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Evaluating the Feasibility and Economic Viability of Rainwater Harvesting in Commercial Buildings: A Case Study of Dhaka, Bangladesh

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ABSTRACT

Rainwater harvesting (RWH) is most widely used in residential sectors, with the commercial building sector being quite rare and where most are just piloting a very negligible number of projects, especially on the corporate side. This study finds the feasibility and economic viability of RWH systems in commercial buildings in Dhaka, Bangladesh, where the supply of water is increasingly crucial. A daily water balance model was developed for simulating rainwater collection under various climatic conditions of commercial buildings and for different catchment areas and tank capacities. Water-saving potential, payback periods, and benefitcost ratios were analyzed to judge the economic viability of the RWH systems. The results are expected to show high levels of savings due to dependence on municipal water supplies; fairly short payback periods and benefit-cost ratios support the economic sustainability of RWH. To the extent that results may vary for other cities with different climates and economic scenarios, this study points to the wider general applicability of RWH as one viable option in areas where rainfall is adequate to support human consumption.

Keywords: *Rainwater harvesting; Economic validity; Payback period; Water Balance; Simulation Model; Reliability*

INTRODUCTION

Rainwater harvesting (RWH) is a sustainable approach to urban water cycle management. It has many benefits, including the ability to reduce a city's external water demand and ease regional water stress by promoting significant potable water conservation, lowering pollution loads from non-point sources, lowering urban runoff, preventing flooding, and lessening the effects of climate change.

Numerous water organizations and river basin authorities are actively working to control water demand while exploring alternative sources such as greywater and wastewater recycling, desalination, and rainwater harvesting. Of these alternatives, rainwater harvesting has garnered significant interest globally [2]. Rainwater harvesting involves gathering rainwater from different surfaces like rooftops, roads, and station areas during rainfall, saving it in tanks for use as a substitute for tap water for both potable and non-potable activities [3] [4]. The implementation of RHS not only conserves water but also alleviates stormwater runoff that requires to be maintained during rainfall occasions [2]. Controlling peak discharge and stormwater runoff volume was reported as further advantages of RHS [4]. Remarkable investigations have been conducted to examine the financial feasibility of the installation of RHS [5]. [6] reported that the financial feasibility of RHS could be obtained in areas with more rainfall for reasonably designed RHS. [7] [8] reported that collecting rainwater is less expensive than desalinating seawater at energy-based desalination plants in four major Saudi cities.

Bangladesh ranks sixth in the world for countries with the largest estimated annual groundwater extraction, according to the "U.N. World Water Development Report 2022." Groundwater extraction became widespread in Bangladesh after the country gained independence in 1971, owing to a scarcity of potable drinking water. Currently, roughly 98% of the population relies on groundwater for drinking water, while groundwater sources meet approximately 77% of irrigation needs. According to collaborative research conducted by the Directorate of Groundwater Hydrology and the World Bank, the country withdraws an estimated 32 cubic kilometers (7.7 cubic miles) of groundwater per year, with 90% being utilized for irrigation and the remainder for home and industrial reasons. According to a study by the Bangladesh Water Partnership (BWP) and supported by the 2030 Water Resource Group (2030 WRG)- groundwater levels in the greater Dhaka area might drop by 3 to 5.1 meters (9.8 to 16.7 ft) per year by 2030, which is nearly 70% quicker than the current rate. DHAKA— Bangladesh is looking to recharge its aquifers with storm water, reclaimed water, desalinated water and potable water, in an effort to ward off the depletion of this precious resource.

