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Developing Design Curves for Rainwater Harvesting in the Coastal Region of Bangladesh

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Abstract

The potable water crisis in the southwestern coastal zone of Bangladesh arises due to the saline intrusion into surface and groundwater. Rainwater harvesting can be a potential alternative water supply source in coastal regions as these regions receive a large quantity of annual rainfall > 2400 mm. Government agencies and non-government organizations (NGOs) have provided rainwater harvesting systems with a storage tank ranging from 0.5-5 m^3 without assessing the optimal storage tank required for residents considering rainfall, family size, water demand, and catchment area and thus limiting rainwater harvesting (RWH) system's functionality to the wet season only (6-7 months). The current study aims to develop design curves for a reliable RWH system for three climate conditions (wet year, dry year, and average year) using the mass curve and subsequent peak algorithm techniques for 13 coastal stations, considering the factors such as available catchment area (20-70 m^2), rainfall loss, water demand 0.01 m^3/day, and household sizes (4-11). To assess the tank's reliability and determine the spilled volume, a spreadsheet-based daily water balance model was developed. Slight variations have been observed in dry and average-year climates, but reliability for the same tank during the wet year ranges between 82 and 85 percent. The economic analysis also reveals that the tank will have a return period of 6-10 years. The developed design curves can be used as a guideline for building a storage tank in coastal Bangladesh to provide optimal drinking and cooking water for the longest possible span of a year.

Keywords: Rainwater harvesting, Water balance model, Design curve, Reliability, Coastal Bangladesh.

1. INTRODUCTION

The scarcity of potable water in the coastal region of Bangladesh is one of the significant challenges for the inhabitants in the twenty-first century. The southern coastal region of Bangladesh is the home of approximately 35 million people (BBS 2011). Locally built rain-feed ponds, pond sand filters (PSF), rainwater harvesting (RWH), and tubewell are commonly used water sources by coastal residents for drinking, bathing, and washing purposes (Ghosh et al, 2015). However, saline intrusion into aquifers and surface water reduces the effectiveness of PSFs and shallow tubewell in supplying fresh water. Although deep tubewell can be a solution in coastal regions for its low concentration of salinity, according to Kabir et al (2021) the water contains heavy metals like arsenic, cadmium, iron, and chromium; thus, limiting access to safe potable water and also the cost is very high. To ameliorate drinking water problems in the coastal region, several programs have been undertaken in recent years to promote and install home and community-based RWH systems as the most suitable option for fresh water supply sources as stated by Islam (2015). Rainwater is a suitable potable water source as it is free of salinity, physical and chemical quality is acceptable and also free of microbial contamination (if harvested properly), and can be easily harvested from rooftops. Rainfall in the coastal areas is much higher (> 2400 mm) and roof catchments are suitable (Karim, 2010). Thus, RWH is a good promising

alternative waste supply option in the coastal areas of Bangladesh. The main component of the RWH is the storage tank, which must be assessed carefully for a reliable year-long water supply.
Without any prior analysis of the storage tank volume, the Bangladesh government and several NGOs have provided RWH systems with water storage tanks ranging from 0.5 to 3 m^3 or more (Karim et al, 2015). Due to insufficient storage tank volume, residents are availing water from the RWH systems for about 6 to 7 months and thus depend on unreliable and unsafe water sources like a pond and other surface water for the rest of the year. The coastal region of Bangladesh experiences heavy rainfall of more than 2400 mm, thus, the RWH system could be a potential water source for coastal residents if the system is properly designed. The objective of the study is to develop the design curves for a reliable RWH in the coastal areas of Bangladesh. Design curves for the coastal region were developed, considering RWH factors such as climatic conditions (wet, dry, and average), catchment sizes, water demand, and runoff coefficient. The design curves will assist the authorities in selecting the appropriate storage tank volumes for the year-long availability of harvested rainwater for use in drinking and cooking purposes. An economic analysis was also provided to support the decision-makers in adopting the appropriate tank size for a particular family size.

2. DATA

Daily rainfall data for 29 years (1991-2019) was collected from the Bangladesh Meteorological Department (BMD) for 13 stations covering the coastal region like Bhola, Barishal, Chittagong, Cox's Bazaar, Feni, Khepupara, Khulna, Mongla, Patuakhali, Sandwip, Satkhira, Shitakunda, and Teknaf. Three climatic conditions were chosen from the data based on total annual rainfall: a wet year (the year with the most rainfall), dry year (the year with the least rainfall), and an average year (the year equivalent to the average rainfall). Table 1 shows the selected year and corresponding rainfall for all stations. A catchment area ranging from 20-70 m^2, and a drinking and cooking water demand of 10 lpcd for a family size ranging from 4 to 11 were considered for developing the mass curves, as specified by Ahmed and Rahman (2000), and the BBS (2011). Moreover, in this model, reliability and economic analysis (payback period) were estimated for various tank sizes (0.2-8 m^3), and catchment areas (20-70 m^2) for a family of six people for each climate condition.

