nanjing (reproduced by author)

Source: https://weather-and-climate.com/average-monthly-Rainfall-Temperature-Sunshine,Nanjing,China

The rainfall distribution of the three cities is different, and most of the rainfall in Nanjing and Tokyo is focused on June, July, and August, while the rainfall in Berlin is more evenly distributed. Tokyo and Nanjing are similar, which means that the rainwater harvesting system in Tokyo, Japan is more valuable to Nanjing, China.

3.1 RAINWATER HARVESTING SYSTEM IN JAPAN

Japan is an island country with a large population density and a lack of water resources. Therefore, Japan advocates saving water, reducing waste of water resources, and actively opening up new water resources. As early as 1980, Japan began to promote a rainwater storage and infiltration plan, and many cities used public facilities like parking lots, courtyards, green spaces, and parks to build a large number of rainwater storage ponds to collect rainwater (Cheng et al. 2007).

3.1.1 LEGAL TOOLS OF RAINWATER HARVESTING SYSTEMS IN JAPAN

In 1980, the Ministry of Construction of Japan promoted the utilization of rainwater resources by popularizing the plan of rainwater storage and infiltration. In 1988, the Ministry of Construction of Japan set up a civil organization “Japan Rainwater Storage and Infiltration Technology Association.” This association prepared a rainwater utilization guide, which provided the basis for the formulation of Japanese rainwater utilization laws and regulations (Cheng et al. 2007). Then in 1992, the Japanese government promulgated the “Second-generation Urban Drainage Master Plan,” requiring that large-scale public buildings must set up a rainwater infiltration facility, which will incorporate pervious pavement, a bioretention basin, and an infiltration pond as an integral part of the urban planning (YANG, PAN, and LI 2010). In July 2011, the “Guidelines for Rainwater

Harvesting Architecture" published by the Architectural Institute of Japan, shows the existing standards for rainwater harvesting systems in public and large buildings. It covers the design, construction, and operation of facilities for rainwater harvesting systems (Kamiya 2012).

3.1.2 ECONOMIC TOOLS OF RAINWATER HARVESTING SYSTEMS IN JAPAN

Japan, through tax breaks, subsidies, funds, policy loans, and other economic tools, has promoted the rainwater utilization. For example, in 1996, Tokyo Sumida set up a rainwater utilization subsidy system for underground storage cisterns, medium storage cisterns, and small storage cisterns, as shown in table 2, so as to promote the application of technology of rainwater utilization (Peng 2006).

Table 2: Category of subsidy in Sumida, Tokyo (Peng 2006)

Type of rainwater storage cistern	Capacity	Subsidy amount (Dollar)	Limit(Dollar)
Underground storage cistern	>5m³	354.70*Effective storage capacity	8867.6
Medium storage cistern	>0.5m³	1. Fiberglass, plastic and steel products：1064.11*Capacity 2. High density polyethylene products: 399.04*Capacity	2660.28
Small storage cistern	<0.5m³	Price of the cistern*1/2	221.69

Other cities in Japan also provide subsidies for their rainwater utilization system. According to a survey conducted by the Association for Rainwater Storage and Infiltration Technology in April 2011, 208 municipalities in Japan were implementing subsidy programs for the installation of facilities for storing rainwater. According to the subjects to which the assistance programs are applied, they are classified into two kinds of programs: systems for rainwater cisterns and systems for rainwater seepage pits. The rainwater cistern collects rainwater from the roof and then stores it in a container to be used as water to fight fires. In addition, it can be used as domestic water and as drinking water in an emergency. The rainwater seepage pit directs rainwater from the roof and the rainwater that falls in the garden into a rainwater seepage pit. Rainwater is temporarily stored and infiltrate into the ground. Rainwater that infiltrates through the pit effects aquifer recharge and thus, can improve the natural environment (Kita et al. 1999).

Table 3: Assistance programs for rainwater cistern (Kita et al. 1999)

City	Subsidy amount (Dollar)
Kawagoe City	$ 168.48 in the case of 1 unit $ 336.97 in the case of 2 units
Kamakura City	$ 221.69 or less in the case of volume between 100L and 200L $266.03 or less in the case of volume greater than 200L Two units or less and within 1/2 of total cost in both cases
Chofu City	Between $ 221.69 and $ 487.72 and half of the price of the product Only products designated by the city are available Two kinds of volume, 100 L and 200 L
Sumida Ward	$ 886.76 or less in the case of 1,000L $ 2660.28 or less in the case of between 500 L and 1,000 L $ 221.69 or less within 1/2 in the case of less than 500 L
Takamatsu City	$ 886.76 or less within 1/2 of total cost in the case of volume between 100 L and 1,000 L $ 354.70 per ton and $ 886.76 or less in the case of volume of over 1,000L Once per year in both cases

Table 4: Assistance programs for rainwater seepage pit (Kita et al. 1999)

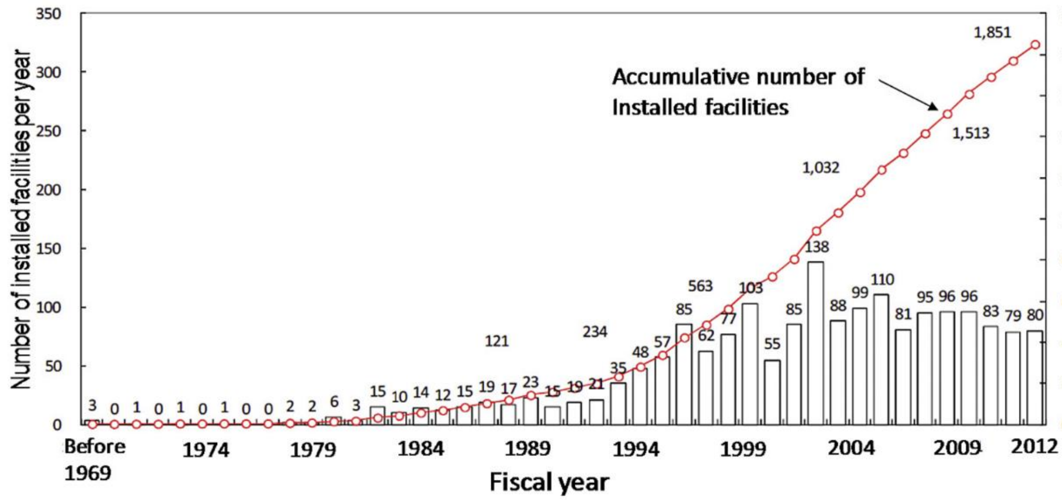
City	Subsidy amount (Dollar)
Kawagoe City	$ 168.48 in the case of 1 unit $ 336.97 in the case of 2 units $ 407.91 in the case of 3 units $ 514.32 in the case of 4 units
Kamakura City	$ 177.35 or less in the case of products made of concrete $ 88.68 or less in the case of products made of synthetic resin Four units or less within 1/2 of total cost in both cases
Chofu City	Whole cost
Ichikawa City	$ 3547.04 per one place
Chiba City	$ 212.82 or less and within 2/3 per unit and up to 4 units 35 cm or greater in the inside diameter and 65 cm or greater in depth
Yokohama City	Whole cost
Mitaka City	Whole cost
Ohta Ward	Whole cost and only avaible in the regions designated by the Ward
Musashino City	$ 1773.52 yen or less

Figure 17: Rainwater seepage pit

Source: https://oldcastleprecast.com/11006_id_idf_48-72_seepage_pit_02-4/

According to a survey of the number of public facilities and office buildings using rainwater harvesting systems in Japan over the last four decades (MLIT, 2014), after the implementation of governmental financial support, the number of rainwater harvesting systems increased significantly, with 10 times more installations recorded at the end of 2012 as compared with 1990. It indicates that the Japanese plan of using subsidies to encourage the use of rainwater harvesting systems has been successful (Campisano et al. 2017).

Table 5: Rainwater harvesting systems in public facilities and office buildings in Japan (MLIT, 2014)



3.1.3. TECHNICAL TOOLS OF RAINWATER HARVESTING SYSTEMS IN JAPAN

A primary component of rainwater utilization systems in Japan is the multifunctional rainwater storage pond. It can not only be used to collect rainwater in the rainy season, but also can serve other functions like sports, parking, and entertainment in the dry season. During the non-rainy season, the storage ponds maintain their dry state or maintain a relatively low normal water level. High elevation regions above the normal water level can be used to build green space, parking lots, sports, or other activities. In the event of a multi-year heavy rainfall, the system uses the huge space between the normal water level and the highest water level to store the storm peak.

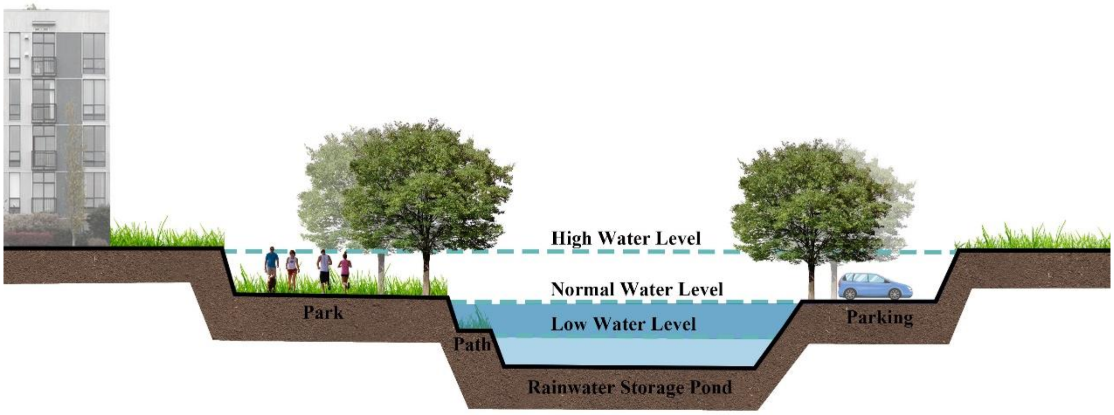


Figure 18: Section of the multifunctional rainwater storage pond (produced by author)

There are also residential level rainwater harvesting systems in Japan. These rainwater harvesting systems can collect rainwater, then it can be used for firefighting, green space irrigation, washing cars, flushing toilets, and can also be treated for residents to use. These facilities have a small size and can be built in front or behind the house (Cheng et al. 2007). For example, a simple and unique rainwater utilization facility "Rojison" has been set up by residents in the Mukojima district of Tokyo to utilize rainwater collected from the roofs of private houses (Figure 19). Residents can pump up water by hand from the underground tanks for watering flowers in daily life and as water for fire-fighting and drinking in an emergency. This rainwater utilization facility is not only functional but also artful with its design based on a traditional Japanese architecture form. The use of wood building materials allows it to fit into the surrounding environment.

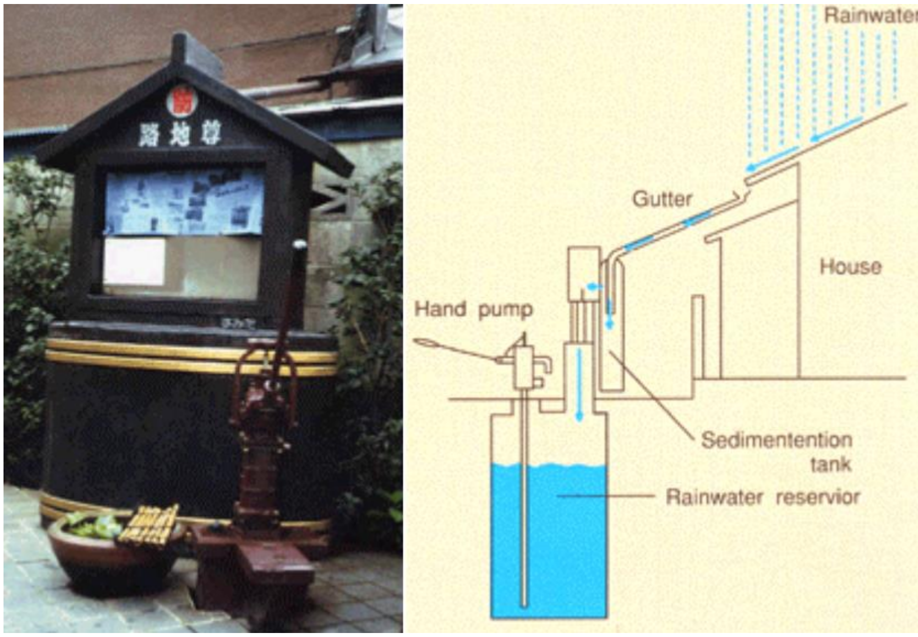


Figure 19: "Rojison" A simple and unique rainwater utilization facility at the community level in Tokyo, Japan (Harvesting 2002)

3.2 RAINWATER HARVESTING SYSTEMS IN GERMANY

The rain distribution is relatively uniform across Germany and through all seasons, so water resources are abundant. However, to maintain a good water environment and achieve sustainable use of water resources, the German government has not only formulated strict laws and regulations, but also strictly controlled the development and utilization of water resources and the discharge of sewage water. It has also vigorously promoted water resources management technology research and development, relying on technological innovation to promote the sustainable use of water resources (Zheng, Zhou, and Ji 2005). Today almost one third of new buildings in Germany are equipped with a rainwater harvesting system (Campisano et al. 2017).

3.2.1 LEGAL TOOLS OF RAINWATER HARVESTING SYSTEMS IN GERMANY

The German federal government is responsible for developing the overall design of the legal framework for water resources utilization. The Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) is the federal agency responsible for environmental and water legislation. In 1986, the German government enacted the "Federal Water Act," which is the basic law for water resources management in Germany. The law details water management and protection provisions to specific technical details, and there is a clear stipulation on the standards of water intake, water treatment, water use and wastewater discharge for citizens and enterprises (Schuetze 2013). The Federal Water Act provides policy guidance to states in their efforts to establish codes of rainwater use. A series of laws and regulations on rainwater utilization has been formulated based on the Federal Water Act, such as when Germany constructs large public buildings and new or reconstructed residential areas, rainwater utilization measures must be taken, or the project would not be authorized. Each state and municipality must introduce local legislation to translate federal law into local law and can also make its own supplementary provisions. Furthermore, the German government has also enacted the "Waste Water Charges Act" and the "Federal Nature Conservation Act" to enhance the protection of the natural environment and the sustainable use of water resources. According to the Waste Water Charges Act, state and local governments have the right to collect and use waste water fees (Kraemer and Piotrowski 1995).

3.2.2 ECONOMIC TOOLS OF RAINWATER HARVESTING SYSTEMS IN GERMANY

To achieve the goal of zero growth of runoff into the pipe network, each city has formulated its own standards of collecting rainwater discharge fees, on the basis of the Federal Water Act and the Federal Nature Conservation Act. According to the local rainfall data and the impervious surface area, the owner can calculate the rainwater discharge fees (Zheng, Zhou, and Ji 2005). For those who use rainwater utilization technology, rainwater discharge fees may not be levied, and some subsidies for rainwater utilization may even be granted. The fee for rainwater discharge is generally about 1.5 times the price of the tap water fee (Kraemer and Piotrowski 1995).

For example, from January 1, 2001, when Hanover, Germany began collecting a rainwater discharge fee, the city's government stipulated that if rainwater could not infiltrate into the soil due to the building and the impervious surface, then the landowner needed to pay the rainwater discharge fee. The amount of the rainwater discharge fee was calculated based on the area of the house and impervious surface at a cost of 1.18 $\$/m^2$. In the new industrial, commercial, and residential areas, before construction, they had to design rainwater utilization devices. In the absence of rainwater harvesting facilities, the government would impose a fee of 2% of the building cost for the rainwater discharge fee. The fees collected by the government would be mainly used for investment subsidies of rainwater projects to encourage the construction of rainwater utilization projects. For the households that take the initiative to collect rainwater, the government grants $1,828 a year for rainwater utilization subsidies (Li et al. 2010).

There are also some other federal states or municipalities that support the installation for rainwater harvesting systems and utilization. The collection of rainwater discharge fees has effectively promoted the implementation of rainwater harvesting systems in Germany. There are approximately 75,000 new facilities of rainwater harvesting systems installed in Germany per year (Lesjean et al. 2009), and two-thirds of all new single-family and duplex houses in Germany are equipped with rainwater harvesting systems (Schuetze 2013).

Table 6: Subsidy policy of different Federal States in Germany (table by author) (Schuetze 2013)

Federal States	Subsidy Policy
Bremen	Support the installation of rainwater harvesting systems in new or existing households with subsidies of 1/3 of the total costs, up to $2,356.60
Thuringen	Loans up to $ 5,892 for a yearly interest rate of only 2% can be provided to residential property program
Schleswig-Holstein	The construction of facilities for rainwater harvesting and infiltration are financially supported by means of loans with low interest rates and a contract period of 25 years in the framework of their social housing program

3.2.3 TECHNICAL TOOLS OF RAINWATER HARVESTING SYSTEMS IN GERMANY

German urban rainwater utilization technology has undergone three major changes since 1980s. The rainwater harvesting system was successfully introduced in the “German Industrial Standards” (DIN). The DIN 1989 rainwater harvesting standards regulate the planning, installation, maintenance and operation of rainwater harvesting systems, marking the maturity of "first generation" rainwater utilization technology (Schuetze 2013). The basic rainwater harvesting systems consist of collection areas, conveyance systems, purifying facilities and storage tanks.

Upgraded self-control technology was invented in 1992. This technology can record the volume of collected rainwater and the quality of collected rainwater to control the collection time. The third major change in rainwater utilization technology was the integration of equipment, from the roof rainwater collection, interception, storage, and filtration. Reuse and control both have a series of stereotypical products. After years of development, German rainwater utilization technology has entered the stage of standardization (Peng 2006).

There are three types of rainwater utilization systems in Germany: the roof rainwater harvesting system, the green roof rainwater harvesting system, and the rainwater interception and infiltration system. The roof rainwater harvesting system consists of the roof, drainage system, sewage interception system, filtration and purification system, rainwater storage facility and water distribution system. The rainwater collected by this system is mainly used for irrigating green areas, flushing toilets, washing clothing and vehicles (Figure 20). The green roof rainwater harvesting system consists of vegetation planted on the roof, synthetic soils, filter membrane, drainage layer, waterproof layer, insulating layer, and structural roof support. It can be used as the pretreatment facility of the rainwater harvesting system to reduce the urban storm runoff volume, to control the non-point source pollution and to beautify the city (Mentens, Raes, and Hermy 2006) (Figure 21). The rainwater interception and infiltration system is mainly used to deal with the rainwater on the road, with the sewage basket equipped at the inlet to intercept the pollutants carried by the rainwater runoff. This strategy is mostly incorporated with pervious pavement and bioretention swales in cities to help infiltrate rainwater to recharge the underground water or collect rainwater with an underground water tank to reuse it (Zhong, et.al) (Figure 22).

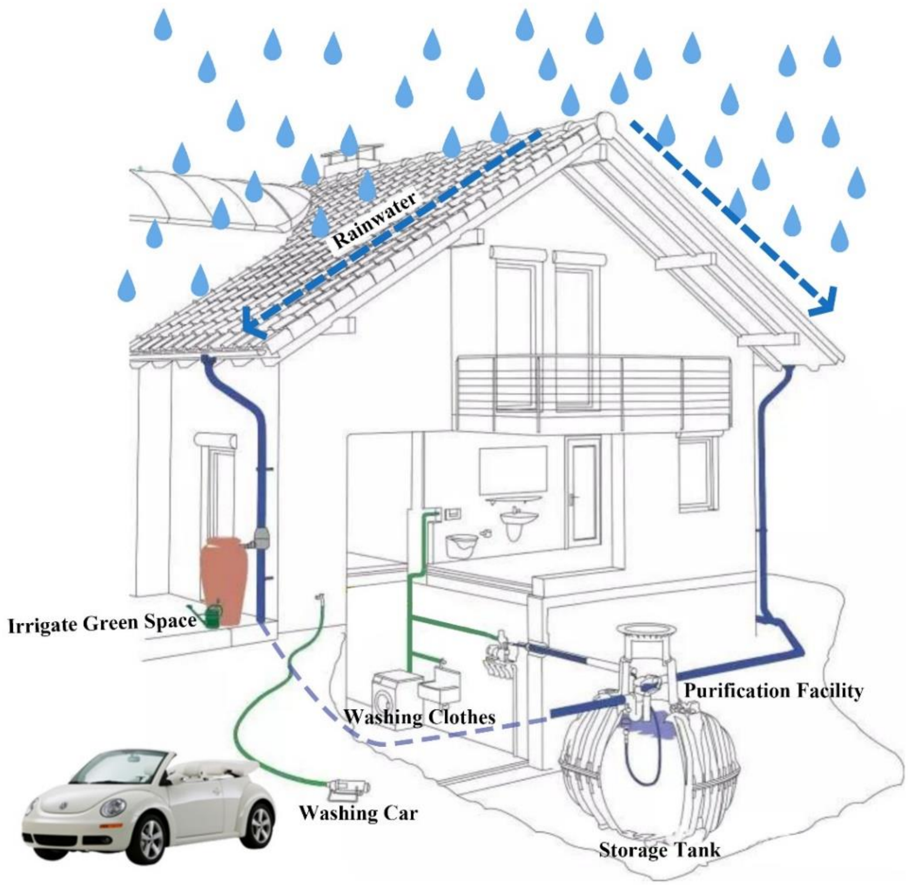


Figure 20: Roof rainwater harvesting system (enhanced by author)

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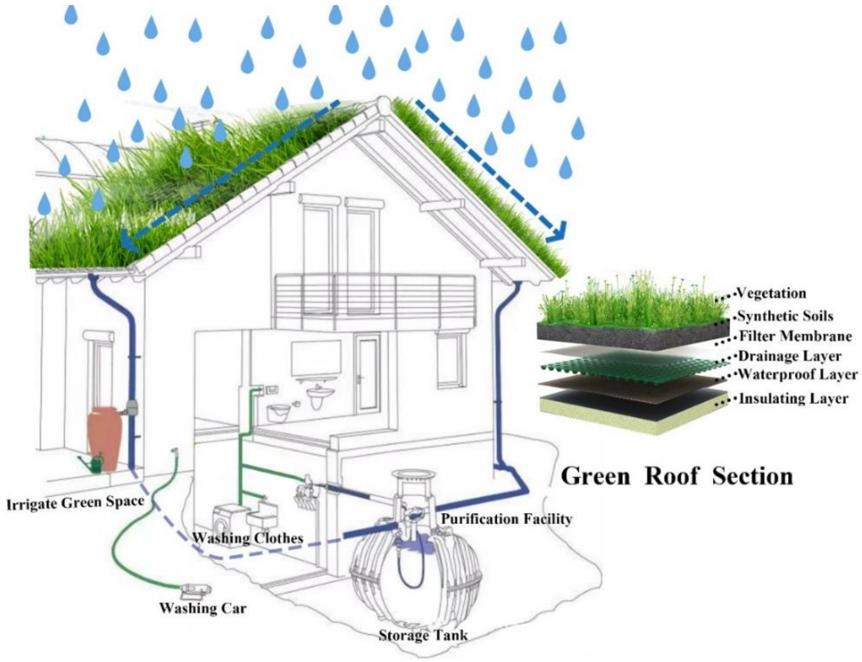

Figure 21: Green Roof rainwater harvesting system (enhanced by author)

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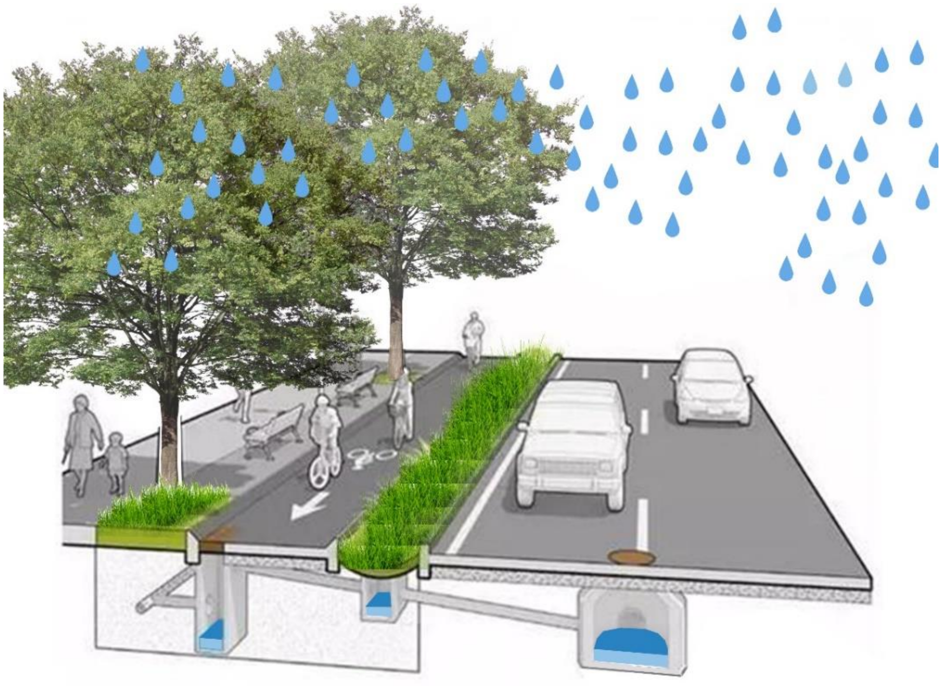


Figure 22: Rainwater Interception and Infiltration system (enhanced by author)

Source: https://www.pinterest.ca/pin/612348880554059500/

In Germany, most of the people live in detached houses, and its rainwater utilization technology used for detached houses is well developed. For example, from Figure 23, the rainwater harvesting system consists of two systems. The first one is the rainwater harvesting system, which is depicted with blue lines in the figure. The rainwater collected from the roof of the building flows into the street rainwater collection pipe through the vertical pipes, and the rainwater collected from the impermeable square and street also enters the street rainwater collection pipe. The rainwater collection pipe discharges into the underground rainwater storage tank in the building. The second system is the rainwater utilization system, which is depicted with green lines in the figure. After the rainwater collects in the rainwater storage tank, the pump sends rainwater to flush the toilet or for landscape irrigation purposes. Similar to the principle of a constructed wetland, the rainwater is purified when it flows through the planting bed by using soil filtration, decomposition, assimilation and metabolism of soil microorganisms. The purified water then flows into the clean rainwater storage tank at the bottom and is pumped for flushing toilets or irrigating green spaces (Peng 2006).

