Assessment of rainwater harvesting and maintenance practice for better drinking water quality in rural areas

Dung A. Dao, Son H. Tran, Huyen T. T. Dang, Viet-Anh Nguyen, Viet Anh Nguyen, Cuong V. Do and Mooyoung Han

ABSTRACT

In many areas of the world, rainwater has been collected and consumed by people. Our research aims to assess the use of rainwater and the impact of operation and maintenance activities of the rainwater system on drinking water quality in rural areas where there is no access to a public drinking water system. Through the questionnaire, direct visits, interviews and sampling of water at surveyed households (HHs), it was found that 100 and 98% of surveyed HHs used rainwater for drinking and cooking, respectively. Nearly, 80% of them were aware of the necessity of frequent reservoir cleaning as well as first-flush removal. Cleaning the water reservoir had a significant impact on water quality, in particular the total dissolved solids (p-value < 0.05). The use of strainers and more frequency of cleaning the catchment roofs and gutters would make the lower turbidity in water. However, the use of strainers would reduce the dissolution of oxygen in the reservoirs. A recommendation on the frequency of maintaining the rainwater harvesting systems was proposed after assessment of the operation and maintenance behaviors at surveyed HHs.

Key words | field survey, operation and maintenance, rainwater harvesting, rainwater quality, rural area

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HIGHLIGHTS

- This is the first study on assessment of the operation and maintenance of rainwater harvesting (RWH) systems at the household scale in the rural area.
- Most of them (>90%) were aware of frequent reservoir cleaning as well as eliminating the first rains.
- The majority (95%) of households did not add disinfectant in the reservoirs but boiled water or filtered with membrane units before drinking.
- Harvested rainwater showed significantly higher pH, dissolved oxygen (DO) and coliforms but much less dissolved solids than groundwater.

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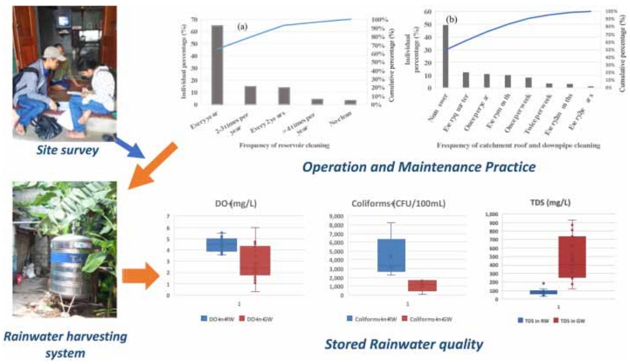
GRAPHICAL ABSTRACT



INTRODUCTION

With the increasing shortage of underground water and surface water due to human activities and climate change, rainwater harvesting (RWH) has drawn much attention as an additional water supply option for domestic and drinking purposes (Bocanegra-Martínez *et al.* 2014; Hanson & Vogel 2014). In developing countries, rainwater is considered as an important source for water for drinking and cooking in rural areas (Islam *et al.* 2010; Özdemir *et al.* 2011).

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. The Vietnam Government has paid great attention to promoting the use of rainwater in some legal frameworks such as the Decree No 80/2014/CP of the Government issued in 2014 on drainage and wastewater treatment. It encouraged the use of rainwater to meet the domestic needs, contribute to flooding reduction and minimize groundwater's exploitation. Organizations and individuals applied collection and use of rainwater are entitled to preferential loans. Still, there are many barriers in pushing this into common practice at a large scale. Thuy *et al.* (2019) rendered some solutions to 'remove the barriers' including (1) development of a sustainable rainwater management plan, considering not only technical aspect but also cost and benefit analysis, and risk assessment, (2) development of technical guidance in RWH in Vietnam, which provide instructions on rainwater collection and use and (3) provision of the incentive programs to encourage the practice of using RWH systems, in particular at a large scale.

Findings from more than 1000 papers on rainwater collection and utilization revealed that many researches focused on the technical issues and design of the RWH system (Zhu 2015; Du *et al.* 2019; Senevirathna *et al.* 2019; Zhao *et al.* 2019; Campos *et al.* 2020) or financial aspect and life cycle (Dallman *et al.* 2016; Bashar *et al.* 2018; Lani *et al.* 2018). The performance of the RWH system has also been assessed by significant studies (Cerqueira *et al.* 2014; Dobrowsky *et al.* 2017; Chubaka *et al.* 2018). Nevertheless, there has been no paper discussed about the proper operation and maintenance of the RWH systems. Only WHO (2018) recently has recommended a Sanitary Inspection form with a list of assessment questions that should be conducted frequently for RWH systems to maintain and improve the quality of water, sanitation and hygiene.

In general, the rainwater has been proved to be ineligible for direct use as drinking water due to contamination of microorganisms, heavy metals and organic matter (Lee *et al.* 2010, 2017; Tran *et al.* 2020). The insufficient hygiene of water quality could be due to ill maintenance of the collection system including catchment roofs, guts, standing pipes, first-flush tanks or storage tanks. It seems to be that the collection, treatment, storage and maintenance of the RWH systems at households' scale is mainly based on long-standing habits and lifestyles, in particular in rural areas. Previous studies rendered that different kinds of catchment roofs would affect the harvested rainwater to some certain extent (Lee et al. 2012; Tran et al. 2020). The catchment roofs can be made from different materials such as metal sheets (Fuentes-Galván et al. 2018), clay tiles, metal, and asphalt–fiberglass shingle (Keithley et al. 2018) or concrete roofs (Amin et al. 2013) or even non-toxic waterproof cloth (Islam et al. 2010). The cleaning of these roofs is different to some extent. For the guttering channels or downpipes, the most common material is plastic. The storage tanks could be varied from ferro-cement (Fuentes-Galván et al. 2018), zinc–aluminum alloy steel, polyester (Van Der Sterren et al. 2013), polyethylene high-density (PEHD) (Vialle et al. 2011) or plastic, concrete (Despins et al. 2009). Besides the basic collection and storage units, the treatment units can be as simple as just a sand filter (Zhao et al. 2019) to more comprehensive ones such as membrane (Du et al. 2019; Tran et al. 2020). In reality, most of the RWH systems at HHs scale in Vietnamese rural areas have no formal treatment units besides a strainer on top of downpipes. Given the facts that the RWH system involves quite a few collection and storage units, the maintenance of these units is indeed important as they would impact the water quality.

