Water saving potential and economic viability assessment of rainwater harvesting system for four different climatic regions in China

Chen Shiguang and Zhang Yu

ABSTRACT

Rainwater is one of the most promising alternative water sources. However, the financial outcomes of the rainwater harvesting (RWH) systems are not always assured as economic performance of RWH systems vary greatly under different climatic conditions.This paper investigates reliability, water saving and benefit–cost ratio of an RWH system with different storage tanks and under three distinct climatic conditions (i.e., wet, average and dry year) at four cities in China. It was found that for a standard building (1,600 m^2 roof having 560 people), the rainwater supply reliability varies significantly (3.85–20.55%) across four cities. It was found that Guangzhou (South China) always achieves the highest reliability, greatest annual water saving and highest benefit–cost ratio under three distinct climate conditions. By contrast, Beijing (North China) is mostly ranked as having the lowest one. These findings are well in line with the historical annual precipitation in these regions. Also, it was found that across these four regions, it was not possible for a RWH system to achieve a benefit–cost ratio higher than 1.0. These findings indicate that the RWH systems in most regions of China are currently economically unfeasible without government subsidies.

Key words | benefit–cost ratio, climate condition, rainwater harvesting system, spatial variability, tank sizes

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HIGHLIGHTS

- The rainfall scenario plays a decisive role in ensuring economic feasibility of an RWH system.
- Guangzhou is the most promising city in terms of water savings and financial performance.
- An RWH system using 15–20 m^3 storage tank was found to achieve the best financial outcome in four cities.
- For RWH systems in most cities of China it is difficult to achieve financially viability without government subsidies.

INTRODUCTION

Urban development, along with the economic and population growth experienced in many regions in China, has led to an increase in the demand for water, especially in highly populated areas such as the region of Pearl River Delta and Yangtze River Delta. Moreover, uncertainties associated with climate change will intensify the pressure of future water supply in these regions (Alamdari *et al.* 2018). To address the issue of water crises, national and local water authorities are considering different measures including promoting water efficient devices, rainwater collection and greywater recycling (Imteaz *et al.* 2015). Among all these sustainable water alternatives, rainwater harvesting (RWH) is considered as the most promising

doi: 10.2166/ws.2020.307

measures due to its easy collection, less contaminated by chemical residues (Grace 2017), low cost and low treatment requirements (Zhang & Hu 2014). e.g., Zhu *et al.*(2004) examined the quality of harvested rainwater in arid regions of North China, and it was found that the rainwater harvested from a roof-yard catchment system mostly agreed with the World Health Organization standards for drinking water.

However, operating experience suggests that the efficiency of rainwater collection system varies with the change of regional characteristics such as climate, rainfall, water consumption habits and tap water price (Khastagir & Jayasuriya 2010; Sample & Liu 2014).

China is one of the largest countries in the world. Its territory spans four climate zones from south to north, namely: tropical monsoon climate, subtropical monsoon climate, temperate monsoon climate and temperate continental climate, respectively. These situation leading to a high rainfall gradient across the country (i.e., mean annual precipitation ranging from 400 mm in the northwest to over 3,000 mm in the southeast over China mainland). Considering the changes of rainfall in different regions, the benefits of an RWH system may various. Therefore, it is obvious that rainwater availability as well as water demand for the specific location should be considered when assessing the water saving potential and financial viability of an RWH system (Lin *et al.* 2018). However, China currently has only limited regional data for the operation of RWH system, yet there is an issue here in the national guidelines only provide general advice, they do not pay attention to the varied conditions that exist throughout China, such as rainfall patterns, water demand profile, levels of runoff, and tap water price, etc. (Ma *et al.* 2017). Local authorities simply imitate other cities' guidelines that may not be suitable for their area since every city has its own distinctive climatic conditions, water demand profile and public water price (Nguyen *et al.* 2019).

As the rainfall patterns, water demand scenarios as well as water price in China vary greatly from one city to another, there is a need for a comparative study regarding the rainwater supply reliability and economic benefits of an RWH system to help the authorities to set a more accurate guideline for different cities (Bashar *et al.* 2018).

In this study, the impacts of spatial variability and climate conditions on water saving potential and financial performances of RWH systems at four different cities (i.e., Guangzhou, Wuhan, Beijing and Harbin, since they represent four different climate zones in China) of China mainland were investigated. A daily scale water balance model is developed to calculate the water saving potential and economic benefits of the proposed RWH systems using historical rainfall data and daily water demand data. With the realization that using historical rainfall data may not accurately evaluate the water saving potential of a RWH systems (as Hajani & Rahman (2014a) pointed out, the average daily rainfall of long period statistic data will be more evenly distributed than single year data thus probably leading to more preferable result for water saving efficiency), three distinct rainfall conditions (i.e., dry, average and wet year) are considered in this study.

METHODOLOGY

The following sections present the study site, and detail the methodology assumed in this work to compute the water savings efficiency, benefits and costs of the RWH system.

Survey region

The study considered four different cities across China, from south to north according to the geographical location these were Guangzhou, Wuhan, Beijing, and Harbin, which locates on the north edge of the Pearl River Delta Plain, the west edge of Yangtze Plain, the north edge of the North China Plain, and the central of the Northeast China plain, respectively. Figure 1 shows the geographic locations of the selected cities along with their average annual rainfalls. These cities represented four typical climate zones, namely tropical monsoon climate, subtropical monsoon climate, temperate monsoon climate and temperate continental climate, respectively. The average annual precipitation of these four target cities is 1,799.8 mm, 1,256.0, 624 and 616 mm (statistical average from 1990s to 2019s), respectively, while the average annual temperature in these four cities is 22.5 °C, 16.6 °C, 11.6 °C and 3.5 °C, respectively.