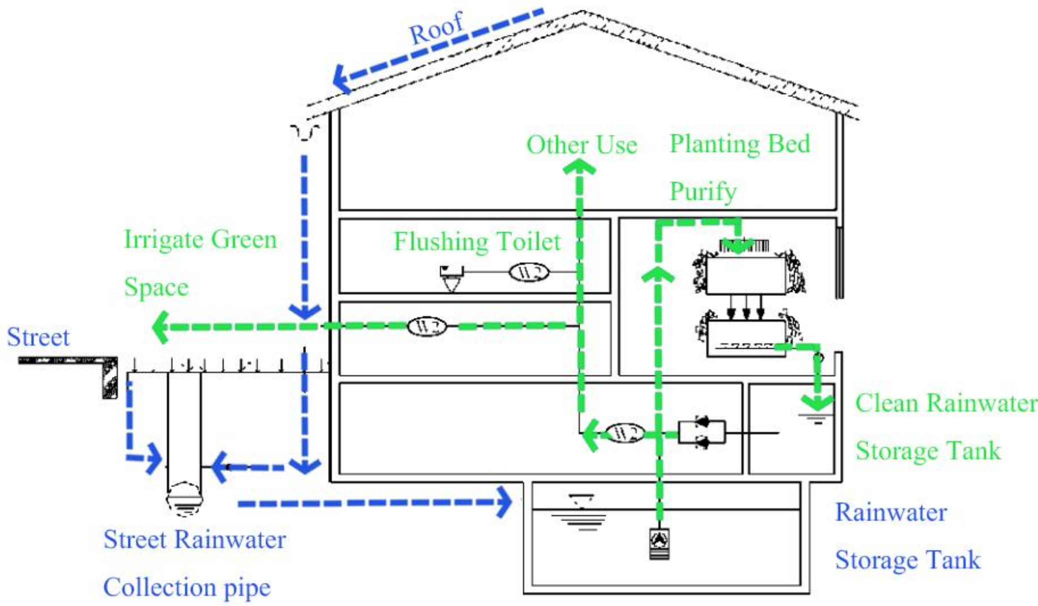


Figure 23: Rainwater harvesting and purification system of a detached house in Germany (Peng 2006)

These experiences from Japan and Germany have reference values to the thesis topic. The Chinese government should learn from these experiences to use legal, economic, and technical tools to help promote the use of the rainwater harvesting system. The following are some suggestions for promoting rainwater harvesting systems in China.

1. Formulate relevant laws and regulations, technical specifications, and standards. Due to the low water price in our country at present, the economic cost of collecting and utilizing rainwater far exceeds the price of water. Government agencies and related departments should introduce relevant policies and regulations on rainwater utilization as soon as possible. On the one hand, they can set standards for the water quality of rainwater facilities and on the other hand, encourage the development of rainwater harvesting and utilization

projects. The government should develop long-term and short-term plans to meet the requirements of sustainable city design in China so that the urban rainwater harvesting system can be fully utilized and promoted (Cheng et al. 2007).

2. Establish special funds to subsidize rainwater harvesting projects. China can formulate a rainwater discharge fee policy based on foreign experience. The establishment of a rainwater discharge fee can be calculated according to the area of impervious surface. A subsidy will be given to buildings using rainwater, and government subsidies will be granted to companies that produce rainwater harvesting equipment. However, in the actual implementation process, according to China's national conditions, we should study such issues like the standard of collection, and the use and management of funds (Li et al. 2010).
3. Education and publicity. Eliminate people's misunderstanding of traditional rainwater harvesting systems through education and the participation process and promote public awareness of the important role of urban rainwater utilization in people's lives and its benefits in the economic and social development. If the public can understand and participate in the utilization of rainwater, the rainwater harvesting system can be promoted more efficiently in China (Li et al. 2010). Public education and participation should include training of specialized urban rainwater management personnel, education of urban residents, and special events to publicize the benefits and knowledge of rainwater harvesting systems (Li et al. 2010).

CHAPTER 4

CASE STUDIES OF RAINWATER HARVESTING SYSTEMS

4.1 DOMESTIC RAINWATER HARVESTING SYSTEM

Ecological Apartment in Heshi Yuan Community, Beijing, China

This project is located in a high-density community, Beijing Heshi Yuan Community. The community consists of five-story apartment blocks and is a typical community in China. Beijing's weather is cold in winter, hot in summer, and dry in spring and autumn. The annual rainfall is 500mm, and mainly occurs in the summer. This project retrofitted two adjacent apartments on the 5th floor; most of the retrofitted areas are the two balconies and the partition walls separating the two apartment living rooms. The area of the balcony is 30 m^2, and the area of the partition wall is 11 m^2 (Figure 24). This project uses a rainwater harvesting system to collect rainwater and then uses the rainwater to irrigate the plants and vegetables in the balcony and also to improve the ecological climate inside the apartment. For the present, most of the residential buildings in China are in high density, so it is not possible to have enough open space for large rainwater cisterns. The direct use of rainwater is more suitable for the current situation of Chinese residential areas (Yu 2016).

Figure 24: Current condition of the community (Yu 2016)

Before the transformation, the balcony was an open space, and on rainy days, the rain fell on the rooftop and balcony, draining through the downspouts on the balcony to the city drainage pipe network. The goal of this project was to collect the rainwater and then use it according to the residents' demands (Figure 25).

Figure 25: The balcony before transformation (Yu 2016)

The first part of this project was to change the structure of the balcony. The design used the entire rooftop as the rainwater collecting surface. According to the original drainage structure of the roof and the structure of the downspouts, the rain gutter was set at the drain gully to allow the rainwater to flow through the drain gully into the pipe that connects the rainwater storage tank. Then the project design set the filter at the pipe port to prevent blockage of the pipe, and the rainwater filtration device was settled at the end of the pipe to further purify the rainwater. The water tank was placed inside the balcony. When the height of the water pool was high enough, the excess rainwater would flow through the overflow device into the downspouts of the building to prevent the water tank from becoming full and unable to collect rainwater (Yu 2016). After the rainwater purification, the rainwater directly flowed into the water tank (Figure 26). The entire rainwater harvesting system, in combination with the building drainage system, collected the rainwater that the roof was supposed to drain away from the balcony and discharged it when the water tank was full. It’s like a retention basin, which can help reduce the peak rainwater runoff when a storm is coming (Yu 2016). To the residents, using the rainwater is a good way to save water fees.

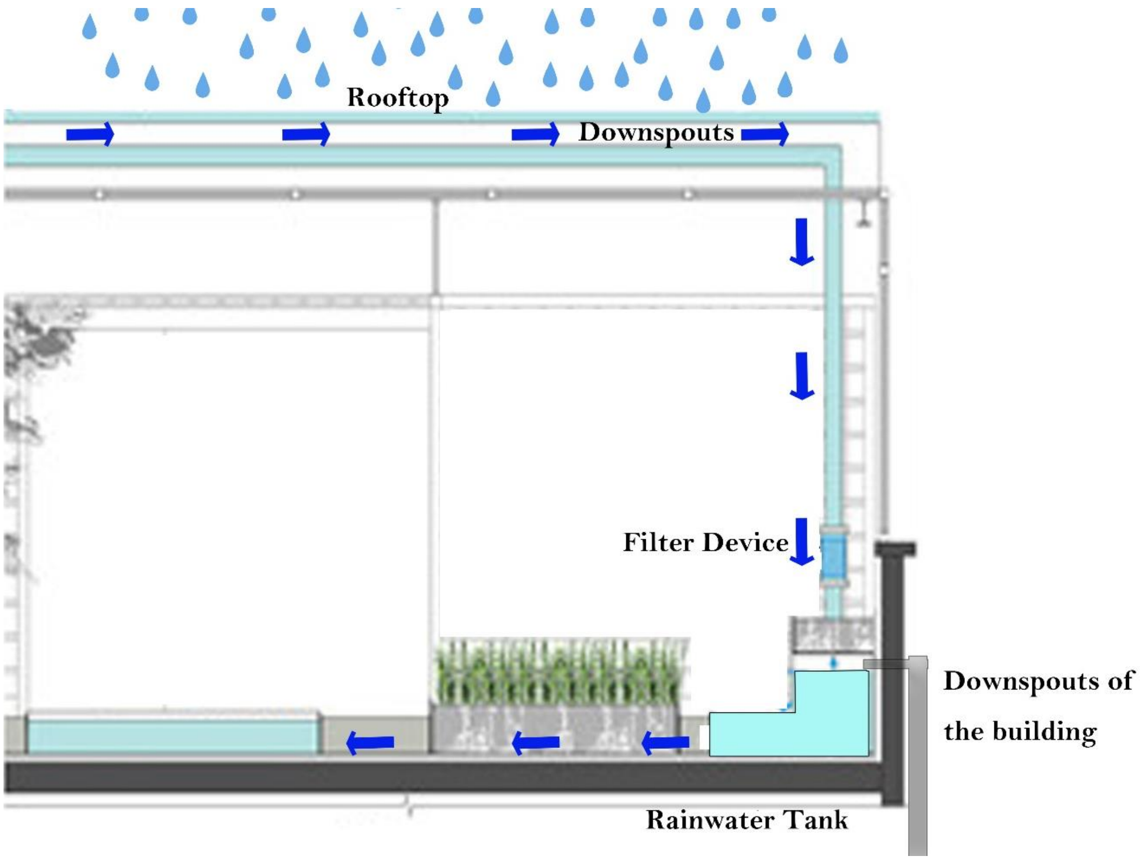


Figure 26: Water flow inside the balcony (enhanced by author) (Yu 2016)

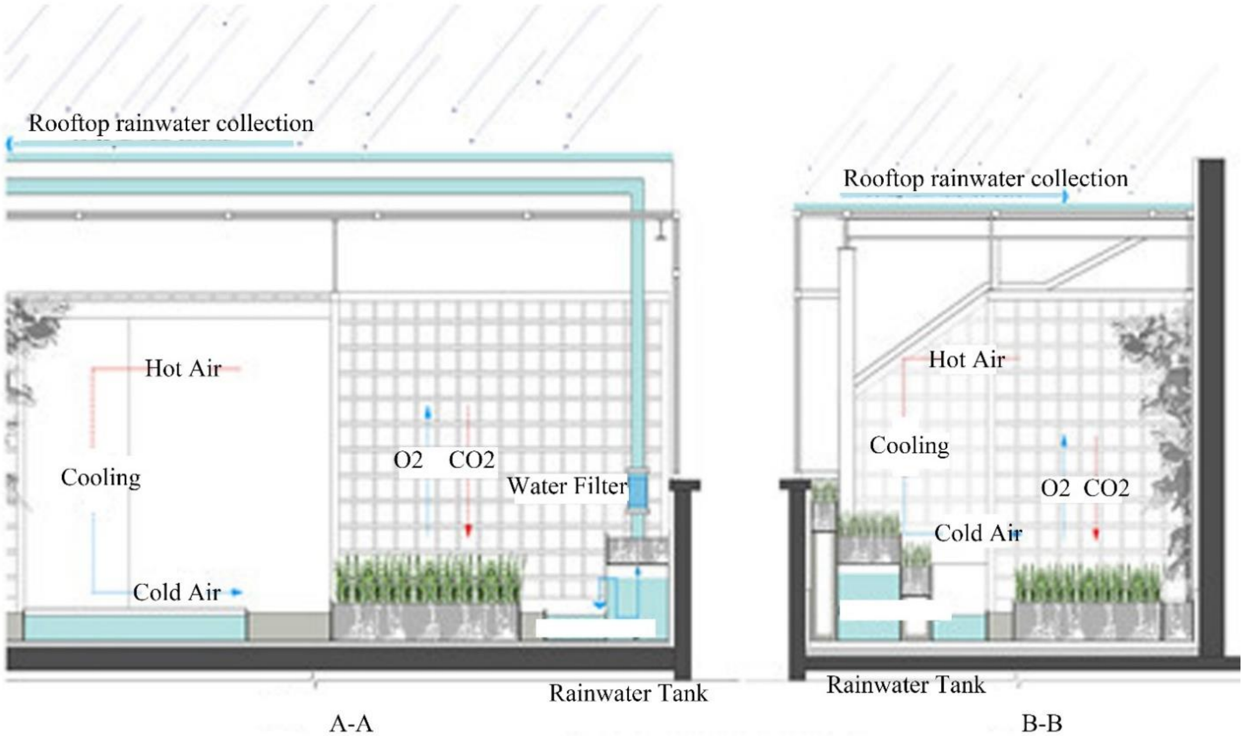


Figure 27: Section A-A, B-B (Yu 2016)

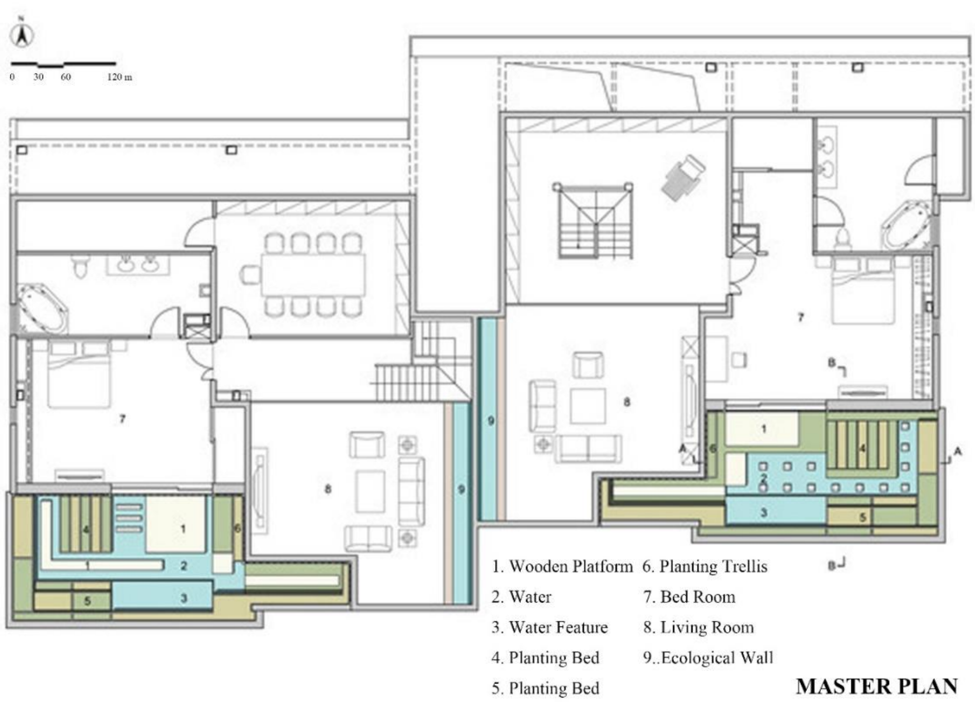


Figure 28: Master plan of the design (Yu 2016)

Figure 29: Perspective of the design (Yu 2016)

There are mainly two ways to use the collected rainwater: the first way to use rainwater is to irrigate the vegetable garden and flower garden inside the two balconies. The two gardens have the same floor layout and spatial structure. These two gardens consist of a pool and stepping stones on the water surface in the middle so that residents can get to all the areas of the balcony (Yu 2016). The pool uses a steel structure to prevent water seepage in the pool, and by controlling the rainwater tank's water valve, the residents can easily increase the amount of water in the pool and use the water in the pool to irrigate the plants inside the balcony. The balcony garden is a buffer zone between the outdoor and indoor environment. It can cool the hot air from outside in the summer, and then help warm and humidify the cold and dry air in the winter (Yu 2016).

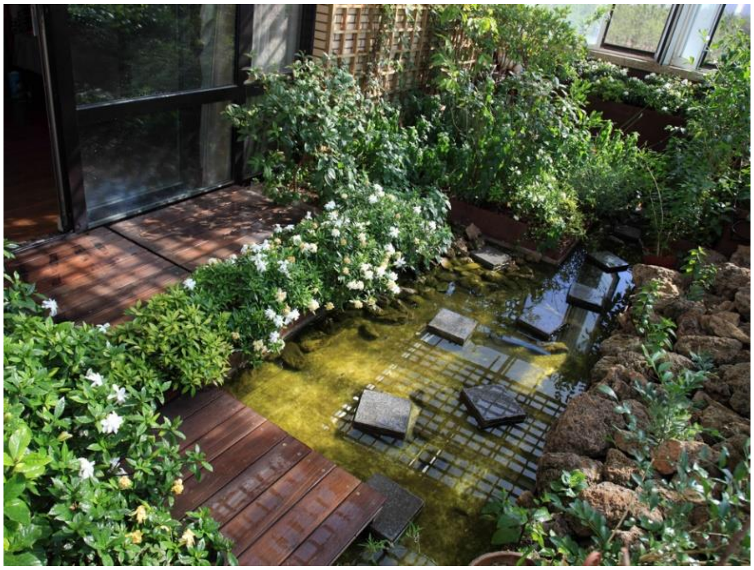
 

Figure 30: Photos of the balcony (Yu 2016)

Another way to use rainwater is to transform the partition between the two apartments into an ecological wall. This design has obtained an invention patent. This wall is more environmentally friendly than a traditional electric humidifier. The main frame of the ecological wall is formed by steel, the inner side of the frame is connected to the apartment, and the outer side of the frame has porous limestone. There are overflow gratings on the top of the ecological wall, the water pump circulates rainwater through the water pipe to the overflow gratings, and then the rainwater drenches the porous limestone (Yu 2016). There is a pool at the bottom of the ecological wall to collect the water fall from the wall. This design uses the characteristics of the porous limestone. The wall can absorb and retain water, providing an environment for the growth of moss and rock plants, and the water inside the wall evaporates in the summer to reduce the room temperature. It can also provide moisture in the winter so that the entire wall becomes a climate regulator (Yu 2016).

Figure 31: Photo of the ecological wall (Yu 2016)

This project both reduces energy consumption and improves the indoor environment. The rainwater collected on the two balconies is 52 m^3 per year, and the vegetables grown in the balcony can provide enough vegetables to meet the residents' demand.

Table 7: Rainwater collected in one balcony from 2009-2010 (Yu 2016)

Time Period	Rainwater Collection Volume (m^3)	Total (m^3)
07/2009-09/2009	15.8	26
10/2009-12/2009	1.9	
01/2010-03/2010	2.1	
04/2010-06/2010	6.2	

This project is a good case to show how to reuse rainwater in an urban Chinese residential area. In this case, rainwater is not only used to irrigate plants and vegetables in the balcony, but it is also used to monitor the micro climate in the apartment. And it is a good example to show how to celebrate rainwater in an urban Chinese area. Finally, people can see how rainwater has become part of the landscape in the balcony.

Three design principles can be learned from this case:

1. Collected rainwater can be used for irrigating the vegetables in the balcony.
2. Collected rainwater can be used for controlling the microclimate inside the apartment.
3. Rainwater should be stored as close as possible to the reuse location.

4.2 RAINWATER HARVESTING SYSTEM COMBINED WITH GREEN ROOFS

Potsdamer Platz, Berlin, Germany

Potsdamer Platz, Berlin, Germany, designed by Atelier Dreiseitl, has been an important square and intersection in Berlin since the 20th century. After the fall of the Berlin wall in 1989, the city of Berlin realized that a reinvention of the city was necessary. One specific area chosen for the renovation was Potsdamer Platz district, and this project was completed in 1999. The revitalized area has the functions of art, entertainment, and shopping. The water system in the area not only has ecological benefits, but also has cultural and aesthetic significance. This draws people to the plaza to relax and engage by the water in the highly dense commercial area (Figure 32).

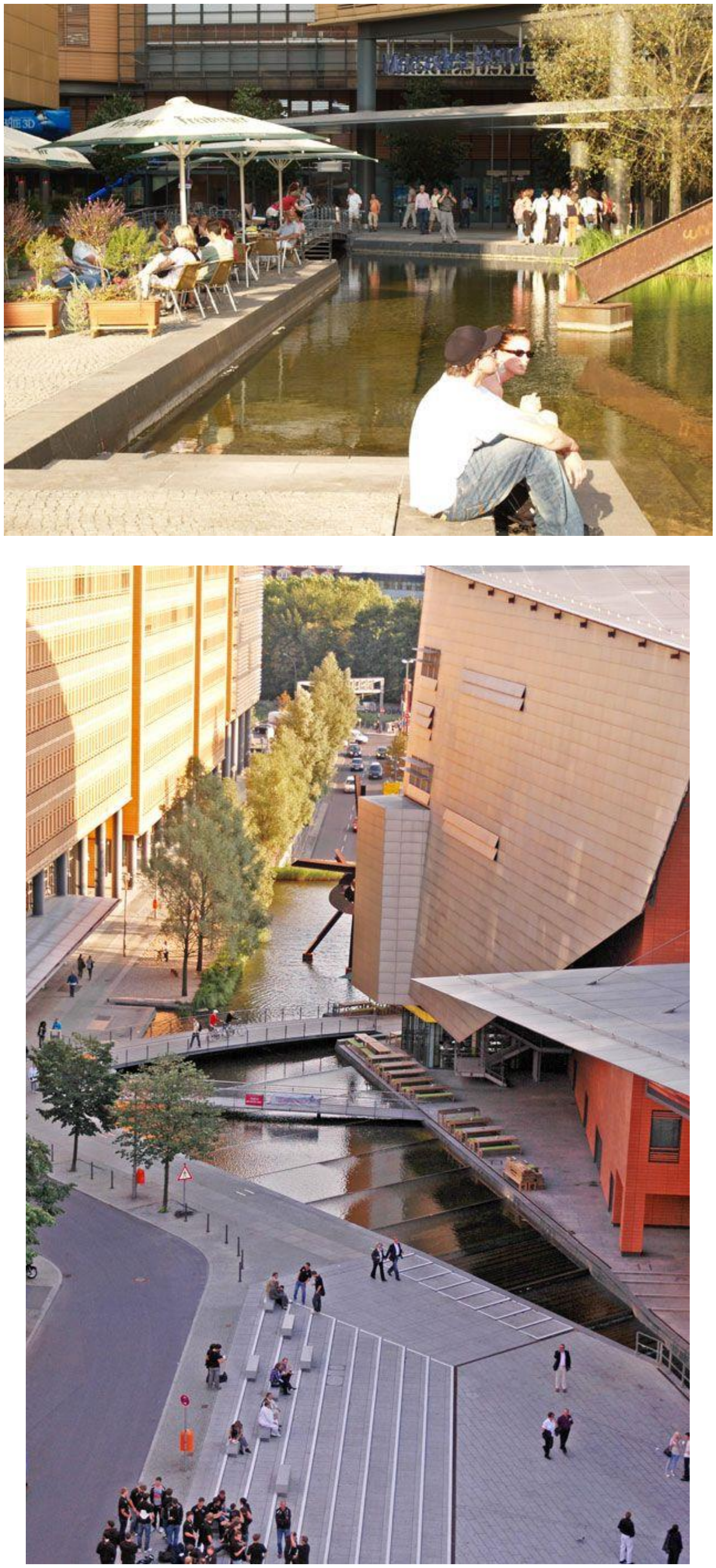


Figure 32: Photos of Potsdamer Platz (courtesy of Atelier Dreiseitl)

Figure 33: Master plan of Potsdamer Platz (courtesy of Atelier Dreiseitl)

The design of the water system has two objectives: aesthetic and ecological. The water system is fed entirely by collected rainwater. As shown in Figure 33, the water system is composed of: 1. a narrow channel in the north, 2. water features near the plaza, 3. the large main water feature, 4. another small water feature in the south. The water system improves the urban climate because the water slightly lowers the surrounding temperature in summer and binds dust particles and humidifies the air. A characteristic of the design is to integrate green roofs with rainwater harvesting. Green roofs can serve as retaining rainwater, filtering airborne pollutants, and reducing roof surface temperatures. These intensive and extensive green roofs capture 20,000 cubic meters of rainfall every year (Köhler et al. 2002). Water is not only captured and retained in the soils and plants on the green roofs, it is also filtered, stored in five large unground cisterns, and reused for toilet flushing and irrigation (Figure 34).

