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Spatiotemporal characteristics analysis of water saving potential and economic effectiveness of rainwater harvesting system in China

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ABSTRACT

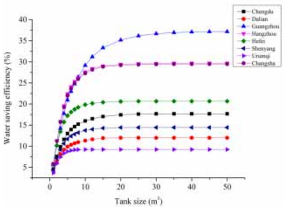
The financial viability of a rainwater harvesting (RWH) system is highly determined by regional conditions such as rainfall pattern and water prices. Successful implementation of rainwater harvesting systems depends largely on the identification of suitable sites. This paper presents the water saving potential and economic effectiveness of rainwater harvesting systems across eight major cities in China, using a daily water balance model. Results show six to 81 days (or 1.6% to 22.2%) of dependability can be achieved by using a rainwater harvesting system over these cities. The annual water saving efficiency ranges from 10% to 37% and the benefit–cost ratio varies between 0.45 and 1.20 across the studied cities. South China achieves the maximum annual water saving and the highest benefit–cost ratio, while southeast China has the most regular profile of precipitation use. Northwest China was found to be the region with the worst performance, both in yearly water saving and in regularity of rainwater use on a yearly scale. It was also found that the RWH system is not financially feasible in the northeast, southwest and central plains due to the benefit–cost ratios being smaller than 1.0.

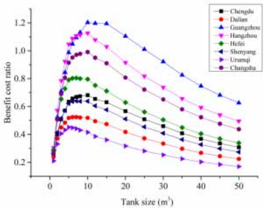
Key words: rainwater harvesting, spatial, temporal, variability

HIGHLIGHTS

- RWH systems have the best water saving and financial fits for southern China.
- The northwest is ranked as having the lowest annual water saving.
- Southeast China (represented by Hangzhou) has the most regular profile of rainwater use.

GRAPHICAL ABSTRACT





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1. INTRODUCTION

Due to rapid movement of industrialization and urbanization, China has been facing increasing urban water scarcity, and this situation will not be changed for a long time in the future (Zhao *et al.* 2013; Jing *et al.* 2017; Severis *et al.* 2019). Rainwater in a way is less contaminated than waste water from residential and industrial activities and it requires less time and cost in the treatment processes for its recycling and reuse to offset the demand for freshwater (Ding 2017). Despite rainwater harvesting having been demonstrated by many studies (Zuo *et al.* 2010; Liang & van Dijk 2011; Zhang & Hu 2014) as one of the best methods available for establishing sustainable water cycles in urban developments, and local governments having launched many incentive programs to encourage people to install this green infrastructure (Li 2009), most city dwellers are still showing reluctance to adopt this green infrastructure mainly due to the lack of sufficient data to support the benefits of RWH systems (Bashar *et al.* 2018).

As has been well demonstrated by previous studies, different regions with varied rainfall pattern, water price, and water demand pattern will result in different outcomes and levels of success (Amos *et al.* 2016; GhaffarianHoseini *et al.* 2016; Andrade *et al.* 2017). Therefore, each region should identify its own appropriate rainwater harvesting measures. For instance, with regard to the design of RWH systems, each installation should determine its optimum tank size to ensure maximum water supply reliability and water saving efficiency under local rainfall conditions (Amos *et al.* 2016; GhaffarianHoseini *et al.* 2016). Despite regional conditions having great impact on the economic feasibility of RWH systems, within China there has been little research devoted to comparing the water saving potential and economic benefit of RWH systems under different regions.

Except for the economic factors, for most end-users, an additional concern of RWH system usage is the instability of rainfall in many areas. This would indicate the need for a large storage tank which would not only increase the entire cost of the RWH system, but also significantly increase the likelihood of water quality deterioration. In general, the more irregular the rainfall is, the larger the storage tank will need to be, and thus there will be an even greater threat of water quality deterioration. Therefore, the seasonal unpredictability of precipitation is also a significant aspect that must be taken into consideration with the performance evaluation of an RWH system, since it can lead to a considerable variation in the results of the system with the same yearly rainfall. That is, it has superior potential for the utilization of rainwater in areas that have a more regular rainfall pattern. Even though the chronological variability of rainfall has a significant impact on the performance of a rainwater harvesting system, to date, no research has been discovered that surveys the regularity of rainwater harvesting on a yearly scale in different locations.

China is located on the west coast of the Pacific Ocean. Bearing double impacts from both the temperate continental climate and monsoon climate, the precipitation regime in China mainland is highly irregular both in time and space. The annual precipitation in China ranges from 400 mm in the northwest to over 2,000 mm in the southeast. On an annual time scale, precipitation also shows a remarkable seasonal variability. Most of the annual rainfall occurs in the three summer months (from June to August), leading to frequent water-logging in this period. while the climate is prone to drought in spring and winter. As the rainfall pattern and water price varies greatly from one region to another, there is a need to carry out a comparative study regarding the water saving potential and economic parameters of RWH systems in various regions to help the authorities to set a more accurate guideline for the planning, design, construction and operation of RWH systems.

Therefore, the objective of this study is to assess the potential performances of RWH systems in different weather conditions across different climate zones in China. Water saving parameters and economic benefits are calculated based on a scenario of a high-rise office building with 560 occupants and catchment area of 1,600 m^2, where the non-potable water consumption is assumed according to the *Code for Design of Building Water Supply and Sewerage* (GB50015-2019). Eight major cities located in three different climatic zones (i.e., humid, semi-humid and arid, respectively) of China are selected.

2. METHODOLOGY

The following sections present the study locations (Section 2.1) and scenario assumptions of the rainwater harvesting system (Section 2.2), and detail the methods assumed in this project to compute the water savings (Section 2.3) and benefit–cost ratio (Section 2.4).

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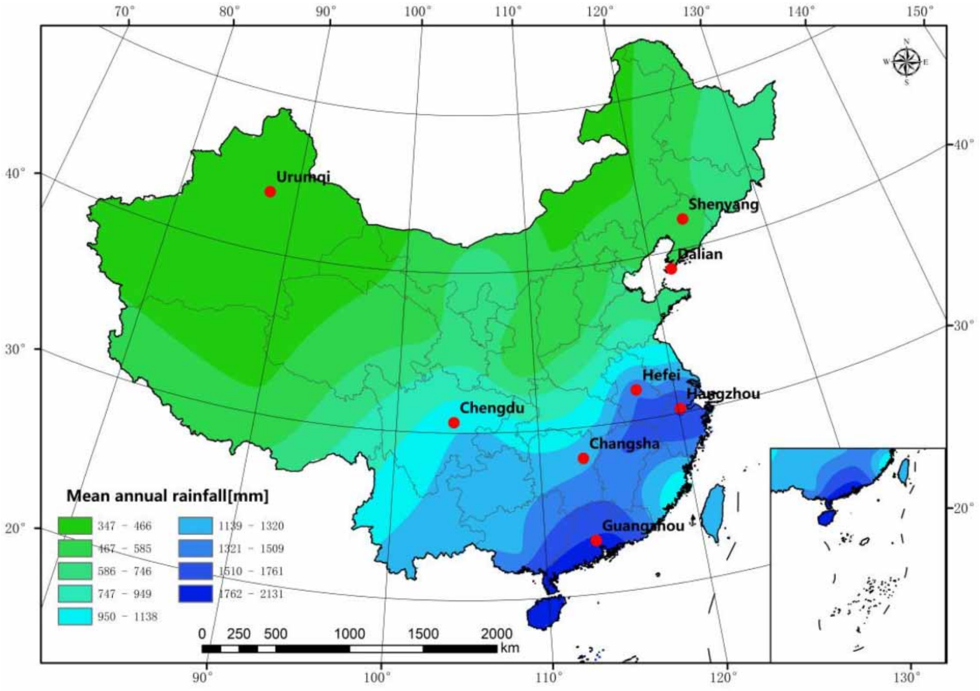

Figure 1 | The locations of the selected cities and the mean annual rainfall distributions.

