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Analysis of Optimum Rainwater Tank Size in a Multi-building

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Synopsis

The size of rainwater storage tank is crucial to cost-efficiency of rainwater harvesting (RWH) systems and the optimum capacity is variable with the main purposes of RWH systems which determine the criteria used in calculation. In this research, four scenarios were analyzed to evaluate the differences of optimum tank sizing under different RWH springboards using a daily simulation and economic analysis in a multi-building. Results showed that with the criterion of maximum potable water saving percentage, the ideal capacity was 55m^3. The best tank sizing was 85m^3 with the criterion of maximum extent to reduce roof runoff but there was economic deficit. With the purpose to obtain the maximum financial savings the best size was 60m^3 and the percentage of reduced roof runoff was 72.92%. When there was no saving and deficit, the ideal size was 75m^3 and the percentage of reduced roof runoff was 91.15%.

Keywords: rainwater harvesting; daily water balance simulation; criteria; economic analysis; tank size

1. Introduction

Rainwater harvesting (RWH) presented as a strategy to address water scarcity problems and mitigate urban waterlogging has been studied by many researchers. In Australia, rainwater has been used in single and multi-family residences (Imteaz et al., 2011). Ghisi (2007, 2009) has taken several researches on RWH in Brazil. The similar examples are also found in other countries (Campisano et al., 2012). In this context, it is necessary to provide criteria for tank size of RWH systems, bearing in mind that the idea size of a tank for storing rainwater is essential to avoid its functioning in an unproductive manner. Some light has been shone on the size of rainwater cisterns by several authors (Khastagir and Jayasuriya, 2010; Imteaz et al., 2012). And the prevailing method is to calculate financial savings under different tank capacities to obtain the best one that leads to an efficient and feasible system (Tam et al., 2010; Farreny et al., 2011). However, the optimum tank capacity is variable with the main purposes of rainwater harvesting systems which determine the criteria used in calculation and to our knowledge there is little research on this issue. In addition, most researches focus on direct financial savings and neglect its function in some special circumstances.

The goal of the study is to evaluate the optimum tank size with different criteria according to the purposes of RWH systems with a case study in a residential multi-building in Nanjing, China.

2. Method

2.1 Case selection

The multi-building selected is a 6-storey building with 700m^2 of roof area and 104 residents,

located in an urban residential district of Nanjing city, China.

2.2 water balance analysis

Water balance analysis considering daily rainfall, catchment area, spillage, storage volume, rainwater uses and toilet flushing water demand is performed (Imteaz et al., 2011). The amount of rainwater usage is estimated by following Eq. (1):

$$R_t = \begin{cases} D_t & \text{if } I_t + S_{t-1} \geq D_t \\ I_t + S_{t-1} & \text{if } I_t + S_{t-1} < D_t \end{cases} \quad (1)$$

Where t subscript is the day and D_t is the daily toilet flushing water demand (m^3); S_{t-1} is the storage volume at the end of the previous day (m^3); R_t and I_t are the amount of rainfall usage and collected rainfall (m^3), respectively. The spillage in day t (SP_t) can be determined by Eq. (2):

$$SP_t = \begin{cases} I_t + S_{t-1} - D_t - S & \text{if } I_t + S_{t-1} - D_t \geq S \\ 0 & \text{if } I_t + S_{t-1} < D_t \end{cases} \quad (2)$$

Where S is the capacity of rainfall tank (m^3) and the volume of storage rainfall in tank at the end of day t (S_t) is estimated by following Eq. (3):

$$S_t = \begin{cases} S & \text{if } SP_t > 0 \\ I_t + S_{t-1} - R_t & \text{if } SP_t = 0 \end{cases} \quad (3)$$

The collected rainfall is estimated by Eq. (4):

$$I_t = (H_t - h) \times A \times a \times 10^{-3} \quad (4)$$

Where H_t is the rainfall in day t (mm); h is the volume of first flush rejection, which is 2mm (Zhang et al., 2012); A is the roof area (m^2); a is the runoff coefficient, assumed to be 0.9.

2.3 Potable water saving percentage

Based on water balance analysis, the potable water saving percentage (P) is a function of tank capacity when rainfall, catchment area and toilet flushing water demand are determined, shown as formulae (5):

$$P = f_1(S) = \frac{\sum R_t}{\sum D_t} \times 100 \quad (5)$$

2.4 Runoff volume reduction

The surface runoff in a rainstorm is estimated by using Eq. (6).

$$W = a \times A \times H \times 10^{-3} \quad (6)$$

Where W is the surface runoff in a rainstorm (m^3); H is the rainfall (mm) in a rainfall event. The percentage of reduced runoff volume (U) is a function of tank capacity which is determined by using Eq. (7).

