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Rainwater Harvesting System for Contiunous Water Supply to the Regions with High Seasonal Rainfall Variations

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Abstract Generally, rainwater harvesting has been less acceptable as a stable water resource for the countries with large disparities in seasonal rainfall including Korea. In this study, rainwater harvesting system suitable for South Korea was investigated systematically. The simulation method utilizing daily rainfall data collected for the last 10 years was developed to determine the critical size of rainwater tank which could supply harvested rainwater continuously. The estimation of rainwater tank size was further simplified by developing a correlation of volume to area fractions. Extensive simulation was performed to evaluate the feasibility of rainwater harvesting for seven major cities in South Korea. The resulting rainwater tank was too large to be economically feasible, compared to daily harvested rainwater used. Thus, rainwater harvesting system was integrated with alternative water resources such as wastewater reclamation by membrane bioreactor (MBR) to enhance the applicability of rainwater harvesting without compromising continuous water supply.

Keywords Rainwater harvesting · Rainwater tank size · Alternative water resources · Wastewater reuse · Blending

1 Introduction

As the world's climate continues to change due to global warming, localized water shortage problems are expected to worsen. This inevitable problem has resulted in higher water price, and often caused conflict over drinkable water, leading to a great demand for augmenting water resources such as rainwater harvesting. Rainwater can be collected and used for non-potable purposes, e.g. for flushing toilets, gardening and irrigation, without long distance transportation and complicated treatment. It can be also used for potable purpose with proper collection, storage and treatment.

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However, rainwater harvesting in many countries has shown only limited success mainly due to large seasonal rainfall variations. Korea is such an example, where seasonal changes are clear and significant. The wet season typically begins in late June and extends to mid-September in South Korea. The number of rainy days and the amount of rainfall decrease significantly in the dry season (December~February). Recently, rainfall intensity has increased along with higher seasonal variation of rainfall. As a result, harvested rainwater has been utilized mainly in the wet season.

Rainwater harvesting in the regions of high rainfall fluctuation has been a topic of many studies. Kim and Yoo (2009) evaluated three rainwater harvesting systems by a hydrologic model and concluded that, as the amount of rainwater consumption increased, the number of days with available rainwater decreased. Rainwater usage could be correlated with typical seasonal rainfall patterns, indicating more water usage during wet periods (Aladenola and Adeboye 2010; Jones and Hunt 2010). In a study by Fewkes (1999), spatial and temporal fluctuations in rainfall were incorporated into behavioral models, and the performance of the rainwater harvesting system was assessed by annual water saving efficiency. If the rainfall variation increased, the number of days with available rainwater was concentrated in the wet season.

In order to assure the reliability of rainwater harvesting as alternative water resources particularly for decentralized urban construction, the rainwater collection and storage system should be designed in a more scientific manner (Ward et al. 2010). Guo and Baetz (2007) obtained analytical equations that could be used at different locations for the sizing of rainwater storage units to provide the desired use rate and reliability. However, they incorporated a variety of simplifying assumptions regarding water usage rates, overflow volume, and rainfall depths. Ghisi et al. (2007) suggested that ideal tank capacity was the one in which the potential for potable water savings increased 2 % or less when increasing tank capacity by 1,000 L. Zhang et al. (2009) proposed that optimal tank sizes could be determined by adopting the concept of annual volumetric reliability. The optimal tank corresponded to the one for which further increases in size produced only a small increase in reliability.

The majority of previous works mentioned above evaluated the potential for water savings with yearly rainwater used. These approaches, however, were not successful since rainwater tanks were frequently depleted when rainwater was used to meet daily demand, and often overflowed during the wet season. Therefore, our study has attempted to determine the size of rainwater collection tank based on the simulation of residual water in the rainwater tank by utilizing daily rainfall data of the last 10 years.

There have been some efforts to utilize other compromised water resources along with rainwater harvesting. Ghisi and Oliveira (2007), for example, evaluated the potential water savings by combining the use of rainwater and graywater. Despite recent endeavors, integrating various water resources with rainwater harvesting still remain at the developmental stage. In this work, we have explored the concept of rainwater harvesting combined with wastewater reclamation to enhance the reliability of water supply system in a more systematic manner.

