بسم الله الرحمن الرحيم

RELIABILITY ANALYSIS OF URBAN RAINWATER HARVESTING: A CASE STUDY OF DHAKA CITY

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DECLARATION

We hereby declare that the undergraduate project work reported in this thesis has been performed by us and this work has not been submitted elsewhere for any purpose except for publication.

November 2014

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Md. Zobair Ibne Bashar

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Khondokar Kamrujjaman Nabil

Dedicated to

Our Beloved Parents

ACKNOWLEDGEMENT

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ABSTRACT

Rainwater harvesting is a decentralized practice that provides both water supply and runoff reduction benefits that are often difficult to assess. In a city like Dhaka where the water table is falling rapidly & concrete surfaces and landfill dumps are taking the place of water bodies due to increased population and water demand as well, non-conventional water resources such as rainwater harvesting must be introduced to partially offset the increasing water demand.

According to the upcoming Bangladesh National Building Code, every building proposed for constructing on plots having extent of 300 square meter or above shall have the facilities for conserving and harvesting rainwater though a very few studies have been carried out to check the efficiency of rainwater harvesting in Dhaka city. The research presented in this paper is undertaken in the light of current knowledge gaps to access the efficiency of a RWH system in Dhaka to provide guidance to water authorities to enhance the acceptance of a RWH system.

The objectives of this research is to analyze the reliability of a rainwater harvesting system, to utilize programming and visualization to assess the efficacy of a rainwater harvesting system and to assess the economic savings if rainwater harvesting system is integrated with the supply water system.

This paper investigates the applicability and reliability of rainwater harvesting (RWH) systems to meet the daily water demand in the multistoried residential buildings in combination with the conventional water supply systems. The major difference with the other studies carried out in this field is that the model presented in this research uses the existing underground water reservoir as rainwater harvesting tank.

In order to calculate the reliability, 20 years rainfall data starting from 1988 to 2007 was considered and all the calculations were performed for three different climatic conditions (i.e. wet, average and dry years). Years corresponding to maximum and minimum annual rainfall were considered wet year (2007) and dry year (1992) respectively. The average year (1990) was considered the year having annual rainfall close to the average annual rainfall over 20 years' period. A water balance model was developed considering the Daily rainfall runoff, Underground reservoir capacity and Daily water demand. Cumulative water stored in the water balance model is the sum of rainfall runoff and the stored water of the previous day less the daily water demand. When volume of stored water exceeded the tank capacity, the excess

amount of water is considered as spilled water. When water demand exceeded the volume of stored water then the additional water was taken from the town water supply.

Based on the water balance model a rainwater harvesting analysis software has been developed. The software has been developed using C# (C sharp) language in Microsoft Visual Studio. It calculates reliability, percent of water saved, overflow ratio and at the same time benefit-cost ratios based on the given input.

Different authors and organizations estimated the daily water demand for Dhaka city differently. . For this study a range of 120-180 lpcd has been selected as most of the recent estimated values lies within this range. The roof of the building is the the rainwater catchment area. This study is concerned with the rainwater harvesting in the multistoried residential buildings of Dhaka city having a plot size 3 to 5 katha i.e. 200-334 m^2. The catchment area was considered as 60- 70% of the plot size i.e. for a plot size of 200 m^2 the catchment area is 140 m^2 and for a plot size of 334 m^2 the catchment area is 200 m^2.

The reliability relationships with the varying tank sizes showed that both the time base and volumetric reliability increases up to a tank volume of 30 m^3 for the wet year and beyond that reliability does not increase with the increasing tank volume. But in case of average and dry conditions tank size have no significant impact on reliability. For all the cases volumetric reliability was found 5-8% more than the time based reliability.

Both time based reliability and volumetric reliability decreased with the increasing water demand. The demand being high and the tank sizes being large no spilled water was found for any of the cases. So the overflow ratio relationships with the varying water demand and tank size remained zero. Economic savings showed that around BDT 4000 on average can be saved each year if rainwater harvesting system is integrated with the conventional water supply system.