The BWDB has already conducted MAR pilot projects in Dhaka and the Barind Tract, as well as coastal areas. MAR, which will increase freshwater availability for drinking, agriculture, industry, and environmental protection. Along with Dhaka and the Barind Tract, the BWDB has recognized the Gazipur region and coastal areas as having significant groundwater stress. Rainwater harvesting can help to replenish aquifers in Dhaka, Gazipur, and the coastal districts. Rooftop rainwater harvesting in cities can help to reduce flooding and waterlogging. However, there are very few studies on rainwater harvesting in public or commercial structures compared to those focused on residential properties, and there have been no investigations into commercial buildings in Bangladesh. Due to elevated water costs in the commercial sector and increased rainfall, rainwater harvesting (RWH) in commercial structures may serve as a viable alternative source for non-potable water, leading to considerable financial savings while also alleviating the strain on the city's water supply. Therefore, it is crucial to explore the practicality, efficiency, and potential savings in both water and money through a rainwater harvesting system in commercial buildings in Dhaka. The aim of this study were to investigate the economic benefits and water-saving potential of RWH in multi-story commercial buildings for nonpotable water demands (such as floor cleaning, toilet flushing, and car washing) in three different climate conditions (wet, dry, and normal year) in Dhaka. In order to facilitate and validate the results from the water balance model, the other integrated objectives of this study were to identify the precipitation events that were extreme, heavy, moderate, low, and nonexistent in the study regions using Python.

MATERIALS AND METHODS

Study Area

In spite of being a riverine country, Bangladesh's water demand is increasing day by day for the purposes like agriculture, residential and commercial because of the population and economic development [8]. Our study area Dhaka, known as the capital of Bangladesh which is the ninth-largest and seventh-most densely populated city in the world. The density of the city is 23,234 people per square kilometre within a total area of approximately 300 square kilometre [9]. In Dhaka, the mean annual precipitation averages around 2200 mm with 75% of it received during the monsoon period which lasts from June to October [10]. By installing efficient rainwater harvesting systems, rainwater can become a viable water source in Dhaka city. Data obtained from the NASA Power Satalite (Retrieved from: https://power.larc.nasa.gov/data-access-viewer/).indicates that from 1994 to 2003, the average annual rainfall in Dhaka ranged from 1500 to 2300 mm, equating to 1.50 to 2.30 cubic meters of rainwater per square meter of land annually. A research conducted by United Nations Environment Program in 1982 found with reservoirs holding 1100 gallons and an average rainfall of 72 inches, enough water could be collected in 12 hours to sustain a household of six for 45 days. According to the BNBC, water usage for domestic purposes in Dhaka varies between 40 to 260 liters per person per day (lpcd), while the water usage for commercial activities ranges from 3 to 450 lpcd [11]. Generally, the water supply system maintained by Dhaka WASA relies on groundwater resources. Water is drawn from 887 deep tube wells while utilizing surface water taken from the Shitalakshya and Buriganga rivers which passes through four water treatment plants [11]. Although this water shortage greatly affects the residents of the city regarding their water usage, it however is also having an effect on the waste load on the sewerage lines. Economic extraction and usage of water supply, more seriously, is also a major problem for the consumers and suppliers as well. For the analysis, data of roof catchment areas and underground reservoir capacity were collected from 5 commercial buildings which are at different parts of Dhaka.

