Research Paper

Economic Feasibility Analysis of Rainwater Harvesting System at Typical Public Buildings in Guangzhou

Chen Shiguang[†] · Zhang Yu[✉]

College of Urban and Rural Construction, Zhongkai University of Agriculture and Engineering, Guangzhou 510225, China

(Received November 24, 2020; Revised February 8, 2021; Accepted February 23, 2021)

Objectives : Rainwater harvesting (RWH) is one of the most promising alternative water sources, since rainwater can easily be collected and used without significant treatment for non-potable purposes. However, the economical viability of these systems is not always assured. The objective of this study is to assess the potential water saving and financial performance of an RWH systems for a typical multifunctional building (with a rooftop area of 2,725 m²) in Guangzhou, China.

Methods : The water saving and economic feasibility of the RWH system were examined using a yield after supply model for fourteen rainwater tank schemes (from 1 m³ to 30 m³).

Results and Discussion : According to the simulation results, an annual potable water saving of 3,923.56 m³ can be achieved and a corresponding annual revenue of 11,496.04 CNY can be obtained from the RWH system. The economic viability expressed by benefit cost ratio is 1.50 and by payback periods are within 6.26 year, respectively. Sensitivity analysis indicates that the water price is the most important factor affecting the economic viability of an RWH systems. The widespread implementation of rainwater harvesting systems in the public buildings will not only lead to economic savings, but also go further to relieve pressure on urban drainage systems and natural water body. Therefore, the actual benefits achieved by a RWH system will be greater than we predicted in current study.

Conclusions : These results demonstrating that the application of RWH system is a very promising adaptation strategy for coping with the water crisis and climate change in urban areas of southern China.

Keywords : Rainwater Harvesting, Precipitation Pattern, Payback Period, Benefits Costs Ratio

[†] Corresponding author E-mail: luyi813929@163.com Tel: +86-20-89002673 Fax: +86-20-89002673

1. Introduction

With the increasing population, continued urbanization, and over-exploitation of water bodies, Most cities in China have face water scarcity to satisfy the demands for human activities.¹⁾ Guangzhou, which is the third largest city in China, with over 15.9 million populations. The city was under severe water restriction since 2010 due to rapid urbanization and population growth, which prompted the search of new strategies for the sustainable use of water.²⁾ A number of alternative water sources have received attention in recent years in China, which includes rainwater harvesting (RWH), grey water reuse and waste water recycling.³⁾ Among these, rainwater harvesting has received the greatest attention as rainwater is fresh in nature and can be easily collected and used for non-potable purposes.

However, due to the lack of sufficient researches on financial viability of RWH system^{3,4)}, many people in China do not readily see the benefit of RWH system over longer term, and still show reluctance in adopting a rainwater harvesting system. Even the policy makers (e.g., the Ministry of Housing and Urban-Rural Development of PRC) have casted doubts on the energy efficiency of the water reuse systems, and this dilemma is delaying further expansion of implementation of water reuse systems in China.⁵⁾ For this reason, a campaign promoting the implementation of RWH systems in urban areas for the purpose of showing their economic benefits and the potable water saving potential become extremely necessary, especially in regions with frequent precipitation and the ones with insufficient water supply.⁶⁾

The direct economic viability of RWH system depends on the balance between the investment, operating and maintenance costs of the system and the public water supply cost savings. This balance comes to the potential amount of available rainwater, the effective amount of rainwater that is used for different purposes and the cost of the alternative water sources.⁷⁾ Therefore, whether implementing an RWH system is financially viable or not depends on the specific climate conditions of the site and the consumption distribution pattern of non-potable water in the building.

The research proposed in this paper is undertaken in the light of the current knowledge gaps to assess the financial viability of an RWH system in a specific region. This study quantifies the economic benefits and costs of a rainwater harvesting system in a multi-functional building that located in Guangzhou, to explore whether the utilization of rainwater on the scale of single buildings is an effective water-saving and

Fig. 1. Geographic location of the study site in Guangzhou, China.

economic feasibility strategy, and consequently to provide guidance to water authorities and public to enhance the acceptance of this green infrastructure.