The present analysis indicates that about 20-30% reliability can be achieved if sufficient rainfall is available throughout the year. Approximately 250-550 kL of rainwater can be harvested each year from a catchment area of 200 m^2.The study also revealed that the current underground tank sizes of the residential buildings of the city are sufficient to prevent the overflow of the harvested rainwater. Though the reliability and the economic savings found is not much greater, it will have a significant impact if rainwater harvesting system is practised at a larger scale as it will reduce a certain portion of the pressure from the conventional water supply and it will also play a significant role in alleviating the water clogging problem.

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NOMENCLATURE

CUM	Cubic Metre
kL	Kilo Litre
LPCD	Litre Per Capita Per Day
MLD	Million Litres per Day
OF	Over Flow
RW	Rain Water
RWH	Rainwater Harvesting
RWHS	Rainwater Harvesting System
SFT	Square Feet
SW	Spilled Water
TW	Town Water

CHAPTER 1
INTRODUCTION

1.1 Rainwater Harvesting

Rainwater harvesting is the process of collection, preservation and use of natural rainfall. It is a decentralized practice that provides both water supply and runoff reduction benefits that are often difficult to assess.

Rainwater harvesting is an ancient technique that has been practiced for thousands of years in different part of the world. It has been often found that areas where surface water or groundwater is not available in sufficient amount, rainwater harvesting is the best available option and popular also. Rainwater is an open source of water, everybody can use it once the initial cost of collection process is met. Rainwater can be harvested for both potable and non-potable use. For non-potable use, rainwater is directly available. But for potable use, rainwater should be filtered or boiled. Rainwater harvesting ensures both economic and environmental sustainability of water resource.

1.1.1 Benefits of harvesting rainwater

Rainwater harvesting provides an independent water supply during regional water restrictions and in developed countries is often used to supplement the main supply. Harvesting rainwater offers a great range of advantages.

a) Ensures the productive use of rainwater.
b) Reduction of stress on the groundwater.
c) Runoff reduction benefits which will reduce the water logging problem.
d) In coastal regions, rainwater can be used as a direct alternative to the saline water.
e) Rainwater harvesting saves energy requiring only a small pump or gravity flow.
f) Rainwater is one of the purest sources of water, so the treatment cost is very small.
g) Rainwater harvesting ensures economic sustainability if integrated with the conventional water supply system.

1.1.2 Limitations of Rainwater harvesting system

The major limitation of the rainwater harvesting is the uncertainty of the rainfall throughout the year.

1.1.3 Rainwater harvesting techniques

Based on the collection process rainwater can be harvested in a variety of techniques:

a) Capturing runoff from rooftops
b) Capturing runoff from local catchment
c) Capturing water through watershed management.

1.1.4 Components of Rooftop RWH system

Typically, the roof of the building is be the main rainwater catchment surface. Supplemental water can be captured from other outbuildings if necessary. The gutter system captures the water that flows off the catchment surface. Leaf screens, first-flush diverters, and roof washers remove debris, such as bird droppings, dust, and leaves from the water before it is directed to the cistern. The water must be brought up to household water pressure through a delivery system, which is typically an electric booster pump and a pressure bladder, but in some places the water can be gravity-fed. Potable water systems will need to have some or all of the water filtered by some kind of treatment system.

1.1.5 Rooftop rainwater harvesting

It is a system of catching rainwater where it falls. In rooftop harvesting, the roof becomes the catchments, and the rainwater is collected from the roof of the house/building. It can either be stored in a tank or diverted to artificial recharge system. This method is less expensive and very effective.

Rainwater from rooftop should be carried through down take water pipes or drains to storage/harvesting system. Water pipes should be UV resistant (ISI HDPE/PVC pipes) of required capacity. Water from sloping roofs could be caught through gutters and down take pipe. First flush is a device used to flush off the water received in first shower. The first shower of rains needs to be flushed-off to avoid contaminating storable/rechargeable water by the probable contaminants of the atmosphere and the catchment roof. It will also help in cleaning of silt and other material deposited on roof during dry seasons Provisions of first rain separator should be made at outlet of each drainpipe. After first flushing of rainfall, water should pass through filters. There are different types of filters in practice, but basic function is to purify water.

