Evaluation of rainwater harvesting performance for water supply in cities with cold and semi-arid climate

Oweis Molaei, Mahdi Kouchakzadeh and Fereshte Haghighi Fashi

ABSTRACT

In this study, the performance of rainwater harvesting (RWH) was assessed in terms of potential applicability for rainwater saving and non-potable water supply. Rainwater collecting from roofs of buildings was simulated in two cities with cold and semi-arid climate, namely Qazvin and Sanandaj. Rainfall statistics, information on the storage tank size, building roof areas and water demand (non-potable) were obtained. Buildings with roof areas of 100 m^2 to 300 m^2 were considered for the present study. It can be concluded that for cities located in cold and semi-arid climates, at least 60% of non-potable water can be supplied from roofs with a large area, a minimum 16% and maximum 70% for a low roof area, a minimum 8% and maximum 44% of the days per year from harvested rainwater. It is also found that for cities located in cold and semi-arid climates, it is possible to achieve at least 70% of non-potable water from large surface roofs. For the studied cities, with increasing tank size (1,000 to 5,000 L) rainwater saving was tangible for the same roof areas.

Key words | cold and semi-arid climate, non-potable water, rainwater harvesting, roof area

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INTRODUCTION

Clean water supply is an important issue in developing countries, especially in most cities of Iran where existing water sources are not adequate to meet demand. A rainwater harvesting (RWH) approach would help people to overcome crises in water supply. RWH would provide economic benefit and environmental advantage over traditional water systems (Notaro *et al.* 2016). Jones & Hunt (2010) have evaluated the applicability of rainwater harvesting systems in North Carolina and reported that with increased education and planning, RWH systems are valuable tools to reduce municipal water demand. Imteaz *et al.* (2011a) attempted to devise a comprehensive tool for analysis of rainwater storage tanks in Melbourne. For three climatic conditions, they presented reliability charts for rainwater storage tanks in relation to tank size, roof area, and numbers of residents in each house and water demand to be supplied by rainwater. Their findings showed that for the situation with a household of two occupants, reliability was about 100% with a roof area of 150 to 300 m^2 and a tank size of 5,000 to 10,000 L. Imteaz *et al.* (2012) investigated the reliability for domestic rainwater tanks in combination with tank size, roof size, number of occupants in each building and water demand supplied using rainwater collecting in various climatic conditions. They reported that for a roof area of 100 m^2, 100% reliability would not be achievable. Palla *et al.* (2012) examined the performance of domestic RWHs in different European climate zones. Their analysis demonstrated a strong correlation between the performance indexes and the antecedent dry weather period.

Jing *et al.* (2017) assessed the efficiency of RWHs for meeting non-potable water demands in four climatic conditions of China. They found that higher water supply reliability (time reliability) and water storage efficiency were possible for RWHs with a larger storage capacity for lower water demands, while a higher RWH efficiency was in relation to higher water demand, larger saving capacity

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and lower rainfall amount. Santos & Farias (2017) assessed the potential for water storage under the dry climate (semi-arid region) in northeast Brazil. They showed a reduction in pressure on the water supply system by using RWHs.

Although RWHs have good potential to supply safe water, there is a lack of knowledge about the roof size in combination with suitable tank size to achieve the expected reliability under cold and semi-arid climatic conditions in Iran and the world. In such regions, the water supply is inadequate to meet agricultural demands. Low rainfall during dry seasons leads to increased groundwater abstraction for irrigation. Moreover, rainwater harvesting potential and design will be different in various regions with different characteristics and climate conditions. It is necessary to document and quantify the expected amount of water storage under various climate conditions and water demands to adopt a cost-effective tank volume (Imteaz et al. 2011b). The aim of this investigation was to evaluate the potential applicability of RWHs for rainwater saving and non-potable water supply from building roofs in the cold and semi-arid climate areas of two Iranian cities with different spatial conditions: Qazvin and Sanandaj.