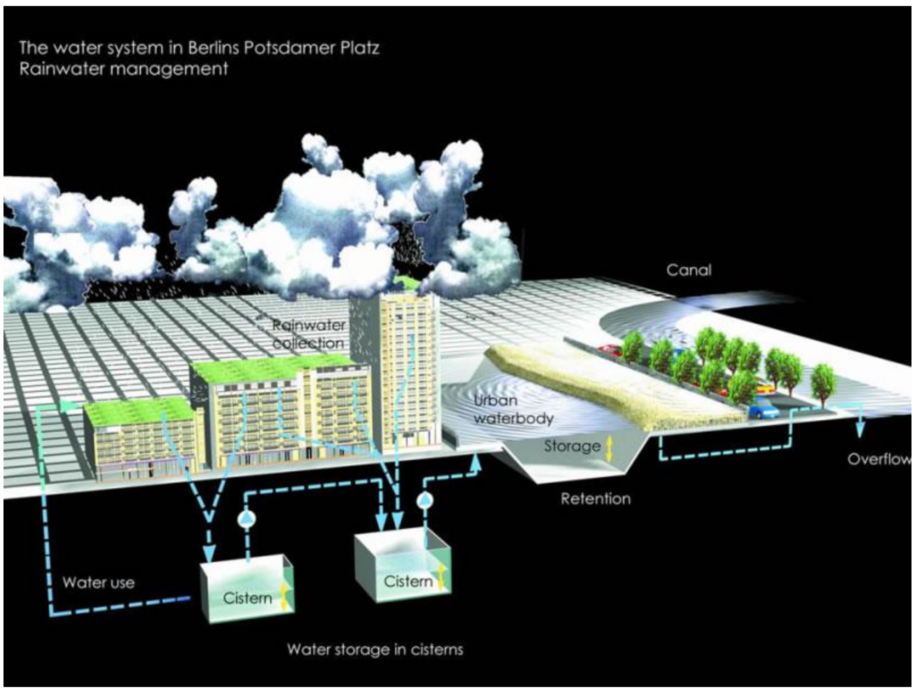


Figure 34: The rainwater harvesting system in Potsdamer Platz (courtesy of Atelier Dreiseitl)

The five large underground cisterns can contain 3,500 m^3 rainwater. The collected rainwater can be reused for toilet flushing and irrigation, and the excess rainwater can be slowly discharged into a series of narrow pools located along sidewalks and streets and finally to the southern pool. The series of pools and streams near the plaza, beside the streets and pavements are integrated with vegetated bioslopes. As it passes through the biofiltration beds, these aquatic plants treat the rainwater to purify it organically (Figure 35).

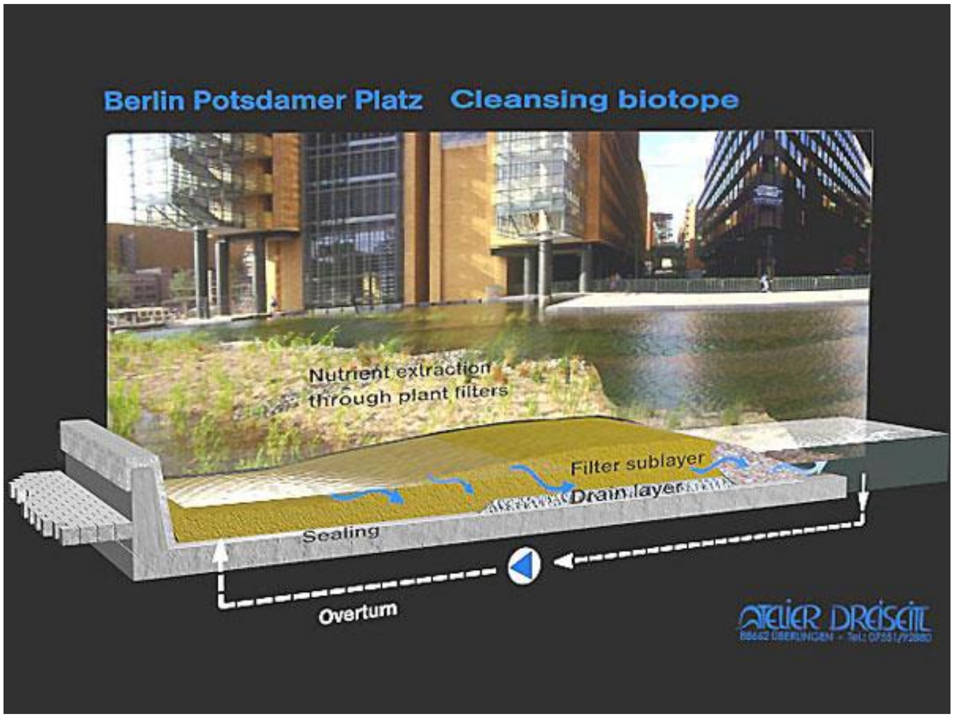


Figure 35: Bioslopes in Potsdamer Platz (courtesy of Atelier Dreiseitl)

This project is important to this thesis because it shows one way how to integrate rainwater harvesting systems and green roofs. In this case, two design principles can be applied:

1. Green roofs can be integrated with rainwater harvesting systems.
2. Rainwater harvesting systems also have cultural and aesthetic significance, which can draw people in to relax and engage by the water.

4.3 RAINWATER HARVESTING SYSTEM COMBINED WITH BIORETENTION

Stephen Epler Hall at Portland State University, Portland, Oregon

Stephen Epler Hall is a six-story building that contains 130 units of student housing, with offices and classrooms on the first floor (Echols and Pennypacker 2015). This building is a LEED Silver building, the first one to use rainwater to flush toilets in Oregon, using “bio-paddies” which is a stormwater management system to reduce stormwater runoff (Echols and Pennypacker 2015).

Figure 36: "Bio-paddies" in front of the building (Echols and Pennypacker 2015)

Rainwater first falls on the 12,000 square feet of roof and then falls via downspouts into four splash boxes. There are small spouts at the bottom of each splash box which spill rainwater into stone runnels, and then the stone runnels transfer the rainwater into "bio-paddies". Finally, there are perforated pipes in the bottom of each "bio-paddy" that transfer the remaining water into an underground cistern (Echols and Pennypacker 2015). In a large storm, if there is overflow in the "bio-paddies", the excess water is discharged to the city existing stormwater system, and if the cistern fills, excess water also goes to the city sewer system (Echols and Pennypacker 2015).

Figure 37: Perspective diagram of the stormwater management system in Stephen Epler Hall (Echols and Pennypacker 2015)

The rainwater is first biofiltered in the “bio-paddies” to remove sediments and other contaminants, and then the rainwater is treated in the cistern by ultraviolet rays to kill bacteria. Lastly, the treated rainwater is used for toilet flushing and irrigation (Echols and Pennypacker 2015). This rainwater harvesting system can collect 111,000 gallons of rainwater per year, with 10,000 gallons of the rainwater used for irrigation, and the other 100,000 gallons of water used to flush toilets in the building (Echols and Pennypacker 2015).

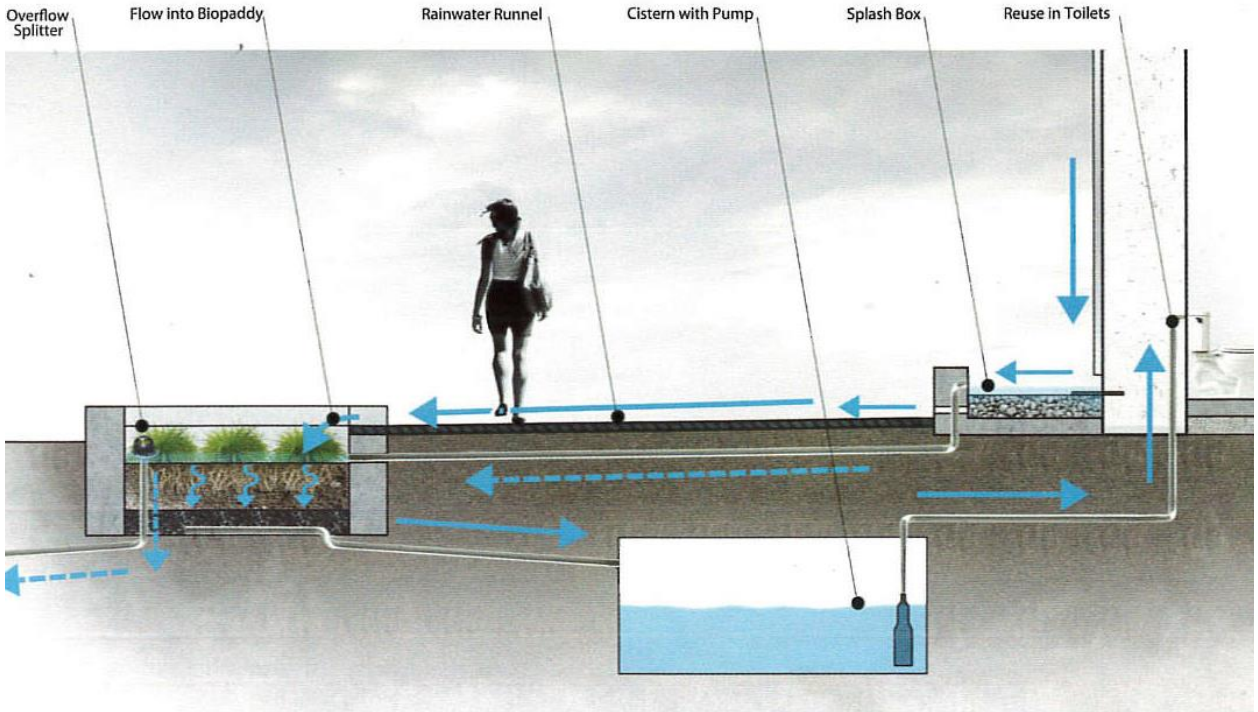


Figure 38: Diagram of water flow of the rainwater harvesting system (Echols and Pennypacker 2015)

The rainwater harvesting system at Stephen Epler Hall not only can reduce stormwater runoff effectively, but also presents a fun and engaging celebration of rainwater. The highly visible water trail can help pedestrians see that rainwater can be a resource (Echols and Pennypacker 2015).

In this case, two design principles can be applied in the thesis:

1. Rainwater harvesting systems can be integrated with bioretention devices.
2. Highly visible rainwater harvesting systems can attract pedestrian interest into the rainwater harvesting system.

4.4 ARTFUL RAINWATER HARVESTING DESIGN IN AN URBAN AREA

10th@Hoyt, Portland, Oregon

10th@Hoyt is a five-story building, built in 2003 by Ankrom Moisan, which comprises an entire city block in Portland, Oregon. Inside this building is a 8,500 square foot courtyard designed by Steven Koch and Koch Landscape Architects (Sparnicht 2012). Before this building was built, the city of Portland required that the stormwater impact of this building on the city sewer system had to be mitigated (Echols and Pennypacker 2015). To achieve this goal, this courtyard needed to serve two purposes: a storm water delay facility and a gathering space for residents in this building. To do that, the concept of artful rainwater harvesting had to be applied in this project.

Figure 39: 10th@Hoyt from the outside

Source: http://www.ankrommoisan.com/project/10th-hoyt/discipline/architecture

The basic stormwater management concept at 10th@Hoyt is capture, convey, detain, reuse in water features, and discharge. One challenge of this project was that it is located above an underground parking garage, which means that there was no opportunity for rainwater infiltration and aquifer recharge (Echols and Pennypacker 2015). Therefore, the only way for this project to reduce the stormwater runoff was to collect the rainwater and reuse it.

All the rainwater from the roof is carried by three copper downspouts into the courtyard. Half of the runoff is carried into a 33 foot-long, 2500-gallon raised concrete detention vault by one copper downspout on an axis with the entry gate (Echols and Pennypacker 2015). The other half of the runoff is carried by the other two downspouts in the courtyard corners into two shallow, above ground concrete containers, each of which can collect 500-gallons of rainwater. After the rainwater is collected in the cistern, the rainwater is pumped over the two sculptural Corten fountains, and this reuse provides both visual and auditory interest. The rainwater is cleaned through oxygenation, and the drainage period is extended up to 48 hours (Echols and Pennypacker 2015).

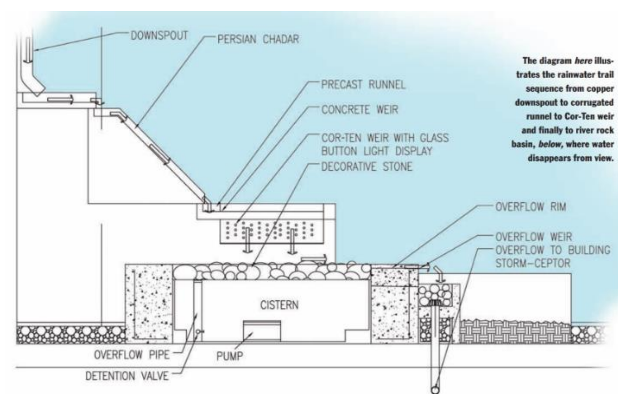


Figure 40: Rain harvesting system on one side of the courtyard (Echols and Pennypacker 2015)

In this design, the designer uses three ways to create visual and auditory interest:

1. Create visual interest through an axis. All the landscape in this courtyard like the seating, planters, and Corten weir boxes are placed symmetrically along the central downspout axis (Echols and Pennypacker 2015) (Figure 41).

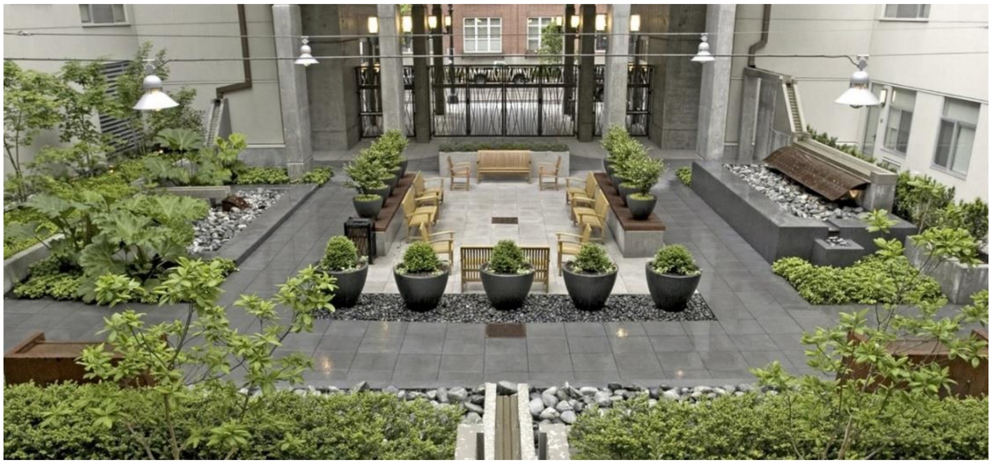


Figure 41: Axis in the courtyard

Source: http://www.ankrommoisan.com/project/10th-hoyt/discipline/architecture

2. Create visual interest through color and texture: in this design, the three most important materials are Corten steel, river rock, and Dinosaur Food Plants (Gunnera tinctoria) (Figure 42). The Corten steel is rough and red, the river stone is smooth and gray, the dinosaur food plant is soft and green, and the contrast of the three different materials in this courtyard fills this space with tactile sensations (Echols and Pennypacker 2015).

Figure 42: Contrasting textures in the courtyard (Echols and Pennypacker 2015)

3. Create auditory interest through sound of water flow -- in this design, the sound of moving water provides an opportunity for the designer to draw people's attention to the importance of rainwater in this project. This is a good way to teach people that with good design rainwater can also be an artful landscape (Echols and Pennypacker 2015).

This project is a good case to demonstrate how to create an artful rainwater harvesting design in an urban area. Two priniciples can be learned from this case to help achieve aesthetic richness:

1. The aesthetic richness of the rainwater harvesting system can be achieved by creating visual interest, like color and texture.
2. The aesthetic richness of the rainwater harvesting system can be achieved by creating auditory interest, like the sound of moving water.

CHAPTER 5

ARTFUL RAINWATER HARVESTING DESIGN IN CHINA

5.1 OVERVIEW OF ARTFUL RAINWATER DESIGN

Two important parts of landscape architecture are engineering and art. Engineering makes the landscape useful and economical, but art makes it attractive and inspiring (Sparnicht 2012). In the history of stormwater management, people's attitudes toward rainwater have changed a lot. First, people think rainwater is a waste product and blame it for property damage through flooding. Due to the development of stormwater management, people have found that rainwater is a valued natural resource to us. Now, a growing number of people realize that through a celebration of rainwater, rainwater management systems can educate and entertain the public (Echols and Pennypacker 2015). This is how the concept of artful rainwater design emerged; it has become an important part of stormwater management, and many landscape architects have talked about artful rainwater design:

> Water is one of our most fundamental elements and essential to every living system: it needs to be celebrated and reveled in as many productive ways as possible. Since we have always understood landscape architecture as a synthesis of artistic, scientific and cultural values, it seems that taking an "artful" approach to designing with rainwater should not really even be a choice, it should be an expectation. - Warren Byrd, Nelson Byrd Woltz (Echols and Pennypacker 2015).
>
> For me, the motive for taking an artful rainwater design approach was to make environmentally beneficial design last. I used what I had learned in my research about the

> aesthetic of everyday landscapes to propose patterns that were intended to win the affection of the public for those early green infrastructure designs. This reduced the risk that innovative landscape patterns would disappear with the next landowner or new manager. - Joan Nassauer (Echols and Pennypacker 2015).
>
> I look at artful rainwater design opportunity as a way of creating incredibly rich places that are highly efficient "working landscapes" and improve life at all levels. For this reason, I always team with creative and talented landscape architects and designers! – Steve Benz (Echols and Pennypacker 2015).
>
> "Artful rainwater design" is based on the premise that new stormwater management techniques focusing on non-point source pollution, water balance, and small storm hydrology can also be used to create new site amenities. Most simply put, artful rainwater design is sustainable stormwater management that celebrates rain. – Eliza Pennypacker, Stuart Echols (Echols and Pennypacker 2015).

These landscape architects make it clear that artful rainwater design is a sustainable design approach that contains the function and aesthetic part of rainwater design, and it can help make rainwater design be accepted by residents. A set of design principles of the aesthetic part of rainwater design is shown below (Table 8).

Table 8: Design principles of aesthetic part of rainwater design (Echols and Pennypacker 2008)

AESTHETIC RICHNESS GOAL Create an interesting experience of beauty or pleasure focused on the stormwater	
OBJECTIVES To create	***DESIGN TECHNIQUES***
VISUAL INTEREST	
Point	Create water collection basin as a feature or focal point Create visual emphasis on stormwater direction change using scuppers, basins, cisterns, splash blocks, or rain chains
Line	Use downspouts, runnels, flumes, or bioswales to draw attention to the line of the stormwater trail, enhancing legibility as well as interest and curiosity
Plane	Stack horizontal and vertical planes such as pools and falls to exploit visual interest of stormwater flowing over surfaces, plunging down planes, through weirs, or over edges
Volume	Create visual interest or themes with basins that hold plants and water: sunken, raised, orthogonal, curved, organic, geometric, small, or large
Color and Texture	Contrast natural elements such as plant and rock with man-made elements, such as clipped lawn, steel, or concrete Juxtapose river rock and riparian grasses for compositional contrast
Axis	Create stormwater trail using axial runnels, downspouts, and bioswales Dramatize implied axis using aligned treatment systems, basins and runnels connected by the water trail
Rhythm and Repetition	Create unified design themes by using multiple bioswales, basins, weirs, ponds, or rain gardens
AUDITORY INTEREST	
Volume	Create a variety of volumes by allowing stormwater to fall from various heights onto different materials such as stone or steel
Pitch	Create changes in pitch by allowing stormwater to fall on different forms such as flat block, metal tubes, drums, and ponds
Rhythm	Create different rhythms by varying the amount and rate of stormwater falling and flowing through the treatment system
TACTILE INTEREST	
Texture	Use a variety of water-related plants such as rushes and grasses Use various water-related hardscape such as river pebbles or driftwood to provide interesting surfaces
Wetness	Allow people to touch stormwater in different forms such as flowing, falling, splashing, standing, and sheeting, or on damp surfaces where water can soak in or evaporate

To do an artful rainwater harvesting design in China, and to get the greatest public acceptance, I believe the aesthetic design principles should be addressed from a Chinese aesthetic standpoint, and also in a way that is functionally appropriate for China. To identify Chinese aesthetic principles that can be applied to artful rainwater harvesting, classical Chinese garden designs can serve as a study source.

5.2 CLASSICAL CHINESE GARDEN DESIGNS

The classical garden design in China is characterized by its elegant and natural artistic expression and traditional national style, which is unique in world garden design history. According to the affiliation, the classical Chinese gardens can be divided into three categories: imperial garden, private garden and temple garden. The most representative of the characteristics of Chinese classical gardens is private gardens. Suzhou is one of the original places of classical Chinese gardens. It has gathered the essence of private gardens in the south of the Yangtze River and has a long history (Fu-ming 2013). The exquisite garden design skills of the gardens carry a profound Chinese garden culture and many of these gardens are famous all over the world (Keswick and Hardie 2003).

Figure 43: The location of Nanjing and Suzhou (produced by author)

Most of the well-known classical gardens in Suzhou were built in the Ming and Qing dynasties, and most of them are in the urban area of Suzhou, which was mainly determined by the builders of classical private gardens. These classical private gardens were built by wealthy dignitaries after retirement; they wanted to live in peace and in a natural environment with mountains and rivers, and then formed an aesthetic tendency to mimic the form of natural rivers and mountains in order to seek spiritual comfort and harmony in nature. From this idea we can see that classical private garden designs in Suzhou relate closely to the water and hills found in nature. Hills and water are the two basic elements in Chinese classical private garden design, so the Chinese classical garden is also called the "Hill and Water Garden" (Lin-di 2004). Classical garden designers made great use of water in Suzhou gardens, and combined with artificial hills, trees, and buildings, water scenery gardens rich in the beauties of nature were created at Suzhou and elsewhere in southern China (Wang 2003).

5.2.1 ARTIFICIAL HILLS IN CLASSICAL SUZHOU GARDEN DESIGNS

The artificial hills in the classical gardens of Suzhou can be divided into earth hills, rock hills and earth-rock hills. The traditional way of creating artificial hills is by piling up different kinds of natural rocks, like Taihu lake stone, and Huang stone. The rich variety of hills inside the classical Chinese gardens are miniatures of real mountains by drawing on their characters. They produce an illusion that mountains and forests exist in such a small area as the garden, with all their grandeur and characters. With the appropriate plants, viewers can recall the magnificence of mountains, feeling as if they are among the nature (Fu-ming 2013).

Normally, there are four different kinds of artificial hills, and they are placed in different areas of the garden and serve as different functions (Table 9) (Figure 44).

Table 9: Types of Artificial Hills (Fu-ming 2013)

Types of Artificial Hills	Features and functions	Example
1. Pool Hill	Hill located on the side of the pool, combined with the water, to mimic the natural landscape	Wangshi Garden (Figure 5.2.1.1.1)
2. Hall Hill	Hill located in front of the hall, mainly for viewing or barrier use	Liu Garden (Figure 5.2.1.1.2)
3.Pavilions Hill	Hill located in front of the pavilion, or hidden in the side of the pavilion, form like a ladder in air, which means people can have a good future	Wangshi Garden (Figure 5.2.1.1.3)
4.Cliff Hill	Use the wall as a paper, then use the hill as the drawings on the paper, make it looks like traditional chinese landscape painting	Wangshi Garden (Figure 5.2.1.1.4)

Figure 44: Photos of Artificial hills in the classical gardens (Fu-ming 2013)

Most of the large artificial hills are earth-rock hills, and most of the small artificial hills are rock hills. Small size artificial hills can be easily adapted to the modern garden. Functionally, they can be integrated in a rainwater harvesting system. For example, in 10th@Hoyt, Portland, Oregon, the two Corten weir boxes could conceptually be replaced by pavilion hills to fit into a Chinese cultural context (Figure 45). Similarly, in Washougal Town Square, Washougal, Washington, the splash sculpture functions much like a hall hill (Figure 46).

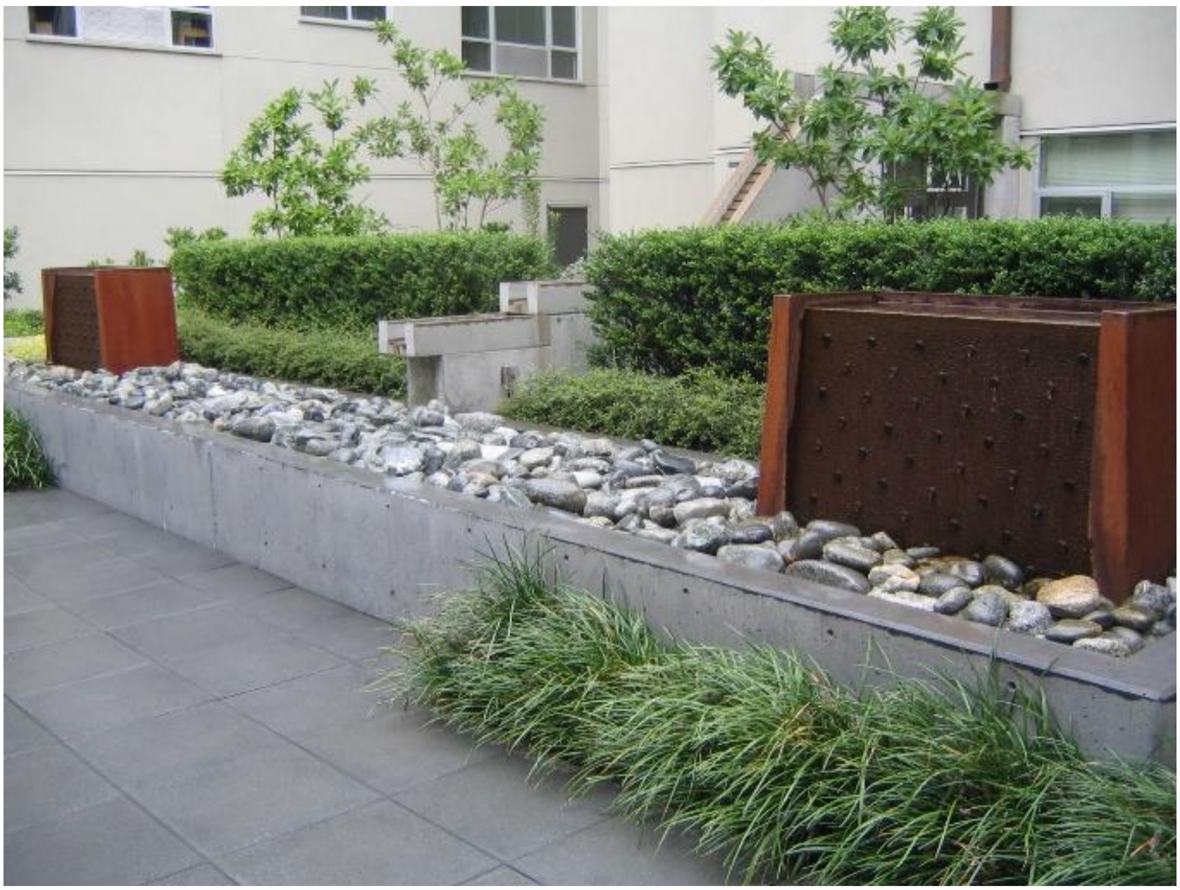


Figure 45: Two Corten weir boxes in 10th@Hoyt (Echols and Pennypacker 2015)

Figure 46: The splash sculpture in Washougal Town Square (Echols and Pennypacker 2015)

Artificial hills are good elements to integrate with rainwater harvesting systems. They can be incorporate a cistern, or they can be formed to convey rainwater from a roof, and they can also use collected rainwater to form a waterfall landscape.

