Development of a water cycle management approach to Sponge City construction in Xi'an, China

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Abstract:

In recent years, climate change, population growth, and inefficient use of water have exacerbated the water resources scarcity problems around the world. Hence, this paper establishes a new approach of Sponge City construction (SCC)based on water cycle management (WCM)for the sustainable exploitation ofgroundwater, recycled wastewater and rainwater in the Xi'an Siyuan University.The Universityis located in an isolated area that is far away from the city center so that no centralized water supply system could be utilized. To mitigate water scarcity problems in the University, 39% of the annual rainfall is harvested and stored from impervious surfaces and grasslands by using the Curve Number (CN) method. This stored water is reused for non-potable purposes: 40% for toilet flushing and 60% as miscellaneous water. According to findings, the available rainwater of500 – 700 m^3/d accounts for 16 – 23% of the non-potable water from April to December. Moreover, the utilization rate of water resources increases from 204% to 227%. With the minimum volume of large-scale rainwater harvesting cistern of 52760 m^3, the environment could be adequately watered while improving the expansion and development conditions on the campus. Furthermore, water scarcity problems could be mitigated through optimization of the water resources utilization system. This study demonstrates that this new approach of SCC based on WCM could alleviate water resources scarcity problems in Xi'an Siyuan University effectively. It is hoped that this study will provide a model and example of the new approachfor future applications.

Keywords:

Sponge City construction (SCC); Water cycle management (WCM); Rainwater harvesting; Water resources utilization; System optimization

1. Introduction

The UN Comprehensive Assessment of the Fresh-water-Resources of the World estimated that approximately a third of the world's population was considered to suffer from water scarcity problems(Arnell, 2004). Moreover, two-thirds of the world's population would be living in water-deficient countries by 2025 (Arnell, 2004; Zhang, 2016). In addition, due to the differences in the spatial and temporal distribution of water resources, water scarcity problems (both of quality and quantity) are becoming increasingly prominent in many countries and regions, such as South and West Asia, Middle East and North Africa, Eastern Australia and Western United States (Rasul, 2016; Cao et al., 2015; Fox et al., 2011; Bichai and Smeets, 2013; Philpot et al., 2016). More specifically, the per capita water availability in Northern China is as little as 1/25 of the world average, so that this region experiences an extreme shortage of water resources (Guan and Hubacek, 2007;Zhang, 2016; Dou, 2018; Yan et al., 2018;).

Several theories and techniques have been proposed and applied in many countries to solve the water scarcity problems.Examples include Low Impact Development (LID) and Best Management Practices (BMPs) in the United States, Sustainable Urban Drainage Systems (SUDS) in the UK and Sponge City construction (SCC) in China (Baek et al., 2015; Sun et al., 2016; Loperfido et al., 2014; Tedoldi et al., 2016; Shao et al., 2016; Chan et al., 2018; Thuy et al., 2019; Li et al., 2019). These theories and techniques demonstrate that water scarcity problems could be alleviated by returning the land uses to natural state and harvesting rainwater. A common point can be summed up that water scarcity problems must be considered within the natural hydrological cycle if it is tobe solved. The natural hydrological cycle is not merely the circulation of water through the ocean, atmosphere, land, surface and subsurface water bodies, but also a process of water purification through natural processes. Thus,both the quantity and quality of renewable water resources could be secured simultaneously. (Bennett, 2008; Liu and Xia, 2012; Wang, 2015; Pokorný and Rejšková, 2008). Consequently, a conventional water resources utilization approach was formed, whereby the water resources in the upstream of a river is first used by humans and then discharged to the downstream after treatment. This approach was more than ideal when the world population was no more than 2 billion and natural resources were considered as plentiful for human consumption in an unrestricted manner.Duringthis period, this artificial water cycle causedminimal disturbances to the natural hydrological cycle (Feng et al., 2008). However, nowadays, with climate change and population growth, increased water consumption by human beings has significantly disturbed the natural hydrological cycle and led to severe shortage of water resources (Kundzewicz, 2008). Hence, this conventional water resources utilization approach also needs to change and reformed, at least in the near future, in order to maintain the characteristics of the natural hydrological cycle, as far as possible. Therefore, the concept of water cycle management (WCM), whichrefers to a multidisciplinary and multi-objective approach used to promote the sustainable exploitation of all available water resources in ways that best deliver multiple community objectives have been proposed. This presents a new approach to the design of urban water and wastewater systems by which freshwater supply and use, water reclamation and reuse, and the urban water environment are integrated into one water cycle(Gross et al., 2007; Ding et al., 2018).As a result, on the one hand, the efficiency of water resources utilization can increase.On the other hand, human disturbance on the natural hydrological cycle can significantly decrease because the quantity of water resources from upstream of the river, and that discharged into the downstream decrease. Therefore, combined with experiences from previous successful case studies(Wang et al., 2015), this approach of WCM is feasible and effective.

