Journal of
Water, Sanitation & Hygiene for Development

© 2021 The Authors Journal of Water, Sanitation and Hygiene for Development Vol 11 No 6, 1048 doi: 10.2166/washdev.2021.120

Research Paper

Enhancing the resilience of the rainwater for drinking (RFD) system through systematic monitoring: a case study at the Ly Nhan rural hospital in Vietnam

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ABSTRACT

Many rainwater harvesting systems have been installed and operated to supply drinking water to rural regions. However, they often lacked the management method to supply safe and reliable drinking water. The current practice of operating rainwater harvesting systems did not have systematic monitoring as the basis of reliable operation so that the operators did not have confidence in their operation. To overcome these limitations, a rainwater for drinking (RFD) system has been suggested which was to produce drinking water by adding the proper treatment processes and setting up the proper operational mode. This study aimed to evaluate stable regular monitoring results from a pilot RFD system at a local hospital in Vietnam. Water quality and quantity were monitored by the trained local operator on a quarterly and weekly basis. The raw dataset was then shared with the study team by uploading into an open data access platform, from where the technical support was provided to prevent the provision of unsafe water to users. Ultimately, employing systematic monitoring would help to enhance the resilience of the RFD system, contributing to resolving the drinking water issue in rural areas of developing countries, aiming at the achievement of Sustainable Development Goal 6.

Key words: developing countries, rainwater for drinking system, rural health-care facility, safe drinking water, SDG 6, Vietnam

HIGHLIGHTS

- Rainwater can be a viable drinking water supply option in developing countries.
- A pilot rainwater for drinking (RFD) system has been in operation successfully at a rural hospital in Vietnam.
- A weekly and quarterly monitoring system by the local operators was developed for safe and reliable operation.
- Open data sharing was also developed and used for distance technical support.
- This systematic monitoring system can enhance the resilience of future RFD systems.

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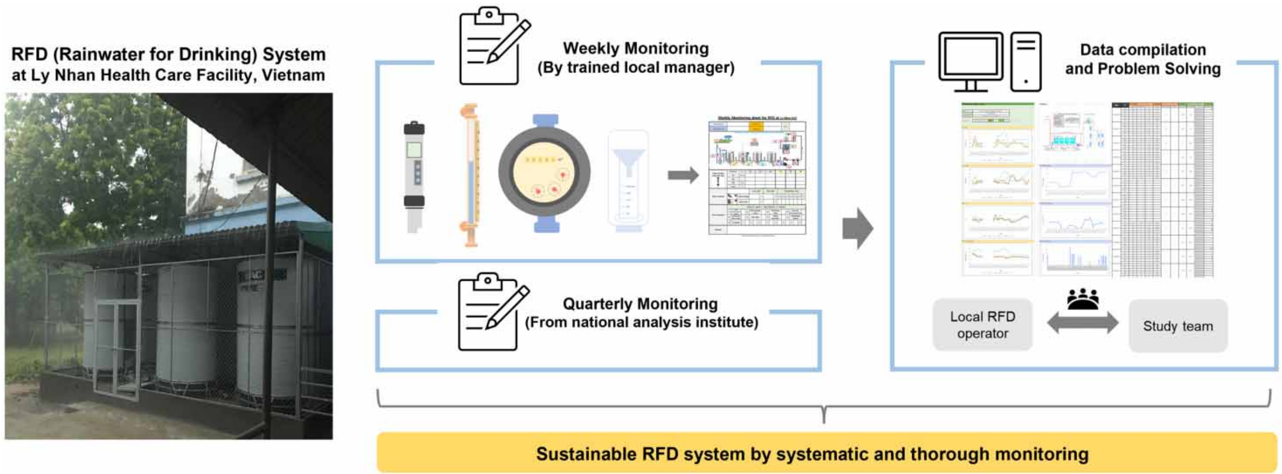
GRAPHICAL ABSTRACT



1. INTRODUCTION

Access to safe drinking water is a basic human right (UN General Assembly 2010). However, approximately 29.7% of the global population does not have access to affordable water (Drinking-Water 2019). Insufficient drinking water supply issues are prevalent, especially in low-income countries (Water 2018). As a result, only a limited proportion of these countries can access safe drinking water (WHO/UNICEF JMP 2021). The solution to achieve sufficient drinking water quantity should be derived. Not only the water quantity that is served to the public, but the drinking water quality is also directly connected to public health problems (WHO/UNICEF JMP 2017). When people drink mismanaged water, waterborne diseases, such as diarrhea, dysentery, cholera, and other symptoms, occur (Prüss-Ustün *et al.* 2014).

Health-care facilities, where hygiene control is most important, are also vulnerable to drinking water issues in developing countries, with patients, visitors, and staff are exposed to unsafe drinking water (Cervia *et al.* 2008; WHO 2019). Therefore, a patient's condition can worsen because of complications caused by waterborne diseases. Vietnam is one of the countries currently suffering from the drinking water crisis. Especially, health-care facilities are an essential part of the lives of residents in rural areas to achieve better health. However, only 51% of local health-care facilities in Vietnam have an improved drinking water source, which can lead to worse public health expansion (WHO 2019). Most tap water in hospitals are still not drinkable, and, in many cases, patients and staffs buy the bottled water. Therefore, to improve public health in rural areas in developing countries, an affordable drinking water source is required.

Considering the economic status of the country, supplying an advanced drinking water treatment system in rural regions is not affordable. Hence, this research focuses on alternative drinking water services. Vietnam has both tropical and temperate climates, and the mean annual precipitation (1991–2020) is 1,839.8 mm (World Bank Group 2021). Owing to the monsoon climate condition, rainwater can be a viable solution as a safe drinking water source for rural areas in Vietnam, where access to drinking water is low. Rainwater has been recognized as an affordable water resource. Therefore, regarding the installation site condition, rainwater harvesting systems are introduced at both the household (HH) and community levels (Musayev *et al.* 2018). This collected rainwater can be used as drinking water after simple treatment and is known as an alternative drinking water source (WHO 2004). Therefore, individuals in several regions utilize rainwater as part of their daily routine (Senevirathna *et al.* 2019).