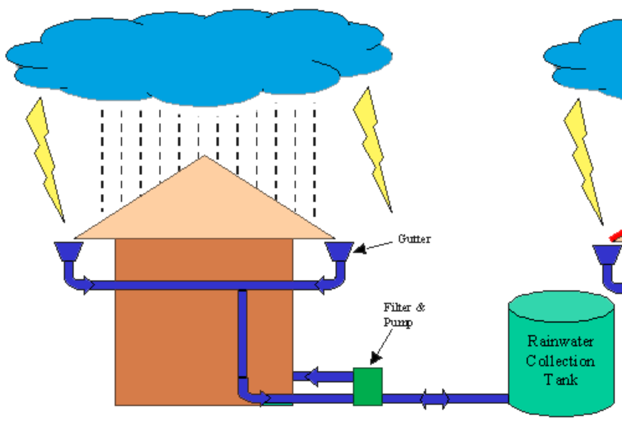


Figure 1.1: Overview of the rainwater collection system.

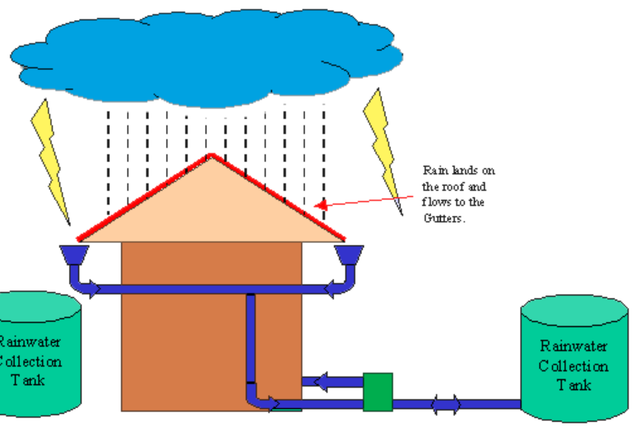


Figure 1.2: Rainfall on the rooftop.

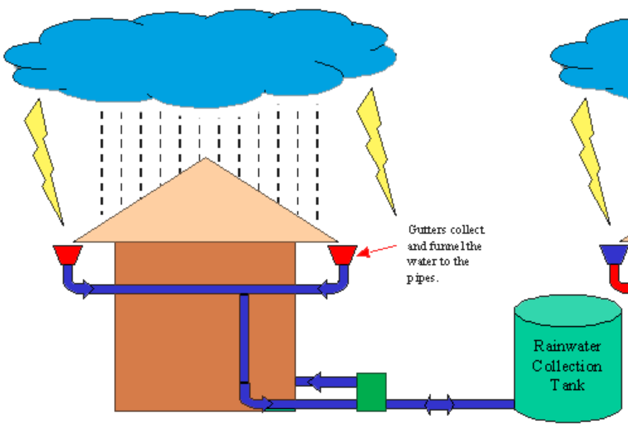


Figure 1.3: Gutter functionality.

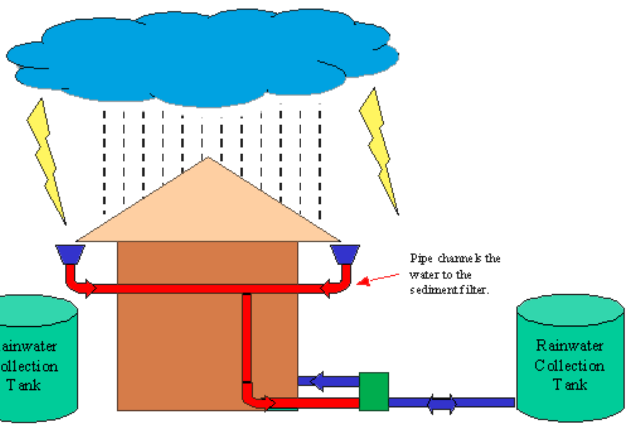


Figure 1.4: Piping the water

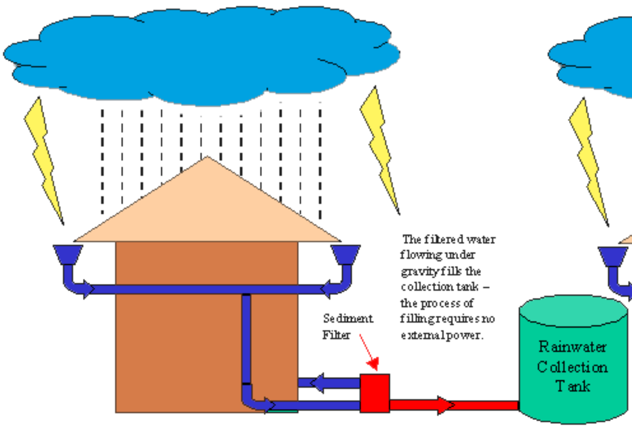


Figure 1.5: Filtering and filling the collection tank.