The layout of artificial hills is an important part of artificial hill design in classical Suzhou gardens. Normally, there are four different ways to lay out the artificial hills in the classical gardens in Suzhou, they are central arrangement, oppositive scenery, corner arrangement, surrounding arrangement (Table 10). For the different sizes of artificial hills, there are different ways to lay out the artificial hills. The central arrangement method normally is for large artificial hills, and the hills are located at the center of the garden where everyone can see them. The other three layout methods are for small artificial hills, where the artificial hills are placed at the corners of the garden or placed surrounding the boundaries of the garden.

Table 10: Different layout of Artificial Hills(Fu-ming 2013)

Layout method	Characteristics	Example
1.Central Arrangement	Big size, Hills are located in the central of the garden	Canglangting Garden (Figure 5.2.1.2.1)
2.Oppositive Scenery	Small size, in order to create an open space, located in opposite of the building	Yipuchi Garden (Figure 5.2.1.2.2)
3.Corner Arrangement	Small size, put the artificial hills in the corner space to fill the garden	Huanxiushanzhuang Garden (Figure 5.2.1.2.3)
4.Surrounding Arrangement	In a small garden, place the hills along the boundry of the garden to create a continuous mountain landscape	Shizilin Garden (Figure 5.2.1.2.4)

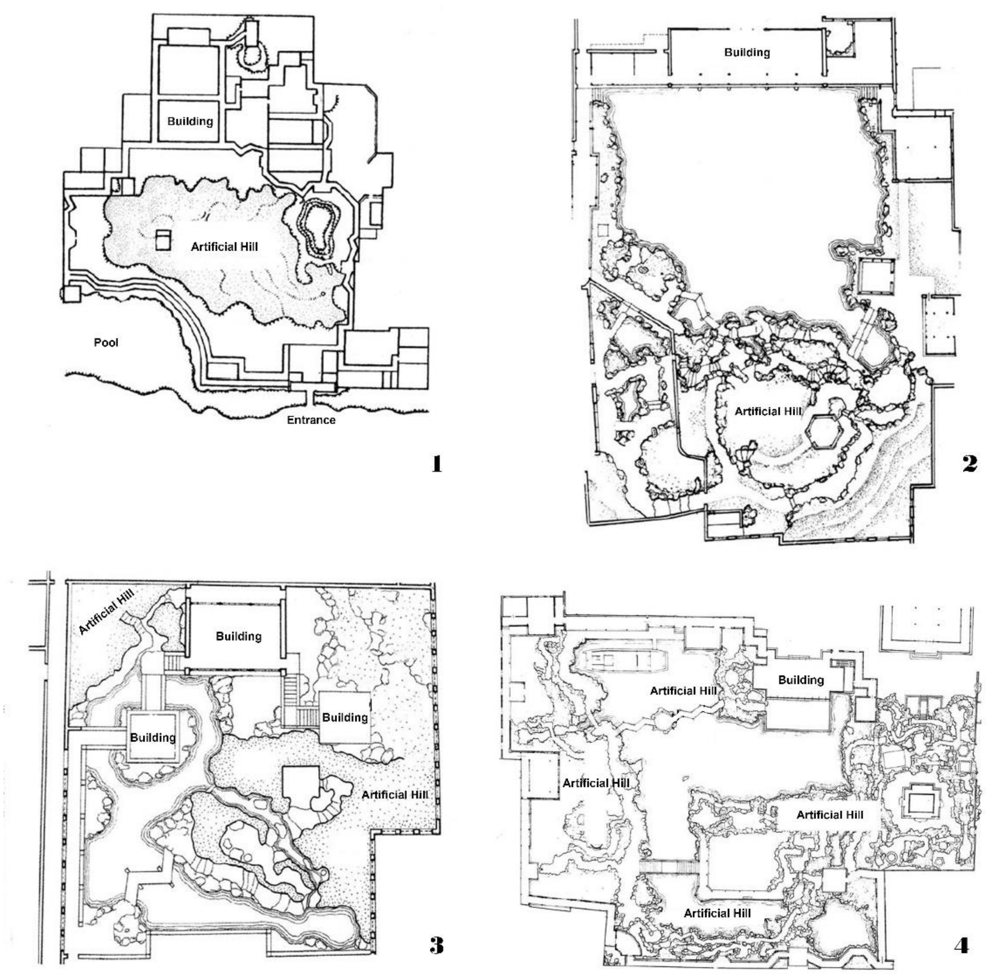


Figure 47: Different layouts of artificial hills (Fu-ming 2013)

5.2.2. WATER IN CLASSICAL SUZHOU GARDEN DESIGNS

The design of water systems in classical Chinese gardens is called “lishui,” which literally means organizing and arranging the water system. In the design of the classical gardens in Suzhou, "lishui" is of great importance. The theories and methods of “lishui” are mainly inspired by the shape of lakes, pools, bays, streams, and rivers, etc. There are many kinds of water bodies in the world. The classical garden in Suzhou draw inspirations from the landscape of nature, by artistic recreation, creating sceneries superior to natural ones. Imitating nature but not limited by nature, it achieves a kind of “harmony between nature and man” (Liu 1993).

Landscape gardeners and craftsmen from the previous generations have accumulated rich experience in the layout of water systems. They have summarized a set of aesthetic principles and these principles in Suzhou are as follows:

1. The beauty of the water shape

   In the classical gardens in Suzhou, the most common waterscape is the pool, which appears as the center of the garden and along with artificial hills, creates the basic layout of hill-water gardens. In ancient days, the landscape gardeners paid great attention to the design of the shape of water bodies. The water bodies of classical gardens in Suzhou mainly imitate natural forms; geometric shapes are rarely used. For example, in Zhuozhengyuan Garden (Figure 47), the pool twists and turns, so that people can’t see all the pool in one place. The water line of the pool is irregular, and just like natural rivers and mountain streams, it is different from Western garden designs, where the shape is regular, and the line is straight.

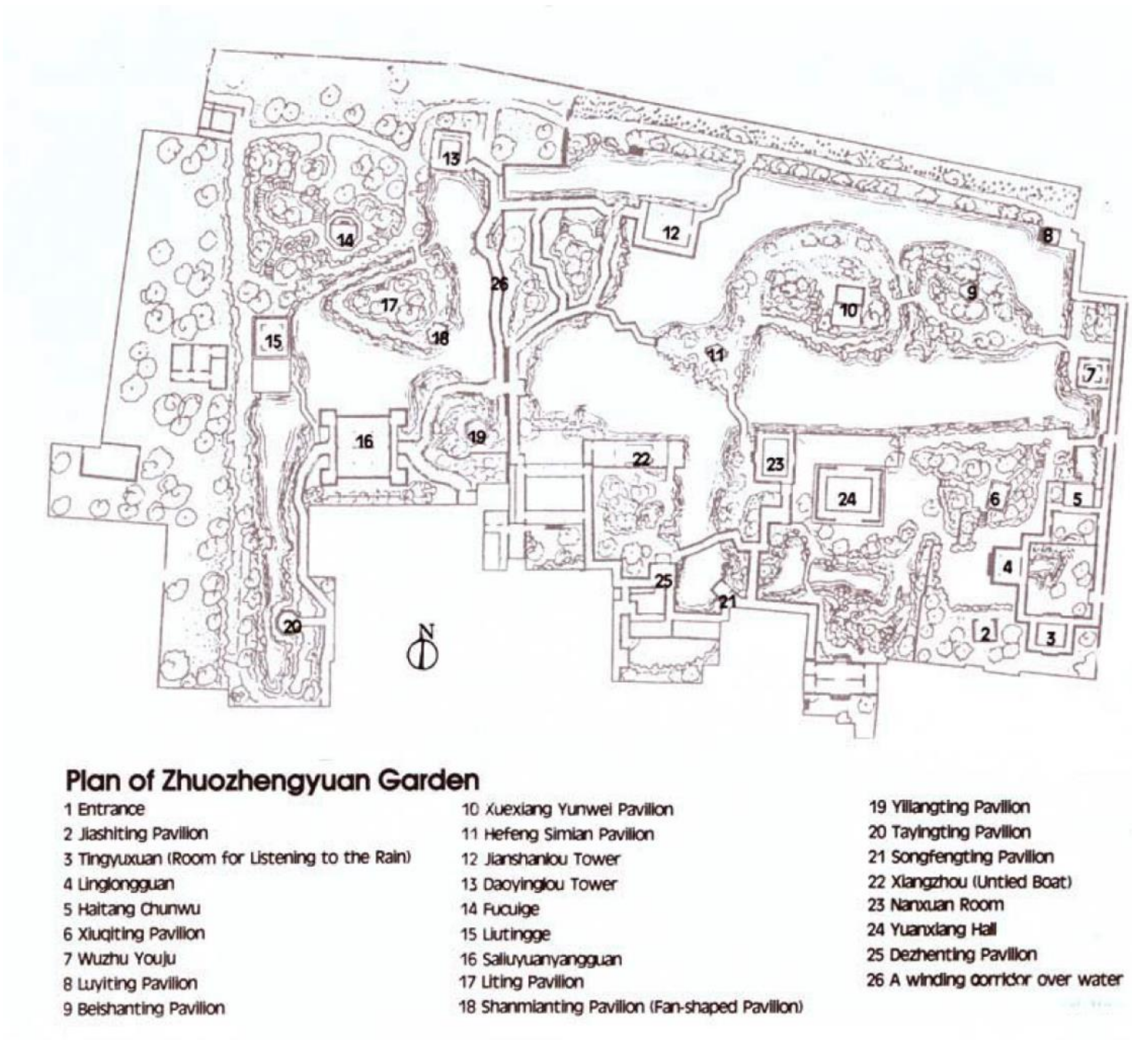


Figure 48: The plan of Zhuozhengyuan Garden (Wang 2003)

Another common kind of water shape in classical Suzhou gardens is Xi (creek). Creeks are designed with changes in both height and plan. The water flows from one part to the next because of the elevation change, intermittently rushing down a steep gully and then slowing as the creek changes to a nearly level bed. Furthermore, creeks meander through the garden to divert the visitor's line of vision and to create the perceptual illusion of extensive space of the garden (Wang 2003). Also, there are other two aesthetic principles that can be applied into this kind of water shape, the flowing beauty of water and the sound beauty of water.

2. The flowing beauty and sound beauty of water

The flowing water in classical gardens mainly refers to creeks and waterfalls. The pool demonstrates the static beauty of water, while the creeks and waterfalls demonstrate the dynamic beauty of water. Also, the flowing creates the sound of water which can enhance the vitality of the gardens. These water sounds can create different psychological feelings. The beautiful sound of water can make people feel comfortable and allow them to forget their troubles.

Flowing water design needs to take advantage of the height difference between the water source and water surface to form a waterscape of waterfalls, and it combines with rocks to move the water. A good example of it can be seen in the Jichang Garden. The garden designer channeled spring water from Huishan Mountain to the garden and created a stream called the Baying Gully which means gully of eight musical tones. It is a stream of water falling from different heights on stones of different sizes, shapes, and densities. The gully gets its name because as the water strikes differently shaped holes in the rocks, it produces sounds reminiscent of musical instruments playing eight tones (Wang 2003).

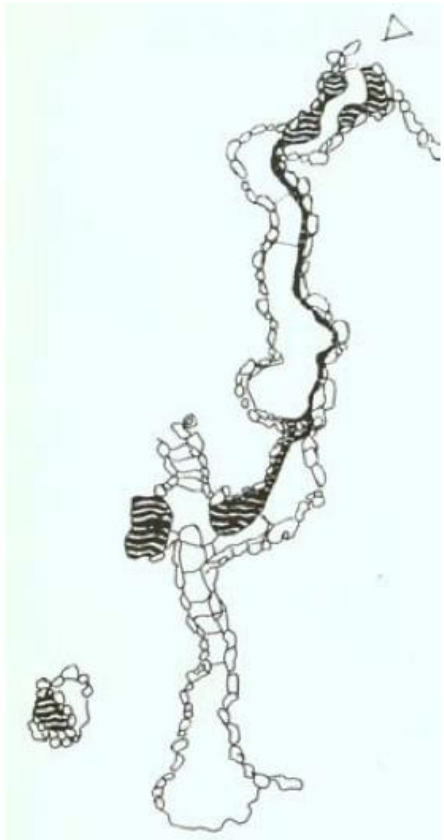
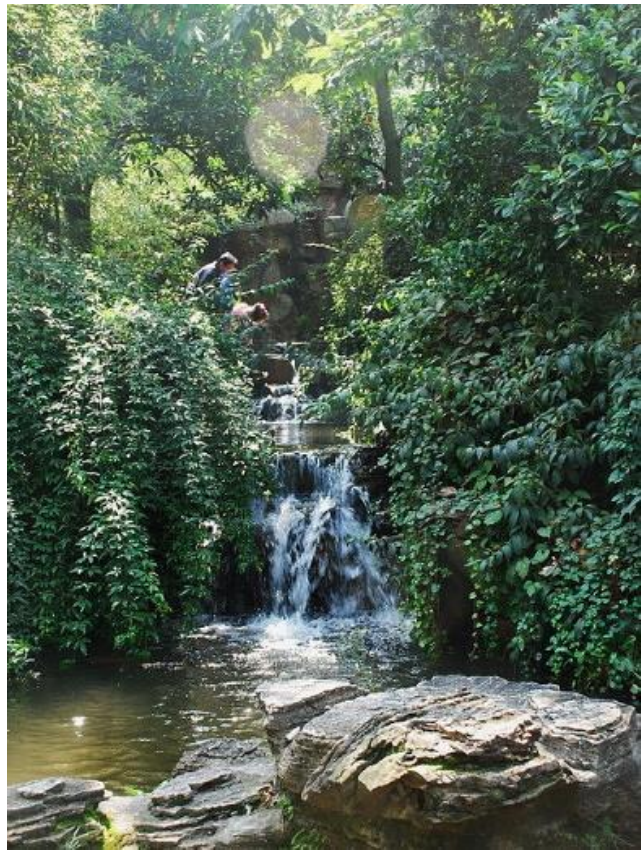
 

Figure 49: The plan of Baying Gully (left) (Wang 2003)

Figure 50: The photo of Baying Gully (right)

Source: http://blog.sina.com.cn/s/blog_5cea55900102wwcx.html

Another example is in Shizilin garden. It has a waterfall which uses the height difference between the water source and the water surface, and the rock to move the water in order to imitate the natural form of a water fall (Figure 51).

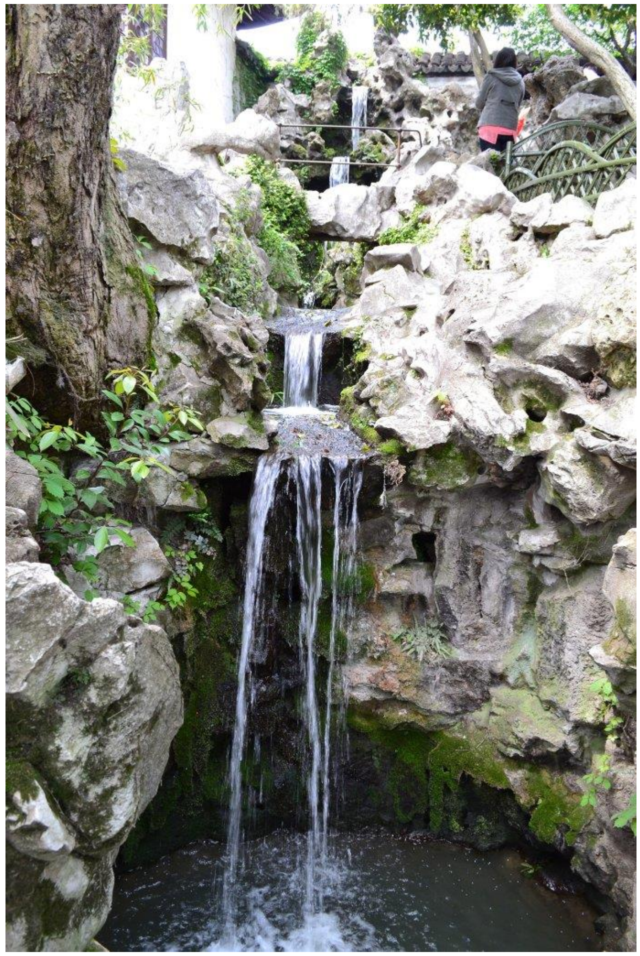


Figure 51: Photo of flowing water in Shizilin Garden

Source: http://blog.sina.com.cn/s/blog_5173c05d0101o2q4.html

3. The reflection beauty of water

In ancient times, landscape designers made good use of the reflection of water to introduce the surrounding trees, buildings, and artificial hills into the landscape. In this way, water can include the surrounding landscape, and then the water itself is displayed in the garden. However, reflection needs to have a big water surface area, which can limit its use in the design (Figure 52).

Figure 52: Photo of water reflection in Zhuozhengyuan Garden

Source: http://blog.sina.com.cn/s/blog_514248600102edse.html

According to the three aesthetic principles discussed above, a set of five design principles for water design in classical Suzhou gardens can be summarized as in the Table 11.

Table 11: Principles of water design in classical Suzhou garden designs (produced by author)

Aespect	Principles	Limitation
Basic concept	Get inspiration from the nature environment, imitate the nature water form	
Shape of Water	Pool: the shape needs to be twist and turn, the shape of the line is irrgular. Creek: change with height and plan, the shape also needs to be irrgular, and meander through the garden, to divert the visitor's line of vision. Geometric shapes are rarely used.	Pool needs bigger area than creek, but creek needs elevation change
Flow of Water	Use the elevation change between water source and water surface to create waterfall, it needs to combine with rocks to imitate the nature form of waterfall	Need to have elevation change between the water source and water surface
Sound of Water	Use the waterfall to create the sound of water, with different height and different materials can create different sound	Need waterfall to create sound
Reflection of Water	Use pool to reflect the surrounding landscape, like trees, buildings and the sky	The area of the pool needs to be big to reflect the surrounding

5.2.3 COLOR IN CLASSICAL SUZHOU GARDEN DESIGNS

The design of classical Suzhou gardens emphasizes achieving harmony between nature and humans, so the colors and textures in classical Suzhou garden designs mainly come from nature. Because buildings, artificial hills, water and plants are the four most important components in classical Suzhou gardens, the colors and textures in the garden are shown by their materials.

Figure 53: Photo of Huanxiushanzhuan Garden

Source: http://www.naic.org.cn/html/2017/gjfs_0715/6272.html

Figure 54: Photo of Liuyuan Garden

Source: http://lvyou.71lady.com/jqmt/2013102278468.html

From the two photos (Figure 53) (Figure 54), the color in classical Suzhou gardens can be extracted as the green of plants, the gray of stone, the white of the wall, and the dark gray of the roof. Those four colors constitute the foundation colors of classical Suzhou gardens (Jun-qiao 2011). A great example of extracting those four colors and applying it into modern garden design is Suzhou Museum designed by Ieoh Ming Pei. This museum is located in the historic area of Suzhou, close to Zhuozhengyuan Garden, and other famous classical gardens. The Museum uses white walls and dark gray roofs, combined with water in the center, plants in the garden, and artificial hills along the wall. This museum fits into the surrounding environment and reflects the cultural context (Figure 55) (Figure 56).

Figure 55: Photo of Suzhou Museum(Left) (ZHANG and Hang 2017)

Figure 56: Photo of artificial hill in Suzhou Museum(Right) (ZHANG and Hang 2017)

According to the three parts of classical Suzhou garden designs, a set of design principles for classical Suzhou gardens can be developed.

Table 12: Principles for classical Suzhou garden designs (Yang and Volkman 2010) (reproduced by author)

Aspect	Principles
Composition	Asymmetrical
Artificial hills	Used as sculpture in the garden, imitate the nature form
Building	Integrated with garden
Water	Naturalistic shape, get inspiration from natural pool, river and creek
Color	White, Gray, Dark gray, Green
Texture	Nature materials: stone, vegetables, water, and buildings

Artificial hill design and water design are two important parts in the classical garden design in Suzhou. The design principles of artificial hills and water are important not only to the classical garden designs, but also the modern landscape designs. Combined with the design principles for color, they can be useful to the thesis. Because Nanjing and Suzhou are in the same historic area, it can have reference value to the thesis. By learning from it, the design proposed in the thesis can be applied to Nanjing, reinforcing the historical context of the city.

5.2.4 INTEGRATE AESTHETIC DESIGN PRINCIPLES OF ARTFUL RAINWATER DESIGN WITH DESIGN PRINCIPLES OF CLASSICAL SUZHOU GARDEN DESIGNS

By comparing the aesthetic design principles of artful rainwater design and the design principles of classical Suzhou garden designs, it can be shown that there are some commonalities and also some differences (Table 13).

Table 13: Comparison of aesthetic design principles of artful rainwater design and the design principles of classical Suzhou garden design (table by author) (Echols and Pennypacker 2008)

Objectives Create	Aesthetic design principles of artful rainwater design		Aesthetic design principles of Classcial Suzhou Garden Design
Visual Interest	Point	Create water collection basin as a feature or focal point Create visual emphasis on stormwater direction change using scuppers, basins, cisterns, splash blocks.	Similar to the shape of water design in Classical Suzhou Garden Design, the scuppers and splash blocks can be replaced by artificial hills
	Line	Use downspouts, runnels, flumes, bioswales.	Similar to the shape of water design in Classical Suzhou Garden Design, but the shape of the line needs to mimic the nature form
	Plane	Stack horizontal and vertical planes such as pools and falls	Simliar to the shape of water design and the flow of water design in Classical Suzhou Garden Design
	Volume	Create visual interest or themes with basins that hold plants and water	Not mentioned, but it can be integrated into the artificial hill design
	Color/Texture	Contrast natural elements with artificial elements	Different from Classical Suzhou Garden Design. In Classical Suzhou Design, there is only natural elements used and only four kinds of color are mainly used.
	Axis	Create stormwater trails using axial runnels	Different from Classical Suzhou Garden Design, there's no clear axis in Classical Suzhou Garden.
	Rhythm/ Repetition	Create unified design themes by using multiple bioswales, or other rainwater focused props.	Not mentioned, but it can be integrated into the artificial hill design
Auditory Interest	Volume	Create a varity of volumes by allowing stormwater to fall from various heights onto different materials	Similar to the sound of water design in Classical Suzhou Garden Design
	Pitch	Create changes in pitch by allowing stormwater to fall on different forms such as flat blocks, metal tubes, drums, and ponds	Similar to the sound of water design in Classical Suzhou Garden Design
	Rhythm	Create different rhythms by varing the amount and rate of stormwater falling and flowing through treatment systems	Similar to the sound of water design in Classical Suzhou Garden Design
Tactile Interest	Texture	Use a varity of water-related plants and water-related hardscapes such as river pebbles and driftwood	Not mentioned, but it can be connected to Classical Suzhou Garden by using the texture in Classical Suzhou Garden Design.
	Wetness	Allow people to touch stormwater in different forms such as flowing, falling, splashing, standing, sheeting.	Not mentioned, but it can be used in Classical Suzhou Garden Design
Similar		Not Mentioned	Different

The table shows in green that most of the aesthetic design principles of artful rainwater design are similar to the principles of classical Suzhou garden designs and can be directly applied in Nanjing, China. However, there are still some differences in red that need to be changed or deleted in order to fit into the cultural context in Nanjing, China. Some artful rainwater design principles in yellow are not mentioned in classical Suzhou garden design, but they can still be connected to this design. According to the results of table 13, a set of artful design principles of rainwater harvesting systems for Nanjing, China can be developed (Table 14).

Table 14: Aesthetic design principles of artful rainwater harvesting systems for Nanjing, China (table by author)

Objectives Create	**Aesthetic design principles of artful rainwater harvesting system for Nanjing, China**	
Visual Interest	Point	Create water collection basin as a feature or focal point Create visual emphasis on stormwater direction change using artificial hills.
	Line	Use downspouts, runnels, flumes, bioswales to mimic the nature form of creek and streams.
	Plane	Stack horizontal and vertical planes such as pools and falls
	Volume	Create visual interest or themes with basins that hold plants and water
	Color/Texture	White, Gray, Dark Gray, Green. Natural elements
	Axis	No clear axis.
	Rhythm/ Repetition	Create unified design themes by using multiple bioswales, or other rainwater focused props.
Auditory Interest	Volume	Create a varity of volumes by allowing stormwater to fall from various heights onto different materials
	Pitch	Create changes in pitch by allowing stormwater to fall on different forms such as flat blocks, metal tubes, drums, and ponds
	Rhythm	Create different rhythms by varing the amount and rate of stormwater falling and flowing through treatment systems
Tacile Interest	Texture	Use a varity of water-related plants and water-related hardscapes such as river pebbles.
	Wetness	Allow people to touch stormwater in different forms such as flowing, falling, splashing, standing, sheeting.