In Vietnam, rainwater has been widely used as a nature-based and low-cost water supply in rural areas which also gives better taste compared with underground water (Dao *et al.* 2021). Özdemir *et al.* (2011) reported that rainwater was the most used (88%) compared with other sources (private wells: 44%, canals: 28%, vendors: 18%, rivers: 16%, bottled water: 14%, and private piped connection: 13%) in Vietnam Mekong River Delta. Dao *et al.* (2021) had done a comprehensive survey which found that 98% of surveyed HHs confirmed the use of rainwater frequently as the alternative water source besides underground water, 100 and 98% of surveyed HHs used rainwater for drinking (RFD) and cooking, respectively, at Ngoc Son and Dai Cuong communes in Kim Bang rural district, Ha Nam province. Besides at the HH level, a few rainwater harvesting systems was also installed at community places such as schools, kindergartens, and temples for drinking water supply in Viet Nam which has been reported (Tran *et al.* 2021).

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Normally, rainwater is collected from a catchment area. The process of rainwater harvesting for drinking water includes particle separation and disinfection process. First, particulate contaminants are separated at the first flush tank, which is followed by the sedimentation process in the rainwater storage tanks (Han & Mun 2007). Chemical and microbiological contaminations are removed via filtration (such as membrane filtration) and disinfection process (such as UV lamp) (Lee *et al.* 2017). At the end of the process, people can have access to drinking water that meets the drinking water standard.

Several RFD systems are installed in the rural areas of developing countries with comparatively high precipitation (Alim *et al.* 2020). However, successful management of these RFD systems has not been achieved due to the lack of a proper maintenance method. Owing to fragmentary and irresponsible management, the existing RFD system is not safe and sustainable. According to the users, water quality and quantity were unreliable (Gwenzi *et al.* 2015). Without access to the official water quality test results, it is difficult to positively recognize rainwater as a drinking water source (Sheikh 2020). In addition, the amount of stored water and the water usage patterns were not examined. The quantity of water in the tank represents the amount of available water. Indiscriminate water usage without consideration of the dry season leads to unrecognized water depletion. At this point, the tanks become empty until they are refilled by the next rainfall. In this study, this period was called no-water day (NWD). Ideally, the number of NWD in a year should be zero or kept as low as possible. The operator cannot be confident about the quality and quantity of water without carrying out careful management practices, being educated on the system is thus important (Kim *et al.* 2016). Frequent system management failure demoralizes the operator and is linked to the poor maintenance due to a lack of ownership. Responsibilities must be carried out to ensure successful RFD system management.

Regular system monitoring is essential for determining the cause of various matters of RFD systems (Vázquez *et al.* 2003). The monitoring system should be organized systematically, including the basic parameters such as water quality, water quantity, and the visual inspection of the system (catchment area, tanks, pipes, filter, and faucet) (Lee *et al.* 2015). In addition to considering these physical and scientific factors that may affect the management of existing systems, the social aspect must also be considered (Campisano *et al.* 2017). To boost the self-confidence of the monitoring and promote ownership of the RFD system, the operator should be supervised by the study team. The operator should take regular educational courses regarding system operation maintenance, ensuring that he/she understands the system. The monitoring results should also be shared with the managers of the community.

The regular monitoring and data discussion cycle is key to this research. The RFD system of the Ly Nhan health-care facility (HCF) in Vietnam was selected as the location of the case study. The system is installed in 2019 for 2 months to supply affordable drinking water sources. The system operation and maintenance (O&M) team was organized, and a monitoring operator was designated among Ly Nhan HCF staff. After the designation, the operator is trained with the contents of general information about the RFD system, system management logic, monitoring method, and monitoring device guidelines. Since its installation, the system has been monitored to identify problems and propose a safe and sustainable management method. Systematic monitoring was performed for 10 months after the initiation of this study.

This study aimed to identify the limitations of mismanaged RFD systems and propose a strategy to achieve safe and sustainable RFD systems through systematic regular monitoring, which will enhance the resilience of the RFD system.

2. MATERIALS AND METHODS

2.1. RFD system installed at the Ly Nhan HCF

The Ly Nhan HCF at Ly Nhan district, Ha Nam province is located 100 km south of Hanoi, Vietnam. The HCF has a 150-bed capacity and 300 visitors a day. The RFD system at the Ly Nhan HCF was designed to supply 300 L/day based on 10 years of rainfall data. Figure 1 shows a schematic diagram of the RFD system at the Ly Nhan HCF. Details of the system can be found elsewhere (Bak *et al.* 2020). The system contains a catchment area made of a corrugated steel roof, a first flush tank with a capacity of 200 L, and four connected tanks of 4 m^3 each. An ozone generator was also installed for advanced water treatment. The treated water was distributed to seven fountains containing nanofiltration and UV lamp disinfection.