2. Methodology

The following sections presents the case study area, and detail the methodology assumed in this work to compute the water savings and costs in this project.

2.1. Study area

Guangzhou was selected as the study region. It locates on the North edge of the Pearl River Delta (PRD) Plain with latitude $22^{\circ}26'-23^{\circ}56'$ north and longitude $112^{\circ}57'-114^{\circ}3'$ east. It has a typical subtropical monsoon climate and the average annual precipitation is 1,720 mm (statistical average from 1989s~2019s). The average annual temperature is 22.5°C .

Fig. 1 shows the geographic locations of the study site.

2.2. System description

A vertical height of 36 meter, eight-story multi-functional building with 600 occupants, located in 40 miles southeast from central of Guangzhou city, South China, was selected as the target building (**Fig. 2**). A rainwater harvesting (RWH) system, was installed at the top floor of a multi-functional building at Zhongkai University of Agriculture and Engineering in Guangzhou, China. As illustrates in **Fig. 3**, the RWH system includes five main elements: a catchment surface with total area of $2,725\text{ m}^2$; a rainwater storage tank; a rainwater treatment units which encompass a sediment tank to deposit large solids (e.g. leaves and twigs) and a gravity driven micro-filter (GDM) system to removal suspend solids and dissolved pollutants; a

Fig. 2. Satellite images of the target building.

Fig. 3. The schematic diagram of RWH system.

clean water storage tank, and a convey system through which the treated rainwater is sent into the end user of building. After GDM process, the quality of treated rainwater can well meet the standard of Chinese Recycling Water Guidelines, which has been confirmed in our previous researches (published online). The harvested rainwater is mainly used for non-potable purposes (toilet flushing and hand washing) in the target buildings.

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 for the city of Guangzhou, information about the non-potable water demand, and the components and prices of the system.

2.3.1. Rainfall data

To analyze the water supply reliability of RWH system, the latest three decades historical rainfall data were considered. Historical daily rainfall data from 1989 to 2019 were obtained from the Official Website of Guangzhou Meteorological service Bureau (<http://www.tqyb.com.cn/>). The average daily rainfall data of the periods between 1989 and 2019 are shown in Fig. 4.

At a year scale it becomes evident that the precipitation in Guangzhou is markedly seasonal. Even so, during the dry season (September to March of the next year) there are relatively long periods of precipitation and high rainfall intensity, there were no periods of several days without precipitation observed.

2.3.2. Water consumption

To determine the daily water consumption data by user, a year long survey was conducted on water consumption in this multi-functional buildings during the period from January to December 2019. According to the data obtained from the water meter readings, the total water consumption in 2019 was 6,935 m³, corresponding to an average daily water consumption of 19 m³. This water mainly used for toilet flushing, hand washing and floor cleaning, which do not require potable water quality since there are only four kinds of sanitary appliances in the toilet of this multifunctional building, i.e. toilet, urinal, wash basin and sink. The water consumption data were then used to estimate the water saving

Fig. 4. Average daily precipitation data of 30 years record (1989-2019) in Guangzhou.

Table 1. The capital of an RWH system in Guangzhou, 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	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 (DN50, 1.6 Mpa)	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	
Total capital cost (except for storage tank, sum of 1~12)					14,901

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

Table 2. Price of storage tank (stainless steel) with various size.

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.

efficiency and reduction of tap water, as well as the benefits costs analysis of the RWH system. The daily water consumption of the target building was summarized in Supplementary material.

2.3.3. Economic data

The costs analysis of the system considers the capital and operating costs of the RWH system. The capital costs include the collection facilities, rainwater tank, pipe lines, treatment devices and installation costs, the labour costs are already included in the installation costs.

The RWH system used in this study consist of a flush diverter, a stainless tank, mosquito nets, PVC pipelines, a set of physical filters (GDM system), and a Chlorinator. The capital of which can be divided into two categories: the constant investment (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 of the rainwater harvesting system components and price of the public water supply were drawn from the cost information of Guangzhou in the third quarter of 2019 (a database released by Guangzhou construction project cost management station) and combination use of a market survey. The database provides information on prices, technical details, and installation costs (labour) of RWH system.

