Design and management of rainwater harvesting systems to control water quality for potable purposes in Cu Khe, Vietnam

Yonghwan Kim, Anh Dzung Dao, Mikyeong Kim, Viet-Anh Nguyen and Mooyoung Han

ABSTRACT

There are debates about whether rainwater is suitable as drinking water. A serious shortcoming of the debate is that there are differences in the design and management of rainwater harvesting (RWH) systems. This study is based on the performance of two RWH systems that are used for drinking purposes at a kindergarten and a primary school in Cu Khe, Vietnam. Each system comprised a painted galvanized iron roof, a first-flush diverter, two stainless steel tanks connected in series, a calmed inlet, mosquito screens on open holes, PVC pipelines, filter cartridges, and a UV sterilizer. During 18 months, stored rainwater was sampled five times, and treated rainwater was sampled four times. Twenty-three water quality parameters were analyzed, including pH, total dissolved solids, turbidity, nitrate, nitrite, ammonia, hardness, arsenic, iron, cadmium, nickel, chromium, manganese, mercury, selenium, lead, zinc, *Escherichia coli*, and total coliform. It was found that all the physicochemical qualities of the stored rainwater, prior to treatment, satisfied the World Health Organization (WHO) drinking water guidelines. After physical filtration and UV sterilization, all parameters, including microbiological indicators, satisfied the WHO drinking water guidelines. Further management strategies to stabilize water quality were discussed.

Key words | design, drinking water, management, microbiological contamination, physicochemical parameters, rainwater harvesting system

Yonghwan Kim
Anh Dzung Dao
Mooyoung Han (corresponding author)
Civil and Environmental Engineering Department,
Seoul National University,
599 Gwanak-ro, Kwanak Gu,
Seoul 151-742,
Republic of Korea
E-mail: *myhan@snu.ac.kr*

Mikyeong Kim
Institute of Construction and Environmental Engineering (ICEE),
Seoul National University,
599 Gwanak-ro, Kwanak Gu,
Seoul 151-742,
Republic of Korea

Viet-Anh Nguyen
Institute of Environmental Science and Engineering,
National University of Civil Engineering,
55 Giai Phong Road,
Hanoi 100,
Vietnam

INTRODUCTION

Roof-harvested rainwater is increasingly being considered as an alternative drinking water supply option, especially in rural areas of developing countries (Amin & Han 2009). There are debates, however, regarding the suitability of rainwater as drinking water. In some places, rainwater is generally perceived as potable, even without treatment (Dillaha & Zolan 1985). In contrast, some studies have recommended that rainwater be used as graywater because contaminants have been detected (Gikas & Tsihrintzis 2012). To date, rainwater has not been widely adopted as a drinking water source despite its many advantages, because of a lack of information regarding the quality of roof-harvested rainwater.

Although there is concern about rainwater quality because of air pollution, air pollutants are not the major contributors to rainwater contamination, even in urban areas with reasonable air quality (Huston *et al.* 2012). Instead, contamination is primarily affected by the design and management of rainwater harvesting (RWH) systems (Wilbers *et al.* 2013).

Different RWH systems produce water of varying quality. In Table 1, rainwater samples of Sazakli *et al.* (2007),

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Table 1 | Various RWH systems in previous studies

References	Roof material	First-flush diverter (Capacity[a]: mm)	Storage Material (Capacity: mm)	Storage Mosquito screen	Storage Tank cleaning	Filtering
Yaziz *et al.* (1989)	Galvanized iron, concrete tile	X	Polyvinylchloride (0.3)	Unknown	O[b]	X[c]
Chang *et al.* (2004)	Wood shingle, composition shingle, aluminum, metal	X	High-density polyethylene (3.7)	Unknown	O	X
Sazakli *et al.* (2007)	Cement	O (Unknown)	Ferro-concrete (330–500)	Unknown	O	X
Farreny *et al.* (2011)	Clay tile, metal sheet, polycarbonate plastic, gravel	X	Polyethylene (8–24)	Unknown	Unknown	X
Mendez *et al.* (2011)	Asphalt fiberglass shingle, metal, concrete tile, green roof, cool roof	O (0.4–0.7)	Polypropylene (4–7)	O	O	X
Lee *et al.* (2012)	Wooden shingle, concrete tile, clay tile, galvanized steel	O (2.0)	Unknown (196)	Unknown	Unknown	X
Naddeo *et al.* (2013)	Unknown	X	Unknown	Unknown	Unknown	Granular activated carbon, physical filter (0.5 μm), UV disinfection