2.2. Weekly and quarterly water quality test

The water quality of the system was carefully monitored by a local operator who is an employee of the Ly Nhan HCF. Water quality was verified once per week using four parameters: electrical conductivity (EC), pH, total dissolved solids (TDS), and water temperature using portable equipment (HM COM-300). These basic water quality parameters ensure general water

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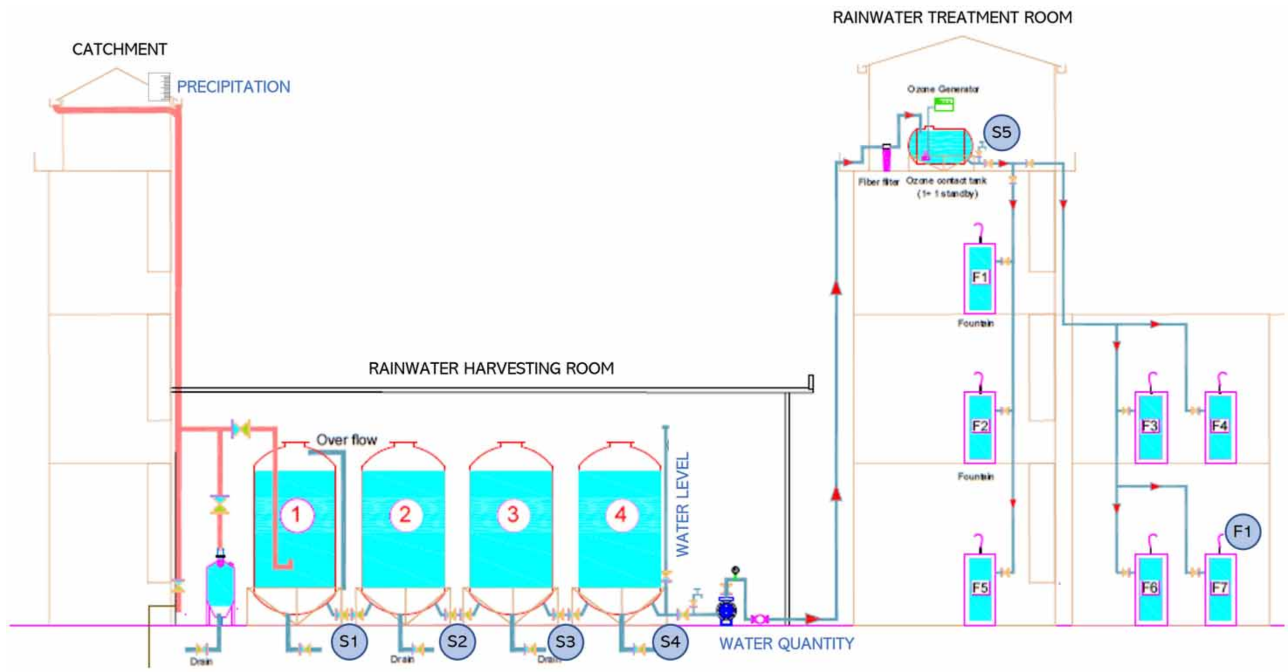

Figure 1 | RFD system installed at the Ly Nhan HCF.

quality safety (WHO 2011). When abnormal data were retrieved, the system was checked and repaired immediately by the monitoring operator. The monitoring period is 10 months. Every Wednesday, one sample was collected from every six points (S1, S2, S3, S4, S5, and F1), and the water quality was directly checked on-site. For better water quality, the visual inspection of the overall system was also conducted on a weekly basis. The catchment area, rainwater harvesting system, rainwater treatment system, and fountain were examined (WHO 2017a).

An advanced water quality test containing the microbiological test was conducted every 3 months by the National Institute of Occupational and Environmental Health under the Ministry of Health, Vietnam. Two samples were collected from the fourth tank faucet and the fountain to compare the water quality before and after water treatment. The test contains 26 parameters that are essential for determining whether the water meets the drinking water quality standard of Vietnam. These parameters include pH, temperature, TDS, color, odor, turbidity, EC, NH_4^+-N, NO_3^-, NO_2^-, SO_4^{2-}, COD ($KMnO_4$), Cd, phenol, As, Fe, Hg, Pb, Zn, total coliforms, *Pseudomonas aeruginosa*, *Streptococci fecal*, sulfite-reducing anaerobic bacteria, *E. coli*, and *Staphylococcus aureus*. Therefore, the level of microbes in the water can be determined with this test. Samples were analyzed following the Environmental Protection Agency (EPA) standard methods (Socialist Republic of Vietnam 2009).

2.3. Weekly water quantity test

The water quantity was monitored every Wednesday for 10 months using two parameters: tank water level (m) and weekly water consumption. Weekly water consumption is the amount of water that is utilized by users. A transparent hose was connected to the rainwater storage tank of the system. The water level in the tank was measured by reading the gauge. The height of the storage tank, when filled with water, was 2.3 m, and each tank had a volume of 4 m^3. Therefore, the quantity of water can be calculated using Equation (1) based on the water-level monitoring result.

$$\text{Water quantity } (m^3) = \text{Water level } (m) * 1.74 \quad (1)$$

The weekly water consumption was verified by reading the water flow meter installed at the pipe connected to the tank and pump. The amount of rainfall was measured on-site over 10 months using a manual acrylic rain gauge. The operator placed a rain gauge on the rooftop and measured and recorded the depth of the rainfall after each rain event.

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2.4. Data compilation

10 months of quarterly and weekly monitoring results were compiled and shared with the entire research group. The Vietnamese management team assembles raw quarterly monitoring sheets from the analysis institute and raw weekly monitoring datasheet, which is completed by the local operator at the Ly Nhan HCF. Thereafter, the monitoring results are screened by the management team to directly resolve issues that occur in the system. The results are finally checked by the management team in South Korea for advanced scientific issue checking. The final data are shared via a Google Drive spreadsheet with open access for members of the research group. Every monitoring parameter has its own graph. Data of weekly monitoring were accumulated every week and produced more data on the graph. Based on the monitoring data value and the change of the data, monitoring results were analyzed. The operator responded to feedback or questions from group members as part of their responsibility for the system.

2.5. Interview with the RFD system operator

To determine areas that required improvement, a questionnaire was administered to the RFD system monitoring operator. The operator who directly manages the system was interviewed to identify the system sustainability. The designated operator has the responsibility to deal with most of the issues that are expected to occur in the system. The purpose was to focus on the subject of the monitoring. The questionnaire had two questions regarding general perception about the RFD system, one question regarding system management and maintenance of each part (catchment area, rainwater harvesting system, rainwater treatment room, and fountain), three questions regarding water quality, four questions regarding water quantity, two questions regarding the educational training, and additional questions for active feedback.

