Research Paper

Improving the hydrological performance of a rainwater for drinking (RFD) system at a rural hospital in Vietnam

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ABSTRACT

Rainwater harvesting has been recognized as an alternative water supply method with many environmental benefits. This method can also produce drinking water for people who cannot access safe water resources. In this study, we evaluate the newly developed rainwater for drinking (RFD) system built at Ly Nhan Hospital in Vietnam. Most evaluation methods are not suitable for the RFD system because they focus on given conditions and overlook the potential of the system via operation and management practices. The hydrological performance was evaluated based on the system supplying drinking water sustainably, with zero no water days and a rainwater utilization ratio of 22%. Methods for improving performance indicators under adverse conditions were determined using sensitivity analysis and include increasing catchment area and tank volume and maximizing water use by utilizing rainwater overflow. Among them, an additional tank should be prioritized considering the cost, or it can be replaced by a plastic bag. The RFD system can be designed based on system monitoring data despite a lack of daily rainfall data and unexpected changes in the conditions. Appropriate regional RFD guidelines can be established with the continued evaluation of the RFD system worldwide.

Key words | evaluation, performance indicators, rainwater, SDG6, water supply

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HIGHLIGHTS

- The rainwater can be used as a drinking water source in health care facilities.
- Indicators about the rainwater for drinking (RFD) system are the basis of operation and management.
- The RFD system is critical to solve water and sanitation problems around the world.

INTRODUCTION

A rainwater harvesting system (RWHS) collects rainwater for potable and nonpotable water use, and these systems have been used since historical periods when centralized water supply systems were not well established. The RWHS has been expanded to areas of ecosystem management, urban flood control, nonpoint source pollution control, integrated basin management, green infrastructure, and so on. Researchers worldwide have investigated whether rainwater collected from roofs is suitable for drinking, and their results show improper water quality, particularly regarding microbial quality. Vietnam has abundant rainfall and has traditionally used the RWHS for drinking water (Thuy *et al.* 2019). Rainwater is simpler and easier for individuals to use to produce drinking water compared to river water, which requires treatment, and groundwater, which is contaminated by arsenic. Filtration

doi: 10.2166/washdev.2020.104

and disinfection systems can make rainwater meet drinking water standards even though collected rainwater might contain pollutants from the atmosphere or roofs.

The rainwater for drinking (RFD) system, consisting of catchment, storage, and treatment components, was built in the Ly Nhan Health Care Facility (HCF) to produce drinking water. The water quality from the RFD system met all requirements by the drinking water standards of Vietnam, QCVN 01-1:2018 (Domestic water standard) and QCVN 06-1:2010/BYT (Drinking water standard). In this study, we focus on only the quantity of rainwater and not the water quality, which will be analyzed in future research. The performance of most RFD systems has been evaluated with certain fixed conditions, which result in a fragmented understanding of the performance and cannot provide suggestions to improve the operational efficiency. This type of conservative and passive performance evaluation is not reliable due to a lack of rainfall data (Ghisi *et al.* 2007) and could cause much overflow during the rainy season. No matter how well the catchment area and tank size of the system are designed, the system might be useless during unpredictable changes in rainfall if its operating performance is fixed. Performance improvement is critical for sustainably utilizing the RFD system, and this system needs to be evaluated hydrologically.

Hydrological evaluation methods have been reported in terms of reliability based on mass balance (Kim & Yoo 2009; Ward *et al.* 2010; Mun & Han 2012; Temesgen *et al.* 2015; Dao *et al.* 2017; Nguyen & Han 2017; Guo & Guo 2018). Reliability is the most suitable nondimensional indicator for quantitative analysis and is divided into two types, volumetric reliability and time reliability (Liaw & Tsai 2004; McMahon *et al.* 2006; Unaini *et al.* 2017), which are also considered as efficiency (Fewkes 1999; Palla *et al.* 2011) and security (Umapathi *et al.* 2019). Kim & Yoo (2009) evaluated three cases of an RWHS for nonpotable purposes in Korea using sensitivity analysis and presented the number of rainfall days and the amount of water consumption. Guo & Guo (2018) analyzed the water supply reliability of an RWHS in a humid and arid area and found that the relationship between reliability and the controlling factors is nonlinear. Those results presented the capacity of rainwater tanks considering water demand but not methods for improving operational performance. Therefore, this study aims to hydrologically evaluate RWHS and suggest operation methods to ameliorate performance under varying conditions.

MATERIAL AND METHODS

System configuration

Ly Nhan HCF is a part of the Ly Nhan District Preventative Medical Center in Ha Nam Province and is 90 km from Hanoi, Vietnam (Figure 1). Ly Nhan is located in the Red River region, and most of its groundwater is contaminated by arsenic (Berg *et al.* 2001; Nguyen *et al.* 2009). Ha Nam province has a tropical monsoon climate with 1,900 mm of annual rainfall, which is concentrated from May to September (People's Committee of Ha Nam Province 2016).