Therefore, the key objective of this study was to conduct the investigation on the quality of harvested rainwater and the impact of operation and maintenance (O&M) of the RWH systems on rainwater quality. The results will support the promotion of using RWH at a large scale effectively and sustainably.

MATERIALS AND METHODS

Description of studied location

The reason that Ha Nam, a northern province in Red River Delta of Vietnam, was chosen because the quality of both underground water and surface water sources has been degraded in the past 10 years. In this province, the proportion of the households (HHs) having hygienic water was only 87%, lower than that of the national average (95.7%), Red River Delta region (99.3%) and the average number in rural areas (93.7%) in 2018 (General Statistic Office of Vietnam 2018). The percentage of HHs in rural areas having clean and hygienic water should be 100% in 2020 according to the National Rural Clean Water Supply and Sanitation Strategy up to Year 2020. Thus, Ha Nam province should be readily improved this index to at least greater than the national average.

As mentioned above, the groundwater in the Red River Delta has been long claimed to be contaminated with high levels of iron and arsenic (Larsen et al. 2008). Hence, people in Ha Nam province, especially in rural areas, have had a habit of using rainwater for drinking purposes instead of groundwater for a long time. It should be noted that these areas have not yet had access to piped water.

In addition, the average precipitation in these areas was reported as high in the rainy season (i.e., from June to September) and varied unexpectedly with years (Figure 1). Furthermore, the precipitation tends to increase recently in the rainy season probably due to the impact of climate change (General Statistic Office of Vietnam 2018). It should be noted that data from Ha Nam province was not available and had to be referred to data from the meteorological station in Nam Dinh, an adjacent province.

Overall, it can be seen that the issue of polluted underground water, which is the main source for water supply at present, and the increasing precipitation have led to the potential of applying RWH system at a larger scale in the rural area with proper system design and operation.

Site survey

For the investigation of O&M of the RWH system at a HH scale and understanding the perception of people in utilization

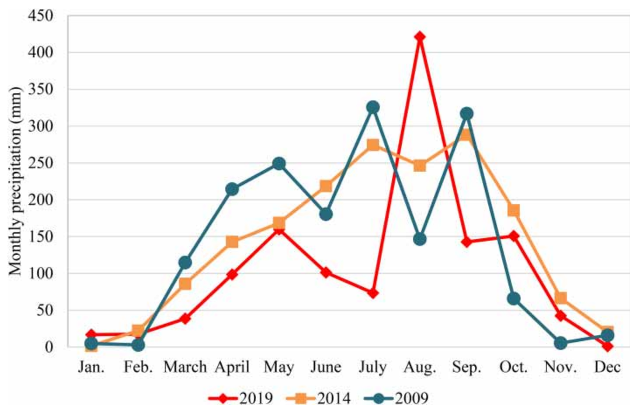


Figure 1 | The average precipitation in the studied area.

of different water sources, a comprehensive survey was conducted at Ngoc Son and Dai Cuong communes in Kim Bang rural district, Ha Nam province. They are two traditional agricultural communes, where every HH grows rice crops and raises pigs and poultry. They do not have access to tap water from the city or rural centralized water supply stations. Two main water sources are groundwater and rainwater.

The structure of questionnaires involved: (1) general information which provides evidence of ages, gender, income, job and level of education; (2) water use habits and training on water use; (3) assessment of water quality, hygienic conditions in exploitation, treatment, storage and use of water sources in HHs; (4) every aspect of using rainwater (exploitation, treatment, storage and maintenance of RWH); and (5) other recommendations. The contents were formed and designed based on a series of consultation meetings with the experts in this field and local authorities. The questionnaires were distributed to HHs individually and data were collected via in-person interview. The survey group was closely coordinated with the heads of villages in the communes, who were representatives of the villagers. Questionnaires were sent to 350 HHs in 2 communes (Ngoc Son and Dai Cuong communes) from May to December 2017. Out of these, only 234 HHs responded the full form (accounting for 5.8% of total HHs in the two communes). The remaining did not answer all questions, so they were rejected for data analysis. The number of responded HHs would render the margin of error of 6% with a confidence level of 95%. Certainly, the lower margin of error (i.e., 5%) which corresponds to 350 HHs sample size would give better representative of the population for your survey.