The objective of this research is to develop a more reliable rainwater harvesting system which can provide water continuously for urban construction in South Korea. A simulation method utilizing 10 years of daily rainfall data was first developed to determine the size of rainwater tank for continuous supply of harvested rainwater. In addition, field monitoring was performed more than a year to ensure the quality of harvested rainwater. Lastly, a rainwater harvesting system with wastewater reuse by membrane bioreactor (MBR) was developed and examined to enhance the applicability of rainwater harvesting in South Korea which has large disparities in seasonal rainfall.

2 Materials and Methods

2.1 Field Monitoring of Rainwater Harvesting

The rainwater was collected from the roof of a small building in Korea University over a year (2009 to 2010). The catchment surface of this building was covered with concrete material. The roof area was free of overhanging trees and had no evidence of human activity. Rainwater was collected by a portable 20 L sampling bag. Rainwater harvesting tank size was 1 m^3 which was made of fiber reinforced plastic. Harvested rainwater was taken from the collection tank for analysis. Rainwater and harvested rainwater qualities were determined by international and Korean standard methods.

2.2 Simulation for Rainwater Harvesting

2.2.1 Rainfall Data

To determine suitable rainwater tank size, continuous simulation that took into account 10 years of daily rainfall data (2001~2010) was used. The daily rainfall data of seven major cities with weather stations were obtained from the Korea Meteorological Administration.

2.2.2 Assumption of the Study Area

The simulation was performed based on the S-multipurpose building which is located in eastern suburb of Seoul, South Korea. This was a major real-estate development project of more than 1,300 apartments, comprising four buildings on 5 ha. The assumption of catch basin area was 50,000 m^2, and average runoff coefficient was 0.8. There has been operating data collected with a 3,000 m^3 rainwater tank. The volume of rainwater supply was approximately 26,000 m^3/year and the harvested rainwater was mainly utilized in the wet season (Han and Mun 2011), indicating that the average rainwater supply was 71.2 m^3/day. Thus, in this simulation, the daily demand volume of rainwater was assumed to be 72 m^3/day and the installable rainwater tank size to be 3,000 m^3.

2.2.3 Simulation Process

A simulation tool was developed to model rainwater harvesting system performance based upon historic rainfall data. The simulation process is shown in Fig. 1. The simulation was based on the evaluation of residual water amount in the rainwater tank with rainfall data of the last 10 years. The volume of runoff daily on the roof surface was estimated by Eq. (1).

$$VRH = R \times A \times C \times 10^{-3} \tag{1}$$

VRH is the volume of runoff at the time t (m^3/day), *R* is the rainfall depth at the time *t* (mm/day), *A* is the roof area (m^2), and *C* is the runoff coefficient which was assumed to be 0.8 to represent loss of 20 %. The daily volume of residual rainwater could be estimated as described in Eq. (2).

$$VRT = VRT(t{-}1) + VRH(in){-}VRD \tag{2}$$

VRT is the daily volume of residual rainwater in the tank (m^3/day), *VRD* is the daily demand of rainwater, *VRT*(*t*–1) is the volume of residual rainwater in the tank from the previous day

