Exploring optimal tank size for rainwater harvesting systems in Asian tropical climates

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Abstract:
This paper explores optimal tank size for domestic rainwater harvesting systems in Asian tropical climates. A total of 128 locations in Vietnam covering three regional climate patterns were selected for the study. The system behavior was simulated on a daily basis using between 27 and 32 years of rainfall data. Annual water cost was investigated to determine optimal tank size. The relationship among optimal size, climate and system conditions was also analyzed. Results of the study emphasize the economic benefit of rainwater harvesting for the whole study area. The optimal tank size for a non-potable rainwater harvesting system has a range of 1.2–2.6 m³, exhibiting 19–65% supply efficiency and a payback period of 7–17 years. Extended system scenarios reveal a contrast in the influences of demand and roof area on optimal size in relation to rainfall amount. The roof area is critical in determining optimal size in the low rainfall area while the demand is important in the high rainfall area. Although there is a certain degree of variability in optimal tank size, it does not considerably undermine the economic benefit of a rainwater harvesting system.

KEYWORDS rainwater harvesting; optimal tank size; roof area; water demand; Asian tropical climates

INTRODUCTION

Design of rainwater harvesting systems involves several parameters, of which tank size appears the most challenging factor (Hanson and Vogel, 2014). A number of approaches were developed to select appropriate tank size which cover various points of view, such as meeting desired supply reliability (Khastagir and Jayasuriya, 2010), balancing supply and runoff capturing efficiency (Sample and Liu, 2014), maximizing rainwater utilization (Imteaz et al., 2011), minimizing total annual water cost (Pelak and Porporato, 2016) and minimizing annual water cost and fresh water consumption (Bocanegra-Martinez et al., 2014). Optimization of tank size based on economic analysis is the most common approach.

Most of the previous studies on optimizing tank size focus on a specific climate condition, such as semi-arid climate (Campisano and Modica, 2012; Okoye et al., 2015). As an attempt of generalization, Pelak and Porporato (2016) developed the equations that provided optimal tank size across diverse precipitation and system conditions using a parametric description of rainfall, in which rainfall was modelled as a marked Poisson process. This approach has, however, a limitation in terms of transferability, particularly for areas having rainfall seasonality (Basinger et al., 2010). Thus, there is a need to evaluate optimal size under a variety of climates and physical system conditions.

The Asian tropical region has traditionally had interest in rainwater harvesting (Özdemir et al., 2011). The region also covers several different climatic patterns resulting in a large range of annual precipitation and seasonality (Vuong et al., 2016). Despite abundant rainfall and strong user interests, only a few studies are available which document the economic benefit and optimal tank size such as Hashim et al. (2013) reporting optimal tank size for a large-scale rainwater harvesting system in Malaysia. Evaluating optimal tank size and its variation with different precipitation and system conditions in this region, especially at household scale, provides beneficial information to local users and broadens understanding of optimal size variation.

The objectives of the current study are (i) to investigate the economic benefit of rainwater harvesting systems and (ii) to evaluate optimal size under interaction of precipitation conditions and physical system parameters in Asian tropical regions, especially focusing on Vietnam, which presents typical climate conditions of the regions. This study relies heavily on the circumstances of Vietnam, however the obtained results are expected to promote user awareness of the benefit of rainwater harvesting and serve as a guideline on selecting optimal tank design for the areas that bear a similarity to physical and climatic conditions considered in the study. This study assumes a household that has access to public water supply and utilizes rainwater harvesting as a supplementary water source, and attempts to evaluate performance of rainwater harvesting by reduction of public water cost accompanied with using rainwater harvesting. A household that does not have access to public water supply should place the highest priority not on economic benefit, but on reliability of rainwater harvesting, and accordingly it is out of the scope of this study.

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The current research selected the whole area of Vietnam, being approximately 331,200 km², as the study area in the Asian tropical region. A total of 128 locations are used to represent rainfall characteristics in the region, of which daily observed rainfall data is available for between 27 and 32 years. According to the world climate classification (Peel et al., 2007), Vietnam represents three major regional climates of the South East Asia area, which are monsoon climate (Am), savannah climate (Aw) and temperate climate (Cwa). Figure 1 presents the variation of average annual rainfall and temporal distribution are expected to result in significant impacts on rainwater harvesting.

The domestic water situation in the study area varies mostly depending on public water supply condition. In rural and sub-urban areas, rainwater harvesting is usually practiced as a major potable water source due to lack of sufficient public water supply, contaminated groundwater and surface water (Özdemir et al., 2011). By contrast, rainwater harvesting serves as a supplementary water source in urban areas that have full time access to public water supply.