METHODOLOGY

In this study, the method used by Rashidi Mehrabadi et al. (2013) was applied. In this research, the overflowed water and initial water volume in the tanks has been taken as zero. Amounts of harvested rainwater were calculated by Equation (1):

$$I_t = R_t \times A \times \varphi \tag{1}$$

where R_t is daily rainfall (mm), A is roof area (m^2), φ is roof runoff coefficient, and I_t is total rainwater harvested from a roof. The volume of stored rainwater was computed based on Equation (2):

$$V_t = I_t + V_{t-1} - O_t - SP_t \tag{2}$$

V_{t-1} and I_t are base water in a tank before harvesting rainwater and rainwater volume harvested from the roof, respectively. O_t is the non-potable water withdrawal from the tank (L) and SP_t is the amount of water overflow (L) from the tank. Finally, V_t is the remainder of rainwater in the tank (L).

Based on the following equation, D_t is considered as follows:

$$\text{If: } I_t + V_{t-1} > D_t \rightarrow O_t = D_t \tag{3}$$

If:

$$I_t + V_{t-1} < D_t \begin{cases} O_t = I_t + V_{t-1} \\ U_t = D_t - O_t \end{cases} \tag{4}$$

where U_t is the water volume withdrawn from the piped system and D is the demand. Overflowed water volume was obtained based on Equation (5):

$$SP_t = V_{t-1} + I_t - O_t - V_{max} \tag{5}$$

In Equation (5), V_{max} is tank volume (L).

In this research, tank size in system modeling was considered from 1,000 litres to 10,000 litres by incremental changes of 1,000 litres and roof areas of 100 m^2, 200 m^2 and 300 m^2 were considered. An amount of water demand ranging from 48 to 192 litres per day per resident (the totals for each building were estimated at 192 to 768 litres) was assumed based on the estimations of earlier studies, literature review and existing statistics for Iran. Considering the water demand percentage to be fulfilled by rainwater storage tanks, 60% and 80% demand scenarios were examined based on the results of the earlier study by Rashidi Mehrabadi et al. (2013). Based on the household sizes in Iran, it was assumed that 4, 8 and 12 people live in residential buildings having a roof area of 100 m^2, 200 m^2 and 300 m^2, respectively.

STUDY AREA

Cities for the research were selected in a cold and semi-arid climatic condition; Qazvin and Sanandaj cities in Iran. In such regions, the water sources are not capable of sufficient agricultural water demand supply. Locations of the investigated cities on a map of Iran are shown in Figure 1. Table 1 presents physical characteristics of the investigated regions. Average and time series of rainfall statistics of the studied cities are shown in Figure 2 and Table 2.

RESULTS AND DISCUSSION

According to Figure 3 showing rainwater saving in Qazvin city, for a minimum 60% of daily water demand (non-potable water), the most and the least rainwater savings for a roof area of 100 m^2 were 26.7 m^3 and 20.23 m^3 annually, respectively. For 80% of daily water demand, the most and the least rainwater savings for a roof area of 300 m^2 were 78 m^3 and 49.47 m^3, respectively in Qazvin and 90.15 m^3 and 51.91 m^3 in Sanandaj.

Rainwater saving for roofs of 100 m^2 was nearly constant at 30,000 litres per year. The most rainwater saving was from a roof area of 300 m^2, which could store rainwater amounts of 51,910 to 90,150 litres per year. In Sanandaj, averages of rainwater saving for small roof areas (100 m^2) were volumes of 29,395 to 30,510 litres and for large roof areas (300 m^2) were 72,530 to 77,665 litres yearly. According to Figure 3 showing rainwater saving in Sanandaj city, the most rainwater saving for a roof area of 300 m^2 was 90,150 litres annually and would be practical for 10,000 litres volume. For Qazvin city, the average of rainwater saving for small roof area (100 m^2) was 25,382 to 25,861 litres.