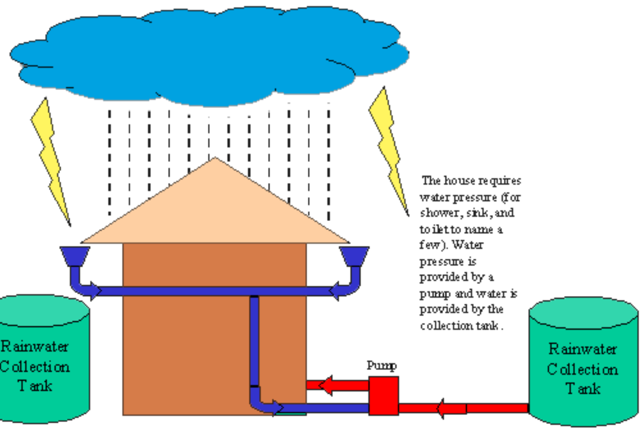


Figure 1.6: Supplying water to the house.

1.2 Scope of Rainwater harvesting in Bangladesh

According to Bangladesh Bureau of Statistics, Bangladesh received 2666 mm of rainfall in average during the period of 2006-2008. This amount of rainfall is significantly higher than most of the countries. So there lies a huge scope to harvest rainwater to meet the domestic, industrial and irrigation water demand.

Bangladesh used the surface water as the principal source for drinking water up to the recent past. Although rainwater harvesting is a familiar term for Bangladesh, it is not a common practice as only 35.5 percent of the households in coastal areas use this method as source of drinking water due to high salinity problem. The coastal area of Bangladesh receives a great amount of rainfall each year. Using the rainwater instead of the slightly saline water will not only meet the daily water demand of the local people but also will increase the crop production.

Not only in the coastal region, rainwater harvesting can play a significant role in the rural areas by providing fresh water to the local people at a very little cost and in the urban areas by reducing the stress on groundwater and supply water system by supplementing the supply water system. It will also help in alleviating the water logging problem in the cities like Dhaka.

Many organizations of Bangladesh are working on the rainwater harvesting projects in the rural areas of Bangladesh. Despite positive outcome from many studies, there remains a general community reluctance to adopt storm water harvesting on a wider scale. Part of the reason for this reluctance can be attributed to lack of information about the effectiveness of a storm water harvesting system and the optimum storage size required to satisfy the performance requirements under the specific site conditions (Imteaz et al., 2011).

1.3 Research objectives

- To analyze the reliability of a rainwater harvesting system when rainwater harvesting system is integrated with the supply water system.
- To utilize programming and visualization to assess the efficacy of a rainwater harvesting system.
- To assess the economic savings of a RWH system.

1.4 Scopes and limitations of the study

According to the upcoming Bangladesh National Building Code, every building proposed for constructing on plots having extent of 300 square meter or above shall have the facilities for conserving and harvesting rainwater. The same has been proposed in the Imarat Nirman

Bidhimala, 2012 though a very few studies have been carried out to check the efficiency of rainwater harvesting in Dhaka city. The research presented in this paper is undertaken in the light of current knowledge gaps to access the efficiency of a RWH system in Dhaka to provide guidance to water authorities to enhance the acceptance of a RWH system.

This study has been carried out only for the multistoried residential buildings of Dhaka city having a plot size of 200 to 334 m^2. This is a limitation of this study as it does not include the scenarios when the plot size will exceed this limit and where the water demand is different such as commercial buildings, stadiums, warehouses etc. This study also does not cover the assessment of the harvested rainwater quality.

