Desalination and Water Treatment
www.deswater.com

doi: 10.1080/19443994.2014.923201

54 (2015) 3544–3550
June

Taylor & Francis
Taylor & Francis Group

Analysis of storage volume and reliability of the rainwater harvesting tanks in the coastal area of Bangladesh

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Received 15 January 2014; Accepted 14 March 2014

ABSTRACT

The annual average rainfall in the coastal area of Bangladesh is more than 2,400 mm and rainwater harvesting (RWH) has been practiced for a long time for drinking water supply. For household RWH, the capacity of the storage tanks varies from 1,000 to 5,000 litres, which are the model-type storage tanks provided under several RWH programs of government and NGOs. The optimum storage tank volume has not been investigated considering family size and demand, roof types and rainfall. As a result, most of the households can avail water from rainwater tanks for about six months and rest of the year, they have to depend on other unreliable and distance sources. With the aim of developing a comprehensive decision support tool for a reliable RWH system, design curves for the storage volume were developed for three climatic conditions (i.e. dry, average, and wet years), available roof catchment area (10–50 m^2), rainfall loss factor and household demand (2–12 lpcd) for a typical six members family using mass curve. Moreover, a spreadsheet-based daily water balance model was developed to assess the reliability of the currently used water tanks (1,000–5,000 L). The analysis showed that the currently used tanks are insufficient to meet the year-long drinking and cooking water demand. Under average and dry climatic conditions, the achievable reliability does not significantly varies with increase of catchment area and tank size; and the maximum achievable reliability is about 70%. A large quantity of water is lost as spilled water even with a tank size of 5,000 L. This water can be used for other purposes if larger tanks are used to capture the excessive spilled water.

Keywords: Rainwater tank; Daily water balance model; Climate condition; Reliability; Coastal areas; Bangladesh

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Presented at the 5th IWA-ASPIRE Conference, 8–12 September 2013, Daejeon, Korea

1. Introduction

Rooftop rainwater harvesting (RWH) is receiving increased attention worldwide as an alternative source of domestic water in water scarce regions [1]. This is acknowledged as a sustainable source of water that has less impact on the environment and now-a-days, rainwater is used as a source for numerous domestic applications like drinking, cooking, bathing, laundry, toilet flushing, hot water supply and gardening purposes [2,3]. Roof-collected tank rainwater is the major source of untreated drinking and domestic water supply in Australia, New Zealand, and other countries [4,5]. In the recent years, rooftop RWH has received an increased attention as a potential alternative water supply source both in the coastal and arsenic-affected rural areas in Bangladesh. During the last few years, several projects have been undertaken to promote and install both household and community-based RWH systems in order to mitigate drinking water problem both in the coastal- and arsenic-affected areas in the country [6,7].

Bangladesh as a tropical country, receives high seasonal rainfall all over the country. The seasonal high rainfall and suitable roof catchments in the rural areas make RWH a potential alternative water supply option in the country [8]. The average annual rainfall is about 2,400 mm and in most part of the country, people normally can have the access to rainwater for 6 to 8 months on an average. In the coastal areas, suitable aquifers at shallow depths are rarely available; surface water especially the river water is highly saline and turbid. The scarcity of potable water is very acute in these zones [9,10]. Rain-feed ponds water, pond sand filters (PSF) and direct collection of rainwater are the major sources of drinking water in most parts of the coastal zones. About 28% of the country's total population lives in these areas and supply of safe water is one of the important environmental issues for human health and sustainable development in the coastal areas. As rainfall in the coastal areas is much higher than the country's average rainfall with suitable roof catchments [7]; thus RWH has a good potential to supply drinking and cooking water in the coastal areas of Bangladesh.

For a reliable RWH systems, the storage volume must be assessed carefully in order to meet the year-long demand of a family. For household RWH in the coastal areas of Bangladesh, the volume of the rainwater tanks varies from 1,000 to 5,000 litres or more [7], which were promoted under several specific projects of government and donor agencies without undertaking any investigation like family size and demand, roof types and rainfall. As a result, most of the households can avail water from rainwater tanks for about six months and rest of the year, they have to depend on other unreliable and distance sources like PSF or pond water. A proper in-depth understanding of the effectiveness of any proposed onsite RWH is necessary to planning for adequate and reliable RWH schemes.