For Qazvin city, it was determined that the most number of days (per year) on which the least 60% of daily water demand could be met is 69.3% of total days per year for 300 m^2 of roof area, tank size of 10,000 L and 320 L non-potable water demand per day. In addition, the least number of days is 18.12% and 20% for Qazvin and Sanandaj for 100 m^2 roof area (80% of daily water demand), 320 L water demand, and tank size of 1,000 L.

By increasing tank volume, the daily water demand (non-potable water) supply was increased, but by increasing daily water demands, the days for water supply were

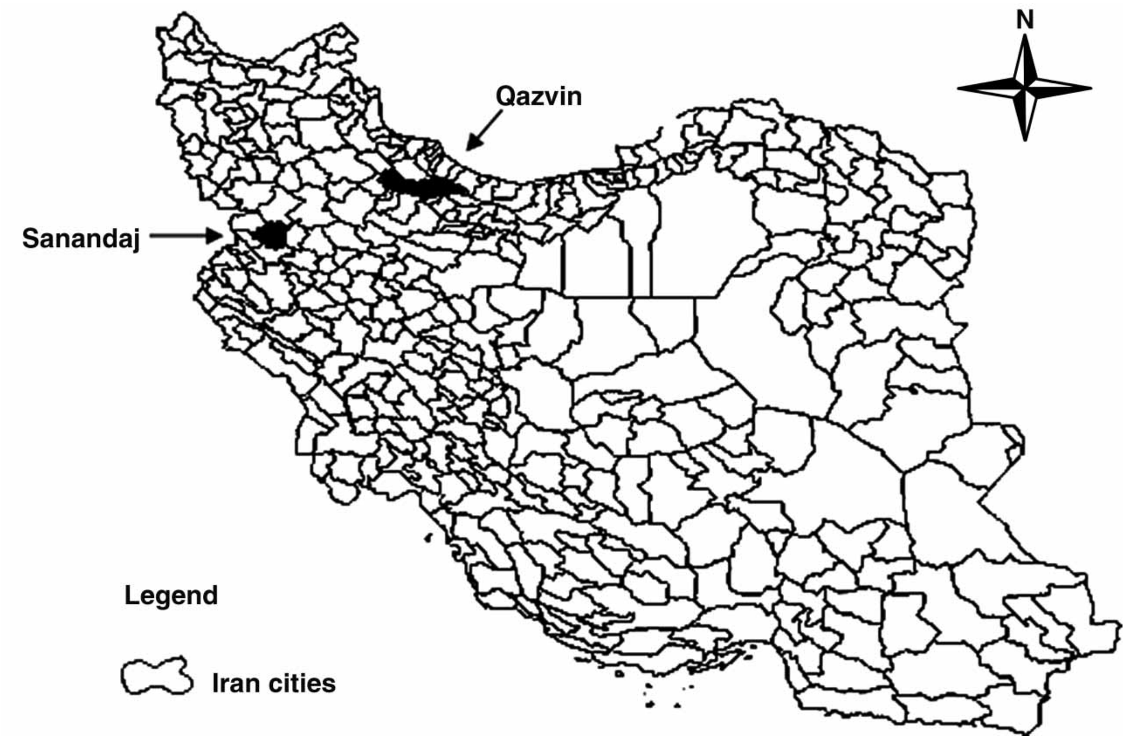

Figure 1 | A map of study cities in Iran.

Table 1 | Physical characteristics of the studied regions

	Sanandaj	Qazvin
Latitude	35° 19′ 1.92″E	36° 9′ 36″ E
Longitude	46° 59′ 56.04″N	50° 0′ 0″ N
Average elevation	1,494 m	1,347 m
Topography	hilly	flat

decreased. By average, the days per year on which 60% of daily water demand could be met were equal to 32.42%, 52.78% and 59.06% of days per year for roof areas of 100 m^2, 200 m^2 and 300 m^2, respectively. The number of days in a year on which 80% of water demand could be supplied was 43.02%, 23.25% and 51.2% of total days per year for roof areas of 100 m^2, 200 m^2 and 300 m^2, respectively.