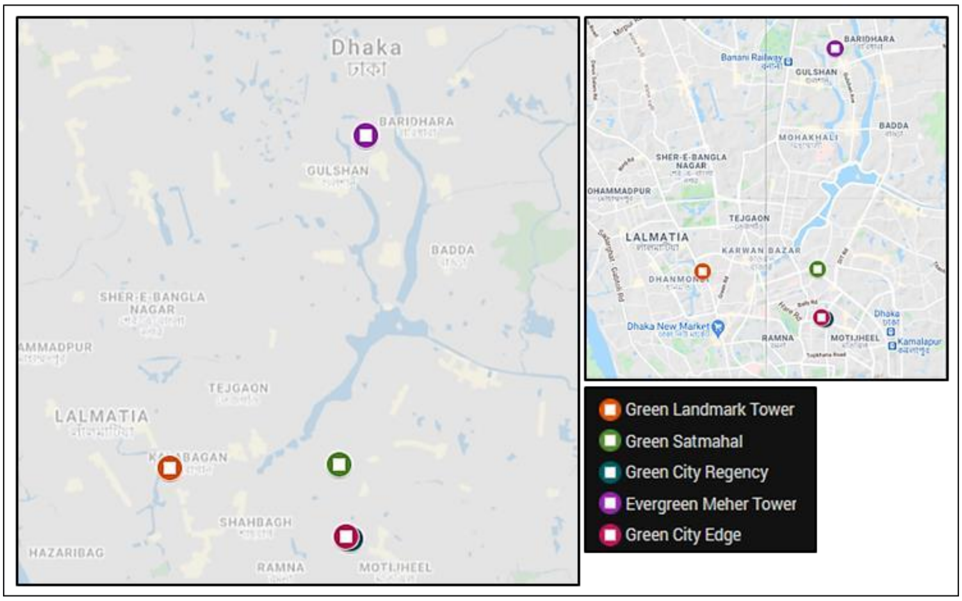


Figure 1 Map and location of selected commercial buildings in Dhaka [13].

2.2. Data Source

For 42 years (1981–2023), Dhaka's historical daily rainfall data was gathered from the NASA Power Satellite. The rainfall data was examined for both the average annual rainfall over the 42-year period and the annual rainfall for each year. Wet year, dry year, and normal year were the three climate scenarios for which the model was run. The years with the highest annual rainfall (1934 mm) and the lowest (1169mm) were designated as the wet year (2007) and the dry year (1992), respectively. A year that had an annual rainfall that was nearly equal to the average for the previous 42 years (1767 mm) was deemed normal (2002).

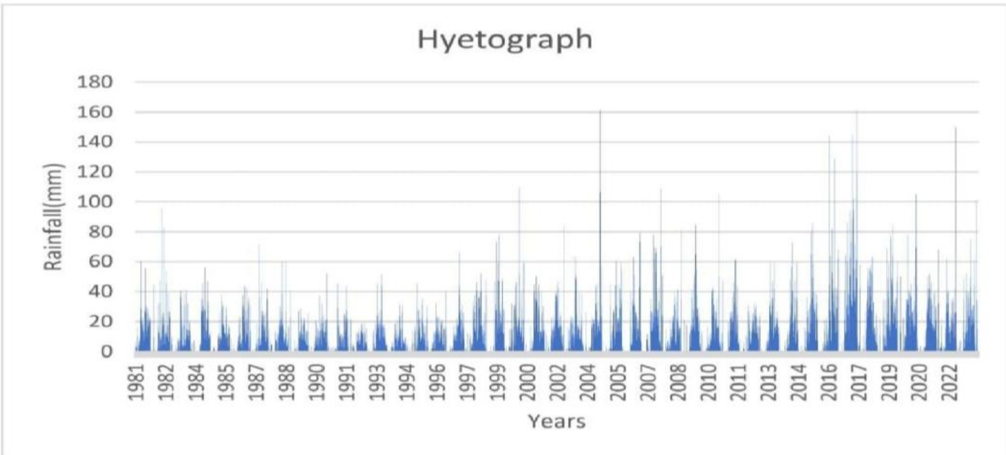


Figure 2 Annual rainfall variations (1981–2023) in Dhaka [13].

Figure 2 illustrates the annual rainfall (mm) in each year. Taking into consideration a 150 mm deviation from the average annual rainfall, the normal years occurred 7 times (1990, 1996, 1997, 2000, 2002, 2006, 2008). Accordingly, having higher values from the average was considered as the wet years, which occurred 9 times (1988, 1991, 1993, 1998,1999, 2004, 2005, 2007, 2015). The dry years occurred 12 times (1989, 1992, 1994, 1995, 2001,2003, 2009, 2010, 2011, 2012, 2013, 2014) in this 42-year period.

A field survey was carried out for the current study in order to gather data about the underground reservoir capacity and roof catchment areas of five commercial buildings spread across Dhaka. Evergreen Meher Tower's roof catchment area was 315 m2, Green Landmark Tower's was 452 m2, Green Satmahal's was 532 m2, Green City Regency's was 562 m2, and Green City Edge's was 727 m2. These buildings' underground reservoirs had capacities of 162 m3, 109 m3, 114 m3, 324 m3, and 566 m3 to hold the city supply water, respectively.