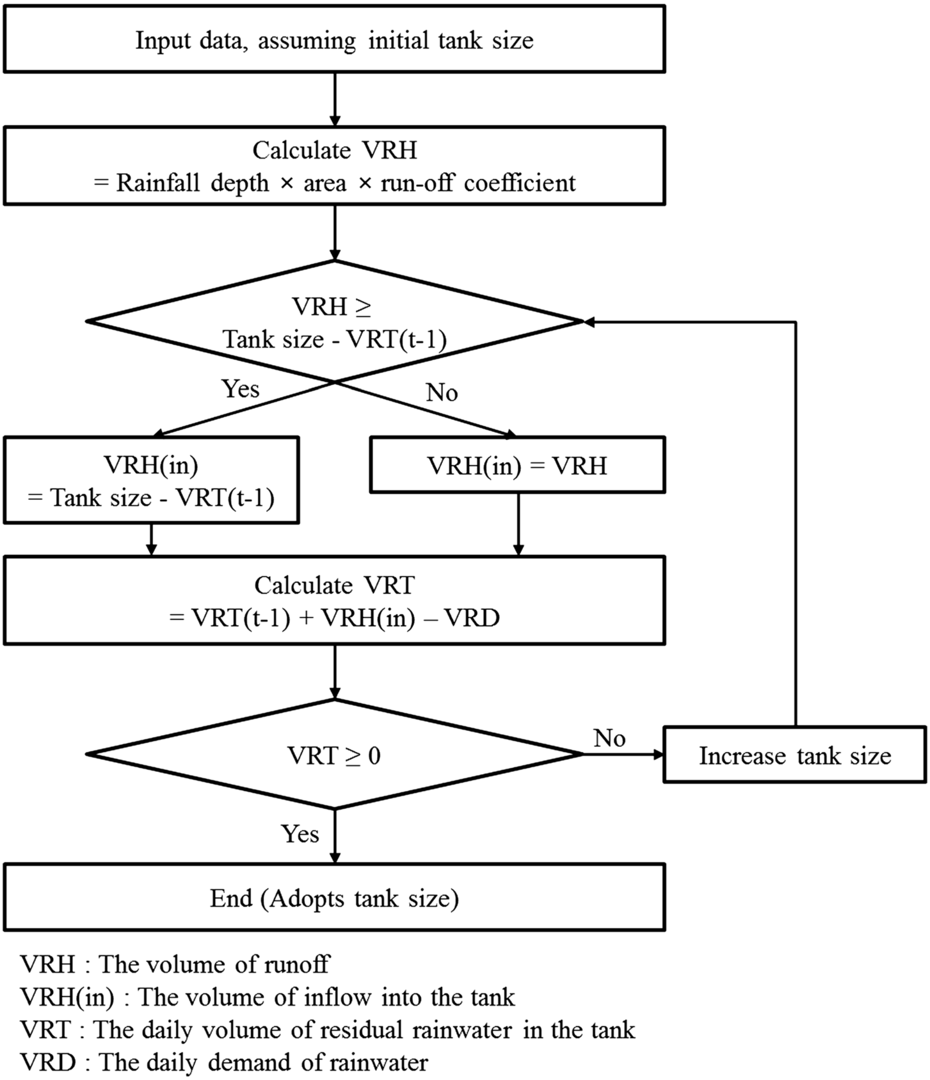

Fig. 1 Simulation process for determining rainwater tank size. A simulation tool was developed to model rainwater harvesting system performance based upon historic rainfall data

(m^3/day), and *VRH*(*in*) is the volume of inflow into the rainwater tank (m^3/day) which is considered by rainwater tank size using Eqs. (3) and (4).

$$If\{VRH \geq Tank\,size - VRT(t-1)\}then\ VRH(in) = Tank\,size - VRT(t-1) \tag{3}$$

$$If\,VRH \leq Tank\,size - VRT(t-1)\,then\,VRH(in) = VRH \tag{4}$$

It should be noted that *VRT* is in the range from 0 to rainwater tank size, and available space in the rainwater tank is *Tank size* – *VRT*(*t*–1). If the volume of runoff at time t is larger than or equal to the available space in the rainwater tank, the volume of inflow into rainwater tank is equal to available space. If the volume of runoff at time t is less than the available space, the volume of inflow into rainwater tank is equal to the volume of runoff at time t.

2.3 Rainwater Harvesting With Wastewater Reuse

Figure 2 shows the lab-scale MBR system installed for the integrated rainwater harvesting and wastewater reuse. Feed water was a septic tank effluent in Korea University. Activated sludge was brought from the Jung-Rang wastewater treatment plant in Seoul. When adopting wastewater reuse systems such as MBR, some of effluent water qualities, particularly color, might exceed the standard of reclaimed water quality. Blending MBR effluent with harvested rainwater could be a good solution to stabilize water quality and quantity without sophisticated post-treatment processes. A series of blending experiments were performed at various blending ratios to demonstrate the applicability of such integrated systems.

3 Results and Discussion

3.1 Field Monitoring of Harvested Rainwater

The harvested rainwater in the rainwater tank was collected after 3 h of runoff. Initial turbidity was 0.77±0.49 NTU. After 50 days, it was maintained at below 0.5 NTU. The turbidity of harvested rainwater decreased due to the settling effect. The concentration of COD showed no specific changes during 2 years. DO and pH were also almost constant. Thus, it can be concluded that harvested rainwater in the rainwater tank was very stable, and maintained good