Based on Figure 4, for Sanandaj city, it was determined that the most days of water supply for a 320 L water demand (60% of water demand) and for large tank sizes was equal to 68.5% of total days per year and the least total days of water supply for a 960 L daily water demand (80% of water demand) and for a tank size of 1,000 L was equal to 5.4% of days per year.

For a roof area of 100 m^2 and tank size of more than 8,000 L capacity, total days of supply was constant and equal to 43% and 34% of total days per year for 60% and 80% of daily water demand, respectively. For roof area of 200 m^2 and 300 m^2, total water supply days for tank sizes of larger than 10,000 L were constant, equal to 64% and 68% of total days per year (for 60% of daily water demand), respectively and were 55% and 61% (for 80% of daily water demand).

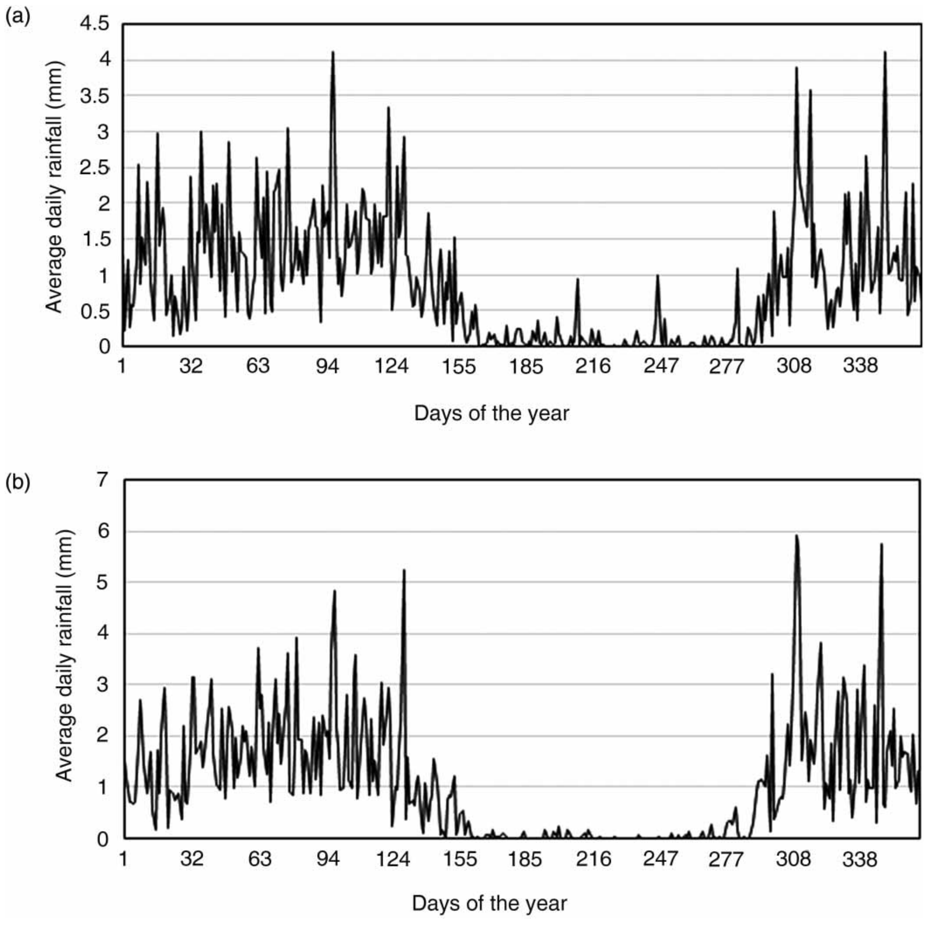

Figure 2 | Daily rainfall in (a) Qazvin and (b) Sanandaj from 1987 to 2016 (from January).

