Status of water use and potential of rainwater harvesting for replacing centralized supply system in remote mountainous areas: a case study

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Abstract

The failure of the centralized water supply system forced XY community to become more dependent on uncertain and unstable water sources. The results of surveying 50 households showed that 89.18% of total households depended on water collected from rivers, which contributed 58.3% of the total water volume used for the domestic demands. The average water volume consumed was 19.5 liters/person/day (l/p/d), and 86.5% of households used more than one source; 13.5% of households collected water only from rivers, and 45.94% of families had rainwater harvesting (RWH) for their activities (domestic water demand); however, RWH only provided 9.9% of total water consumption. In this study, basic methods were applied to calculate the storage tanks necessary to balance the water deficit created by drought months. Three levels of water demand (14, 20, and 30 l/p/d) can be the best choices for RWH; for a higher demand (40 and 60 l/p/d), small roof area (30–40 m^2), and many people (six to seven) per family, RWH might be impractical because of unsuitable rainfall or excessively large storage tanks.

Keywords Rainwater harvesting · Domestic consumption · Remote area · Optimal tank · Water sources

Highlights

- The status of current water use in remote mountainous areas is defined.
- The average water volume consumed was 19.5 liters/person/day
- 45.94% families had rainwater harvesting, but it provided only 9.9% of total demand
- The quality of the rainwater tested was suitable for drinking purposes.
- A rainwater-harvesting system was designed with different scenarios and variations.

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Introduction

Most modern societies have easy access to centralized water supply systems that are safe, sanitary, convenient, and readily available. However, many rural areas worldwide still have limited access to clean water sources, meaning that traditional water resources such as groundwater, surface water, and rainwater are still primarily being used in daily activities (Kirs et al. 2017). Therefore, rainwater harvesting (RWH) is gaining more attention as a method of promoting significant water savings in different nations (Behzadian et al. 2018; Campisano et al. 2017; Gado and El-Agha 2019; Lúcio et al. 2020) and as a promising alternative water source for domestic demands in areas that suffer from water shortage and/or contaminated water sources (Assayed et al. 2013; Fernandes et al. 2015; Islam et al. 2010; Nguyen and Han 2017). Thus, RWH is considered a decentralized water supply source that is being encouraged in many rural areas (Aladenola and Adeboye 2010; Karim et al. 2015b) or even in humid and well-developed regions (Tamaddun et al. 2018; Ward et al. 2010). In addition, with rational RWH, local communities will have easy access a plentiful source of drinking water at a very low health risk (Mahmoud et al. 2014; Tran et al. 2020; WWAP 2015).

Currently, many remote and rural areas in central Vietnam are using a combination of water sources (centralized and decentralized water sources) for domestic use. However, in recent years, the centralized water supply system has often been unstable because of an insufficient capacity for service and because of technical problems, such as water quality, as well as breakage and/or blockage of pipelines. Moreover, prolonged drought (UNDP 2016) and groundwater and surface-water contamination (patho- gens, nutrients, alum, salinity, chemicals, heavy metals, etc.) (Chau et al. 2018; Le Luu 2019; Lee et al. 2017) resulting from human activities, climate change, and glob- al warming (Nguyen et al. 2020; Nguyen et al. 2019; Schmidt-Thome et al. 2015; Thriveni et al. 2017) threaten to cause serious shortages of clean water and less-sanitary water sources in these areas.

For these reasons, rainwater is one of the most promising alternatives for overcoming water shortages in such areas. In addition, using rainwater can be safer and more economical/efficient than using other water supply sources (Lee et al. 2017; Lopes et al. 2017; Nguyen et al. 2013; Norman and Amilcare 2016; Rahman et al. 2012). Although rainwater has long been used in these areas, its present form is no longer suit- able for safety, hygiene, and year-long service (capacity) through the dry season and low rainfall periods consid- ering collection methods, collection and storage systems, and local rainfall patterns/intensities.

Methods previously introduced to determine RWH include the statistic method (Guo and Baetz 2007), water balance model (Karim et al. 2015a; Rahman et al. 2014), non-dimensional design (Palla et al. 2011), behavioral approaches (Fewkes and Butler 2000; Liaw and Tsai 2004), the "detailed approach" based on daily simulation (Santos and Taveira-Pinto 2013), the rainwater analysis and simulation program model (Sample and Liu 2014), the linear approach (Okoye et al. 2015; Palla et al. 2012), analytical expression (Pelak and Porporato 2016), and web-geo applications (Fonsecaa et al. 2017). The sizing approaches were based on a specific period of the year when the water demand was fully met in comparison with the yearly, monthly, or daily rainfall pattern.