5.3 INTEGRATE RAINWATER HARVESTING SYSTEMS WITH LID METHODS

The ability of rainwater harvesting systems to reduce stormwater runoff is constrained by the capacity of the cistern. In order to use rainwater harvesting systems to effectively mitigate the flooding issue in Nanjing, China, they should be integrated with low impact development (LID) methods to increase their ability to control stormwater at the source, to reduce runoff, and to improve water quality. According to the case studies discussed above, green roofs and bioretention swales can be fully integrated with rainwater harvesting systems to help reduce the stormwater runoff. This chapter will analyze the two LID methods.

5.3.1 GREEN ROOF

Overview:

A green roof is a vegetated roof system designed to capture, temporarily store, and evaporate rainwater on the top of roofs, which is a key LID method and is being increasingly recognized for its "valuable ability to absorb, reduce, and delay stormwater from reaching sewers or other grey infrastructure systems," says Richard Hayden, the garden roof product manager with the Chicago based American Hydrotech. (Brzozowski, 2016)

Green roofs can be divided into two categories: an intensive green roof and an extensive green roof. The planting medium depths of an intensive green roof should be greater than 6 inches in which any type of vegetation may grow, from lawn and groundcover to shrubs and trees. An intensive green roof is accessible to people and can serve as recreation space for the public (Figure 57). However, it is more costly than extensive green roofs and would require irrigation, fertilization, and maintenance (Ngan 2004).

The planting medium depth of extensive green roofs is usually 3-6 inches, which limit the plants to mosses, succulents, herbaceous plants, and grasses (Figure 58). They have the ability to maintain themselves over long periods of time, and are able to withstand the harsh conditions of cold, heat, drought and wind (Ngan 2004). Extensive green roofs are often not accessible to the public, and they have less maintenance. Extensive green roofs are much cheaper when compared with intensive green roofs (Ngan 2004).

Figure 57: Intensive green roof (Left) (Ngan 2004)

Figure 58: Extensive green roof (Right) (Ngan 2004)

The two types of green roofs require specific layers of roofing materials not found on regular roofs. Each of these layers performs a specific function to keep the plants alive and to protect the structure beneath (Figure 59).

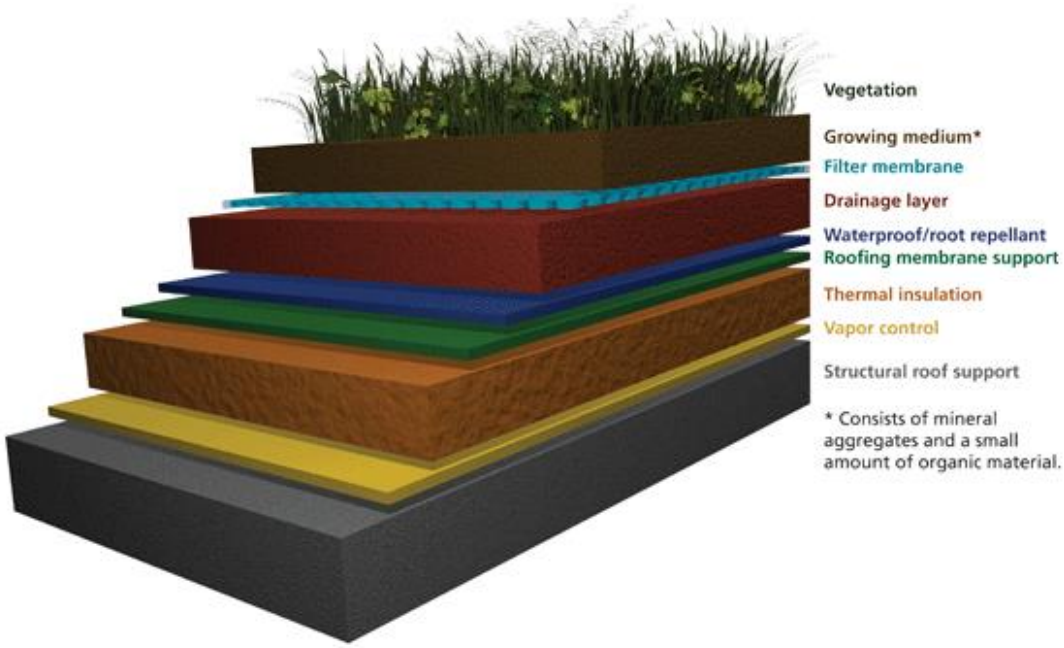


Figure 59: Green roof section

Source: https://www.nps.gov/tps/sustainability/new-technology/green-roofs/define.html

Benefits:

The most important benefit of green roofs is their ability to help control the stormwater in urban areas. Rainwater is first retained in the green roof components where a portion of it evaporates and is absorbed by the plants thereby reducing stormwater volumes. Then the extra portion is delayed in its release. Therefore, green roofs can help reduce the peak flow of a rainfall event which causes storm overflow and pollution, as well as floods. They can also absorb and infiltrate pollutants. Other benefits of green roofs would be their ability to neutralize the urban heat island effect because they can reduce impervious surfaces in urban areas, which cause temperatures to rise; it can also cool the air through the processes of evaporation to keep the rooms beneath the roof cooler. Thus, it can reduce the need for air conditioning which reduces energy use, major contribute to climate change (Ngan 2004).

Green roofs not only have ecological benefits, but also have social benefits. Intensive green roofs are accessible to the building's occupants so that it can provide an aesthetically-pleasing space for meetings or recreation without taking up valuable ground space.

5.3.2 BIORETENTION

Overview:

Bioretention is a best management practice developed in the early 1990's by the Prince George's County, MD, Department of Environmental Resources (PGDER) (EPA 1999). Bioretention is a terrestrial-based, water quality, and water quantity control practice using the chemical, biological, and physical properties of plants, microbes, and soils for removal of pollutants from stormwater runoff (County 2002).

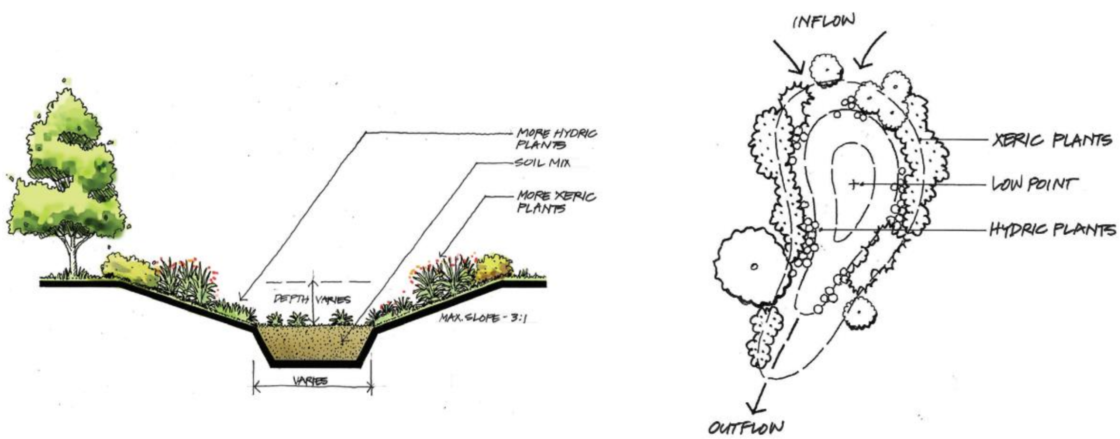


Figure 60: Depiction of typical bioretention area (Clark and Acomb 2008)

Bioretention typically treats storm water that has run over impervious surfaces at commercial, residential, and industrial areas (EPA 1999). It can be designed into different forms to fit into the site and manage the rainwater efficiently (Figure 60). For example, it can be designed into planters can collect storm water runoff from parking areas or sidewalks. The planter can capture runoff from the impervious surface via curb cuts and then filter water as it drains through the soil. Bioretention areas also provide an opportunity to bring vegetation to beautify the area (Figure 61) (Figure 62).

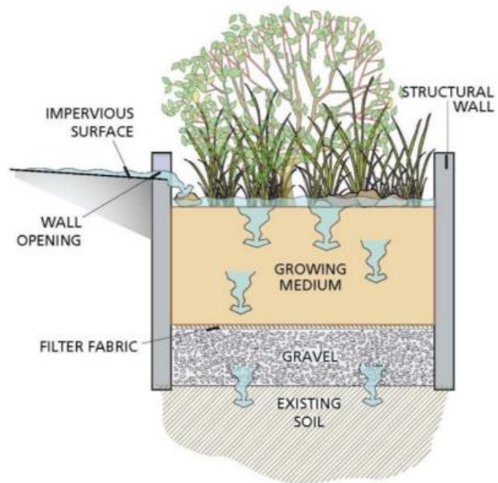


Figure 61: Portland State University street planters (Left) (Courtesy of Martina Keefe)

Figure 62: Section of bioretention planter (Right) (Source: Portland Bureau of Environmental Services)

A rain garden is a kind of bioretention device. It is a planted shallow depression that collects rainwater runoff from roofs, parking lots, and other impervious surfaces. While a rain garden can blend into the landscape and serve as a garden area, its main function is to retain and treat collected rainwater (Figure 63).

Figure 63: Photo of rain garden

Source: http://sunnyside-gardens.com/2008/11/planning-and-planting-a-rain-garden-in-minnesota/

Benefits:

Bioretention provides storm water treatment by using vegetation in retention areas to reduce nutrient export through plant uptake, filtering, and absorption. In the process, rainwater can be captured and retained, and then the stormwater runoff can be reduced. Also, it can increase biodiversity in the site with wildlife and provide aesthetic values (Clark and Acomb 2008).

5.3.3 HOW TO INTEGRATE LID METHODS WITH RAINWATER HARVESTING SYSTEMS

A rainwater harvesting system is a decentralized technique of collecting and storing rainwater for later use at or near the point where water is needed. (Maksimović, Kurian, and Ardakanian 2015). A typical rainwater harvesting system typically consists of a catchment area on which the rain falls; gutters and downspouts to collect rainwater from the catchment area and transfer it to the storage system; storage tanks or cisterns to store the rainwater; a filtering system to remove debris, solids and other materials; and, a distribution system to convey rainwater for future use (Maksimović, Kurian, and Ardakanian 2015) (Figure 64).

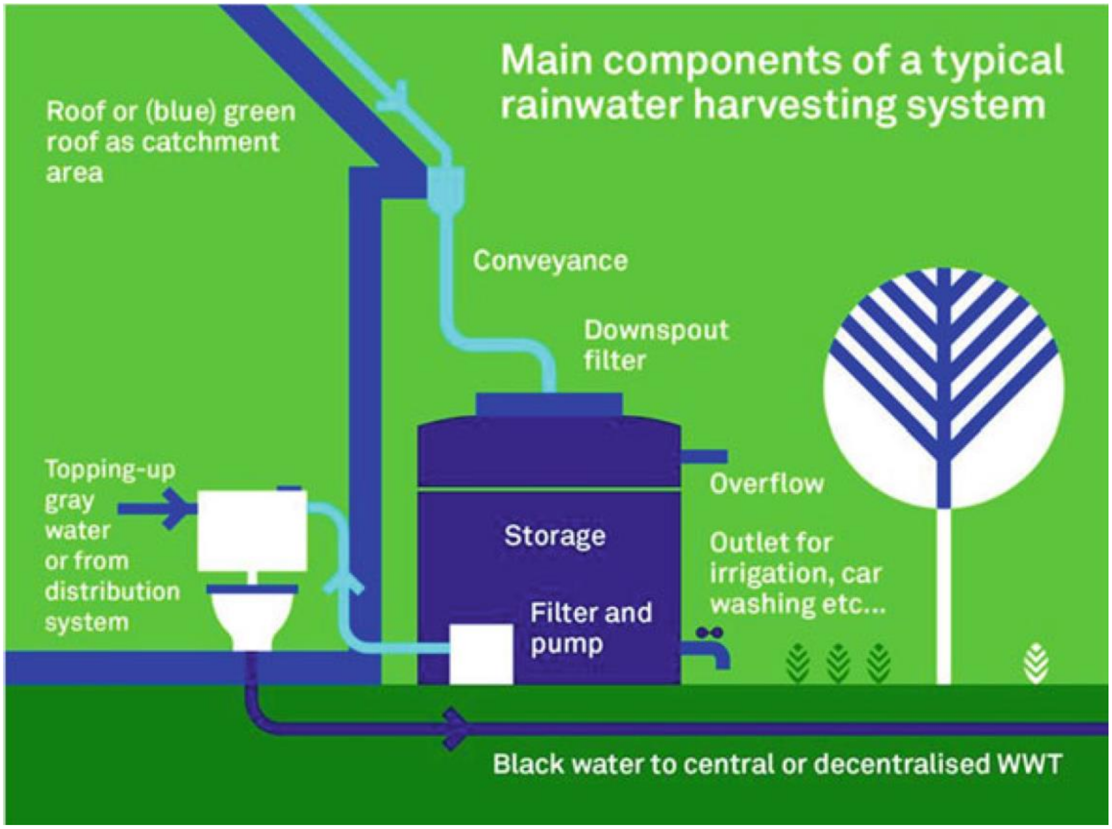


Figure 64: Components of a typical rainwater harvesting system (Maksimović, Kurian, and Ardakanian 2015)

The capacity of a rainwater harvesting system to reduce stormwater runoff is limited by the size of the storage cistern, while the size of the storage cistern is limited by the area of the open space in the site. In order to break the limitation, a rainwater harvesting system can be integrated with LID methods, like green roofs and bioretention devices to increase its ability to reduce stormwater runoff.

Green roofs can be used in the catchment area of rainwater harvesting systems, in which rainwater would be retained and absorbed by the green roof. In small rainfall events, all the rainwater would be retained in the green roof; in large rainfall events, the excess rainwater would flow through the downspouts and be collected in the cistern. A great example is Potsdamer Platz in Berlin, Germany (Figure 65).

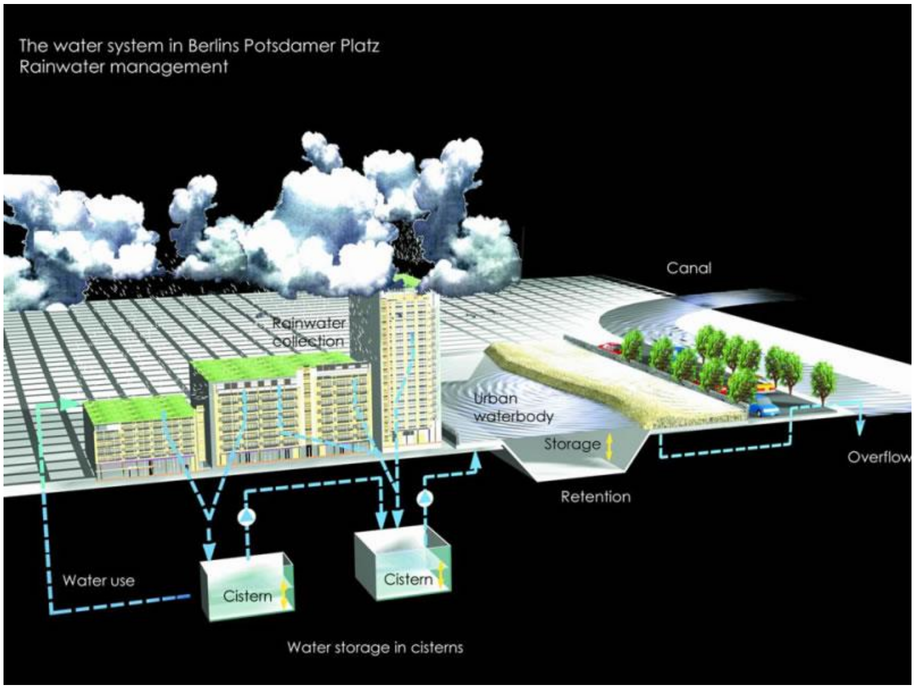


Figure 65: The rainwater harvesting system in Potsdamer Platz (courtesy of Atelier Dreiseitl)

Bioretention can be integrated with rainwater harvesting systems which use underground cisterns. It can function just like a green roof, but in a different part of the rainwater harvesting system. Installed between the downspouts and the cistern, bioretention can help infiltrate rainwater and be absorbed by the plants, then the excess water flows into the underground cistern. An excellent example is at Stephen Epler Hall at Portland State University, Portland, Oregon (Figure 66) (Echols and Pennypacker 2015).

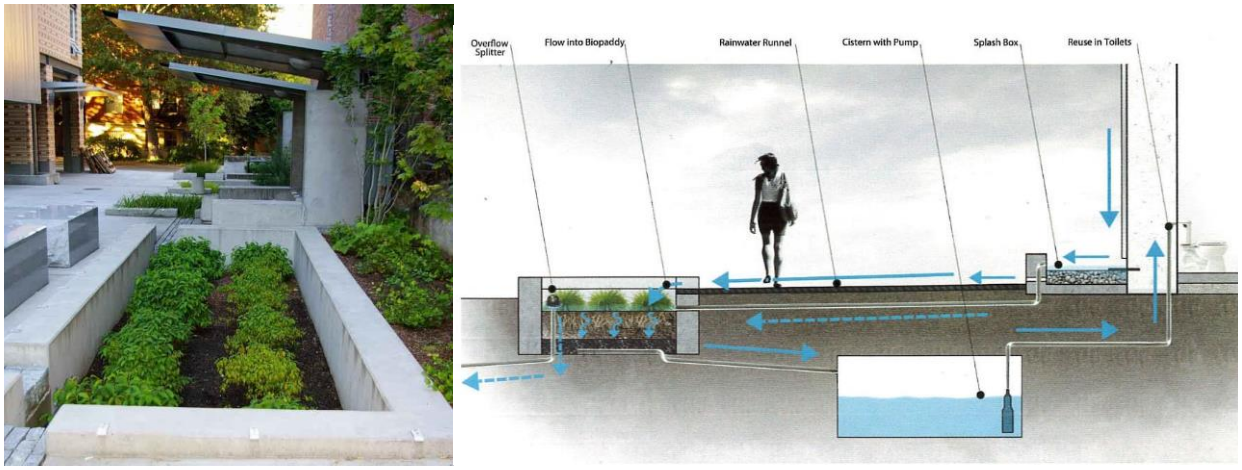


Figure 66: The four bio-paddies in Stephen Epler Hall (Echols and Pennypacker 2015)

The two LID methods discussed above can be integrated with rainwater harvesting systems to help increase their ability to reduce the stormwater runoff.

CHAPTER 6

PRACTICAL APPLICATIONS OF ARTFUL RAINWATER HARVESTING SYSTEMS IN NANJING, CHINA

6.1 REGIONAL ANALYSIS

Nanjing, the capital city of Jiangsu province, is located in the Yangtze River delta (Figure 67). The administrative area of the total area of Nanjing is 6597 km^2 (2547,12 square mile). The population of Nanjing in 2016 was 8.27 million. Nanjing has been rapidly urbanizing in recent years, and its level of urbanization in 2013 had reached 83%. (Level of urbanization describes the proportion of urban population to the total population of the city, including agriculture and non-agriculture population).

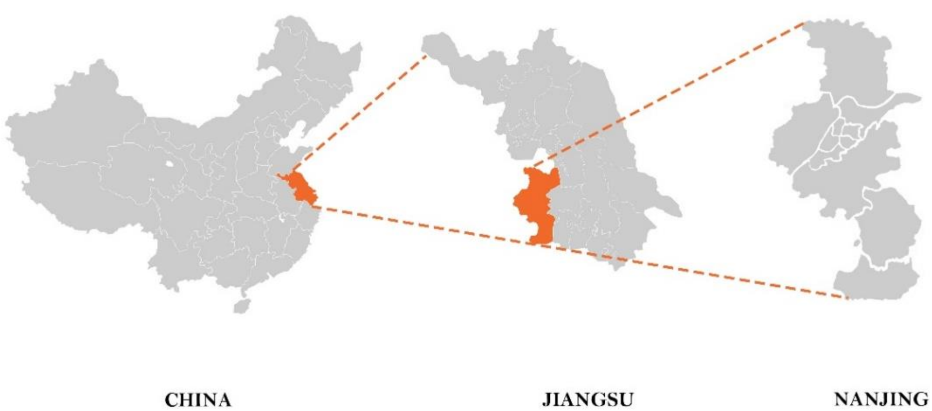


Figure 67：Location of Nanjing (diagram by author)

Under the humid climate conditions, its average annual rainfall is about 1,052 mm. However, rainfall in dry years is far lower than that in rainy years, e.g. the annual rainfall in 1978 was only 535 mm which is about 51 % of the average annual rainfall (Zhang et al. 2012) (Figure 68).

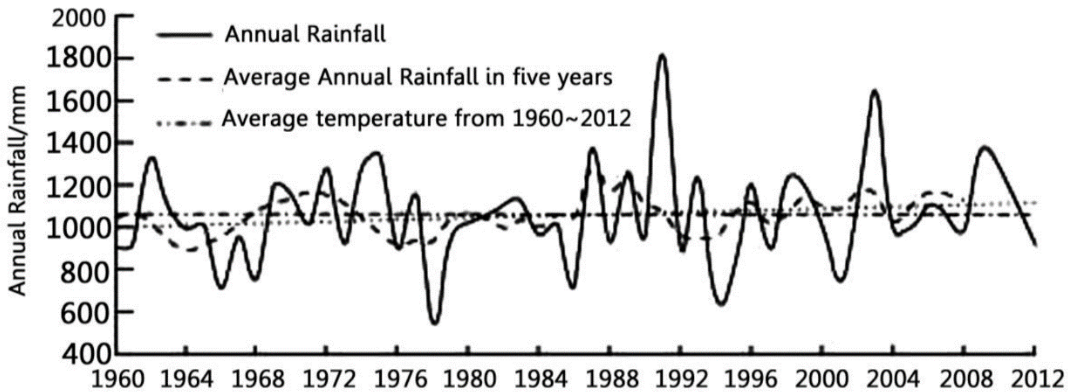


Figure 68: Illustration of annual precipitation from 1960-2012 (Deng et al.2014)

Daily rainfall data (1951–2008) was obtained from the Nanjing Weather Station. Table 15 and Table 16 show the average monthly rainfall and the average monthly rainfall days of different daily rainfalls, respectively. According to the tables, it can be observed that rainfall from February to November accounted for 94 % of the annual rainfall. Rainfall in January and December was much lower than in the other months, and the rainfall days of the different daily rainfall in those two months were also the lowest. The average annual maximum daily rainfall was 95.5 mm, and the maximum daily rainfall was 207.2 mm (Zhang et al. 2012).

Table 15: Average monthly rainfall during the period of 1951–2008(Zhang et al. 2012)

Month	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
Rainfall (mm)	38.5	49.4	75.9	85.5	96.4	168.6	191.6	128.7	82.4	54.1	51.7	28.7

Table 16: Average monthly rainfall days of the different daily rainfall(Zhang et al. 2012)

Month	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
Days of daily rainfall >2 mm	4.5	5.4	6.8	6.5	6.3	7.2	7.9	6.9	5.2	4.5	4.7	3.2
Days of daily rainfall >5 mm	2.5	3.6	4.9	4.4	4.6	5.7	6.3	5.1	3.5	2.9	2.9	1.9
Days of daily rainfall >10 mm	1.2	1.6	2.6	3.0	3.0	4.2	4.8	3.6	2.3	1.7	1.6	0.9

Due to the rapid acceleration of the urbanization process in Nanjing, the city's impervious area has increased remarkably which has weakened the rainwater infiltration capability of the city (Yang 2017). The existing drainage system is not sized to handle the increased runoff from large storms, causing flooding problems to increase.

On the other hand, although Nanjing is near the Yangtze River, the local water resource is still insufficient. Because of the economic growth, the growth of population, and the sharp rise of pollution in the area, Nanjing is facing a water shortage (Zhang et al. 2012).

Rainwater harvesting systems are an appropriate way to help mitigate the flooding problem in Nanjing, which cannot only help reduce the stormwater runoff volume but can also collect rainwater to help mitigate the water shortage problem.

6.2 GENERAL SITE INFORMATION

Shazhou Cun is a typical “village in the city” located in the Jianye district in Nanjing. It is an old residential area built in the 1970s, with the area of the site about 2.44 acres (Figure 69). The elevation of the site is lower than the surrounding area, and because of old facilities and an insufficient sewer system, there are many flooding problems. In addition, this is a high density residential area, and unlike other newly built residential areas which have lots of open space to apply LID methods, the best to way to mitigate the flooding problem in this area which is mostly impervious, is to use a rainwater harvesting system combined with limited LID methods to help reduce the stormwater runoff.