The optimum storage volume of rainwater tanks has been investigated by numerous researchers [11–13]. Various methodologies such as continuous mass balance simulations, non-parametric approaches based on probability matrix methods and statistical methods are used. The most common methodology is the behavioural analysis that uses continuous simulation to assess inflow, outflow and change in storage volume of the rainwater tanks according to a mass balance equation [11,13–15].

The main objective of this study is to develop a comprehensive decision support tool for a reliable RWH system in the coastal areas of Bangladesh. For the purpose, design curves for the storage volume of rainwater tanks were developed for three climatic conditions (i.e. dry, average, and wet years) considering available roof catchment area, rainfall loss factor due to run-off and household demand using mass curve. Moreover, a spreadsheet-based daily water balance model was developed to assess the reliability of the currently used water tanks in the coastal areas of Bangladesh. Reliability is defined as percentages of days in a year when rainwater tank was able to meet the water demand of family of six members.

2. Methodology

Mass curve techniques based on daily water demand (drinking and cooking) and rainwater supply was used to develop the design curves for storage volume calculation. A behavioural model [13,15] was developed in Microsoft Excel considering daily rainfall, contributing roof area, losses due to leakage, spillage and evaporation, storage (tank) volume and water uses. The model was run at a daily time resolution with daily rainfall amount for three different years (dry, average, and wet years). The daily run-off volume was calculated by multiplying the rainfall amount with the contributing roof area and deducting the losses. For this study, a 10% deduction was applied to account for several losses (leakage, spilling and evaporation). Generated run-off was assumed to divert to the connected storage tank. Available storage capacity was compared with the accumulated daily run-off. If the accumulated run-off was bigger than storage tank volume, excess water (spilled water) was deducted from the accumulated run-off. Amount of water use(s) was deducted from the daily accumulated/stored run-off amount, if sufficient amount of water was available in the storage. In a situation, when sufficient amount of water was not available in the storage, the model assumed that the remaining water demand was supplied from other sources like PSF or rain-feed pond.

The model calculated daily rainwater use, daily water storage in the tank, daily spilled water volume and daily water needed from other sources like PSF or pond. In addition, model calculates accumulated annual rainwater use, accumulated annual spilled water and accumulated annual water needed from other sources. The water balance equation for the study is given by:

$$S_t = V_t + S_{t-1} - D \quad (1)$$

$$S_t = 0, \quad \text{for } S_t < 0 \quad (2)$$

$$S_t = C, \quad \text{for } S_t > C \quad (3)$$

where S_t is the cumulative water stored in the rainwater tank (L) after the end of tth day; V_t is the harvested rainwater (L) on the tth day; S_{t-1} is the storage in the tank (L) at the beginning of tth day; D is the daily rainwater demand (L), and C is the capacity of rainwater tank (L). On a particular day if the water storage was greater than the tank capacity C, the excess water would spill over and the tank storage level at the end of the day was reset equal to C. The amount of water spilled and the water supplied from other sources are given by

$$\text{Spilled water} = S_t - C \quad \text{for } S_t > C \quad (4)$$

$$\text{Water needed from other sources} = D - S_t \quad \text{for } S_t < D \quad (5)$$

In this calculation, time-based reliability was used to quantify the performance of RWH system, which can be defined by the following equation:

$$R_e = \frac{N - U}{N} \times 100 \quad (6)$$

where R_e is the reliability of the tank to be able to supply intended demand (%); U is the number of days in a year the tank was unable to meet the demand, and N is the total number of days in a year (365 d).

3. Data

Daily rainfall data for 10-years period from 1998 to 2007 was collected from Bangladesh Meteorological Department for a coastal meteorological station located at Satkhira. From the historical daily rainfall data (1998–2007), three separate climatic conditions were selected based on the total annual rainfall. Years corresponding to minimum and maximum rainfall were considered as dry and wet years, respectively. The average year represented the average daily rainfall over 10 years' period. Selected years and corresponding annual rainfall amounts are shown in Table 1. For the three climatic conditions, design curves for storage volumes were developed using mass curve considering roof sizes from 10 to 50 m^2 and drinking and cooking water demand from 2 to 12 lpcd, which are the typical range of drinking and cooking water requirement for rural communities in Bangladesh [16]. An average household of six members and thus a daily water requirement of 12–72 L/d were considered in this calculation. Moreover, several reliability curves were developed for a wide range of domestic rainwater tanks (500–5,000 L), roof areas (10–40 m^2), and drinking and cooking water demand for an average household. Spilled water volume and water collected from other sources when the harvested rainwater is not available to meet the demand were also calculated using the model.