Table 1. Annual rainfall under different climatic conditions in the coastal area

Rainfall Station	Dry Year		Wet Year		Average Year	
	Year	Rainfall (mm)	Year	Rainfall (mm)	Year	Rainfall (mm)
Bhola	2012	1493	2004	3080	2006	2160.28
Barishal	2018	1418	1998	2858	2006	2048.72
Chittagong	2016	2208	2007	4340	1997	2974.17
Cox's Bazaar	2014	2483	2015	4716	1996	3736.62
Feni	1992	1748	2017	4476	2009	2952.93
Khepupara	2014	1877	1995	3510	1997	2890.34
Khulna	2018	1073	2002	2594	1997	1815.62
Mongla	1992	1232	2002	2786	2004	1962.17
Patuakhali	2012	1895	2015	3098	1997	2563.69
Sandwip	1995	2234	2001	6095	2007	3693.62
Satkhira	2018	1292	2011	2121	1998	1716.69
Shitakunda	2006	2031	2017	4868	2004	3249.03
Teknaf	2014	3507	2015	5447	2003	4401.55

3. METHODOLOGY

The most widely used technique for determining the storage volume is a behavioral analysis using a mass balance equation as suggested by Khan et al. (2017), Imteaz et al. (2017). The sequent peak algorithm and mass curve or ripple technique based on daily water demand were used to formulate the mass balance model. In Microsoft Excel, a behavioral model was formed considering daily rainfall, roof-catchment area, runoff coefficient, tank volume, and water consumption as per the approaches adopted by Karim et al. (2015), Imteaz et al. (2017). To determine the optimal storage, the model was run with a daily time resolution using daily rainfall amounts for three climatic conditions. Daily rainfall, catchment area, and the runoff coefficient (0.90) were multiplied to estimate the daily runoff volume. The storage tank was assumed to receive the generated runoff. The daily accumulated water was calculated by deducting the daily water demand from the prior storage and daily runoff. Whenever the volume of the storage tank is insufficient to accumulate runoff, the spilled water was calculated by subtracting the capacity from the accumulated runoff. The mass balance equations are given by:

$$T_s = V_t + T_{s-1} - WD \quad (1)$$
$$T_s = 0;\ for\ T_s < 0 \quad (2)$$
$$T_s = C;\ for\ T_s > C \quad (3)$$
$$S' = T_s - C;\ for\ T_s > C \quad (4)$$

Where, T_s is the cumulative water stored in the RWH tank after the t^th day, V_t is the harvested rainwater on t^he day, T_{s-1} is the storage in the tank at the beginning of the t^th day, D is the total daily water demand, C is the tank capacity, and S is the spilled water volume. In the current study, volumetric reliability was computed to estimate the overall efficiency of the system as suggested by Bashar et al. (2018) and Imteaz et al. (2017). The volumetric reliability is expressed as:

$$Volumetric\ Reliability,\ R_v = \frac{volume\ of\ water\ harvested\ in\ a\ year}{Total\ harvested\ rainwater} x100 \quad (5)$$

The economic feasibility of the RWH system has been estimated using the payback period which is the estimation of the time it will take for the revenue, savings, and other benefits to fully recover the initial investment. As suggested by Blank and Tarquin (2005), the payback periods (n) were calculated using the following formula, with the value of net present value (*NPV*) set to zero

$$Net\ Present\ Worth,\ NPV = -IC - AC\left(\frac{P}{A}, i\%, n\right) - S\left(\frac{P}{A}, i\%, n\right) \quad (6)$$

where *IC* is the fixed cost, *S* is the annual savings, *AC* is the maintenance cost, *n* is the payback period, *i* is the internal rate of return (%), and *P/A* is the conversion factor of the annual cost to the present cost for *i%* rate of return in *n* years.

4. RESULTS AND DISCUSSION

In this study, several design curves were developed for different climatic variations comprising 13 coastal stations of Bangladesh to estimate the storage volume required for a family. A typical storage-volume-demand relationship for Teknaf and Khulna for different family sizes over an average year is shown in Figure 1. The graph outlines that storage volume increases with family size and decreases with the increment of the catchment area. A family of six would require a storage volume of 9.74 m^3 and 4.88 m^3 in Teknaf and Khulna, respectively, for an average year rainfall condition with a roof catchment area of 50 m^2 and water demand of 0.06 m^3/day. The design curves show that Khulna requires less optimal storage for rainfall variations than Teknaf for average climate conditions. Similar design curves have been developed for other regions in the coastal areas and can be used to estimate the optimal RWH tank storage volume required for a family for the year-round water supply.