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

The storage tank represents the most significant initial costs for an 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 annual operating cost here refers to the expenses of purchases, installs, operates and maintains the infrastructure (water tanks, pumps and pipes) needed for the RWH system by the building owners, as well as depreciation of fixed assets. In this analysis, the periodic replacements of filter materials were taken into accounted. However, the labor 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 consumption points are delivered by gravity, thus no power consumption occurred in this case. The annual operating cost is estimated at 10% of the total capital

cost according to empirical data collected from existing RWH system in the regions and from some historical data in previous studies. The annual depreciation cost of equipment is estimated at 4% of the total capital costs.

The financial benefit comes from the water savings by applying an RWH system, which is estimated based on the volume of tap water savings and water price. The value of possible environmental benefits from an RWH system (e.g. reducing greenhouse gas emissions from water treatment processes) is not considered in the costs benefits analysis due to limited data availability, which would have disfavored the RWH system.⁸⁾ The water price considered in this study is 3.88 CNY/m³ (2020 Guangzhou Water price). It should be noted that the water price varies from one city to another, and therefore the outcomes of this study need to be interpreted in relation to the water price at other locations of interest.

Life span of the system is estimated at 40 years and a basic 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, PRC, 2010). The selected discount

period was 40 years, taking into account the lifespan of the proposed infrastructures.⁹⁾

2.4. Data analysis

The rainfall and water consumption data was subsequently used to assess the performance of the RWH system through a water quantity balance model, which focused on: (1) The water saving potential, (2) the economical feasibility.

In order to calculate the water saving of an RWH system, a yield after supply (YAS) model on daily scale in excel is developed following the recommendation of Mitchell (2007).¹⁰⁾ The YAS model considers various factors such as daily rainfall, runoff coefficient, daily water demand, tank capacity and tank spillage. The Flowchart of yield after supply model is show in **Fig. 5**. 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.

Fig. 5. Calculation procedure of the water savings.

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 harvested rainwater is calculated as the difference between the tank capacity and the stored rainwater at the end of the previous time step (shows in **Fig. 5**). Afterwards, the used 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 used 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 used rainwater is limited by the stored rainwater and the rainwater tank will be empty. This compute procedure will repeat for each day of the year.⁷⁾

For daily scale, the available rainwater in this case is mathematically expressed as:

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

Where V_c is the volume of available rainwater (m^3), R is the local daily rainfall (m), A_c is the catchment area of roof (m^2), R_c is the surface runoff coefficient, assumed equal to 0.8 to represent losses of 20%.

For water saving efficiency (WSE), the method outlined in Ward et al. (2012)¹¹⁾ was adopted. It is calculated by dividing the volume of rainwater consumed by the total demand for water, as follows:

$$WSE = \frac{V}{D} \times 100\% \quad (2)$$

Where, V is the volume of drinking water substituted by harvested rainwater and D is total water demand (m^3).

In this work, the economical feasibility of the proposed RWHS system were evaluated using two economic indicators, which are Payback Period (PBP) and Benefit-Cost Ratio (BCR).¹²⁾ To carry out the economic performance analysis, all the present and future values are converted to present day CNY value using a discount rate of 6%. These indicators are calculated use the following formulas:

$$PBP = \frac{\sum_{t=0}^s \frac{I_t + M_t}{(1+r)^t}}{\frac{S_t P_t - (I_t + M_t)}{(1+r)^t}} \quad (3)$$

$$BCR = \frac{\sum_{t=0}^s \frac{S_t P_t}{(1+r)^t}}{\sum_{t=0}^s \frac{I_t + M_t}{(1+r)^t}} \quad (4)$$

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

3. Results and analysis

These sections present the water saving and economic analysis of the proposed RWHS system in target building.

3.1. Water savings analysis

The performance of an RWHS system in reducing potable water consumption is examined by quantifying its water saving defined as the total volume of rainwater supplied by the system.