4. Results and discussion

4.1. Storage volume-demand relationship

Design curves were developed for average, wet and dry year conditions to estimate the storage volume required for a household of six members. A typical storage volume-demand relationship for an average year condition is shown in Fig. 1. As shown in Fig. 1, the storage volume increases when demand increases and decreases when catchment area increases. A family of six members with a water demand of 72 L/d for drinking and cooking would need to have a storage volume of more than 14 m of water for an average year condition with a roof catchment area of 10 m. Table 2 shows the optimum storage

Table 1
Annual rainfall for dry, average, and wet years

Year	Annual rainfall (mm)
Dry year (1999)	1,694
Average year (1998–2007)	1,855
Wet year (2004)	2,111

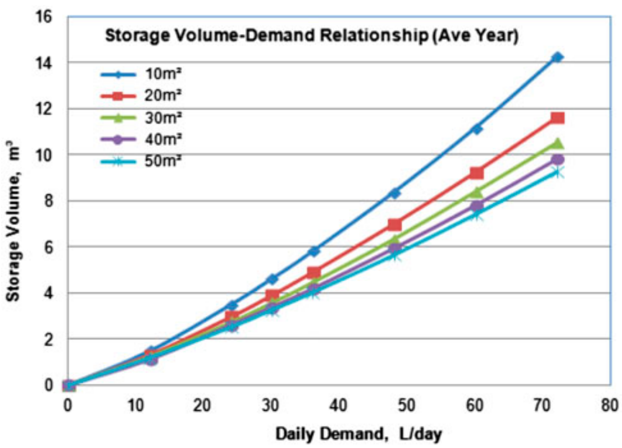

Fig. 1. Typical storage volume-demand relationship of rainwater tank in the coastal areas of Bangladesh.

Table 2
Optimum storage volume required for different catchment areas

Weather condition	Catchment area (m)				
	10	20	30	40	50
Average	11.17	9.24	8.38	7.79	7.42
Dry	16.66	15.87	15.56	15.42	15.33
Wet	17.05	16.48	16.21	16.08	15.99

volume required for year-long water supply for a family of six members with a daily demand of 60 L/d under three climatic conditions (dry, average, and wet years). The required storage volume for dry year is much higher than the storage volume calculated based on average year condition due to shortage of rainfall. It is interesting to observe that the storage volume required under wet climate condition is quite higher than that for dry climate condition. Analysis of the rainfall data showed that although the total rainfall was higher, the number of rainy days for that particular year (2004) was comparatively lower, so the rainfall was less effective in meeting the daily demands. The available storage tanks for household RWH in the coastal areas of Bangladesh vary from 1,000 to 5,000 L. This analysis showed that the storage volume of the currently used tanks is much lower than that required for year-long uses of harvested rainwater. During the non-supply period, rural people normally collects water from unreliable and distance sources like pond water or PSF. The pond water is found to be seriously microbial contaminated [10] and in most cases, people are found to use some in-house treatments like alum coagulation or filtration to treat the pond water before drinking. Several studies [6,10] showed that the performance of PSF is still unsatisfactory to produce safe water. Rural people especially women, who are responsible to collect drinking water would need to travel a long distance (some cases more than 2 km) and also to have a long queue to collect PSF water. The design curves can be used in calculating the required storage volume of rainwater tanks for year-long water supply. Such curves can also be developed for other uses of rainwater, which can be used to assess the required storage volume for reliable and sustainable RWH in the coastal or other water scarce areas.

4.2. Reliability and spilled water volume

Fig. 2 shows the reliability curves under different climatic conditions (wet, average and dry years) for different tank sizes for roof catchment areas of 10–40 m^2 for a household of 6 members with 10 lpcd of water consumption. For roof areas of 10–40 m^2, the maximum reliability that can be achieved under average climate condition varies from 70 to 85% and the reliability does not increase significantly beyond the tank volume of 3,000 L. In general, the reliability increases with tank sizes; however 100% reliability cannot be achieved even with larger catchment area and tank capacity of 5,000 L. Under wet and dry climatic conditions, the achievable reliability does not significantly varies with increase of catchment area and tank size; and the maximum achievable reliability is about 70%. This means that a tank size of more than 4,000 L can meet the drinking and cooking water demand for maximum 70% of the days in a year.