All of these—except the water balance method—are relatively complex, depend on numerical optimization, and have subjective parameters that are difficult to apply in practice. Also, in a study on the sociotechnical theory and practice of RWH in UN, Pelak and Porporato (2016) found that the complicated tools were rarely utilized by even UK nonacademic stakeholders. Much research in recent years has concentrated on applying RWH to support or save centralized water supply systems in terms of potable water, irrigation, washing, and toilet flushing (Fonsecaa et al. 2017; Imteaz et al. 2012; Ward et al. 2010). There have been, however, few investigations that focused on how the RWH system can meet all household water demand, especially in remote mountain areas.

The aim of this study was to identify and clarify the status of current water uses and assess the potential of RWH to meet the demands of local people by various scenarios of water use. This work should provide a better understanding of the components of the hydrological cy- cle. The current and expected levels of water consumption were investigated, and then data on the rainfall were ob- tained. The calculation method proposed is a practical tool that is easy to apply at the local level.

Materials and methods

Study area and precipitation data

The study area is located in XY commune, Huong Hoa district, Quang Tri province, Vietnam. It is ~ 36 km from the center of the district (16° 26′ 42.8″ N, 106° 44′ 26.3″ E) (Fig. 1a). XY is an ethnic minority community that has 2013 people and 355 households. This region is heavily affected by the dry and hot southwest wind, with rainy (from July to November) and dry (from December to June) seasons. The terrain covers predominantly hills and is divided by mountains and narrow valleys.

Water usage was investigated by interviewing the local people for household samples. The sample size of this study was 50