Each building's reservoir served as a rainwater tank to hold the amount of rainfall that ran off the roof catchment (Figure 3). Storage reservoirs in Dhaka typically have an area of 100 to 600 m3, while the catchment area of commercial buildings typically falls between 300 and 800 m2. A commercial building must have a net usable area of 15 m2 per person, according to the BNBC [11]. Based on this, the estimated number of occupants in each commercial building was determined. The BNBC [11] states that the non-potable daily water demand, which was taken into account in this analysis, is between 30 and 45 L per capita per day (lpcd). Runoff coefficients between 0.8 and 0.9 were taken into consideration to account for different losses from net precipitation, and the runoff volume from the rooftop catchment area was computed daily. The survey data for the commercial building occupants, catchment size, and installation and maintenance expenses used in the model are shown in Table 1.

The commercial sector's water demand is primarily non-potable (utilized for tasks like cleaning floors and parking areas, flushing toilets, etc.), and it does not need to meet drinking water quality standards. Rainwater is viewed as the cleanest type of water and, when collected correctly, is free from harmful substances; it can be used for non-drinking purposes without presenting major health risks. The share of the water supply allocated for drinking is typically purified by water filters in each office section within the building; treatment for the collected rainwater is usually unnecessary and was not included in the annual maintenance cost calculations.

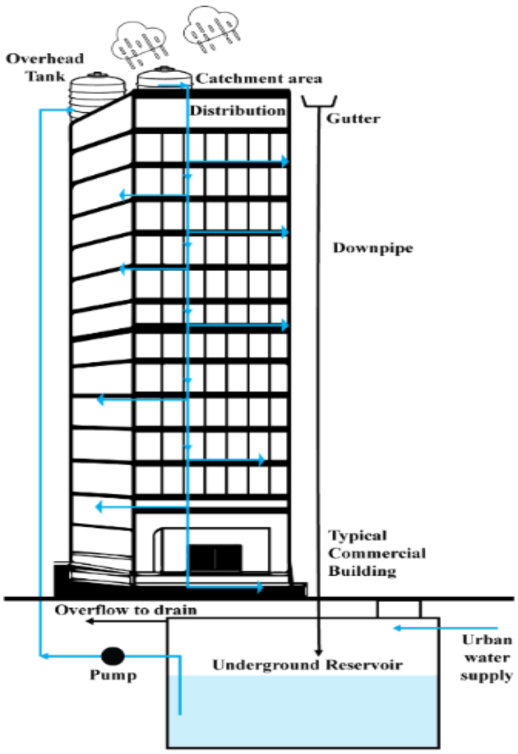


Figure 3 Typical commercial building and model assumption in a non- potable water supply system [13].

Operational and maintenance expenses were taken into account for an annual cleaning necessity. Since the underground water reservoir contains both rainwater and water supplied by DWASA, the maintenance expenses were shared between the two sources. An overall water usage of 30–40 lpcd (including the need for drinking water) as per the BNBC [11].was taken into account for the evaluation of commercial buildings.

Table 1 Surveyed data of the commercial buildings (catchment area, commercial activities, floors, occupants, tank size, installation and maintenance costs).

Building Names	Catchment Area (m2)	Commercial Activities	Total Floors	Total Occupants	Tank Size (m3)	Installation Costs (BDT) *	Maintenance Costs (BDT/Year) **
Evergreen Meher Tower	315	Offices, restaurant	2 Basement +14	294	162	30,000	10,000
Green Landmark Tower	452	Offices, doctors' offices	2 Basement +13	392	109	40,000	13,000
Green Satmahal	532	Offices, bank, and restaurant	2 Basement +14	496	114	45,000	15,000
Green City Regency	562	Offices, bank, and food court	2 Basement +22	824	324	50,000	18,000
Green City Edge	727	Offices, bank, and restaurant	2 Basement +15	727	566	60,000	20,000

BDT, Bangladeshi taka. * Installation costs include the cost of downpipe (PVC) and installation costs of downpipe and other fittings to convey the runoff into the underground reservoir, not the cost of construction of the underground reservoir. ** Maintenance costs include annual maintenance of downpipe and other fittings and cleaning of the tank. [13]