Scenario assumption

For economic benefits analysis of the RWH system in different cities, a base scenario of multi-storey official building

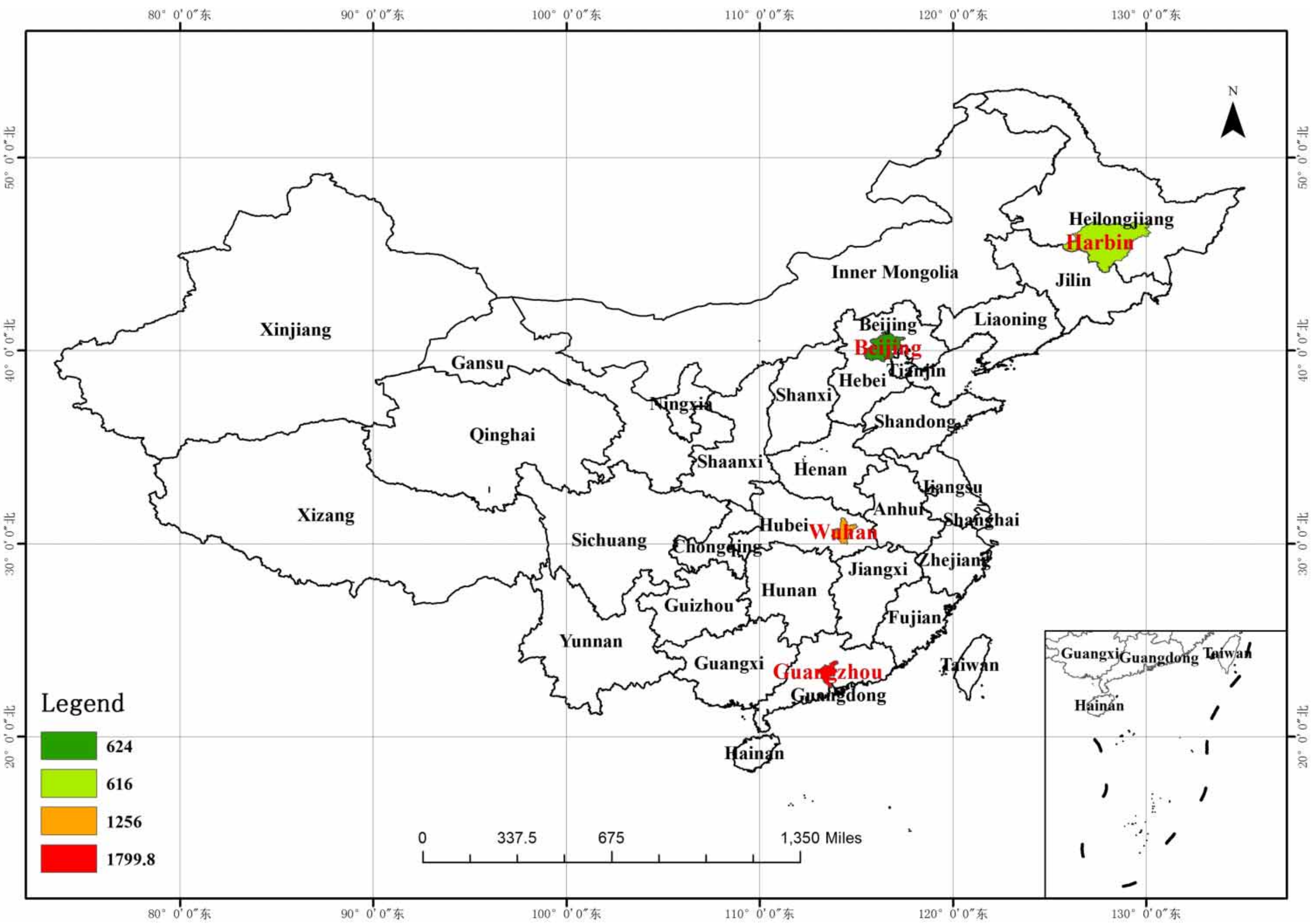

Figure 1 | Location of the fours, Guangzhou, Wuhan, Beijing and Harbin.

that has 560 employees was assumed. For the uniformity in analysis, a impervious roof size of 1,600 m^2 is considered, which is a very common roof size for the official buildings in these cities. The target building is assumed to have an RWH system for non-potable use. The water consumption of this building is calculated based on per capita water consumption quota, and the available rainwater can be estimated by precipitation and catchment area.

The newly established RWH systems were synthesized into the water network in the office building to satisfy the non-potable water demands. Three different water use are considered, they are toilet flushing, hand washing, and cleaning, which do not require potable water quality since there are only four kinds of sanitary appliances in the toilet of the office building, i.e. toilet, urinal, wash basin and sink. A sediment and filtration treatments process was considered for regenerating rainwater. First flush and leaf-eater devices are considered to filter contaminants from roof runoff before water enters into the tank. in such a way that the quality of this water can satisfy the demands of the different uses.

Data

In order to conduct an economic benefit analysis, daily rainfall data for four study cities, information about the water demand profile, and detailed financial data of installing and operating a RWH system are therefore need to be collected.

Rainfall data

To analyze the water supply reliability of RWH system, the latest decades historical rainfall data were considered. Historical daily rainfall data from 2010 to 2019 were obtained from the National Meteorological Science Data Center of China (http://data.cma.cn). Considering the variation of climate between years, as such for each study city, three years' data represent dry year, average year and wet year were used, respectively. The dry, wet and average years were identified following the recommendation of Bashar *et al.* (2018). The year receiving annual rainfall close to the average annual rainfall of the period between 2010 and 2019 is considered as the average year, e.g., in Wuhan, precipitation in 2014 is 1,207.6 mm, which is very close to the average annual rainfall of 1,256 mm (see Figure 1), is selected as the average year. While the dry and wet years are identified as the years receiving the lowest and highest annual rainfall during the period between 2010 and 2019. Selected years and corresponding rainfalls for each city are shown in Table 1.

Water demand scenarios

The total water consumption at the target building was determined based on the standard for design of building water supply and drainage (GB50015-2019). In China, daily water consumption quota in office building were estimated ranges from 30 to 50 L per person per day according to climate conditions and economic development level, 90% of which can be replaced by non-potable water.

In this study, rainwater is considered only for non-potable uses, they are toilet flushing, hand washing, and cleaning. The daily non-potable water consumption at target building in Guangzhou,Wuhan,Beijing and Harbin was estimated at 45 L, 40 L, 35 L, and 30 L per capita, respectively, and these water demand were assumed to be constant from Monday to Friday. Therefore, the total average daily water consumption for target building is equivalent to 22.5, 20, 17.5 and 15 cubic metres, respectively. The water consumption on weekends is estimated to be one-fifth of that in weekdays.

According to the data registered by water meters in another similar office building located in Guangzhou, the average daily water consumption during the period between January to December 2019 was 44.3 m^3, it was well in accordance with the value calculated according to the standard for design of building water supply and drainage (GB50015-2019), which demonstrated that the estimated water consumption data were accurate and reliable.