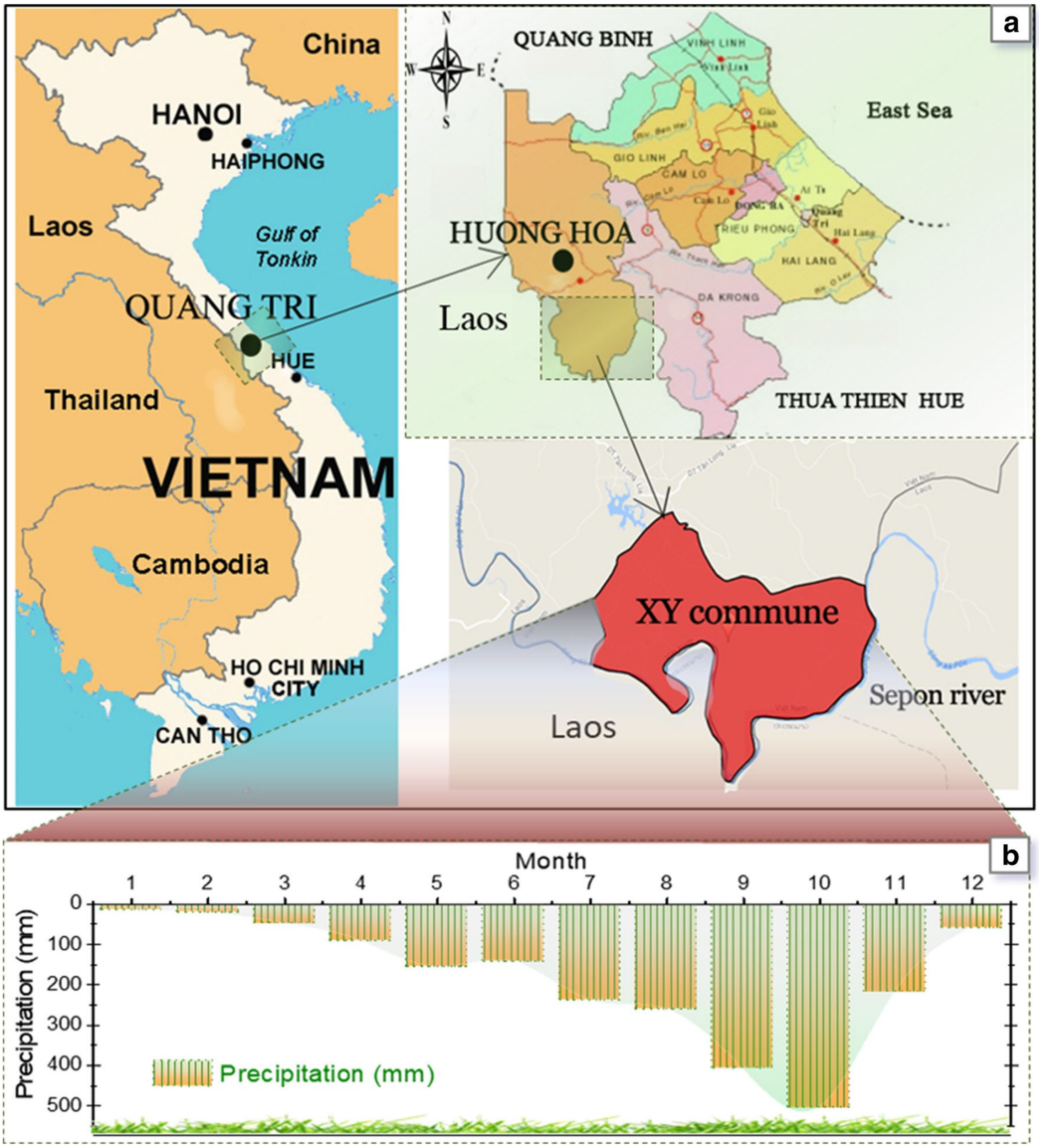

Fig. 1 a Map and geographic location of the site of the investigation carried out in the case study area in Vietnam and b its average monthly rainfall

households. Households were chosen randomly from six villages, and the house owners were interviewed via questionnaire. For the volume of water usage, in some cases, it was necessary to redefine the real volume of containers, because local people only provided the number of different buckets used.

Rainfall data were collected at Huong Hoa Meteorological Station. The data were recorded for 10 years from 1993 to 2013 (Fig. 1b), and XY commune is 8 km from Huong Hoa Meteorological Station. The average rainfall was 225 mm/month. The extreme drought months were from January to March: the data were one-tenth to one-fifth of the average value of 12 months (180.6 mm). The rainy season reached a peak of 505 mm in October (Fig. 1b).

Rainwater quality analysis

Rainwater samples were taken from different houses in XY commune in October, November, and December of 2017, during which there was good material for the collection system. Rainwater was collected directly from gutters after a 15–20-min rain period. Nine rainwater samples were taken during the 3 months for analyzing water quality parameters. Turbidity, hardness, total dissolved solids (TDS), NH_4–N, *Escherichia coli* (*E. coli)*, and NO_3–N of the rainwater samples were analyzed according to the standard methods of 2130B, 2340C, 2540C, 4500-NH_3C, 9222G, 4500-NO_3^-E, respectively (APHA/WEF/AWWA 1995). In addition, pH was measured by a multi-parameter water quality meter (HQ40D; Hach, USA).

Determination of RWH system

In the RWH system, the storage tank has been reported to be the most costly investment (Fernandes et al. 2015; Santos and Taveira-Pinto 2013); therefore, the ideal dimensions are crucial for the efficiency and feasibility of the system. Because of the assumption that the water demand corresponding to the scenarios is a constant and monthly average precipitation data are available, the ripple method or mass balance was used for sizing the storage volume, as mentioned in previous reports (Fernandes et al. 2015; Matos et al. 2013; Santos and Taveira-Pinto 2013; Ward et al. 2010). In the present study, the calculated storage capacities required balancing the deficit during the critical drought months by using the excess water in the rainy season.

To facilitate for calculation of the storage tank volume, a Microsoft Excel spreadsheet calculator was developed and used in this work. In this spreadsheet, the data were organized in columns. Column C_1 is monthly data, C_2 is the monthly rainfall (i, mm, Fig. 2b), C_3 is the roof area (A, m^2), C_4 is the runoff volume (Q_v, m^3), C_5 is the water demand for each household (D_m, m^3), C_6 is the water balance (deficit or excess, m^3), and C_7 is storage tank volume (S_t, m^3, Table 4).

The result of C4 was calculated by the rational method with $C = 0.9$ (Lancaster 2006), using Equation (1), as described by Wilson (1990).

$$Q_v = C \times i \times A \tag{1}$$

Here, Q_v is the runoff volume (m^3), C is the runoff coefficient, i is the rainfall (mm), and A is the catchment area (m^2).

Column C_6 of the Excel spreadsheet is the results of Equation (3), in which monthly water demand per household is defined as the scenarios in Table 3 and Equation (2). The value of $C_6 < 0$ means the water balance is deficit, and $C > 0$ is excess.