As illustrates in **Fig. 6**, the annual water saving of the RWHS system increased significantly with increasing tank sizes before reaching a plateau (first stage). It is calculated that no more than 400 m^3 potable water can be saved by a 1 m^3 storage tank, nevertheless, this is boosted to over 3,300 m^3 if a 15 m^3 storage tank is used (**Fig. 6**). These patterns are in agreement with previous studies.¹³⁻¹⁶⁾ For the first stage, it is evident that increasing the tank volume affords an opportunity to store more rainwater. However, the amount of water saving reaches a plateau since the rainwater tank is able to store the total rainwater captured from the rooftop. Therefore, it is useless to increase the tank size once it exceeding 20 m^3 .

Another indicator is the water savings efficiency (WSE), defined as ratio between the used rainwater and the non-potable water demand. Generally, high water saving is well in line with high water saving efficiency of RWHS system under the same water demand pattern.¹²⁾ **Fig. 6** also shows the effect of increasing storage capacity on the water saving efficiency of an RWHS system. As obvious, the WSE, follow

the same pattern as the water saving curves. The results demonstrate that with successive increases in the tank capacity up to 20 m³, the WSE increase up to 57%. Afterwards, this indicator reaches a plateau for the range of 20 m³ to 30 m³.

Significantly, an RWH system can achieve an annual water saving of 3,923.56 m³ and a WSE of 56.86%, respectively, with a storage capacity equal to or greater than 20 m³ (Fig. 6).

3.2. Payback period analysis

One method to estimate the financial viability of installing an RWH system is to evaluate the time period required to recover the project investment, namely payback period. In order to be competitive, a return on investment is expected within a reasonable period of time, and the lower the payback period is, the more attractive the project becomes.⁷⁾ In current study, only direct costs using market values for the RWH components were taken into account. The payback period of the RWH system with different tank size are schematized in Fig. 7.

It can be observed that the PBP decreases with the increasing of rainwater tank in the range of 1 m³ to 10 m³, then increases when tank size ranges from 10 m³ to 30 m³, similar to the indicator of water saving obtained within these ranges of storage tanks, a positive relationship between the payback period of investment and tank capacity was observed, i.e., the greater the tank size, the shorter the PBP could be achieved. The PBP values of RWH system for 1 m³ and 2 m³ schemes are incomputable according to formula (3). As illustrates in Fig. 7, the payback period for 3 m³ tank is more than 50 years. Whereas it is commonly to regard an investments project as economically viable when the payback periods of which are less than its lifespan. For office buildings,

the service life is generally within 40 years in China, therefore, the RWH system with a storage tank less than or equal to 3 m³ are consider to be economically unfeasible. As Fig. 7 illustrates, the payback period of RWH system can be shortened to lower than 18 years if the tank capacity increases to 4 m³. The PBP values are all shorter than the threshold of 40 years with rainwater tank range from 4 m³ to 30 m³, while a RWH system within the range of 6 m³ to 25 m³ tank even gives a PBP of lower than 10 years. Obviously, the shortest PBP (6.26 years) is achieved for a 10 m³ rainwater tank scheme.

It is obvious that the payback period increase again when tank capacity over 10 m³, this is due to the fact that increases tank size raises initial investment and operating costs of the RWH system, while the amount of captured rainwater does not increase with the increase of tank capacity since the available rainwater is limited. Thus a successive increase in tank size will eventually leading to a point that the annual increase in expenditures exceeds the increase in revenues.

According to Fig. 7, it is not difficult to find that the growth rates of payback period decreased as the capacity beyond 5 m³, for instance, a nearly 80% decrease in payback period was found when rainwater capacity increased from 3 m³ to 5 m³. Nevertheless, the payback period decreased by only 26.9% when rainwater capacity increased from 6 m³ to 8 m³, and only a 5.6% increase in PBP was witnessed with tank size increasing from 8 m³ to 20 m³. This is because, with the continuous increasing of storage capacity, the tank size became a less limited factor, instead, the rainfall will becomes a more relevant variable for benefit effectiveness of an RWH system.

Fig. 6. Annual water saving and WSE of the RWH system with increasing storage capacity.

Fig. 7. Effects of tank sizes on the PBP of the proposed RWH system.