Financial data

The costs analysis considers the capital and operating costs of the RWH system. The capital costs include the facilities expenses and installation cost. The RWH system used in this study consists of a flush diverter, a stainless tank, mosquito nets, PVC pipelines, a set of physical filters, and additional facilities, etc. Price information of the RWH system components was mainly obtained through a market survey.

Table 2 provides a summary of the initial capital (excluding storage tank) of an RWH system. The estimated total facilities expenses are 14,901 yuan (CNY) (Table 2). The installation cost was estimated at 10% of the total facilities expenses, which is equivalent to 1,490.1 CNY, thus the total capital cost is 16,391.1 CNY.

In this study, influences of different tank capacity on the cost–effectiveness of an RWH system are assessed. The tank size was defined based on market availability with the goal of determining the maximum benefit–cost ratio (BCR). The prices of storage tanks (stainless steel) with different sizes are listed in Table 3.

The annual operating cost here refers to the expenses of purchases, installatons, operating costs and maintenance for the infrastructure (water tanks, pumps and pipes) needed for

Table 1 | Selected years and corresponding rainfalls of four study site

	Guangzhou		Wuhan		Beijing		Harbin	
	Year	**Rainfall (mm)**	**Year**	**Rainfall (mm)**	**Year**	**Rainfall (mm)**	**Year**	**Rainfall (mm)**
Dry	2011	1,631.7	2018	1,110.6	2014	455.5	2017	480.8
Average	2018	1,870.8	2014	1,207.6	2018	546.6	2018	651.3
Wet	2019	2,459.2	2016	1,810.2	2016	669.1	2019	705.6

Table 2 | The components costs of an RWH system

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	Liquid chlorinator	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 (DN 50, 1.6 Mpa)	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 capital cost (except for storage tank, sum of 1 – 12) 14901				

Note: Average currency data from 07/2019 to 07/2019,1 yuan (CNY) was equal to 0.1427 USD.

Table 3 | Price of different water tanks (stainless steel) available on the market

Size (m^3)	1	2	3	4	5	6	7	8	10	12	15	20	30
Price (CNY)	388	792	1,228	2,098	2,268	2,890	3,520	4,150	4,940	6,550	8,160	11,608	18,600

The price information in the table comes from market survey.

the RWH system by the building owners, as well as depreciation of fixed assets. In this study, the periodic replacements of filter materials, daily consumption of disinfectants, as well as maintenance, replacement and management of the RWH system were taken into account, while the labour costs and losses during suspended period have been neglected. Because the harvested rainwater from roof to storage tank and from the storage tank to the points of user are delivered by gravity, therefore no power consumption in this case. The amount of material, labour, and chemical consumption are directly collected from existing RWH system and from some historical data in previous studies, which are estimated at 10% of the total capital cost. In this study, the annual depreciation cost of equipment is estimated at 4% of the total capital costs.

The benefit comes from a reduction in the annual potable water bill achieved from an RWH system, which is estimated as the product of potable water savings and water tariff. The value of possible environmental benefits from an RWH system (e.g., reducing resources consumption from water treatment processes) is not considered in the benefit–cost analysis due to limited data availability (Campisano *et al.* 2017).

The terminal domestic water price, including water supply price and sewage treatment fee, both of which vary substantially across the country, is employed in the economical viability analysis of RWH system. Terminal water prices of the four locations in 2019 are shown in Table 4.

Table 4 | Terminal water price at Guangzhou, Wuhan, Beijing and Harbin in 2019

Location	Water supply price (CNY/m^3)	sewage treatment fee (CNY/m^3)	terminal domestic water price (CNY/m^3)
Guangzhou	0.95	2.93	3.88
Wuhan	1.10	2.47	3.57
Beijing	1.36	5.00	6.36
Harbin	0.95	3.35	4.30

Data analysis

The data were subsequently used to assess the economic performance of the RWH system, these analysis mainly involve water saving potential (savings in drinkable water annually) and BCR of the RWH system. In order to calculate the water saving of an RWH system, a water balance simulation model on daily time scale in Microsoft Excel is built that considers various factors such as daily rainfall, runoff coefficient, daily water demand, tank capacity and tank spillage. In the water balance model, rainfall is regarded as inflow and the consumption, as well as possible spill as outflow following the method outlined by Su *et al.* (2009). Figure 2 demonstrates the flowchart of logical sequences and formulations used in the daily water balance model tailored to the target official building. As illustrates in Figure 2, running the model allows the water saving (by calculating the cumulative consumed rainwater from storage tank) of the system to be examined.

According to the water balance model, the potential volume of rainwater harvested was estimated 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:

$$V_c = \frac{R \times A_c \times R_c}{1000} \quad (1)$$

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 R_c the surface runoff coefficient, assumed equal to 0.8 to represent losses of 20%.

In this work, the water saving performance of the proposed RWH system was evaluated using two indicators, which are annual water saving and percentage of reliability (R). The daily consumed rainwater is calculated based on the following equations:

$$C_t = D_t \quad \text{if} \quad V_t + S_t - 1 \geq D_t \quad (2)$$

$$C_t = V_t + S_{t-1} \quad \text{if} \quad V_t + S_{t-1} < D_t \quad (3)$$

where D_t is the daily demand (m^3) on day t, S_{t-1} is the stored water at the end of the previous day (m^3), C_t is consumed rainwater (m^3) and V_t is the harvested rainwater (m^3).

