Performance assessment of rainwater harvesting considering rainfall variations in Asian tropical monsoon climates

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Abstract:

Rainwater harvesting is increasingly recognized as an important source of water supply. However, the technique is practiced for very different purposes depending on region and rainfall conditions. In this study, the performance of rainwater harvesting was evaluated in accordance with local user practice to determine its suitability as a primary water supply. A water balance model using a long-term time series was applied to simulate system behavior under various scenarios of tank size and monsoon patterns in the Asian tropical monsoon region, investigated at 111 sites in Vietnam. The results of the study show that a limited range of 20–110 L/d can meet basic demand with 95% reliability. However, an additional water of 50–400 L/d is available for extra supply during rainy season. The diversity of monsoon patterns leads to considerable variation of additional available water (AAW) despite uniform amounts of annual precipitation. Tank size is recognized as playing a crucial role in improvement of supply capacity for basic demand while roof area and precipitation exerts a higher influence on AAW.

KEYWORDS rainwater harvesting; monsoon precipitation; basic demand; additional available water; reliability

INTRODUCTION

Increase of water demand due to population growth and changes of precipitation regimes owing to climate change are presenting serious challenges to satisfying water demand for human activities (García-Montoya et al., 2015). Under that circumstance, rainwater harvesting has increasingly drawn attention as an important alternative water supply (Bocanegra-Martínez et al., 2014; Hanson and Vogel, 2014). Various studies show that rainwater harvesting can provide 40–60% of domestic non-potable water demand (Villarreal and Dixon, 2005; Silva et al., 2015). Imteaz et al. (2011) presented a study showing that rainwater harvesting can achieve 100% reliability for the household water demand of two people.

However, the technique is applied for very different purposes across countries and regions. In developed countries, collected rain tends to be used for non-potable demands, including gardening, toilet-flushing and cleaning (DeBusk et al., 2013; Palla et al., 2011). On the other hand, rainwater is considered as an important source for water for drinking and cooking in rural areas of developing regions (Islam et al., 2010; Özdemir et al., 2011). These different purposes thus require different approaches in evaluating rainwater harvesting potential. A non-potable water harvesting system might prioritize efficiency in annual water saving or runoff capture, while a system used for drinking water might put priority on supply reliability (Hanson and Vogel, 2014).

Intensive studies have been conducted for regional assessment of rainwater harvesting in European climates (Palla et al., 2012), US humid climates (Steffen et al., 2013) and African tropical climates (Cowden et al., 2008). However, there is little study on the Asian tropical monsoon region, where precipitation is abundant in terms of annual availability but highly seasonally distributed. Thus, the traditional evaluation approach, which examines rainfall on an annual basis, might fail to demonstrate the impact of rainfall seasonality and monsoon diversity.

Overall, there is a need for integrated assessment of rainwater harvesting considering local user practice, system conditions and the variety of precipitation regimes in the Asian tropical monsoon region.

In Vietnam or South East Asia (SEA), generally, rainwater harvesting is common practice (Özdemir et al., 2011). People consider rainwater harvesting as a good source for drinking water throughout the year, compared to surface water or groundwater, which are often characterized by high metal concentration (Wilbers et al., 2013). However, the actual potential of rainwater harvesting is still a question. Hence, a proper understanding of the efficiency of rainwater harvesting would be valuable in promoting awareness of the importance of technology and practical implementation.

The main purpose of the study is to assess the capability and suitable solutions of rainwater harvesting as a primary water supply system, considering different spatial and temporal variation of tropical monsoon precipitation. The specific objectives of the study are as follows: (i) to evaluate impact of precipitation and tank size on continuous supply capacity, (ii) to examine influence of rainfall seasonality and monsoon diversity on system performance, and (iii) to propose suitable rainwater harvesting solutions for different scenarios of demand, tank size and precipitation.
STUDY AREA

The selected study area is the whole Vietnam territory, including 111 rainfall stations with daily rainfall observation over 27 years from 1980 to 2006. The time series is considered as being sufficient for rainwater harvesting evaluation (Mitchell, 2007).

According to the world climate classification proposed by Kottek et al. (2006) and updated by Peel et al. (2007), there are three climate zones in the study area, consisting of two tropical climates (Am and Aw) and one temperate (Cwa), which are three typical climates of continental SEA. However, average annual precipitation is observed to vary greatly between locations in climate zones (Figure 1).