[a]Capacity (in mm) was calculated by dividing volume by corresponding catchment area.
[b]O: presence.
[c]X: absence.

Lee *et al.* (2012), and Farreny *et al.* (2011) are shown to have met the requirements for safe drinking water in terms of physical and chemical composition. On the other hand, other rainwater samples have exceeded World Health Organization (WHO) drinking water guidelines: Pb of Yaziz *et al.* (1989), Zn of Chang *et al.* (2004), and Al of Mendez *et al.* (2011). Although stored rainwater generally contains microorganisms, Naddeo *et al.* (2013) showed that these could be eliminated by filtration and UV sterilization. Therefore, when assessing rainwater quality, the diversity among RWH systems should be taken into account.

Many studies have been conducted to determine the origins of contaminations and to suggest management strategies (Dillaha & Zolan 1985; Pinfold *et al.* 1993; Chang *et al.* 2004; Farreny *et al.* 2011; Mendez *et al.* 2011; Gikas & Tsihrintzis 2012; Lee *et al.* 2012). However, the performance of well-designed and well-managed RWH systems that integrate the results of previous research, especially those planned for potable purposes, have not been studied much.

Two RWH systems were installed to supply drinking water to a kindergarten and primary school in a rural area in Vietnam, where safe surface water or groundwater sources are scarce. The systems were designed and managed to have potable water for pupils and teachers. The objectives of this paper were (1) to assess rainwater quality with respect to the actual performance of the RWH systems and (2) to suggest design and management guidelines for better performance.

METHODS

Study site

The study site was Cu Khe, a rural area in the Red River Delta, Vietnam. It is located 15 km southwest of Hanoi.

The average annual rainfall is 1,676 mm and over 90% of rainfall occurs from April to October (WMO 2012). During the dry season, from November to March, average monthly rainfall is less than 50 mm.

Despite the adjacency to Hanoi, Cu Khe does not benefit from a centralized water supply. The Nhue River, which flows alongside Cu Khe, is severely polluted by wastewater from Hanoi (Do *et al.* 2014). In addition, elevated arsenic levels have been found in groundwater of the Red River Delta (Berg *et al.* 2001). The tube wells of Cu Khe have the warning 'As >0.05 mg/L,' indicating that arsenic concentrations exceed the Vietnamese drinking water standard of 0.01 mg/L (QCVN 01:2009/BYT).

The kindergarten and the primary school of Cu Khe bought bottled water, priced at 0.5 USD for 19 L, to supply drinking water for the children. The kindergarten spent 1,280 USD per year to buy cooking and drinking water and the primary school spent 870 USD per year to buy drinking water. The money was imposed on students. In both schools, non-potable water is supplied using groundwater after sand-filtration. Groundwater is almost free of charge.

In July 2014, an RWH system was installed at each school to save on fees for bottled water. Both schools have painted galvanized iron roofs. A total volume of 12 m^3 storage was installed at a two-story building of the kindergarten and a total volume of 10 m^3 storage was installed at a two-story building of the primary school. Furthermore, a 150 m^2 catchment area from 450 m^2 roof area was used at the kindergarten, and a 100 m^2 catchment area from 900 m^2 roof area was used at the primary school. The kindergarten used 91.4 m^3 of rainwater for 18 months since the installation, and the primary school used 86.2 m^3 for the same period.