The distribution of samples by the HH sizes, ages of HH head, levels of education, jobs and average incomes is listed in Table 1. It can be seen from Table 1 that the sampled HHs are evenly distributed by different types of indicators. More specifically, only 3 samples (1.3%) are one-member HHs and 17 (7.3%) are large families with more than six members. Around 24% of the samples have either two or three family members, the four-person HHs share the highest percent which is about one-third of the total (33%). This result of HH size reflects quite well the data surveyed conducted via Vietnam national census, in which the average HH size was 3.8 and the majority (44%) had 4–5 members in a house (United Nations 2017). This is also the typical size

Table 1 | Distribution of samples

HH size	Number	%	Age of household head	Number	%	Level of education	Number	%	Jobs	Number	%	Average income (mil. VND/month)	Number	%
1	3	1.3	20–30	17	7.3	Primary	12	5.1	Farmer	167	71.4	Under 1	74	31.6
2	31	13.2	30–40	21	9.0	Secondary	120	51.3	Small trader	15	6.4	1–2	43	18.4
3	25	10.7	40–50	48	20.5	High school	46	19.7	State officer	20	8.5	2–3	48	20.5
4	77	32.9	50–60	90	38.5	College	14	6.0	Enterprises' staff	12	5.1	3–4	20	8.5
5	46	19.7	60 and above	58	24.8	University and above	12	5.1	Teacher	2	0.9	4 and above	46	19.7
6	35	15.0	In total	234	100	No answer	30	12.8	Worker	3	1.3	No answer	3	1.3
6 and above	17	7.3				In total	234	100	Retirer	15	6.4	In total	234	100
In total	234	100							In total	234	100			

Note: 1 USD = 23,200 VND.

for Asian families (with three to four members per HH), while smaller HH sizes (i.e., fewer than three members per HH) are concentrated in Europe and Northern America and larger HH sizes (i.e., five or more persons per HH) are observed across much of Africa and the Middle East (United Nations 2017).

Looking at the age of the head of HH, only 16% of the samples is in between 20 and 40 years old, around 20% of samples is either their 40's or 50's and 38.5% of samples in between 50's and 60's is and about 25% greater than 60 years old. The percentage of the age of head of the HH fits right in the range of 20–35% for Asian countries studied by the United Nations, lower than European countries (from 35 to 45%) and higher than African countries (15–25%) (United Nations 2017). In terms of the level of education, the majority of surveyed people only completed secondary school (51.3%), some only completed primary (12%) and a few graduated high school (19.7%). That figure is quite common in rural areas where they do not have enough motivation to study further and consider the secondary level is sufficient for a farmer.

Most of the people living in the communes are farmers, who are living based on crop cultivation and husbandry (71%), so their incomes are very low. The majority shares the average monthly income of less than 1 million VND (45 USD/month), accounting for 31.6%, followed by 2–3 mil. VND earning per month. The income of surveyed villages was quite low compared with the average income in rural areas of Vietnam in 2018 (3.0 mil VND or US$130/month) (General Statistic Office of Vietnam 2018). The low income has influenced the habit of using water to some extent which will be discussed in the next sections.

Water sampling

For water quality assessment, the samples were conducted at the same time with the survey to validate the impact of system maintenance (i.e., surveyed people's O&M) on water quality. Due to limited budget, only 23 HHs (out of 234 HHs) were randomly selected to collect samples. Water was collected from the harvested rainwater reservoirs and the groundwater's reservoirs, and then transferred to 2-L sterilized bottles for microbiological analysis (*Escherichia coli* and coliform) and 500-mL polyethylene bottles for on-site measurement. The main on-site parameters of concern were pH, total dissolved solids (TDS), dissolved oxygen (DO), temperature (T, °C) and electrical conductivity (EC). These parameters were recorded using a Multiparameter Portable Meter (HandyLab 680, SI Analytics, Germany). *E. coli* and coliform were analyzed following the 'Standard Methods for the Examination of Water and Wastewater' (APHA 2012).

Valuation of the dependent variables

The main objective of this study was to understand the behavior of surveyed HHs in O&M activities of RWH systems on the water quality. For this purpose, dependent variables were indicators of rainwater quality including pH, TDS, turbidity (Tur), EC and DO (Table 2). The accepted values were referred from the National Technical regulation (QCVN 01-1:2018/BYT) on quality of drinking water.

Valuation of the independent variables and controls

The description of the independent variables and controls is presented in Table 3. As described earlier, the main purpose of this analysis is to examine the effectiveness of O&M activities on stored rainwater quality. For instance, even though the first flush is very important, not always people remember applying it. In addition, the frequency of cleaning the rainwater reservoirs or clean the catchment roofs and guttering channels are changing sometimes. Thus, these activities would probably affect the stored water quality.

Table 2 | Description, abbreviation and valuation of dependent variables

Description	Abbreviation	Valuation
pH of the rainwater	pH	Continuous 6.5–8.0: acceptable range
Total Dissolved Solids	TDS	Continuous 0–1,000: acceptable range
Turbidity	Tur	Continuous 0–2: acceptable range
Electrical conductivity	EC	Continuous Not regulated in national standard
Dissolved Oxygen	DO	Continuous Not regulated in national standard

Table 3 | Description of the independent variables and controls

Variable	Description	Abbreviation	Valuation	Definition of valuation
Panel A: Independent variables				
	(1) Use first flush to remove the initial rainwater	OM1	1–5	1: <5 min 2: 5–10 min 3: 10–15 min 4: 15–20 min 5: 20–30 min
	(2) Use strainers	OM2	0–1	0: Use strainer 1: No use
	(3) Clean the RW reservoir	OM3	1–4	1: Every 2 years 2: Every year 3: Biannual 4: Every quarter
	(4) Clean the catchment roofs and guttering channels	OM4	1–6	1: Every year 2: Biannual 3: Every 2 months 4: Every month
Panel B: Controls				
	(1) Household size	Size	1–6	1: 1 member 2: 2 members 3: 3 members 4: 4 members 5: 5 members 6: 6 members
	(2) Age group of household head	Age	1–5	1: 20–30 years old 2: 30–40 years old 3: 40–50 years old 4: 50–60 years old 5: >60 years old
	(3) Education level	Edu	1–4	1: Primary 2: Secondary 3: High school 4: College/university

Besides the O&M behaviors, the rainwater quality could be indirectly impacted by the HH members as their awareness and activity of O&M may be different depending on their ages, education levels and jobs. For instance, young people may not be cautious or careful to take good care of the RWH system as the old ones, leading to low water quality. Thus, they are chosen as controls in the regression modeling.