STUDY AREA

METHODOLOGY

Basic framework

Rainwater harvesting for each location in the study area was at first simulated on a daily basis using observed rainfall datasets for between 27 and 32 years, and the annual water cost was then estimated for each year in consideration of the initial cost for the tank and the public water cost. The average annual water cost of each location was calculated from the annual costs during the above simulation period as the expected value of the annual water cost under inter-annual variation of rainfall conditions. The optimal tank size was finally determined that gives the minimum average annual water cost.

Rainwater harvesting simulation

Rainwater harvesting was simulated using a behavior model (Vuong et al., 2016). The continuity equation of the model was as follows:

\[ V_t = V_{t-1} + Q_t - Y_t - O_t \] \hspace{1cm} (1)

where \( V_t \) and \( V_{t-1} \) are storage volume (m³) at the end of day \( t \) and \( t-1 \), and \( Y_t, Q_t \) and \( O_t \) are supply yield, runoff inflow and overflow in volume (m³) on a daily basis, respectively.

The runoff inflow was assumed to have a linear relationship with rainfall depth and collection area as per the following equation.

\[ Q_t = (P_t - F_t) \times A \times \varphi \] \hspace{1cm} (2)

where \( P_t \) is daily rainfall (m), \( F_t \) is first flush (m), \( A \) is roof area (m²), and \( \varphi \) is runoff coefficient. The main purpose of the study is to explore the benefit and optimal tank size of a rainwater harvesting system as a supplementary water source at the household scale. This study accordingly assumed the following household conditions: 4 residents, 30 m² roof area, 200 Ld⁻¹ water demand for cleaning and toilet flushing (supplied by rainwater and public water) under full domestic water demand of 600 Ld⁻¹. This condition was deemed typical in the study area from a local survey done by the authors and empirical knowledge of the first author. A runoff coefficient was assumed as 0.8. First flush is subtraction of initial rainfall at the beginning of rainfall events in order to enhance water quality. This study considered the first 1 mm rainfall as first flush volume, assuming non-potable rainwater use.

Operation of a rainwater harvesting system was simulated by following a yield-after-spillage algorithm. Yield was assumed to be equal to the minimum amount of demand \( D_t \) (m³) or total available water as in Equation (3). When total available water exceeds tank size \( S \) (m³), excessive water was diverted as overflow prior to yield supply as in Equation (4). The initial storage was set as empty.

\[ Y_t = \min \left\{ \frac{V_{t-1} + Q_t}{D_t} \right\} \] \hspace{1cm} (3)

\[ O_t = \max \left\{ \frac{V_{t-1} + Q_t - S}{0} \right\} \] \hspace{1cm} (4)

Performance of rainwater harvesting was evaluated using two volumetric indicators, namely supply efficiency and runoff capturing efficiency. The former index measures ratio of yield versus demand while the latter examines ratio of overflow versus runoff inflow (100%: no overflow) (Sample and Liu, 2014).

Exploring of optimal tank size

Optimal tank size was determined that minimizes the
total annual water cost, which consists of the initial cost and the public water cost.

The initial cost was for tank installation and construction. This study assumed that a tank was made of concrete because it was commonly available in the local community and was inexpensive compared to plastic and metal material. The tank cost was estimated using a government guideline on construction labor and material (Ministry of Construction of Vietnam, 2007) while unit costs were taken from market prices in the local currency of Vietnam, VND (10,000 VND = 0.44 USD, as of November 2017) (Table S1). Figure S1 shows estimated tank costs for different tank sizes (1, 2, 3, 4, 5 and 10 m³). The estimated tank cost had a strong correlation to tank size as is shown in the figure, with the coefficient of determination \( R^2 = 0.9987 \). The annualized initial cost \( C_S \) then was estimated by dividing the tank cost by tank lifetime, considering zero inflation rate, as in Equation (5):

\[
C_S = \frac{1}{N}(0.929S + 0.784) \times 10^6
\]

where \( N \) is tank lifetime (year) and \( S \) is tank size (m³). This study used 40 years for tank lifetime, according to a local survey done by the authors. For the simulation, optimal tank size was explored at increments of 0.1 m³.