In China, the South-to-North Water Diversion Project, which is a large-scale water transfer project from Southern China to Northern China has partially solved the unequal distribution of water resources between the North and South (Zhao et al., 2015; Pohlner, 2016; Chen and Wang, 2012; Yan and Chen, 2013; Zhuang et al., 2019). However, finding long-term solutions to the water resources problems in the region remain very difficult.Consequently, China recently initiated the implementation of the concept of Sponge City and put forward a strategic plan for 30 cities (Juárez and Jiang, 2016; Wang et al., 2015; Liu et al., 2016; Qian, 2016; Qian, 2016). Sponge City is a concept closely relatedto WCM. Its purpose is to recycle rainwater and ensure the sustainable development of society and the environment, while also mitigating potential flood and water-related disasters (Karim et al., 2015; Mehrabadi et al., 2013; Mahmoud et al., 2014). Consequently,the concept of WCM is becoming increasingly important.

Therefore, in this study, a new approach of SCC based on WCM is considered. A pilot study in China is put forward to provide a new model and example with good promotion and application value. The case study area of Xi’an Siyuan University is located in Northern China.The university occupies an isolated area located on a mountain that is far away from the city center. Consequently, no centralized water supply system can be used. Therefore, groundwater and recycle wastewater is exploited to meet water demands. However, water resources utilization seems to remain very high,whereby the over-exploitation of groundwater has caused significant groundwater table declines.Expansion and development of the isolated area further exacerbate the stated problem. Therefore, SCC based on WCM for the sustainable utilization of groundwater, reclaimed wastewater and rainwater has beenproposed for this region. The specific objectives of the study were to: (1) determine the maximum potential of rainwater harvesting (surface runoff) by using the Curve Number (CN) method; (2) establish the approach of SCC based on WCM; (3) optimize the utilization of water resources in Xi’an Siyuan University. By this concept, water scarcity problems could be improved. Also, this new approach could provide some new ideas and good suggestions for the development and utilization of water resources in the future.

2. Materials and methods

2.1. Study area and data collection

This study was conducted in Xi’an Siyuan University, which is an isolated area, located in Xi’an, Shaanxi Province, China(E107°40′~109°49′ and N33°39′~34°45′). Xi’an Siyuan University occupies an area of 0.8 km^2 and consists of buildings, impervious roads, green spaces and water spaces (Fig.1). Land uses include 60% of grasslands with good condition and 40% of impervious surfaces. This campus is situated on widely distributed sandy loam soil and light loam soil, which have high permeability and low potential runoff. There is an artificial lake on the campus, with an area of 3100 m^2 and an effective water depth of 0.6 m. There is a population of 25000, and the potable water demand is 80 – 120 L/person·d on the campus. The types and volumes of water resources utilization are shown in Table 1.