1.5 Organization of the thesis

This thesis is divided into six chapters. Following this introductory part is Chapter 2, which reviews the literatures regarding RWH studies carried out in Bangladesh and in other parts of the world and also provides an overview of the existing RWH models. Chapter 3 describes the methodology of this research. Description about the study area and the data's used in reliability analysis has been sighted in the Chapter 4. The results of the reliability analysis and economic analysis have been presented in Chapter 5. Chapter 6 is the summary and conclusions of the research. This chapter has been divided into four sub sections which describes the main findings of this research, the limitations of this study and the recommendations for the future studies. The reference section concludes this thesis.

CHAPTER 2
LITERATURE REVIEW

2.1 General

The government of People's Republic of Bangladesh is planning on amending the Building Construction Rules 2008 to incorporate the system of rainwater harvesting as mandatory for all new houses in Dhaka Metropolitan area. According to the upcoming Bangladesh National Building Code, every building proposed for constructing on plots having extent of 300 square meter or above shall have the facilities for conserving and harvesting rainwater. But a very few or insignificant number of studies have been carried out to investigate the applicability, reliability and efficiency of the rainwater harvesting system in Dhaka city.

2.2 RWH studies in Bangladesh

Rooftop rainwater harvesting has received an increased attention as a potential alternative water supply source both in the coastal and arsenic affected rural areas of Bangladesh. Karim et al. (2013) investigated the reliability of household based rainwater harvesting in the coastal areas of Bangladesh and found that the maximum reliability that can be achieved under average climatic condition varies from 70% to 90% and the reliability does not increase significantly beyond the tank volume 3000 L. This study also revealed that significant amount of water is lost as spilled water for smaller tank sizes and the potential uses of rainwater can be increased by capturing this huge spilled water if a proper combination of storage tank capacity, catchment (roof) area and rainwater demand is used.

A study by Rahman et al. (2014) to assess the sustainability of RWH system for Dhaka city found that 11% water can be saved annually in a building having a roof area of 1850 sft and this volume of rainwater can serve a building with 60 people for about 1.5 months in a year without the help of traditional water supply. This study also showed that with an 1850 sft catchment area, about 69,026 gallons of water can be harvested over one year. This volume of water can reduce the potable water demand and approximately 100 kWh electricity can also be saved as well if rainwater capturing system is introduced in the residential buildings of the city.

Dakua et. al. (2013) investigated the potential of rainwater harvesting in buildings to reduce over extraction of groundwater in urban areas of Bangladesh. Rainwater harvesting potential was calculated by multiplying the catchment area with the average rainfall and runoff coefficient. Results revealed that more than 60% water bill can be saved during the period from May to October.

A study in the Kazipara, Mirpur area showed that about 402,097 cubic meters of rainwater can be harvested annually which can meet upto 66% demand of water for toilet flushing and cleaning purposes used by the residents of Kazipara all year round (Tabassum et. al., 2013). It also shows that if rainwater harvesting system is used in in every buildings of the study area then 2,872.12 cum/hr surface runoff would be reduced during a rainfall event of 15 mm/ hour. Which means 61.71% of surface runoff would be reduced from the current surface runoff. Thus water logging problem can be decreased in Dhaka city.

Islam et. al. (2007) studied the feasibility of rainwater harvesting techniques in Bangladesh. Rainwater was experimentally harvested at Bangladesh University of Engineering and Technology (BUET) in the monsoon using a small catchment area (15'x 15') made of water proof cloth and a ferro-cement storage tank having capacity of 3200 liters for 05 members' family and the rainwater was stored for 04 months. Additionally, the research also looked at the quality aspect of the stored rainwater including color, total solids, total dissolved solids, lead, turbidity, hardness, acidity, pH, nitrate, fluoride, total coliform, fecal coliform, COD, and BOD. Initial test results indicated that the stored rainwater had a slightly higher pH value (8.1 to 8.3) and presence of coliform bacteria (when water is stored for more than three months) also detected. The traditional filtering system removed contaminants completely and coliforms were removed up to 60% of the total.

2.3 Global studies on RWH

Optimization of the rainwater tank size is the most widely studied topic of RWH. Notable researchers have conducted on the relationship between rainwater tank sizing and water savings. Imteaz et al. (2011a) developed a daily water balance model to assess the reliability of the rainwater tanks in Melbourne. This study found 100% reliability for a two-people household scenario with a roof size of 150-300 m2 having a tank size of 5,000-10,000 L but for a four-people household scenario it is not possible to achieve 100% reliability even with a roof size of 300 m2 and a tank size of 10,000L.