2.1. Survey region

As shown in Figure 1, eight cities located in three different climatic zones (i.e., humid, semi-humid and arid, respectively) of China are selected. They are Guangzhou, Hangzhou and Changsha (humid zone), Chengdu and Hefei (semi-humid zone), Shenyang, Dalian and Urumqi (arid zone). The climatic zones are classifed by mean annual rainfall, i.e. the humid zones are defined with mean annual rainfall larger than 1,200 mm, semi-humid zones are defined with mean annual rainfall between 800 and 1,200 mm, and arid zones are defined with mean annual rainfall less than 800 mm. Figure 2(a)–2(h) shows the monthly rainfall of the selected study sites.

2.2. Scenarios

The most common building form for installing a rainwater reuse system in those cities is high-rise office buildings (the proportion of flushing water consumption is quite large) with flat roofs. It should be noted that the areas of building roofs, the number of occupants and water use patterns are expected to change from one site to another. For uniformity in evaluating the performance of an RWH system across different cities, in this study, a hypothesized development is considered at each of the study locations with an office building having a roof area of 1,600 m^2 and serving about 560 inhabitants. A gravity system is assumed to be serving indoor use (Figure 3). Rainwater generated from the building roof is collected and considered as being used for toilet flushing (which accounts for a great portion of non-potable demand) in the building.

The RWH systems are defined considering the most common system layouts implemented in public buildings. Figure 3 shows the layout of the RWH system, which consists of four main elements: a catchment surface, a storage tank, treatment facilities and conveyance system.

Generally, rainwater needs further treatment before use in order to lower health risks (Leong *et al.* 2017). The treatment system considered in the current study is a gravity-driven membrane (GDM) filter system, which was designed based on the treatment degree of the captured rainwater and possible water uses in the building. As illustrated in Figure 3, in the RWH system, the rainwater is harvested from the rooftop of the model building. After that, the rainwater flows through a first-flush device to abandon the early runoff, and then flows into a storage tank through a static sieve to remove large solids (e.g. leaves and twigs). After the storage stage, the rainwater passes through a micro-membrane filter under gravity head.

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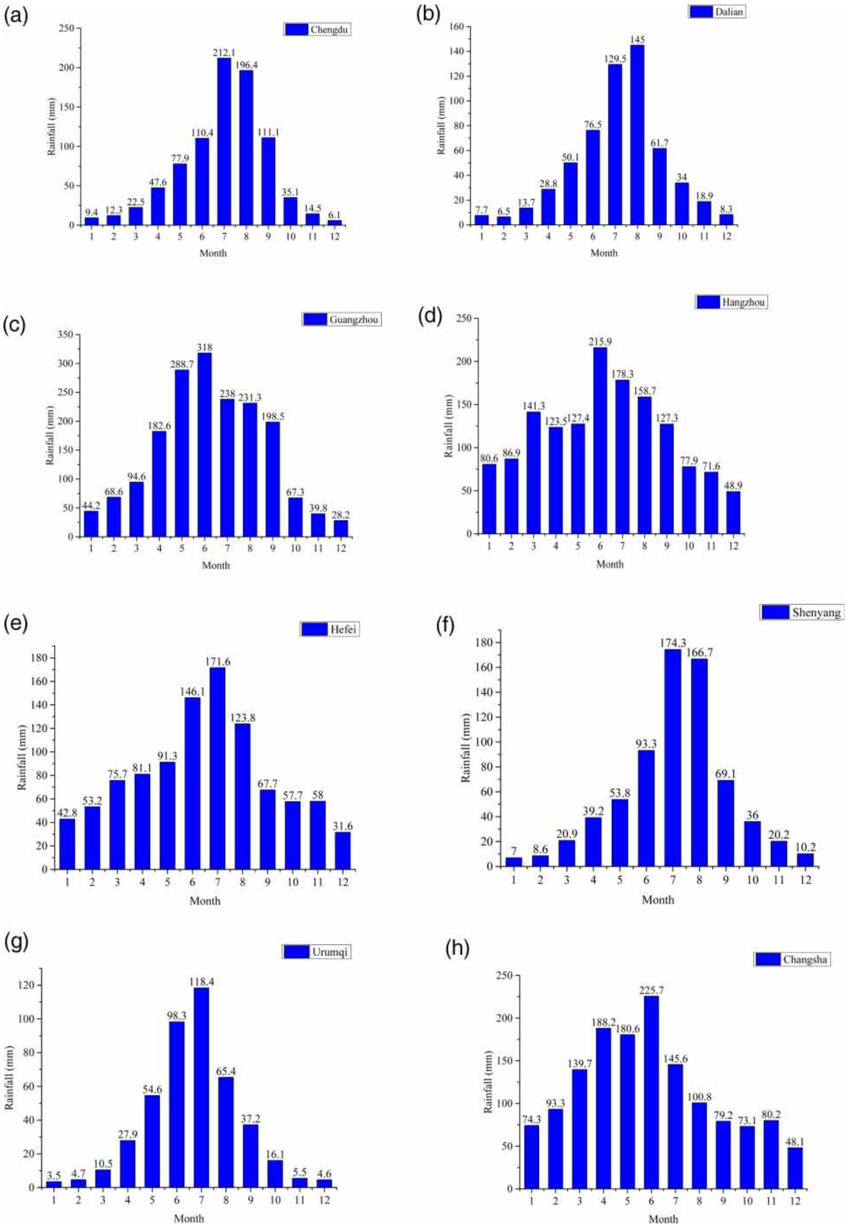

Figure 2 | Monthly rainfall at eight different cities: (a) Chengdu, (b) Dalian, (c) Guangzhou, (d) Hangzhou, (e) Hefei, (f) Shenyang, (g) Urumqi, (h) Changsha.

The treated water is temporarily stored in an effluent tank (where chlorine is added) and made available for non-potable purposes such as toilet flushing and hand washing (Figure 3).

2.3. Data

For the benefit analysis of the proposed RWH system, the first step is to collect some basic data consisting of historical precipitation data, information about the non-potable water demand, and detailed financial data for each study city.

2.3.1. Rainfall data

Historical daily rainfall data from 1990 to 2019 of these study cities are obtained from the China Meteorological Data Service Center (http://data.cma.cn) (Appendix 1–8). The mean annual rainfall varies from 446.7 mm in Urumqi (located in northwest

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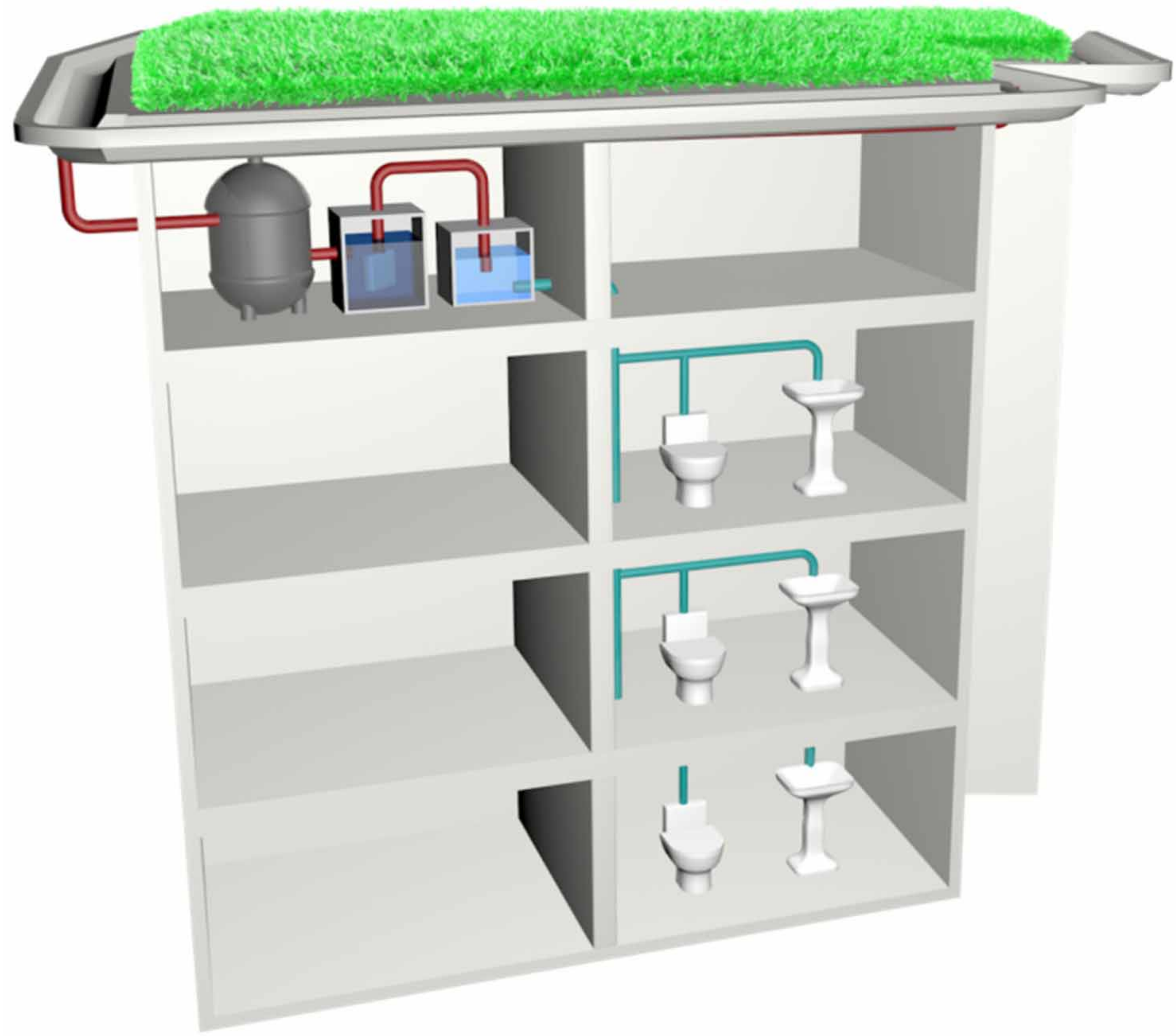