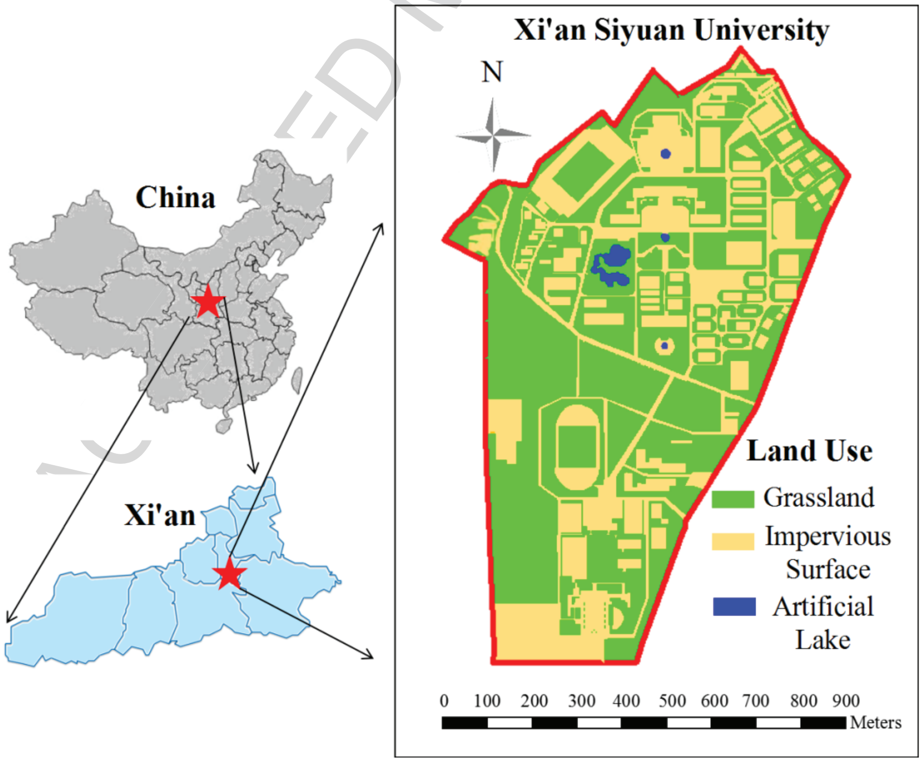

Fig. 1. Location and land use map of Xi’an Siyuan University in China.

Table 1

Types and volumes of water resources utilization in Xi'an Siyuan University.

Water resources utilization	Type	Volume(m^3/d)
Potable water use	Potable water	3000
Non-potable water use	Toilet flushing water	1200
	Miscellaneous water	1800
	Supplemental artificial lake water	109

With a temperate continental climate, Xi'an has an averagetemperature of 14.9 ℃, an average wind speed of 1.8 m/s, an average annual rainfall of 545 mm and an average annual evaporation of 990 mm(Jia et al., 2016). The rainy season is between May and October, which accounts for 80% of the annual rainfall. This study uses published data of monthly precipitation between 1993 and 2015 in Xi'an from China Statistical Yearbook (http://www.stats.gov.cn/tjsj/ndsj/) (Fig. 2).

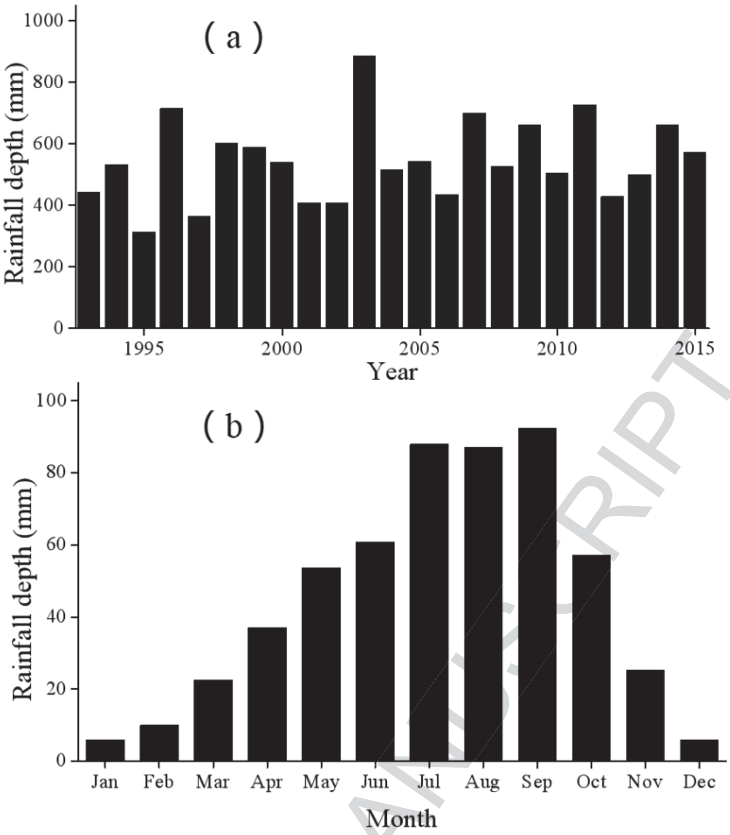

Fig. 2. (a) annual precipitation between 1993 and 2015 in Xi'an, (b) average monthly precipitation between 1993 and 2015 in Xi'an.