According to the logical sequences in the water balance model, the consumed water (C_t) is determined

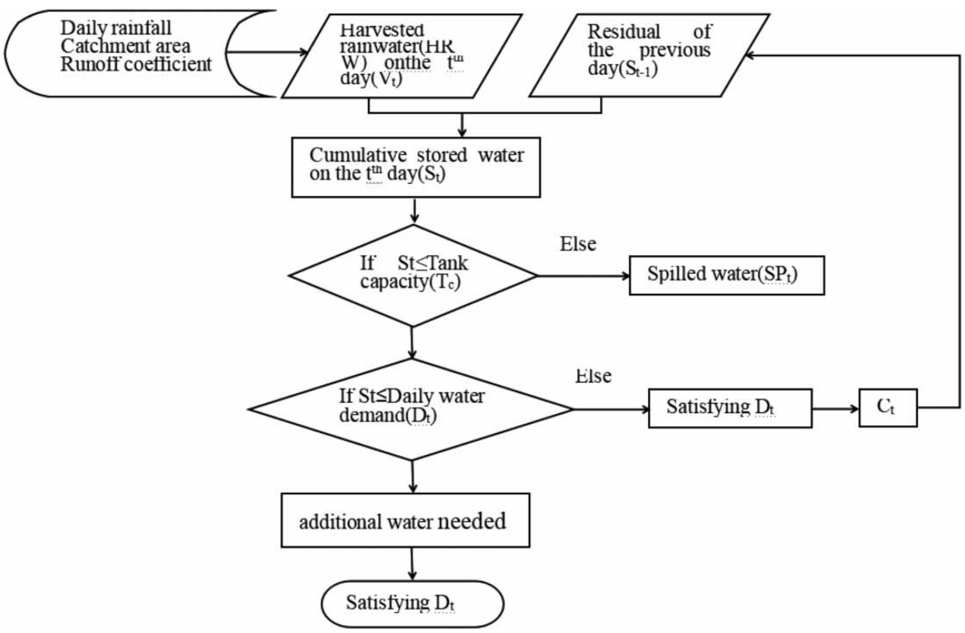

Figure 2 | Flowchart of daily water balance model.

depending on whether the sum of harvested rainwater and the previous stored rainwater (V_t+S_{t-1}) is enough to satisfy the daily non-potable demanded (D_t) or not. For example, if the sum of harvested rainwater and the previous stored rainwater is greater than or equal to the non-potable demanded, the consumed rainwater is equivalent to the non-potable water demand. Otherwise, the consumed rainwater is equal to the sum of harvested rainwater and the previous stored rainwater as shown in Equation (4) and Equation (5). This compute procedure will repeat for each day of the year.

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 follows:

$$R_t = \frac{N}{365} \times 100\% \quad (4)$$

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.

In the economical feasibility analysis, the BCR is performed considering the installation and maintenance costs, annual drinkable water savings of an RWH 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. Water price comes from the data issued by the local water company (Table 4).

To carry out the economic performance analysis, all the present and future values are converted to present day CNY value. In this study, a discount rate of 6% is consider according to the economic evaluation methods and parameters of municipal public facilities construction projects (Ministry of Housing and Urban-Rural Construction of the People's Republic of China 2010). To convert a nominal cost (C_N) to a discounted cost (C_D), following equation is used

$$C_D = C_N \times \left(\frac{1}{(1+d_n)^y}\right) \quad (5)$$

where d_n is the nominal discount rate per annual and y is the appropriate number of years. The BCR 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 BCR analysis, the approach outlined in Cbabuilder (2016) is used, which is calculated by the following formula:

$$BCR = \frac{\Sigma_{t=0}^{s} \frac{S_t P_t}{(1+i)^t}}{\Sigma_{t=0}^{s} \frac{I_t + M_t}{(1+i)^t}} \quad (6)$$

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 discount rate (%).

RESULTS AND ANALYSIS

The application of the daily water balance model allowed us to evaluate the system performance in each study city. The following sections present the results of water saving analysis and economic analysis of the RWH system across four locations.

Reliability analysis

Based on the daily rainfall data of the identified dry, average and wet years on record, the rainwater supply reliability of the proposed RWH system at four regions for a series of rainwater tank was determined and the results are shown in Figure 3(a)–3(d). It is noticeable that, although non-linear, the reliability of RWH system increased with the tank sizes from 1 to 30 m^3 in four locations. The supply reliability is zero for a rainwater tank less than 5 m^3 at all these four cities (Figure 3(a)–3(d)), and then the reliability kept on increasing even with a tank size of up to 30 m^3 L in all four cities. For example, at Guangzhou, a 7 m^3 rainwater tank can meet the non-potable demand for 6.7% of the days in a wet year, which increases to 20.5% for a 30 m^3 tank size. This is because larger tanks are expected