3. RESULTS AND DISCUSSION

3.1. Water usage monitoring to secure stable water quantity

The results of water quantity indicated the importance of proper management. Precipitation was measured using a locally manufactured rain gauge. The precipitation of the monitoring period was 541.7 mm for approximately 10 months (Figure 2); however, the annual average precipitation of the entire country was approximately 1,839 mm (World Bank Group 2021). The precipitation of manual monitoring was approximately 30% less than published precipitation data at the closest weather station. There are two reasons for this percentage difference. One is that the precipitation significantly differs according to the site. Therefore, site-specific precipitation data are essential before installing the RFD system to derive the system capacity. Precipitation monitoring should be continued to enable more precise management of the system. In addition, the RFD system

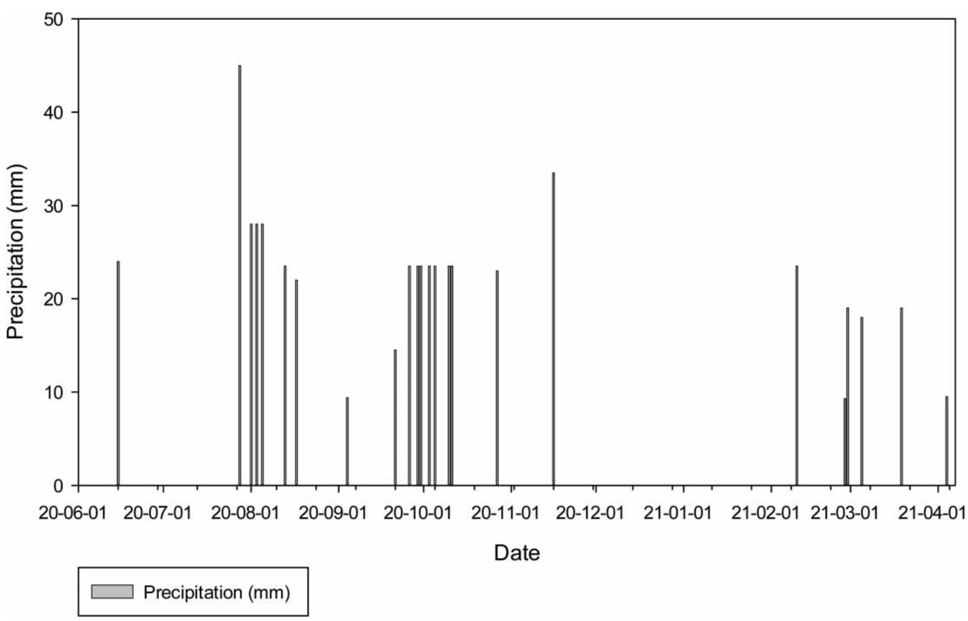

Figure 2 | Local precipitation monitoring results using the manual rain gauge.

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must be carefully monitored. Herein, the RFD system operator placed a rain gauge on the roof when rainfall occurred. The precipitation could thus be underestimated, as data for the first few minutes or hours are not captured. Placing the rain gauge at a fixed place at all time can provide more reliable precipitation monitoring results. This point will be addressed in future researches.

The water level inside the storage tank is shown in Figure 3 which varies according to the rainfall and water usage. Water usage (Figure 4) was also monitored, and water quantity was estimated from the water-level data. At the early stage of monitoring, two abnormal data were found and fixed. First, the water level did not increase, although there was one rainfall event during that period. It was found that the connection valve to the water-level measuring hose was closed. After this is fixed, the data afterward are reliable. Second, the water usage data are found zero, although water was used. It was due to the broken

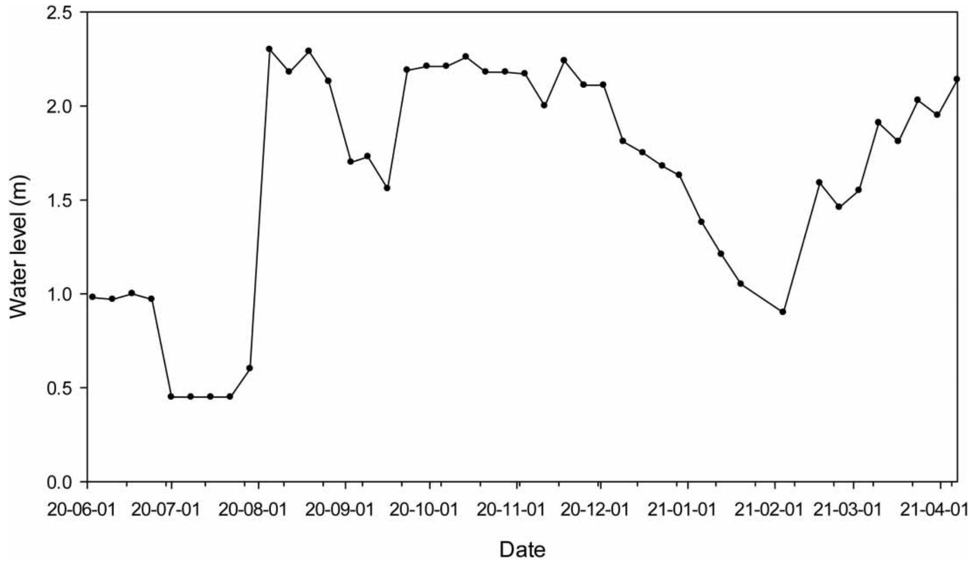

Figure 3 | Water level inside the storage tank to estimate water quantity and prevent the NWD.