Table 3. Sensitivity analysis of water price, initial investment and operating cost variation to benefits costs ratio.

No.	Item	-20%	-10%	Benchmark scheme	+10%	+20%
1	Water price	2.68	3.02	3.35	3.69	4.02
2	Initial investment	3.52	3.44	3.35	3.27	3.20
3	Operating cost	3.80	3.56	3.35	3.17	3.00

Fig. 8. Effects of tank sizes on the BCR of the proposed RWH system.

3.3. Benefit cost ratios analysis

Benefit-cost ratio (BCR), is another basic standard evaluates the economic benefit of investment, and the judgement whether an investment plan is feasible or not. A lowest cost and

highest profit scheme is therefore consider as the optimum.¹⁷⁾ In this study, the BCR is determined by comparing the present value of accumulated expenditures with the accumulated income within lifespan of the recycling system (as formula 4).

The effects of tank sizes on the BCR values of the proposed RWH system are depicted in **Fig. 8**. The BCR response to varying tank size of the RWH system can be divided into three stages. First, there is a clear trend of increasing in BCR (from 0.29 to 1.50) when tank sizes from 1 to 10 m³, then the BCR reaches a plateau of around 1.50 when the tank sizes is between 10 m³ and 15 m³. Afterwards, the BCR values start to decrease from 1.50 when the tank size is range from 15 m³ to 30 m³, which shows a similar pattern as the PBP does. The current work found that the maximum BCR (1.50) of the RWH system is achieved for a 10 m³ tank scheme. The present study also found that the benefit cost ratio were below the desired value of 1.00 for small tank scenarios (between 1 m³ and 4 m³).

Indeed, the correlation between benefits costs ratio with the capacity of storage tank can be expressed by the following equations:

$$y = -0.0174x^2 + 0.3271x - 0.0424 \quad (5)$$

Where y is benefits-costs ratio of the RWH system and x is

the capacity of rainwater tank.

3.4. Sensitivity analysis

A sensitivity analysis was carried out for the water price, initial investment and operating cost for the case of an RWH system with a 10 m³ tank installed in the target building. The water price considered in this study is 3.88 CNY/m³ (2019 Guangzhou water price) and both positive and negative variations of the water prices were considered.

The water price considered in this study is 3.88 CNY/m³ (2020 Guangzhou water price). **Table 3** illustrates that a 10% increase in the current water price (from 3.88 to 4.27 CNY/m³) would give a benefit cost ratio of 3.69 (which represents a 10.15% increase) for the RWH system, while a 20% increase in the current water price (from 3.88 to 4.66 CNY/m³) would give a benefit cost ratio of 4.02 (which represents a 20% increase), presenting a clear linear relationship between the water price and BCR values. However, an variation of -20% to +20% in the initial investment resulted in variations of the benefits costs ratio from +5% to -4.5%, and an 20% increase in the annual operating costs (from 2,655.64 CNY per year to 3,186.77 CNY/ per year) only leading to a 10.4% decrease in BCR for this RWH system (**Table 3**). These results demonstrates that water price is the most important factor affecting the return on investment, followed by operating costs and initial investments.

4. Discussion

In this study, the water saving potential and costs effectiveness of an RWH system at a typical building were examined using a yield after supply model. According to the simulation result. The proposed RWH system achieved an annual potable water saving of 11,496.04 m³. The economic indicators in term of benefit cost ratio is 1.50 and payback periods are within 6.26 years, respectively, implying that this green infrastructures is economically viable for the a public building in Guangzhou.

However, it is found that the annual water savings and economic benefits from RWH system are strongly correlated

with tank sizes. As mentioned in sections 3.1, both the annual water saving and the water saving efficiency of the RWH system for this multifunctional building increased significantly with increasing tank volumes before reaching a plateau. These findings are in agreement with previous studies.¹³⁻¹⁶⁾ In fact, the potential water saving depending on the precipitation amount and its temporal distribution, catchment area, as well as tank capacity. For small tank schemes ($< 20 \text{ m}^3$), the tank capacity is a limiting factor. It is evident that increasing the tank capacity within these ranges offered an opportunity to store more rainwater. However, with a further increase in tank sizes, the annual water saving and WSE reached a plateau of $3,923.56 \text{ m}^3$ and 56.86% , respectively. In this case, tank capacity is no longer a limiting factor. Instead, the catchment area of target building becomes a new constraint to the water saving potential of the RWH system. Hence, it will be uneconomical to increase the tank capacity considering the total amount of rainwater available is limited.