Simulation and Interpretation of Water Balance Model

The meteorological data was pre-processed at the time of collection to ensure the rainfall data could be sectioned into 7 groups. Days without rain are characterized as spring (March–May) and autumn (September - November) days featuring at least three millimetres of rainfall, and summer (June–August) days with at least 5 millimeters of rainfall . The period of time with the highest number of consecutive days without rain can be utilized to gauge the severity of a drought [14] It is also referred to as an "extraordinary drought" if these days without precipitation occur throughout two or three different seasons. "Light rain" denotes rainfall that totals less than 10 mm within a 24-hour period. Rainfall measuring between 10.1 and 25.0 mm over 24 hours is classified as "moderate rain." "Heavy rain" is identified by precipitation levels ranging from 25.1 to 50.0 mm in a 24-hour timeframe. "Rainstorms" are described as precipitation amounts that range from 50.1 to 100.0 mm within a 24-hour duration [15]. "Heavy rainstorms" are defined as periods of precipitation with a total precipitation of between 100.1 and 250.0 mm in 24-hours. Last but not least, "extraordinary rainstorms" are rainfall events that produce more than 250.0 mm of precipitation in 24-hours [16]. An inventive method created using the Python programming language and Jupyter Notebook was used to determine the total number of days connected to each precipitation event. To organize and analyze data, the "Pandas" library was established. The dataset was then entered into the system in the.xlx file extension. A constructed conditional function was used to classify the precipitation data. By replacing any missing numbers with zero, the unstack method reorganizes the grouped data to make it easier to understand.

The current study's simulation model was constructed using the following essential data: the area of catchment, tank size, total occupants, and water consumption. These parameters were utilized to determine the RWH capabilities, reliability for the RWH, and the potential for water saving. Using the roof area as a starting point, the value range for the catchment area is set at 315,452, 532,562, and 727 square meters, respectively. This research considers five various sizes of storage tanks: 162 kL, 109 kL, 114 kL, 324 kL, and 566 kL. The modeling of the water balance is created using the Microsoft Excel spreadsheet program. The current study has produced a number of spreadsheets for various combinations of selected factors. Total days, total water-spills, total water savings, and total tank-filled days were calculated using the computation sheet once the supplied data was completed. By using important formulations and logic, the aforementioned characteristics have been determined before. CIA, where I represents the amount of rainfall, A represents the size of the roof catchment, C represents the coefficient of runoff determined by the kind of roofing used in the region in question, and Q represents the maximum runoff. The initial period of rainfall that washes the majority of rooftop's dust and debris is known as First Flush(Lay, [17]. A number of variables, including terrain, vegetation cover, rainfall intensity, land use, soil type, and human activity, affect the runoff coefficient by determining how much water seeps into the ground as opposed to producing surface runoff [18]. The first flush was determined using a runoff coefficient of 0.8 and 40L or 0.04kL [16]The following formula is then used to calculate the total discharge: Runoff x runoff coefficient - first flush equals total runoff. This considers initial flushes, runoff, and the runoff coefficient. Although the total runoff will be expressed in kL, the value will be 0 if f the logic result is less than 0. Eventually, using the reasoning provided in Equation (1), the following spill will be identified.

$$Spill = Storage\ level\ before\ usage + Total\ runoff - Release - Tank\ size \quad (1)$$

$$Reliability = \frac{Total\ number\ of\ days\ when\ demand\ was\ fulfilled}{Total\ number\ of\ days\ analysed} \quad (2)$$

Afterwards, tank filled days and water savings are calculated consecutively using the corresponding specifications. Another sheet has been developed to evaluate the water savings and reliability of the RWHS based on these computed values. Equation (2) yields the reliability of RWHS [16] The RWHS model's outline and material selection may be carried out once the required data have been obtained. The building expenses of the RWHS in the study area may then be estimated. The price difference between these two systems is huge since the Bangladeshi municipality mostly uses a conventional water delivery network. The present study aims to compare the expenses of the traditional system in order to ascertain if the RWHS is a simple reservation method that is easily accessible and economically viable in the region under consideration. The complete procedure for the municipality includes the following phases: surveying, planning, design, pre-construction, construction, and monitoring. RWHS costs include site selection, material costs (such as tanks, pipelines, reservoir base, filters, and leaf trap), installation, and maintenance.