2.2. Methodology

2.2.1. Curve Number method

According to the theory of Sponge City, rainwater is an important non-conventional water resource, especially in the isolated area, so it can be harvested for reuse to mitigate water shortage problems. The potential of rainwater harvesting (surface runoff) is simulated by the CN method using monthly precipitation, land use and hydrologic soil group in the Storm Water Management Model (SWMM) and the Long-Term Hydrologic Impact Assessment-Low Impact Development (L-THIA-LID) model(Ahiablame et al., 2013). However, even a little change in the monthly precipitation, land use or hydrologic soil group could cause a large variation in the potentiality of rainwater harvesting because the relationship is not linear between the monthly precipitation, CN and harvested rainwater. The CN method is a simple procedure, which was developed empirically to simulate the potentiality of rainwater harvesting in a given region, and the steps involved are listed as follows:

1) Step 1: selecting the *CN* according to different land uses and hydrologic soil group,

2) Step2: calculating the potential maximum retention (S) (mm/month) according to the selected *CN*,

$$S = 25400 / CN - 254 \tag{1}$$

3) Step 3: calculating the initial abstraction (I_a) (mm/month), which includes interception, infiltration, surface storage and evaporation according to potential maximum retention (S) (mm/month),

$$I_a = 0.2 \cdot S \tag{2}$$

4) Step 4: calculating the potentiality of rainwater harvesting (Q) (mm/month) according to potential maximum retention (S) (mm/month), initial abstraction (I_a) (mm/month) and monthly precipitation (P) (mm/month).

$$Q = [(P - I_a)^2] / [(P - I_a) + S] \quad \text{for} \quad P > I_a \tag{3}$$

$$Q = 0 \text{for} \quad P \le I_a \tag{4}$$

2.2.2. Water balance

In order to fully meet all water demands and realize the target of zero dischargeof water resources in the isolated area, wastewater reuse is necessary.

Reclaimed wastewater is suppliedfor various types of non-recoverable water uses.The water balance of water resources utilization in the isolated area is listed as follows:

$$\sum_{\mathrm{i}=1}^{\mathrm{n}} Q_{\mathrm{Si}} = \sum_{\mathrm{j}=1}^{\mathrm{m}} Q_{\mathrm{NRj}} + \sum_{\mathrm{k}=1}^{\mathrm{s}} Q_{\mathrm{Lk}} \tag{5}$$

where Q_{Si} is various types of water supply and i is from 1 to n, Q_{NRj} is various non-recoverable water and j is from 1 to m and Q_{Lk} is various losing water and k is from 1 to s.

2.2.3. Efficiency analysis

The efficiency of water resources utilization is related to wastewater reuse, and the goal of wastewater reuse is always to meet the demand of non-drinking water, so the efficiency of water resources utilization can be affected by non-potable water. Equation (6) is the efficiency of water resources utilization in the isolated area.

$$\eta = (\sum_{i=1}^{n} Q_{Si} + \sum_{t=1}^{p} Q_{NPt}) / \sum_{i=1}^{n} Q_{Si} \tag{6}$$

where Q_{NPt} is various non-potable water and t is from 1 to p.

2.2.4.Optimization processes

In order to mitigate the water scarcity problems, the water balance and efficiency of water resources utilization system in the isolated area need to be further optimized by establishing a new paradigm of SCC based on WCM. Fig. 3 shows the optimization processes of water resources utilization system in the isolated area.

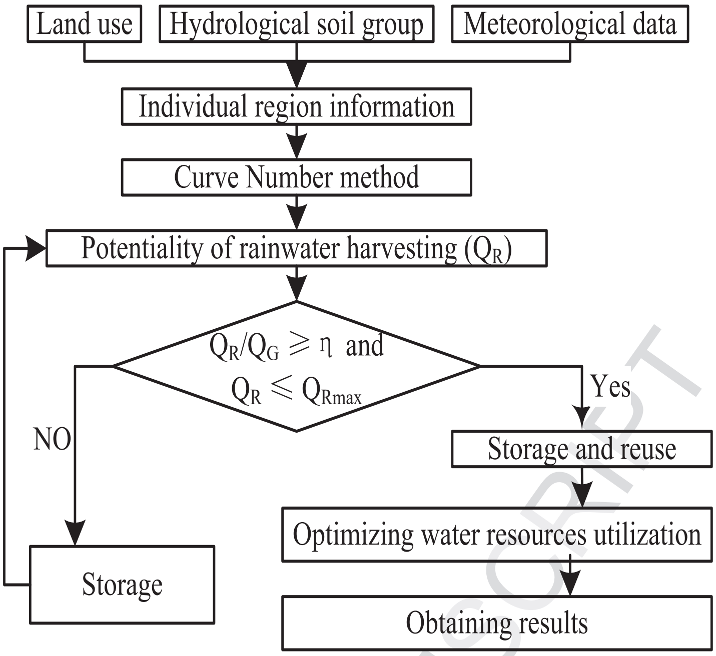

Fig. 3. Optimization processes of water resources utilization system in the isolated area according to Sponge City construction based on water cycle management.