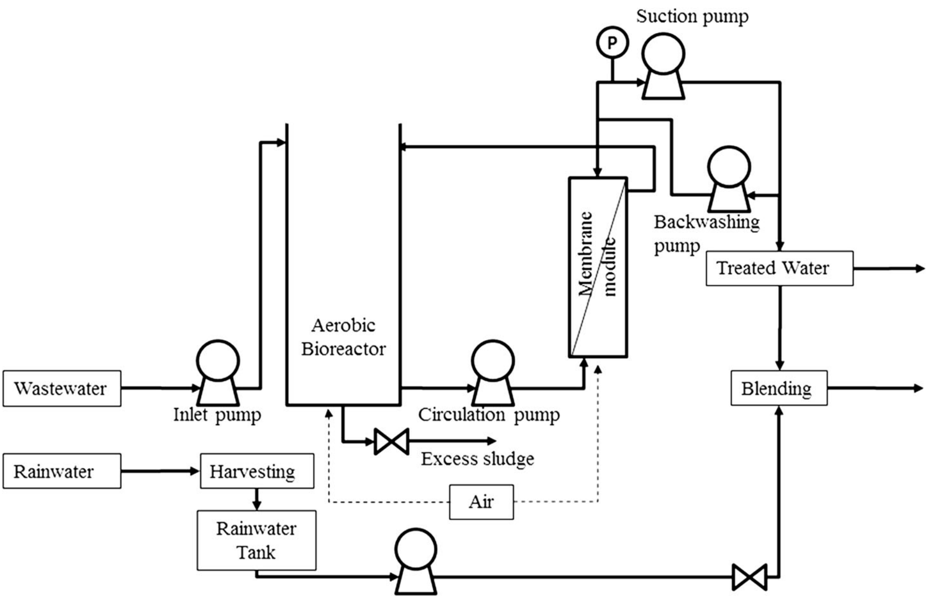

Fig. 2 Schematic illustration of a rainwater harvesting system integrating with membrane bioreactor (MBR). A external tubular module was installed in MBR, and aeration was continuously provided to the bottoms of the MBR to assure sufficient dissolved oxygen and mixing for activated sludge. The membrane module was made of hydrophilic coating polyethersulfone (PES) with a nominal pore size of 0.2 μm and an effective filtration area of 0.16 m^2/module

quality. The quality of harvested rainwater satisfied the reclaimed water quality standard in South Korea.

3.2 Determination of Rainwater Tank Size for Continuous Supply

Figure 3 shows the daily volume of available rainwater in the rainwater tank which was estimated through the simulation described in the earlier section. The suitable rainwater tank size for continuous supply of 72 m^3/day was estimated by 9,720 m^3 which is 135 times more than the daily demand of rainwater. The daily volume of available rainwater decreased in the dry season and increased in the wet season. Thus, the critical size of rainwater tank was determined by the daily volume of available rainwater in the dry season.

3.3 Estimation of Rainwater Tank Size by Volume and Area Fractions

Different combinations of catchment area, daily rainwater demand, and tank size were expressed in terms of two ratios, namely area fraction and volume fraction. The area fraction is defined as A/R, where A is the catchment area (m^2) and R is the daily rainwater demand (m^3). The volume fraction is given by V/R, where V is the volume of the rainwater tank (m^3). Figure 4 shows the curve of volume fraction to area fraction which is expressed by Eq. (5).

$$Volume\,fraction = 14,705 \times (Area\,fraction)^{-0.71},\ at\ Seoul\,(C = 0.8) \tag{5}$$

Equation (5) was derived from Fig. 4 by trend line of involution and the resulting R^2 value was 0.989, which indicated that it could be very useful to estimate the rainwater tank size without rigorous simulation using daily rainfall data for each case. According to the rainwater demand and suitable catchment area, the rainwater tank size could be easily estimated by Eq. (5).

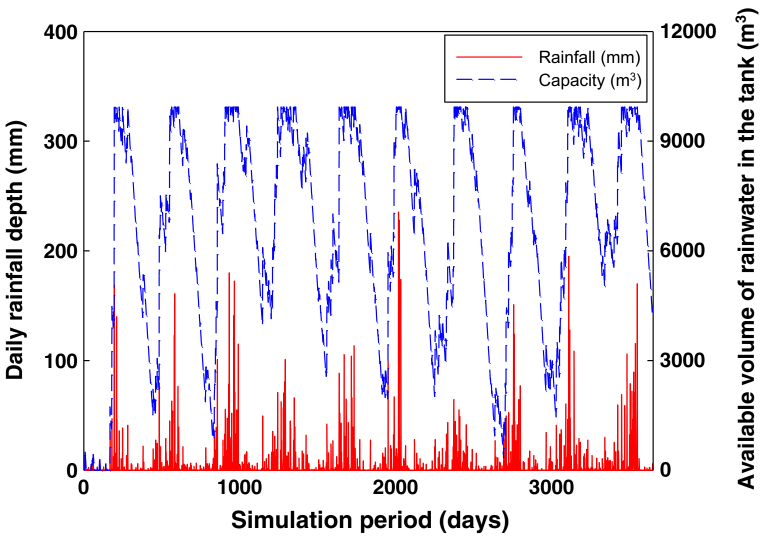

Fig. 3 Daily volume of available rainwater in the rainwater tank. The daily volume of available rainwater was calculated by subtracting daily demand volume from the rainwater tank through the simulation based on the rainfall data in Seoul