RESULTS AND DISCUSSION

RWH Potential from Python Simulation

Droughts, light rain, moderate rain, heavy rain, heavy rainstorms, rainstorms, and unusual rainstorms are the seven types of rainfall occurrences that occur in Dhaka, as shown in Figure 4. According to research, Dhaka station experiences, on average, 126 days of drought, 190 days of light rain, 37 days of moderate rain, and 8 days of heavy rain year. Dhaka is less likely to see unusual rainstorms because it is a region that is prone to drought.

This station is extremely drought-prone and water-demanding, as seen in Figure 4. For RWH potentials, this station might be selected. For small commercial building, rainwater collection might be focused on days with moderate to heavy rainfall. Light rainy days may also be better for collecting rainwater for offices, schools, universities, and commercial buildings. Potable water can therefore be provided for a sizable portion of the year. As a result, both stations' groundwater extraction pressure will drop.

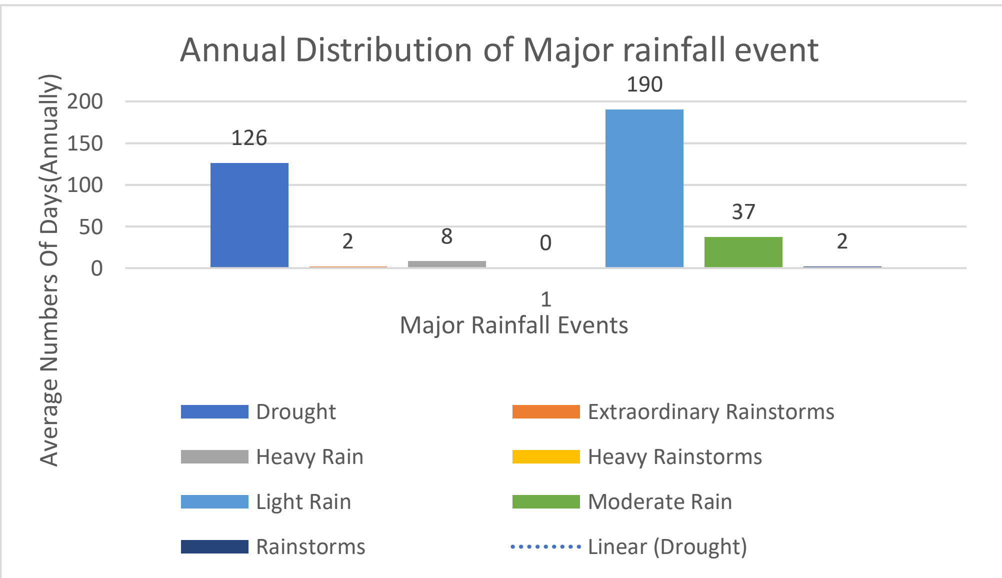


Figure 4 Annual Distribution of Rainfall Events for Dhaka

RWH Potential from MS Excel

Table 1 displays the water savings and dependability numbers together with the associated tank capacity that were determined in Dhaka using an MS Excel spreadsheet. The dependability and water savings graphs, together with the associated tank size, have been plotted using the data from Table 1.

This graph is a detailed comparison of tank size(m2) which varied from 0 to around 600 m2 and reliability (%) for 5 distinct catchment areas which are-727,315,562,532 & 452 m2.Here the analysis – The impact of catchment area , Reliability increases with the increase of catchment area as larger area capture more water. Here the most large catchment area(727 m2) achieved higher reliability compared to smaller areas(e.g.315 m2) for the same tank size. Now tank size and Reliability : Reliability is low for the tanks with small capacity. • The increase in reliability is slow after tank size surpass a certain limit.(e.g.400-500 m2),indicating diminishing returns. The increase in reliability can be slow for various factors such as-Diminishing return, Catchment area limitation, Water demand vs. Supply, Saturation point, Evaporation and overflow losses. The final observations are for a maximum value of reliability a balance between tank size and catchment area is