$$U = \begin{cases} f_2(S) = 100S/W & \text{if } S < W \\ 100\% & \text{if } S \geq W \end{cases} \quad (7)$$

2.5 Economic assessment

Life Cycle Costing (LCC) analysis is an economic analysis technique to estimate the total cost of a system over its life span (Farreny et al., 2011). Within the LCC approach, the calculations of the net present value, the ratio of present value and present cost (RPVC) and the payback period are conducted. In the research, economic evaluation is performed based on RPVC analysis and the analysis requires a rate at which costs and benefits are reduced over time, known as the discount rate (MJA 2007). The assumed rate 7% is similar to the value proposed by Zuo et al. (2009) and Rahamn et al. (2012). The equation is shown in Eq. (8).

$$RPVC = \frac{B \times \frac{(1+i)^n - 1}{i \times (1+i)^n}}{E + C \times \frac{(1+i)^n - 1}{i \times (1+i)^n}} \quad (8)$$

Where $RPVC$ is the ratio of present value and present cost; E is the initial cost of the system (￥); C is the annual operating costs (￥); B is the annual monetary saving(￥); i is the discount rate, assumed

to be 7%; *n* is life span (year), assumed to be 20 years.

(1) Cost

The initial cost of a system (*E*) includes rainwater tank charges (materials, installations etc.) and other costs such as piping, drains and connections. According to the survey on local shops and empirical data of demonstration projects in Nanjing, tank charges are 800￥per m^3 of tank volume and other costs are 30￥per m^2 of roof area. The annual operating costs (*C*) are divided into two parts, including energy cost and maintenance cost. The value of energy cost is 0.1￥per m^3 of rainwater usage amount (V) and maintenance cost is assumed 1% of the initial cost.

(2) Financial savings

The potential benefits obtained from rainwater harvesting and utilization is the reduction in runoff volume into the urban drainage system and a reduced risk of overflow from rainstorm events, mitigation of water shortage problems and environmental improvement (Farreny R. et al., 2011). The profit is a complex system involving natural-social-economic factors. It is difficult to calculate all profits, thus we choose the benefits from potable water savings and flood prevention investment savings (FPIS) as annual benefits (B). The value of potable water savings is 3.1￥per m^3 of rainwater usage amount (V). The FPIS is replaced by flood control maintenance fees, the value of which is 10￥per m^2 of roof area in Nanjing. Thus, the FPIS is $7000*U_1$, where U_1 is the percentage of reduced roof runoff volume in the case of the 24 hours rainfall with return period equalled to 20 years.

Table 1 shows the costs and benefits of the RWH system.

Table 1 Economic parameters for RPVC analysis

Items		*Cost (￥)*
Initial costs of the system	Rainwater cistern charges	800S
	other costs	30A
Annual operating costs	Power expenditure	0.1V
	Maintenance and management	0.01E
		Profit (￥)
Annual monetary savings	Potable water savings	3.1 V
	FPIS	$7000*U_1$

2.6 Optimum capacity

The optimum capacity varies with the main purposes of rainwater harvesting systems. In this study, three criteria of potable water saving percentage, runoff volume reduction and RPVC are chose to evaluate the ideal tank size. With respect to different springboards of RWH systems, four scenarios are considered:

Scenario 1: The RWH system is used to address water scarcity;

Scenario 2: The system is used to mitigate urban waterlogging;

Scenario 3: The purpose of RWH is to obtain maximum financial savings;

Scenario 4: In this case, the system is used to obtain environmental benefits and the financial savings is not the main factor. However there should be no economic deficit.

3. Results

3.1 Data

(1) Rainfall

The daily rainfall used to water balance analysis is the daily rainfall in an average year obtained from Nanjing Weather Station. The 24 hours rainfall with the return period equalled to 20 years is 130.6mm, which is used to evaluate the reduced roof runoff with RWH.

(2) Non-potable water demand

The daily average potable water demand is

assumed to 220L per capita. And the toilet flushing water demand is 20% of the potable water consumption in residences (Su et al., 2009).

3.2 Potable water saving percentage

The potential potable water savings as a function of tank capacity is depicted in Fig.1. The percentage increases with increase of tank capacities within a certain range of tank capacity. Nevertheless the growth rate reduces with the increase of tank capacities and finally the curve tends to be a horizontal line. The curve shape is influenced by factors such as precipitation, rainwater harvesting area, rainwater demand.