Value C_7 is the sum of monthly water demand for each household, the sum of the deficit (absolute value), and monthly reserve water volume, and it is described in Equation (4).

$$D_m = K.N.30 \tag{2}$$

$$D_f = D_m - Q_v, if D_f < 0 \tag{3}$$

$$S_t = D_m + \sum|D_f| + R_s \tag{4}$$

Results and discussion

Status of the current water sources and consumption

The results of the water sources used by 50 households are presented in Table 1. The main water sources for XY are clearly natural, among which the Sepon River contributed to 89.18% of total households and other small streams supplied 58.3% of the total water used. Among families, 78.37% consumed water from wells, which contributed nearly one-third of total water used (31.8%). Although 45.94% of local households had RWH, it provided only 9.9% of the total water consumed. RWH was rudimentary, with small tanks from 0.3 to 1.0 m^2, and the collecting gutters were made from bamboo or reusable sheet metal bending without any sanitary protective coating (Fig. 2). Most households (86.5%) accumulated water from more than one source (wells, RWH, and river, lake, and streams), with 13.5% of households depending on one source (river and streams) for their domestic water use. Due to the disruption of centralized water supply system, the public wells provided nearly one third of water consumption. However, water from wells contain high concentration of iron, calcium and magnesium (hardness minerals) and thus need to be settled before using. Furthermore, wells cost a lot of money to build because of their deep groundwater levels and under layers of hard rock. For the water sources from surface water (e.g., rivers and streams), although this water quality is not currently contaminated by industrial pollution sources or

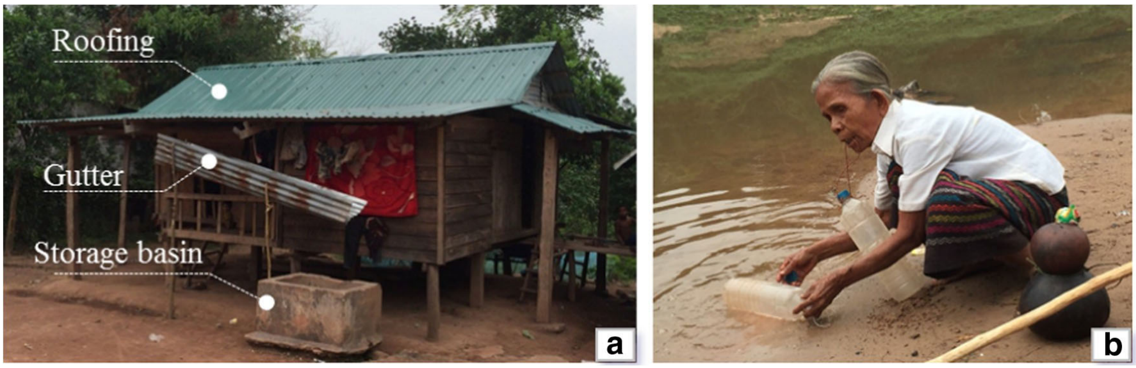

Fig. 2 a Roof and collection materials for RWH and b local person collecting water from the river

Table 1 Water supply sources for households in XY commune

Water sources	Percentage of households that used each source	Percentage of total water consumption	Percentage of households using one source	Percentage of using greater than or equal to two sources
Centralized system	0	0	13.5	86.5
Wells at home	21.62	12.3		
Public wells	56.75	19.5		
Rivers and streams	89.18	58.3		
Rainwater harvesting	45.94	9.9		

high-density urban areas, the water shortage in the dry season as well as high turbidity in the flood event is serious.

Of roof catchments, 73% were made (concatenated) from corrugated sheet steel, and the others were asbestos cement roof shingles (27%). The material of roof catchments partly effects to the quality of rainfall. It can dissolve metals and other impurities from roof materials and storage tank, leading to bad taste and odor in the harvested water (Sánchez et al. 2015). In a study on rainwater quality from different roof materials, authors concluded that asbestos roof had the highest values for some water quality parameters (e.g., pH, total hardness, and copper) as compared to roofs of aluminum, concrete, and corrugated plastic, but all these parameters were met the water quality standard except for coliform (Olaoye and Olatunji Sunday 2012). Mendez et al. (2011) reported that rainwater harvested from roofs of metal, concrete tile, and cool had lower concentrations of fecal indicator bacteria as compared to other roofing materials. In addition, Lee et al. (2012) indicated that galvanized steel is the best roof material for harvesting rainwater as the combination of effect of ultraviolet light and the high temperature could effectively disinfect the harvested rainwater.