Seoul National University (SNU) cooperated with the World Health Organization representative office in Vietnam (WHO Vietnam) and the Vietnam Health Environment Management Agency (VIHEMA) to build an RWHS called the RFD system. In the first survey for understanding the current situation, they used to boil the water for the patients, which incurred energy and labor expenses. To install the system, which supplies 300 L of water per day, part of the roof was used for the catchment, four 4-ton tanks, and water treatment facilities, and drinking fountains were set in the building (Figure 2). This system is expected to enhance water, sanitation, and hygiene as a pilot implementation of the Water, Sanitation, and Hygiene-Facility Improvement Tool (WASH-FIT). Based on the lessons from this RFD system at Ly Nhan HCF, other RFD systems may be distributed to other medical centers in rural areas to supply safe, clean water.

The RFD system in Ly Nhan HCF consists of five parts, as shown in Figure 3: catchment, first flush tank, rainwater harvesting tank, rainwater treatment room, and drinking water fountains. Rainwater harvested from the roof flows to a downpipe through gutters. The downpipe connected to the first flush tank has a valve to control the flow of rainwater. When the storage tank is full, the valve will be opened to direct overflow away. A first flush tank removes the first flush of rainwater with contaminants because pollutants on a roof are mostly swept away by the initial rain. Four stainless steel tanks (4 m^3 each) store the rainwater and

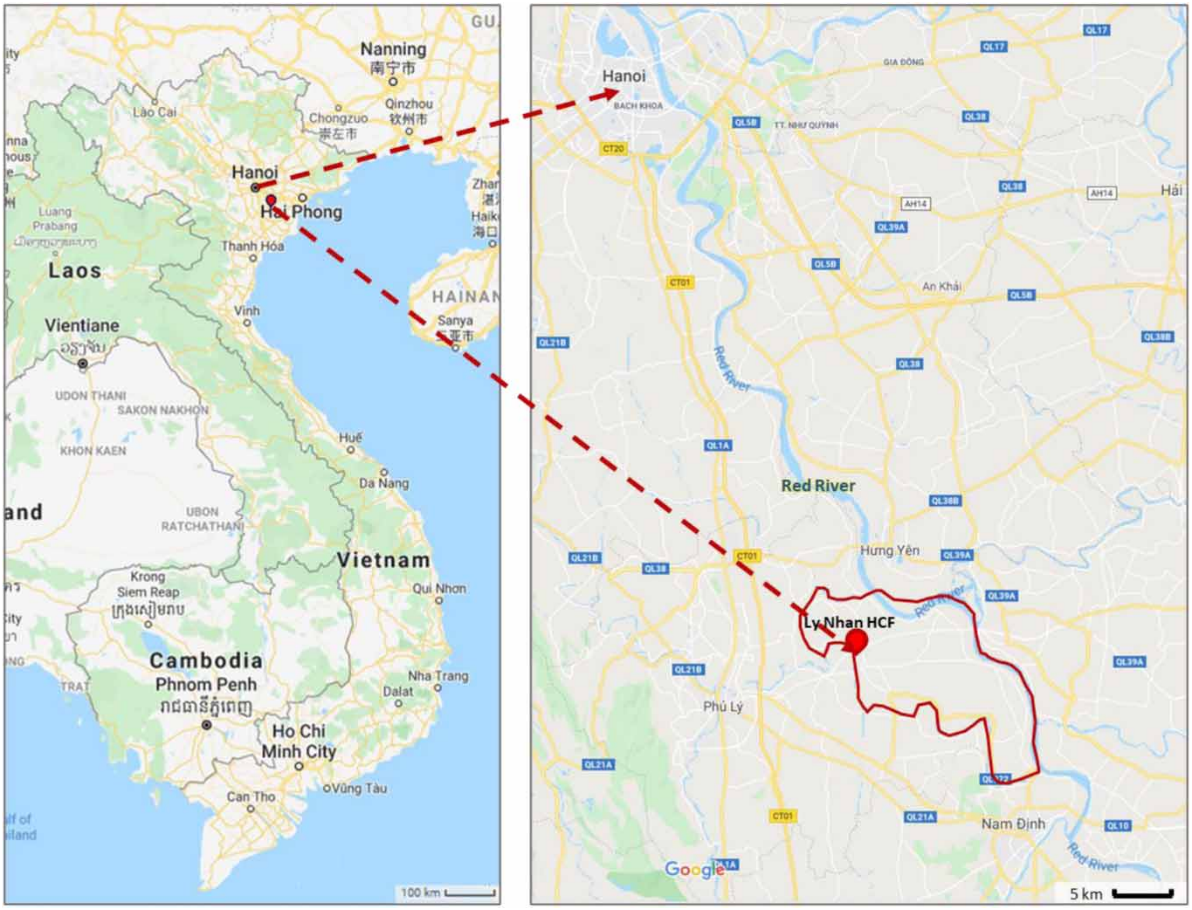

Figure 1 | Location of the study site (Ly Nhan HCF, Ly Nhan District, Ha Nam Province, Vietnam).