Figure 3 | Scheme of the RWH system.

China) to 1,799.8 mm in Guangzhou (located in south China). Distributions of average annual rainfall of the selected cities are shown in Figure 1.

2.3.2. Water demand profile

The non-potable water demands for target building were estimated based on the water use for toilet flushing and hand washing. Only these two end uses were considered since they reflect high indoor water uses, and present a low viral infection risk from using non-potable water (Lim *et al.* 2015), use-frequency (i.e., every day for flushing and hand washing), and building-occupancy. Daily water demand data for toilet and hand washing use for occupants of the target buildings are obtained from the *Standard for Design of Building Water Supply and Drainage* (GB50015-2019) (Ministry of Housing and Urban–Rural Construction of the People's Republic of China 2019). In accordance with the standard, the toilet-flushing water consumption assumed in this study is 6 L per time, and a frequency of toilet use of four times per person per day is considered, which is equivalent to 24 L per person per day. The hand washing considered in this study is 12 L per time, and a frequency of six times per person per day, which is equivalent to 12 L per person per day. The estimated number of employees for the target building is 560 (which was based on an actual office building in Guangzhou). Therefore, the total non-potable water

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demand of this building is equivalent to 20.16 m^3 per day. It is assumed that the non-potable demand at weekends can be estimated at one-fifth of that during weekdays, which is equal to 4 m^3 per day. We assumed that rainwater was the primary source for both toilet flushing and hand washing use in the target building, only supplemented by tap water when the harvested rainwater was insufficient to meet these demands.

2.3.3. Economic data

The costs analysis of the system considers the capital and operating costs of the RWH system. The initial investment includes the rainwater tank, pipelines, treatment devices and necessary labour costs, which can be divided into two categories: the constant capital (e.g., the treatment device, pipelines, valve and additional facilities) and the variable capital (i.e., the storage tank, the price of which varies with its capacity). Costs information of the RWH system components were obtained from a market survey.

Table 1 provides a summary of the constant capital of an RWH system. The estimated total facilities expenses are 14,901 CNY (Chinese Yuan). The installation cost is estimated at 10% of the total facilities expenses, which is equivalent to 1,490.1 CNY, thus the total constant capital is 16,391.1 CNY.

The storage tank represents the most significant variable capital for an RWH system, and its volume should maximize the efficiency of the system. In this study, the tank size was defined based on market availability with the goal of estimating the optimal capacity through evaluating the influence of the various commercial tanks in water saving efficiency and benefit–cost ratio of the RWH system. The prices of storage tanks (stainless steel) with different sizes are listed in Table 2. The price information in the table comes from a market survey.

For the estimation of operating costs, the periodic replacements of filter materials and daily consumption of disinfectants were taken into account. However, the labor costs and losses during suspended periods have been neglected, because the harvested rainwater from rooftop to storage tank and from the tank to the points of use was delivered by gravity (Figure 3), so no electricity was consumed in this case. Therefore, the average annual operating costs mainly come from periodic replacement of flat membrane, the consumption of chlorine, as well as maintenance, repair, replacement and management of the RWH system, the costs of which were estimated at 10% of the total capital cost. In addition, depreciation of equipment is taken into account in the cost analysis. In this study, the annual depreciation cost of equipment is estimated at 4% of the total capital costs.

The financial benefit comes from a reduction in the annual potable water bill achieved from an RWH system. This annual revenue is estimated as the product of potable water savings and water tariff. The value of possible environmental benefits

Table 1 | The constant investment of an RWH system in China

No.	Item	Unit	Amount	Unit price (CNY)	Total price (CNY)
1	GDM treatment unit	set	1	6,800	6,800
2	Flush diverter	set	1	140	140
3	Water level control valves	set	1	480	480
4	UV sterilization	set	1	265	265
5	Flow meter (DN 50)	set	2	110	220
6	Mosquito nets	set	1	56	56
7	Flat ceramic membrane	set	1	500	500
8	Pipelines (DN50,1.6Mpa)	metre	280	15.42	4,312
9	90-degree elbow	set	45	1.0	45
10	Tee joint	set	33	19	627
11	Gate valve	set	56	26	1,456
12	Installation costs (including labour cost)			10% of total facilities expenses	
	Total constant capital (except for storage tank, sum of 1–12)				16,391.1

Note: average currency data from 01/07/2019 to 31/07/2019,1 CNY was equal to 0.1427 USD.

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Table 2 | Price of storage tank (stainless steel) with various sizes

Size (m^3)	Price (CNY)	Size (m^3)	Price (CNY)
1	388	12	6,550
2	792	15	8,160
3	1,228	20	11,608
4	2,098	25	15,100
5	2,268	30	18,600
6	2,890	35	22,950
7	3,520	40	27,250
8	4,150	45	31,520
10	4,940	50	35,800

Table 3 | Terminal water price of the selected cities in 2019

Location	Terminal water price (CNY/m^3)	Location	Terminal water price (CNY/m^3)	Location	Terminal water price (CNY/m^3)
Guangzhou	2.93	Changsha	2.58	Hangzhou	2.90
Hefei	2.85	Chengdu	3.03	Shenyang	3.30
Dalian	3.25	Urumqi	3.20		

Note: terminal domestic water price consist of two parts: water supply price and sewage treatment fee, e.g., the terminal water price in Guangzhou is 2.93 CNY per cubic metre, which is the sum of a water supply price of 1.98 CNY per cubic metre and a sewage treatment fee of 0.95 CNY per cubic metre.

from an RWH system (e.g., reducing resource consumption from water treatment processes) is not considered in the cost–benefit analysis due to limited data availability. The terminal domestic water price, including water supply price and sewage treatment fee, is used in the economic viability analysis of an RWH system. The terminal water prices of the selected cities in 2019 are shown in Table 3. It can be observed that both the water supply price and sewage treatment fees vary substantially across the country.

2.4. Data analysis

These data were subsequently used to assess the performance of the proposed RWH system through a balance simulation model on daily scale, which focused on: (1) the water saving potential, and (2) the economic feasibility.

In order to calculate the water saving of an RWH system, a yield-after-supply (YAS) model on a daily scale in Excel is developed following the recommendation of Mitchell (2007). The YAS model considers various factors such as daily rainfall, runoff coefficient, daily water demand, tank capacity and tank spillage. As illustrated in Figure 4, running the model allows the water saving efficiency (WSE, a measure of how much potable water can be saved in comparison with the overall consumption of non-potable water) of the system to be examined.

