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Performance Benefit Analysis of Linked Rainwater Harvesting Systems

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ABSTRACT: This study investigated the performance of connected rainwater harvesting systems (RWHSs) in regions with different rainfall characteristics. Physical and analytical performance models were developed for modeling reference and connected RWHS performance. Four regions, namely Seoul, Taipei, Los Angeles, and New York were selected to reflect the effects of different rainfall characteristics. The performance efficiency of connected RWHS increased with increased RWHS size, the connected total RWHS size, and combined water demands. The connected RWHS size reduction rate increased with increased water demands, combined water demands, and combined RWHS efficiency. Conclusively, the results of this study imply that connected RWHSs in rainy regions, such as Seoul, Taipei, and NY, show superior benefits with increasing efficiency at a constant RWHS size. Conversely, connected RWHSs in semi-arid or arid regions demonstrate greater benefits with constant efficiency at a reduced RWHS size.

KEYWORDS: Environmental Engineering, Rainwater harvesting system; Performance model; Efficiency; RWHS size.

Introduction

Water resource availability, including water use and supply, has become a crucial concern in urban areas due to the population increase. Rainwater harvesting system (RWHS), which stores water in barrels or cisterns, has emerged as a method for promoting water conservation and improving water supply availability. In RWHS, rainwater gathered from the roof of a building or house is used for multiple purposes, including gardening, flushing toilets, and washing cars. Although RWHS is based on a simple concept, measuring the rain barrel performance can be challenging. Most studies have used yield after spillage (YAS) and yield before spillage (YBS) models for the physical performance modeling of RWHS.[1-6] Rupp *et al.* have suggested a comparative analysis of different methods to estimate the RWHS size.[7] They used the Netuno program, which calculates the potential for potable water savings for different tank capacities based on daily rainfall. Cordova and Ghisi investigated the difference between the Netuno, YAS, and YBS models and revealed that the results of the three models are statistically equivalent.[8] Additionally, the Spreadsheet version of the Storage, Treatment, Overflow, Runoff Model (SS STORM) was developed for evaluating the RWHS performance model.[9,10] This study adopted the SS STORM model to produce a reference result for RWHS performance. The objective of this study was to investigate the efficiency of connected RWHS compared with unconnected RWHS. Specifically, this study analyzed (1) the benefits of connected RWHS efficiency based on RWHSs size, combined RWHSs, and combined water demands, and (2) the benefits of RWHS size reduction based on water demands, combined water demands, and combined efficiency of RWHSs. For this study, the better operation of RWHSs. This study estimates better RWHS operation efficiencies through the linked existing RWHSs in different rainfall characteristic regions. The results of this study provide a better understanding of RWHS performance and show the optimized RWHS installation approaches based on different water demands.

Methods

It is necessary to verify the results of the physical performance and analytical models. In this study, a physical performance model was used as a reference to adjust the analytical performance model. A physical-based RWHS model was used in this study to consider the actual RWHS performance.[9,10] For evaluating connected RWHS performance, an analytical method was applied.[11,12] The analytical methods used in this study were calibrated to match the physical model performance results.[13] The concept of this study is demonstrated in Figure 1. This study compared the performances of two independent RWHSs (Figure 1(a)) and connected RWHSs (Figure 1(b)). Furthermore, RWHS performance efficiency was investigated based on water demand and RWHS size.

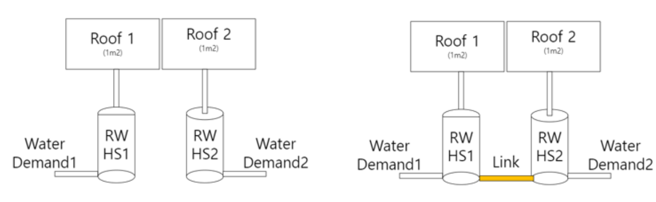

Figure 1: Schematic of rainwater harvesting system (RWHS); (a) two single RWHS; (b) connected RWHS

Daily rainfall data were collected from four different cities in East Asia and the USA, including Seoul, Republic of Korea; Taipei, Taiwan; Los Angles (LA), USA; and New York (NY),

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USA. These four regions represented different Köppen climate zones with varying rainfall characteristics (Table 1). The period of retrieved precipitation data was 59 years for Seoul, Taipei, and NY and 64 years for LA.

Table 1: Daily precipitation data is retrieved from four different cities.