The public water cost was for public water consumption. Because of limited availability in water tariff information, this study applied the block-wise public water tariff of Hanoi to the whole study area, with unit price of 6,900, 8,100, 10,000 and 18,300 VND per m³ in blocks of 0–10, 10–20, 20–30 and over 30 m³ on a monthly basis, respectively. The difference in public water fee among places in the study area may give uncertain impacts on results of the study. A comparison of public water fee based on the tariff of Hanoi showed a small difference (approx. 4%) among large cities (Hanoi, Hue and Ho Chi Minh city) and a relatively large difference (approx. 30%) between large (the above 3 cities) and small cities (Nam Dinh). This study omitted the difference to highlight the impact of rainfall condition on the economic benefits of rainwater harvesting systems, and the impacts of the difference in public water fee need to be clarified in further analysis. Water price was assumed to be constant over time. Although this assumption leads to conservative results as increase of water price results in increase of water cost in increase of economic benefit (Rahman et al., 2012), it aims at avoiding mixing impacts of precipitation and water price on optimal size.

The annual water cost was estimated by summing up monthly costs for public water consumption, and the average annual water cost was then calculated by taking the average of annual water costs during the entire simulation period.

**RESULTS AND DISCUSSION**

**Finding optimal tank size**

In order to evaluate the feasibility of using rainwater harvesting in combination with public water supply, an economic analysis of the system is conducted with regards to the annual water cost. Figure 2(a) presents inter-annual variation of annual water cost with tank size in Hanoi. The dark and light gray bands show 50% and 100% variation of annual water cost, and the black line represents the average annual water cost during the simulation period. The vertical variation of annual water cost reflects different meteorological conditions (amount and temporal pattern of rainfall) from year to year. The lowest point in the average annual water cost is used to determine the optimal tank size. The optimal size for Hanoi is observed at approximately 2.2 m³ with the corresponding minimum average annual water cost of 1.46 million VND, whereas the annual water cost is 1.64 million VND if they rely on public water supply only (tank size = 0 m³). The optimal tank of 2.2 m³ provides approximately 11% reduction of annual water cost in Hanoi during the whole tank lifetime, while the above annual water cost without using rainwater harvesting (1.64 million VND) is deemed affordable for a moderate-income household (Wright-Contreras et al., 2017). The average annual water cost is equal to or less than the cost of public water supply only over a range of tank size from 0 through to 13 m³, while the profitable range decreases in width (0 to 8 m³) if the maximum annual cost (the upper end of the light gray band) is considered.

Figure 2(b) shows relationships of average annual water costs and tank size for all 128 stations. It can be seen that there are reductions of water cost in all locations, which emphasize economic feasibility of rainwater harvesting across the whole study area. Minimum annual water costs
are observed between 1.3–1.5 million VND, leading to an optimal tank size of 1.2–2.6 m$^3$. Rainwater harvesting is still beneficial until annual water cost is balanced to the cost of public water use only, even after the optimal tank size is exceeded. Further tank size increase beyond the beneficial range is not recommended as it results in negative economic benefits.

**Influences of rainfall on optimal size**

With a view to understanding the interaction of optimal size and economic benefit with climatic conditions, Figure 3 presents optimal sizes and payback periods regarding average annual rainfall. Generally, the optimal size has a positive correlation with annual rainfall. It increases with the increase of annual rainfall in the low rainfall area of which annual rainfall is less than 2000 mm. In the higher rainfall area, the optimal size remains almost constant (approximately 2.2 m$^3$) with a fluctuation of 0.3–0.5 m$^3$. In contrast to the optimal size, the payback period shows a gradual decreasing trend with annual rainfall. The lowest rainfall area has the longest payback period of approximately 17 years. The area of 1800 mm average annual rainfall, accounting for a substantial fraction of the study region, has an average 10 years payback period, while for higher rainfall area the payback period is 7–8 years.

**Figure 4** presents the performance of rainwater harvesting at optimal tank sizes. It is observed that there are opposite trends of the supply efficiency and the runoff capturing efficiency. While the supply efficiency increases gradually from 20% to 65% with increase in annual rainfall, the runoff capturing efficiency shows a decreasing trend from approximately 80–90% to 40%. This is explained by effects of rainfall availability and seasonality. When rainwater supply is limited, increase of tank size in response to increase of annual rainfall is favorable so as to improve supply efficiency, as observed in low-medium rainfall areas. In the high rainfall area, the supply efficiency stays constant (60%) but the runoff capturing efficiency shows a decreasing trend, which means that a significant amount of overflow occurs in the wet season, given its constant optimal tank size (2.2 m$^3$). A larger tank in the high rainfall area would be able to catch much rainwater in the wet season, but it is not profitable after considering that it stands empty in the dry season.

**Influences of physical parameters on optimal size**

In order to explore the effects of physical system parameters on optimal size in different rainfall conditions, Figure 5 presents optimal size changes associated with variation of roof area and demand. The two additional scenarios for small and large roof areas of 15 and 60 m$^2$ are examined in Figure 5(a), and another two demand scenarios are investi-
gated in Figure 5(b) to consider rainwater use only for toilet flushing of 100 Ld⁻¹ and full household demand of 600 Ld⁻¹. It is observed that both roof area and demand have distinct impacts on optimal size depending on rainfall condition, while a contrast is found between them.