This algorithm starts by setting the initial stored rainwater to zero. The available rainwater is then calculated from the catchment area, the daily rainfall and the runoff coefficient. According to the YAS model described by Mitchell (2007), the stored rainwater is updated based on the available rainwater and previous stored rainwater. If the calculated stored rainwater is less than the tank capacity, all available rainwater is collected and the stored rainwater remains unchanged. If not, the stored rainwater is limited to the tank capacity and the collected rainwater is calculated as the difference between the tank capacity and the stored rainwater at the end of the previous time step (as shown in Figure 4). Afterwards, the consumed rainwater is determined depending on whether the stored rainwater is enough to satisfy the daily non-potable demand or not. For example, if the stored rainwater is greater than or equal to the non-potable demand, the consumed rainwater is equivalent to the non-potable water consumption and the remaining stored rainwater will be the difference between the stored rainwater and the non-potable consumption. Otherwise, the consumed rainwater is limited by the stored rainwater and the rainwater tank will be empty. This computational procedure will be repeated for each day of one year (Silva *et al.* 2015).

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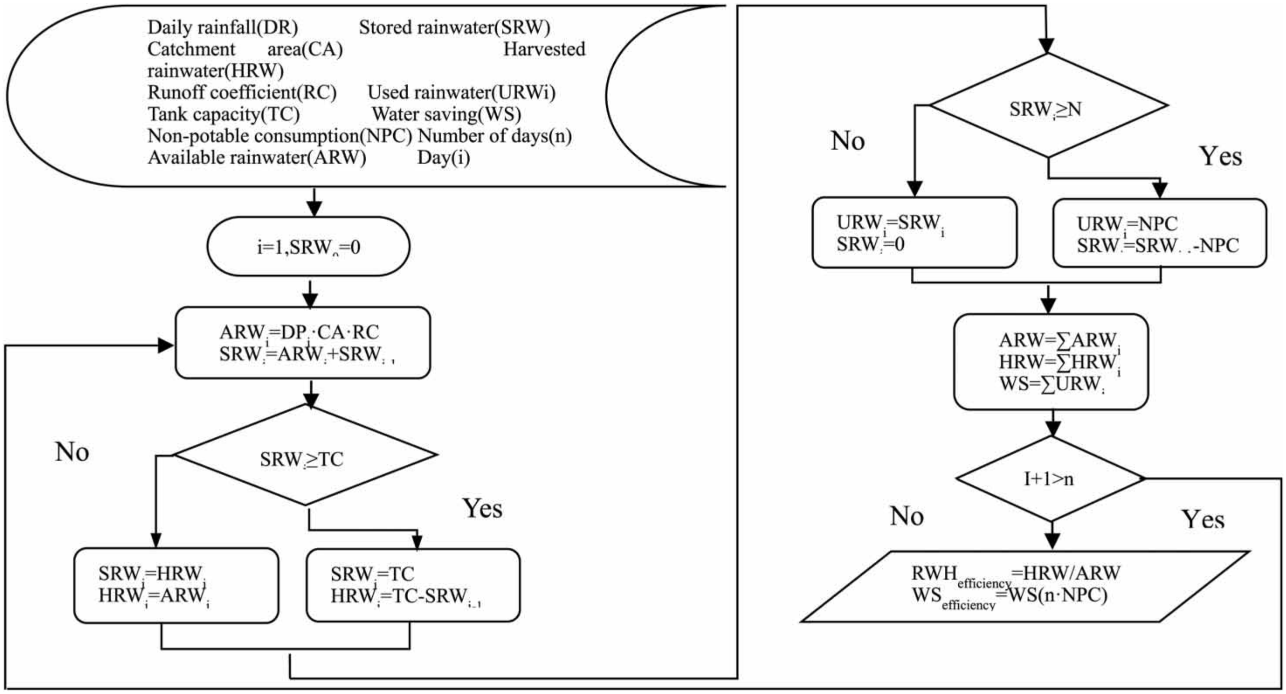

Figure 4 | Calculation procedure of the water savings.

The potential volume of rainwater harvested was estimated based on the catchment area of the target building and daily rainfall data obtained from the meteorological observation stations of each study site, which is calculated as:

$$V_c = \frac{R \times A_c \times C}{1{,}000} \tag{1}$$

where V_c is the volume of daily available rainwater (m^3), R the local daily rainfall (mm), A_c the catchment area (m^2) and C the surface runoff coefficient, assumed equal to 0.8 to represent losses of 20% (Zhang & Hu 2014).

In this work, the water saving performance of the proposed RWH system was evaluated using two indicators, which are percentage of reliability (R) and water saving efficiency. The reliability of the RWH system is calculated as the ratio of the number of days when the intended non-potable water consumption is met fully by the available rainwater and the total number of simulated days, which is defined as follows:

$$R_t = \frac{N}{365} \times 100\% \tag{2}$$

where R_t is the reliability of the RWH system to be able to supply the intended demand (%), and N indicates the number of days in a year when rainfall runoff meets the daily water demand in the target building.

The water saving efficiency (WSE) is calculated as the ratio of the volume of rainwater consumed and non-potable water demand of a year, and is defined as follows:

$$WSE = \frac{V}{D} \times 100\% \tag{3}$$

where V is the volume of rainwater consumed (m^3) and D is total water demand (m^3).

In the economic feasibility analysis, benefit–cost ratio (BCR) was performed considering the installation and maintenance costs, and the annual drinkable water savings of a rainwater harvesting system.

For the benefits, potential water saving was converted to monetary savings by multiplying the unit price of water with the unit volume of water saved.

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To carry out the economic performance analysis, all the present and future values are converted to present-day RMB values. In this study, a basic financial internal rate of 6% is considered according to the economic evaluation methods and parameters of municipal public facility construction projects (Ministry of Housing & Urban Rural Development China 2010). This study employs the concept of nominal cost (the expected price that will be paid when a cost is due to be paid, including estimated changes in price due to changes in efficiency, inflation/deflation, technology and the like) and nominal discount rate (the rate to use when converting nominal costs to discounted costs). To convert a nominal cost (C_N) to a discounted cost (C_D), the following equation is used:

$$C_D = C_N \times \left(\frac{1}{(1+d_n)^y}\right) \tag{4}$$

where d_n is the nominal discount rate per annum and y is the appropriate number of years. The benefit–cost ratio is estimated as the ratio of the sum of all the discounted benefits and discounted costs. It is assumed that the RWH system has a life of 40 years.

For the benefit–cost ratio (BCR), the approach outlined in CBAbuilder (2016) was used, which is to calculate by the following formula:

$$BCR = \frac{\Sigma_{t=0}^{s} \frac{S_t P_t}{(1+i)^t}}{\Sigma_{t=0}^{s} \frac{I_t + M_t}{(1+i)^t}} \tag{5}$$

where S_t is the volume of water saved over a period of time t (m^3), P_t is the cost of water over a period of time t (CNY/m^3), I_t is the investment required for a period of time t (CNY), M_t is the maintenance costs over a period of time t (CNY), s is the system life-span (year), t is the system operation period (year), and i is the interest rate (%).

The statistical analysis was performed in the Statistical Product and Service Solutions (SPSS 22.0) statistical package (IBM Corp, USA) for personal computers. Regression analysis was performed to fit the relationship between the reliability of rainwater supply, water saving efficiency and regional annual rainfall, and the F test <0.001 was considered statistically signficant. The time variability of daily water saving efficiency for each city was determined by analysis of standard deviation, skewness and variation coefficient.

3. RESULTS AND ANALYSIS

With the original water-balance model, this paper examined the water saving potential and the economic analysis converting water savings into monetary benefits, and the following subsections detail the water saving efficiency, reliability and the cost-effectiveness of the proposed RWH system.