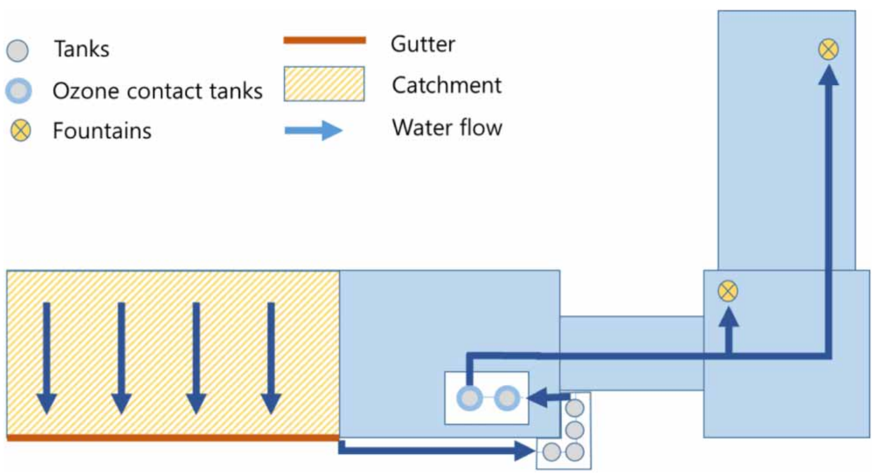

Figure 2 | Layout of the Ly Nhan HCF.

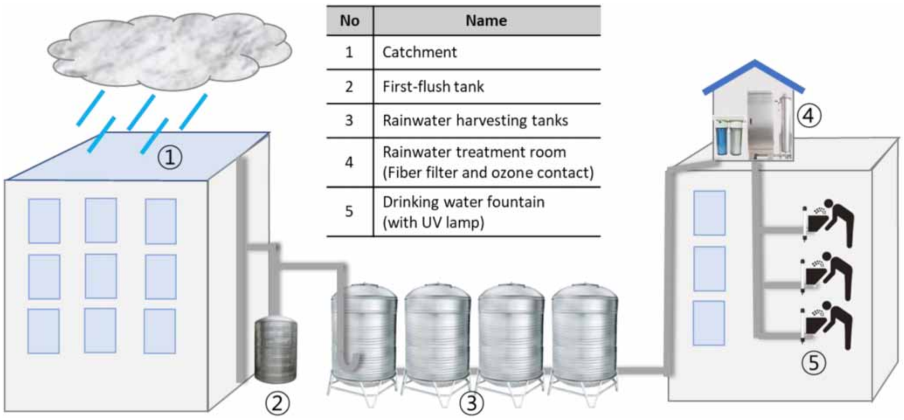

Figure 3 | Layout of the RFD system at Ly Nhan HCF.

have a drain valve at the bottom of the tank to drain sediments from the tanks. The four tanks-in-series improve water quality by successively removing sediments. To improve water quality, fiber filters remove residual sediment, and ozone is applied to remove odor and color in the ozone contact tanks at the water treatment room. The facilities in the water treatment room are equipped on the basis of requests by Vietnam agencies although the ozone contact tanks are unusual parts of the RWHS. The drinking fountains are distributed to several buildings and equipped with taps, nanofilters, and UV lamps to guarantee the best drinking water.

Daily rainfall data for Ly Nhan District were not obtained and were replaced by that for Hanoi in 2005 as an alternative (Figure 4). The amount of rainfall in Hanoi is normally between 1,200 and 2,300 mm/year, and the

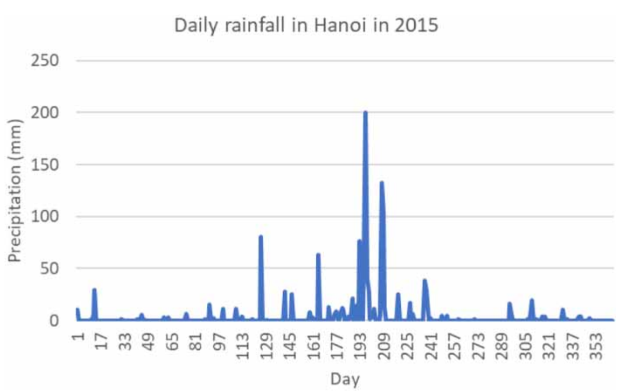

Figure 4 | Daily rainfall data from Lang station in Hanoi in 2005.

average annual rainfall is 1,665 mm based on records from 2002 to 2018 (General Statistics Office of Vietnam 2020). In 2005, the annual precipitation reached 1,355 mm at Lang station in Hanoi, which was the only daily rainfall we were able to obtain.

Evaluation methods

Understanding rainfall is critical to determine the optimum design for the RWHS. A well-designed RWHS allows people to use rainwater continuously all year in terms of supply.