RWH system

The design of the RWH systems is shown in Figure 1. According to previous studies, roof materials, leaves, wild birds, and animals on roofs affect the quality of harvested rainwater (Chang *et al.* 2004). Some roof materials have an effect on heavy metal contaminants such as lead, zinc and aluminum (Yaziz *et al.* 1989; Chang *et al.* 2004; Mendez *et al.* 2011). The installed systems collect rainwater from an existing painted galvanized iron roof that is free from overhanging trees and human access. Although some studies have warned that galvanized metal roofs leach high concentrations of zinc into harvested rainwater (Huston *et al.* 2012), the use of painted galvanized metal roofs has been found to yield low concentrations of zinc (Kingett Mitchell Ltd 2003). When it comes to maintenance, though roof cleaning is a method to improve water quality, the roofs have not been cleaned since the installation, as access is difficult.

First-flush removal plays an important role in collected water quality. First flush is one of the leading causes of the degradation of harvested rainwater quality (Gikas & Tsihrintzis 2012) as it contains pollutants from the atmosphere and roof surface. Previous studies of rainwater quality from galvanized iron roofs showed that the concentration of metals, pH, total suspended solids, conductivity, turbidity, nitrate, and nitrite were significantly higher in the first flush than in the subsequent rainwater (Mendez *et al.* 2011). The volume of the first flush also plays an important role in collected water quality (Gikas & Tsihrintzis 2012). A 120-L

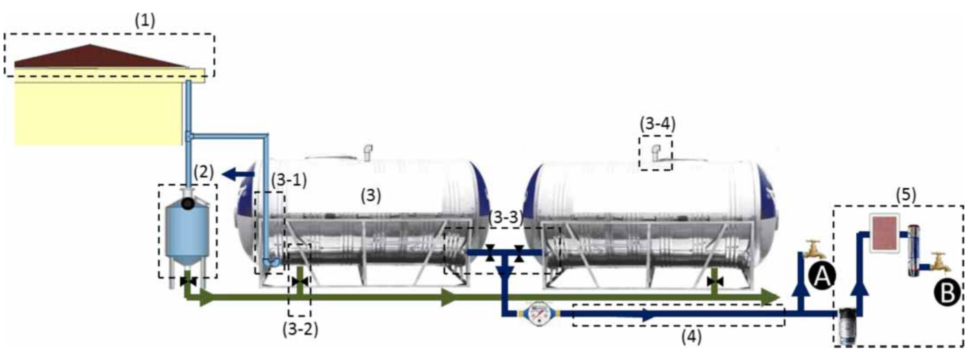

Figure 1 | Schematic diagram of a RWH system: (1) catchment area, (2) first-flush diverter, (3) storage tank in series, (3–1) calmed inlet, (3–2) drain, (3–3) outlet, (3–4) ventilation, (4) PVC pipe, (5) filter, (A) tap directly connected to storage tank, and (B) point-of-use after treatment.

first-flush diverter was installed to remove the first 0.8 mm of rainfall at the kindergarten and 1.2 mm at the primary school. A buoyancy ball inside the device blocks the inlet when the first flush fully fills the diverter, and users empty the first-flush diverter before the next rainfall.

Storage conditions also affect water quality. Stainless steel tanks certified for drinking purposes were used. The function of the storage tank is not only to store water but also to separate particles. While the tanks are filled with water, suspended solids settle to the bottom. To increase particle separation efficiency and to prevent the resuspension of sediment, a U-shaped pipe called a 'calmed inlet' was installed. Two tanks were also serially connected to retain most of the sediments in the first tank. The sediment was removed yearly by using the drain connected to the bottom of the tank. Tank lids were kept closed to block sunlight that might induce algal growth. Ventilation was installed to adjust the air volume in the tank according to the change in water level. An overflow pipe was also installed. To prevent sediment from entering the distribution pipe, the outlet connected to the tap was located approximately 10 cm above the tank bottom. All open holes to the outside were covered with wire mesh to function as a mosquito screen. Tanks should not be allowed to provide breeding sites for mosquitoes.