In terms of the PBP and BCR, their increasing patterns for the RWH system suggest increasing benefit by increasing the tank capacity. Conversely, the decreasing PBP and BCR patterns are due to the potential economic benefit that can't offsets the higher operating cost. As obvious, a small tank scenario would leading to extremely long payback periods. E.g., a 3 m^3 tank scheme gives a PBP of 56.4 years. The high value of PBP (more than 40 years) implying that the RWH system is not economically viable in that case.

As presented in **Fig. 8**, the BCR values of the RWH system at target building increased from 0.29 to 1.50 for tank sizes from 1 to 10 m^3 , after that, the BCR values reaches a plateau between 1.45 and 1.49 for tank sizes range from 8 m^3 to 15 m^3 . Beyond this, the BCR values start to decrease when the tank size is increased from 15 m^3 to 30 m^3 . but still show positive values (see **Fig. 8**), implying that further investment for increasing tank capacity gives less benefit compared to the cost.

With regard to economic feasibility of RWH system, several studies have reported that a rainwater harvesting system can not achieve financial viability in the case of without government rebate, E.g., Domenech and Sauri (2010)¹⁸⁾ investigated the financial viability of the RWH system in single and multi-family buildings in the metropolitan area of Barcelona (Spain), they found that in single-family households an expected payback period was found to be between 33 and 43 years depending on the tank size, while in a multi-family building a payback period was 61 years for a 20 m^3 tank.

Whereas in another study, Tam et al. (2010)¹⁹⁾ investigated the cost effectiveness of RWH system in residential houses around Australia and found that although this system can offer a considerable portion of non-drinking water, but is hard to achieve desirable financial benefit for Brisbane. The same study found that it could not be possible to achieve "pay back" for the RWH system without some favourable scenarios and conditions for multi-storey buildings in Sydney.⁹⁾ Literature also reported that rainwater collection would only be feasible in South Korea for during 6 months of the year.²⁰⁾ As has been noted, the financial viability of an RWH system depending on the tank size, climatic conditions, non-potable water consumption pattern, public water price as well as a discount rate considered. Our study found that for a multifunctional building in Guangzhou, the total investment of an RWH system can be recovered within 6.26-16.56 years time depending on the tank size. The humid climates in South China (with average annual precipitation higher than $1,700 \text{ mm}$) is the main reason account for these high costs effectiveness of an RWH system in Guangzhou. This finding is also consistent with the results found by Imteaz²¹⁾ and Jing²²⁾, as they stated that the local rainfall is the major variables of interest in the design and evaluation of RWH systems, as it determines the amount of collectible rainwater generated from a given contributing catchment.

It should be mentioned here that in this study, the results of the economical feasibility analysis performed should be considered conservative for the economic benefit only considers the reduction of potable water consumption resulting from rainwater reuses. Firstly, in this economic evaluation, the value of possible environmental and social benefits from an RWH system were not considered due to limited data availability. For example, RWH system has the potential for reducing resources and energy consumption requiring to assure drinking water quality, convey it to end-user and removal pollutants from waste water before discharge²³⁾, these may contribute to the reduction of greenhouse gas emissions from water pumping and water treatment processes which causing climate change. Secondly, the widespread implementation of RWH system in densely urbanized areas may contribute to the reduction of the peak discharges in stormwater drainage systems⁸⁾, reduce the size of downstream drainage infrastructure²⁴⁾, and with potential benefits on reduce urban floods frequency.²⁵⁾ If all these benefits have been incorporated into the economic evaluation of the RWH system, the actual benefits costs ratio would increase and the payback period would be shorter than

predicted.