Table 2 | Rainfall characteristics of the studied regions

	Sanandaj	Qazvin
Mean (mm)	386.007	316.8813
Standard deviation	93.95916	78.14481
Maximum (mm)	645.16	469.26
Minimum (mm)	235.91	155.46

According to Figure 5, it was determined that for Sanandaj city, the greatest efficiency of the RWHs and the days of water supply was 70% of total days per year for a roof area of 300 m^2, tank size of 10,000 L and 300 L daily water demand (60% of daily water demand). Moreover, the least efficiency of the RWHs and the days of water supply was 6% of the total days of a year for a roof area of 100 m^2, tank size of 1,000 L and daily water demand of 1,000 L (80% of daily water demand).

By increasing the tank sizes and roof area, the days of water supply were increased, for 300 L water demand it was 20% to 70% of total days per year and for 1,000 L water demand it was 6% to 38% of total days per year.

As averages, the days of water supply for demands of 300 to 1,000 L for a roof area of 100 m^2 and tank sizes of 10,000 and 1,000 L were 21% and 14% of the total days per year. For a roof area of 300 m^2, non-potable water supply was 50% and 25% of the total days per year and for 200 m^2 roof area it was 34% and 20% of the total days per year.

Figure 6 represents the number of days of water supply for Qazvin city. Variations in the number of days of water supply for roof areas of 100 m^2, 200 m^2 and 300 m^2 were 4% to 35%, 10% to 63% and 13% to 70% of the total days per year, respectively. The average total days of water supply for tank sizes of 1,000, 4,000, 7,000 and 10,000 L and for roof areas of 100 m^2, 200 m^2 and 300 m^2 (300 L daily water supply) were 28%, 47% and 55% of the total days per year, respectively. Consequently, for the studied cities, with increased tank size (1,000 to 5,000 L), rainwater saving for the same roof surface areas was tangible, but the