Tank-volume to catchment-area ratio also affects water quality. If the ratio is too small, contaminated rainfall might not be sufficiently diluted when mixing with clean rainfall later. For example, a reason for the high levels of heavy metals reported by Yaziz *et al.* (1989), Chang *et al.* (2004) and Mendez *et al.* (2011) might be the small tank volume to catchment area ratio, as shown in Table 1. In this study, the ratios of tank-volume to catchment-area (volume:area) were 80 mm for the kindergarten and 100 mm for the primary school.

PVC piping was used because the slight acidity of rainwater and the lack of buffering can make rainwater corrosive to plumbing (enHealth Council 2011). Less than 30 m of PVC pipes with an outer diameter of 110 mm were used for the inlet from the rooftop to the tank, and less than 15 m of PVC pipes with an outer diameter of 21 mm were used for the outlet connected to the point-of-use treatment system.

A point-of-use water treatment system comprises a diaphragm pressure pump (Headon, Taiwan), a 5-μm spun polypropylene progressive-density cartridge filter (Dewbell, Korea), two 1-μm spun polypropylene progressive-density cartridge filters (Dewbell, Korea), a granular activated carbon filter (Dewbell, Korea), a 0.01-μm membrane filter (Dewbell, Korea), and an ultraviolet sterilizer equipped with a 6-W UV lamp (Top Aqua, China). The flow rate of the treatment system was 0.5–0.7 L/min. Approximately 1 m of PE tubes with an outer diameter of 6 mm was used for the filter system. The distance from the point-of-use treatment system to the faucet was less than 0.3 m. The 5-μm spun polypropylene progressive-density cartridge filter was replaced every 3 months, whereas the two 1-μm spun polypropylene progressive-density cartridge filters were replaced every 6 months. The granular activated carbon filter and the 0.01-μm membrane filter were replaced annually. All the materials were available at the local market.

Water quality monitoring

Rainwater samples were collected from both the kindergarten and primary school on the same day. The samples were taken five times from a tap directly connected to the storage tank (A in Figure 1) to measure rainwater quality and four times from the other tap after treatment (B in Figure 1). Sampling at point A was carried out in August, September, October, and November 2014 and March 2015 for both systems. Sampling at point B was carried out in January, June, and November 2015 and January 2016 for both systems. A total of 18 samples were analyzed. Sterilized polyethylene bottles were used for sampling. Total dissolved solids (TDS), pH, and turbidity were measured on site with a pH meter HI 991300 (Hanna Instruments, Germany) and a turbidity meter HI 93703 (Hanna Instruments, Germany), respectively. Samples were transported to the Institute of Environmental Science and Engineering in Hanoi and analyzed. The following parameters were analyzed for each sample: hardness, nitrate, nitrite, ammonia, sulfate, hydrogen sulfide, chloride, arsenic, iron, cadmium, nickel, chromium, manganese, mercury, selenium, lead, zinc, aluminum, *Escherichia coli*, and total coliforms; these are included in Vietnamese drinking water guidelines

(VDWGs) as perceptible parameters, inorganic constituent parameters and microorganism parameters.

RESULTS AND DISCUSSION

Physicochemical qualities

Table 2 shows the results of the physicochemical water quality analysis. At the point-of-use after treatment, only pH was occasionally found not to satisfy VDWGs. Measured pH was 5.44–7.43, but had no direct impact on consumers, and health-based guidelines have not been established for pH (WHO 2011). The reason for controlling pH is to ensure the efficiency of disinfection via chlorine and to minimize the corrosion of materials in household water systems (WHO 2011). If chlorine is not used for disinfection and acid-resistant materials are used for tanks and pipelines, a pH range such as that found in this study is no longer a problem.

Measured turbidity of stored rainwater was below 1.3 FTU. Even though turbidity was below that recommended by VDWGs, turbidity before filtration might be higher during rainfall events as small particles need time for settling. Turbidity is an important indicator of the presence of contaminants and interferes with the efficiency of disinfection (WHO 2011). This was the reason for installing filtration in the RWH system.