3.1. Water saving efficiency analysis

The annual water saving efficiency of the proposed RWH system for each studied city (under different precipitation scenarios) has been calculated using Equation (3) and the results are shown in Figure 5. Generally, higher water saving efficiencies can be obtained by an RWH system with larger storage capacity and in more humid regions. As is obvious, the water saving efficiency sharply increases when the storage capacity changes from 1 to about 10 m^3. However, as is obvious, with the successive increasing of the rainwater tank, the volume of water savings become nearly constant. As shown in Figure 5, except for Guangzhou, the water saving efficiency becomes nearly constant when the storage tank is beyond a capacity of nearly 15 m^3. This can be attributed to the fact that the volume of rainwater captured by the RWH system is determined by its storage capacity when the storage tank is small. However, when the storage capacity increases and exceeds a certain volume, the volume of rainwater captured by the system keeps constant, and further increases in storage capacity can only translate to marginal increases in WSE (Jing *et al.* 2017). Guangzhou has a relatively higher threshold value of WSE due to the fact that it has higher annual rainfall than the other cities, while the lower threshold values of WSE in arid regions (e.g., Urumqi, Dalian and Shenyang) result from very limited collectable rainwater caused by very limited rainfall. This can be further explained as that for arid or semi-arid regions, the efficiency is mainly limited by the collectable rainfall, and an

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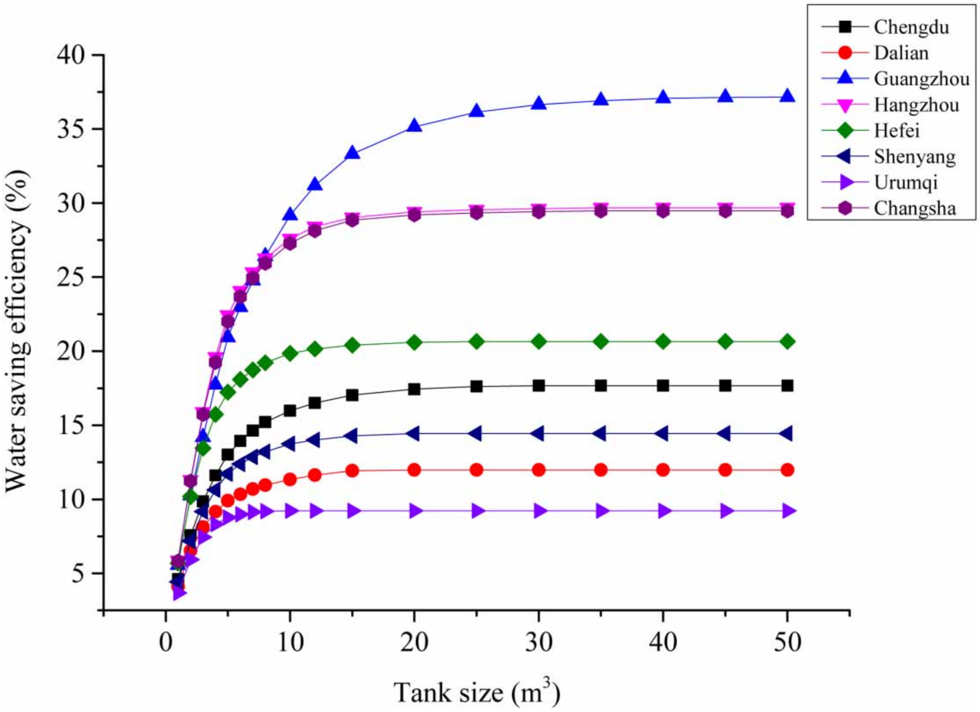

Figure 5 | The expected annual water saving efficiency of the proposed RWH system across eight cities in China.

RWH system with relatively small storage capacity is adequate to harvest all rainwater, but with an increase in annual rainfall, the storage capacity becomes the limiting factor, thus, a larger storage tank is required to collect roof rainwater.

From the figure it is evident that the expected water saving efficiency of the RWH system varies significantly among different cities. As shown in Figure 5, different threshold values (from 10% to about 37%) of WSE can be obtained depending on climate condition scenarios. In arid regions (i.e., Shenyang, Dalian and Urumqi), the water saving efficiencies stay at very low values below 15% (Figure 5). Lower values of water saving efficiency in arid regions result from the very limited collectable rainwater caused by very limited rainfall, whereas in humid regions result (e.g., Changsha, Hangzhou and Guangzhou), water saving efficiencies can reach 30% or more. Lower threshold values of WSE result from the very limited collectable rainwater determined by local climate conditions. Taking Urumqi as an example, its average annual rainfall is only 446 mm, only one-quarter that of Guangzhou. Also it is found that the water saving efficiency of the RWH system at Changsha is very close to that at Hangzhou. It should be noted that the annual rainfall at Changsha and Hangzhou is 1,427.2 mm and 1,438.3 mm, respectively. These results suggest that the WSE values are well connected with the mean annual rainfalls of the study locations.

3.2. Reliability analysis

Time-based reliability of the RWH system under different climate conditions is calculated using Equation (2), and the results are shown in Figure 6. Similar to the trends of WSE, higher supply reliability can be obtained by the RWH system with larger storage capacities, in more humid regions. As can be seen from Figure 6, there is remarkable increase in time-based reliability with the tank sizes from 5 m^3 to 8 m^3. However, it is obvious that when the rainwater tank sizes were increased up to around 10 m^3, the reliability become nearly constant, e.g. the time-based reliability reaches a plateau of around six days at Urumqi, 12 days at Dalian, 15 days at Shenyang, 25 days at Chengdu, 43 days at Changsha and 48 days at Hangzhou, respectively (Figure 6). However, as shown in Figure 6, the reliability at Guangzhou still increases with rainwater tank size increase from 20 to 50 m^3.

With regards to regional variability, it was found that southeast China (Hangzhou and Guangzhou) mostly achieves higher reliabilities and north China has mostly lower reliabilities. As illustrated in Figure 6, for non-potable water demand, the highest achievable reliability of the RWH system is found to be for Guangzhou (81 days or 22.2%) and the lowest is found to be for

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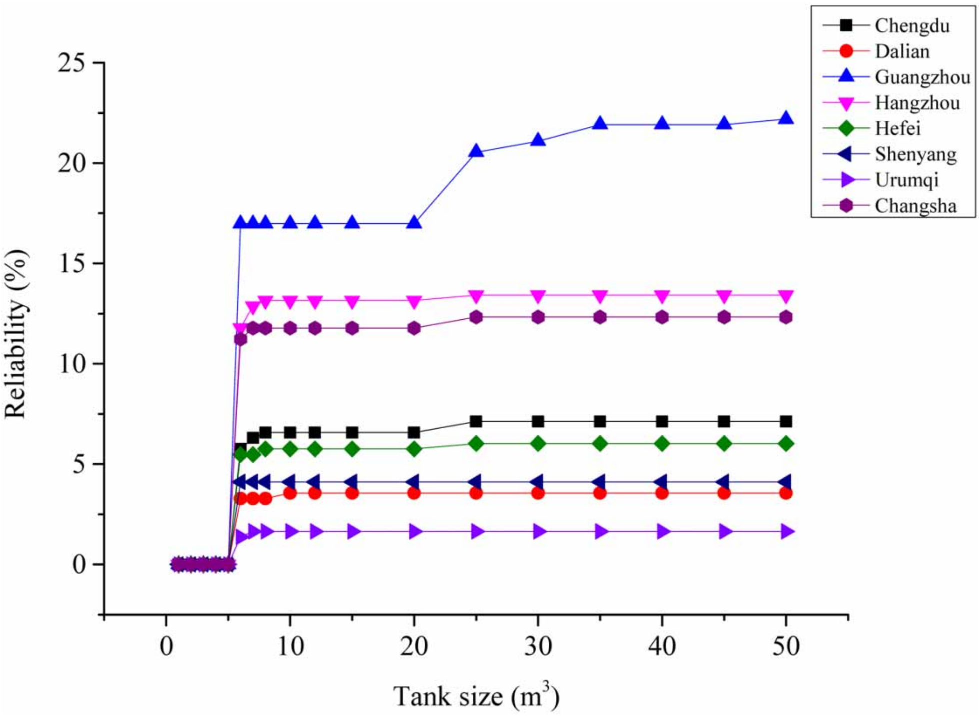

Figure 6 | The expected reliability of the proposed RWH system across eight cities in China.