Fig. 3 shows the spilled water (annual) curves varying with tank sizes under different climatic conditions (dry, average and wet climates). It is found that volume of spilled water can be reduced with increase in tank size. It was also found that even with a smaller catchment area (10 m^2), the spilled water volume was more than the maximum tank capacity of 5,000 L under wet climate condition. The spilled water volume under wet climate is much higher than that calculated under average or dry weather condition. Fig. 3 also indicates that spilled water volume significantly increases with increase in catchment area. For a 40 m^2 roof catchment area under average climate condition, the ratio of spilled water volume to tank volume for 1,000 and 5,000 L tanks are 50 and 10, respectively. This huge spilled water can be used for other domestic purposes like washing and thus potential uses of rainwater can be increased with a larger tank size.

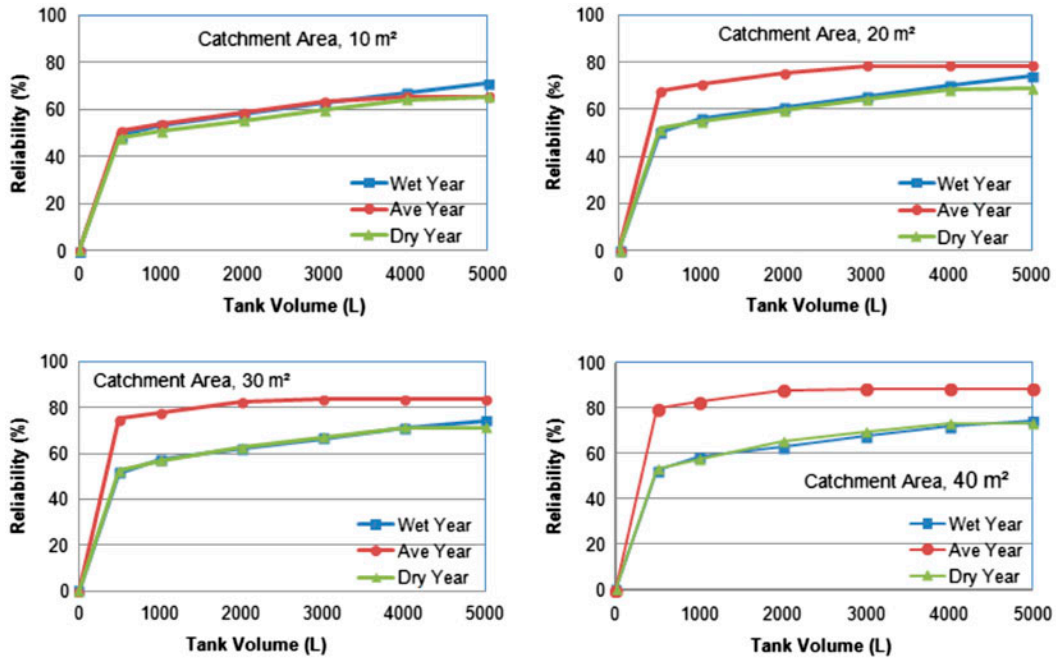

Fig. 2. Reliability curves for a household of six persons with a water demand of 10 lpcd for different roof catchments.