Table 2 summarized the optimum storage volume required to provide year-round drinking and cooking water for a family of six people at each of the 13 stations under different climatic variations. The analysis shows that the optimum storage volume for a station during a dry year is usually less compared to an average or wet year due to a lack of adequate rainfall. However, due to the diurnal variation of annual rainfall, several stations of the study- Cox's Bazaar, Feni, Khepupara, Khulna, Satkhira, and Shitakunda, have higher optimum storage volume in dry climate conditions. During the dry year, total annual rainfall was lower in these stations, but the number of rainy days was significantly higher. According to Karim et al (2015), the dry year's daily rainfall has been more effective in meeting daily demands, thus higher storage volume compared to the wet and average year.

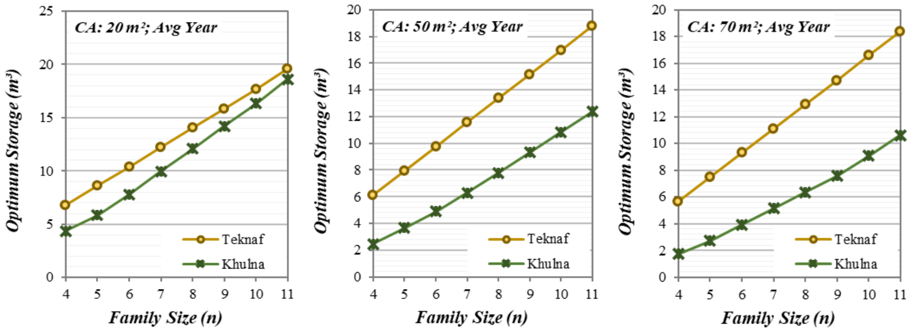

Figure 1. Typical storage-volume-demand relationship of harvesting tanks under average climate conditions (Stations: Khulna and Teknaf)

Table 2. Optimum storage volume required for a family of six under climatic variation

	Catchment Area	20 m²			50 m²			70 m²		
	Climate condition	Dry	Wet	Average	Dry	Wet	Average	Dry	Wet	Average
	Optimum Storage Volume Required (m³)									
Rainfall stations	Bhola	8.20	8.90	11.77	7.83	8.58	10.34	6.83	8.36	9.92
	Barishal	8.81	8.86	11.14	7.83	7.95	8.81	7.28	7.36	8.68
	Chittagong	6.03	6.31	6.26	4.71	4.83	4.88	4.32	4.72	4.67
	Cox's Bazaar	11.37	8.02	6.80	9.35	4.88	5.16	8.11	3.92	5.02
	Feni	8.98	5.44	8.84	4.71	3.54	6.50	4.39	3.54	5.94
	Khepupara	10.10	8.68	7.25	8.97	8.12	4.68	7.59	7.74	4.07
	Khulna	10.91	7.21	7.81	9.18	5.96	4.88	8.87	5.43	3.92
	Mongla	7.81	7.77	9.03	5.07	5.19	8.67	4.69	4.77	8.49
	Patuakhali	7.51	7.73	7.88	5.06	5.73	5.72	4.89	4.92	5.35
	Sandwip	5.95	8.34	9.79	3.77	7.26	8.09	3.72	6.54	7.35
	Satkhira	9.78	9.66	7.37	8.61	7.16	6.01	8.43	7.14	6.28
	Shitakunda	10.74	6.43	9.03	8.88	5.04	8.90	8.81	4.14	8.81
	Teknaf	10.03	7.82	10.41	8.43	6.14	9.74	7.55	5.69	9.29

Figure 2 illustrates a typical reliability curve for various tank sizes (0.2-8 m³) for the stations under climate variations for a family of six. The graph shows that the reliability of the RWH system increases with catchment area and tank size. The maximum achievable reliability in average climate conditions ranges from 70% to 85%. In wet and dry climate conditions, the maximum achievable reliability is 85%, as shown in Figure 2. In comparison to Teknaf, Khulna offers a more reliable RWH practice because, in an average climate, it can achieve up to 85–90% for a catchment area of 70 m². Regardless of tank volume, there is no significant increase in reliability for any station with a tank larger than 4 m³. The daily rainfall analysis reveals that achieving a 100% reliable RWH system for the currently used storage tanks is difficult, forcing residents to rely on alternative sources.

According to Khan et al. (2017), spilled water has the opposite effect on the tank capacity and thus overestimates the water which can be supplied by the tank. The smaller catchment area with a larger tank size will have no or less spillage volume than the larger catchment area with a smaller tank volume. Spillage volume decreases with the increase in tank size, so a larger catchment area with a smaller tank size will not be effective in preventing overflow, especially in the rainy season.