As shown in Figure 5, the design changes based on rainfall, catchment area, runoff coefficient, storage tank volume, and water demand. To evaluate the hydrological performance of the RFD system, we applied the same mathematical equation and performance indicators as Nguyen & Han (2017) because they evaluated RWHS performance with the same daily rainfall data that we obtained. The water balance under certain conditions is described as follows:

$$Q_{\text{in},t} = I_t \times A \times C \times 0.001$$

$$V_t = V_{t-1} + Q_{\text{in},\,t}\Delta t - Q_{\text{out},\,t}\Delta t - Q_{\text{sup},\,t}\Delta t$$

where $Q_{\text{in},t}$ is the inflow rate into the tank (m^3/day) at time t, A is the catchment area (m^2), C is the runoff coefficient, I_t is the rainfall intensity (mm/day) at time t, V_t is the accumulative water in the tank (m^3) at time t, $Q_{\text{out},t}$ is the overflow rate from the tank (m^3/day) at time t, Δt is the time increment

Figure 5 | Schematic diagram of the RFD at Ly Nhan HCF.

(day), and $Q_{\sup,t}$ is the water supply rate from the tank (m^3/day) at time t.

$$\text{If}\quad V_t \leq 0 \ \rightarrow Q_{\sup,t} = 0$$

If $V_t > 0$, the amount of water supply is limited by the quantity of cumulative water stored and inflow to the tank.

$$V_{t-1} + Q_{\text{in},t}\Delta t < D_t\Delta t \rightarrow Q_{\sup,\,t}\Delta t = V_{t-1} + Q_{\text{in},\,t}\Delta t$$

$$V_{t-1} + Q_{\text{in},t}\Delta t \geq D_t\Delta t \rightarrow Q_{\sup,\,t}\Delta t = D_t$$

$$\text{If}\quad V_t \leq V \ \rightarrow Q_{\text{out},t} = 0$$

If $V_t > V$, the tank is full,

$$Q_{\text{out},\,t}\Delta t = V_{t-1} - V + Q_{\text{in},\,t}\Delta t - Q_{\sup,\,t}\Delta t$$

where D_t is the water demand (m^3/day).

The evaluation parameters are based on reliability and efficiency, which estimate the amount of water used compared with the total amount of rainfall for the number of days the RFD system is well supplied with water. In this study, no water days (NWD) and rainwater utilization efficiency (RUE), suggested by Mun & Han (2012) and Mwamila et al. (2015), are adopted. NWD is a parameter for reliability and is defined as the number of days in a year when stored water is less than the one-day demand. Umapathi et al. (2019) defined the same concept as security, which is the average number of days with zero supply. The parameter for efficiency is RUE, which is defined as the ratio of the amount of rainwater supplied to users to the total rainwater harvested from the catchment area. RUE is also called the rainwater utilization ratio (RUR). These parameters were also applied by Mwamila et al. (2015), Temesgen et al. (2015), Dao et al. (2017), Nguyen (2017), and Han & Nguyen (2018). NWD and RUR can be illustrated as follows:

$$\text{NWD} = T \times \left(1 - \sum Q_{\sup,t}\ \Delta t / \sum D_t\ \Delta t\right)$$

$$\text{RUR} = \sum Q_{\sup,t}\ \Delta t / \sum Q_{\text{in},t}\ \Delta t$$

where T is the simulation period (day), which is mostly 365 because rainfall data for a year are applied. $Q_{\sup,t}$ is the water supply rate (m^3/day) at time t, and D_t is the water demand (m^3/day).

An RFD system with low NWD and high RUR is better because it ensures a more stable supply and maximizes rainwater use with less overflow, which flows without use. After evaluating the RFD system at Ly Nhan HCF for the initial plan of 300 L/day of water demand, 400 m^2 of the catchment area, and 16 m^3 of tanks, other scenarios with different water demands were simulated to suggest methods for achieving lower NWD and higher RUR.

RESULTS

System performance evaluation

The RFD system at Ly Nhan HCF obtains 22.2% annual RUR and zero NWD with a catchment area of 400 m^2, a tank volume of 16 m^3, and a daily water consumption of 300 L when starting with fully filled tanks (Figure 6). NWD changed to 4 days in the case of starting with empty tanks, which means that the RFD system would be vulnerable to insufficient rainfall initially unless operation starts with full tanks or in the rainy season. An empty tank cannot supply water before it is filled with rainwater from rain events. Full tanks at the start work the same as pump priming, the process of introducing fluid into a pump to operate it.

As shown in Figure 6, the volume of stored rainwater changes daily with rainfall events and cannot store excessive rainwater, which affects the RUR value. The annual RUR is an indicator of where annual precipitation is evenly distributed throughout all 12 months. Monthly RUR, on the other hand, is more useful for understanding the RFD operation and to take countermeasures in areas where rainfall is concentrated within a few months. The RFD system at Ly Nhan HCF shows a broad range of RUR from a minimum of 5% to a maximum of 1,722% (Figure 7). The stored rainwater at the end of a previous month makes RUR high because more water is available than that collected in the month.

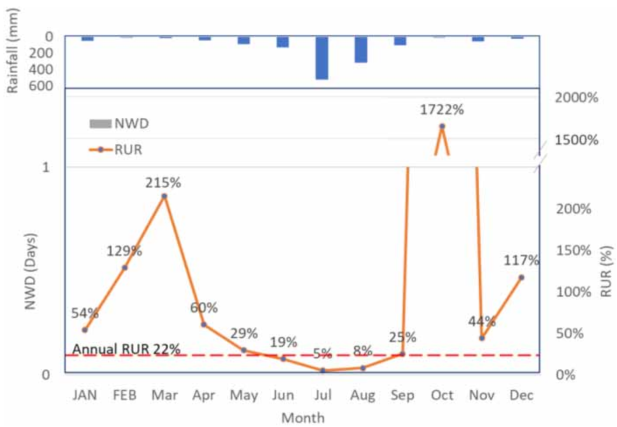

Figure 7 | Monthly simulation of RUR and NWD.