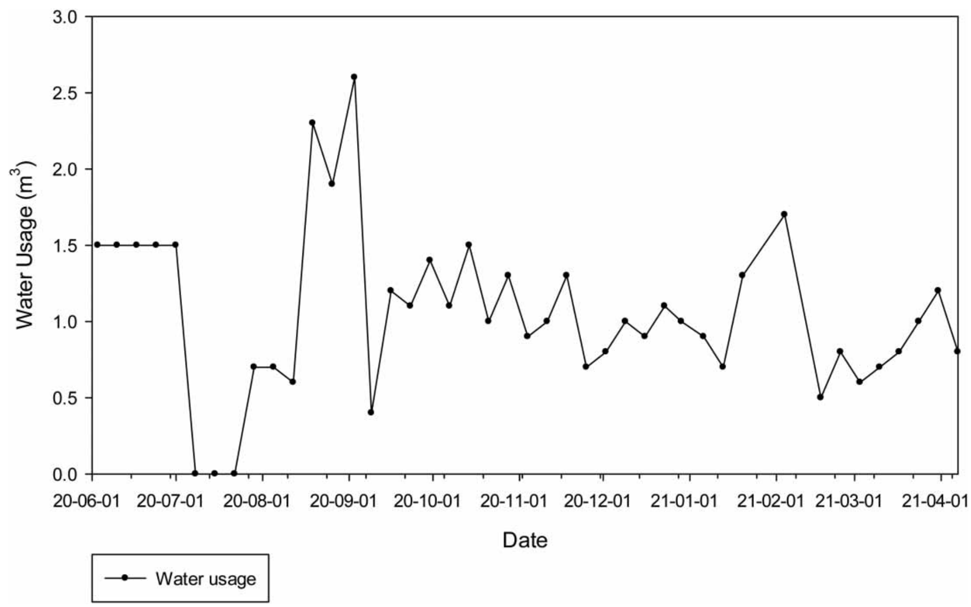

Figure 4 | Weekly water usage pattern of the rainwater for drinking system.

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water meter. After it is fixed, reliable water usage data were obtained. These events revealed that it is important to properly monitor the instruments used to record data and to promptly determine issues; this directly connects to the responsibility of management. Appropriate educational training for the local operator and careful monitoring of all components are required to obtain accurate and reliable monitoring data and achieve sustainable management of the RFD system. The research team provided additional educational training to the local operator.

As time progressed, NWD did not occur, indicating that people constantly drink rainwater. The strategy was alarming for users who normally forgot to save the drinking water. The operator performed weekly checks of water usage and water level in the storage tank. As a result, the water level was found to decrease from August to September (Figure 3). The water-level change is directly related to water consumption. More patients and visitors visited the HCF in August after the lock-down, which was implemented to deal with the 2020 pandemic (Coronavirus disease-2019), was lifted. By tracking water usage based on water level and a water meter, if rapid water usage was found, this was carefully controlled by alerting users of the excessive use of water. Users were also asked to not waste the water. Thereafter, the average trend of water consumption would be restored.

The water usage pattern was stabilized by monitoring. Careful and continuous monitoring is required to ensure system sustainability. Herein, the responsibility of the local operator and immediate action are important to ensure such monitoring is achieved.

3.2. Weekly and quarterly water quality monitoring

Although samples were monitored from six sampling points each week (S1, S2, S3, S4, S5, F1) as shown in Figure 1, only the results from three sampling points are shown in Figure 5, because the data from S1, S2, S3, and S4 did not show a significant

