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

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ABSTRACT

Financial viability of 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 6 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 uppermost benefit cost ratio, while southeast China has the most habitual summary 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 feasibility 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 industrialization and urbanization movement, China has been facing increasingly 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; Roni et al. 2019). Whereas 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 (Grace & Chun 2017). Despite rainwater harvesting has been demonstrated by many studies (Zuo et al. 2010; Liang & Dijk 2011; Zhang & Hu 2014) as one of the best methods available for establishing sustainable water cycles in urban developments, and the local governments have launched many incentive programs to encourage people to install this green infrastructure (Li 2009). Most city dwellers are still showing reluctant in adopting this green infrastructure mainly due to the lack of sufficient data to support the benefits of RWH system (Mohammad et al. 2018).

As have 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 (Ali et al. 2016; Amos 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 determining its optimum tank size to ensure maximum water supply reliability and water saving efficiency under local rainfall conditions (Ali et al. 2016; Amos et al. 2016). Despite the regional conditions have great impacts on the economic feasibility of RWH system. However, within China, few researches have devoted to compare the water saving potential and economic benefit of RWH system under different regions.

Except for the economic factors, for most end-users, an additional concern of the 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 would need to be, and thus there will be an even greater threat of water quality deterioration. Therefore, the seasonal unpredictability of precipitation is also an 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 utilisation of rainwater in areas that have a more regular rainfall pattern. Even though the chronological variability of rainfall has a significant variation in 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, and 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 system.

Therefore, the objective of this study is to assess the potential performances of RWH system in different weather conditions across different climate zones in China. Water saving parameters and economical benefits were calculated based on a scenario of high-rise official building with 560 occupants and catchment area of 1,600 m², where the non-potable water consumption was 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 scenarios assumption of rainwater harvesting system (Section 2.2), detail the methods assumed in this project to compute the water savings (Section 2.3) and benefits costs ratio (Section 2.4).

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 classified by mean annual rainfall, i.e. the humid zones were defined with mean annual rainfall larger than 1,200 mm, semi-humid zones were defined with mean annual rainfall between 800 and 1,200 mm, and arid zones were defined with mean annual rainfall less than 800 mm. Figure 2(a)–2(h) show the monthly rainfall of the selected study sites.

2.2. Scenarios

The most common building form for installing rainwater reuse system in those cities is high-rise office buildings (the proportion of flushing water consumption is quite large) with fat 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 the uniformity in evaluating the performance of RWH system across different cities, in this study, a hypothesized development is considered at each of the study locations with an official building having a roof areas of 1,600 m² and serves about 560 inhabitants. A gravity system is assumed to be serving indoor use (Figure 3). Rainwater generated from the building roof were collected and considered being used for toilets flushing (which account for a great portion of non-potable demand) in the building.

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

Generally, rainwater needs further treatment before use in order to lower health risks (Leong et al. 2017). The treatment system considered in 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 illustrates in Figure 3, in the RWH system, the rainwater is harvested from rooftop of the model building. After that, the rainwater flows through a first flush device to abandon the early runoff, and then flow into a storage tank through a static sieve to remove large solids (e.g. leaves and twigs). After storage stage, the rainwater passes through a micro-membrane filter under gravity head. 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, first step is to collect some basic data consist of the 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 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 consider 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

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 standard for design of building water supply and drainage (GB50015-2019). According to 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 2 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 demand of this building is equivalent to 20.16 m$^3$ per day. It is assumed that the non-potable demand at the weekends is estimated at one fifth of that during the 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 were 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 include the rainwater tank, pipe lines, 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 is 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 a RWH system. The estimated total facilities expenses are 14,901 CNY (China 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 a RWH system, 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 benefits cost ratio of the RWH system. The price of storage tank (stainless steel) with different size are listed in Table 2.