Urumqi (six days or 1.6%), respectively, which is well associated with the average annual rainfall values at these two locations (1,799.8 mm and 446.7 mm for Guangzhou and Urumqi, respectively).

Furthermore, it can be observed that the values of reliability are much less in dry areas as compared with those in humid regions under the same rainwater tank scenarios. For example, at Guangzhou on average a 10 m^3 rainwater tank can meet the demand for toilet use of up to 62 days in a year. At Chengdu, it can meet the demand for toilet use of 23 days a year, while at Shenyang, it can only meet the demand of 15 days a year. This finding is consistent with results presented by Zhang *et al.* (2019) that the relatively high rainfall in a humid area allows for smaller storage capacity when compared with RWH systems in arid and semi-arid regions at the same levels of water supply reliability.

From the figures it is evident that the reliabilities of the RWH system under dry climate conditions are very small. For instance, in the arid cities of Shenyang, Dalian and Urumqi, which have mean annual rainfalls of 699.3, 580.7 and 446.7 mm, respectively, the reliability is 15 days (or 4.1%), 13 days (or 3.6%), and six days (or 1.6%), respectively. Due to the extremely low reliability, it is not recommended to install this infrastructure in these regions. With this reality of achievable maximum reliabilities it can be concluded that for most cities in China, rainwater solely is unable to supply total non-potable water demand throughout the year. Rather, rainwater should be harvested with the aim of reducing potable water demand from public water supply systems.

3.3. Benefit–cost ratio analysis

For the economic analysis, the calculation of the benefit–cost ratio (BCR) is conducted. The BCR analysis method is one of the most commonly used tools to determine the current value of future investments to compare alternative water system options (Swamee & Sharma 2008). In this analysis, the revenues (due to the reduction in public supply charges) are balanced against the associated–costs of RWH systems, such as initial investment and operational costs (Farreny Gabarrell & Rieradevall 2011). Figure 7 shows the benefit–cost ratio of the RWH system based on the current water price in all study cities.

It is evident that the values of benefit–cost ratio vary significantly with tank sizes and locations. As illustrated in Figure 7, in all cities, both in humid regions and in arid regions, the BCR of the rainwater harvesting system increase to peak values fast and then drop as storage capacities rise from 10 to 50 m^3, suggesting that the RWH systems with too small or too large storage tanks may not provide high benefit–cost ratios. This may link to the factor that in a specific area, the amount of rainwater that can be collected being certain, and a rainwater harvesting system with small storage capacity can only provide very limited water saving and economic benefits, while an RWH system with large storage capacity will be associated with very high fixed

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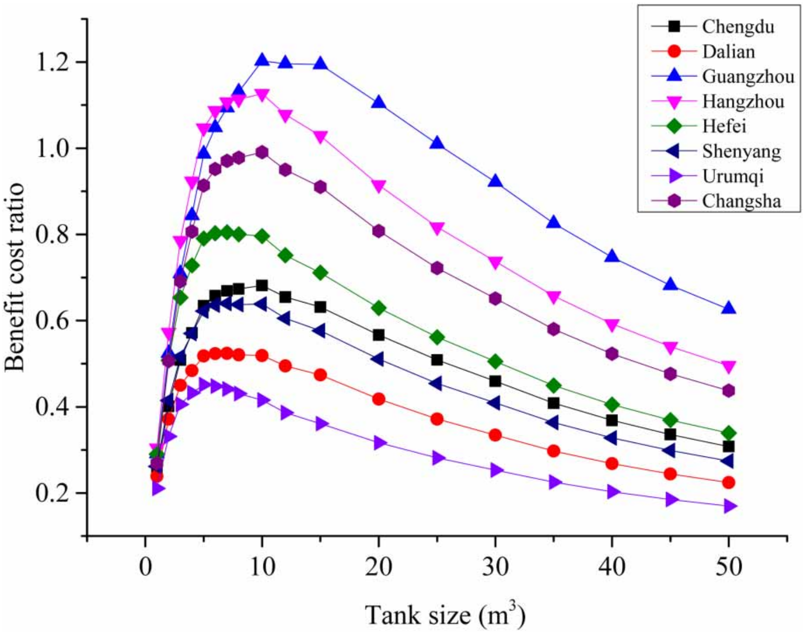

Figure 7 | The expected BCR of an RWH system under current water price.

investment and operational costs (Jing *et al.* 2017). The peak BCR values indicate the most economically feasible storage capacities of the RWH system for specific locations, e.g. as demonstrated in Figure 7, the most financially viable storage capacity of the RWH system is around 8–10 m^3 as the BCR gets its peak value in the range 0.4–1.52 depending on climate conditions.

As shown in Figure 7, the benefit–cost ratio is the highest for Guangzhou (1.20) and the lowest for Urumqi (0.45). Also it is found that the benefit–cost ratios in the semi-humid and arid regions (Chengdu, Hefei, Dalian, Shengyang and Urumqi) are below 1.00 under all rainwater tank sizes. The maximum achievable benefit–cost ratio at Chengdu is 0.68 for a 10 m^3 tank, and 0.45 at Urumqi with a 5 m^3 tank. The maximum achievable BCR values at Dalian and Shenyang are 0.52 and 0.64, respectively, both with a 7 m^3 rainwater tank. It can be inferred from these results that for the assumed RWH system scenario in this study, almost two-thirds of the regions in China are unable to obtain a BCR higher than 1.0.

3.4. Temporal variability analysis

The regularity of water supply is one of the most important indexes to judge the performance of the RWH system, because it affects the expedience of water use for the end-users, that is, whether it will be required to change water sources frequently.

Figure 8(a)–8(h) presents how much water the RWH system will save on a daily basis over a 12-month period at each of the eight cities. It is assumed that the target building has a unvarying water-use rate throughout the year. As is obvious, water saving efficiency is considerably higher in the wet season than in the dry season. Wet and dry seasons for all cities are classified based on the mean monthly rainfall in those cities, i.e., the months receiving higher rainfall than average are classified as rainy seasons, while those that receive less rainfall than the usual are classified as dry seasons. For example, the mean WSE in the wettest month (August) at Dalian is 40.4% (Figure 8(b)), which is over 15 times more than the driest month (January, 2.63%) experiences. In contrast, the temporal distribution of water saving efficiency in rainy regions is more even (Figure 8(d)). For example, in Hangzhou, the wettest time of year is from March to September, and the driest period is from October to February of the next year. The typical water-saving efficiency in a wet season is 14.2%, and that in a dry season is 8.6%, with a difference of 40%. The annual average water-saving efficiency is 11.86%, but in the wettest month (June) it is 18.7%, and in the driest month (January) it is 8.07%. The disparity between the driest month and the wettest month is only 57%.

As illustrated in Figure 8, the cyclic inconsistency of water saving efficiency of the RWH system in northern cities (i.e., Urumqi, Dalian, Shenyang and Hefei) seems to be more noteworthy than that of southern cities (Guangzhou, Hangzhou and Changsha). This divergence is most likely connected to the fact that these northern cities are largely affected by the