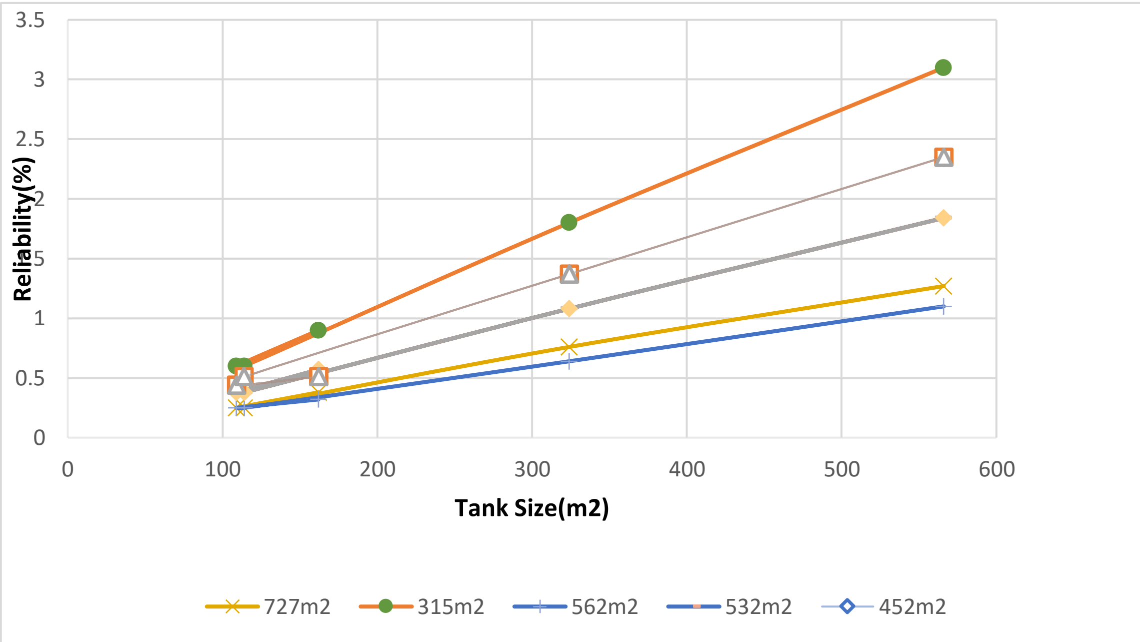
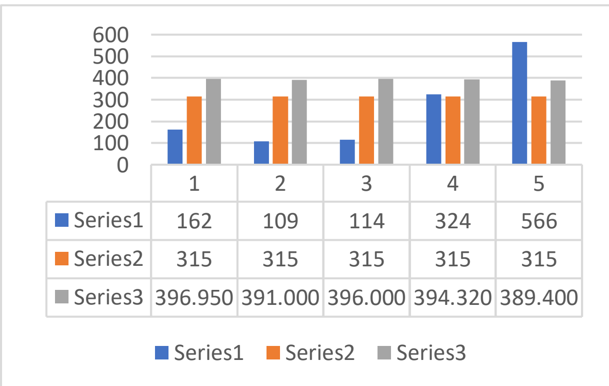
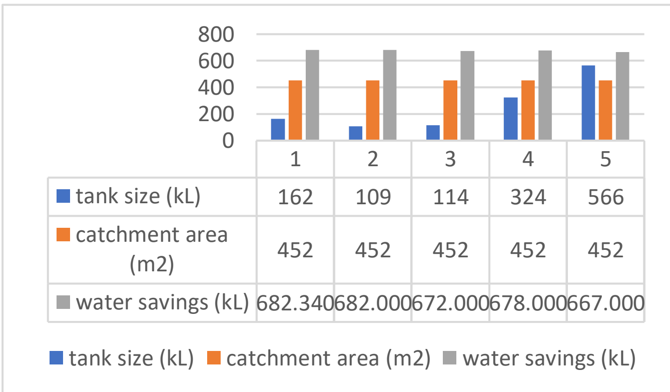


Figure 5 Water reliability obtained by proposed RWHS in 5 commercial buildings in Dhaka

necessary and Increasing tank size can improve reliability only up to a point for small catchment areas