Empirical model and data analysis

The multivariate regression model capturing the relationships between water quality indicators (WQIs) and the classified independent variables and controls is expressed by the given equation, where β_i is the model's constants. WQIs include pH, TDS, turbidity, EC and DO.

$$\begin{aligned} \mathrm{WQI} = \beta_0 + \beta_1 \mathrm{OM1} + \beta_2 \mathrm{OM2} + \beta_3 \mathrm{OM3} + \beta_4 \mathrm{OM4} \\ + \beta_5 \mathrm{Size} + \beta_6 \mathrm{Age} + \beta_7 \mathrm{Edu} \end{aligned} \quad (1)$$

The statistical analysis was also conducted to compare water quality of stored rainwater and stored groundwater by using paired *T*-test. Both regression and *T*-test were performed using SPSS Statistics 20 (IBM, USA) software.

RESULTS AND DISCUSSION

Rainwater utilization and maintenance

Before the evaluation of the impact of O&M activities on the water quality, it is worthwhile to understand the current rainwater utilization and maintenance in the surveyed areas. It should be noted from our survey's results that 98% of surveyed HHs (230/234 HHs) confirmed the use of rainwater frequently as the alternative water source besides underground water. The harvested rainwater was used for different purposes such as drinking, cooking, washing body, washing clothes or flushing the toilets. 100% of surveyed HHs ((234/234 HHs) reported to use harvested rainwater for cooking as it is considered safe and delivers good taste for the food. About 95% preferred using harvested rainwater for daily drinking (Figure 2). Via interviewing the residents about quality of rainwater, they claimed that rainwater offers the best taste. Making the green tea with rainwater had the better taste than one made with groundwater. The rainwater would have no unpleasant odor (i.e., iron smell) from the groundwater. For other purposes such as washing body, clothes or flushing toilet, people use groundwater. In a similar survey in the Mekong Delta region (Southern part of Vietnam), Özdemir *et al.* (2011) found that the rate of using rainwater for drinking purpose in that area was 85%, a bit lower than in the Ha Nam province which is in the Northern part. The demand of rainwater for drinking purpose would depend on many factors, one of which is the availability of piped/tap water. High percentage of using rainwater for drinking was reported from this study because the piped water was not accessible in these areas.

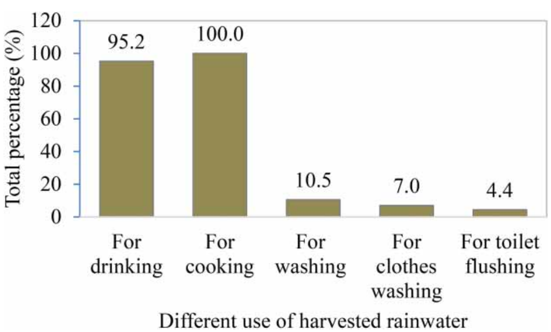


Figure 2 | Different use purposes of harvested rainwater at the surveyed HHs.

The general statistics for listed rainwater maintenance and utilization in the surveyed HHs is shown in Figure 3. Among them, 'clean the RW reservoir' achieved the highest practice ratio. More specifically, nearly 97% of the surveyed HHs cleaned their rainwater harvested reservoirs while only 6% added disinfectant into the reservoir periodically. More than 30% used strainers/filtration box prior to the storage tank. In terms of rainwater utilization, 'Boiling water' or 'Filtration with reverse osmosis filter' showed highest response (98%). That is the reason why the rate of residents having water-borne illness (i.e., cholera, diarrhea, etc.) was marginal (7.8%). Normally, four-fifths of all the illness leading to childhood death in developing countries were caused by water-borne diseases (Noosorn & Niamkamnerd 2009).

Looking into the behavior of cleaning rainwater reservoir (Figure 4(a)), most of the surveyed HHs cleaned every year (64.8%). Some HHs cleaned 2–3 times per year (15%) or some only cleaned every 2 years (13.5%). The rate of no clean at all or clean too often (>4 times per year) was very marginal (3%). Depending on the quality of the rainwater, which mainly relies on the local air quality, type of catchment roofs or maybe just the owner's cleaning habit, they decide the frequency of tank cleaning. Notably, the rainwater at the surveyed area was collected from different kinds of roofs including corrugated tiles and cement, corrugated steel sheets or concrete roofs and then stored into concrete reservoirs. Brick and concrete tanks are used quite commonly for the rainwater storage because it has a long lifespan. The users can easily climb inside the tank for cleaning the moss on the tank wall and removing settled solids at the tank bottom. Direct interviews of some farmers

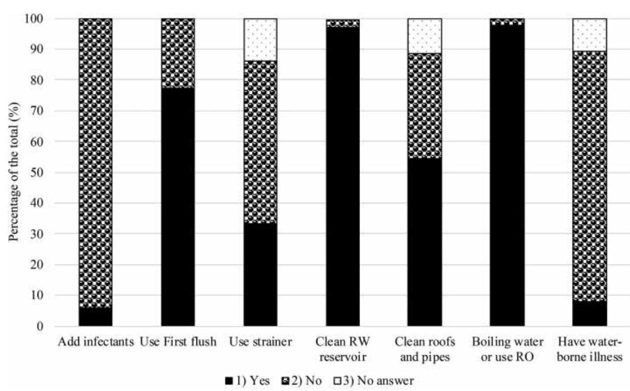


Figure 3 | Maintenance and utilization of rainwater at the surveyed HHs.