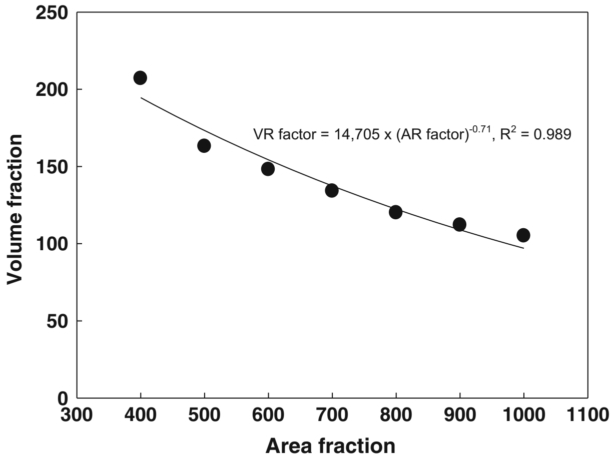

Fig. 4 Correlation between volume fraction and area fraction. The resulting correlation was expressed in Eq. (5)

By further examining Fig. 4, it should be noted that, as the area fraction increased, the volume fraction decreased, implying that the rainwater tank size is inversely proportional to the catchment area. For example, if the daily rainwater demand is 2 m^3 and catchment area is 1,000 m^2, the area and volume fractions are calculated to be 500 and 178.3 by Eq. (5), respectively. This means that the rainwater tank size is 178.3 times to the daily rainwater demand and the rainwater tank size is 356.6 m^3. Table 1 shows the comparison of rainwater tank size determined by complete simulation and simple Eq. (5). The results demonstrated that the rainwater tank size could be determined simply by Eq. (5) with less than 10 % error at a runoff coefficient of 0.8 in Seoul.

3.4 Spatial Variation of Rainwater Tank Size

The simulation method developed in this work was performed extensively for seven major cities in South Korea which have weather stations and thus 10 years of daily rainfall data, in order to further investigate spatial variations of rainwater tank size. The results are graphically summarized in Fig. 5. It should be noted that specific year in this study was defined as the year in which the rainwater tank size was determined. As shown, the size of rainwater tank size varied among seven cities with different rainfall characteristics. The results suggested that rainwater tank size was

Table 1 Error of estimated tank size determined by volume to area fraction relationship shown in Fig. 4 (i.e., Eq. (5))

Daily rainwater demand (m^3/d)	Simulated tank size (m^3)	Area fraction	Volume fraction	Estimated tank size (by Eq. (5), m^3)	Error[a] (%)
40	3,720	1250.0	93.04	3721.60	0.04
65	8,060	769.2	131.33	8536.45	5.91
80	11,600	625.0	152.19	12175.20	4.96
90	13,950	555.6	165.47	14892.30	6.75
100	16,300	500.0	178.32	17832.00	9.40

[a] Error={(Estimated tank size – Simulation tank size) / Simulation tank size}×100