Note: Q_R is the monthly potentiality of rainwater harvesting; Q_G is the quantity of non-potable water; η is the ratio of Q_R and Q_G (determined according to the actual situation); Q_{Rmax} is the maximum Q_R which can be reused in the water resources utilization (determined according to the capacity of wastewater treatment plant).

3. Results and discussion

3.1. Potentiality of rainwater harvesting

3.1.1. Impervious surface analysis

A CN of 98 was obtained for impervious surfaces and the hydrological soil group of B. Therefore, the potentiality of rainwater harvesting was calculated by using Equations (1), (2), (3) and the monthly precipitation shown in Fig. 2. Fig. 4 illustrates the monthly potentiality of rainwater harvesting in Xi'anSiyuan University. According to the findings, monthly collectable rainwater quantities increases steadily up to a maximum in the middle of the yearin July, August, and September, and then declinesrapidly during the rest of the year (Fig. 4).

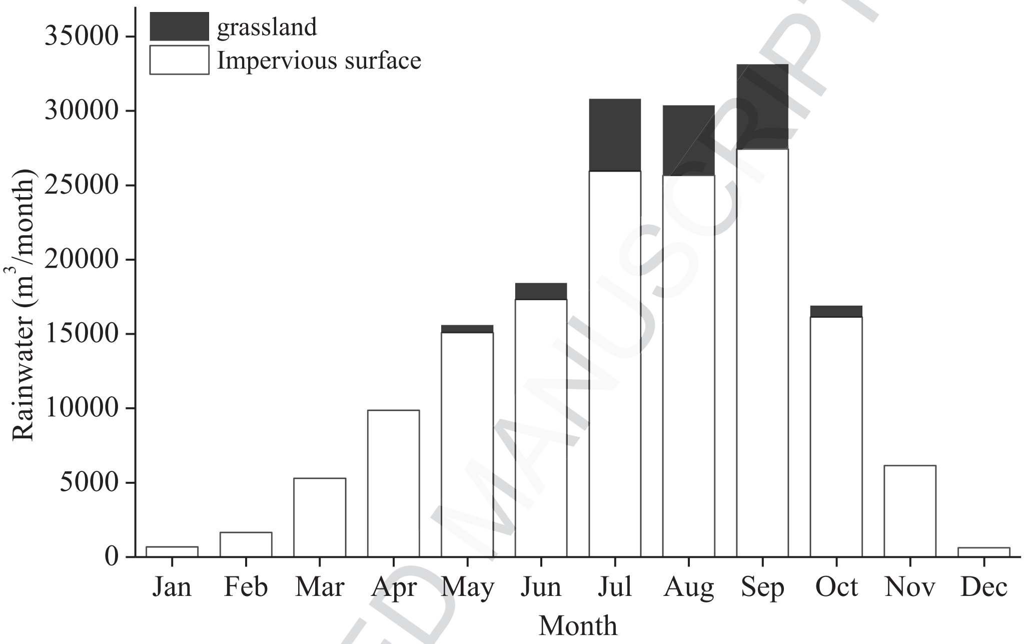

Fig. 4. The monthly potentiality of rainwater harvesting (impervious surface and grassland) in Xi'an Siyuan University.

3.1.2. Grassland analysis

A CN of 61 for the land use of grassland with good condition and the hydrological soil group of B.The monthly potentiality of rainwater harvesting for grasslandsare presented in Fig. 4. For this land use type, the maximum monthly collectable rainwater quantitieswere also recorded in July, August, and September.In the other months, values were almost zero.

Fig. 4 demonstrates that the total harvestable rainwater amounts to 39% of the total annual rainfall in the isolated area. Furthermore, grassland areasshowed higher infiltration capacities compared to impervious surfaces, whereby the impervious surfaces tend to produce large surface runoff. Nonetheless, surface runoff would be generated on the grasslands when precipitation was greater than the infiltration capacity, for example, in July, August, and September.