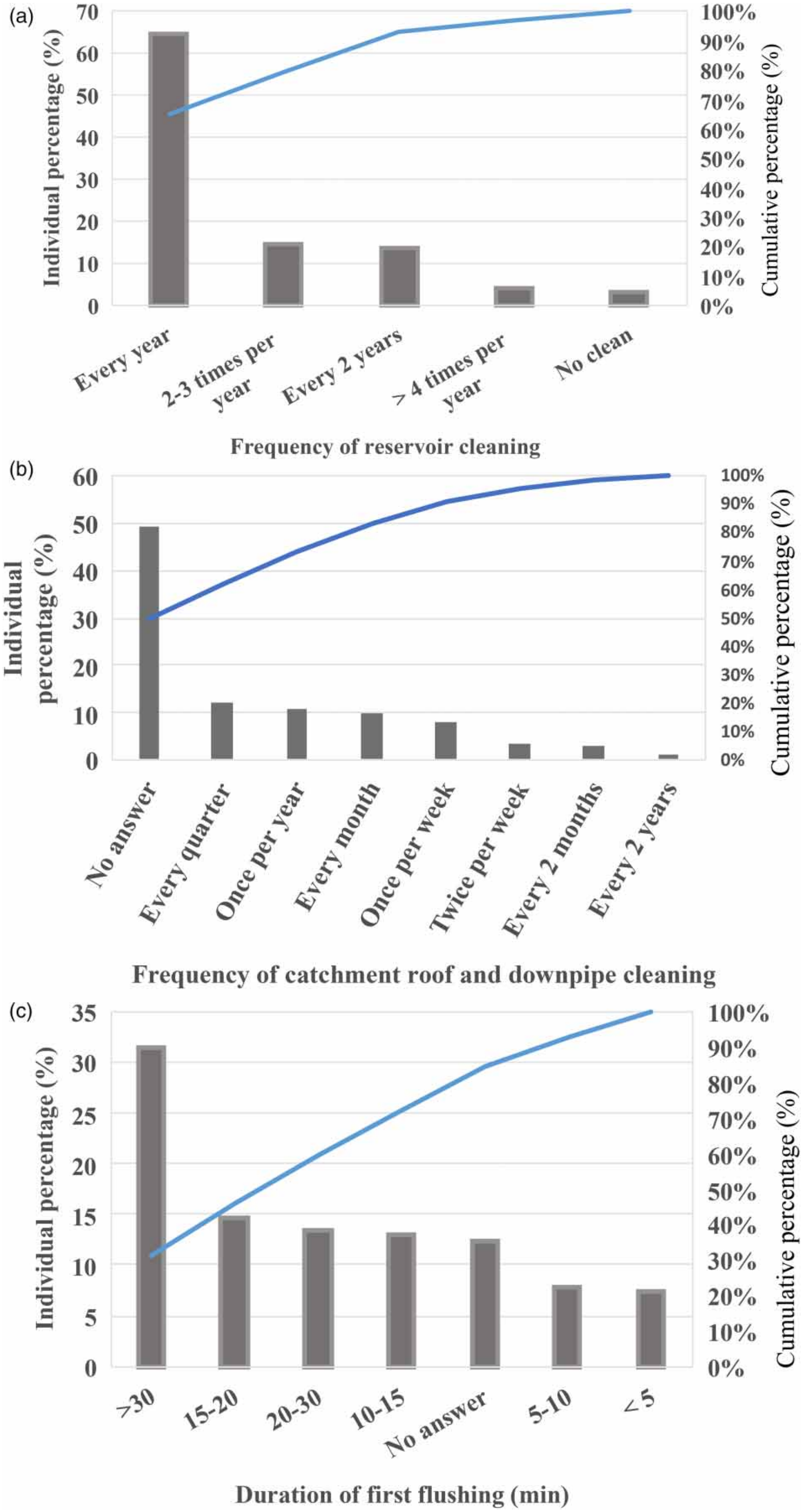


Figure 4 | Response of surveyed HHs on (a) frequency of reservoir cleaning and (b) duration of first flushing and (c) frequency of harvested roof and guttering channel cleaning.

in the surveyed area rendered that a rural HH with 4–6 members, just build a tank with a capacity of 8–12 m^3 of concrete collecting rainwater from 50 m^2 roof area and it costs about VND 5–7 million (US$220–US$300) per tank. This can provide enough water for cooking and drinking for them throughout the year. Cleaning the RWH tank has been regulated in detail in many guidelines and manuals on RWH design and operation. According to the Rainwater Harvesting Manual of Virginia (LaBranche *et al.* 2007), if a first-flush filter is not used, tanks will require yearly cleaning to remove organic debris buildup. If a first-flush filter is used, tanks will not require cleaning as the biofilm on the bottom of the tank or in the wall of the tank is reduced by frequent oxygen adding. In areas where acid rain is a problem, water pH should be tested periodically. A neutralizing agent, i.e., lime, can be added to the tank to combat pH problems. World Health Organization (WHO 2020) recommended a periodic disinfection of the tank (e.g., after long periods without rain), but not specify the exact required cleaning frequency.