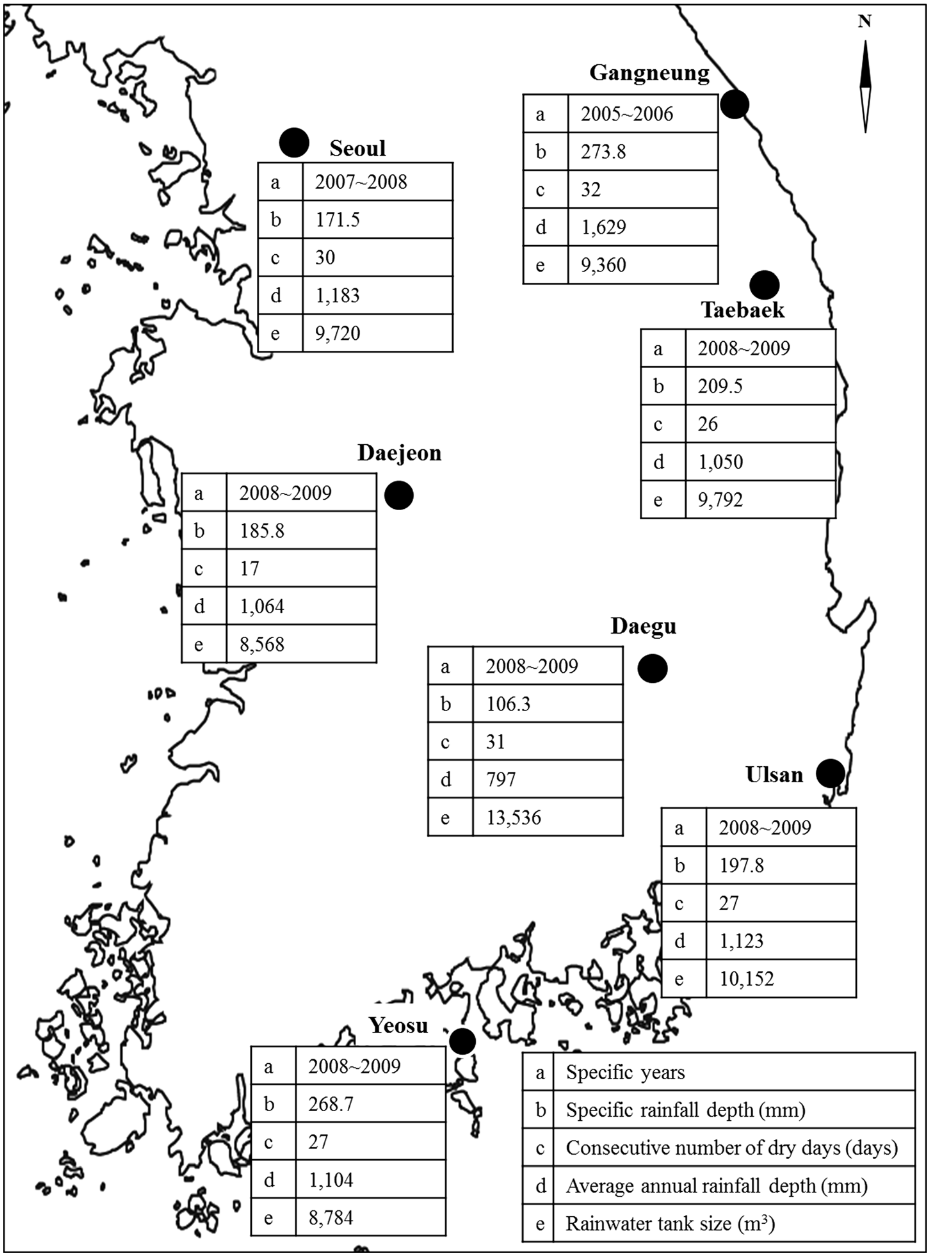

Fig. 5 Location and rainwater tank size for seven cities which have a weather station in South Korea

correlated with specific rainfall depth which was defined as rainfall depth during specific year (R^2=0.7). The rainwater tank size decreased when specific rainfall depth increased. For instance, the largest rainwater tank size was determined for the city of Daegu in which specific rainfall depth was the smallest. Lastly, a trend of increasing rainwater tank was also observed with increasing the consecutive number of dry days during specific year

3.5 Determination of Available Rainwater Volume

Figure 6 presents the daily volume of available rainwater according to rainwater tank size. It was possible to determine the daily volume of available rainwater with constraint of installable tank size. For instance, if the installable tank size is 3,000 m^3, the daily volume of available rainwater is estimated to be 38 m^3/day. Therefore, another water resource of 34 m^3/day is needed for a continuous supply of 72 m^3/day. Otherwise, much larger rainwater tank needs to be constructed and the economic feasibility of rainwater harvesting is greatly compromised.

In order to ensure reliable water supply, various water resources should be considered to compensate unstable rainwater harvesting for the regions with large seasonal rainfall variations. Such example could be wastewater reclamation. Wastewater is often characterized as a more reliable alternative water resource with constant daily quantity, compared to rainwater. However, reusing wastewater suffers greatly from its poor water quality and requires more intensive and expensive treatment. Thus, combining rainwater harvesting with wastewater reclamation could be a perfect solution to minimize their disadvantages and to maximize their advantages as alternative resources. By developing a hybrid water supply system integrating rainwater harvesting and wastewater reuse, stable water supply can be achieved without employing larger rainwater storage tank and expensive wastewater post-treatment. The concept of such hybrid system is schematically illustrated in Fig. 7.