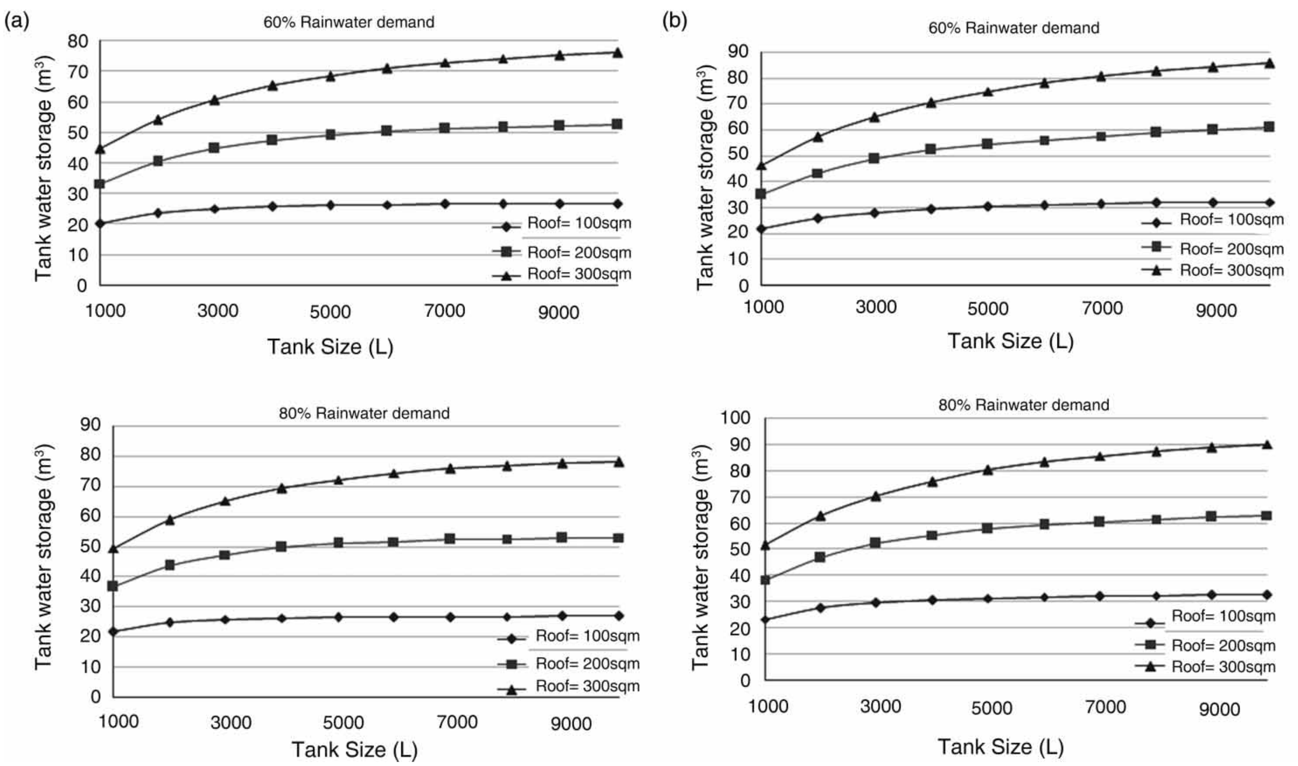

Figure 3 | Annual rainwater saving in tanks for various roof areas in (a) Qazvin and (b) Sanandaj.