3.2. Integrated water cycle management

3.2.1. Rainwater reuse

According to section 2.1, 3000 m^3/d of groundwater has been exploited, and wastewater has also been reused in order to meet the demand for potable and non-potable water. However, water use remains intense in the isolated area. Therefore, rainwater (surface runoff) from the impervious surfaces and grasslandsis proposed to be harvested. Collected rainwater may bestored firstly in cisterns, and then, treated in the wastewater treatment plant for non-potable reuse (see Fig. 5). Storage and treatment would guarantee the quality of harvested rainwater(Wang et al., 2017)..

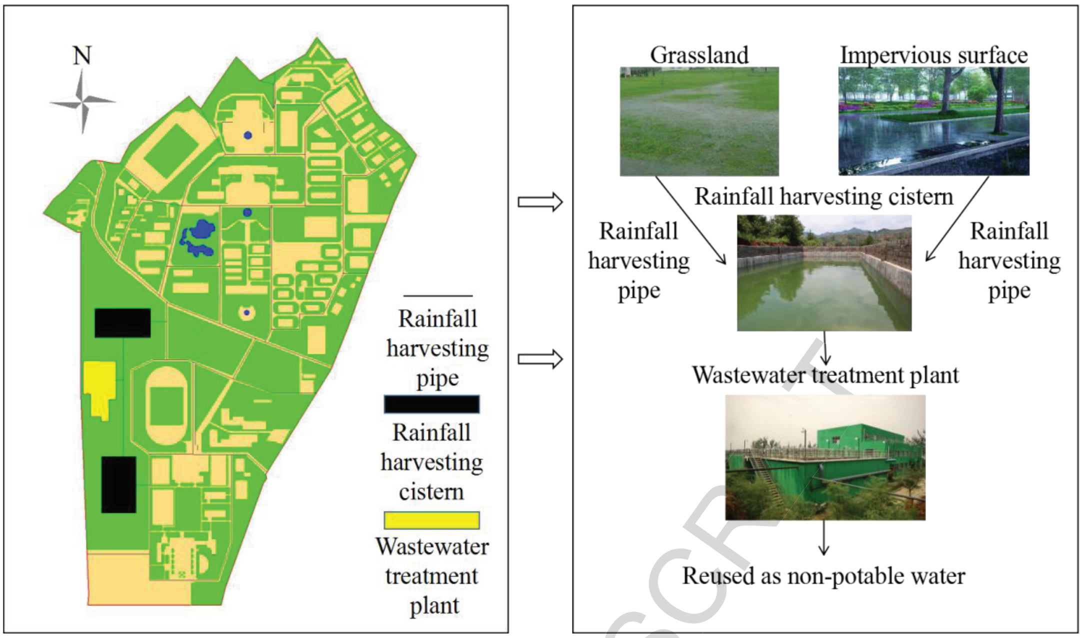

Fig.5. Schematic diagram of rainwater reuse in Xi’an Siyuan University.

3.2.2. Water resources utilization system optimization

Fig. 6 shows how the exploitation of groundwater and recycle wastewater in Xi’an Siyuan University helped meet the total water demand.A final residual water of 23 m^3/d is obtained after the reclamation of sewage, which demonstrates a nearly zero discharge rate for the water resources utilization. Moreover, the reuse of wastewater met the demand for non-potable water and the rate of water resources utilization increased by up to 204%.

The introduction of rainwater harvesting into the water resources utilization system changed the utilization rate of non-potable water (see Fig. 6). About 40% of the rainwater would be used for toilet flushing, and 60% for miscellaneous water. However, for the effective recycling of rainwater, the ratio of rainwater reuse and non-potable water is required to be greater than 15%. On the other hand, based on the capacity of the wastewater treatment plant, the maximum quantity of treatable rainwater is less than 700 m^3/d. Therefore, an optimal rainwater reuse scheme could be obtained by minimizing the volume of rainwater harvesting cisterns (see Fig. 7).