3.6 Blending Harvested Rainwater with MBR Effluent

The concept of a hybrid rainwater harvesting system presented in the previous section was experimentally examined with wastewater reclamation by MBR. In the last decade, the MBR technology has proved its superiority over conventional wastewater treatment (Judd 2008). The advantages of MBR include smaller land requirement, easy operation and maintenance, and better water quality management, which make this technology more suitable for the decentralized system (Drews 2010; Judd 2008; Lin et al. 2014). The acceptance of MBR effluent for the reclaimed water quality standard is summarized in Table 2. The quality of MBR effluent was relatively good and satisfied the majority of reclaimed water standard in

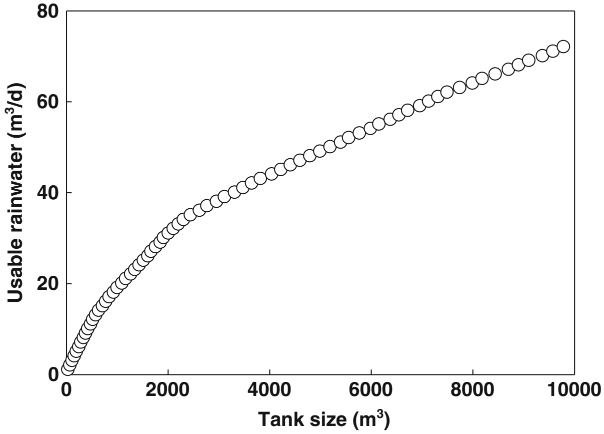

Fig. 6 Daily volume of available rainwater according to tank size

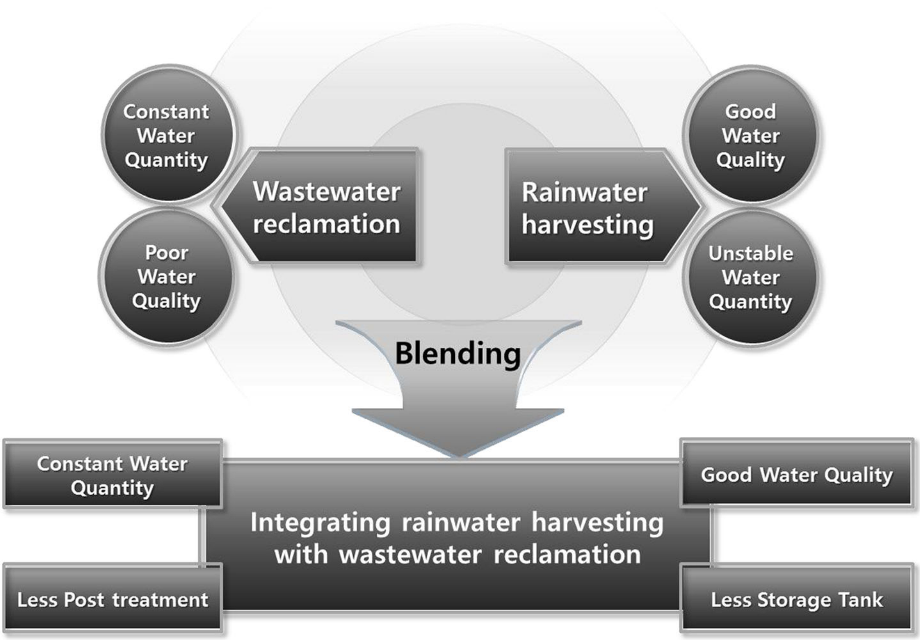

Fig. 7 Concept of integrating rainwater harvesting with wastewater reclamation. This hybrid system compensates disadvantages of rainwater and wastewater as alternative water resources and optimize their advantages to provide stable water supply to the regions of high temporal and spatial rainfall variations

South Korea, except for color. More specifically, turbidity was 0.62 NTU and BOD was 8 mg/L when operating at 20 LMH and 4 HRT. The color of MBR effluent, however, exceeded its standard and thus required further post-treatment to be accepted for reuse.