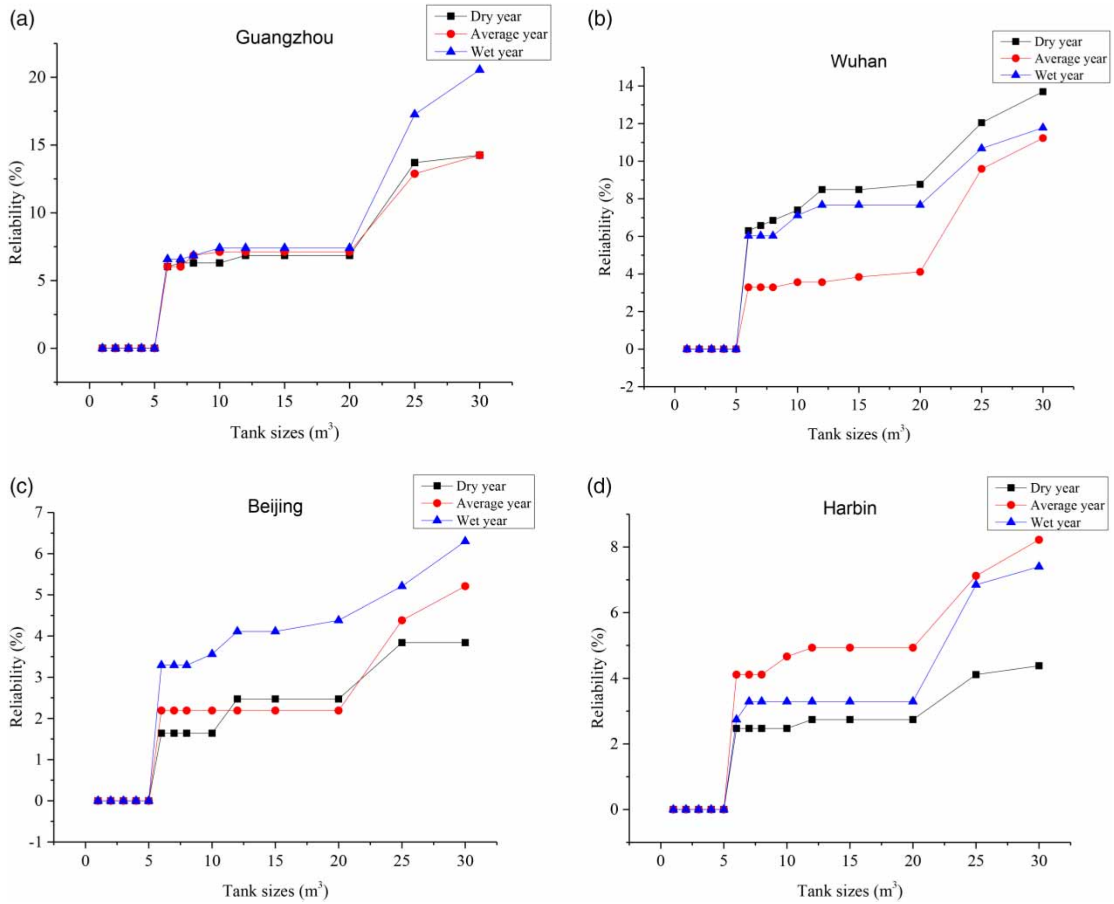

Figure 3 | Effects of tank sizes on the reliability of the proposed RWH system across four locations: (a) Guangzhou, (b) Wuhan, (c) Beijing and (d) Harbin.

to capture more rainwater generated from a given catchment area so that the higher reliability of rainwater supply could be achieved.

As shown in Figure 3, there are notable differences in reliability across four cities. Among the four cities, Guangzhou achieved the highest reliability (14.2%, 14.2% and 20.5% for dry, average and wet years, respectively), Wuhan comes second (13.7%, 11.2% and 11.8% for dry, average and wet years, respectively), followed by Harbin (4.38%, 8.22% and 7.40% for dry, average and wet years, respectively), while Beijing is the lowest one (3.84%, 5.20% and 6.30% for dry, average and wet years, respectively) for a 30 m^3 tank scenario. These reliability values over the four selected locations are generally connected with its annual rainfall data (as shown in Table 1).

As can be seen from Figure 3, the RWH systems are almost not able to ensure a supply reliability higher than 21% at the four study cities, especially those under dry climate conditions such as Beijing (3.84–6.30%) and Harbin (4.38–8.22%). According to these results, it can be concluded that for a great part of the country, rainwater solely is unable to supply total water demand throughout the year, but rather, rainwater should be used for non-potable purposes with the aim of reducing potable water demand from the public water supply system.

It can be seen from Figure 3, the time-based reliability of RWH system under the same storage tank scenarios varies greatly among years. For example, the maximum reliability varied between 14.2% and 20.5% across the dry, average and wet years at Guangzhou. For Wuhan, the maximum reliability ranges from 11.2% to 13.7% over three distinct years. For Beijing and Harbin, the maximum reliability is in the range of 3.84–6.30% and 4.38–8.22%, respectively. The differences in reliability of the RWH system for different years at the same location suggest that there is a considerable inter-annual variation in rainwater supply reliability at each region.

As mentioned above, the reliability values of the city are generally connected with its annual rainfall data. However, it can be observed that at Wuhan, the values of time-based reliability in dry years is significantly higher than those in average years and wet years, with the calculated reliability of dry years is 22–91% higher than that in average years and 16–45% higher than that in wet years (Figure 3(b)), respectively. The same scenes also appeared at three other cities. For instance, it can be observed from Figure 3(d) that at Harbin, the values of supply reliability under wet years are less as compared to those under the average year for rainwater tank range from 6 m^3 to 30 m^3, despite the average year have less rainfall availability (Table 1).

From this finding it can be concluded that it is not necessary that regions with higher annual rainfalls will have higher reliability. As documented by Zhang *et al.* (2018) the supply reliability of the RWH system mainly depends on the rainfall event characteristics and the water use patterns, this indicator tend to increase if the rainfall events and water consumption are evenly distributed in temporal, contrarily, it can significantly aggravate the reliability. Which leads to the conclusion that, up to a point, the supply reliability of RWH system are not solely dependent on annual rainfall amounts, rather it also depends on proper demand and rainfall pattern of a particular location (Imteaz *et al.* 2015).

Water savings

The performance of an RWH system in reducing potable water consumption is examined by quantifying its annual water saving, defined as the total volume of rainwater supplied by the system. Figure 4 showing the expected annual water savings achieved by an RWH system for a series of tank sizes, under three distinct climatic conditions from the four regions. As clearly shown, the amount of annual water saving increased linearly with increasing storage capacity across four locations. This is because a larger tank offers an opportunity to capture more rainwater for the RWH system.

It can be seen from Figure 4, there is significant difference in terms of water saving for RWH systems among these four regions. As expected, Guangzhou achieved highest annual water savings (1,776.5 m^3) for a 30 m^3 rainwater tank scheme, whereas Beijing is lowest. It was found that a maximum spatial variation of 1,300 m^3 can be expected among these regions and extent of variations is comparatively higher for larger rainwater tank sizes (Figure 4(a)–4(d)). The higher values of annual water saving in Guangzhou and Wuhan result from more collectable rainwater caused by higher annual precipitation. Take Guangzhou as an example, its annual rainfall volume in a wet year is 2,459 mm, which is 3.68 and 3.49 time higher than that of Beijing (669.1) and Harbin (705.55), respectively.

In general, RWH systems with larger storage capacities, in more humid regions, have higher annual water saving. However, it is interestingly to note that the annual water saving in wet years is lower than that in average years at Beijing. A similar situation occurred in Wuhan where annual water saving in average years is comparatively lower than that in dry years and for all tank sizes. From these results we can draw a conclusion that the potential water savings do not depend solely on total annual rainfall amount, but also on rainfall pattern of a particular region. In other words, under similar conditions an area with lower annual rainfall may provide higher water savings due to rainfall pattern (Imteaz *et al.* 2015).

From Figure 4(a)–4(d) it is clear that climate change variabilities for expected water savings are more significant at Guangzhou and Harbin than that at Wuhan and Beijing. For instance, when at Guangzhou, in an average year the maximum annual water saving is expected to be 28.3% lower than that in a wet year and in an average year the maximum annual water saving is expected to be 29.6% higher than that in dry years (Figure 4(a)). For Harbin, compared to average year's annual water savings, in wet years 15.3–35.2% higher annual water savings and in dry years 10.8–35.4% lower water savings can be expected (Figure 4(d)). Nevertheless, as can be seen from Figure 4(c), the calculated water savings in wet years are very close to the water savings in average years (with difference less than 5.8%) at Beijing under similar tank capacities. Similarly, there is only a 4.9–5.3% difference (depending on tank size) between wet years and dry years at Wuhan (Figure 4(b)).