Information from this study will be useful for local government authorities, who can form a policy that will contribute to addressing urban water issues and provide guidance for building-owners to promote the campaign of green architecture construction. Moreover, 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.²⁶⁾ Although the current study is specific to Guangzhou, China, however, this paper presents an insight on potential economic returns of RWH system and such study will motivate others to conduct similar investigations in elsewhere.

5. Conclusions

In this study, a yield after supply model was used to examine the water savings potential and assesses the economic performance of an RWH system at a multifunctional building in Guangzhou, China. The simulation results show that, the RWH system is able to provide excellent financial returns to building owners. The cost effectiveness of the proposed RWH system in terms of payback period and benefit cost ratio is 6.26 years and 1.50, respectively. These results demonstrate that the concept of RWH is financially viable in Guangzhou.

Nevertheless, a widespread implementation of a rainwater harvesting system in the public buildings will not only lead to economic savings, but also go further to relieve pressure on urban drainage systems and natural water body. These benefits were not considered in the economic analysis due to inaccessibility of sufficient data. For practical purposes, it will be wise for other cities to quantify these benefits that will affect the financial returns from installation of RWH systems. Future research should focus on refining the data and expanding the study regions.

Acknowledgments

This work was financially supported by the Key scientific research project of Guangdong University (Grant numbers: 2018KTSCX100). 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.

Abbreviations

RWH: rainwater harvesting
PBP: payback period
BCR: benefit cost ratio
PRC: The people's Republic of China
PRD: Pearl River Delta
GDM: gravity driven micro-filter water saving
WSE: efficiency
YAS: yield after supply

References

1. W. Zhang, C. Wang, Y. Li, P. Wang, Q. Wang, D. Wang, Seeking sustainability: multiobjective evolutionary optimization for urban wastewater reuse in China, *Environ. Sci. Technol.*, 48(2), 1094-1102(2014).
2. X. Lin, L. He, R. Zhang, X. Guo, H. Li, Rainwater in Guangzhou, China: oxidizing properties and physicochemical characteristics, *Atmos. Pollut. Res.*, 10(1), 303-312(2019).
3. Y. Zhang, A. Grant, A. Sharma, D. Chen, L. Chen, Alternative water resources for rural residential development in Western Australia, *Water Resour. Manag.*, 24, 25(2010).
4. A. Rahman, J. Keane, M. A. Imteaz, Rainwater harvesting in greater Sydney: water savings, reliability and economic benefits, *Resour. Conserv. Recycl.*, 61, 16-21(2012).
5. H. Yang, K. C. Abbaspour, Analysis of wastewater reuse potential in Beijing, *Desalination*, 212(1-3), 238-250(2007).
6. C. Matos, C. Santos, S. Pereira, I. Bentes, M. A. Imteaz, Rainwater storage tank sizing: case study of a commercial building, *Int. J. Sustainable Built Environ.*, 2(2), 109-118(2013).
7. C. M. Silva, V. Sousa, N. V. Carvalho, Evaluation of rainwater harvesting in Portugal: application to single-family residences, *Resour. Conserv. Recycl.*, 94, 21-34(2015).
8. M. J. Burns, T. D. Fletcher, B. Hatt, A. R. Ladson, C. J. Walsh, Can allotment-scale rainwater harvesting manage urban flood risk and protect stream health, In *Proceedings of the Novatech 2010-7th International Conference on Sustainable Techniques and Strategies for Urban Water Management*, The Graie, Lyon, pp. 1-10(2010).
9. A. Rahman, J. Dbais, M. Imteaz, Sustainability of rainwater harvesting systems in multistorey residential buildings, *Am. J. Eng. Appl. Sci.*, 3(1), 73-82(2010).
10. V. G. Mitchell, How important is the selection of computational analysis method to the accuracy of rainwater tank behaviour modelling, *Hydrol. Processes*, 21(21), 2850-2861(2007).
11. S. Ward, F. A. Memon, D. Butler, Performance of a large building rainwater harvesting system, *Water Res.*, 46(16), 5127-5134(2012).