Even without treatment, other physicochemical parameters displayed lower values than VDWGs and WHO guidelines. Since data were collected both from the kindergarten and primary school during various time intervals throughout the year, both schools satisfied the guidelines

Table 2 | Physicochemical water quality analysis results

			A (Stored rainwater)			B (Point-of-use)		
Variables	**VDWG**	**WHO**	**Min**	**Max**	**Ave**	**Min**	**Max**	**Ave**
pH	6.5–8.5	–	7.02	8.17	7.61	5.44	7.43	6.55
TDS (mg/L)	1,000	–	26	55.2	45.0	21	47.6	32.8
Turbidity (FTU)	2 (NTU)	–	0.1	1.3	0.86	0	1.63	0.45
Hardness (mgCaCO$_3$/L)	300	–	5	22	14.2	10	25	15.9
Nitrite (mg/L)	3	3	0	1.4	0.4	0.01	0.35	0.11
Nitrate (mg/L)	50	50	0.1	8.59	2.11	0.7	2.43	1.65
Ammoniac (mg/L)	3	–	0.03	0.86	0.36	0.03	0.56	0.23
Sulfate (mg/L)	250	–	<1	<1	<1	0.2	1	0.53
Hydrogen sulfide (μg/L)	50	–	20	35	29.5	30	40	32.5
Chloride (mg/L)	300	–	0.05	0.35	0.14	0.05	31	10.54
Arsenic (μg/L)	10	10	0.1	5	2.41	1	5	2.5
Iron (μg/L)	300	–	30	84	53.8	10	50	24.6
Cadmium (μg/L)	3	3	0.2	0.2	0.2	0.1	0.2	0.2
Nickel (μg/L)	20	70	<1	<1	<1	1	3.6	1.8
Chromium (μg/L)	50	50	<1	<1	<1	1	4	1.9
Manganese (μg/L)	300	400	1	21	4.9	1	35	9
Mercury (μg/L)	1	6	0.1	0.2	0.16	0.1	1	0.2
Selenium (μg/L)	10	10	1	1	1	1	4	2.1
Lead (μg/L)	10	10	1	3.4	1.46	1	2	1.5
Zinc (μg/L)	3,000	–	30	1,460	294.4	10	50	36.4
Al (μg/L)	200	200	1	100	29.76	1	18	7.1

VDWG, Vietnamese drinking water guidelines; WHO, World Health Organization; Ave, average.

regardless of season. Water quality after treatment also satisfied VDWGs, excluding pH, and was not significantly different than before treatment. Consequently, the RWH systems provided safe drinking water at the point-of-use in terms of physicochemical water quality through the year.

Microbiological quality

Table 3 shows large variation of coliform (0–78,000 MPN/100 mL) and *E. coli* concentrations (0–3,200 MPN/100 mL) in the untreated rainwater. The most significant issue in relation to the consumption of untreated roof-harvested rainwater is the potential public health risk associated with microbial pathogens (Ahmed *et al.* 2011). Sources of microorganisms are typically bird and animal feces, and dust, which are difficult to predict. Although microorganisms are generally present in rainwater, their health effects are not yet clearly explained. Epidemiological surveys in southern Australia reported that drinking untreated rainwater poses no increased risk of illness (Rodrigo *et al.* 2011). One explanation is that animal infectious microbial species only infect animals (enHealth Council 2011), and the roof environment cannot sustain human infectious species. Another explanation is that ongoing exposure to organisms in rainwater could result in increased immunity (Rodrigo *et al.* 2011). However, in general, many drinking water standards such as WHO guidelines and VDWGs require that there be no coliforms in drinking water.