Cities	Periods	Precipitation			Köppen climate zone
		Annual (mm)	Standard deviation of monthly data (mm)	Average rainy days	
Seoul, South Korea	1960.1.1. ~ 2018.12.31.	1,403	157.30	80.24	Hot summer continental climate (Dwa)
Taipei, Taiwan	1960.1.1. ~ 2018.12.31.	2,283	153.76	133.11	Humid subtropical climate (Cfa)
Los Angeles, CA	1945.1.1. ~ 2018.12.31.	298	25.47	42.88	Mediterranean climate (Csa)
New York, NY	1960.1.1. ~ 2018.12.31.	1,078	7.43	94.75	Hot humid continental climate (Dfa)

1. Physical performance model:

The physical performance of the RWHS model was evaluated using the YAS algorithm. The governing equations for computation are as follows[9]:

$$Rff^j = max(0, Prcp^j) \quad (1)$$

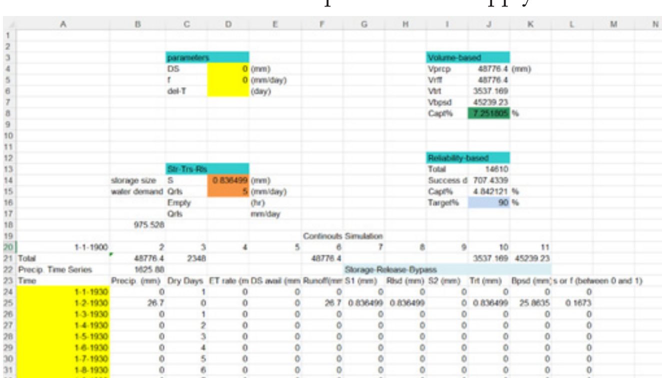
$$S_{av}^j = min(S_{max}, max(0, S_{av}^{j-1}) + Rff^j) - min(S_{av}^{j-1}, Q_{dm})\Delta t \quad (2)$$

$$Cpt^j = \begin{cases} Q_{sp}^j = Q_{dm}, & Cpt^j = 1 \\ Q_{sp}^j < Q_{dm}, & Cpt^j = Q_{sp}^j/Q_{dm} \end{cases} \quad (3)$$

$$Efficiency = \frac{\sum_{j=1}^{n} Cpt^j}{\sum_{j=1}^{n} j} \quad (4)$$

where R_{ff}= runoff depth during a time step (mm);
Prcp=precipitation pulse (mm)
Δt=precipitation data time step (day);
S^j_{av}= available rainwater harvesting storage at time step j (mm)
S_{max}=maximum rainwater harvesting storage (mm)
Q_{dm}=water demand (mm/day);
Q^j_{sp}= water supply at time step j (mm/d)
Cpt^j= water supply rate at time step j
n = number of simulation time (days); and
Efficiency= water supply efficiency of rainwater harvesting storage.

This study calculated the efficiency of the RWHS with water supply/water demand, not with zero in Equation (4), as it is more accurate to consider the partial water supply.



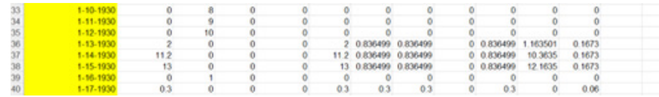


Figure 2: An example of an RWHS result is based on the physical performance method in an Excel spreadsheet.

2. Analytical performance model:

We used Equations (5) and (6) for the analytical approach.[11] Equations (1) and (2) describe the efficiency and optimal size of the RWHS. These two equations were derived based on the assumption that the distributions of event depth, inter-event time, and duration follow an exponential distribution.[13,14]

$$Eff = \frac{A\varphi\psi}{A\varphi\psi+\xi G} e^{-\xi v_{ff}}\left[1 - e^{-\xi B/(A\varphi) - \psi B/G}\right] \quad (5)$$

$$B = \frac{A\varphi\psi}{A\varphi\psi+\xi G} ln\left[\frac{A\varphi\psi e^{-\xi v_{ff}}}{A\varphi\psi e^{-\xi v_{ff}} - R_e(A\varphi\psi+\xi G)}\right] \quad (6)$$

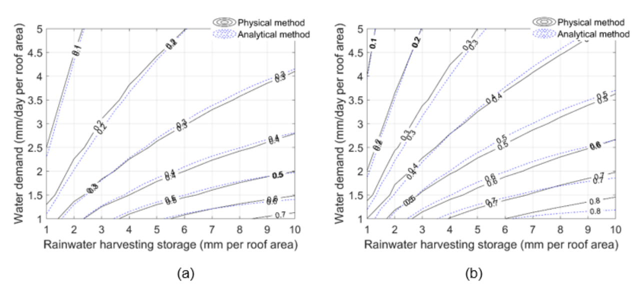
Where *Eff* is the efficiency. is the roof area (m^2)(= 1 m^2. in this study), and
B is rain barrel size (m^3),
v_{ff} is first flush (m) (= 0 in this study),
ϕ is runoff coefficient (= 1 in this study),
ψ = 1/b (b = average inter-event time (days),
ξ = 1/v (v = average event depth (m), and
G= water use (m^3).