The price information in the table comes from 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 period have been neglected. Because the harvested rainwater from rooftop to storage tank and from the tank to the points of use were delivered by gravity (Figure 2), so no electricity consumed in this case. Therefore, the average annual operating costs are 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 a RWH system. This annual revenue is estimated as the product of potable water savings and water tariff. The value of possible environmental benefits from a RWH system (e.g., reducing resources consumption from water treatment processes) is not considered in the costs benefits analysis due to limited data availability. The terminal domestic water price, includes water supply price and sewage treatment fee, is used in the economical viability analysis of RWH system. The terminal water price 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, (2) the economical feasibility.

### Table 1 | The constant investment of a 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 sterilise                | 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)    | Meter | 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 | 14,901 |

Note: average currency data from 01/07/2019 to 31/07/2019; 1 CNY was equal to 0.1427USD.
In order to calculate the water saving of a RWH system, a yield after supply (YAS) model on 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 to 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 (shows in Figure 4). Afterwards, the consumed rainwater is determined depending on whether the stored rainwater is enough to satisfy the daily non-potable demanded or not. For example, if the stored rainwater is greater than or equal to the non-potable demanded, the consumed rainwater are 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 compute procedure will repeat for each day of one year (Silva et al. 2015).

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

\[
V_c = \frac{R \times A_c \times C}{1000}
\]

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 were 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 intended non-potable water consumption is met fully by the available rainwater and the total number of simulated days, which is defined as follow:

\[ R_t = \frac{N}{365} \times 100\% \]  

(2)

where, \( R(t) \) is the reliability of the RWH system to be able to supply the intended demand (%), N indicates the number of days in a year when rainfall runoff achieve to meet 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, is defined as follows:

\[ WSE = \frac{V}{D} \times 100\% \]  

(3)

where, \( V \) is volume of rainwater consumed (m³) and \( D \) is total water demand (m³).

In the economical feasibility analysis, Benefits Cost Ratio (BCR) were performed considering the installation and maintenance costs, 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.
To carry out the economic performance analysis, all the present and future values are converted to present day RMB value. In this study, a basic financial internal rate of 6% is considered according to the economic evaluation methods and parameters of municipal public facilities 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) (AS/NZS, 1999). To convert a nominal cost ($CN$) to a discounted cost ($CD$), the following equation is used

$$CD = CN \times \left( \frac{1}{(1 + d_n)^y} \right)$$

(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 Benefits Cost Ratio (BCR) the approach outlined in Chabuilder (2016) was used, which is calculated by the following formula:

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

(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 (CNY), $s$ is the system life span (year), $t$ is the system operation period (year), and $i$ is the interest rate (%).

The statistical analysis were performed in Statistical Product and Service Solutions (SPSS 22.0) statistical package (IBM corp., US) 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 significant. The time variability of daily water saving efficiency for each city were determined by analysis of standard deviation, Skewness and variation coefficient.

### 3. RESULT AND ANALYSIS

With the original water balance model, this paper examined the water saving potential and the economic analysis convert water savings in to monetary benefits, the following subsections detailed 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 (5) and the results are shown in Figure 5. Generally, higher water saving efficiencies can be obtained by RWH system with larger storage capacity and in more humid regions. As obvious, the water saving efficiency sharply increases when storage capacity changes from 1 to about 10 m$^3$. However, as obvious, with the successive increasing of the rainwater tank, the volume of water savings become nearly constant. As shown in Figure 5, except Guangzhou, the water saving efficiency becomes nearly constant when storage tank 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 certain volume, the volume of rainwater captured by the system keep constant, 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 is due to the fact that it has higher annual rainfall that other cities, while lower threshold values of WSE in arid regions (e.g., Urumqi, Dalian and Shenyang) are resulted from very limited collectable rainwater caused by very limited rainfall. This can be further explained that for arid or semi-arid regions, the efficiency is mainly limited by the collectable rainfall, a RWH system with relatively small storage capacity is
adequate to harvest all rain-off, but with an increase in annual rainfall, the storage capacity become the limiting factors, 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 conditions scenarios. In arid regions (i.e., Shenyang, Dalian and Urumqi), the water saving efficiencies stay at very low values that below 15% (Figure 5). Lower values of water saving efficiency in arid regions are resulted from very limited collectable rainwater caused by very limited rainfall. Whereas in humid regions, (e.g., Changsha, Hangzhou and Guangzhou), water saving efficiencies can reach 50% or more. Lower threshold values of WSE are resulted from very limited collectable rainwater determined by local climate conditions. Take Urmuqi as an example, its average annual rainfall is only 446 mm, only one fourth of Guangzhou. Also it is found that the water saving efficiency of RWH system at Changsha are very close to that at Hangzhou. It should be note 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
Tame-based reliability of RWH system under different climate conditions are calculated using Equation (2), and the results have been shown in Figure 6. Similar to the trends of WSE, higher supply reliability can be obtained by 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 50 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 6 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 incerase with rainwater tank size increase from 20 to 50 m$^3$.