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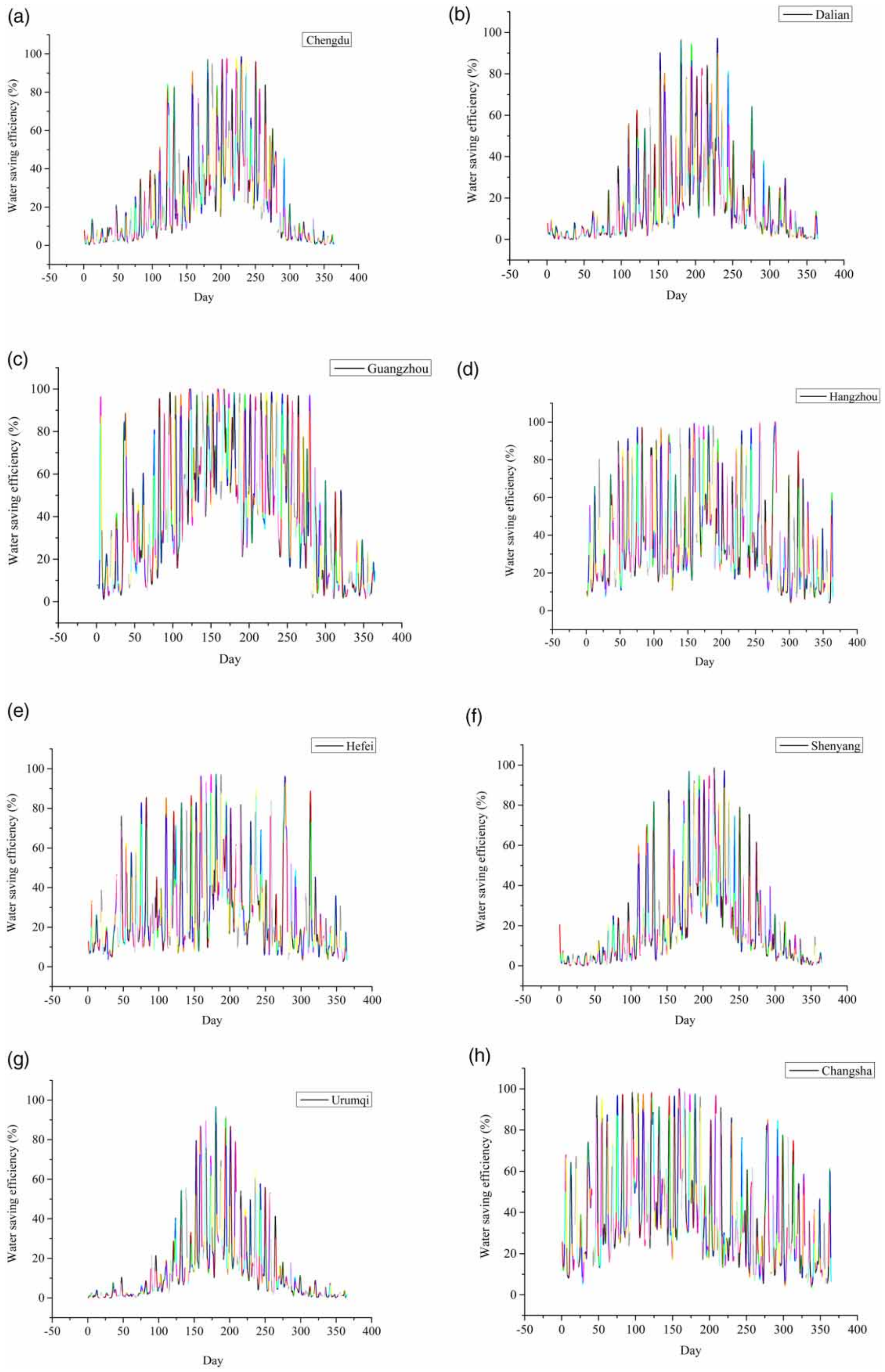

Figure 8 | Daily water saving efficiency of RWH system at eight different cities: (a) Chengdu, (b) Dalian, (c) Guangzhou, (d) Hangzhou, (e) Hefei, (f) Shenyang, (g) Urumqi, (h) Changsha.

continental monsoon climate. The characteristic trait of this climate is that there are noticeable alternations of dry season and rainy season in a year. Taking Dalian (Figure 8(b)) as an example, August has the highest monthly rainfall of 145 mm, which accounts for 25% of the annual rainfall, followed by July with 129.5 mm. January, February, March, October, November and

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December are typically dry months with a very low rainfall. This climatic characteristic leads to the WSE values in arid regions presenting a unimodal rainfall pattern of one high season and one low season per year (as shown in Figure 8(a), 8(b), 8(f) and 8(g)).

This irregular seasonal distribution of water supply makes it very difficult to manage an RWH system, for the reason that users must switch between rainwater and tap water. Additionally, users in barren areas must also face the dilemma of water quality deterioration caused by the long period with no precipitation. The results of this study show that it is exceptionally appropriate for owners south of Yangtze River in China to use rainwater as a non-drinking water resource.

Table 4 presents the mean, standard deviation, skew and variation coefficient of the daily water saving efficiency within one year in these eight cities. It should be pointed out that, due to the fact that the mean value of daily water saving efficiency varies greatly across different cities, the standard deviation presented in Table 4 cannot be taken to contrast the reliability of daily rainwater saving between each city. The variation coefficient is likely to be more precise to reflect the different extent of daily water saving. It can be seen from Table 4 that Urumqi has the largest variation coefficient, followed by Dalian, Shenyang, Chengdu, Hefei, Guangzhou, Changsha and Hangzhou. This outcome confirms that Hangzhou has the most regular profile of rainwater usage. From this point of view, Hangzhou is more appropriate for the application of the RWH system than Guangzhou, even though the mean annual rainfall is less than that of Guangzhou. Obviously, Urumqi is the poorest match for the RWH system, as it not only has the smallest annual rainfall, but also has the worst regularity of precipitation usage.

4. DISCUSSION

This paper examines the performance of an RWH system at eight different cities in China. It is found that the water saving efficiencies, reliabilities and benefit–cost ratio of the rainwater harvesting systems under various climatic conditions vary widely for these cities. As presented in Sections 3.1 and 3.2, the percentages of water saving efficiency and time-based rainwater supply reliability of the RWH system are generally in line with the historical mean rainfalls of these regions. These patterns are in agreement with earlier studies (Rahman *et al.* 2012; Amos *et al.* 2016). Among the studied cities, Guangzhou was found to be the most promising city with regards to water saving efficiency and rainwater supply reliability, achieving a maximum WSE and time-based reliability value of 37% and 81 days, respectively.

As Figure 5 illustrates, the water saving increases significantly with increasing tank size in the range of 1 m^3 to 10 m^3 for an RWH system in Urumqi, 1 m^3 to 15 m^3 for an RWH system in Dalian and Shenyang, and 1 m^3 to 20 m^3 for an RWH system in Chengdu, Hefei and Changsha, respectively. However, increases in tank capacity above these ranges do not return significant increases in water saving. This is mainly because of the fact that the total amount of rainwater that can be collected is limited. Once the storage tank is larger than the threshold, tank capacity is no longer a limiting factor, instead, the rooftop catchment area of the target building becomes a new constraint on water saving for the RWH system. In this case, it is not an economical method to increase the volume of the rainwater storage tank. In contrast, the water saving continues to increase for the whole range for an RWH system in Guangzhou, suggesting that a larger tank may be more suitable for rainy regions.

These results highlight the importance of selecting the optimal tank size in order to reach a high value of water saving efficiency and maximize the return of the initial investment, since optimal tank sizing can minimize the capital and operational cost of the system. On the basis of the system reliability and economic criteria analysis performed in the present paper, it is

Table 4 | Deviation analysis of daily water saving efficiency at eight different locations in a year

Item	Chengdu	Dalian	Guangzhou	Hangzhou	Hefei	Shenyang	Urumqi	Changsha
Dataset	365	365	365	365	365	365	365	365
Mean (E)	0.23	0.171	0.421	0.39	0.287	0.199	0.14	0.385
Standard deviation	0.275	0.242	0.342	0.307	0.277	0.258	0.214	0.303
Skewness	1.576	2.085	0.59	0.938	1.402	1.915	2.457	0.939
Variation coefficient	1.193	1.416	0.812	0.786	0.965	1.295	1.531	0.787

Note: the value of the variation coefficient is equal to the standard deviation divided by the mean, and it is a statistic of the degree of data deviation, which can better reflect the extent of data deviation than the standard deviation.

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found that under the current assumed building scenarios (an office building having a roof area of 1,600 m^2 and serving about 560 inhabitants), the appropriate range of tank capacity for an RWH system at Chengdu, Dalian, Guangzhou,Hangzhou, Hefei, Shenyang, Urumqi and Changsha is 10–25 m^3, 8–20 m^3, 15–40 m^3, 10–30 m^3, 8–25 m^3, 7–20 m^3, 6–10 m^3, and 10–25 m^3, respectively.