Taking annual precipitation as a reference, median precipitation of the country is approximately 1850 mm per year (Figure 2a). Approximately 37% of the study area has precipitation in the range of 1600–1900 mm; however, temporal precipitation variation could differ significantly between locations in terms of monsoon duration (4–6 months) and monthly precipitation intensity as is the case for Hanoi, Quy Nhon and Can Tho (Figure 2b). Monsoon precipitation season generally occurs during the 6 months from May to October in Northern and Southern regions and for 4–5 months in Central area. Detail of monsoon precipitation characteristics with regards to duration and timing dates are found in Ho et al. (2011) with updates of onset monsoon dates (Nguyen-Le et al., 2013).

METHODOLOGY

Rainwater harvesting simulation

A number of methods were developed for simulating the performance of rainwater harvesting, including behavior model (Schiller and Latham, 1987; Fewkes, 2000), stochastic rainfall generation (Basinger et al., 2010) and probabilistic analysis (Su et al., 2009). In this study, the behavior model that allows long-term simulation of rainwater harvesting performance is selected, taking advantage of the availability of time-series data in the study area. The governing equation of the model is as follows:

\[ V_t = V_{t-1} + Q_t - Y_t - O_t \]  

where:
- \( V_t \) and \( V_{t-1} \) (m³) are stored volume at end of day \( t \) and \( t - 1 \),
- \( Y_t \) (m³) is supply yield volume,
- \( Q_t \) (m³) is inflow volume,
- \( O_t \) (m³) is outflow volume (Figure 3).

Inflow and first flush

Runoff inflow is assumed to have a linear relationship with rainfall depth and collection area by a runoff coefficient, as in the following equation:

\[ Q_t = (P_t - F_t)A\phi \]  

where:
- \( P_t \) (m) is daily rainfall depth,
- \( F_t \) (m) is first flush depth,
- \( A \) (m²) is roof area and \( \phi \) is the runoff coefficient. A reference roof area of 30 m² is assumed, considering its wide affordability at household scale. The runoff coefficient varies between 0.7–0.9 depending on roof material, and is here selected as 0.8, taking into account all losses including evaporation and infiltration.

As dust and atmospheric pollutants accumulate on the roof surface and are washed out at the beginning of rainy events, subtracting this initial rain from the system (“first flush”) is recommended for enhancing water quality. Depending on purpose of rainwater harvesting, diversion of 0.33 or 0.40 mm is proposed for non-potable rainwater demand (Basinger et al., 2010; Khastagir and Jayasuriya, 2010), while diversion of 2–5 mm is recommended for com-
RAINWATER HARVESTING CONSIDERING RAINFALL VARIATIONS

pliance of harvested water with drinking water standards (Kus et al., 2010). However, Huston et al. (2009) noted that atmospheric deposition is not the major contributor to quality of stored rainwater in a reasonable air environment. This might suggest that the amount of first flush should be flexible according to the antecedent dry period, ADP (day), during which dust and pollutants are accumulated.

In Vietnam, first flush is common practice and users consider harvesting after several heavy rainfall events at the beginning of the rainy season, or after 5 minutes rainfall (Wilbers et al., 2013). Taking consideration of the use of rainwater harvesting as a potable water source plus the frequent rainfall events in monsoon season, this study treats first flush practice as following:

\[
F_r = \begin{cases} 
0.005 : & \text{ADP} \geq 0.007 \\
0.002 : & 0.002 \leq \text{ADP} < 0.007 \\
0.001 : & \text{ADP} < 0.002 
\end{cases} 
\]  

(3)

The difference of first flush depth according to ADP aims at optimizing utilization of rainfall during the wet season while ensuring sufficient diversion of contaminated water in the dry season. If the amount of rainfall does not meet first flush requirement, the rainy day will be considered as dry for the purposes of the model.