For the behavior of cleaning the catchment roof and downpipes, it was found in Figure 4(b) that not many HHs had the habit of cleaning the roofs or they even did not remember doing it (50%). It seems that they rely on the first rain of the season to wash the roofs for them. This is actually a common practice everywhere in Vietnam, where RWH systems have been applied. Only a few of them clean every year (11%), every quarter (12.6%), every month (10%) or every week (8%). Up to now, there is no official guideline on utilization of rainwater as well as O&M of RWH systems properly. In 2016, the Ministry of Construction, Vietnam, cooperated with the GIZ group to publish a Manual on RWH system, in which it mentions that the HHs should check the roof every week to see if dust, debris or falling leaves are accumulated a lot or not to swept away (GIZ-MOC 2016). The Australian Guide on Rainwater Harvesting (RHAA 2018) does not recommend any cleaning frequency but suggests paying more attention to the cleaning of guttering channels if there are overhanging trees. Recent guide from WHO (2020), however, is quite general which recommends keeping the gutters clean to prevent ponding of stagnant water during short dry spells, and again, not specify the required cleaning frequency. Despite reusing rainwater for landscape irrigation only, the Rainwater Harvesting Guide for New York city (GrowNYC 2018) provides clearly the seasonal maintenance schedule for RWH systems, including: (1) clean any leaves and debris from gutters, leader inlets and rooftop in Spring; (2) check monthly the roof, gutters and leader inlets clear of debris during Summer when they collect rainwater the most; (3) drain all water from your RWH system in Fall to prevent water freezing during the Fall and Winter time.

Figure 4(c) presents the duration of first flushing that the surveyed HHs applied. More than 30% of HHs spent at least 30 min to remove the first rain, 13.5% used 20–30 min, 14.6% used 15–20 min and 13% waited for 10–15 min before collecting water. However, about 12% of the HHs did not answer the question, indicating that there are still a few HHs who did not know about the bad quality of the first rainwater. Many studies showed that the roof is often polluted with many pollutants such as atmospheric dust particles, bird droppings, leaves and other debris (Cunliffe 1998; Fewkes 2006), and these pollutants would be blended into the rainwater, causing bad water quality. In addition, a long dry period often leads to an increase in the pollutant load from the catchment roofs (Gould & Nissen-Peterson 1999). The quality of first-flush water was reported by Gikas & Tsihrintzis (2012) to be 3–12 times higher than the limit in terms of suspended solids. Therefore, the elimination of the first rainwater will help increase the quality of harvesting water. The Australian guideline recommends installing a single first-flush diverter just prior to the point of entry into the tank. The optimum capacity of a first-flush device is 20 l for a typical HH roof of at least 100 m^2 in Australia (RHAA 2018). Proper first-flush diverters are also recommended for use in Nepal to minimize dust, particles and pathogenic bacteria (Shakya & Thanju 2013).

Overall, the maintenance of RWH systems is very critical. It depends on the climate conditions (precipitation, freezing or not, etc.), surrounding air pollution (if there are nearby industrial areas or condensed vehicle transportation), legal regulation (national approved guidelines) and people awareness. Based on this survey in a rural area, it can be recommended that (1) yearly cleaning of harvested water reservoir is acceptable and doable, (2) monthly check the catchment roofs, gutters and downpipes clear of debris during the harvesting season is essential and (3) every RWH system needs to install first-flush diverter and drain it after each rain. Beyond the scope of the survey (which is not included in the questionnaires), from what we observed during the site visit, a quarterly check of filtration box/strainers and biannual check of the treatment units (if any) would be also recommended for the complete maintenance requirement of the whole RWH system.

Evaluation of harvested rainwater quality

In this part, the water quality of the stored rainwater shall be evaluated itself, and also compared with that of the filtered-and-stored groundwater as both kinds of water were used in 23 surveyed HHs. It is worth noting that nearly 80% of these HHs filtered the groundwater before storing, in which nearly 70% employed sand filters. On the contrary, only 70% of them filtered the rainwater simply with a strainer before storing because they thought it was readily clean.

Statistical analysis of two kinds of water in term of pH, TDS, turbidity, EC, DO, *E. coli* and coliforms is depicted in Figure 5. It is a graphical representation of key values (i.e., minimum, 25th percentile, median, 75th percentile and the maximum).

In comparison of the two waters, it can be seen from Figure 5 that pH and DO values in the stored rainwater are significantly higher than that in the stored groundwater, while the opposite happens for the parameters of TDS and EC. This confirms by the results of *T*-test in Table 4, where these *p*-values were less than 0.05 and *t*-values were negative for TDS and EC. The coliforms were distributed evenly from 1,000 to 2,000 CFU/100 mL in groundwater, while in rainwater, the distribution is abnormal and shifts to high values (e.g., 4,000–6,000 CFU/100 mL). Surprisingly, there is no statistical difference of turbidity in stored rainwater and groundwater (p-value > 0.05). *E. coli* is not presented in Figure 5 as it was the same averagely 60 CFU/100 mL for both waters. The possible explanation of higher pH in stored rainwater can be due to the fact that rainwater is mostly stored in concrete tank for a long period of time. The tanks are often plastered inside with Portland cement to enhance waterproofing. This kind of cement is rich in CaO, leading to the high possibility of leaching CaO into the water after a long storage time, and eventually higher pH in the water. Due to the exposure to the air, it is logical that DO in the stored rainwater can be higher and especially, the coliforms can be significantly elevated. As for the TDS and EC parameters, which both implies the dissolved and charged ions in the water, there are more dissolved ions in groundwater as the dissolution of metal ores under the ground occurs more significantly. Rainwater has only some ions which it catches on the way down to the roof and through harvesting system.