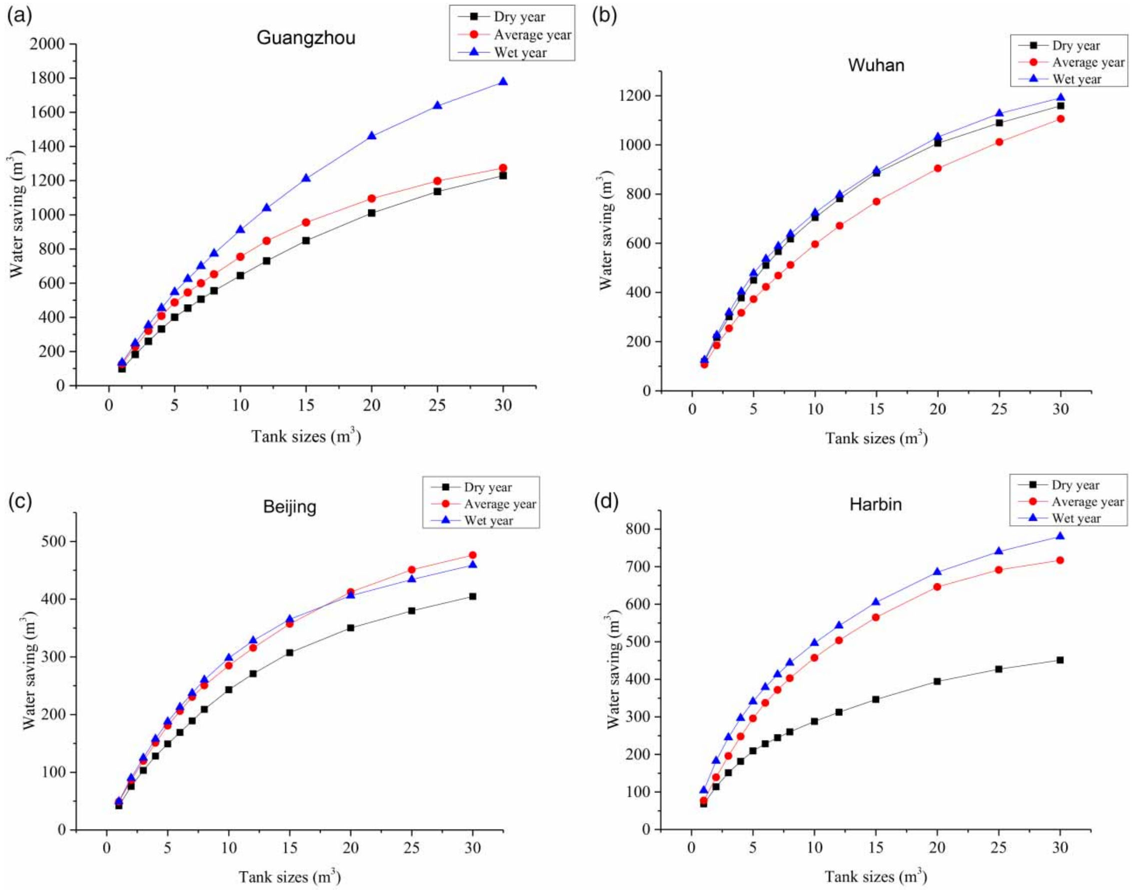

Figure 4 | Annual water saving in four cities: (a) Guangzhou, (b) Wuhan, (c) Beijing and (d) Harbin.

Benefit–cost ratio analysis

The BCR, reflecting the relationship between input and output of the project, is a basic standard which evaluates the economic benefit of investment, and judges whether an investment plan is feasible or not (Morales-Pinzón *et al.* 2014). In this study, the BCR is defined as the ratio between the converted annual benefit and the converted annual cost of the project (as Equation (7)).

Figure 5(a)–5(d) provides the effects of tank sizes on the BCRs of RWH system at four locations. It can be seen from these figures that the BCRs of the proposed RWH system increased to peak values rapidly across four studied regions, and then decreased with storage tank beyond a certain capacity (varies from 15 to 20 m^3, depending on geographical and climatic conditions). For instance, the BCR values of the RWH system at Guangzhou increased from 0.1 – 0.15 to 0.7 – 0.98 for tank sizes from 1 to 20 m^3. and then drop for storage capacities beyond 20 m^3 (Figure 5(a)), which reflects a typical single peak BCR pattern. Similar trends were observed at Wuhan, Beijing and Harbin. As illustrated in Figure 5(c) and 5(d), there is noticeable increase in the BCR with the tank sizes increasing from 1 to 15 m^3. When the rainwater tank sizes were increased up to 15–20 m^3, the BCR values tended to drop with further increase in tank sizes, implying that further investment for increasing tank capacity gives no increase in BCR. According to the results, it is not difficult to draw the conclusion that RWH systems with too small or too large storage capacities cannot provide high BCRs.

It can be seen from these results that a 15 or 20 m^3 tank presents the most favourable financial outcomes for the 14