Operation algorithm

The simulation of rainwater harvesting operation is conducted on a daily basis, thus taking into account two assumptions regarding: timing of supply (at either beginning or end of day) and order between supply versus spillage. In this study, demand is assumed to be withdrawn at the end of day of day and order between supply versus spillage. In this case where total available water is larger than tank size, overflow occurs. It is assumed that all excessive water is first being considered for spillage prior to supplying demand, due to conservative simulated results and lower sensitivity to tank variation (Mitchell, 2007). These assumptions are represented as follow:

\[
Y_t = \min \left\{ \frac{V_{t-1} + Q_t}{D_t} \right\} 
\]  

(4)

\[
O_t = \max \left\{ \frac{V_{t-1} + Q_t - S_t}{0} \right\} 
\]  

(5)

where: \( D_t \) (m³) is rainwater demand at day \( t \), and \( S \) (m³) is tank size. Three different tank sizes of 3, 5 and 8 m³ are considered, reflecting investigation of local user tanks (Özdemir et al., 2011). Stored water at the beginning time step is set at empty for alleviating impact of data length on yield estimation (Mitchell, 2007).

Figure 4 presents a schematic diagram of the two-stage methodology adopted in this study. The first stage determines a suitable basic demand scenario, which satisfies the assumption of desired reliability. This is the same as the traditional approach used for selection of optimal tank size or basic demand (Khastagir and Jayasuriya, 2010; Hanson and Vogel, 2014). However, it is argued that application of this traditional approach leads to conservative results regarding rainwater use efficiency, owing to an absence of consideration of monsoon precipitation. Thus, the second stage in this methodology seeks an opportunity for enhancing rainwater use by examination of additional available water (AAW). The AAW is defined as extra water that could be utilized during rainy season while maintaining capacity to meet demand at desired reliability. Desired reliability is selected in the range of 0.8–0.98 and is taken as 0.95 in this study.

Rainwater harvesting evaluation

The performance of rainwater harvesting systems is evaluated by time-based or volumetric indices. A time-based index will assess reliability of the system in fully supplying demand. Partially supplying the day’s demand is considered as not reliable (Basinger et al., 2010). Due to this conservative characteristic, volumetric indices, which accept both partial and full supply into system performance, are widely applied (Palla et al., 2011; Sample and Liu, 2014). In this study, two volumetric indicators, namely water supply reliability \( (E_s) \) and runoff capturing efficiency \( (E_{rc}) \) are employed. The \( E_s \) is measured by ratio of total rainwater use (yield) versus demand over the whole time series, while \( E_{rc} \) is examined through ratio of total overflow versus total inflow.

\[
E_s = \frac{\sum_{t=1}^{N} Y_t}{\sum_{t=1}^{N} D_t} 
\]  

(6)

\[
E_{rc} = 1 - \frac{\sum_{t=1}^{N} O_t}{\sum_{t=1}^{N} Q_t} 
\]  

(7)

where \( N \) is total number of time steps.

Investigation framework

Firstly, the supply capacity of the system under varying scenarios of precipitation and tank sizes is investigated, to
identify suitable basic demand. Then, three major monsoon precipitation patterns are considered for evaluating influence of monsoon rainfall on system performance. Rainwater harvesting solutions based on suitability of basic demand, precipitation levels, and tank sizes are analyzed. Finally, impact of roof area variation is examined.

RESULTS AND DISCUSSION

Assessing supply capacity for basic demand

In order to explore the supply capacity of the system, rainwater harvesting performance is firstly evaluated from the perspective of desired reliability for basic demand only. Basic demand is defined as the one for the most fundamental water uses, such as drinking water, which varies depending on places. Supply capacity is potential yield for demands at desired reliability, given a system’s conditions. This assessment follows the traditional approach that assumes constant basic demand throughout the year, and its results serve as a motivation for using the methodology proposed in this study to assess the performance of the system considering rainfall variations and additional available water during the rainy season.

Figure 5 illustrates the relationship of supply capacity at 95% reliability and runoff capturing efficiency, with reference to tank size and annual precipitation. At unlimited tank size, maximum supply capacity appears to have an almost linear relationship with annual precipitation. However, as tank size decreases, the relationship tends to increase its variability as observed by reduction of coefficient of determination ($R^2$) from 0.9883 to 0.7836 when tank size is reduced to 8 m$^3$ and 0.6964 for a tank size of 3 m$^3$. In other words, as tank size decreases, the diversity of monsoon patterns plays an increasing role, which weakens the relationship of annual precipitation and supply capacity. The supply capacity of the whole study area is limited to a range of approximately 20–45, 30–80 and 35–110 L/d at tank sizes of 3, 5 and 8 m$^3$, respectively (Figure 5a).