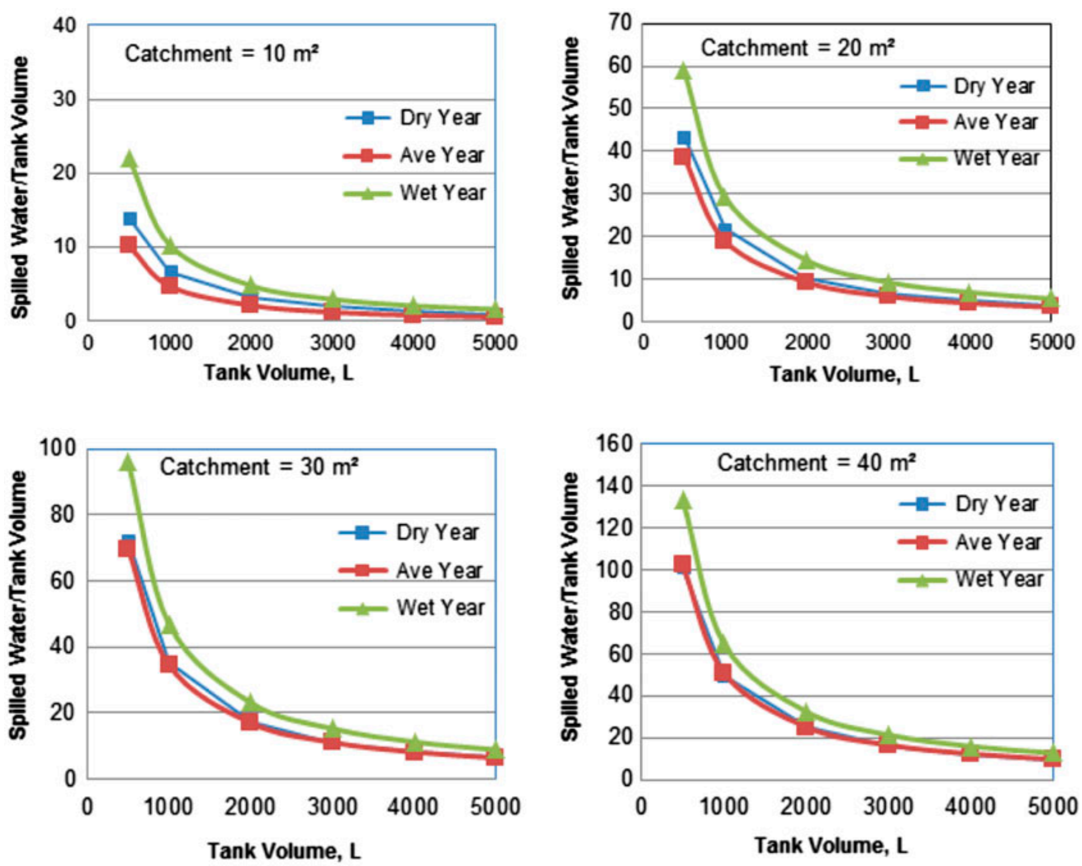

Fig. 3. Spilled water for different roof catchments under different climatic conditions.

Overall, the water supply efficiency of RWH implementation under various roof areas and climatic conditions varies widely [17]. The climate condition of the study area also imposes a major impact on the effectiveness of rainwater tank systems [18]. It is expected that various combinations of climate condition, roof area, tank volume, and water demand can lead to widely different reliabilities. It is necessary to document and quantify the expected water storage under various climatic conditions and water demands to adopt cost-effective tank volume. The temporal variability of rainfall has an important impact on the storage volume and thus planning RWH systems. In an area with more or less uniform monthly rainfall would require less storage tank than the area with high seasonal variation of rainfall and thus the rainfall distribution patterns need to be carefully evaluated. In calculating the required storage volume, the daily water balance model gives a realistic tank volume, whereas calculation based on monthly average rainfall data overestimates the tank size [15].

5. Conclusions

In this paper, design curves for optimum storage volume required for a household of six members under different climatic conditions were developed to estimate the required tank volume for year-long drinking and cooking water supply from RWH system. Moreover, reliability of rainwater tanks in the coastal area of Bangladesh was investigated under different climatic conditions (dry, average, and dry condition), roof areas, tank volumes and household water demands for drinking and cooking. The analysis used the recorded daily rainfall data instead of monthly average rainfall data. The analysis reveals that the currently used storage tanks in the coastal areas of Bangladesh are insufficient to meet the yearlong drinking and cooking water demand. The analysis based on average daily rainfall gives comparative smaller storage tank volumes than based on wet or dry climatic conditions.

The present analysis indicates that 100% reliability cannot be achieved with the tank sizes currently used for household RWH in the coastal areas of Bangladesh. The maximum reliability that can be achieved under average climate condition varies from 70 to 85% and the reliability does not increase significantly beyond the tank volume of 3,000 L. Under wet and dry climatic conditions, the maximum achievable reliability is about 70%. A higher reliability under average climate condition with higher roof catchment area is observed mainly due to presence of some rainfall in the dry periods due to averaging over 10 years' period. This analysis also indicates that a huge quantity of water is lost as spilled water for tank sizes varying from 500 to 5,000 L. The spilled water volume significantly increases with an increase in catchment area. The potential uses of rainwater can be increased by capturing the huge spilled water with a larger tank.

Tank capacity is an important consideration to maximize rainwater storage. In order to determine the optimum tank volume, amount of rainfall and its distribution, roof area and water uses are the critical factors. There are numerous optimum solutions with different combinations of storage volumes, roof sizes and rainwater demand. The analysis presents here can be used as a tool in planning for reliable and sustainable rainwater harvesting in a particular geographical area of Bangladesh, before undertaking a rainwater harvesting project for domestic water supply.

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