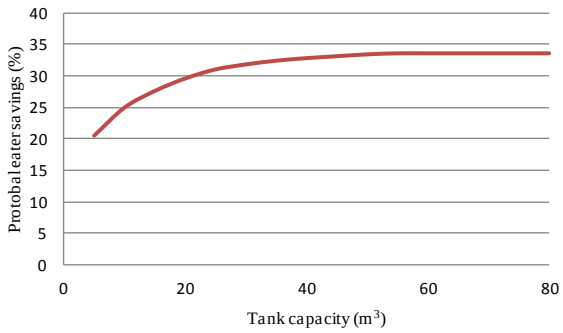

Fig. 1 Potable water savings as a function of tank capacity

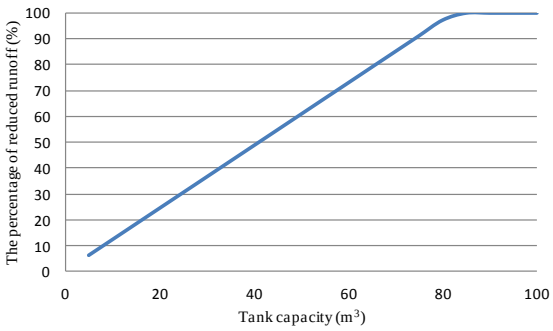

Fig. 2 Reduced runoff as a function of tank capacity

3.3 Runoff volume reduction

In the case of 24 hours rainfall equaled to 130.6mm, the percentage of reduced roof runoff resulting from RWH system as a function of tank capacity is depicted in Fig.2. The reduced percentage of roof runoff volume increases with the increase of cistern capacities and it is a linear relation when the tank capacity is smaller than the critical value at which the reduced percentage of runoff reaches 100%. Above the value, the curve becomes to a horizontal line. The curve shape is determined by rainfall amount and tank capacity.

3.4 Economic assessment

As shown in Fig.3, if tank capacity is less than a certain value, RPVC increases with the increase of tank capacity, whereas it reduces with the increase of tank volume. It is due to the fact that with a small capacity the benefits from potable water savings and flood control are low. For larger capacities the increased cost of the system is higher than the increased benefits as the savings are limited by precipitation and rainwater harvesting areas. The curve shape is influenced by factors such as tank capacity, rainwater harvesting areas, potential potable water savings and reduced percentage of runoff volume.

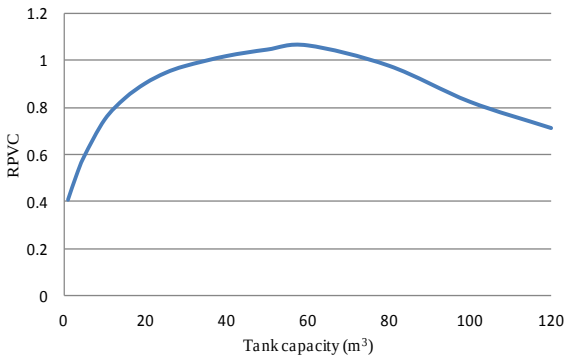

Fig. 3 RPVC as a function of tank capacity

3.5 Optimum capacity

Scenario 1: In this case, the criterion of maximum potable water saving percentage was crucial and the ideal capacity was 55m^3. The potable water saving percentage was 33.64%. The percentage of reduced roof runoff was 66.85% and RPVC was 1.06.

Scenario 2: The optimum capacity was determined by the parameter of the maximum percentage of reduced roof runoff (100%), which was 85m^3. The potable water saving percentage was 33.64% and RPVC was 0.93.

Scenario 3: When the financial savings was the maximum, RPVC was 1.07 and the ideal capacity

was 60m^3. The potable water saving percentage was 33.64% and the percentage of roof reduced runoff was 72.92%.

Scenario 4: With RPVC equaled to 1, the optimum capacity was 75m^3 and the potable water saving percentage was 33.64%. The percentage of reduced roof runoff was 91.15%.

4. Conclusion

This study focuses on the size of rainwater storage tanks. The main goal is to evaluate the best storage volume with different criteria using a daily simulation and economic analysis. Results showed that the differences of ideal tank sizing were large with different criteria of RWH. The optimum capacity varied with the main springboards of rainwater harvesting systems.

The ideal tank size was the smallest and RPVC was 1.06 under the criterion of maximum potable water saving percentage. The best size was the biggest but there was economic deficit on the investment with the criterion of maximum extent to reduce runoff. With the purpose to obtain the maximum financial savings the size was 60m^3 and RPVC was 1.07. And the percentage of reduced runoff was 72.92%. In the last scenario, there was no economic deficit and financial savings on investment. The ideal size was 75m^3 and the percentage of reduced runoff was 91.15%, which was much more than the value with maximum financial savings.

In arid regions, there are few waterlogging problems and the criterion of maximum potable water saving percentage is the best. In some regions with high risk of flooding, the criterion of the extent to reduce runoff should be considered. As the financial savings are low and even deficit, the RWH system is better to be invested by government and the criterion of RPVC equalled to 1 may be best. In other regions, the criterion of maximum financial savings is prior.

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