The water saving potential and economic effectiveness of the proposed RWH system obtained in our study are compared with similar previous studies. There have been many studies that assessed the water saving efficiency and the financial viability of RWH systems based on an analysis of the system life-cycle (Neto *et al.* 2012; Ward *et al.* 2012; Loubet *et al.* 2014; Morales-Pinzón *et al.* 2015). For example, Domènech & Saurí (2011) found that for Sant Cugat del Valles in Barcelona, Spain (mean annual rainfall of 515 mm), an RWH system (roof area of 107 m^2, 22 m^3 tank size) can achieve an average annual water saving of 43 m^3 for toilet and laundry use. For this study, Dalian has a comparable mean annual rainfall (580 mm), and for this city an RWH system (roof area of 1,600 m^2 and 50 m^3 tank size) can achieve an average annual water saving of 743 m^3. If the water saving value of Sant Cugat del Valles is multiplied by the ratio of roof area of Dalian (1,600 m^2) and Sant Cugat del Valles (107 m^2), the water saving becomes 640 m^3, and the amount of water saving between these two cities (Sant Cugat del Valles in Spain and Dalian in China) is not signficantly different. Ghisi & Schondermark (2013) found that an RWH system could meet 60%, 42% and 30% of the water demand for Itaquaquecetuba (Brazil), Florianopolis (Brazil) and Darwin (Australia) where the mean annual rainfall values were 1,380, 1,839 and 1,483 mm, respectively. In our study, a 50 m^3 RWH system at Changsha, Hangzhou and Guangzhou (with mean annual rainfall of 1,427, 1,438 and 1,799 mm respectively) can meet 30%–37% of the non-potable demand. Thus, the results of water saving efficiency obtained in our study are comparable with these three cities.

In terms of benefit–cost ratio of the RWH system, Rahman *et al.* (2012) have found that the benefit–cost ratios for the rainwater tanks are smaller than 1.0 without the government rebate currently offered in some Australian cities. In another study, Dias *et al.* (2007) reported that the RWH system is not viable in northeastern Brazil, with this prospect changing only when water prices are raised. Similarly, Sample & Liu (2014) have evaluated the RWH system across a wide range of locations in Virginia, USA, and found that in a high-density residential area, for an RWH system having a roof area of 1,000 m^2 and 50 occupants, the current water price needs to be increased by about 100% to achieve a benefit–cost ratio of 1 at most of the locations (Hajani & Rahman 2014). However, Tam *et al.* (2010) evaluated the cost-effectiveness of RWH systems in seven cities of Australia and found that RWH systems can offer notable financial benefit and are economically feasible in Gold Coast, Brisbane, and Sydney due to the relatively higher rainfall in those cities. As Tam *et al.* (2010) stated, the favorable financial outcomes achieved by Gold Coast, Brisbane, and Sydney may be supported by the facts that these regions receive higher amounts of precipitation. From the results of previous studies, it appears that a common conclusion can be drawn that the economic feasibility of RWH systems depends largely on the local rainfall. These results are highly in agreement with our findings. In this study, it is found that in all of the arid and semi-humid regions (i.e., Hefei, Chengdu, Dalian, Shenyang and Urumqi, which have a mean annual rainfall lower than 1,200 mm), the benefit–cost ratios are less than 1.0, and this result suggests that it is not financially viable to apply the RWH system in these regions. A preliminary conclusion can be drawn from the present results that an annual rainfall of 1,200 mm is the watershed that determines whether an RWH system in an area can achieve economic feasibility or not.

The distribution of the daily water-saving efficiency on a yearly scale in eight regions is also compared by this paper. From the statistical results (Table 4), the southeast region (represented by Hangzhou) has the lowest coefficient of variation, which suggests that the most regular profile of rainwater use can be found in this area although it does not enjoy the highest annual rainfall. However, it is second only to Guangzhou, which is the highest. By comparison, northwest China (represented by Urumqi) has the highest coefficient of variation regarding daily water-saving efficiency, signifying that the RWH system performance is the worst in this region, for this is where there is not only the lowest yearly water saving, but also the most uneven rainwater use. In general, it is confirmed that the southern areas display better performance in both annual water saving and time regularity than the northern regions. That the southern regions are more adaptable to the RWH system than the northern regions of China is verified by these results.

Although the rainwater supply reliability observed is very small as compared with the present water demand, and the benefits from the RWH system are not enough to offset their costs within the lifespan, encouragement to install RWH systems should be continued. This is because, on the one hand, installation of RWH systems in these public buildings will not only lead to drinkable water savings and water stress reduction but also go further in reducing the water clogging problem in these cities. On the other hand, based on the past water price records, it is predicted that the water tariff is most likely to increase.

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Thus the monetary savings will be increased and the RWH system will be more attractive with increasing water price in future (Bashar *et al.* 2018). For these reasons, governmental water authorities should take initiatives to educate urban dwellers on the benefits associated with implementation of the RWH system to achieve sustainable urban development.

Performance assessment for specific locations helps us to understand the impact of climatic and geographical conditions on the RWH system. Although the current study is specific to China, this paper presents an insight on potential regional variations of RWH system outcomes and such a study will motivate others to conduct similar comparative studies elsewhere. This sort of information is of great significance for decision-makers such as local government authorities, who can accordingly give suggestions to designers or end-users. Moreover, the results presented in this paper will be quite useful for practical designs of RWH systems that take into consideration different scenarios of climate (rainfall amount), with impacts mainly on infrastructure investments. The economic viability analysis presented here will enable an investor to consider the impacts of climate variables on economic viability, in order to ensure an appropriate system design and better economic outcomes (Severis *et al.* 2019).

It is to be mentioned here that in this study to calculate the efficiency, reliability and benefit–cost ratio of the RWH system, an assumed water demand was considered due to the lack of actual water consumption data, and for uniformity in analysis, a common daily non-potable water demand of 36 litres per capita per day was assumed in accordance with the *Code for Design of Building Water Supply and Sewerage*. However, due to differences in climate conditions and water facilities, the non-potable water demand of office buildings may vary in different regions. Further research is needed to assess the installation of the RWH system under each scenario of non-potable water demand, to provide more detailed water saving potential and benefit returns of this green infrastructure under different geographical and climatic conditions.

5. CONCLUSION

In this paper, a comparative study of potential water saving, supply reliability, benefit–cost ratio and temporal distribution of rainwater supply on an annual scale of an RWH system in different cities of China is presented. It is found that for a standard building (1,600 m^2 roof having 560 people), the water saving efficiencies, rainwater supply reliability and the benefit–cost ratio of the RWH system varies significantly across these cities. Guangzhou (south China) is found to achieve the highest efficiency (39%) and rainwater supply reliability (81 days a year). By contrast, Urumqi (northwest China) is mostly ranked as having the lowest efficiency (8.0%) and reliability (six days). The benefit–cost ratio varies between 0.45 (Urumqi) and 1.20 (Guangzhou) across the studied cities. Also, it is found that the southeast region (represented by Hangzhou) has the most regular profile of rainwater use, while northwest China (represented by Urumqi) has the most uneven rainwater use. The water saving potential and financial returns are closely related to the local precipitation. An annual rainfall of 1,200 mm is the watershed that determines whether an RWH system in an area can achieve economic feasibility or not. These results confirm that southern regions are more adaptive to the RWH system than the northern regions of China. The spatiotemporal characteristics analysis of the RWH system will help the authorities to identify the regions where the application of this green infrastructure would be most effective. This study can also help to determine an appropriate tank size for a given building in a given location. For example, it is found that under current building scenarios, the optimal tank capacity for an RWH system to achieve the best financial outcome for the home owners ranges from six to 15 m^3 depending on rainfall across the eight study cities.

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AUTHOR CONTRIBUTIONS

C.S. (Lecturer) conceived the research goals, designed the methodology, and wrote the manuscript. Z.Y. (Graduate student) analyzed data. L.X. (Graduate student) analyzed data. L.X. (Graduate student) analyzed data.

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CONFLICTS OF INTEREST

The authors declare no conflicts of interest

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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