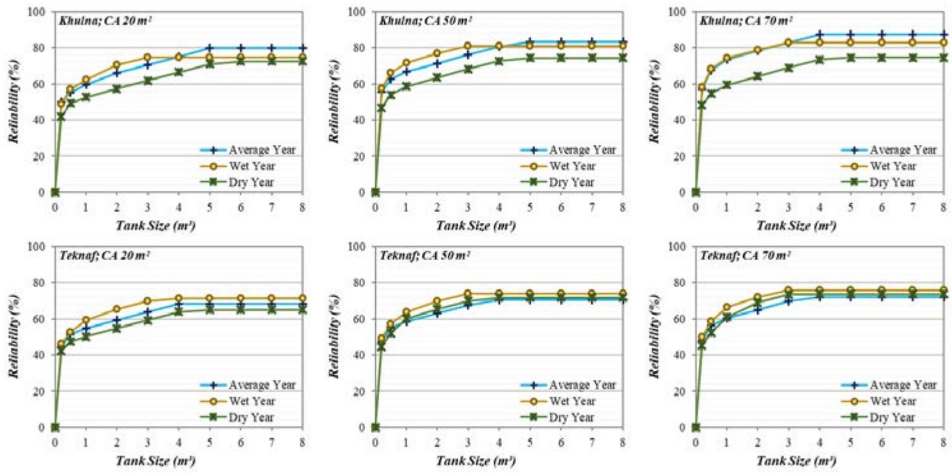

Figure 2. Volumetric and time reliability curves for fixed family size (6) under varying climatic conditions (Stations: Patuakhali, Khulna, and Teknaf).

Table 3 shows the payback period for a 5 m^3 tank for a family of six with a catchment area of 50 m^2 under various climatic conditions. Each year, the annual savings are calculated based on the water savings. An initial investment of 1500 BDT and annual operating and maintenance costs of 200 BDT with a 0.50% internal rate of return was considered. Although the expected payback period under all climate conditions ranges between 6 and 10 years, the period exceeded 10 years in some stations- Bhola, Cox's Bazaar, and Teknaf. Even though the southeast region of the coast experiences a lot of rain, the payback period may not necessarily be shorter because much of it is lost as spilled water. The financial feasibility of an RWH system is determined by the initial cost, the demand for harvested water, and the water price, according to Campisano et al. (2017). As a result, increasing the monetary savings from harvested rainwater will shorten the payback period in the future.

Table 3. Payback period (year) for different stations for a tank volume of 5 m^3

Rainfall Station	Dry Year	Wet Year	Average Year	Rainfall Station	Dry Year	Wet Year	Average Year
Bhola	7.97	9.18	10.51	Mongla	6.82	7.14	7.12
Barishal	8.44	4.86	7.57	Patuakhali	6.70	7.01	6.04
Chittagong	7.33	6.53	2.06	Sandwip	5.93	8.51	7.47
Cox's Bazaar	10.19	7.30	6.77	Satkhira	10.34	8.26	5.41
Feni	6.78	5.91	8.69	Shitakunda	9.63	6.19	9.48
Khepupara	9.66	8.65	5.98	Teknaf	9.24	8.28	11.35
Khulna	9.72	7.01	7.55				

Note: Dry year and wet year are the weather conditions as mentioned in Table 1.

5. CONCLUSION

A water balance model based on daily rainfall is used in this study to analyse data from all coastal stations and develop design curves for optimum storage for climatic variations. According to the analysis, the existing tanks are insufficient to meet the daily water demand of coastal residents. As a result, the developed graphs can be used as a guideline to design a long-term and sustainable rainwater harvesting system for coastal residents. The reliability analysis of different stations along the coast reveals that the southwestern region achieves higher reliability than the south-eastern region. However, due to the seasonal variance and diurnal variation of rainfall 100 percent reliability for household harvesting systems is difficult for currently used tanks in the coastal region of Bangladesh. The maximum reliability under average climatic conditions ranges from 70-90%, and reliability does not considerably rise above the tank volume of 4 m^3. The maximum reliability that can be achieved in both wet and dry climates is around 85%, indicating that considerable amounts of water will spill from tanks ranging in size from 0.2 to 8 m^3. As a result, increasing tank capacity can be considered for the water economy but it does not impose any significant change in reliability. The economic analysis of the payback period reveals that the payback period ranges from 6-10 years for a typical RWH system with a tank volume of 5 m^3 and a catchment area of 60 m^2. Following the completion of this type of analysis, the local authorities will be able to provide adequate subsidies to residents and establish the practice of RWH to a large extent for the people of the coastal region of Bangladesh.

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