Other results of this survey showed that the average area of the roof surfaces of 50 households was 59.5 ± 23.4 m^2 (30–108 m^2) and members per household was 5.0 ± 1.38 (3–7 members). The purposes of XY domestic water included drinking, food preparation, bathing, and washing clothes and dishes. However, 60% of households washed their clothes in the river, which was outside of the total accounted for water volume. The result of the field investigation also shows that the average volume of water consumed was 19.5 l/p/d. This value is much lower than the daily water requirement for each person (80 l/p/d) referenced by Lancaster (2006). It is approximately the "basis" demand (suggested by the World Health Organization for drinking and personal hygiene) (Wilson 1990), and it is one-half of the current average water usage per person of Vietnam (Assayed et al. 2013). The volume of domestic water consumption for each household was relative low because of living habits, and some activities of households happening at the river or public wells (e.g., washing clothes). They are mountainous people who are accustomed to a way of life that consumes less water for daily life. In addition, local inhabitants did not own much water-consuming equipment in their homes.

Rainwater quality

The analytic results of rainwater samples are presented in Table 2. The quality of the rainwater in XY was high. Almost parameters met the Vietnamese national standards for drinking and domestic water quality. Only one rainwater sample with max turbidity was slightly higher than that of drinking water quality regulation (QCVN 01:2009/BYT). Bacteria of the group *E. coli* did not appear in a 100-ml sample of rainwater. Although the quality of the rainwater from the samples is satisfied for drinking, a suitable clarifier or sand filter may be necessary for the health and safety. A storage tank with a space large enough and boil water before using also can enhance the safety for health community.

Water demand and storage tank

From the results of this investigation of water usage in XY, five water consumption scenarios were planned based on current and prospective demands (Tables 3 and 4). Scenario 1 was 14 l/p/d, which was derived from the current consumption in XY after eliminating the contribution of wells (which accounted for 31.8% of the water used). It means that the calculated water of scenario 1 (68.2% of the current consumption) plus the water from the wells will fulfill the current water consumption. Scenario 2 was 20 l/p/d, considered the current water use that local inhabitants do not need the water of public wells. Scenarios 3 and 4 were 30 and 40 l/p/d, respectively, for the average requirement as referenced in the current water usage in Vietnam. Scenario 5 was 60 l/p/d for the proposed standard of Vietnam as considered in replacing the centralized water supply system (WWAP 2015).

Table 2 Physicochemical properties of rainwater in XY

Parameter	Unit	Min.	Max.	Aver.	Vietnamese guidelines	
					QCVN 01:2009/BYT*	QCVN 02:2009/BYT**
pH		6.8	7.7	7.3	6.5–8.5	6.0–8.5
Turbidity	NTU	0.4	2.1	0.8	2	5
Hardness	mg/l $CaCO_3$	40	154	87	300	NA
TDS	mg/l	20	324	157	1000	NA
Permanganate	mg/l	0.6	1.6	1.1	2	4
NO_3-N	mg/l	0.7	4.4	2.5	50	NA
NH_4-N	mg/l	0.02	0.2	0.09	3	3
E. coli	CFU/100 ml	0	0	0	0	20

*Vietnam's national technical regulation on drinking water quality

**Vietnam's national technical regulation on domestic water quality

NA not available

To review the general potential of RWH in XY commune, the storage tank volume was calculated for the average inputs. For this purpose, averages of five people per household (N) and roof area (A) of 60 m^2 were used. These results are presented in Tables 3 and 4.

With water demand of 14 l/p/d for 5 people and an average roof area of 60 m^2, there was no month with a deficit of rainwater in Scenario 1, while the number of deficit months in other scenarios ascends from Scenario 2 to Scenario 5 (Tables 3 and 4). The largest rainwater volume overflowed the storage tank in October. In general, the dimensions of the storage tanks in Scenarios 4 and 5 are quite large, exceeding the planned water demand and the volume of the storage reservoirs in Scenarios 1–3 many times. The rising water demand led to an increase of deficit months and caused the larger storage tank volume. World Bank (2015) stated that the optimal size of a storage tank is based on cost minimization; therefore, Scenario 1 might be the best choice. However, with that scenario, local people also have to collect water from unstable sources, such as wells and rivers. In general, Scenarios 1–3 might be the best decisions for applying RWH in XY commune.