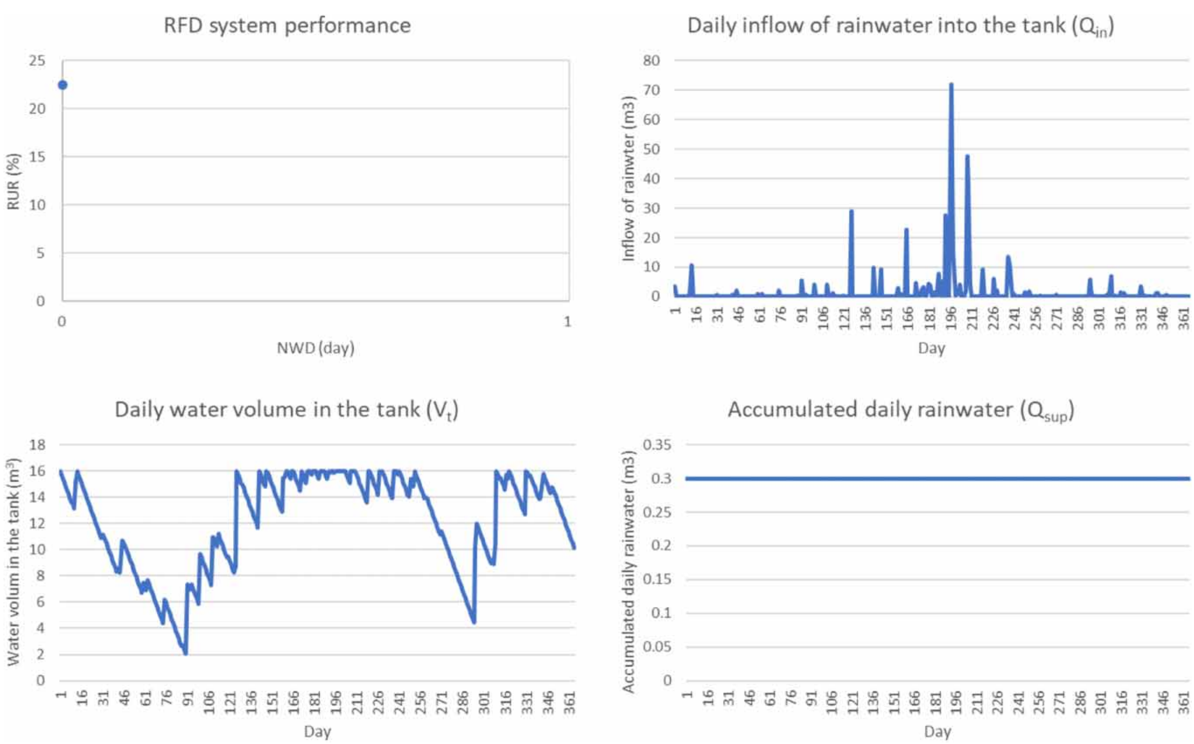

Figure 6 | Daily changes in the RFD system over 1 year (starting with fully filled tanks).

Frequent overflow in the rainy season becomes the main factor for decreasing RUR; thus, complementary operation between the rainy season and the dry season is required to increase both monthly and annual RUR.

Sensitivity analysis of the RFD system

The two results above are based on given conditions. Therefore, sensitivity analysis is essential not only for evaluation but also high-performance operation under variable conditions. Primarily increasing water demand, decreasing precipitation, and broken systems threaten normal operation (Figure 8). The RUR and NWD should be calculated with variable external factors, rainfall, and water demand to determine countermeasures in terms of operation under various conditions. Two operation indicators of catchment area and tank volume were evaluated under varying annual precipitation of 1,200, 1,500, and 1,800 mm and water demand of 0.1, 0.3, and 0.5 m^3/day.

To investigate the NWD and RUR related to the catchment area under variable water demands, tank volume was fixed at 16 m^3, and the daily rainfall data in 2005 from Hanoi were applied. A water demand of 0.1 m^3/day requires just 200 m^2 of the catchment area to achieve zero NWD, but a water demand of 0.5 m^3/day requires more than 1,000 m^2 (Figure 9). Increasing catchment area without additional tanks can reduce NWD and RUR at the same time, but the larger the area is, the less effect it has on them. Considering the expenditure of expanding the catchment, 400–600 m^2 is a suitable range.