Ghisi et al. (2007) investigated the water savings potential from rainwater harvesting systems of Brazil and found the average potential for potable water savings of 12-79% per year for the cities analyzed.

Shaaban et al. (2002) tested the usage of rainwater harvesting installed in a house located in Kuala Lumpur, Malaysia and according to the experiment done he recommended to use the rainwater mainly for washing clothes and flushing toilets.

Ruslan (2003) proposed a computer software for determining the reliability of rainwater tank. Also Ghisi and Ferreira (2006) studied the reliability of rainwater harvesting for 26 cities in Brazil.

Gould and Nissen-Peterson (1999) gave the runoff coefficients for various materials used for roofing. Rahman and Fatima (2006) and Handia et al. (2003) reviewed the materials of rainwater storage tank.

A good number of software and simulation based models were also developed to help assessing the reliability and tank size of RWH system. eTank is a decision support tool for optimizing rainwater tank size, developed by Imteaz et al. (2011b).

To evaluate both the water supply and runoff reduction benefits Sample et al. (2013) developed a model that simulates a single RWH system in Richmond, Virginia, using storage volume, roof area, irrigated area, an indoor non-potable demand and a storage dewatering goals independent design variables.

In Texas and California of USA, Philippine, Germany and Japan, harvested rainwater was being used as drinking, domestic and as well as in irrigation purposes. In Canada, up to 50% of harvested water was used for lawn and irrigation purposes (Western Canada Water, 1993).

The Government of Maldives provided High Density Polyethylene (HDPE) tanks to store the rainwater for the communities free of charge and to individual households on cost recovery basis with financial support from UNICEF.

The system of rainwater harvesting for water supply is being used in many arid and semi-arid countries of the world like Tanzania, Morocco, Kenya, Thailand, India, Pakistan, Nepal, Maldives, Brazil, Portugal, Australia etc.

2.4 Existing RWH models

To study the behavior of rainwater harvesting system several RWH models were developed in the past. The relative functions of the models are shown in the table 2.1.

Table 2.1: Existing models for analyzing RWH systems

Model	Developer	RWH only?	Functionality
DRHM	Dixon *et al.* (1999)	No	Mass balance with stochastic elements for demand proofing, simulates quantity, quality and costs

Rewaput	Vaes & Berlamont (2001)	Yes	Reservoir model, rainfall intensity-duration-frequency relationships and triangular distribution
RWIN (KOSIM)	Herrmann & Schmida (1999) and ITWH (2007)	No	Hydrological-based high resolution (5 min) rainfall-runoff model
PURRS	Coombes & Kuczera (2001)	No	Probabilistic behavioral, continuous simulation, evaluates sources control strategies
RCSM	Fewkes (2004)	Yes	Behavioral, Continuous simulation, detailed analysis of time interval variation and yield-before/after-spill
MUSIC	CRCCH (2005)	No	Continuous simulation, modelling water quality and quality in catchments (0.01 to 100 km^2)
Aquacycle	Mitchell (2005)	No	Continuous water balance simulation using a yield-before spill algorithm
RSR	Kim & Han (2006)	Yes	RWH tank sizing for storm water retention to reduce flooding, using Seoul as a case study
RainCycle©	Roebuck & Ashley (2006)	Yes	Excel-based mass balance continuous simulation using a yield-after-spill algorithm and whole life costing approach
UWOT	Liu *et al.* (2007)	No	Object-based behavioral, continuous simulation using Simmulink

CHAPTER 3
METHODOLOGY

3.1 Introduction

To carry out the reliability analysis of the rainwater harvesting system a daily water balance model was developed. This model assumes that the rainwater will get priority as a water supply source in the residential buildings. When the rainwater will not be able to satisfy the demand alone, the extra demand will be satisfied by the town/supply water system. This model uses the existing underground storage tank as rainwater storage tank i.e. construction of additional tank to store rainwater is not required.

3.2 Water Balance Model

Considering daily rainfall, contributing catchment (roof) area, losses due leakage, spillage and evaporation and storage (tank) volume a daily water balance model was developed. The prime input value in this model was the daily rainfall amount for three different years (Dry, Average and Wet year).