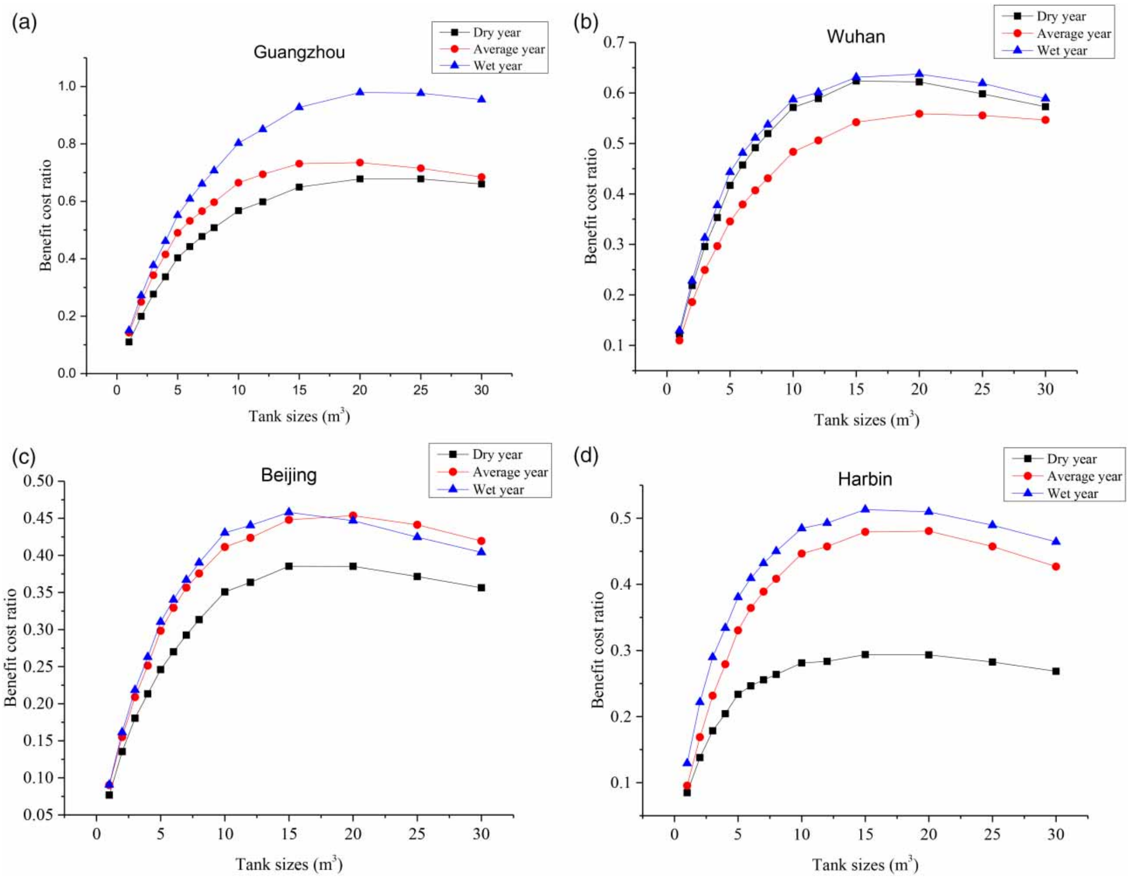

Figure 5 | Effects of tank sizes on the benefit–cost ratio of the proposed RWH system across four locations: (a) Guangzhou, (b) Wuhan, (c) Beijing and (d) Harbin.

different tank scenarios considered here. For example, as shown in Figure 5(a), the most economically feasible tank sizes in wet, average and dry years at Guangzhou were around 20 m^3 as the BCR gets it peak value of 0.98, 0.74 and 0.68, respectively. While the maximum BCR in Wuhan is obtained at tank size of 15 m^3 for dry years, 20 m^3 for average and wet years, respectively (Figure 5(b)). Both at Beijing and Harbin, the maximum BCRs of RWH system are obtained at tank sizes of 15 m^3 for dry and wet years, 20 m^3 for average years, respectively (Figure 5(c) and 5(d)).

Also it is found that the BCR values vary significantly with locations and climate scenarios. Clearly, the highest BCR is found at Guangzhou with 0.98 for a 20 m^3 rainwater tank in wet years, while a 20 m^3 rainwater tank in average and dry years at Guangzhou only gives a BCR of 0.74 and 0.68, respectively. Benefit–cost ratios for the other three cities are relatively smaller due to the low collectable rainwater. For example, the highest BCR is 0.63 at Wuhan for a 20 m^3 rainwater tank in wet years. The highest ratios at Beijing and Harbin are 0.48 and 0.51, respectively, both with a 15 m^3 rainwater tank in wet years. Whereas in dry years, the highest BCRs at Beijing and Harbin are only 0.39 and 0.29, respectively.

As can be seen from Figure 5(a)–5(d), the BCRs in four regions under all rainwater tank sizes are less than 1.0. Even in humid areas such as Guangzhou (with annual rainfall of 2,459 mm), the highest BCR is still less than the desired value of 1.0. While in Beijing and Harbin, its upper limit values vary from 0.29 to 0.51 depending on climate conditions. These results suggest that it is not financially viable to apply an RWH system in these regions.

DISCUSSION

In this paper, a comparative study of supply reliability and economical feasibility of an RWH system at four different regions of China is presented. According to the simulation result, Guangzhou is the most promising city in terms of water savings and financial performance among the four study regions, an annual potable water savings of 1,776.5 cubic metre was obtained and a time-based reliability of 20.55% can be achieved by an RWH system from a typical high-rise public building (with rooftop area of 1,600 m^2), then followed by Wuhan and Harbin, while Beijing was found to be the worst water saving and financial performance region across the four studied sites. The highest annual water saving for Guangzhou is supported by the fact that Guangzhou received the highest amount of annual precipitation among all cities. These results further highlight that the climate condition is the key factor to determine whether an RWH system is financially viability or not.

Tank size is a salient feature in regards maximization of RWH and determination of optimum tank size is a complex function depending on rainfall pattern, catchment area and demand profile (Rahman *et al.* 2012). Figure 3 illustrates that gradual increases in tank capacity usually help increase the rainwater supply reliability, but the relationship between the reliability and tank size is nonlinear. The pattern should be take into consideration the size of tank in design of RWH systems. The evolution of water saving with tank capacity (Figure 4) showed that the annual water saving in the four cities still had not peaked within the 1–30 m^3 tank range, this is because the distribution of precipitation events is highly non-uniform over time in those regions, successive increase in the tank capacity affords an opportunity to store more rainwater according to the water balance model. It can be inferred that the water saving of the RWH systems in Guangzhou,Wuhan, Beijing and Harbin tends to further increase if a larger tank was used, since there had been a steady increase in annual water saving within the range of 1 m^3–30 m^3 (Figure 4). However, the BCR value significant decreases with tank sizes beyond 15 or 20 m^3 (depending on climate conditions) for an RWH system in these cities, this is mainly because the costs increase at a faster rate than the benefits for the 20–30 m^3 tanks scheme although both benefits and costs are increasing.

The water saving potential of the proposed RWH system obtained in our study is compared with similar previous studies. For instance, Sample & Liu (2014) evaluated RWH systems across a wide range of locations in Virginia, USA and found that for a 10 m^3 tank in a high density residential area having a roof area of 1,000 m^2 and with 50 occupants, the RWH system reliability ranges from 0.25 to 0.35. However, in our study, with the assumed non-potable water demand (30–45 L/person/day) it is difficult to achieve a reliability higher than 21% across four cities. The main reason for the lower reliability value achieved in our study may due to the relatively higher water demand supposed here (it should be noted that the assumed number of occupants in our study is 560).