With regards to regional variability, it was found that South-East China (Hangzhou and Guangzhou) is mostly achieving higher reliabilities and North China is mostly having lower reliabilities. As illustrates 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 Urumqi (6 days or 1.6%), respectively, which is well associated to the average annual rainfall values at these two locations (1,799.8 mm and 446.7 mm for Guangzhou and Urumqi, respectively).

Further more, it can be observed that the values of reliability are much less in dry areas as compared to those in humid regions under the same rainwater tank scenarios. For example, at Guangzhou on average a 10 m³ rainwater tank can meet the demand for toilet use 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 founding is consistent with results presented by (Zhang et al. 2019) that relatively high rainfall in the humid area allow for smaller storage capacity when compared to 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 the dry climate conditions are very small. For instance, in the arid city of Shenyang, Dalian and Urumqi, which has a mean annual rainfall of 699.3, 580.7 and 446.7 mm, respectively, the reliability is 15 days (or 4.1%), 13 days (or 3.6%), and 6 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 system.

3.3. Benefit cost ratio analysis

For the economic analysis, the calculation of the benefits costs 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 operation costs (Farreny Gabarrell & Rieradevall 2011). Figure 7 shows the benefit cost ratio of 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 illustrates in Figure 7, in all cities, both in humid regions and arid regions, the BCR of rainwater harvesting system increase to peak values fastly and then drop as storage capacities rise from 10 to 50 m³. Suggesting that the RWH system 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 is certain, rainwater harvesting system with small storage capacity can only provide very limited water saving and economical benefits, while RWH system with large storage capacity will be associated with very high

Figure 6 | The expected reliability of the proposed RWH system across eight cities in China.
fixed investment and operational costs (Jing et al. 2017). The peak BCR values implying that the most economically feasible storage capacities of RWH system for specific locations. E.g., as demonstrates in Figure 7, the most financially viable storage capacity of RWH system is around 8–10 m³ as the BCR gets it peak value range from 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, Shenyang 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 m³ tank, and 0.45 at Urumqi with a 5 m³ tank. The maximum achievable BCR value at Dalian and Shenyang are 0.52 and 0.64, respectively, both under a 7 m³ rainwater tank. It can be inferred from these results that for an assumed RWH system scenario in this study, almost two-third of the regions in China 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-months period at each of the eight cities. It is assumed that the target building has an 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 fifteen 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 was 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
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

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.
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 time 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 among 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 Guangzhou has. 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 a RWH system at 8 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 Section 3.2, the percentage of water saving efficiency, 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 savings efficiency and rainwater supply reliability, which achieves 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, 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 target building becomes a new constraint to water saving for the RWH system. In this case, it is not an economical method to increase the volume of 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 highlighted the importance of selecting the optimal tank size in order to reach 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

### Table 4 | Deviation analysis of daily water saving efficiency at 8 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    |

It is note that the value of the variation coefficient is equal to the standard deviation divided by the mean, it is a statistic of the degree of data deviation, which can better reflect the extent of data deviation than the standard deviation.
paper, it is found that under the current assumed building scenarios (an official building having a roof areas of 1,600 m² and serves 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 m³, 8–20 m³, 15–40 m³, 10–30 m³, 8–25 m³, 7–20 m³, 6–10 m³, 10–25 m³, respectively.