This study modified ψ=c/b and ζ=d/v. Parameters c and d are calibration parameters used to adjust the performance. In addition, the roof area (A) was set as 1 m^2 to simplify the calculations. Therefore, the units B and G were simply presented with depth in m per unit area.

Results and Discussion

1. Comparison of RWHS performance models:

Figure 3 shows the RWHS efficiency based on RWHS size and water demand in four different cities. The analytical and physical models yield very similar efficiency results. This indicates that the application results of the analytical model are reliable for estimating the effects of connected RWHSs. As the RWHS size increases and the water demand decreases, the models produce high RWHS efficiencies, as shown in Figure 3. For a constant RWHS size and water demand, the order of higher efficiency is NY > Taipei > Seoul > LA. Annual rainfall strongly correlates with RWHS efficiency; however, New York has a high RWHS efficiency. In addition, New York exhibited a smaller standard deviation for monthly rainfall than Seoul and Taipei, resulting in a positive effect on the RWHS performance efficiency.



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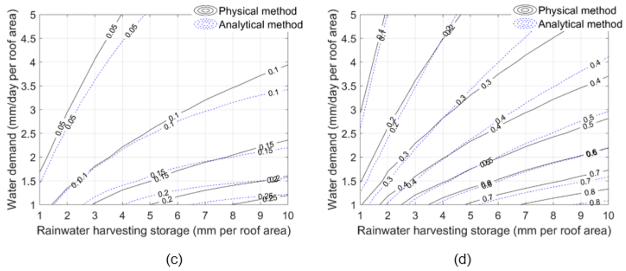


Figure 3: Efficiencies of rainwater harvesting systems between physical and analytical performance models; (a) Seoul, (b) Taipei, (c) Los Angeles, (d) New York. These figures show the RWHS performance efficiencies based on RWHS size and water demand between physical and analytical performance models in each region. These figures also indicate that the results of the analytical performance model are close to the results of the physical performance model in four regions.

2. Efficiency effect of the connected RWHSs:

To quantify the effect of connected RWHS on the efficiency of water demand, two RWHSs of different sizes were investigated. Figure 4 shows that efficiency increases with increased RWHS sizes and combined RWHS sizes. The order of high efficiency is Taipei > NY > Seoul > LA. It was found that annual rainfall and rainy days affect the RWHS efficiency. The RWHS efficiency, based on the RWHS size and combined RWHS size, increased as the annual rainfall and annual rainy days increased. Connected RWHSs in Taipei and NY were 22% more efficient than unconnected RWHSs. Meanwhile, connected RWHSs in Seoul and LA showed higher efficiency compared with unconnected RWHS by 14% and 3.5%, respectively. It was found that Seoul exhibits a lower increasing efficiency compared with NY because the number of annual rainy days in Seoul is much lower than that in NY. Generally, this indicates that connected RWHS in more rainy regions are more beneficial than those in drier regions, based on the RWHS efficiency results.

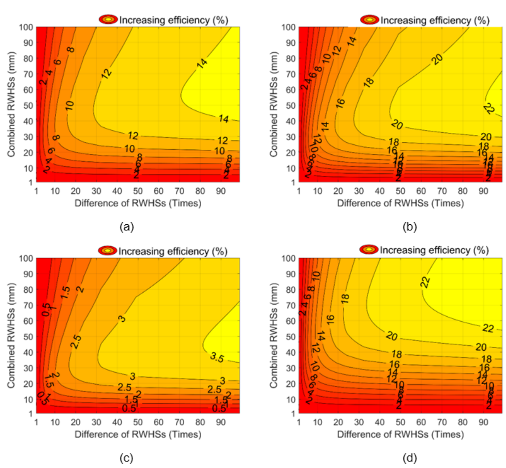


Figure 4: Increasing efficiency percent of combined rainwater harvesting storages and different sizes of RWHSs as a 0.8mm/day combined water demand; (a) Seoul (b) Taipei, (c) Los Angeles, (d) New York. These figures show the increasing efficiencies of the combined RWHSs compared with two single RWHSs based on the difference of RWHS sizes and the combined RWHSs size in each region. These figures indicate that there is an increase in efficiency of the combined RWHSs compared with two single RWHSs as the difference of RWHSs and combined RWHSs size increases. However, the increasing efficiency of the combined RWHSs is different depending on the four rainfalls and their regional characteristics.