At 15 m² roof area, optimal size has an increasing trend with annual rainfall, from approximately 0.6 till 2.0 m³. At a medium roof area of 30 m², an increasing trend is observed only in the low-medium rainfall (≤ 2000 mm). At 60 m², the optimal size is almost uniform around 2.6 m³ over the whole region. As a result, the increase of roof area leads to variation of average 300% and 25% of optimal size in the low and high rainfall areas, respectively. This is supported by the previous analysis of system performance. At 30 m² roof area, the runoff capturing efficiency for the high rainfall area is only 40–50%, thus the increase of roof area results in increasing overflow while a reduction of roof area does not significantly affect supply capacity because of high rainfall. Accordingly, the optimal size in the high rainfall regions stays almost unchanged against roof area variations. In the low rainfall regions, by contrast, the roof area plays an essential role on supply efficiency and has a direct impact on determining optimal size.

The impacts of demand on optimal tank size are opposite to those of roof area. At the demand of 100 Ld⁻¹, the optimal tank remains constant around 1.0–1.2 m³ with rainfall condition. As the demand increases to 200 and 600 Ld⁻¹, the optimal size becomes sensitive to annual rainfall, and accordingly the high rainfall areas show a significant change in optimal size with demand variations, which is clearly different from lesser impacts found in the low rainfall areas.

Overall, it is recognized that roof area and demand play opposite roles on selection of optimal size depending on rainfall condition. A low rainfall area emphasizes roof area for determining optimal size while a high rainfall area places a priority on water demand over roof area. Okoye et al. (2015) indicated an increasing trend of optimal size with increase of roof area while no trend was observed by demand increase. Such performances are similar to the low rainfall area in this study having the similar range of annual rainfall, despite differences of Mediterranean and Asian tropical climates. In addition, the current study shows that the importance of roof area on optimal size tends to decrease while the role of demand is emphasized as annual rainfall increases. The analysis that considered a broad range of annual rainfall was beneficial for providing comprehensive understanding of optimal size in various household conditions.

Discussion on optimal size variability

It is recognized that there is variability of optimal size in areas of similar annual rainfall, as shown in Figure 5. This variability may cause a local user to choose improper tank size, and accordingly it may decrease the economic benefit of using rainwater harvesting. Figure 6 illustrates the sensitivity of annual reduced water cost associated with several deviations from the optimal tank size. The deviations of −1 and +1 m³ from the optimal size lead to average 8% and 5% decreases of the reduced water cost, respectively. However, the deviation of 0.5 m³ results in an average 1–2% decrease of the benefit across the whole region. Consequently, the economic benefit of using rainwater harvesting is not considerably undermined by the tank size variability.

CONCLUSIONS

This paper explored optimal tank size for domestic rainwater harvesting systems in Asian tropical climates. The optimal size was determined at the minimum average annual water cost. Observed daily rainfall datasets of between 27 and 32 years in 128 locations were used for simulating rainwater harvesting systems. The relationship among optimal size, climate and system conditions was also analyzed.

The economic analysis revealed that rainwater harvesting was beneficial across the whole region of the study area. As for a non-potable water system, the optimal size increased with increase in annual rainfall in the area of which annual rainfall is less than 2000 mm, while it remained almost constant for the higher rainfall area. As the annual rainfall increased, the water supply efficiency increased gradually from 19 through to 65%, and the payback period decreased from 17 to 7 years.

The additional scenarios regarding roof area and demand for different household scale and water purposes emphasized a contrast in the influences of demand and roof area on optimal size in relation to rainfall amount. In the low rainfall area, the increase of roof area leads to as much as a 300% increase of optimal size while the demand variation did not cause significant changes in optimal size. In the high rainfall area, by contrast, the demand increase resulted in almost a 5 times increase of optimal size from 1 to 5 m³, and variation of roof area from 15 to 60 m² leads to only a 25% increase of optimal size. In summary, the roof area played a key role in determining optimal tank size in the low rainfall area, while a high priority was placed on the water demand in the high rainfall area.

Although there is variability of 0.5–1.0 m³ of optimal tank size in areas of similar annual rainfall, it does not considerably undermine the economic benefit of rainwater harvesting systems. A further exploration of optimal size variability is recommended towards more comprehensive understanding across different climate conditions.
SUPPLEMENTS

Figure S1. Correlation between concrete tank cost and tank size
Table SI. Summary of material and labor for tank cost estimation

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