The problem with color in MBR effluent could be solved by blending with harvested rainwater. A series of blending experiments was conducted and the results are presented in Fig. 8. As expected, blending of harvested rainwater and treated wastewater reduced color to

Table 2 Comparison of MBR effluent and the reclaimed water quality standard in South Korea

	Toilet	Sprinkling	Landscape	Cleaning	MBR effluent	Acceptance
E. Coli (CFU/ml)	–	–	–	–	–	–
Chlorine (mg/L)	> 0.2	> 0.2	–	> 0.2	–	–
Feature	No displeasure	No displeasure	No displeasure	No displeasure	No displeasure	○
Turbidity (NTU)	<5	<5	<5	<5	0.62	○
BOD (mg/L)	<10	<10	<10	<10	8	○
Odor	–	–	–	–	-	○
pH	5.8~8.5	5.8~8.5	5.8~8.5	5.8~8.5	6.2	○
Color (Pt-Co)	≤20	–	–	≤20	33	×
COD (mg/L)	≤20	≤20	≤20	≤20	12	○

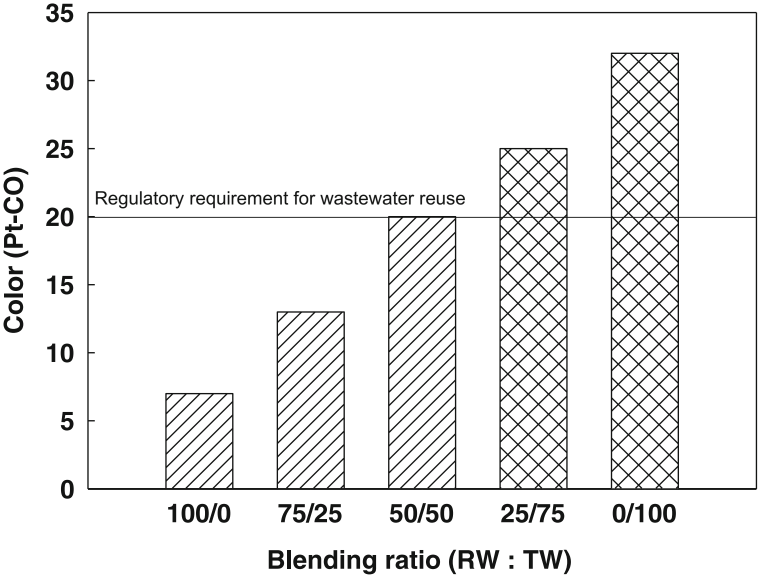

Fig. 8 Color of blended RW and TW waters. RW and TW stand for harvested rainwater and treated wastewater by MBR, respectively. The blending ratio of 50:50 was able to satisfy the standard of reclaimed water quality in South Korea which is 20 Pt-Co or less

be 20 Pt-Co or less at a blending ratio of 50:50, which met the standard of reclaimed water quality in South Korea. This improvement was achieved without expensive post-treatment process. The rainwater tank size was also reduced dramatically due to wastewater reclamation by MBR. More comprehensive approaches to determine the size of rainwater tank should be developed by incorporating not only water quantity but also water quality.

4 Conclusions

The applicability of rainwater harvesting system was systematically investigated for the regions of high seasonal rainfall variations such as South Korea. Primary findings drawn from this research can be summarized as follows:

- Proper rainwater harvesting, such as excluding initial runoff and designing appropriate catchment area, provided the water quality which satisfied the reclaimed water quality standard of South Korea.
- The size of rainwater tank suitable for continuous water supply was determined by the simulation of residual water in the rainwater tank utilizing daily rainfall data of the last 10 years.
- By developing the correlation of volume to area fractions, the rainwater tank size could be estimated simply based on rainwater demand and catchment area.
- The rainwater tank designed to supply hravested rainwater daily in South Korea was found to be too big (e.g., 135 times more than the daily demand of rainwater), which significantly reduced the applicability of rainwater harvesting in the areas of large disparities in seasonal rainfall.

- The feasibility and reliability of rainwater harvesting system were further improved by integrating with alternative water resources such as wastewater reclamation by membrane bioreactor (MBR).

In recent years, decentralizing water supply systems has become one of the most promising approaches for a better water management in urban areas. It is expected that rainwater harvesting plays a more important role in the decentralized systems. However, as examined with South Korea in this work, rainwater harvesting might not be a viable option of water supply to the conturies of high seasonal rainfall fluctuation. Thus, it is of paramount improtance to explore the possibility of utlizing all of the available water resources along with rainwater harvesting, particularly when developing more reliable decentralized water supply system for urban construction.

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