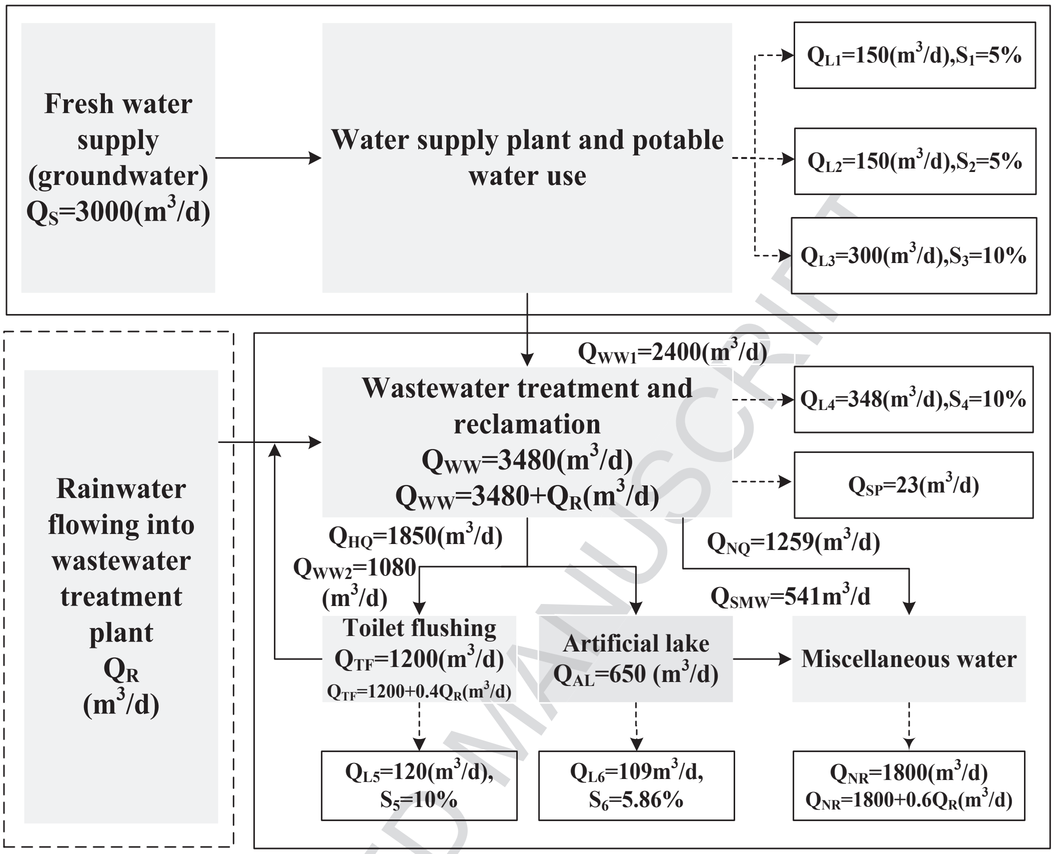

Fig. 6. Water balance and collectable rainwater quantity utilization approach of rainwater and wastewater resources utilization system in Xi'an Siyuan University.

Note: a detailed description of symbols and abbreviationsused in the water resources utilization system are listed in the appendix.

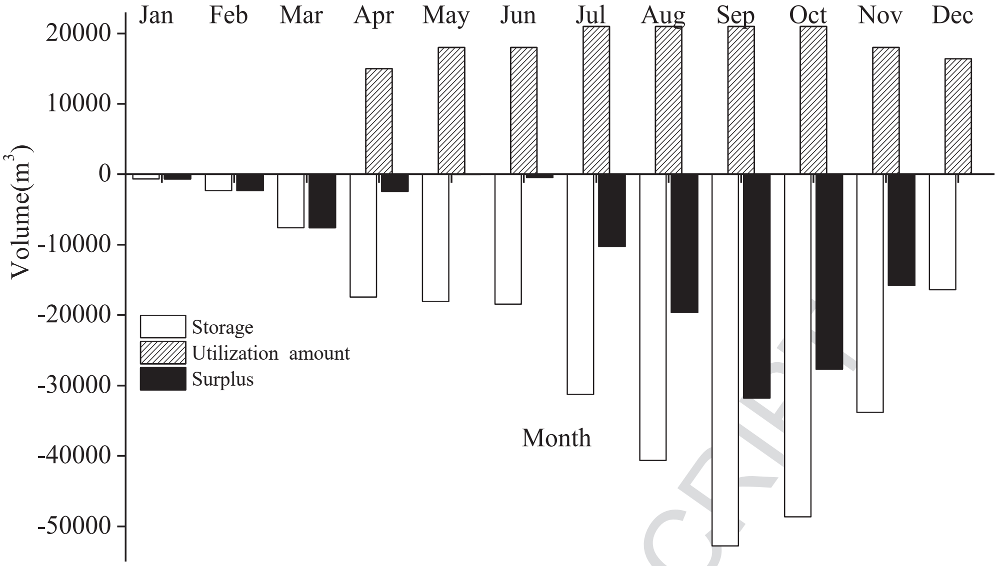

Fig. 7. Volume of rainwater storage and utilization in Xi'an Siyuan University.