Figure 10 presents the effect of increasing tank volume, which decreases NWD and increases RUR. There is no change in RUR by tank volume when water demand is as low as 0.1 m^3/day, but substantial changes in RUR occur when water demand is as high as 0.5 m^3/day. As shown in Figures 8 and 9, 16 m^3 of tank volume for 400 m^2 of the catchment area is suitable for the current water demand, which requires an additional 200 m^2 of the catchment area or two tanks at 4 m^3 to decrease NWD from 58 to 26

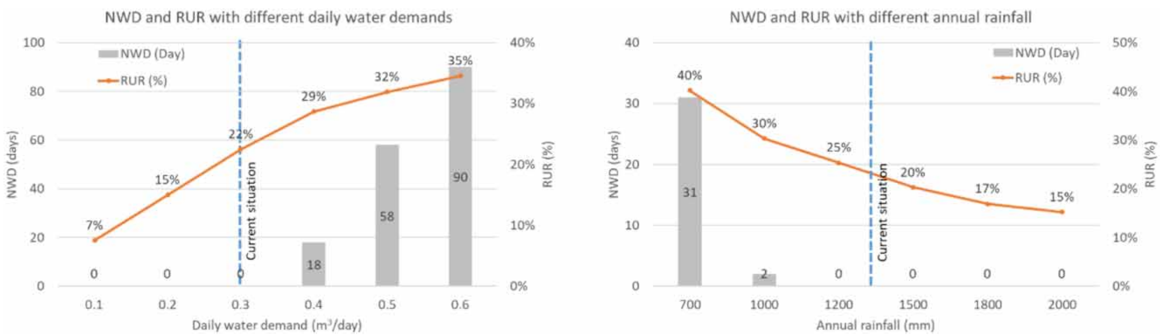

Figure 8 | NWD and RUR with different external factors.

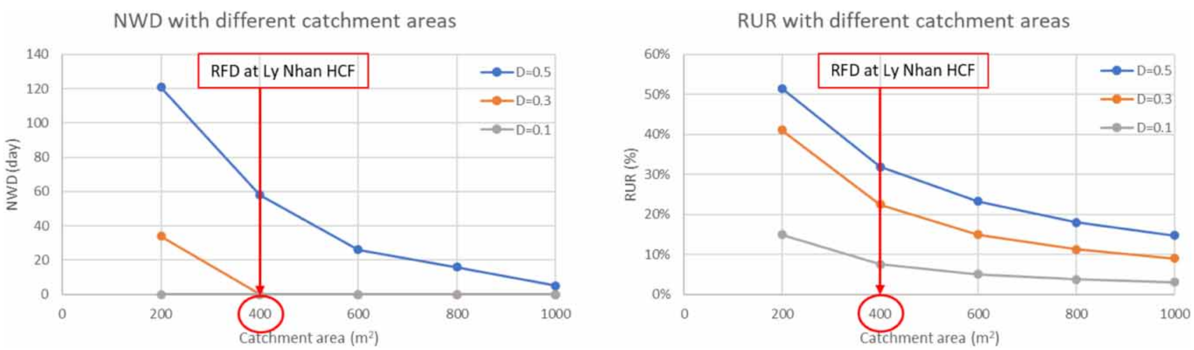

Figure 9 | Sensitivity analysis of catchment area with different water demands.

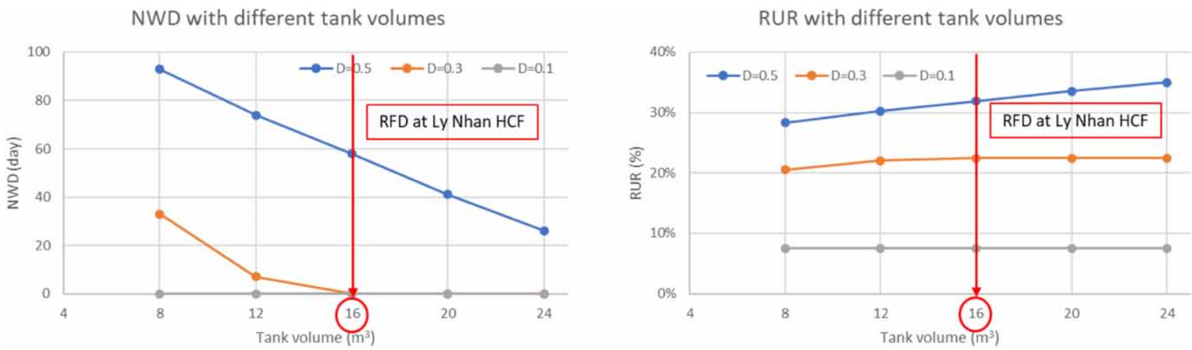

Figure 10 | Sensitivity analysis of tank volume with different water demands.

when water demand increases by 0.5 m^3/day. The RFD system should expand its catchment area or tank volume to achieve zero NWD, and the best method is determined by comparing cost and effect.