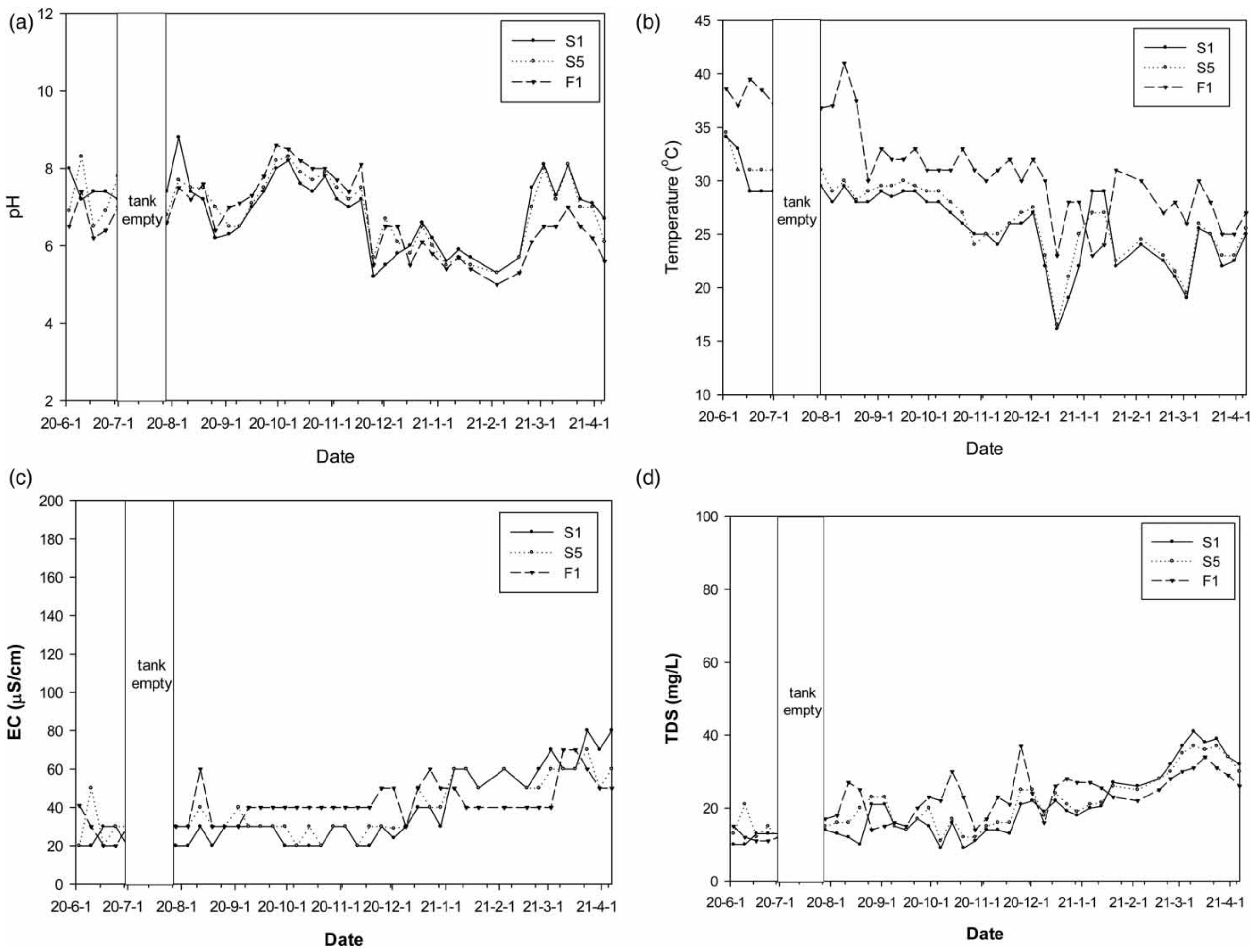

Figure 5 | Weekly water quality monitoring results: (a) pH, (b) temperature, (c) EC (electric conductivity), and (d) TDS (total dissolved solids).

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difference. The pH values are within the range specified in the Vietnamese Drinking Water Standard (pH 6.5–8.0), except sometimes during the winter season (Figure 5a). Overall, the pH was found to be within the range that has no harmful effect on human health.

The temperature of rainwater in the tanks (Figure 5b) is influenced by ambient temperature because the tanks are located outside of the building, although the tank room is covered with a roof. In the case of the fountain, there is a slight increase in temperature, because of the heat from the UV lamp, which operates when the tap is open.

The EC (electric conductivity) fluctuates (Figure 5c) in the range of 20–60 (μS/cm) which is in a much lower range than is specified by the European Union (EU) as <2,500 μS/cm) (WHO 2017b), although it is not specified at Vietnamese Drinking Water Standard. The TDS (total dissolved solids) also fluctuates in the range of 10–40 mg/L which is in a much lower range than is specified in the Vietnamese Drinking Water Standard (<1,000 mg/L).

Because both EC and TDS are related to the concentration of soluble organic and inorganic materials, they can be a good indicator of the sudden inflow of contaminants to the rainwater tank, although the range is within the specified limit. At that time, the roof needs to be cleaned and try to find possible reasons for the increase.

Table 1 shows the results of quarterly tests. For the quarterly test, raw rainwater met most of the chemical drinking water standards. However, microbial instability was observed. The levels of coliform, *E. coli*, fecal coliform, and *P. aeruginosa* exceeded the drinking water standards. The contamination from microorganisms such as coliform, *E. coli*, and *P. aeruginosa* in raw water had been also reported in some previous studies (Lee *et al.* 2017; Hamilton *et al.* 2019; Dao *et al.* 2021; Tran *et al.* 2021). However, these microbes can be degraded by nanofiltration and UV lamp treatment before the water is transferred to the fountain (Sun *et al.* 2003). Therefore, the treated rainwater sample met all drinking water standards except for the nitrate result of 25 August 2020. The raw water met the nitrate standard; however, the treated water did not meet this standard. Such a finding indicates that the cause is the filtration process. The nitrate is stacked at the filter. It exceeded the strict standard of Vietnam. However, it is much lower than the 50 mg/L of WHO drinking water standard for nitrate (WHO 2017a). Even though this event does not occur a health effect, the importance of careful and frequent advanced water quality tests is clarified with this finding. As a result, the research team immediately replaced the filter with a new filter, resolving the problem (Kimura *et al.* 2002).

Without monitoring, the users may drink contaminated water. Regular water quality monitoring results were immediately reported to the research team, and problems were resolved. Therefore, the supplied water was found to meet the drinking water quality standard, which ensures the safety of the water. Such finding not only highlights the importance of implementing the RFD system, but also the need to regularly monitor the system after its installation.

3.3. Encouraging online monitoring and distance technical support

Monitoring operators should provide accurate data. In addition, they should be responsible for the data in its integrity. Triple-checking of raw monitoring data was conducted by the monitoring operators, leading to accurate data being obtained. Advice on filter cartridge exchange was proposed after such issue was tracked in the shared data. The drawback of the early stage of water usage monitoring was examined using the database tracking tool provided by the research group. If a critical point is missed by the monitoring operator, it can be identified by other members. Also, if users request the monitoring data, they can browse the data. The monitoring and data filing method can be educated to users. If they raise some questions while keeping tracking the management status of the RFD system, and it reaches to some findings or new knowledge, users can build ownership. It is expected to expand the monitoring system scope. That system will enable a sustainable and reliable archive to be obtained.

3.4. Assessment of the RFD system management

The RFD system is managed by a local monitoring operator who is the staff of HCF through systematic monitoring considering the social and scientific aspects of the system. Management achievement was evaluated through an interview with the operator. The local operator self-evaluated the management system using a prepared questionnaire. The details of the interview are presented in Table 2. Based on the answer sheet, the operator generally believed that the system was well operated and maintained. The operator checked the system every week, and the entire system monitoring from the catchment area to the fountain is reported to be cleaned every week. The operator kept the fountain clean and changed the filter of the fountain every 6 months, thereby preventing low flow and filter fouling. Regarding water quality, the RFD system operator is confident at operating a portable water quality device. However, it is difficult for the operator to read and understand the instruction, as it is written in English. As a Vietnamese, English is not a familiar language for the RFD operator. However, this was not a

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Table 1 | Quarterly water quality monitoring results