The average storage tank calculation based on average inputs (roof area and members) provides only an overall picture

Table 3 Runoff volume (Q_v) and water balance with scenarios (average roof area = 60 m^2)

Month	Average rainfall (i) (mm/month)	Runoff Volume (Q_v) (m^3/month)	Scenario 1 (14 l/p/d) Water balance ($E_x > 0$, $D_f < 0$) (m^3/month)	Scenario 2 (20 l/p/d) Water balance ($E_x > 0$, $D_f < 0$) (m^3/month)	Scenario 3 (30 l/p/d) Water balance ($E_x > 0$, $D_f < 0$) (m^3/month)	Scenario 4 (40 l/p/d) Water balance ($E_x > 0$, $D_f < 0$) (m^3/month)	Scenario 5 (60 l/p/d) Water balance ($E_x > 0$, $D_f < 0$) (m^3/month)
January	83.6	4.5	2.4	1.5	0.0	− 1.5	− 4.5
February	61.7	3.3	1.2	0.3	− 1.2	− 2.7	− 5.7
March	47.8	2.6	0.5	− 0.4	− 1.9	− 3.4	− 6.4
April	97.8	5.3	3.2	2.3	0.8	− 0.7	− 3.7
May	191.5	10.3	8.2	7.3	5.8	4.3	1.3
June	171.7	9.3	7.2	6.3	4.8	3.3	0.3
July	148.9	8.0	5.9	5.0	3.5	2.0	− 1.0
August	219.1	11.8	9.7	8.8	7.3	5.8	2.8
September	585.8	31.6	29.5	28.6	27.1	25.6	22.6
October	778	42.0	39.9	39.0	37.5	36.0	33.0
November	227.7	12.3	10.2	9.3	7.8	6.3	3.3
December	95.7	5.2	3.1	2.2	0.7	− 0.8	− 3.8
$\sum \lvert D_f \rvert$			0.0	0.4	3.1	9.1	25.1

Table 4 Demand (D_m) and storage tank volume (S_t) with scenarios (average roof area = 60 m^2)

Values	Scenarios				
	1	2	3	4	5
Average water demand (m^3/household/month)	2.1	3	4.5	6	9
Average storage tank volume (m^3)	2.3	3.8	8.4	16.8	37.9
Construction cost of storage tank (US$)	115	217.9	443.8	763.2	1464.3

of the potential of RWH. The practical volume of a storage tank can vary widely according to various roof areas and the numbers of people in households. Therefore, the volume of the storage tanks was determined in detail for a range of the roof areas and numbers of people for each scenario. These results are shown in Figs. 3, 4, 5, 6, and 7.

Figure 3 shows that, with three to five members, each household consumes 14 l/p/d. The volume of the tanks is 1.4–3.7 m^3, indicating that Scenario 1 is feasible for any roof area. With a roof area of 70–110 m^2, the volume of storage tanks ranges from 1.4–3.2 m^3, suggesting that the RWH of these roofs easily meets the water demand of 14 l/p/d, regardless of how many people are in the household. Also, households with seven people with a roof area of 30–40 m^2 or six people with a roof area of 30 m^2 need quite a large storage tank volume (> 5.3 m^3).

Scenario 2 might be practical for households that have roof areas of 90–110 m^2 or three to five people. In that case, the storage tanks require a range of 2.0–5.6 m^3. In contrast, for families with a smaller roof area (30–40 m^2) or more than six people, RWH is impractical (Fig. 4). For a demand of 30 l/p/d, households with small roof areas (30–60 m^2) and more people (five to seven) need quite a large storage tank volume (Fig. 5).

When the projected water demand is 40 l/p/d, families with 30 m^2 of roof area or six to seven people need more than 12 m^3 of storage tank area, which is impractical for the people in XY commune (Fig. 6). Similarly, in Scenario 5, most cases require storage tanks with large volumes (> 10 m^3), except for households with three people and more than 70 m^2 of roof area (Fig. 7).

Based on the lifespan and real conditions, storage tanks constructed of bricks and concrete are appropriate for stilt houses. With the cost of materials fixed in 2017 and tank lifespan expected to be 15 years, a linear model of the tank cost was established. The cost of the storage tank is given by Equation (5) and calculated by combining with Figs. 3, 4, 5, 6, and 7. The real cost for a storage tank or RWH system was different for each household due to the number of members, the real roof area and planned water consumption (i.e., Scenario). For example, a household with 5 members for Scenario 2 needs 5.6 m^3 of storage tank and 90–110 m^2 of roof will cost US$ 310.28 while cost for Scenario 4 (10 m^2 of