Figures 11 and 12 show how NWD and RUR change depending on the amount of annual rainfall. Those rainfall data are derived by multiplying certain rates to determine the desired rainfall, which is assumed to have the same pattern of rainfall being concentrated in a few months during the rainy season. The performance indicators were analyzed by assuming a water demand of 0.3 m^3/day. The lowest rainfall represented extreme drought based on the annual rainfall data in Nam Dhin bordering Ly Nhan. As a result, 2 days of NWD occur when rainfall decreases by 1,000 mm, but it can become zero by increasing the catchment area by 10 m^2 or the tank volume by 1 m^3. The

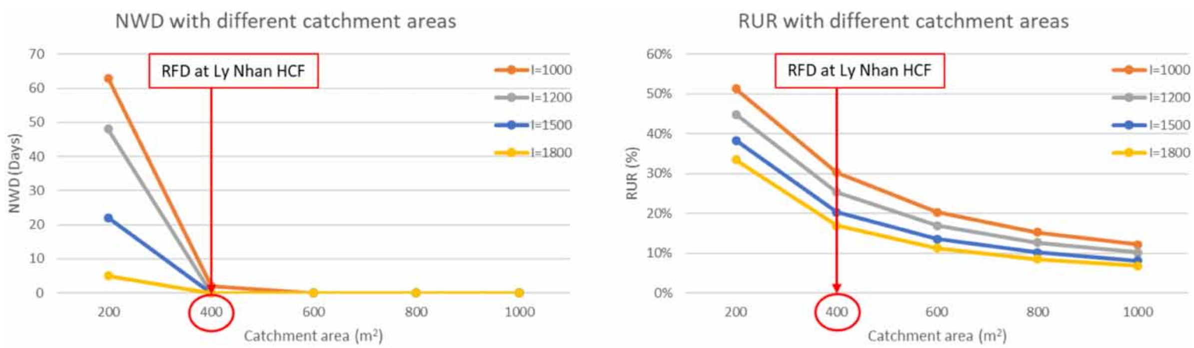

Figure 11 | Sensitivity analysis of catchment area with different precipitation values.

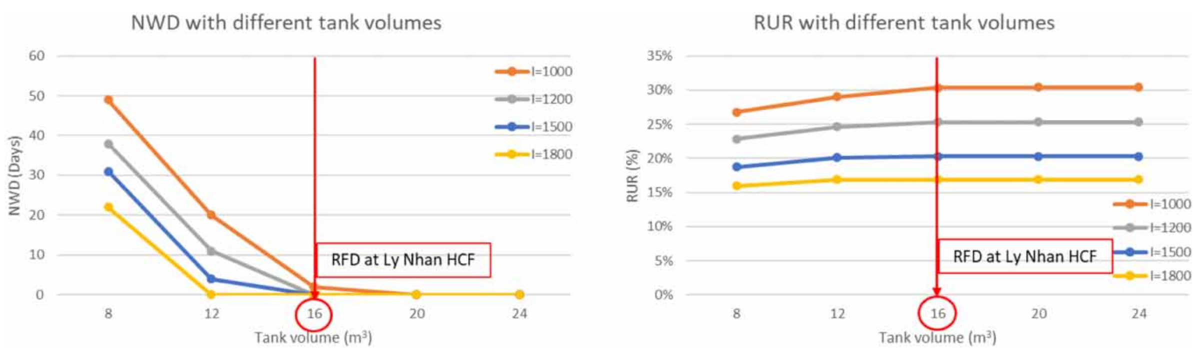

Figure 12 | Sensitivity analysis of tank volume with different precipitation values.

current design is determined to be a nearly sufficient stable water supply even in a drought year.

DISCUSSION

The RFD system at Ly Nhan HCF was confirmed to have enough capacity to supply drinking water over 1 year. The system was also simulated under various conditions changing water demand and annual rainfall. Several methods for improving the hydrological performance of the system are suggested from the NWD and RUR perspectives. First, the tanks should be filled with water at the start of operation to achieve zero NWD. Most RWHS managers overlook utilizing other water resources because the RWHS is considered to use only rainfall in areas that suffer from water scarcity due to lack of clean water. Unless the RFD system is installed in the rainy season, a lack of rainwater is clearly predictable in the early period after establishment. Second, the catchment area determines the total amount of inflow to the system. A sufficient amount of large areas for collecting rainwater can overcome the limit of low precipitation if the costs are acceptable considering the cost and effect. Third, augmenting tank volume decreases NWD by storing the amount of water required during continuous days without rain. Finally, decreasing water use during drought is not recommended because the RFD system is designed for the amount of drinking water needed for humans, and this amount of water should be secured every day.

RUR indicates whether the system is being operated efficiently without wasting water, so the person in charge of operation and management needs to monitor this value closely and not use the yearly value. RUR is the ratio of total inflow and total water supply; in other words, RUR can be improved when total inflow is low and water supply increases. The rainfall in the dry season is used efficiently because of low precipitation, while that in the rainy season is wasted through overflow because water demand is fixed in the case of Ly Nhan. Therefore, the RUR could be improved seasonally, especially during monsoons (Figure 13). First, another water supply line must be connected before rainwater treatment to produce nonpotable water. Washing dishes, laundry, and cleaning consume more water than drinking, and their water source can be replaced with rainwater during monsoon, which causes substantial overflow. Second, rainwater can be stored and used for drinking in the dry season using a foldable plastic bag that can be stored when not in use eliminating the need for a permanent installation space.

We can determine the optimal catchment area, tank volume, and water consumption by considering the cost.