Compared with the rainwater quality in previous studies, it was found that pH in this study was higher than those reported previously (Gikas & Tsihrintzis 2012; Lee *et al.* 2012) with pH of 6–7.5. The difference was due to the tank material. They used stainless steel or plastic tanks as opposed to concrete and brick tank plastered with cement inside applied in this study. The increase of pH within the storage tank was revealed in a review of Sánchez *et al.* (2015) in which pH could be up to 9.5–10.2 in brick tanks, and to 8.7–9.8 in ferro-cement rainwater tanks. In Lee *et al.* (2012) study, they also found a much smaller number of coliforms and *E. coli* in the rainwater tank (i.e., less than 20 CFU/100 mL for each) than those in our study. It seems possibly that microbial contamination in rural areas occurs more significantly than in urban (city) areas due to the nearby farming and husbandry. The findings of turbidity, TDS and EC in this study were, however, in line with those in previous studies (Gikas & Tsihrintzis 2012; Igbinosa & Aighewi 2017).

Overall, the stored rainwater quality all meets the national standard of Vietnam for drinking water (QCVN 01-1/2018/BYT) with pH in the range of 6.5–8.0, TDS $<$ 500 mg/L, turbidity $<$ 2 FTU, except for the coliforms (should be 0 CFU/100 mL). That is the reason why people boil (98%) rainwater or filter it with reverse osmosis prior to drinking (see Figure 3). According to research by Amin *et al.* (2013), the use of sunlight can kill considerable bacteria living in water. Therefore, people use tank covers made of transparent materials such as glass or mica or arrange the tank in a sunny location so that the stored water can absorb the most sunlight. The stored groundwater has problems with not only coliforms but also the dissolved solids, thus it is often used for domestic use such as washing clothes, bodies or flushing toilets only. The overall feedback result on the quality of these two waters revealed that 41.9% of surveyed HHs found the rainwater clean, while only 19.7% of HHs agreed that groundwater was hygienic. 43% of HHs did not like the taste/odor of groundwater and 30% complained about its turbidity. In contrast, only 6.9

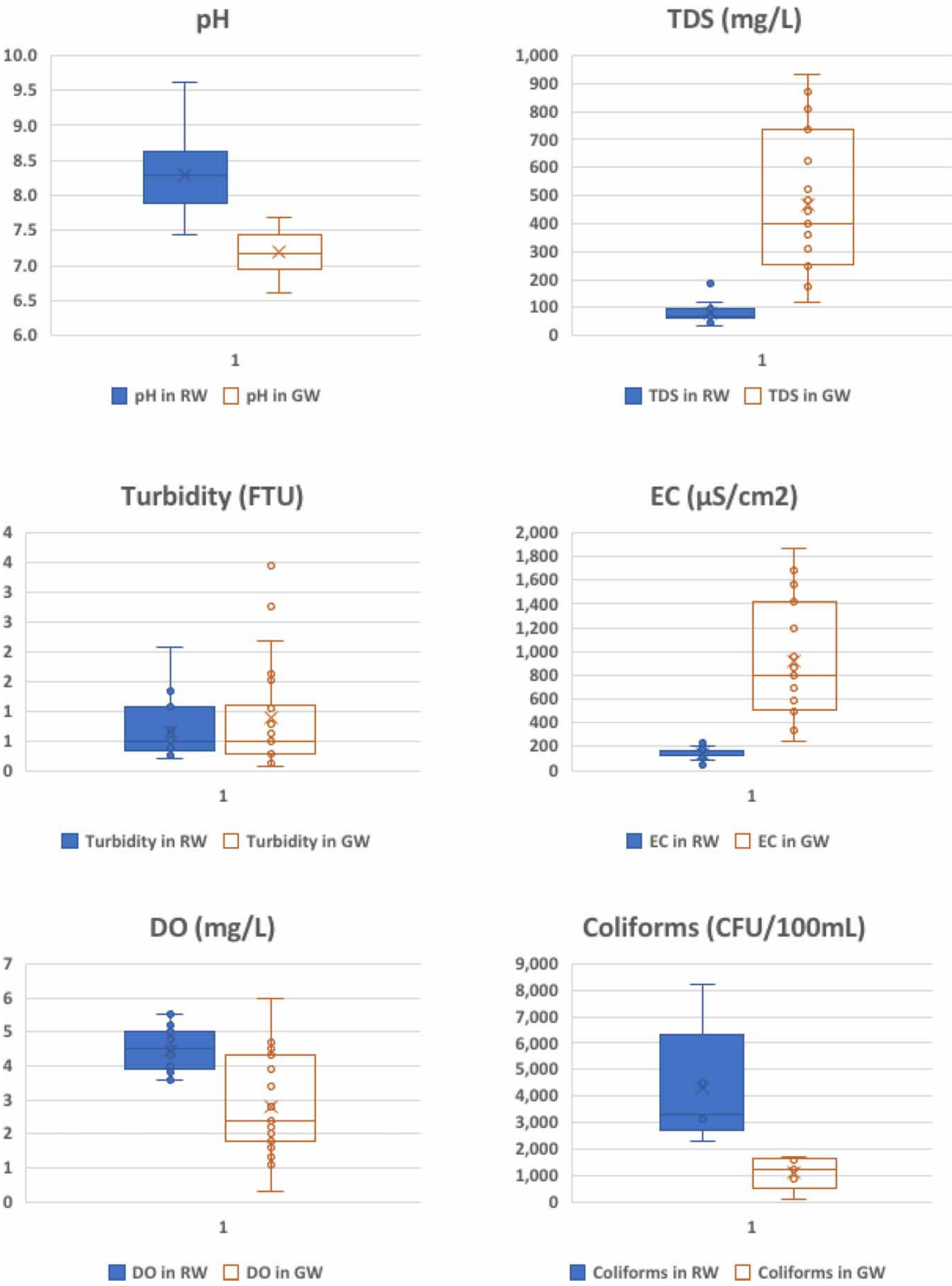


Figure 5 | Box plot graphs of some key water parameters ($n = 23$) (RW: stored rainwater, GW: stored groundwater).