The systems installed for this study included various methods to reduce microorganisms. Galvanized iron roofs are regarded as the best catchment for reducing microorganisms because of there hot temperature under sunlight (Mendez *et al.* 2011; Lee *et al.* 2012). First-flush removal can also reduce microorganisms. Additionally, putting a mosquito screen on the tanks significantly improves rainwater quality (Pinfold *et al.* 1993). Despite these efforts, there were total coliforms and *E. coli* concentrations in the untreated rainwater. There is no technology that completely removes microorganisms during the collection and storage of rainwater. In order to satisfy existing drinking water standards, post-storage filtration or disinfection systems should be installed. Filtration and UV sterilization were applied to remove microorganisms from the system. As a result, both coliforms and *E. coli* were not detected after treatment. Finally, all parameters satisfied WHO drinking water guidelines at the point-of-use. This implies that the post-treatment rainwater was safe enough to drink.

An advantage of an RWH system is the short distance from treatment to faucet. In a developing country, where communal facilities are located, some distance from the home, microbiological contamination of water between the source and point-of-use is widespread and often significant (Wright *et al.* 2004). However, since the distance from UV sterilization to faucet is less than 0.3 m in this system, safety at the faucet can be assured.

Strategy for stabilizing rainwater quality

It is anticipated that this RWH system would provide safe drinking water in other surroundings. It is difficult, however, to reproduce an identical system using the same materials, as available materials vary in different localities. Furthermore, adequate air quality cannot be guaranteed. To stabilize and generalize the results, further efforts should be conducted by government, the private sector and individuals. Recommended strategies are illustrated in Figure 2.

The government could publish guidelines for RWH systems and could organize a certification system for potable purposes regarding materials for roofing, painting, piping

Table 3 | Biological water quality analysis results

			A (Stored rainwater)			B (Point-of-use)		
Variables	**VDWG**	**WHO**	**Min**	**Max**	**Ave**	**Min**	**Max**	**Ave**
Total coliforms (MPN/100 mL)	0	0	10	78,000	9,747	0	0	0
E. coli (MPN/100 mL)	0	0	0	3,200	394	0	0	0

VDWG, Vietnamese drinking water guidelines; WHO, World Health Organization; Ave, average.