Date			Raw rainwater (S4)			Treated rainwater (F1)				
No.	Parameter	Unit	10 Jun 2020	25 Aug 2020	24 Nov 2020	10 Jun 2020	25 Aug 2020	24 Nov 2020	Regular limit	Test method
1	pH	–	6.8	6.7	6.4	7.1	6.07	6.6	6.5–8.0	TCVN 6492:2011
2	TDS	mg/L	18	9	14	11.3	12	11	1,000	SMEWW 2540 C:2012
3	Turbidity	NTU	1.3	<0.80	<0.80	<0.80	<0.80	<0.80	2	Hach - 2100N Turbidimeter
4	Conductivity, EC	µs/cm	42	23.21	28.21	24	29.87	25.87	–	SMEWW 2540 C:2012
5	Color	TCU	3	<8.5	<8.5	<0.15	<8.5	<8.5	15	TCVN 6185: 2015
6	Taste and odor	_	No strange taste and odor	No strange taste and odor	No strange taste and odor	No strange taste and odor	No strange taste and odor	No strange taste and odor	No strange taste and odor	SMEWW 2150:2012 SMEWW 2160:2012
7	COD ($KMnO_4$)	mg/L	<0.96	1.18	1.28	<0.96	<0.96	<0.96	2	TCVN 6186: 1996
8	Ammonia (NH_4^+-N)	mg/L	<0.01	<0.093	<0.093	<0.01	<0.093	<0.093	0,3	SMEWW 4500 - NH_3:2012
9	Nitrite (NO_2^-)	mg/L	<0.01	<0.03	<0.03	<0.01	<0.03	<0.03	0.05	SMEWW 4500 NO_2^- B:2012
10	**Nitrate (NO_3^-)**	mg/L	0.16	1.88	2.08	0.18	**11.78**	1.68	2	SMEWW 4500 NO_3^- E:2012
11	Fluoride	mg/L	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	1.5	SMEWW 4500 F^- D:2012
12	Sulfate (SO_4^{2-})	mg/L	<4.0	<4.0	4.19	<4.0	<4.0	4.07	250	EPA 375.4
13	Total Fe	mg/L	0.10	<0.04	<0.04	<0.04	<0.04	<0.04	0.3	TCVN 6177:1996
14	Arsenic (As)	mg/L	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.01	SMEWW 3125B:2017
15	Cadmium (Cd)	mg/L	<0.0006	<0.0006	<0.0006	<0.0006	<0.0006	<0.0006	0.003	SMEWW 3125B:2017
16	Lead (Pb)	mg/L	<0.0020	<0.0020	<0.0020	<0.0020	<0.0020	<0.0020	0.01	SMEWW 3125B:2017
17	Chromium (Cr)	mg/l	<0.001	<0.001	0.0023	<0.001	<0.001	0.0021	0.05	SMEWW 3125B:2017
18	Zinc (Zn)	mg/L	1.221	0.7773	1.747	1.114	0.6584	2.04	–	SMEWW 3125B:2017
19	Mercury (Hg)	mg/L	<0.0006	<0.0006	<0.0006	<0.0006	<0.0006	<0.0006	0.001	SMEWW 3125B:2017
20	Phenol and its derivatives	µg/L	<0.15	<0.15	<0.15	<0.15	<0.15	<0.15	1	EPA 8270D Revision 5, July 2014

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21	**Coliforms**	CFU/100 mL	**360**	**21**	**18**	NA	NA	NA	<3	TCVN 6187-1 : 2019
22	***E. coli*/fecal coliform**	CFU/100 mL	NA	**3**	**9**	NA	NA	NA	<1	TCVN 6187-1 : 2019
23	*S. fecal*	CFU/250 mL	NA	NA	NA	NA	NA	NA	–	TCVN 6187-2 : 2019
24	Clostridia	CFU/50 mL	NA	NA	NA	NA	NA	NA	–	TCVN 6191-2 : 1996
25	***P. aeruginosa***	CFU/100 mL	NA	**57**	**68**	NA	NA	NA	<1	ISO 16266 : 2006
26	*S. aureus*	CFU/100 mL	NA	NA	NA	NA	NA	NA	<1	SMEWW 9213B

NA, not available/not specified.

Regular limit: QCVN 01-1:2018/BYT: National Technical Regulation on Domestic Water Quality, and QCVN 06-1:2010/BYT: National Technical Regulation on Drinking Water Quality.

Bold values show water quality test results that do not meet the drinking water quality standard.

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Table 2 | Entire answer sheet from the interview with local RFD system operator

1. General perception about the RFD system

1-1. What do you think about the RFD system and its sustainability?

① Catchment Area	Good
② Rainwater Harvesting System	Good
③ Rainwater Treatment Room	Good
④ Fountain	Good

1-2. Please state your overall reasons for selecting those options in Q1-1.

The system provides clean drinking water. Every water treatment step is monitored regularly. The disinfection processes can also demonstrate that the water quality is safe for use. Therefore, in general, the overall RFD system can be considered to be well managed and sustainable.

2. System management and maintenance

	How often do you visit the system?	How often do you clean the system?	Problems and Solution
① **Catchment Area**	Every week	Every week	Leaves, dust, and other particles make the area appear dirty. Careful cleaning can enable a clean catchment.
② **Rainwater Harvesting System**	Every week	Every week	–
③ **Rainwater Treatment Room**	Every week	Every week	–
④ **Fountain**	Every week	Clean and change the filter every 3–6 months	The flow rate becomes slow due to fouling. However, regular filter exchange and cleaning can resolve this problem.

3. Water quality

3-1. How confident are you at operating the portable water quality device? Good

Monitoring cycle	Every Wednesday	**Time consumption for measurement (min)**	50–60

3-2. Are there any difficulties associated with the use of the portable water quality device?

• Every element on the device is written in English. For local people, English is not a familiar language. Therefore, specific education about the device in the native language would be helpful.

3-3. How do you manage the portable water quality tester and what do you do when a problem is found?