12. N. H. M. Lani, A. Syafiuddin, Z. Yusop, U. B. Adam, M. Z. B. M. Amin, Performance of small and large scales rainwater harvesting systems in commercial buildings under different reliability and future water tariff scenarios, *Sci. Total Environ.*, 636(15), 1171-1179(2018).
13. E. Ghisi, D. D. F. Tavares, V. L. Rocha, Rainwater harvesting in petrol stations in Brasília: potential for potable water savings and investment feasibility analysis, *Resour. Conserv. Recycl.*, 54(2), 79-85(2009).
14. Y. Zhang, D. Chen, L. Chen, S. Ashbolt, Potential for rainwater use in high-rise buildings in Australian cities, *J. Environ. Manage.*, 91(1), 222-226(2009).
15. A. Palla, I. Gnecco, L. G. Lanza, P. L. Barbera, Performance analysis of domestic rainwater harvesting systems under various European climate zones, *Resour. Conserv. Recycl.*, 62, 71-80(2012).
16. S. Zhang, J. Zhang, T. Yue, X. Jing, Impacts of climate change on urban rainwater harvesting systems, *Sci. Total Environ.*, 665, 262-274(2019).
17. T. Morales-Pinzón, R. Lurueña, X. Gabarrell, C. M. Gasol, J. Rieradevall, Financial and environmental modelling of water hardness—implications for utilising harvested rainwater in washing machines, *Sci. Total Environ.*, 470-471, 1257-1271 (2014).
18. L. Domènech, D. Sauri, A comparative appraisal of the use of rainwater harvesting in single and multi-family buildings of the metropolitan area of Barcelona (Spain): social experience, drinking water savings and economic costs, *J. Cleaner Prod.*, 19(6-7), 598-608(2011).
19. V. W. Y. Tam, L. Tam, S. X. Zeng, Cost effectiveness and tradeoff on the use of rainwater tank: an empirical study in Australian residential decision-making, *Resour. Conserv. Recycl.*, 54(3), 178-186 (2010).
20. K. J. Kim, C. J. Yoo, Hydrological modeling and evaluation of rainwater harvesting facilities: case study on several rainwater harvesting facilities in Korea, *J. Hydrol. Eng.*, 14(6), 545-561(2009).
21. M. A. Imteaz, A. Ahsan, J. Naser, A. Rahman, Reliability analysis of rainwater tanks in Melbourne using daily water balance model, *Resour. Conserv. Recycl.*, 56(1), 80-86(2011).
22. X. Jing, S. Zhang, J. Zhang, Y. Wang, Y. Wang, T. Yue, Analysis and modelling of stormwater volume control performance of rainwater harvesting systems in four climatic zones of China, *Water Resour. Manag.*, 32, 2649-2664(2018).
23. H. J. Fowler, C. G. Kilsby, J. Stunell, Modelling the impacts of projected future climate change on water resources in north-west England, *Hydrol. Earth Syst. Sci.*, 11(3), 1115-1126 (2007).
24. A. Palla, I. Gnecco, P. La Barbera, The impact of domestic rainwater harvesting systems in storm water runoff mitigation at the urban block scale, *J. Environ. Manage.*, 191, 297-305(2017).
25. M. J. Burns, T. D. Fletcher, H. P. Duncan, B. E. Hatt, A. R. Ladson, C. J. Walsh, The performance of rainwater tanks for stormwater retention and water supply at the household scale: an empirical study, *Hydrol. Processes*, 29(1), 152-160 (2015).
26. M. A. Bashar, M. R. Karim, M. A. Imteaz, Reliability and economic analysis of urban rainwater harvesting: A comparative study within six major cities of Bangladesh, *Resour. Conserv. Recycl.*, 133, 146-154(2018).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors and Contribution Statement

Chen Shiguang

College of Urban and Rural Construction, Zhongkai University of Agriculture and Engineering, Guangzhou 510225, China, Lecturer, ORCID[®] 0000-0002-4102-6886: Conceptualization, Methodology, Validation, Writing - review and editing.

Zhang Yu

College of Urban and Rural Construction, Zhongkai University of Agriculture and Engineering, Guangzhou 510225, China, M.D. Candidate, ORCID[®] 0000-0002-5904-7802: Validation, Writing - original draft.