Fig.7 shows that the available rainwater in January, February, and March may not be enough to meet the 15% minimum ratio of available rainwater and non-potable water.So, this rainwater would be stored until April. From April to December, the rainwater that was stored in the cisterns would be reused. The available rainwater, ratio of available rainwater and non-potable water and utilization rate of water resources are summarized in Table 2. The available rainwater is shown to range from 500 to 700 m^3/d. The ratio of available rainwater and non-potable water is between 16% and 23% and utilization rate could increase from 204% to 227%. Therefore, the volume of cisterns requiredis at least 52760 m^3.

Table 2

Overview ofrainwater recycling in Xi’an Siyuan University.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Available rainwater (m^3/d)	0	0	0	500	600	600	700	700	700	700	600	547
Ratio of available rainwater and non-potable water (%)	0	0	0	16	19	19	23	23	23	23	19	18
Utilization rate of water resources utilization (%)	204	204	204	220	224	224	227	227	227	227	224	222

Thus, the water resources utilization system could be further optimized by this paradigm of SCC encompassing groundwater use, wastewater reuse and rainwater reuse based on the concept of WCM. By this development, the water scarcity problems in Xi’an Siyuan University could be mitigated and the environmental quality could be further improved. Moreover, it could provide some good ideas and suggestion for further expansion and development. Overall, the results suggest that this new integrated WCM concept could mitigate the water scarcity problems, especially for groundwater in the isolated area.

Furthermore, these results demonstrate that rainwater could be fully reused to mitigate groundwater scarcity problem from April to December. So, it is feasible and effective to use rainwater to mitigate water resources scarcity problems based on

WCM.

4. Conclusions

In this paper, a new integrated WCM approach of SCC encompassing groundwater use, wastewater reuse, and rainwater reuse has been established based on WCM to mitigate water scarcity problems, especially for groundwater shortage problems in an isolated area. The potentiality of rainwater harvesting in Xi’an Siyuan University was calculated by using the CN method. Overall, this study demonstrates that the reuse of rainwater can further optimize the water resources utilization system in the isolated area. In turn, the environment quality of Xi’an Siyuan University can be further improved. Of course, it contributes to the expansion and development of the isolated area. Nonetheless, the economic situations and ecological conditions need to be further studied in further detail. It is hoped that this approach of SCC based on the concept of WCM proposed in this paper could provide some new ideas and good suggestions, and of course, be used as a model and example for the development of water resources utilization in the future, especially in developing countries experiencing serious water scarcity problems.

Appendix: Symbols and meanings of the water resources utilization system in Fig. 6.

Symbol	**Meaning**
Q_S	Quantity of supply water.
Q_{L1}	Loss water during the treatment of the supply water plant.
S_1	Loss rate of the supply water plant, 5%.
Q_{L2}	Loss water during the process of drinking.
S_2	Loss rate during the process of drinking, 5%.
Q_{L3}	Loss water from the supply water plant to the wastewater treatment plant.
S_3	Loss rate from the supply water plant to the wastewater treatment plant,10%.
Q_{WW1}	Wastewater from the potable water use.
Q_{WW}	Wastewater in the wastewater treatment plant.
Q_{L4}	Loss water during the treatment of the wastewater treatment plant.
S_4	Loss rate of the wastewater treatment plant, 10%.
Q_{HQ}	Quantity of the high quality treatment.
Q_{NQ}	Quantity of the normal quality treatment.
Q_{SP}	Final surplus water in the system.
Q_{TF}	Quantity of toilet flushing.
Q_{L5}	Loss water during the toilet flushing.
S_5	Loss rate during the toilet flushing, 10%.
Q_{WW2}	Wastewater from the toilet flushing.
Q_{SMW}	Miscellaneous water from the artificial lake.
Q_{AL}	High quality water flowing into the artificial lake.

Q_{L6}	Loss water of the artificial lake.
S_6	Loss rate of the artificial lake.
Q_{NR}	Quantity of miscellaneous water.

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