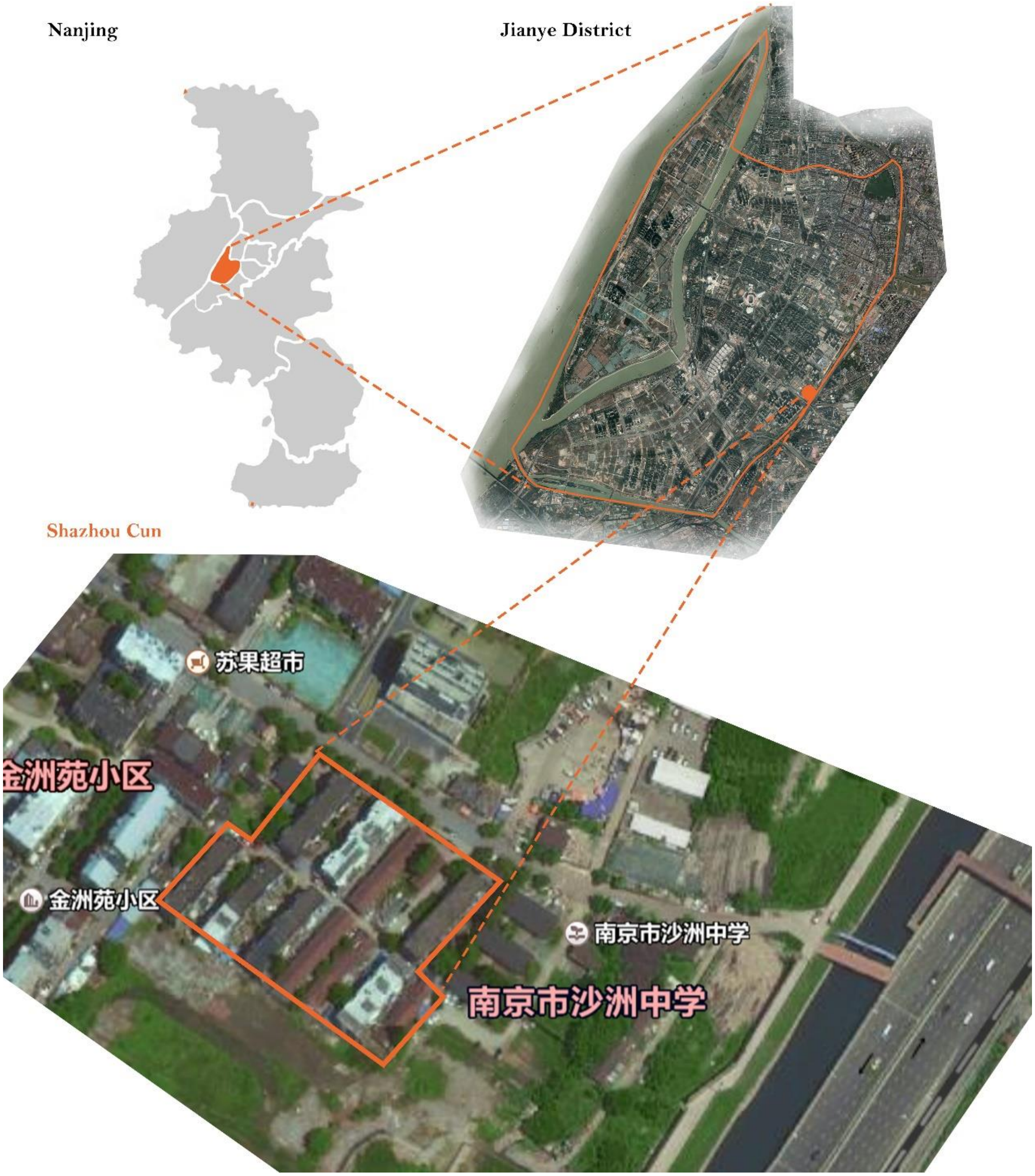


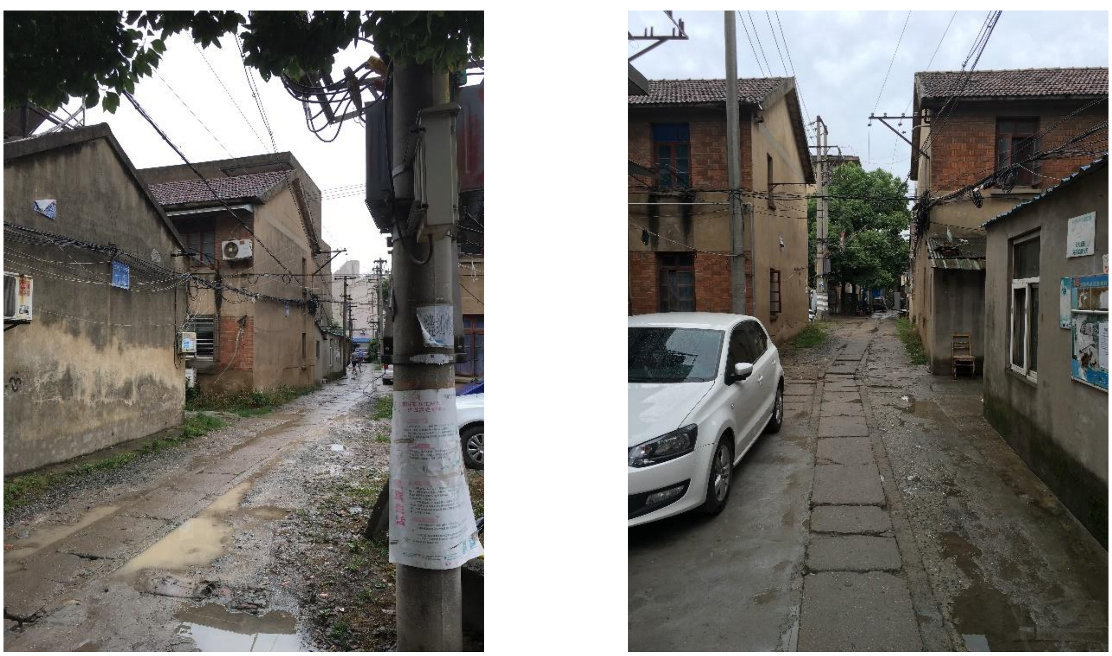
Figure 69: Location of the site (diagrammed by author)

There are 13 buildings in this site: seven of them are four-story buildings, two of them are two-story buildings, and the other four are one-story buildings (Figure 73). The roofs of the seven four-story buildings are flat, and the roofs of the other five buildings are sloped. The current ground condition of the site is chaotic; bikes and cars park in this area without any order and the only public space of this area has become a place to dry clothes (Figure 70). The road is bumpy and badly damaged.

Figure 70: Photo of the site (photo by author)

Almost all of the site is impervious surface, with only 1.2% green space (Table 17). The green space is only in raised planters, which do little to reduce stormwater runoff (Figure 71). The main public alley is in the middle of the site between the two rows of buildings. The residents need to walk through this public alley to get into their apartment (Figure 72). The entire site is enclosed by walls and adjacent building walls.

Figure 71: Elevated planter (photo by author)



Northwest View *Southeast View*

Figure 72: Two views of the public alley (photo by author)

Table 17: Area of different land covers in the site (table by author)

Type	Area	Unit	Percentage
Green Space	1300.28	sq ft	1.22%
Unpaved Area	1252.49	sq ft	1.18%
Impervious	63174.44	sq ft	59.55%
Roof area	40350.99	sq ft	38.05%
Total	106078.2	sq ft	100%

Figure 73: Shazhou Cun general site information map (produced by author)

Figure 74: Overview of the site (produced by author)

6.3 CISTERN PLACEMENT AND SIZE SUGGESTIONS

In Figure 76, placement for various cisterns is proposed. The principle for placing cisterns is to identify open space that would not be used by pedestrians and cars, and that is as near the catchment area as possible. For an above ground cistern, it should be placed where the surrounding area can be graded to provide good drainage of surface water away from the cistern to keep it from being submerged. For a large size cistern, it can be placed underground to save space for other uses. Figure 75 shows the site circulation. There is not a specific parking area in the site; cars park chaotically along the pedestrian path, so it is also necessary to propose parking spaces in the site.

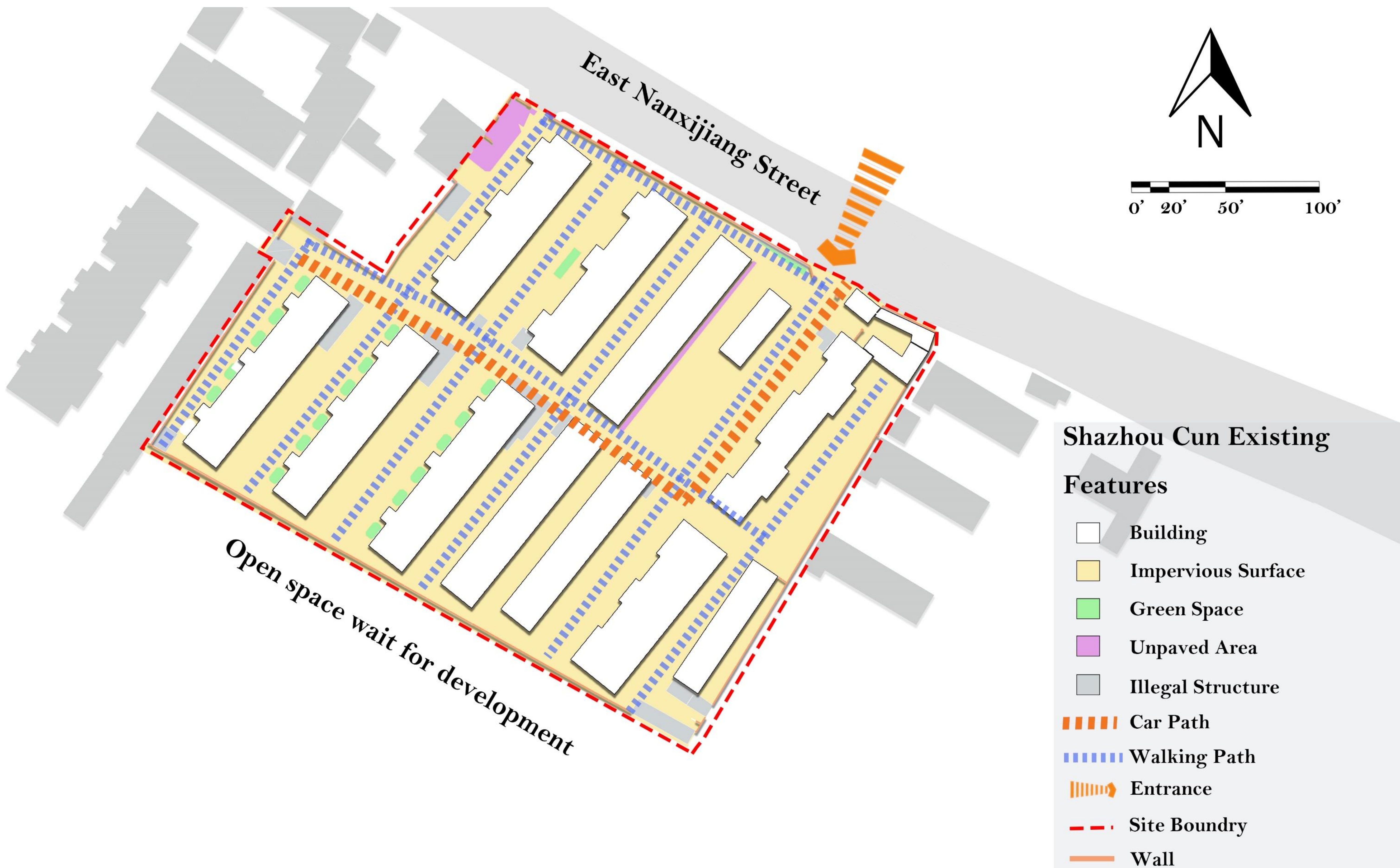
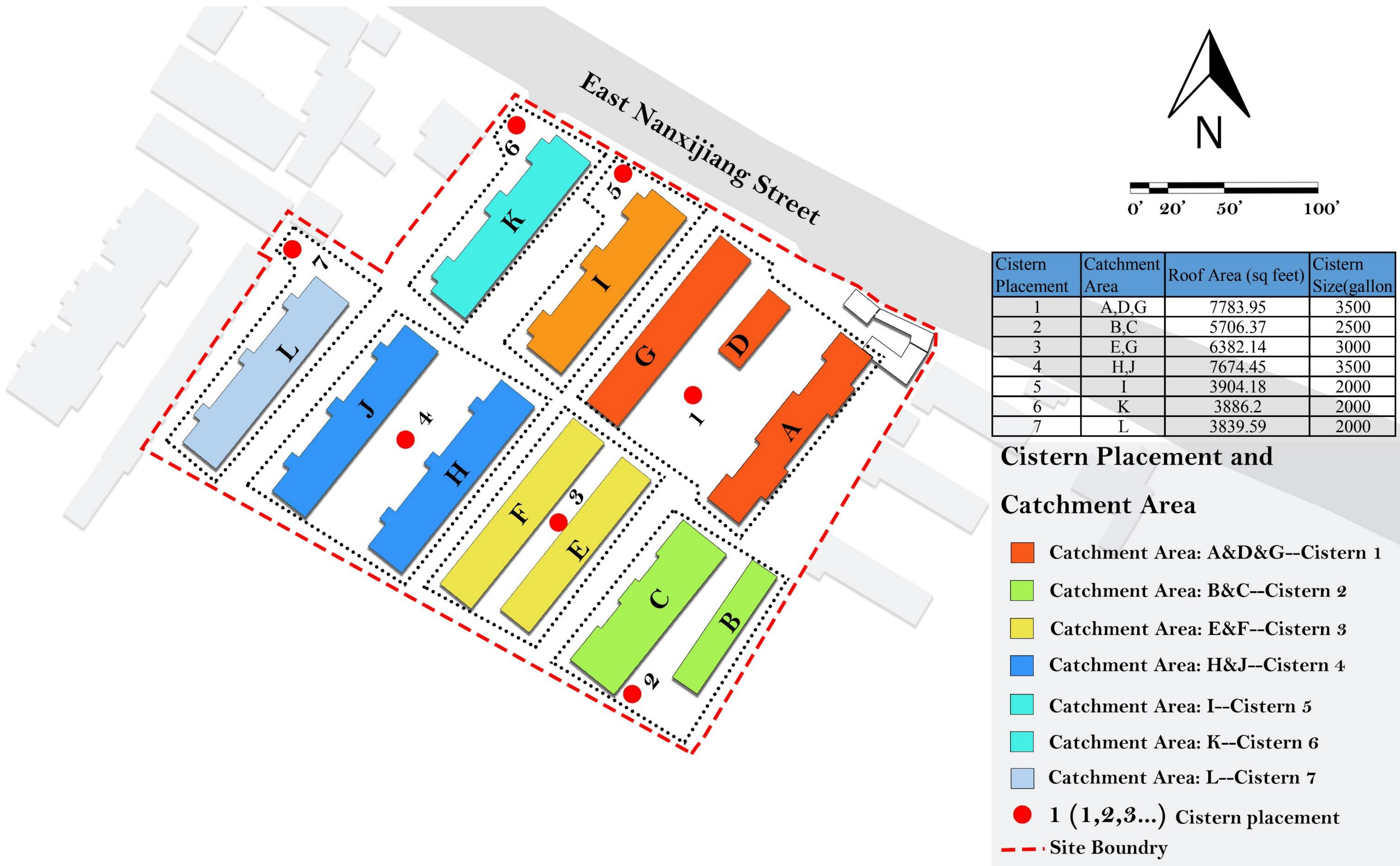


Figure 75: Path analysis (produced by author)



Cistern Placement	Catchment Area	Roof Area (sq feet)	Cistern Size(gallon
1	A,D,G	7783.95	3500
2	B,C	5706.37	2500
3	E,G	6382.14	3000
4	H,J	7674.45	3500
5	I	3904.18	2000
6	K	3886.2	2000
7	L	3839.59	2000

Figure 76: Placement for various cisterns (produced by author)

In sizing cisterns for this site, the catchment area and the rainfall depth should be the factors to determine the cistern size. The water quality amount is a key factor in designing the stormwater quality enhancement facilities (Yang 2017). Rainwater harvesting systems can not only help reduce the stormwater runoff, but they can also help improve stormwater quality by storing and purifying it, so it is appropriate to use water quality volume to size the rainwater cistern. In 1996, Guo implemented the standard for intercepting and treating all of the runoff from 85% of storms that occur within an average year (Yang 2017). Based on his study, Guo recommends simple optimization techniques to capture 82 to 88% of runoff volumes or events generated from the tributary watershed (Yang 2017) (Guo 1996).

This design proposes using the 85% as a standard for Nanjing. To get the data of 85% of Nanjing storms, a table below shows 10 years of Nanjing's daily precipitation data (Figure 76). From this table, we can see that 85% of Nanjing rainfall is 0.81 inches or less.

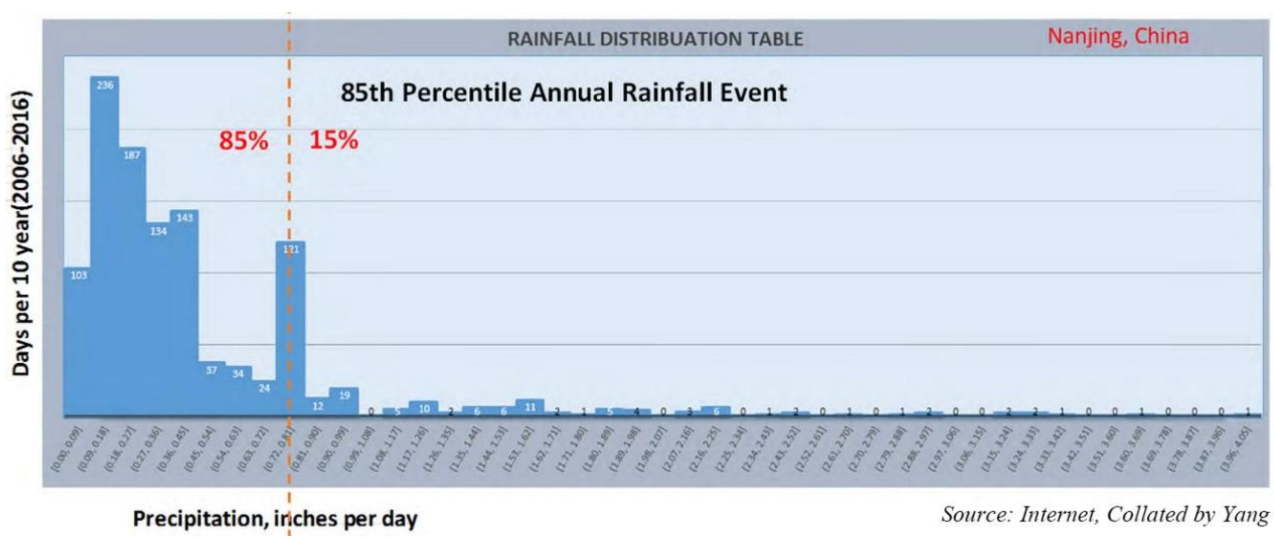


Figure 77: Rainfall distribution table of Nanjing, China (Yang 2017)

In this way, the cistern would be designed to attempt to save the 0.81 inches of rainfall, according to the Water Quality Volume formula (Urbona 1998). The Water Quality Volume formula for Nanjing could be developed as in Figure 78:

$$\text{WQv (ac-ft.)} = \frac{0.81 \times R_v \times A}{12}$$

Where: 0.81" is the 85th percentile rainfall

R_v is the volumetric runoff coefficient,

R_v = 0.05 + 0.009(I)

I = Imperviousness in %

A is the watershed area in acres

12 converts inches to feet

Figure 78: The Water Quality Volume formula for Nanjing, China (Yang 2017), from (Urbona 1998)

According to the Water Quality Volume formula for Nanjing, the WQv of the site can be calculated: WQv (acre-feet) =A*0.81*(0.05+0.009*97.6)/12=0.153 acre-feet=50232.78 gallon.

The formula for sizing the cistern could be expressed as: Cistern size (gallon) = Watershed Area (square feet) * 0.81 (85th percentile rainfall) (inch) * 0.623 (gallon conversion)* 0.85 (collection efficiency) (Krishna et al. 2005). Table 18 gives the cistern size based on the formula discussed above.

Table 18: Cistern size based on 0.81-inch harvest in gallons (produced by author)

Cistern Placement	Catchment Area	Roof Area (sq feet)	Cistern size caculation	Cistern Size(gallon)
1	A,D,G	7783.95	7783.95*0.81*0.623*0.85=3338.81	3500
2	B,C	5706.37	5706.37*0.81*0.623*0.85=2447.66	2500
3	E,G	6382.14	6382.14*0.81*0.623*0.85=2737.53	3000
4	H,J	7674.45	7674.45*0.81*0.623*0.85=3291.84	3500
5	I	3904.18	3904.18*0.81*0.623*0.85=1674.64	2000
6	K	3886.2	3886.20*0.81*0.623*0.85=1666.93	2000
7	L	3839.59	3839.59*0.81*0.623*0.85=1646.94	2000
Total			18,500	

According to The Standard of Water Quality for City's Residential Use (GB/T50331-2002), per capita use of toilet flushing would be 40 L/day. Because of the Chinese family planning policy, one family can only have one child, so it can be assumed that three residents live in each unit. Thus, according to the units in each building, the number of residents who live in each building can be calculated.

For example, in the catchment area of buildings A, D and G, there are 48 units in these three buildings, so we assume there are 144 residents who live in these three buildings. The daily water demand for toilet flushing would be 144*40=5760 L=5760 L/3.79=1519.79 gallon. It can be calculated that the cistern would be empty in three days, when it is full. In the same way, all the cisterns' days to empty can be calculated in the following table 19:

Table 19: Cisterns: number of days to empty (produced by author)

Cistern Placement	Catchment Area	Cistern Size(gallon)	Units	Water Demand (gallon)	Days to Empty
1	A,D,G	3500	48	48*3*40/3.79=1519.79	3
2	B,C	2500	30	30*3*40/3.79=949.87	3
3	E,G	3000	24	24*3*40/3.79=759.89	4
4	H,J	3500	48	48*3*40/3.79=1519.79	3
5	I	2000	24	24*3*40/3.79=759.89	3
6	K	2000	24	24*3*40/3.79=759.89	3
7	L	2000	24	24*3*40/3.79=759.89	3

6.4 GREEN ROOFS AND BIORETENTION

Figure 79 designates the proposed green roofs and bioretention planters. The green roofs and bioretention planters could be used as infiltration facilities before rainwater flows into the cistern. Then ultraviolet LED light disinfection technology in the cistern would clean the rainwater. Green roofs could be used as infiltration facilities for both above ground cisterns and underground cisterns. Bioretention could only be used as infiltration facilities for the underground cisterns, but it could also be used to capture the excess water from the above ground cisterns in large rainfall events.

Green roofs would be proposed on flat roofs, like buildings F, E, G, H, I (Figure 79). Those green roofs would be a typical light-weight extensive green roof, the plants for the green roof should be native low-maintenance plants that could thrive in hot, dry, sunny conditions, like Chinese sedum (Sedum tetractinum) and Sheep fescue (Festuca ovina). All the downspouts for the green roof would overflow into the rainwater cistern. The bioretention would be used in an open space to infiltrate rainwater before it flows into the underground cistern, and also it would be used among the above ground cisterns to infiltrate the excess water into the earth. The existing elevated planting areas would be retrofitted into bioretention planters to help reduce the stormwater runoff.

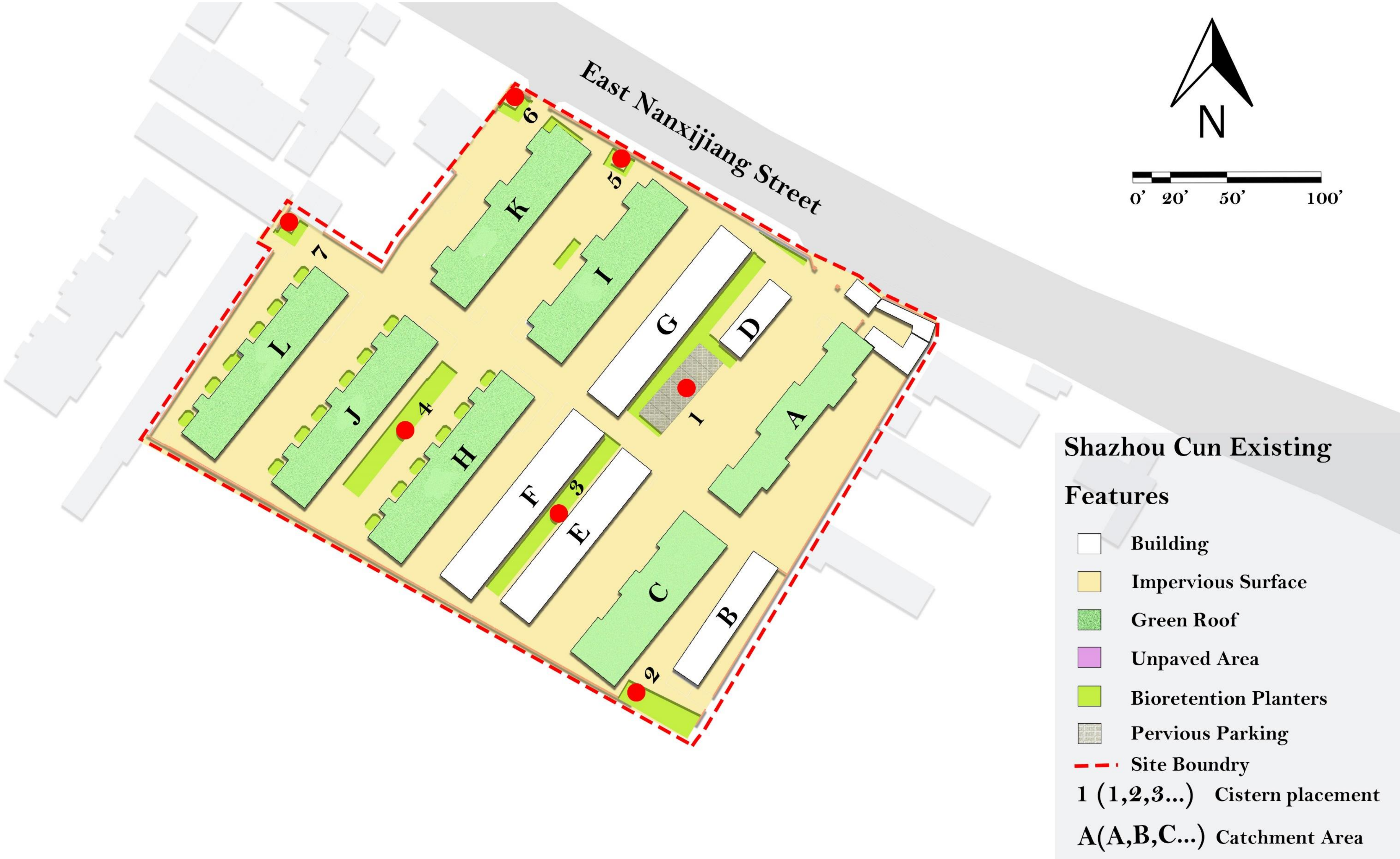


Figure 79: Proposed green roof and bioretention planters (produced by author)

To find out the how much rainwater could be treated by the green roof and bioretention planters, we could subtract a WQv of the green roof or bioretention planter from the WQv of current impervious surface or impervious roof. Using a runoff coefficient of 0.4, which is a typical runoff coefficient for six-inch-deep green roof (Ngan 2004), and using a runoff coefficient of 0.05 for an infiltration-based planter (Thong 2011), Table 20 shows the total volume of rainwater that would be treated by using the rainwater harvesting system combined with green roofs and bioretention planters, as well as the volume of rainwater would be treated by using a traditional rainwater harvesting system.