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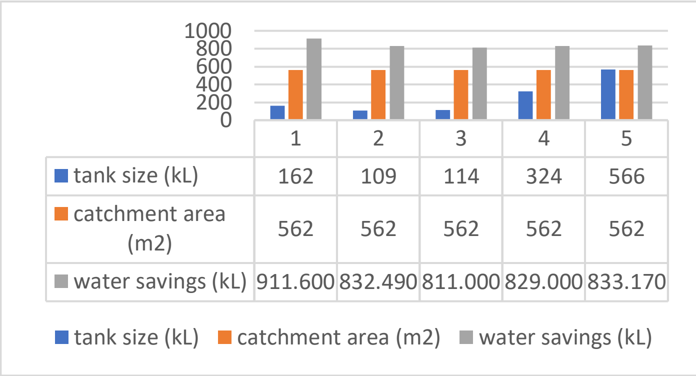

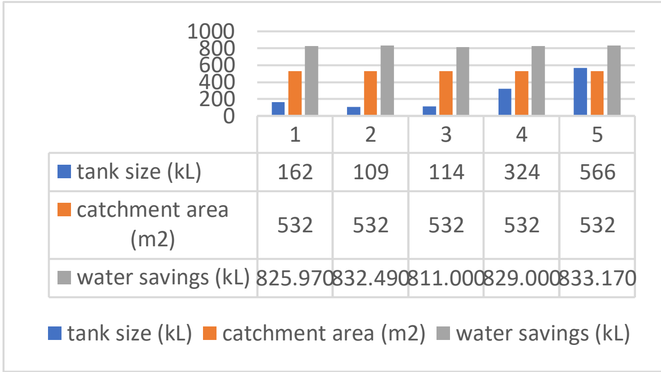

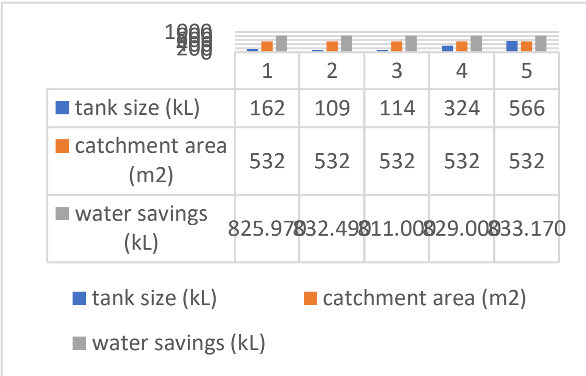

Figure 6 Water savings obtained by proposed RWHS for 5 commercial buldings in Dhaka

There is no uniform correlation between tank size and the quantity of water conserved. For instance, the catchment area of 566 m2 has the highest water savings of 911.6 kL with the tank size of 162 m2 and lowest 829 kL with the tank size 324 m2.On the other hand,the catchment area of 727 m2 has the highest water savings of 1205 kL with tank size 114 m2 and lowest 1192 kL with the tank size of 566 m2 . This indicates that factors beyond just the tank size, such as efficiency and usage habits, may significantly influence water conservation. Given that the catchment area stays the same, the differences in savings are mainly influenced by variation in tank size and possibly external operational influences. As choosing the appropriate tank size for commercial buildings is a issue here, some practical considerations can be taken. Such as- Available Space: Checking that the tank size are appropriate for the building's space constraints. Budget: Larger tanks come with higher initial costs; so achieving a balance between size, budget, and operational needs is important. Overflow Management: Plan for potential overflow during heavy rainfall to prevent water loss or structural damage. Restrictions: Follow local restrictions for commercial rainwater collection systems.

Cost analysis

Catchment area (m^2)	Estimated Cost (Tk)
315	22,057
452	31,650
532	37,252
562	39,352
727	50,906

CONCLUSION

This study focuses on the feasibility and economic viability of deploying rainwater harvesting (RWH) systems in business buildings in Dhaka, Bangladesh. The study indicates significant water savings, reduced reliance on municipal water supplies, and favorable payback times by utilizing a daily water that greater catchment areas and correctly sized storage tanks increase reliability and water-saving potential. The findings also highlight the significance of balancing tank size, catchment area, and operational issues in order to maximize efficiency and cost-effectiveness.

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