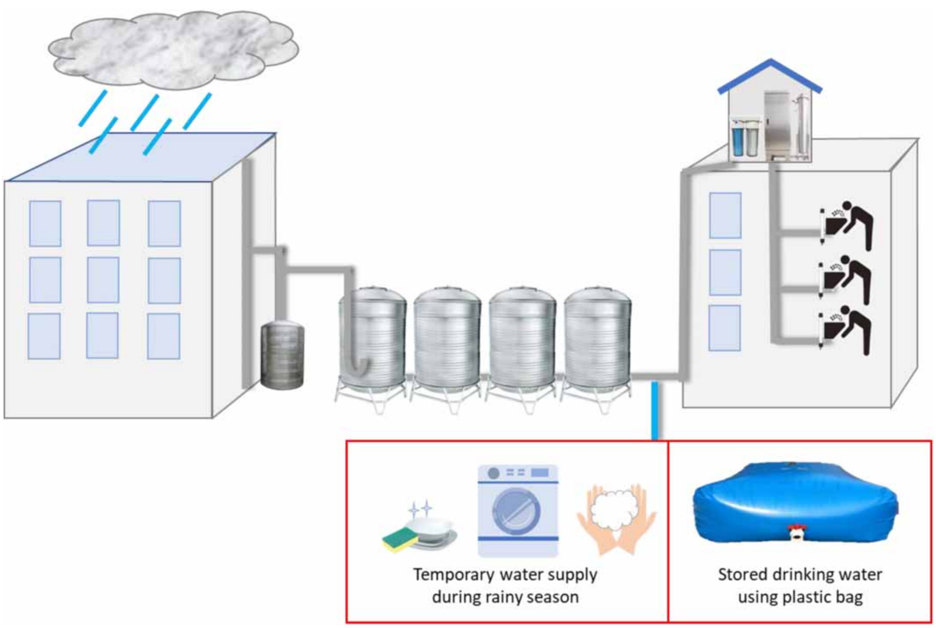

Figure 13 | Improvement by maximizing rainwater use.

Table 1 | Cost for improving the RFD system to achieve zero NWD

Condition	Increase in catchment area (m^2)	Number of 4 m^3 tanks added	Cost (USD)
Water demand	1,100	0	12,000
0.3–0.5 m^3/day	400	1	4,385
	300	2	3,770
Precipitation	100	0	1,000
1,345–1,000 mm/year	0	1	385
Water demand	2,100	0	21,000
0.3–0.5 m^3/day	700	1	7,385
and	500	2	5,770
Precipitation	300	3	4,155
1,345–1,000 mm/year			

The cost is calculated based on the expenses of the RFD system at Ly Nhan HCF, which are 1,000 USD for 100 m^2 of roofing and 385 USD for a 4 m^3 tank. Table 1 shows the cost of various conditions and methods to respond to the change of increasing water demand, decreasing rainfall, or both. Even under conditions that have the same effect, the cost decreases by increasing the number of tanks. If additional roof areas are available, then the cost will decrease, but if not, then additional tanks are prioritized. When the RFD system needs to be revised due to changes in rainfall or water use patterns, installing a tank is suggested first before increasing the catchment area.

CONCLUSIONS

While RFD systems are very simple and easy to use, most of them are designed inaccurately due to a lack of hydrological consideration. Evaluation of the system performance is not useful and reliable because it focuses on the design and not the operation and management. An RWHS consisting of just a catchment and tank cannot satisfy the current water needs and still totally depends on the rainwater itself for quality and quantity. The new RFD system developed in this study is able to supply clean and safe drinking water, and its performance is evaluated by sensitivity analysis simulating different situations for appropriate operation during unfavorable conditions.

On the basis of the sensitivity analysis, we suggest the method of improving performance to enable zero NWD and increased RUR. It is fundamentally possible to enhance the performance by changing the catchment area and tank volume; in particular, extending the catchment area decreases both NWD and RUR, and increasing the tank volume facilitates a low NWD and high RUR during drought and high water demand. In this study, tank installation is recommended prior to building a new catchment area when water demand is higher than the amount of collected rainwater. Another water supply line is also advantageous for reducing overflow waste and preparing for unexpected obstacles.

Every RFD system should be carefully designed using sensitivity analysis for operation under any given situation. Moreover, monthly monitoring of RUR and NWD is important for performance improvement and reflects the value of operation. Daily records of rainfall, water use pattern, and volume of water in the tank should be recorded to support better operation of the RFD system considering seasonal management. We advise that various RFD systems should be evaluated using sensitivity analysis to develop the appropriate RFD system guidelines reflecting the characteristics of each region and seasonal management.

ACKNOWLEDGEMENTS

This research was supported by Science and Technology Support Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science and ICT (MSIT) (NRF-2018K1A3A9A04000025) and the Institute of Construction and Environmental Engineering at SNU. The authors wish to express their gratitude for the support. This paper was supported by the KOICA/WFK Scholarship funded by the Korea International Cooperation Agency (2020-00201).

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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First received 19 May 2020; accepted in revised form 12 August 2020. Available online 23 September 2020