Table 20: Total volume of rainwater that would be treated by the two kinds of rainwater harvesting systems (produced by author)

	Discription	Area (sq feet)	WQv(gallon) before design	WQv (gallon) after design	Storage (gallon)
Site	Before design	106078.2	A*0.9384*0.81*0.623=50232.78		
Green Roof	Where coefficient =0.4	26704.07	A*0.95*0.81*0.623 =12801.89	A*0.4*0.81*0.623 =5390.27	12801.89-5390.27=7411.62
Bioretention Planter	Where coefficient =0.05	6219.42	A*0.95*0.81*0.623 =2981.58	A*0.05*0.81*0.623 =156.93	2981.58-156.93=2824.65
Cisterns	Total volume of Cisterns				18500
Total runoff reduced	Rainwater harvesting system with green roof and bioretention planter	28736.27/50232.78=**57.21%**			28736.27
Total runoff reduced	Only rainwater harvesting system	18500/50232.78=**36.83%**			18500

From Table 20, we can see that the rainwater harvesting system combined with green roofs and bioretention planters can help treat: 57.21%-36.83%=20.38% more rainwater than the traditional rainwater harvesting system.

6.5 APPLICATION OF ARTFUL RAINWATER HARVESTING DESIGNS IN THE SITE

To increase user acceptance of the rainwater harvesting system on the site, it is important to show how the design can use the design principles developed for artful rainwater harvesting systems in Nanjing, China. In the following design, five demonstration locations would be selected to implement artful design. The following images and graphics intend to demonstrate its implementation. Other two rainwater harvesting systems in location 2 and location 3, are not selected, because these two locations are not highly visible to the public, so the artful design here won't get much public attention as the other locations.

Location 1: Buildings A&D&G:

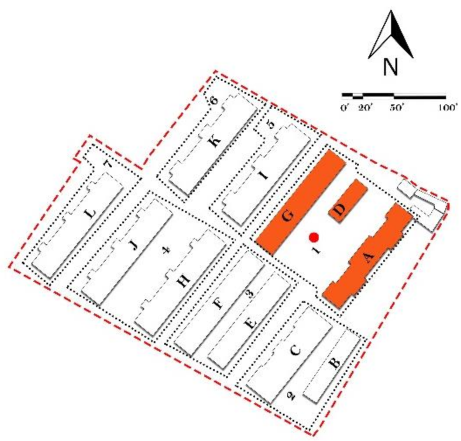


Figure 80：Map of location 1 (produced by author)

With inspiration from Stephen Epler Hall, the rainwater harvesting system can be combined with bioretention planters in location 1. The rainwater would be transfered from the rooftops through downspouts to the bioretention planters; the bioretention planters would infiltrate and absorb the rainwater first, then the rest of the rainwater would flow into a 3500-gallon underground cistern, to be reused in the building to flush the toilets (Figure 81).

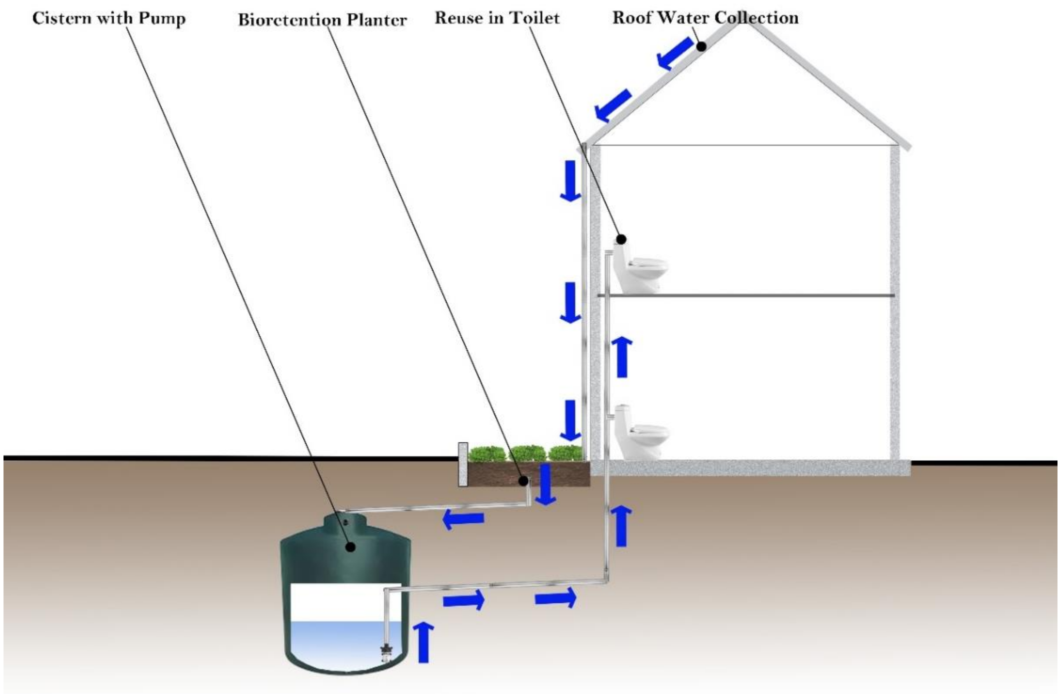


Figure 81: Section of the rainwater harvesting system (produced by author)

The proposed design (Figures 82-85) uses two aesthetic design principles of artful rainwater harvesting system design: 1. Create a point of visual interest by using artificial hills to change the stormwater direction. 2. Create auditory interest by allowing stormwater to fall from various heights onto different materials. The artificial hill can convey rainwater into the bioretention planter, while creating the sound of water flowing to attract people's attention, and letting people know how rainwater is collected in the site (Figure 85). Because it is at the entrance area of the site, everyone who enters the site can see it, so it is a good way to celebrate rainwater. To follow the design principle of color in the classical Suzhou garden design, the design proposes to paint the building gray. To solve the parking problem in the site, the design proposes to retrofit the open space at the entrance area into pervious parking (Figure 83).

Figure 82: The area before the design (photo by author)

Figure 83: Pervious parking and bioretention planters (produced by author)

Figure 84: The area before the design (photo by author)

Figure 85: Artful rainwater harvesting integrated with the pavilion hill (produced by author)

Location 4: Buildings H&J

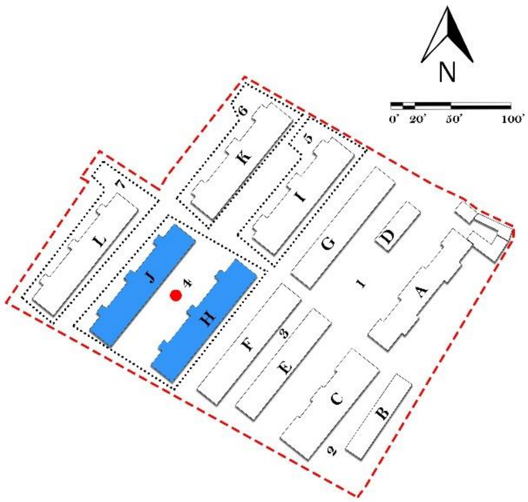


Figure 86: Map of location 4 (produced by author)

There is an alley between building H and building J, and the width of the path is about 36 feet, but the residents who live in the first floor of building J occupy about 12 feet of width for some flowers and trees (Figure 87). Because those plants live in the flower pots, they cannot do much to help reduce stormwater runoff. So, the design proposes a bioretention planter to help reduce stormwater runoff in the center of the alley, where residents can put their flowers and trees inside the planter. The existing raised planters are on the first floor of building H, and those raised planters also can't do much to help reduce stormwater runoff, so the design proposes to change the raised planters into bioretention planters (Figure 88).

Figure 87: Residents' small "garden" (photo by author)

Figure 88: Raised planters (photo by author)

Because the roofs of the two buildings are flat, green roofs can be put on the old roofs. Also, structural analysis should be performed to confirm design suitability. The rainwater would first fall on the green roof, then infiltrate and be absorbed by the green roof. Next, the excess rainwater would flow through the downspouts into the bioretention planters on the first floor, the rainwater would flow through the runnels on the ground into the bioretention planters in the center of the alley, the rainwater would be infiltrated and absorbed by the bioretention planter, and finally, the excess water would flow into the underground cistern and then be reused in the building for toilet flushing (Figure 89).

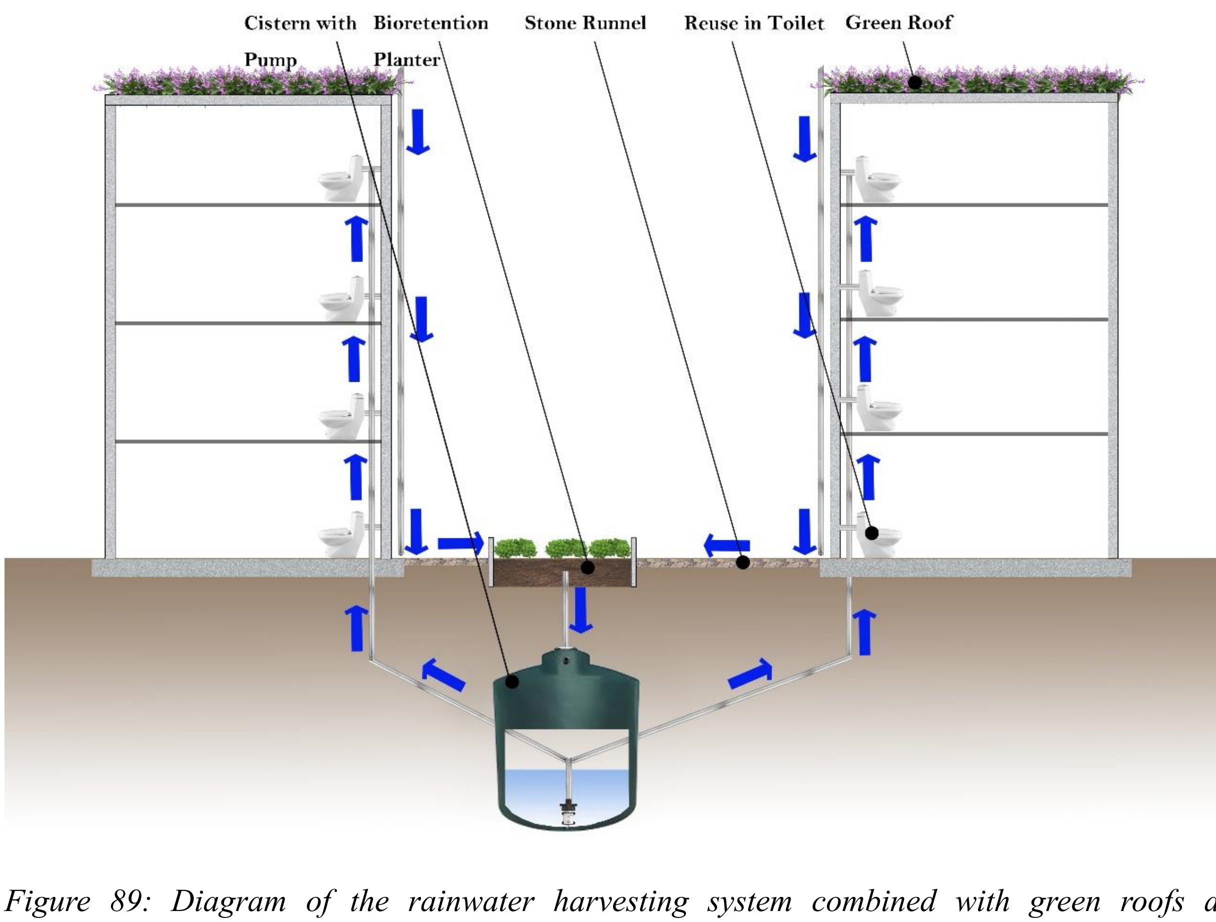


Figure 89: Diagram of the rainwater harvesting system combined with green roofs and bioretention planters (produced by author)

The design uses two aesthetic design principles of an artful rainwater harvesting system design: 1. Create a point of visual interest by using artificial hills to change the stormwater direction. 2. Create a line of visual interest by using runnels to transfer the stormwater. There would be a hall hill placed inside the bioretention planter in the center of the alley, designed into a recirculating water feature to attract people's attention into the rainwater harvesting system. (Figure 91) (Figure 92) The runnel on the ground would imitate the pavement form of the classic Suzhou garden, using cobblestones as the main material (Figure 90).

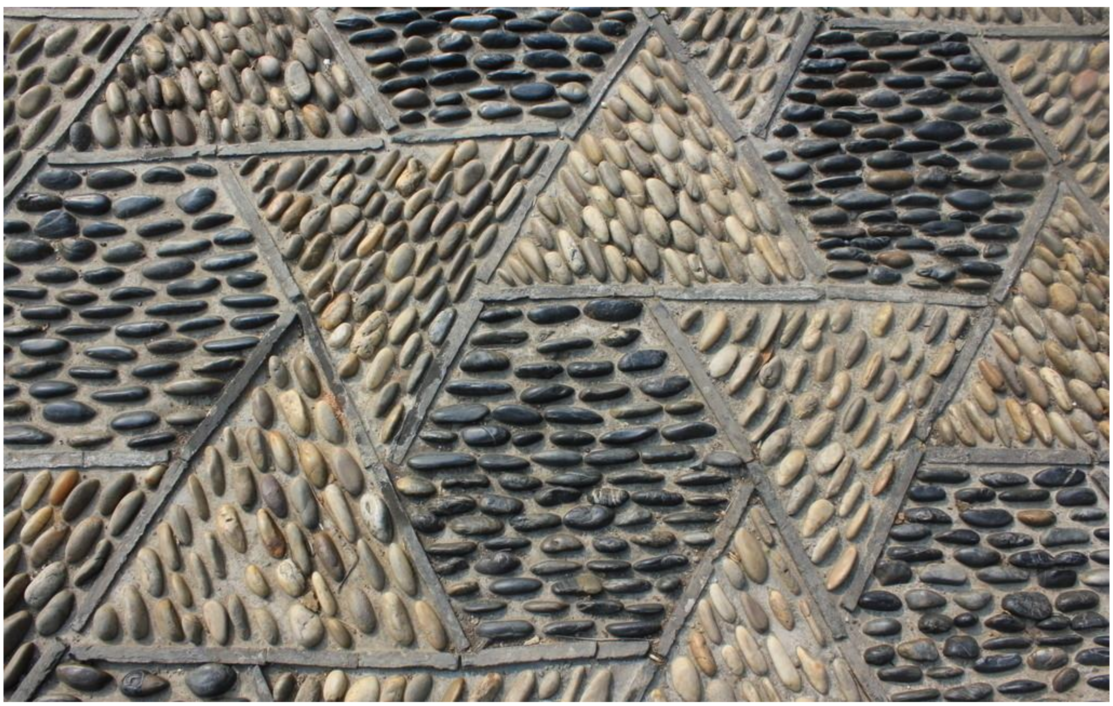


Figure 90: One pavement form of the classical Suzhou garden

Source: https://originarch.wordpress.com/author/originarch/

Figure 91: The alley before the design (photo by author)

Figure 92: The alley after the design (produced by author)

Location 5: Building I

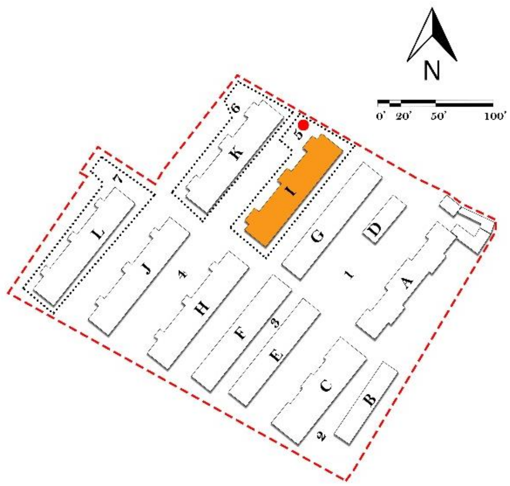


Figure 93: Map of location 5 (produced by author)

The catchment area of building I would need a 2000-gallon cistern to collect 0.81-inch rainfall, and the cistern would be placed on the north side of the alley between building I and building K. The design uses two aesthetic design principles of the artful rainwater harvesting system design: 1. Create a point of visual interest by using artificial hills to change the stormwater direction. 2. Create a line of visual interest by using runnels to transfer storm water.

The cistern would be covered by a cliff hill, and the overflow of the cistern would flow from the top of the cliff hill and then fall into the bottom of the cliff hill. There would be a stone channel connecting the bottom of the cliff hill and the bioretention planter on the north side of building K (Figure 95) (Figure 96). The shape of the stone channel would follow the design principle of the water shape in a classical Suzhou garden, mimic the form of a natural stream, and convey the overflow of the cistern to the bioretention planter. And get inspired from the Chinese ancient rainwater harvesting system design in Circular City. The stone in the channel can use the naturalized trapezoidal style, so that the rainwater can go through gaps between the stones in the channel. The bioretention planter would be placed in the north side of building K to treat the nonpoint pollutants in the area.

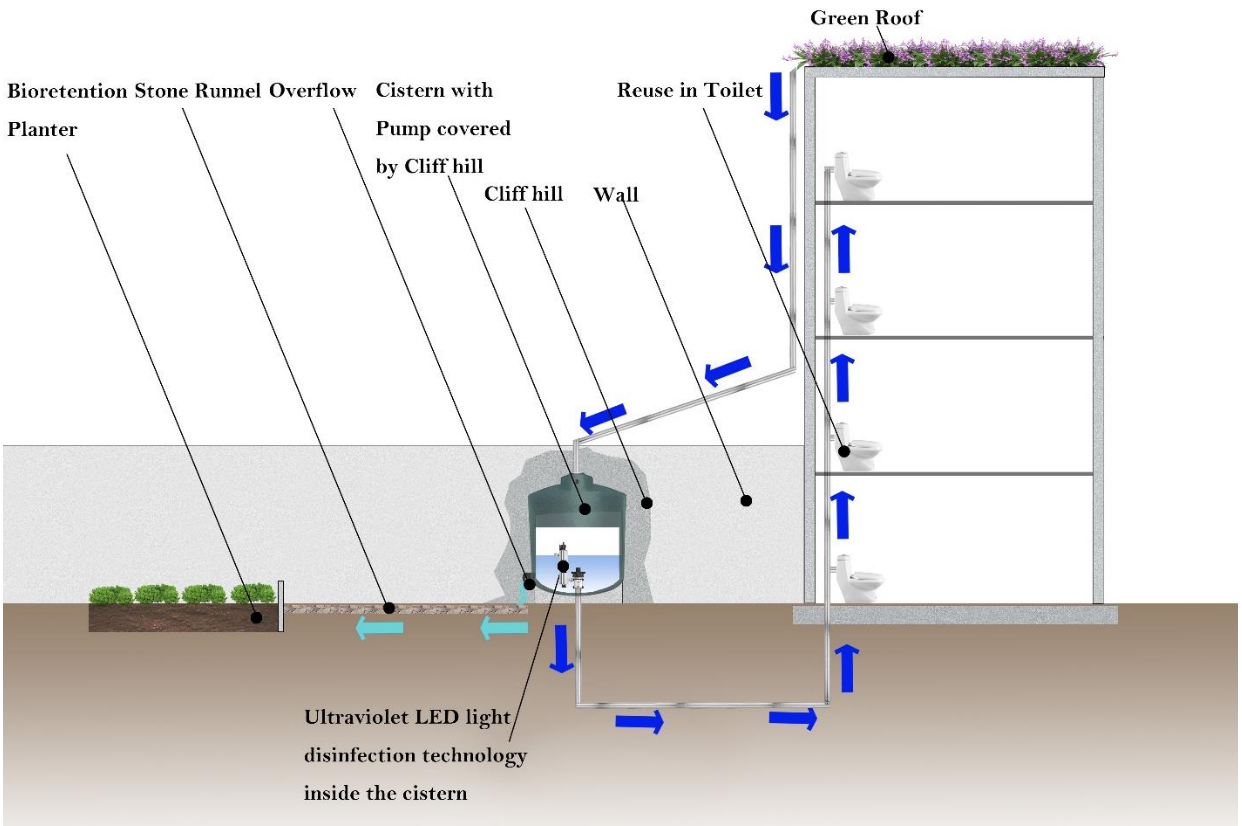


Figure 94: Diagram of rainwater harvesting system in Location 5 (produced by author)

Figure 95: The area before the design (photo by author)

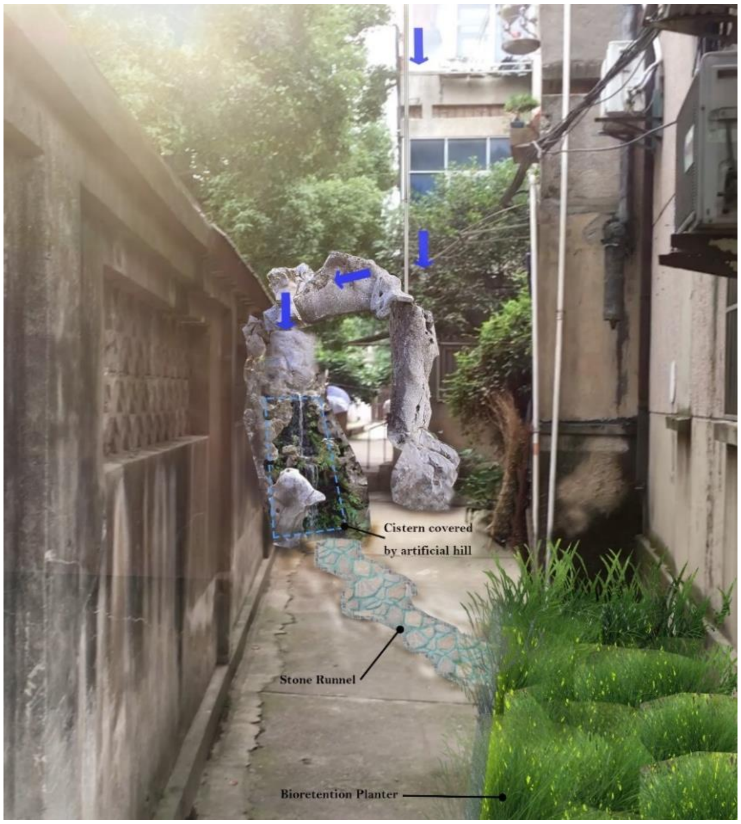


Figure 96: The area after the design (photo by author)

Location 6: Building K

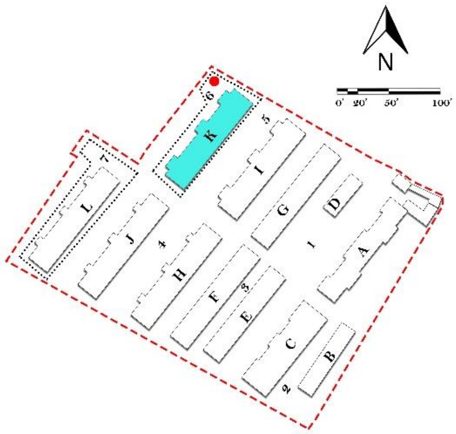


Figure 97: Map of location 6 (photo by author)

This area is another open space in the site, and the current condition of this area is also chaotic, with lots of abandoned furniture and garbage placed here (Figure 98). This area could be retrofitted into a gathering space for the community to provide an opportunity to enhance the cohesion of the community. Two aesthetic design principles of an artful rainwater harvesting design would be applied in this area: 1. Create a volume of visual interest by creating a basin that holds plants and water. 2. Create auditory interest by varying the amount and rate of the stormwater falling and flowing through the treatment system to create different rhythms (Figure 100) (Figure 101).

Figure 98: Current condition of the site (photo by author)

The rainwater would first fall on the green roof of building H, the rainwater would be infiltrated and absorbed by the green roof, and then the excess rainwater would flow through the downspouts into the cistern covered by the artificial hill. The artificial hill would be designed into a recirculating water feature, and the rainwater would be reused in the building to flush toilets. The bioretention planter around the artificial hill would treat the overflow of the cistern (Figure 99).