Table 4 | *T*-test results from comparison of stored rainwater and stored groundwater

	t	df	*p*-value	CI
pH	8.58	22	1.81×10^{-8}*	(0.84, 1.37)
TDS	−7.16	22	3.57×10^{-7}*	(−503.3, −277.13)
Turbidity	−1.28	22	0.21	(−0.62, 0.15)
EC	−7.51	22	1.66×10^{-7}*	(−991.77, −562.56)
DO	5.25	22	2.90×10^{-5}*	(1.00, 2.32)

*p-value < 0.05.

and 2.7% of surveyed HHs were not satisfactory with the taste/odor and its turbidity, respectively.

Statistical analysis of the impact of O&M behavior on harvested rainwater quality

The results of multivariate regressions to identify whether the O&M of RWH system is effective for obtaining good stored rainwater quality are presented in Table 5. It is interesting to find out that most of the water quality are not impacted by the O&M activities. One exception is TDS with an estimated regression equation:

$$\text{TDS} = 59.616 + 3.688\cdot\text{OM1} + 14.496\cdot\text{OM2} + \mathbf{26.094}\cdot\text{OM3} + 6.276\cdot\text{OM4} - 6.855\cdot\text{Size} - 4.2\cdot\text{Age} - \mathbf{17.069}\cdot\text{Edu}$$

From this equation, one can see that OM3 (clean the RW reservoir) indicates as a positive and statistically significant relationship (0.1% significant level) on TDS. This means that the more often the RW reservoirs are cleaned, the lower solids can be found in the tanks. Even though, no statistically significant impact was shown for turbidity or DO, it was found that OM2 (use strainers) or OM4 (clean the catchment roofs and guttering pipes) had a negative impact on turbidity. This finding is logical in a way that the use of strainer and more frequency of cleaning the catchment roofs and gutters would make the lower turbidity in water. Moreover, the use of strainers also hinders the dissolution of oxygen in the reservoirs (negative relation). In addition, TDS was found to be negatively and significantly impacted by the users' education level as a control (5% significant level). This indicates that people who got higher knowledge seem to neglect more often the labor work. More study on the impact of the controls on the water quality should be conducted in the future.

Interestingly, it was found that the intercept coefficients of pH, EC and DO were quite significant at 0.01, 5 and 5%, respectively (see Table 5). That meant the bases of pH, EC and DO parameters were 8.5, 114.1 and 4.2, respectively. Indeed those were intrinsic values of pH, EC and DO regardless of any changes in the conditions of O&M for the harvested rainwater in this survey area.

CONCLUSIONS

A complex survey and water sampling in the rural province revealed that the HHs used groundwater for domestic

Table 5 | Regression results with water quality indicators as dependent variables (N = 23)

	pH		TDS		Turbidity		EC		DO	
Variable	Estimate	S.E	Estimate	S.E	Estimate	S.E	Estimate	S.E	Estimate	S.E
Intercept	8.494***	0.632	59.616	38.437	0.834	0.779	114.116.	61.796	4.221.	1.056
OM1	−0.039	0.073	3.688	4.413	0.083	0.089	−6.412	7.094	−0.095	0.121
OM2	0.302	0.236	14.496	14.333	−0.051	0.290	31.428	23.044	0.254	0.394
OM3	−0.174	0.129	26.094**	7.835	0.030	0.159	13.788	12.597	0.141	0.215
OM4	0.021	0.076	6.276	4.596	−0.024	0.093	6.001	7.390	0.095	0.126
Size	0.122	0.094	−6.855	5.739	−0.061	0.116	−9.797	9.228	−0.073	0.158
Age	0.047	0.083	−4.200	5.048	0.020	0.102	−0.358	8.116	0.060	0.139
Edu	−0.060	0.134	−17.069 .	8.146	−0.119	0.165	0.367	13.097	0.045	0.224
Multiple R^2	0.5937	0.522	0.1505	0.3267			0.1204			

Note: S.E: Significant effect; *** Significant at all level; ** Significant at 0.1% level; * Significant at 1% level; . Significant at 5% level.

purposes while employed rainwater for drinking and cooking.

The majority (95%) of HHs did not add disinfectant in the reservoirs but boil water or filter with reverse osmosis unit before drinking, so the rate of having water-borne illness is low (about 8%). The surveyed HHs had good behavior of frequent cleaning of the reservoirs (97%) but did not pay much attention to cleaning the catchment roofs and guttering pipes. Statistical analysis showed that only 'cleaning the reservoirs' activity had a significant relationship with dissolved solids in the reservoirs. The study also revealed that use of strainer and more frequency of cleaning the catchment roofs and gutters would make the lower turbidity in water. However, the use of strainers would reduce the dissolution of oxygen in the reservoirs.

The stored rainwater has better quality in terms of TDS and DO than those of groundwater, but both rainwater and groundwater are contaminated with microorganisms. They need to be boiled or disinfected before drinking.

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DATA AVAILABILITY STATEMENT

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

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