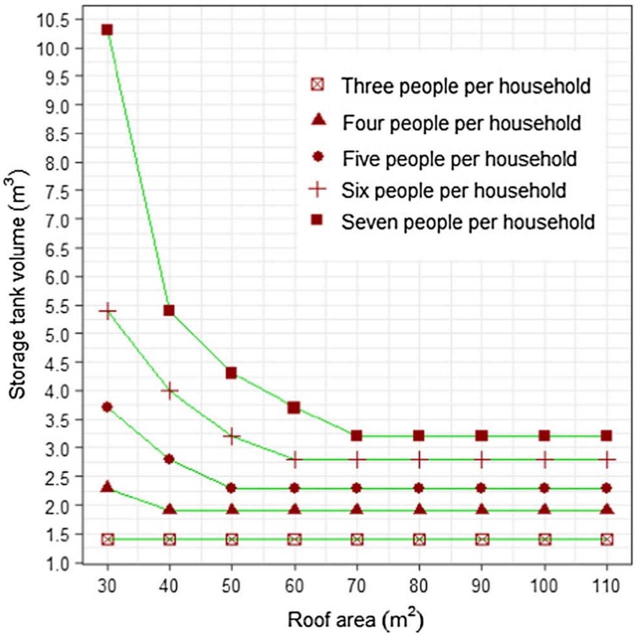

Fig. 3 Storage tank volume regarding the roof area and the number of people of Scenario 1 (water demand = 14 l/p/d)

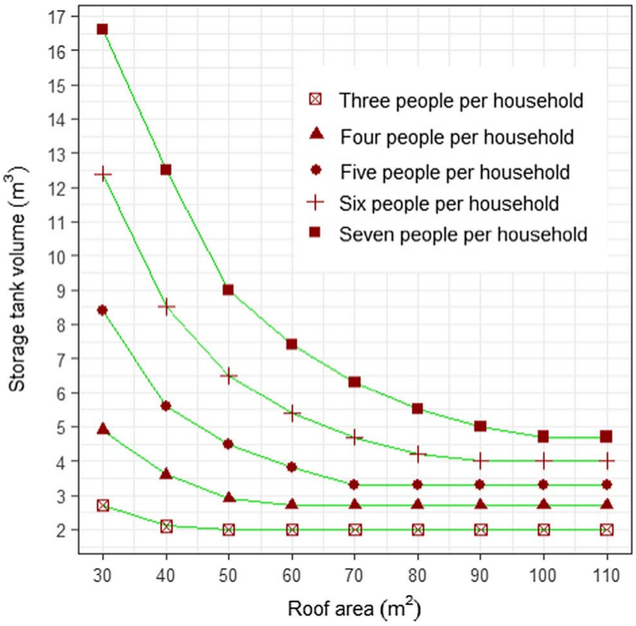

Fig. 4 Storage tank volume regarding the roof area and the number of people of Scenario 2 (water demand = 20 l/p/d)

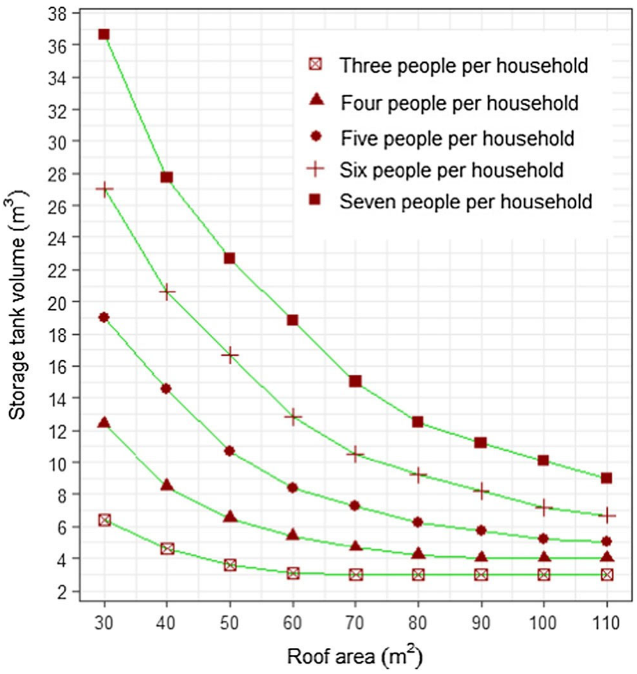

Fig. 5 Storage tank volume regarding the roof area and the number of people of Scenario 3(water demand = 30 l/p/d)

storage tank and 40 l/p/d) will be US$ 470. This cost of storage tank of RWH system may be applicable for the XY commune.

$$Cost_{\text{st}} = 36.3\ V + 107\ \left(\text{Adjusted}R^2 = 0.99, p < 0.0001\right) \quad (5)$$

$Cost_{\text{st}}$ is the total cost of storage tank (US$), and V is storage tank capacity (m^3).