• No specific problem arose when using the water quality tester. The battery had to be changed once.

4. Water Quantity

4-1. Please complete this table.

Parameter	**Water level**	**Water usage**	**Precipitation**
Confidence	Good	Good	Good
Time for measurement	5–10 min	5–10 min	5–10 min
Process description	1. Open the valve 2. Check the level 3. Close the valve	1. Check the number on the water meter 2. Take a photo of the water meter	1. Put the gauge on the roof on rainy days 2. When the rain stops, take the gauge and record the number
Difficulties	No	No	No

5. Education

5-1. How long have you been involved in system management? From August 2019

(*Continued.*)

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Table 2 | Continued

5-2. What kind of educational training did you receive?	Training by project headquarter
6. Will you recommend this system to other HCF in Vietnam?	Strongly recommend
7. Do you think this system is needed in Vietnam?	Strongly agree
8. Do you like this management mission?	Strongly agree
9. Do you think any improvement is required for the entire system?	
• For future RFD systems, a rainwater storage tank that holds a greater volume could supply more sufficient water to users.	
10. Please describe your accomplishment while the system management.	
• I became accustomed to operating the RFD system as the operator.	
• My technical knowledge of the RFD system, such as filter change and system repair, has been enhanced.	
• I became more responsible for carrying out my duty as the operator in charge of the system.	

Table 3 | Comparison of the conventional rainwater harvesting system and the systematically monitored RFD system

Conventional rainwater harvesting system	Systematically monitored RFD system
The system is neglected after installation.	Systematic weekly and quarterly monitoring is performed.
The system is operated based on central precipitation data.	On-site manual precipitation data are obtained.
Water depletes due to overuse; users should wait for the next rainfall.	Water supply is constant through a water usage alarm system.
The water quality test is perfunctory.	Urgent issues can be resolved by regular monitoring.
Monitoring data are unreliable.	Open access to the monitoring data promotes managerial ownership of the system.

significant drawback because the device is easy to use and thoroughly trained before using the device. Monitoring water usage was also reported to be a rather simple task. Therefore, the operator reported being confident at checking all the water usage parameters and precipitation. The monitoring operator inspired the responsibility and the ownership of the system by regular training and enhancing the RFD system management quality. The results of this interview can be used to establish a plan for further RFD system projects. For the next RFD system installation, a person that has the same responsibility as the operator in this case study should be in charge of monitoring the system. This operator interview can be utilized for governmental RFD system installation and management proposals for the sustainability of the RFD system concept. In addition, the water usage pattern and the recognition of rainwater as drinking water should be assessed through a survey with potential users.

3.5. Comparison with the conventional rainwater harvesting system

According to the monitoring results, the novelty of systematic monitoring, which was introduced at the Ly Nhan HCF, was investigated. The monitoring and management practices for the conventional rainwater harvesting system are not sustainable. In addition, their resilience is low. Table 3 summarizes the comparison of the conventional rainwater harvesting system and the systematically monitored RFD system. Limitations, such as water quantity, water quality, and system management, can be overcome by adopting the monitoring system used in this study. Frequent management failure and public suspicion of the conventional rainwater harvesting system can be solved by performing cautious monitoring. On-site manual precipitation monitoring, immediate water quantity alerts, water quality control, and data disclosure serve as state-of-the-art methods. With these approaches, the resilience of the system can increase, and this monitoring system can be applied to manage the RFD system.

4. CONCLUSION

In this study, we developed a systematic monitoring system for rural healthcare facilities in Vietnam. Optimal solutions for issues associated with conventional rainwater harvesting systems were derived from a case study at the Ly Nhan HCF, Vietnam. Raw data were collected through weekly and quarterly monitoring conducted by the local monitoring operator. Weekly

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issues were then summarized and directly solved when abnormal data were retrieved or facility elements were broken. Reviewed data were shared with the entire project team on a Google Spreadsheet. Using this system, possible issues that can occur were determined, and solutions were proposed for the future. As a result, frequently reported issues under the conventional rainwater harvesting system were resolved. Water quality was maintained at a stable level. In addition, the NWD was zero due to careful monitoring and an alarm system. Ownership was promoted by enabling open access to the monitoring data and allowing the operator to carry out his responsibilities. Even if unexpected issues occur, the problem can be solved faster and more clearly than before using this robust system, thereby enhancing the resilience of the RFD systems. This change will inspire people to visit the public HCF, which will enable the establishment of a more sustainable community by educating people and fostering harmonization.

To overcome the current management issues of the rainwater harvesting systems that have already been installed, the unorganized management system should be revised. In this regard, this study can serve as a viable guideline for a sustainable RFD system. The most important step is to promote ownership of the RFD system by the operator, which will lead to the responsible management of the system and ultimately its reliability.

We suggest further studies to overcome the limitation of this study. The collaboration with the RFD system user might also develop the sustainability of the system. The compilation of both spontaneous user and operator monitoring will enrich the RFD system monitoring by developing the ownership. Also, this study focused on the regular monitoring for community-level RFD systems. Establishing an HH scale monitoring system will expand the scope of the RFD system monitoring. Systematic monitoring can ensure a safe and sustainable RFD system and will contribute to the accomplishment of the sixth item of the Sustainable Development Goals of the United Nations for a better world.

ACKNOWLEDGEMENTS

We thank the WHO-Vietnam (Kidong Park and Ton Tuan Nghia) and VIHEMA (Nguyen Thi Lien Huong, Nguyen Thanh Ha, Nguyen Quynh Trang, and Phan Thi Ly) for their generous cooperation and support on RFD system installation at the Ly Nhan HCF.

FUNDING

This work 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) (grant no. NRF-2018K1A3A9A04000025).

DATA AVAILABILITY STATEMENT

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

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First received 15 July 2021; accepted in revised form 14 September 2021. Available online 30 September 2021

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