Figure 5 shows the increased efficiency of connected RWHSs based on different RWHS sizes and combined water demands in the four regions. Generally, RWHS efficiency increases as the difference, and RWHS sizes and combined water demands increase in all four cities. However, in LA, combined water demands remain the same as the efficiencies of connected RWHS. In contrast, the other three cities show an increasing efficiency of RWHSs depending on the difference in RWHS sizes and combined water demands. It was found that annual rainfall and rainy days in LA are significantly small, and combined water demands do not affect the connected RWHSs.

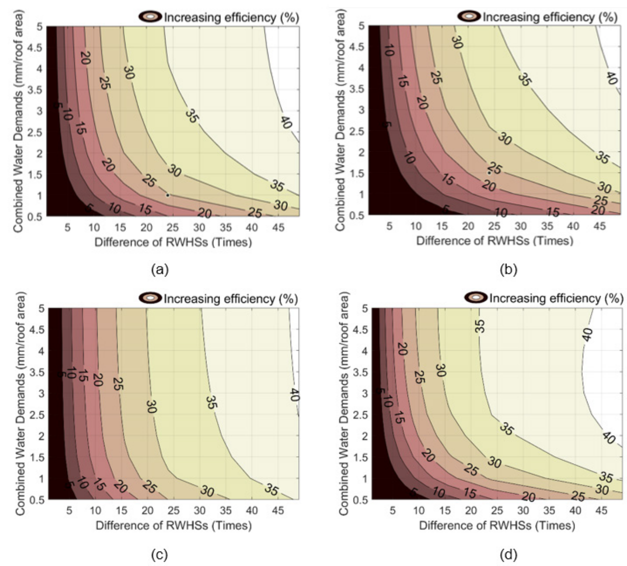


Figure 5: Increasing efficiency of combined rainwater harvesting storages compared with separated rainwater harvesting storages based on combined water demands and difference of connected RWHS in 5 mm/roof area; (a) Seoul, (b) Taipei, (c) Los Angeles, (f) New York. These figures show the increasing efficiencies of the combined RWHSs comparing with two single RWHSs based on the difference of RWHS sizes, and the combined water demands in each region. These figures indicate that the efficiency of the combined RWHSs increases when compared with two single RWHSs as the difference in RWHS size and combined water demands increases. However, the increasing efficiency of the combined RWHSs is different depending on the four rainfalls and their regional characteristics.

3. RWHS Size effect of the connected RWHSs:

Similar to the efficiency variable, it is necessary to analyze the RWHS size reduction effects of connected RWHSs. Therefore, this study investigated the RWHS reduction rate based on the difference in water demands vs. combined water demands and the efficiency of connected RWHSs.

Figure 6 shows the reduction rate of the total connected RWHS size as a function of water demand and total demand. All four regions in Figure 6 show that the RWHS size reduction rate increases as differences in water demands and combined water demand increase. Particularly, LA (Figure 6(c)) produced a much greater RWHS size reduction rate than the other three cities (Figure 6(a), 6(b), and 6(d)). LA in Figure 6(c) shows a higher RWHS storage reduction rate of up to 40%. However, Figures 6(a), 6(b), and 6(d) show low RWHS reduction rates between 0 and 1%. This indicates that the dry region gets advantages from connecting RWHSs in terms of RWHS size reduction. In other words, the LA region was more sensitive to the RWHS size based on the required efficiency than the other three regions.

Similarly, Figure 7 shows the connected RWHS size reduction as a function of differences in water use and combined efficiency. Overall, the RWHS reduction rate increased as the differences in the water demand and combined efficiency increased. Seoul, Taipei, and NY regions in Figures 7(a), 7(b), and 7(d) show low RWHS storage reduction rates of up to about 3%. However, the LA region in Figure 7(c) produces a high RWHS reduction rate up to approximately 80%. Like Figure 6, the LA region (Figure 7(c)) shows more increase in the RWHS size reduction rate than the other three regions (Figures 7(a), 7(b), and 7(d)). This is because the LA region requires greater RWHS size than the other three regions under the same water demand conditions, as shown in Figure 3.