Generated runoff was diverted to the existing underground storage tank. Available storage capacity was compared with the accumulated daily runoff. If accumulated runoff is greater than available storage volume, excess (spilled) water was deducted from the accumulated runoff. Amount of water use(s) is deducted from the daily accumulated/stored runoff amount, if sufficient amount of water is available in the storage. In a situation, when sufficient amount of water is not available in the storage, model will assume that the remaining water demand is supplied from the conventional/town water supply.

The model calculates daily rainwater use, daily water storage in the tank, daily spilled water volume and daily town/supply water use. In addition, the model calculates accumulated annual rainwater use, accumulated annual spilled water volume and accumulated annual town water use.

3.2.1 Cumulative water storage

It is the actual volume of water that is stored in the storage tank after fulfilling the daily demand.

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

$S_t = 0$, when $S_t < 0$

$S_t = C$, when $S_t > C$

Where,

S_t=Cumulative water stored in the tank (L) after the end of the t^{th} day.

V_t = Harvested rainwater (L) on t^{th} day

S_{t-1}=Storage in the tank (L) at the beginning of t^{th} day

D=Daily water demand (L)

C=Capacity of the rainwater tank (L)

3.2.2 Daily rainfall runoff volume

It is the total inflow volume generated due to rainfall in a specific day.

$$V_t = C \times I \times A \quad (2)$$

Where,

C=Runoff co-efficient

I=Rainfall intensity (mm/day)

A=Catchment area (hectare)

V_t = Harvested rainwater on t^{th} day (m^3)

3.2.3 Volume of spilled water

It is the excess amount of water that is spilled out from the tank when storage water volume exceeds the storage capacity.

If $V_t + S_{t-1} - D > C$,

$$SW = V_t + S_{t-1} - D - C \quad (3)$$

Where,

SW= Volume of Spilled water (L)

C= Capacity of the rainwater tank (L)

3.2.4 Volume of town water use

It is the additional amount of water that will be used from the supply water system when rainfall alone will not be able to meet the daily water demand.

If $V_t + S_{t-1} < D$

$$TW = D - V_t - S_{t-1} \quad (4)$$

Where,

TW= Volume of town water used (L)

3.2.5 Volume of rainwater use

It is the amount of rainwater used in a particular day.

If $V_t + S_{t-1} > D$

RW=D (5)

If $V_t + S_{t-1} < D$

$RW = V_t + S_{t-1}$ (6)

Where,

RW= Volume of rain water used (L)

3.2.6 Overflow ratio

It is the ratio of the spilled water to the rainwater inflow to the system. It is expressed in percentage.

$$Overflow\ ratio = \frac{rainwater\ volume\ exceeding\ storage\ capacity\ during\ evaluation\ period}{inflow\ to\ the\ system\ during\ evaluation\ period} \quad (7)$$

3.3 Reliability analysis

Reliability is the ability of the tank to meet the water demand. This is expressed in percentage.

3.3.1 Time based reliability

It is the percentage of days in a year, rainwater was able to meet the daily water demand alone.

$$R_{e\,(t)} = \frac{N-U}{N} \times 100 \quad (8)$$

Where,

$R_{e\,(t)}$ = Reliability of the tank to be able to supply intended demand (%)

U= Number of days in a year the tank was unable to meet the demand

N= Total number of days in a particular year

3.3.2 Volumetric reliability

It is the percentage of rainwater used throughout the year with respect to the yearly water use.

$$Volumetric\ reliability = \frac{Volume\ of\ rainwater\ supplied}{Total\ demand\ during\ evaluation\ period} \quad (9)$$

3.4 Sensitivity analysis

These are efficiency (volumetric reliability) vs. demand fraction or storage fraction graphs.

3.4.1 Demand fraction

Demand fraction is a ratio and it is defined as follows:

$$\frac{D}{Q} = \frac{Total\ yearly\ demand\ (m^3/year)}{Total\ yarly\ inflow\ (m^3/year)} \quad (10)$$

3.4.2 Storage fraction

Storage fraction is a ratio and it is defined as follows:

$$\frac{S}{Q} = \frac{Storage\ capacity\ (m^3)}{Total\ yarly\ inflow\ (m^3/year)} \quad (11)$$

3.5 Economic analysis

Benefit-cost ratio analysis has been performed to assess the economic viability of a rainwater harvesting system.