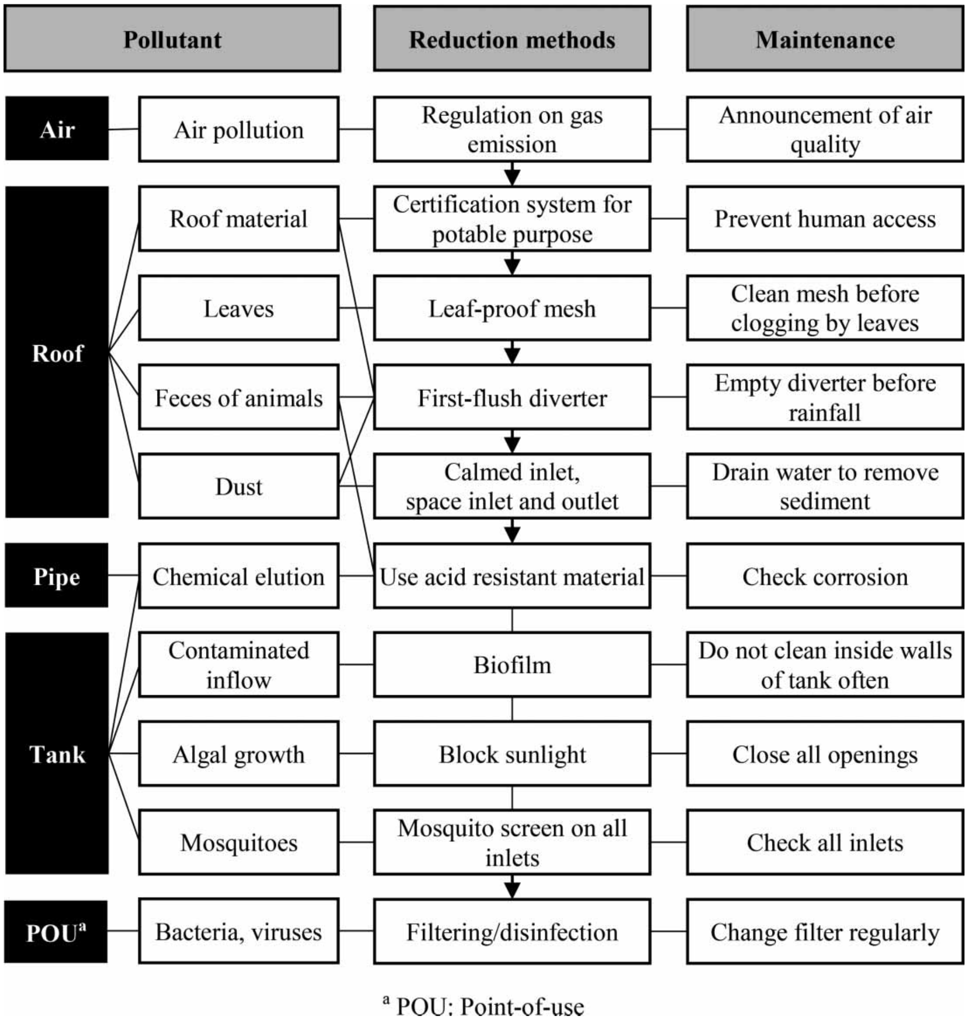

Figure 2 | Pollutant reduction and management methods.

and storing, amongst others. As the composition of each material is generally unknown to the public, it is difficult for individuals to select appropriate products. A certification system would, therefore, aid individuals in the selection process.

Regarding air quality, even if the effects of the atmosphere on rainwater quality are minor, rainwater can be contaminated in areas where air pollution levels are high. In such areas, the government could institute regulations on emissions and issue air quality warnings to citizens, as public awareness plays an important role in air pollution quality control.

The private sector could make RWH systems available for the market. Since water quality for potable purposes is a sensitive issue, guidelines should be followed thoroughly. When designing and installing RWH systems, all possible contamination sources should be considered.

The main thing that individuals can do to improve water quality is to practice proper system management. Most pollutants enter drinking water during the harvesting process. Cleaning roofs can improve microbiological parameters (Sazakli *et al.* 2007). Lead flashing/paint should be avoided since lead can leach into the water (Huston *et al.* 2012). If there are overhanging trees, leaf-proof sieves should be installed before the entrance to the first-flush tank and should be cleaned frequently to remove accumulated leaves. Accumulated leaves clog the pipelines and cause unpleasant taste, odor, and color. First-flush devices need to be emptied before rainfall events. Tanks do not require frequent cleaning as biofilm on the tank wall catches microorganisms (Kim & Han 2011). Only the sediments in the tanks need to be drained before they flow into the tap. All tank covers should be checked to ensure that they block mosquitoes and sunlight.

CONCLUSIONS

RWH systems were installed to supply drinking water to a kindergarten and primary school in an area of Vietnam where safe drinking water sources are scarce. The systems comprised painted galvanized iron roofs with a 100–150 m^2 catchment area, 120-L first-flush diverters, two stainless steel tanks connected in series with a total capacity of 10–12 m^3, calmed inlets, mosquito screens, PVC pipelines, physical filters, and UV sterilizers. The water quality of the stored rainwater and treated rainwater was analyzed. The following conclusions were drawn:

- By proper design and management, all physicochemical qualities of stored rainwater stably satisfied the WHO drinking water guidelines, and only microbiological contaminants exceeded the guidelines. As a drinking water source, rainwater has great potential since the routes of contamination are relatively clear and can be easily controlled by proper design and management.
- After treatment, rainwater satisfied all WHO drinking water guidelines at the tap. Because the distance from filter to tap is short, the possibility of contamination during distribution is unlikely. Therefore, rainwater with a point-of-use treatment system is a viable drinking water option in terms of quality, because it ensures safety at the tap.
- To generalize the results, further efforts should be made by all stakeholders including government, the private sector, and individuals. Government can devise design and operation guidelines for RWH systems since improper design and operation can make rainwater unsuitable for drinking. The private sector is a key player that could make RWH systems available for the market. Individuals can select the market products and manage their own systems by understanding the sources of contamination.

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CONFLICT OF INTEREST

The researcher claims no conflicts of interest.

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