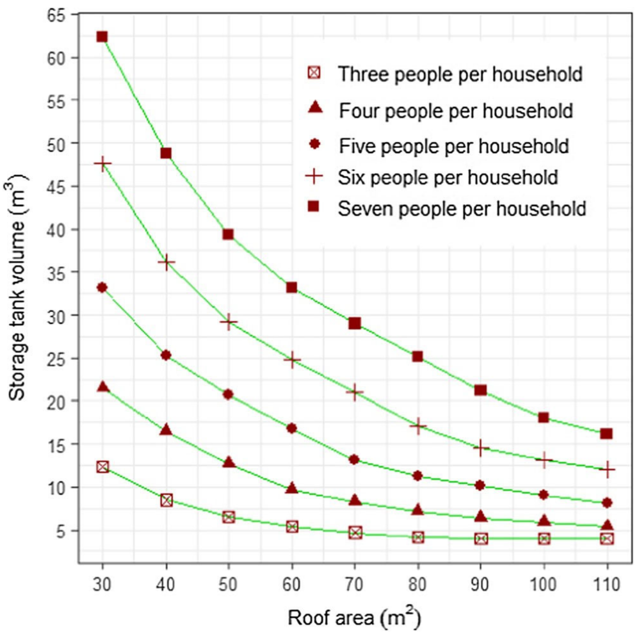

Fig. 6 Storage tank volume regarding the roof area and the number of people of Scenario 4 (water demand = 40 l/p/d)

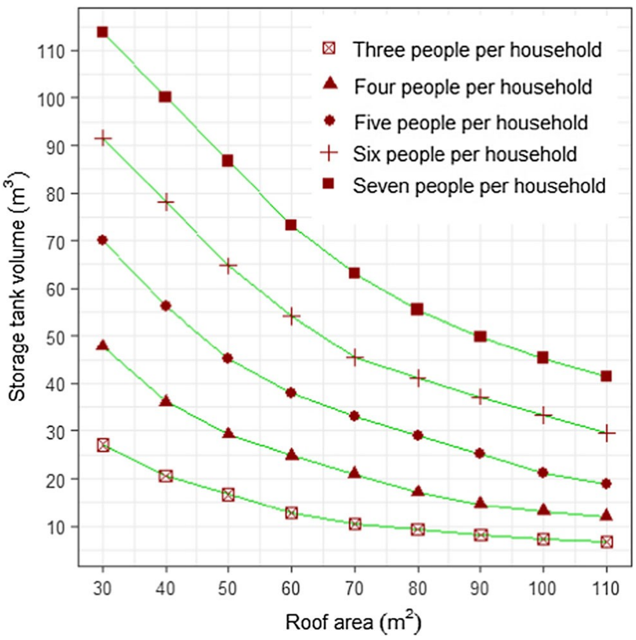

Fig. 7 Storage tank volume regarding the roof area and the number of people of Scenario 5 (water demand = 60 l/p/d)

Conclusions

The local people primarily depend on a river and streams for household water sources. RWH is one of the water supply sources for local people, but it did not significantly contribute to the total amount of water usage in the period studied. RWH was calculated to meet domestic water demand during the dry months by using a simple method. Calculation using the mean number of residents (five) and 60 m^2 of catchment area for each household revealed that storage tank volumes (m^3) of 2.3 (Scenario 1), 3.8 (Scenario 2), and 8.4 (Scenario 3) can be the best choices to meet the current water demands of 14–30 l/p/d. For a higher water demand (Scenarios 4 and 5), accompanied by a small roof area (30–40 m^2) and more people for each household (six to seven members), using RWH alone is not feasible, because it does not fit the rainfall data or requires too large a storage tank volume. Consequently, with high-water-usage requirements, other sources besides rainwater must be combined with RWH. The results provide a tool to determine an optimized tank volume for practical purposes; however, further studies are needed to confirm the real installation cost and ability of RWH to meet water demands.

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Authors' contributions Xuan Cuong Nguyen: Conceptualization, Methodology, Writing. Thi Thanh Huyen Nguyen: Formal analysis, Validation. Xuan-Thanh Bui: Methodology, Visualization. Xuan Vu Tran: Methodology, Data curation. Thi Cuc Phuong Tran: Formal analysis, Data curation. Nhung Thi Tuyet Hoang: Writing—review and editing. Duc Duong La: Software, writing—review and editing. Soon Woong Chang: Writing—review and editing. Huu Hao Ngo: Writing—review and editing. D. Duc Nguyen: Resources, supervision, writing—review and editing

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Data availability The dataset used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval and consent to participate Not applicable.

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