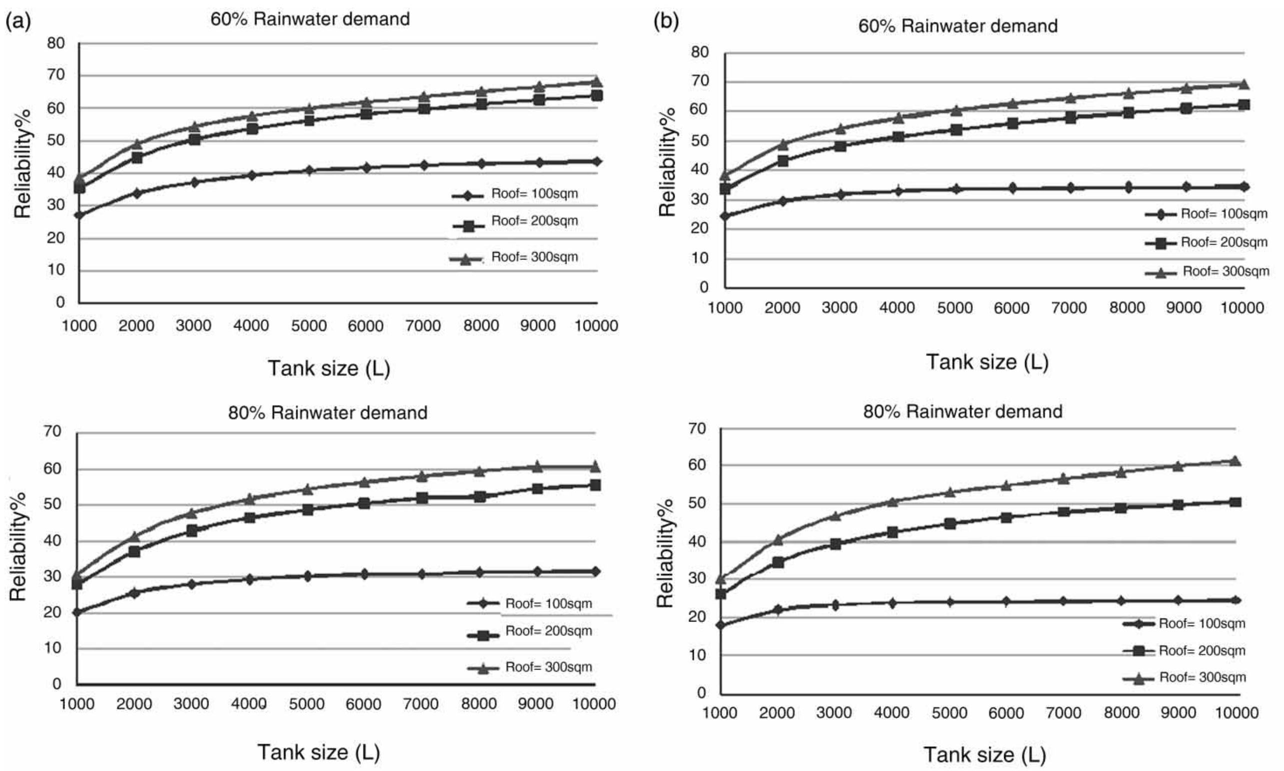

Figure 4 | Reliability for various demands and roof areas in (a) Sanandaj and (b) Qazvin (four people as occupants).

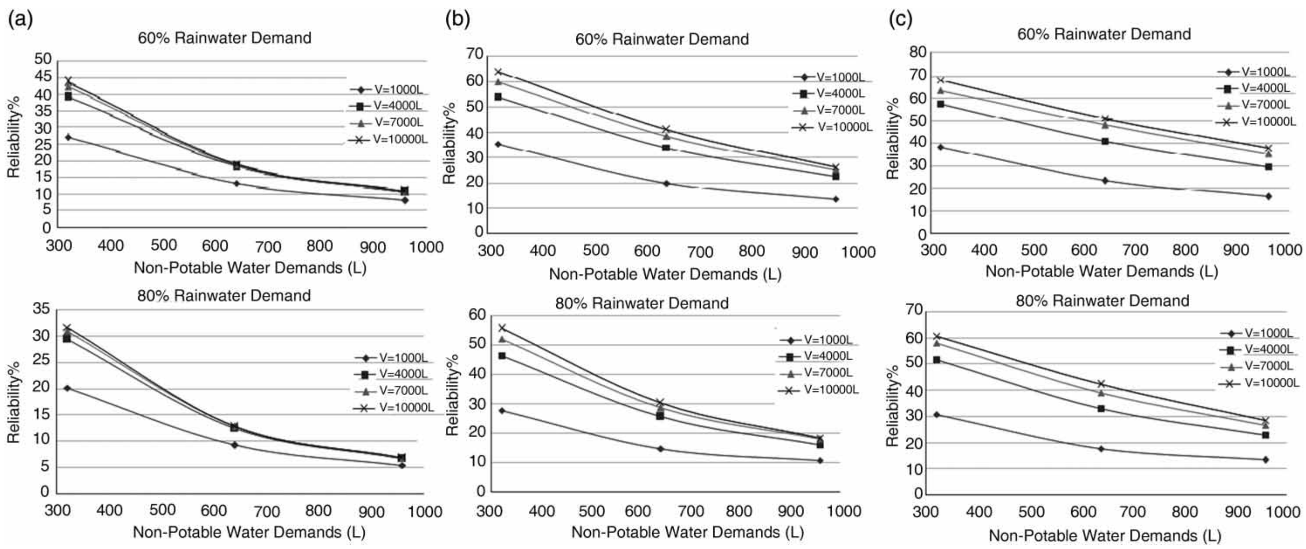

Figure 5 | Days of non-potable water supply in Sanandaj for roof area of (a) 100 m^2, (b) 200 m^2, (c) 300 m^2.

amount of raising was not tangible by increasing tank size from 5,000 to 10,000 L, in contrast to the smaller tank sizes.

According to the results, if the tank size and daily water needs of occupants are calculated based on roof area, rainfall and the number of days required for saving,