The water savings 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 savings 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; Tito et al. 2015). For example, Domenech & Saurí (2011) found that for Sant Cugat del Valles in Barcelona, Spain (mean annual rainfall of 515 mm) a RWH system (roof area of 107 m², 22 m³ tank size) can achieve average annual water saving of 45 m³ for toilet and laundry use. For this study, Dalian has a comparable mean annual rainfall (580 mm), for this city a RWH system (roof area of 1,600 m² and 50 m³ tank size), can achieve an average annual water saving of 743 m³. If the water saving value of Sant Cugat del Valles is multiplied by the ratio of roof area of Dalian (1,600 m²) and Sant Cugat del Valles (107 m²), the water saving becomes 640 m³, the amount of water savings between these two cities (Sant Cugat del Valles in Spain and Dalian in China) is not significantly different. Ghisi & Schondermark (2013) found that a RWH system can meet 60, 42 and 50% 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 m³ RWH system at Changsha, Hangzhou and Guangzhou (with mean annual rainfall of 1,427, 1,458 and 1,799 mm respectively) can meet 50%-57% 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 RWH system, Rahman et al. (2012) have found that the benefit-cost ratios for the rainwater tanks are smaller than 1.0 without government rebate currently offered in some Australian cities. In another study, Dias (2007) reported that RWH system is not viable in northeastern Brazil, with this prospect changing only when water prices were raised. Similarly, Sample & Liu (2014) have evaluated RWH system across a wide range of locations in Virginia, USA and found that in high density residential area a RWH system having roof area of 1,000 m² and 50 occupants, and they found that the current water price needs to be increased by about 100% to achieve a benefit cost ratio of 1 at most of locations (Evan & Ataur 2014). However, Tam et al. (2010) evaluated the cost effectiveness of RWH system in 7 cities of Australia and found that RWH system 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 favourable financial outcomes achieved by Gold Coast, Brisbane, and Sydney may be supported by the facts that these regions are receiving higher amount 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, where has a mean annual rainfall lower than 1,200 mm), the benefit-cost ratios are less than 1.0, this result suggests that it is not financially viable to apply 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 a 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 uppermost 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, that southern areas display better performance in both annual water saving and time regularity than the northern regions is confirmed. That the southern regions are more adaptive 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 to the present water demand, and the benefits from the RWH system are not enough to offset their costs within the lifespan, the encouragement of installing RWH system 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 most likely that the water tariff is predicted to increase. Thus the monetary savings will be increased and the RWH system will be more attractive with increasing water price in future.
For these reasons, water authorities of government should take initiatives to educate the urban dwellers on benefits associated with implementation of RWH system to achieve a sustainable urban development. Performance assessment for specific locations helps us to understand the impact of climatic and geographical conditions on the RWH system. Although, current study is specific to China, however this paper presents an insight on potential regional variations of RWH system outcomes and such study will motivate others to conduct similar comparative studies for elsewhere. This sort of information is of great significance for decision makers such as local government authorities, who can accordingly suggest the designer 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 scenario of climate (rainfall amount), with impacts mainly on the infrastructure investments. The economic viability analysis presented here 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 (Roni 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 the uniformity in analysis, a common daily non-potable water demand of 36 litter per capita per day has been assumed according to the Code for design of building water supply and sewerage. However, due to the difference of climate conditions and water facilities, the non-potable water demand of the official building may varies in different regions. Further research is needed to assess the installation of RWH system under each scenario of non-potable water demand, to provide more detailed water saving potential and benefits 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 the temporal distribution of rainwater supply on a year scale of RWH system at different cities of China is presented. It is found that for a standard building (1,600 m² roof having 560 people), the water saving efficiencies, rainwater supply reliability and the benefit cost ratio of 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). In the contrary, Urumqi (Northwest China) is mostly ranked as having the lowest efficiency (8.0%) and reliability (6 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 uses. 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 a 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 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 is ranges from of 6 to 15 m³ depending on rainfall across 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) analyze data. L.X. (Graduate student) analyze data. L.X. (Graduate student) analyze data.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest.
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