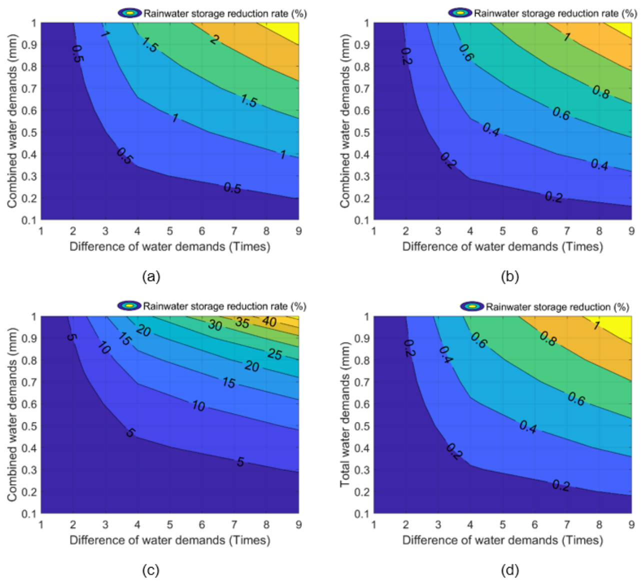
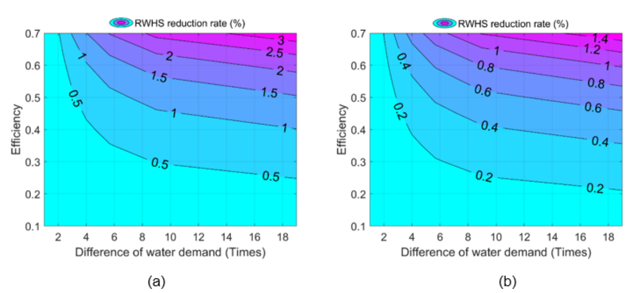


Figure 6: Rainwater storage reduction between the difference of water demands and total water demands in the sharing rainwater harvesting storages system as average efficiency of 30%; (a) Seoul, South Korea, (b) Taipei, Taiwan (c) Los Angeles (d) New York. These figures show the RWHS size reduction rate of the combined RWHSs compared with two single RWHSs based on the difference in water demands and the combined water demands in each region. These figures indicate that the RWHS size reduction rate of the combined RWHSs increases compared with two single RWHSs as the difference between water demands and combined water demands increases. However, the RWHS size reduction rate of the combined RWHSs is different depending on the four rainfalls and their regional characteristics.



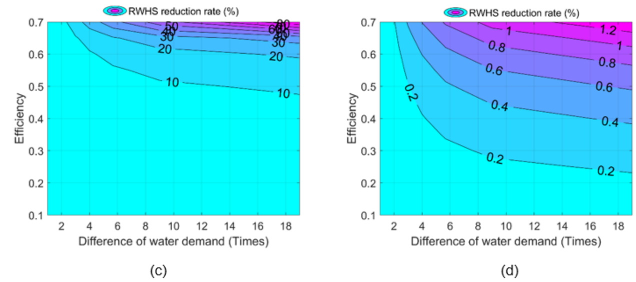


Figure 7: RWHS reduction as a function of the difference of water demand and efficiency for a combined water use of 0.2 mm/day; (a) Seoul, (b) Taipei, (c) Los Angeles, (d) New York. These figures show the RWHS size reduction rate of the combined RWHSs compared with two single RWHSs based on the difference in water demands and the RWHS efficiency in each region. These figures indicate that the RWHS size reduction rate of the combined RWHSs increases compared with two single RWHSs as the difference in water demands and efficiency increases. However, the RWHS size reduction rate of the combined RWHSs is different depending on the four rainfalls and their regional characteristics.

■ Conclusion

This study investigated the effects of linked RWHS based on differences in combined RWHS sizes, water demands, and RWHS performance efficiencies. To verify the analytical method, this study confirmed that most of the conditions match well with the results of the analytical method and the physical performance model in four cities that represent different rainfall characteristics. This study found that the efficiency of the connected RWHS increased as RWHS size, the connected total RWHS size, and combined water demands increased. In addition, the RWHS size reduction rate increased as the difference in water demands, combined water demands, and combined RWHS efficiency increased. As a result, this study suggests that rainy regions, such as Seoul, Taipei, and NY, show greater benefits in increasing efficiency at a constant RWHS size when RWHSs are connected. In addition, semi-arid or arid regions (e.g., LA) show greater benefits in RWHSs size reduction to satisfy a constant efficiency in the connected RWHSs condition. However, the results of this study need to be verified with actual observed data because the results of the analytical performance model are applied. It will be different from the actual performance, although the analytical performance model is verified with the physical performance model used as reference results.

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Saewoong Ian Park is a junior at Seoul International School in Seoul, South Korea. He is a student with an avid curiosity in diverse fields of study including environmental science and public policy. He believes that with the combination of STEM and legislative advancements, there will be effective solutions to solving world issues including the shortage and lack of access to water.