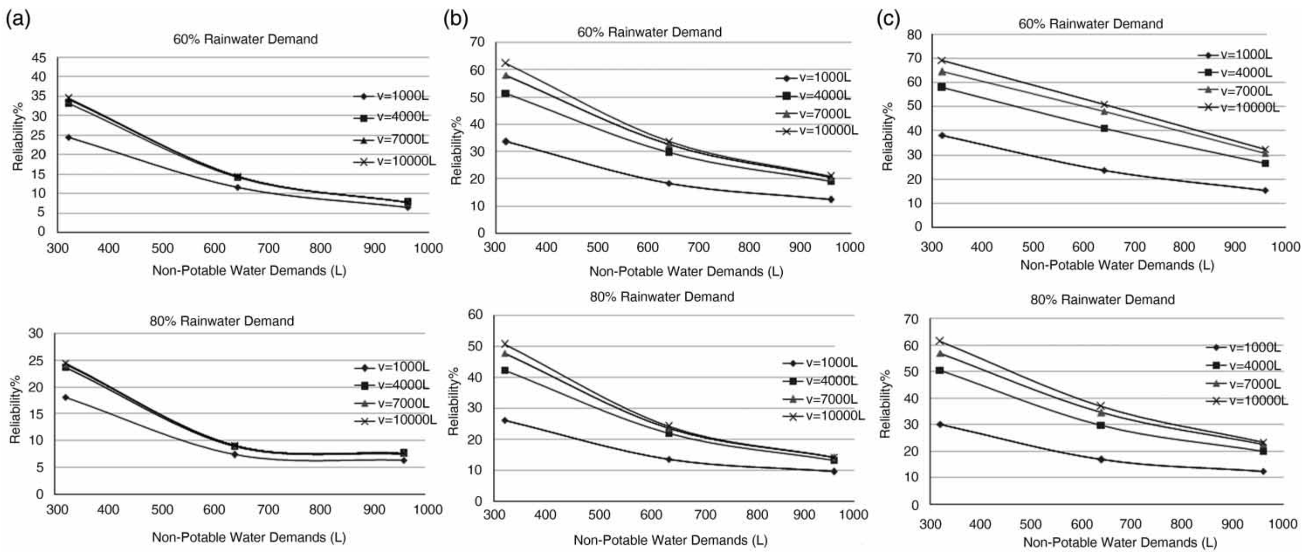

Figure 6 | Days of non-potable water supply in Qazvin for roof area of (a) 100 m^2, (b) 200 m^2, (c) 300 m^2.

the rainwater saving in tanks reaches its maximum and the day number for water supply (non-potable water) from rainwater increases (Rashidi Mehrabadi *et al.* 2013). Similar results were presented by Jenkins (2007), reporting that climate conditions could have a considerable effect on the effectiveness of a rainwater storage tank. In general, various combinations of saving capacity, water demand, roof area, and number of building residents can lead to optimal solutions. A decision support system may be considered for different sites and different values of water saving volume, water demand, roof area and number of residents in buildings (Imteaz *et al.* 2011b). It is valuable to investigate and document the expected rainwater saving in tanks under various water demands to determine the cost-effective saving tank size (Rashidi Mehrabadi *et al.* 2013).

Moreover, it is necessary to know that rainfall temporal and spatial variability is an important issue in implementing RWHs. Climate classification often considers the mean annual rainfall, therefore, average annual rainfall may not be a sufficient factor to estimate tank size and plan of RWHs and further investigations may be needed to assess RWH reliability in dry vs wet times (Rashidi Mehrabadi *et al.* 2013). Finally, further works may be needed to investigate RWH reliability in different regions in the same climatic condition.

CONCLUSIONS

In this study, the reliability of a RWH system was investigated for rainwater saving and non-potable water supply in Qazvin and Sanandaj cities in a cold and semi-arid climate. It was found that with increasing the daily water demand of building residents, the days of water supply by rainwater saving from roofs would decrease. For cities with a low rainfall amount, in order to supply the greatest water demand of the residents, the tank size and roof area may be adopted as large to save more water in rainy days. Rainfall amount and roof area should be mainly considered as important factors to reach optimum water saving in tanks facing the demands of occupants. For the studied cities, with increased tank size (1,000 to 5,000 L) rainwater saving for the same roof areas was tangible, but the amount of raising was not tangible by increasing tank size from 5,000 to 10,000 L in contrast to the smaller tank sizes. Capacity is an important consideration to implement a RWH system with the most rainwater saving in rainy periods.

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