Supply capacity is generally proportional to annual precipitation, but there are large variations. Pleiku station has an annual precipitation of 2200 mm, considerably larger than the 1200 mm annual precipitation at Cam Ranh station. These two locations with their difference of 1000 mm in annual precipitation, however, have similar supply capacity of 25 L/d in a 3 m$^3$ tank.

As far as runoff capture is concerned, it is observed that only 20–30% rainwater is utilized in a 3 m$^3$ tank while the corresponding range of utilization in an 8 m$^3$ tank is 30–80% (Figure 5b). The traditional approach can present supply capacity for basic demand; however, it is limited in terms of proposing solutions for enhancing rainwater utilization, which could be explained by its failure to consider precipitation seasonality.

Figure 5. System performance at 95% supply reliability: (a) supply capacity, (b) runoff capturing efficiency ($S$, tank size; $R^2$, coefficient of determination)

Figure 6. System performance for three monsoon precipitation patterns (Grey and white bars of top graphs denote monthly precipitation of monsoon and dry period, respectively)
Assessing system performance considering additional available water under different monsoon patterns

Taking the limitations of the traditional approach into account, this subsection aims at evaluating the influence of precipitation seasonality and diversity of monsoon patterns on rainwater harvesting system performance. It examines three typical monsoon patterns of Hanoi (HN), Quy Nhon (QN) and Can Tho (CT) (Figure 2b).

Figure 6 shows system performance for these three sites; red and blue lines show reliability contours of basic demand and AAW, respectively, and background gradation shows runoff capturing efficiency. For example, a combination of 100 L/d basic demand and 50 L/d AAW at HN gives 60% and 90% reliabilities for basic demand and AAW, respectively, and the corresponding runoff capture efficiency is approximately 80%.

The newly proposed approach clearly outweighs the traditional approach in terms of enhancement of rainwater utilization efficiency. Considering the target of 95% reliability in meeting demand, the traditional approach shows approximately 38 L/d basic demand could be expected in CT station. Under such condition, only 40% runoff is captured. By contrast, another scenario of 30 L/d basic demand and 125 L/d AAW leads to both 95% demand security, and significant improvement of runoff capture efficiency, reaching over 80%. The considerable increase of runoff capturing efficiency in the latter scenario illustrates the advantage of the proposed approach over the traditional way. This could be attributed to precipitation characteristic of the study area, where rainfall is negligible during the months of the dry season. Supply capacity during such periods is strongly based on tank size. Thus, an evaluation approach based on the assumption of annual supply reliability takes into account tank size conditions while impact of abundant monsoon rainfall receives little attention. The proposed approach improves the traditional way through consideration of both tank size and seasonal precipitation variation in system performance.

The AAW varies widely between monsoon precipitation characteristics. For example, a scenario of 20 L/d basic demand could result in additional available water of approximately 100, 120 and 160 L/d in HN, QN and CT, respectively. The difference of AAW between HN and CT could be explained by the difference of monthly precipitation during the rainy season, which is relatively skewed in the middle of the season at the former site while almost equally distributed in the latter, especially from June to October. Interestingly, locations with shorter monsoon duration and higher rainfall intensity might not expect higher AAW, as in the case of QN versus CT. This implies that increase of rainfall intensity results in increase of overflow rather than enhancement of supply, which is proved by runoff capturing efficiency at 57% and 65%, respectively. Overall, the monsoon’s monthly rainfall distribution and intensity leads to contrasting influence on additional available water.

It should be noted that the aforementioned explanation is based on the assumption of AAW as a daily constant value during the whole monsoon season, which might underestimate AAW in areas having significant variation of monsoon monthly precipitation as QN. Furthermore, the analysis is conducted at a reference tank of 5 m$^3$. Further analysis on different tank sizes supports better understanding the impact of monsoon patterns on variation of AAW.

Suitable rainwater harvesting solutions under different basic demand scenarios

Based on analysis of supply capacity and variation of AAW corresponding to monsoon variability, this subsection aims at investigating suitability of basic demand scenarios and potential AAW under different tank sizes and precipitation of whole study area.

Figure 7 shows the results of four different basic demand scenarios (10, 20, 40 and 60 L/d) at 95% reliability under three tank sizes (3, 5 and 8 m$^3$), considering investigation of average rainwater available per capita per day during the dry season of the study area at 7.4 L/d (Özdemir et al., 2011). The horizontal axis is annual precipitation and the vertical
axis is AAW at 90% reliability. The assumption of 90% AAW reliability was made considering the variation of onset dates in the monsoon season, particularly in the northern area (Nguyen-Le et al., 2013).