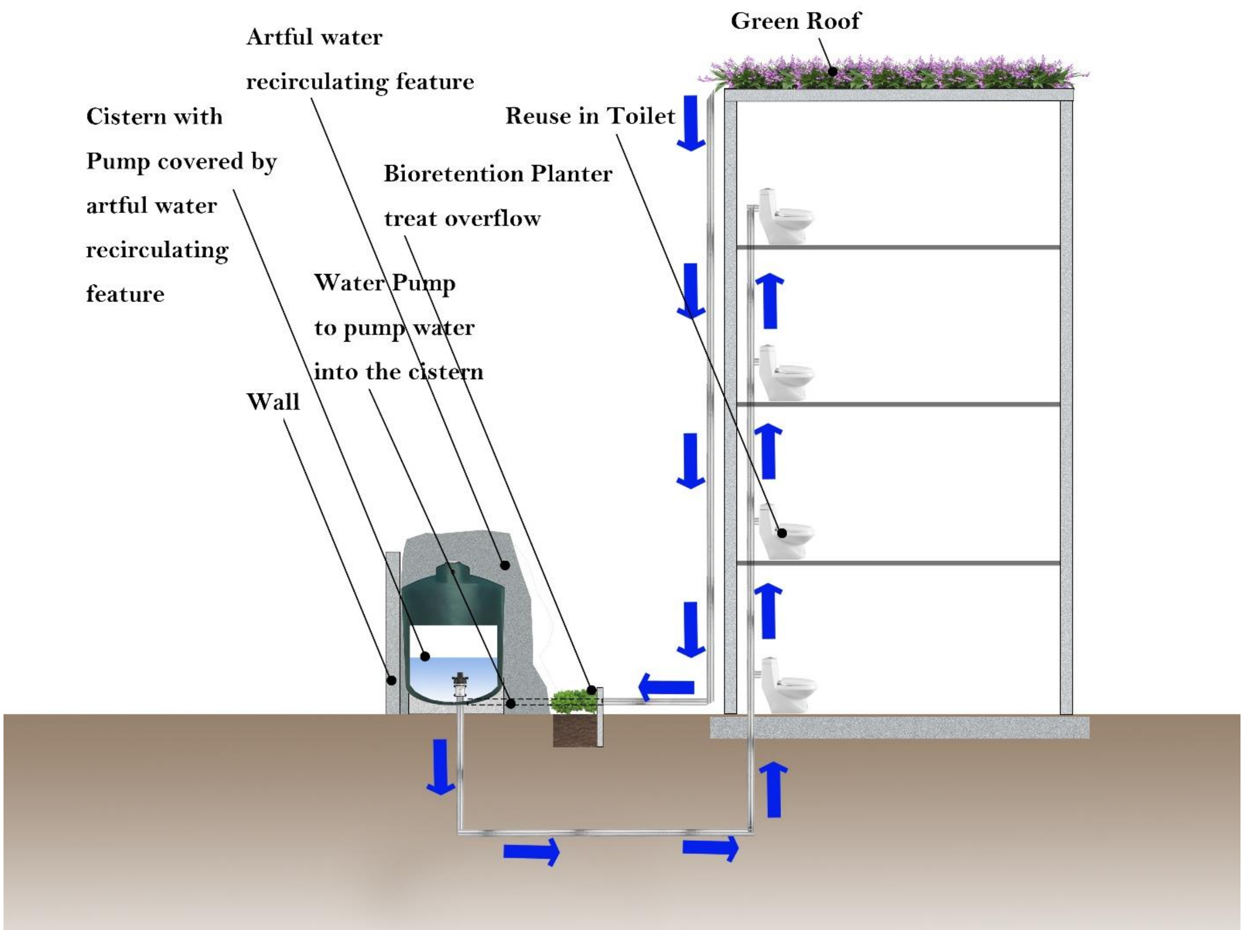


Figure 99: Diagram of the rainwater harvesting system in building K (produced by author)

Figure 100: Site before the design (photo by author)

Figure 101: Perspective of the artful rainwater harvesting system (produced by author)

Location 7: Building L

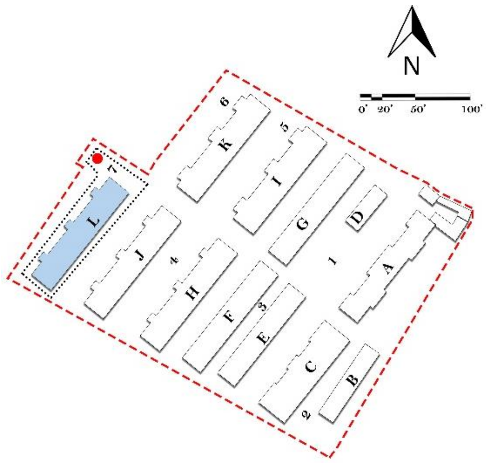


Figure 102: Map of location 7 (produced by author)

There are two illegal structures in the corner of this area, and the design proposes to remove all the illegal structures in the site (Figure 103). After removing these illegal structures, the rainwater cistern could be placed in the corner. The rainwater cistern would mimic the form of the buildings in a classical Suzhou garden design, and a water pump with a wooden barrel would be placed in front of the cistern (Figure 105) (Figure 106). It can provide residents with a way to gain access to use the rainwater in the cistern for irrigation or washing cars. It is a very visible way for people to see the benefits of rainwater harvesting systems. Two aesthetic design principles of artful rainwater harvesting design would also be applied in this area: 1. Create a point of visual interest by creating the rainwater cisterns as a feature or focal point. 2. Create tactile interest by allowing people to touch the stormwater and use it.

Figure 103: The illegal structures on the site (photo by author)

The process of rainwater flow is similar to the rainwater harvesting system in location 6. The rainwater would first fall on the green roof of building L, the rainwater would be infiltrated and absorbed by the green roof, and then the excess rainwater would flow through the downspouts into the cistern. The rainwater would be reused in the building to flush the toilets. The bioretention planter around the cistern would treat the overflow.

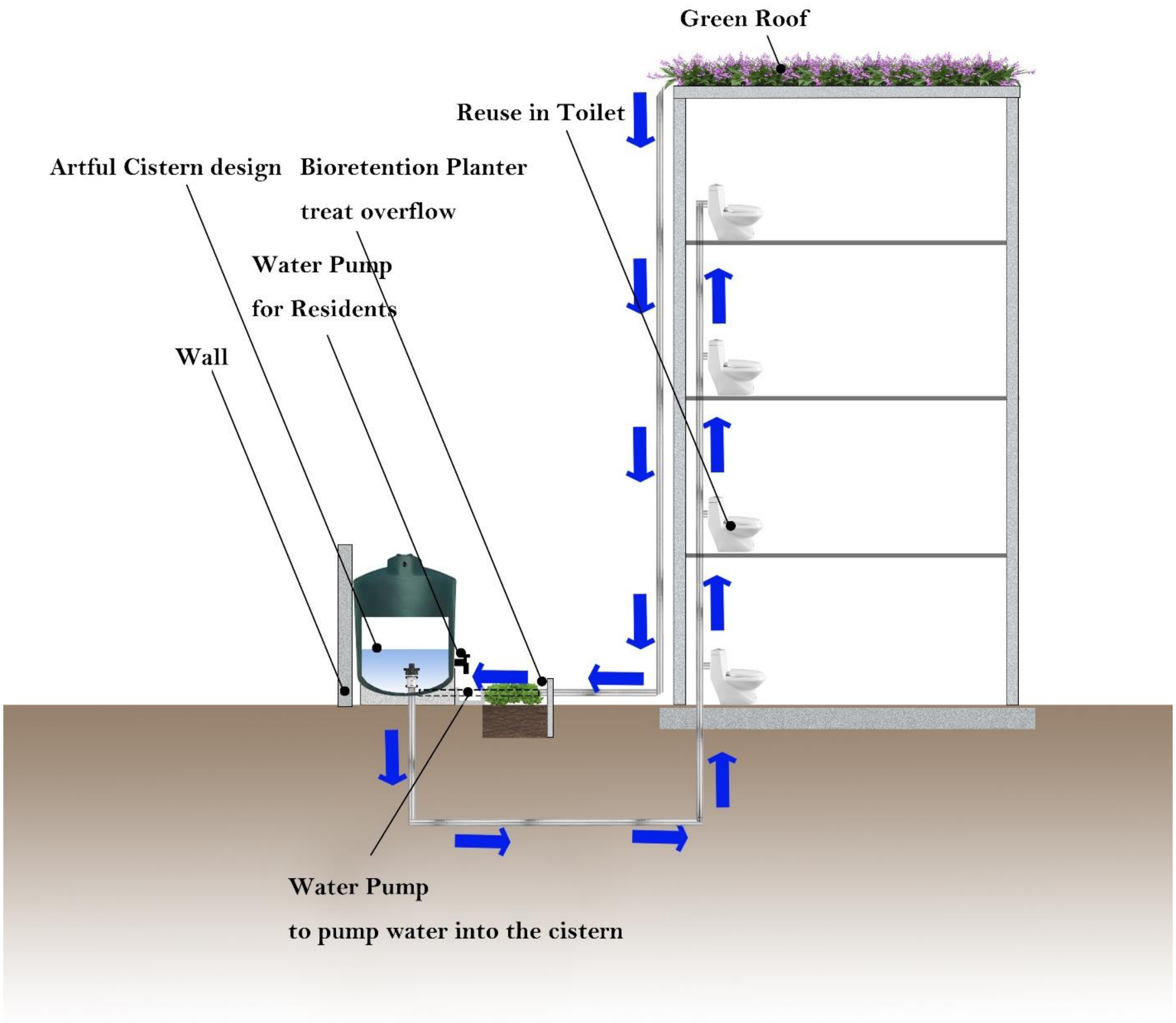


Figure 104: Diagram of the rainwater harvesting system in Building I (produced by author)

Figure 105: Site before the design (photo by author)

Figure 106: Perspective of the recirculating water feature (produced by author)

6.6 EVALUATION

This design is a good example to show how to apply artful rainwater harvesting systems to help mitigate flooding problems for other residential areas in Nanjing, China. This design followed the design principles of a classical Suzhou garden design so that it can fit into the city without disturbing the cultural context. By integrating it with LID methods, rainwater harvesting systems can help mitigate the flooding problem more efficiently.

The design would be evaluated by using the amount of water quality volume treated. According to what has been discussed in Chapter 6.4, the water quality volume can be calculated by the formula: WQv=0.81*R*A/12. Table 21 shows the WQv treated is 28736.27, which is 57.21% of the total WQv before design. It shows that the rainwater harvesting system proposed in the site can help reduce 57.21% stormwater runoff.

Table 21: Treatment volume before and after the design (produced by author)

	Discription	Area (sq feet)	WQv(gallon) before design	WQv (gallon) after design	Storage (gallon)
Site	Before design	106078.2	A*0.9384*0.81*0.623=50232.78		
Green Roof	Where coefficient =0.4	26704.07	A*0.95*0.81*0.623 =12801.89	A*0.4*0.81*0.623 =5390.27	12801.89-5390.27=7411.62
Bioretention Planter	Where coefficient =0.05	6219.42	A*0.95*0.81*0.623 =2981.58	A*0.05*0.81*0.623 =156.93	2981.58-156.93=2824.65
Cisterns	Total volume of Cisterns				18500
Total runoff reduced		28736.27/50232.78=**57.21%**			28736.27

CHAPTER 7

DISCUSSION & CONCLUSION

The purpose of this thesis has been to study how to use rainwater harvesting systems in Nanjing, China, integrated with low impact development methods to help mitigate flooding problems. The research proposed a suitable artful rainwater harvesting system in one residential area in Nanjing, China.

By comparing the aesthetic design principle of artful rainwater design with the design principles of classical Suzhou garden design, it is evident that most of the principles are similar and can be connected; only two principles are significantly different. According to the results of the design principle comparison above, a set of aesthetic design principles for the artful rainwater harvesting systems in Nanjing, China were developed. The aesthetic design principles of artful rainwater harvesting designs combined with LID methods have guided this thesis to implement a design that can not only help mitigate the urban flooding problem, but can also help make the rainwater harvesting system fit into the cultural context of the site.

A classical garden design may not be the only acceptable form of design in Nanjing, China; some people might prefer more contemporary ideas. However, Nanjing is a city with a long history- it has existed for than 2,500 years. In order to make the proposed design fit into the cultural context, a classical design is a reasonable approach. Also, the classical design principles can be used to guide the contemporary designs. By using the color and texture from the classical garden design, the contemporary design also can fit into the cultural context, and the Suzhou Museum designed by Ieoh Ming Pei is an excellent example to show this. The classical design principles of using the sound of water flow to attract people's interest can also be applied in the contemporary design.

Seven locations were chosen for placement of cistern-driven artworks and five of the seven have specific designs proposed. These kinds of artful rainwater harvesting system designs can benefit urban residential areas by providing attractive gathering space, enhancing the cohesion within the community, and educating visitors about rainwater harvesting.

The artful rainwater harvesting designs proposed on the site would be more expensive than typical rainbarrel rainwater harvesting design. In order to promote artful rainwater harvesting design more widely, this type of design could pursue more government support. Since the Chinese government is promoting the program named "Sponge City," artful design should also be part of this program, to gain financial support. Based on available financial support, the design could be achieved by steps. The first step would be to achieve the functional part of the project, and then the artful designs could be placed in public areas or conspicuous locations so that the design would attract more people's attention to the artful rainwater harvesting. Then the last step would be to place all the artful design. The community should be responsible for the maintenance of the system since it can help save water fees and bring more green space into this area.

As a demonstration project, the outcome of this thesis can help guide other places in Nanjing to design artful rainwater harvesting systems. It also shows that rainwater harvesting systems can be integrated with LID methods to help mitigate urban flooding more efficiently. In this design, the rainwater harvesting system integrated with LID methods can help reduce 19.71% more stormwater runoff than the rainwater harvesting system without LID methods. Another outcome of the thesis is an understanding of developed countries' experiences in using rainwater harvesting systems, that can help guide China to develop its rainwater harvesting systems so that they can be widely used. And the ancient Chinese rainwater harvesting system discussed in the thesis can be used as study resource for the artful rainwater harvesting system design, it can help the design fit into the Chinese cultural context. For example, in location 5, the form of the stone runnel is get inspired from the trapezoidal brick in the Circular City. The thesis also proposes a set of design principles from classical Suzhou garden designs that can be applied in rainwater harvesting systems so that the systems can be more readily accepted by local residents in Nanjing, China.

One limitation of the thesis is that although it discuss about the application of an artful rainwater harvesting system design in the residential area in Nanjing, it does not represent other types of land use in Nanjing, such as commercial areas and industrial areas. More studies should be done to address other kinds of land use in Nanjing. A second limitation is the lack of soil and hydrological information due to the lack of GIS and rainfall data in China, so site analysis detail was limited.

Because contemporary rainwater harvesting systems are still a new concept in China and have received little publicity in China, there is not yet enough financial and government support to advance implementation - a third limitation. Many experimental data and policy incentives are needed to carry out popularization and application of the strategy.

A fourth limitation is that the size of the rainwater cistern limits the ability of the system to reduce stormwater runoff. When the cistern is full, the system can't contain more water so that this system can only help mitigate flooding problems, not completely solve them. A larger size cistern would be better, but due to the high density of Chinese residential areas, few areas can accommodate large size rainwater cisterns. To solve this problem, the rainwater harvesting system must be integrated with other stormwater management techniques, like the LID methods.

REFERENCE

Web Page:

"10th @ Hoyt / Portland, OR." 10th @ Hoyt / Portland, OR | Ankrom Moisan Architects 2012, Inc. Accessed December 17, 2017. http://www.ankrommoisan.com/project/10th-hoyt/discipline/architecture.

Ministry of Land, Infrastructure, Transport, and tourism. Water Resources in Japan. 2014. http://www.mlit.go.jp/mizukokudo/mizsei/mizukokudo_mizsei_fr2_000012.html.

"Potsdamer Platz, Berlin, Germany | Urban green-blue grids." Urban green-blue grids for sustainable and resilient cities. Accessed December 15, 2017. http://www.urbangreenbluegrids.com/projects/potsdamer-platz-berlin-germany/.

"Blog Post #3: Case study (Potsdamer Platz, Berlin)." Greenvsgraygkmt. April 19, 2011. Accessed December 15, 2017. https://greenvsgraygkmt.wordpress.com/2011/04/19/blog-post-3-cast-study-potsdamer-platz-berlin/.

Greenroofs.com Projects - Potsdamer Platz. Accessed December 15, 2017. http://www.greenroofs.com/projects/pview.php?id=151.

Campisano, Alberto, David Butler, Sarah Ward, Matthew J Burns, Eran Friedler, Kathy DeBusk, Lloyd N Fisher-Jeffes, Enedir Ghisi, Ataur Rahman, and Hiroaki Furumai. 2017. "Urban rainwater harvesting systems: Research, implementation and future perspectives." *Water Research* 115:195-209.

Cheng, Jiang, QX Xu, Kai Yang, LL Liu, and QJ Fan. 2007. "Comparison of Foreign Urban Rainwater Resource Utilization Management Systems and Some Inspirations." *China Water & Wastewater* 23 (12):68-72.

Chunjie, Zhong, Lu Yongpeng, Yang Kai, Xu Qixin, and Jian Yun. 2009. "Inspirations of urban rainwater resource utilization at home and abroad to Shanghai City." *Water & Wastewater Engineering*:S2.

Clark, Mark, and Glenn Acomb. 2008. "Florida field guide to low impact development." *University of Florida, 4p*.

County, Prince George's. 2002. "Bioretention manual." *Prince George's County (MD) Government, Department of Environmental Protection. Watershed Protection Branch, Landover, MD*.

Deng, Shan, Xiao-ming Lu, Bao-hong Lu, Han-wen Zhang, Chao Zhao, Kun Xu, Dou Mao, Dong-mei Cui, and Xing-xin Wu. 2014. "Variation analysis of annual mean temperature and precipitation near 53 years in Nanjing city." Water Resources and Power 32 (8):14-17.

Duan, Hong-lei, Li Wang, Jin-song Zhang, Xu-hui Liu, Yong-di Chang, De-hao Zhang, Yan-yun Zhai, Wen-yi Dong, Xin-xin Ren, Zheng-hua Yang, Zhi-tong Xu, Pingsheng Zhu, Hua Chen, Han Chen, Zuo-liang You, Qian Liu, Wen-zhang Huang, Yi-xin Lu, Yue-feng Liu, Lin Xu, Chun Wang, and Xiang-lian Liu. 2011. Engineering technical code for rain utilization. edited by Shenzhen Water Resources Bureau: Market Supervision Administration of Shenzhen Municipality (Intellectual Property Office of Shenzhen Municipality).

Echols, Stuart, and Eliza Pennypacker. 2008. "From stormwater management to artful rainwater design." *Landscape Journal* 27 (2):268-290.

Echols, Stuart, and Eliza Pennypacker. 2015. *Artful rainwater design: creative ways to manage stormwater*: Island Press.

EPA, September. 1999. "Storm Water Technology Fact Sheet-Bioretention." *Washington Dc, US Environmental Protection Agency, Office of Water*.

Fu-ming, BU. 2013. "Analysis and Appreciation of Rockery in Suzhou Gardens [J]." *Chinese Landscape Architecture* 2:026.

Geiger, Wolfgang F. 2015. "Sponge city and lid technology--vision and tradition." *Landscape Architecture Frontiers* 3 (2):10-22.

Guo, James C.Y. 1996. "Finding a "Maximized" Water Quality Capture Volume by Runoff Capture Ratio." Water Resources Planning and Management.

Harvesting, Rainwater. 2002. "Utilisation." *An Environmentally Sound Approach for Sustainable Urban Water Management: An Introductory Guide for Decision-Makers*.

Jun-qiao, GAO Zhen-huan SUN. 2011. "Application of Colourgroup in Chinese Ancient Garden." *Jiangsu Construction* 1:010.

Köhler, Manfred, Marco Schmidt, Friedrich Wilhelm Grimme, Michael Laar, Vera Lúcia de Assunção Paiva, and Sergio Tavares. 2002. "Green roofs in temperate climates and in the hot-humid tropics–far beyond the aesthetics." *Environmental management and health* 13 (4):382-391.

Kamiya, H. 2012. "Aim of "AIJ Guideline for RWH" and Practical Case Study." Proceedings of the 3rd IWA Rainwater Harvesting Management International Conference, Goseong County, Korea.

Keswick, Maggie, and Alison Hardie. 2003. *The Chinese garden: History, art and architecture*: Harvard University Press.

Kita, Ichiro, Kouichi Takeyama, Atsuo Takeuchi, and Kunihiko Kitamura. 1999. "Local Government's Finantial Assistance for Rainwater Utilisation in Japan."

Kraemer, R Andreas, and Ralph Piotrowski. 1995. "Financing urban rainwater management in Germany." *European Water Pollution Control* 4 (5):48-58.

Krishna, Hari J, C Brown, J Gerston, and S Colley. 2005. "The Texas manual on rainwater harvesting." *Texas Water Development Board, 3rd Edition, Austin, Texas, United States of America*.

Lesjean, B, M Schmidt, K Schroeder, and MC Huau. 2009. "International review of rainwater harvesting management: practice, market and current developments." Proceedings of the the 8th Urban Drainage Conference and 2nd RainWater Harvesting and Management conference (8UDM & 2 RWHM).

Li, JQ, Yang Liu, Wu Che, and XJ Liu. 2010. "Thinking about Urban Stormwater Discharge Reduction and Economic Incentive Policy." *China Water & Wastewater* 26 (20):28-33.

Lin-di, Cao. 2004. "Suzhou Gardens and Living Wisdom." *Academic Journal of Suzhou University* 3:016.

Liu, Dunzhen. 1993. *Chinese classical gardens of suzhou*: McGraw-Hill Companies.

Li, Shan-zheng, Bo Cao, and Qing-yi Meng. 2003. "An Ancient Rainwater Utilization Project in Tuancheng." Journal of Beijing Water 3:19-21.

Maksimović, Čedo, Mathew Kurian, and Reza Ardakanian. 2015. "What Are the Main Options for Applying the Multiple-Use Water Services Paradigm?" In *Rethinking Infrastructure Design for Multi-Use Water Services*, 27-68. Springer.

Mentens, Jeroen, Dirk Raes, and Martin Hermy. 2006. "Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century?" *Landscape and Urban Planning* 77 (3):217-226. doi: 10.1016/j.landurbplan.2005.02.010.

Ngan, Goya. 2004. "Green roof policies: tools for encouraging sustainable design." *Landscape Architecture Canada Foundation*.

Peng, WANG. 2006. "1, LIN Hua-dong~(1, 2), WANG Ling-xiao~ 3 (1. The Faculty of Urban Construction and Environment Engineering of Chongqing University, Chongqing 4000452, China;? 2. Yongchuan Global Credit Water Conservancy Co. Ltd., Chongqing 402160, China;? 3. Architectural Design and Research Institute of Zhejiang University, Hangzhou 313000, China); Water Precipitation Treatment and Reuse Technology Abroad [J]." *Journal of Heilongjiang Hydraulic Engineering College* 4.

Qing, WANG, ZHANG Guanglu, and WANG Xiaolei. 2009. "Investigation on utilization of rainwater resources in North China cities." *Water Resources Protection* 25 (4):86-90.

Schuetze, T. 2013. "Rainwater harvesting and management–policy and regulations in Germany." *Water Science and Technology: Water Supply* 13 (2):376-385.

Sparnicht, Christopher William. 2012. "Artful urban rainwater harvesting." uga.

Shao Yuqi. 2014. “Give full play to the important role of civil environmental protection organizations” Hangzhou Weekly (7):30-30.

Thong, Michelle. 2011. "Taking LID to the Streets: A Case Study of Stormwater Management on Leland Avenue in San Francisco, California."

Urbona, Ben R. 1998. "Urban Runoff Quality Management."

Wang, Chaozhong. 2003. "Stormwater planning and design: Hangzhou, China." uga.

Ward, Sarah. 2010. "Rainwater harvesting in the UK: a strategic framework to enable transition from novel to mainstream."

Wei, Zesong, Xia Wang. 2016. " The Enlightenment of Rainwater Using in Chinese Ancient for the Contemporary Sponge Urban Construction". Huazhong Architecture(2016.05): 132-136.

Wei, Zesong, Xia Wang, and Xiran Ji. 2017. "Traditional Urban Construction Experience of Rainwater Utilization for Beijing Sponge Urban Construction Reference." *DEStech Transactions on Engineering and Technology Research* (icaenm).

Yang, Bo, and Nancy J Volkman. 2010. "From traditional to contemporary: Revelations in Chinese garden and public space design." *Urban Design International* 15 (4):208-220.

Yang, Chang. 2017. "Lid Appropriateness for Various Land Uses: Making Low Impact Development Work in the Old City, Nanjing." University of Georgia.

YANG, Fang-rong, Pan PAN, and Yan LI. 2010. "Analysis of Measures of Urban Rainwater Utilization in Domestic and abroad [J]." *Acta Agriculturae Jiangxi* 2:044.

Yu, Kongjian. 2016. Sponge City: Theory and Practise. 2 vols. Vol. 2: China Architecture & Building Press.

ZHANG, Lan, and LIN Hang. 2017. "On the Application of Art Design in Tourist Attractions—A Case Study of Suzhou Museum." *DEStech Transactions on Computer Science and Engineering* (ameit).

Zhang, Xingqi, Maochuan Hu, Gang Chen, and Youpeng Xu. 2012. "Urban rainwater utilization and its role in mitigating urban waterlogging problems—A case study in Nanjing, China." *Water resources management* 26 (13):3757-3766.

Zheng, Xing, Xiao-de Zhou, and Bing-xin Ji. 2005. "Rainwater management and technical measures in Germany." *China Water & Wastewater* 21 (2):104-106.

Zhong, Sujuan, Liu Deming, Xu Jingju, and Chen Qiaohui. 2014. "Advanced Concepts and Technologies of Foreign Rainwater Comprehensive Utilization" Fujian Construction Technology (2):77-79.