Mehrabadi *et al.* (2013) found that average annual water saving in Kerman (an arid city in Iran with mean annual rainfall of 150 mm) for a 15 m^3 RWH system (with 180 m^2 roof area) is 22 m^3. In the current study, Beijing has a mean annual rainfall of 624 mm, in this region a 20 m^3 RWH system (roof area of 1,600 m^2) can achieve an average annual water saving of 379–450 m^3 for non-potable use. If the water saving value of Kerman is multiplied by the ratio of mean annual rainfalls of Beijing (546 mm) and Kerman (150 mm), and then multiplied by the ratio of roof area of Beijing (1,600 m^2) and Kerman (180 m^2), the water savings in these two arid cities (Kerman in Iran and Beijing in China) are quite comparable. Whereas in another study, Domenech & Sauri (2011) found that for Sant Cugatdel Valles in Barcelona, Spain (mean annual rainfall of 515 mm) an RWH system (22 m^3 tank size and roof area of 107 m^2) can achieve average annual water savings of 43 m^3 for toilet and laundry use. In our study, Wuhan has a mean annual rainfall of 1,256 mm, the average annual water saving (20 m^3 tank size and with a roof area of 1,600 m^2) is 1,089 m^3–1,127 m^3. Considering the selected annual rainfall in our city is higher and the assumed roof areas are larger, the annual water savings at Wuhan in our study compare well with the case in Barcelona.

Economic analysis revealed that the investment cost of an RWH system could not be equalized within the lifespan of the RWH system at the four study regions. As can be seen from Figure 5, the expected BCRs achieved by a RWH system under optimal rainwater tank at the four cities (Guangzhou, Wuhan, Beijing and Harbin) ranged from 0.38 to 0.98 (depending on tank sizes and climate scenarios), which are less than the desired value of 1.0. A similar conclusion was made by Kyoungjun & Chulsang (2009) who found that a BCR higher than 20% could not be gained for a RWH system due to the price of water being too low in South Korea. In those cases, the implementation of RWH systems generated only negative cash flows, with the sum of the cost of implementation and the cost of operation and maintenance greater than the benefits of water saving generated from an RWH system (Lani *et al.* 2018). Hajani & Rahman (2014b) believe that a less than 1.0 BCR may have partly resulted from unreasonable valuation of water prices used in the calculation. The valuation of per cubic metre of water should be differentiated in arid and humid climatic zones given a reasonable market adjustment mechanism. Sample & Liu (2014) stated that the current water price needs to be increased by about 100% to achieve a BCR of 1.0 at most arid or semi-arid areas.

According to the past water tariff records, it is expected that water tariffs in urban areas of China are going to increase. Thus the monetary savings will be increased and the BCR will be improved with the rise of water price in the future. In addition, it should be mentioned here that in this study, the results of the economical feasibility analysis performed should be considered conservative. Firstly, in this economic evaluation, the values of possible environmental and social benefits from an RWH system were not considered due to limited data availability. For example, an RWH system has the potential for reducing resources consumption in providing water supply that were not considered (Fowler *et al.* 2007), these may contribute to the reduction of greenhouse gas emissions from water pumping and water treatment processes which causing climate change. However, these should also be included in the benefits of the RWH system. Secondly, large-scale implementation of RWH systems in densely urbanized areas may contribute to a reduction in peak discharges into stormwater drainage systems (Burns *et al.* 2010), reduce the size of downstream drainage infrastructure, and with potential benefits for reducing urban flood frequency. If all these multiple benefits were taken into account, the financial benefits would increase and, consequently, the actual payback period would be shorter than predicted (Farreny *et al.* 2011). Consequently, installation of an RWH system should continue to be encouraged. These findings highlight the need for government subsidies to achieve the financial viability for building owners.

Information from this study will be useful for local government authorities, who can provide guidance for building owners. Overall, the reliability of RWH systems with different tank sizes under various climatic conditions varies widely for these regions. The temporal variability of precipitation is one of the most important factors in designing an RWH system. Although the quantities of alternative rainwater found is far less than the total water demand, water supply authorities should consider the potential of rainwater recycling to partially offset the potable water demand in these cities. Installation of RWH systems in public office buildings will not only lead to economic savings and water stress relief but also go further in alleviating the pressure of urban drainage systems in cities. Government should take initiatives to educate the urban dwellers on water conservation benefits associated with RWH implementation in urban areas to achieve a sustainable development (Bashar *et al.* 2018). The current study is specific to four major cities in China mainland, however this paper presents an insight into potential regional variations of economic returns of RWH systems and this study will motivate others to conduct similar comparative investigations elsewhere.

CONCLUSION

This paper examines the performance of an RWH under four different precipitation scenarios in China. Overall, the water saving potential and financial performance of RWH systems under various climatic conditions varied greatly for different cities. Among the studied regions, Guangzhou was found to be the most promising city with regards to annual water saving and BCR for the RWH system, with a BCR value up to 0.98. However, for Wuhan, Beijing and Harbin, for an optimal tank scheme under three distinct climate conditions, the expected BCR is in the range of 0.56 – 0.64, 0.38 – 0.46 and 0.39 – 0.51, respectively, indicating that this infrastructure is economically unfeasible for most cities in China. However, implementation of RWH systems in urban areas should still be promoted as this proposed green infrastructure may be more beneficial in the future than we now predict as some environmental and socioeconomic impacts are usually difficult to estimate in financial terms. Future research will focus on refining the data in order to comprise the external benefits such as the environmental and socioeconomic impacts that come from proposed green infrastructures in economic analysis, and expanding the regional investigation across the whole country.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest

ACKNOWLEDGEMENTS

This work was financially supported by the key scientific research project of Guangdong University (characteristic innovation). We would like to thank the anonymous reviewers for their constructive criticisms, which significantly improved the accuracy and quality of the manuscript. We also thank Wang-Zhihong, professor of the Guangdong University of Technology, for providing valuable suggestions and manuscript revision.

DATA AVAILABILITY STATEMENT

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

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First received 7 September 2020; accepted in revised form 26 October 2020. Available online 20 November 2020