Regarding suitability of basic demand, only scenarios of 10–20 L/d could be satisfied at 95% reliability throughout the study area. Scenarios of 40–60 L/d could be suitable only with medium to large tanks (5–8 m³) and specific precipitation conditions higher than 1500 mm per year. Thus, tank size plays a more important role in enhancement of basic demand rather than precipitation availability.

The AAW is highly sensitive to selection of basic demand scenario and varies in the range of 50–400 L/d. The highest variation of AAW is observed in precipitation regions of 1300–2000 mm per year, which could be explained by diversity of monsoon rainfall patterns. Increase of tank size alleviates the influence of rainfall seasonality, which is evidenced by the increasing correlation of AAW with annual precipitation.

Influence of roof area on system performance

Figure 8 presents the influence of roof area variation on supply capacity and additional available water. It is recognized that a 50% increase of roof area leads to an average 10% increase of supply capacity (Figure 8a). By contrast, AAW is expected to significantly benefit from increase of roof area, as its corresponding rate is approximately 40% per 50% roof increase (Figure 8b).

The impacts of roof area variation on supply capacity and AAW are consistent under different tank scenarios of both 3 and 8 m³ despite larger variation between sites occurring in smaller tanks. It is concluded that there is no significant change to the suitability of basic demand scenarios made by increase of roof area, other than considerable improvement of additional available water.

Discussion on additional available water

It is successfully demonstrated that integrating effect of monsoon precipitation through AAW significantly enhances rainwater-use efficiency in the proposed rainwater harvesting solutions in contrast to conservative results of the traditional design approach. This could be attributed to precipitation features of tropical climates, where dry periods last almost 6 months while intensive rainfall events heavily occur during rainy season. The traditional design approach based on supply reliability tends to emphasize on satisfying continuous water supply during dry season while it pays little attention to heavy precipitation of monsoon season. The AAW is recognized as being strongly affected by monsoon patterns. Regions with higher annual precipitation but heavily skewed monsoon precipitation distribution might expect less AAW than area of less annual precipitation but equally distributed monthly precipitation, though AAW shows better correlation with annual precipitation as the tank size increases. This study suggests that design of rainwater harvesting system in tropical climates needs to consider both desired reliability and relationship of demand-AAW-runoff capturing efficiency.

It is noted that reliability of rainwater demand is considered throughout the year while additional available water is examined during the monsoon season. The assumption for variation of monsoon duration has an influence on additional available water. For example, it is expected that narrowing duration of AAW into highest rainfall months enhances its availability while maintaining capacity to supply basic demand. Further study is recommended to examine effects of modelling AAW in greater detail regarding timing and duration on its potential.

CONCLUSIONS

The performance of rainwater harvesting as a primary water source was evaluated under different scenarios of tank sizes and monsoon climates in the Asian tropical monsoon region. The desired reliability was considered as a major criterion for considering suitability of basic demand scenarios. The influence of rainfall seasonality and monsoon diversity was examined through interaction of basic demand and additional available water with their supply reliabilities and runoff capturing efficiency, in different monsoon patterns.

It is observed that 20 L/d basic demand could be ensured at 95% reliability across the whole study area by 3 m³ tank, and an extra supply of 50–100 L/d and 200 L/d AAW could be available in regions of 1500–2000 mm and 3000 mm annual precipitation, respectively. Scenarios of 40–60 L/d basic demand is recommended under dual conditions of medium-large tank (5–8 m³) and annual precipitation of 1500 mm or more. The AAW is highly sensitive to selection of basic demand scenario. The difference of monsoon rainfall patterns leads to considerable variation of AAW despite similarity of annual precipitation. Tank size is recognized as playing a crucial role in enhancement of supply capacity for basic demand, while roof area and precipitation exerts a higher influence on additional available water.

Further work is required to determine whether modelling of additional available water in greater detail with respect to timing consideration and monsoon monthly precipitation variations significantly improves runoff capturing efficiency.

ACKNOWLEDGEMENTS

Sincere gratitude is expressed to the Ministry of Education, Culture, Sport, Science and Technology (MEXT), Japan and University of Yamanashi for providing financial assistance to this study. The authors would like to thank anonymous reviewers for constructive comments and suggestions that significantly improved the manuscript.

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