3.5.1 Benefit-cost ratio

Benefit-cost ratio compares the users benefits with the sponsors cost. If the ratio is greater than 1 then the project is considered to be beneficial and if the ratio is less than 1 then the project is considered to be non-beneficial.

$$Benefit, B = A \times \frac{(1+i)^n - 1}{i(1+i)^n} \quad (12)$$

$$Cost, C = IC + OM \times \frac{(1+i)^n - 1}{i(1+i)^n} \quad (13)$$

$$Benefit\ cost\ ratio = \frac{B}{C} \quad (14)$$

Where,

i= Rate of return (%/year)

n= Project life (Years)

A= Yearly monetary saving (BDT/year)

IC= Installation cost (BDT)

OM= Operation and maintenance cost (BDT/year)

3.6 Model development

Based on the daily water balance model a spreadsheet based model and a rainwater harvesting analysis software has been developed. It calculates reliability, percent of water saved, overflow ratio and at the same time benefit-cost ratio based on the given input.

3.6.1 Program coding

The software has been developed using C# (C sharp) language in Microsoft Visual Studio.

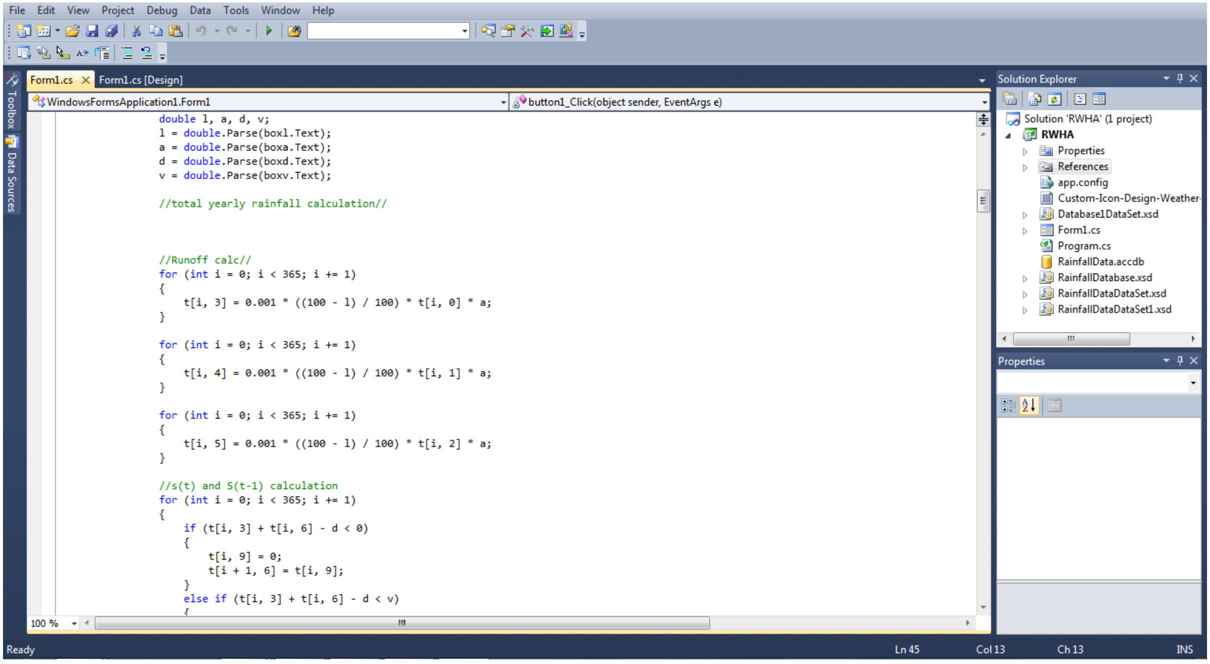


Figure 3.1: Coding of the software in visual studio.

3.6.2 Input data

The software has been designed in three sections. First section basically asks for input data from the user. The software comes with rainfall data for Dhaka city area as default. Reliability for any other area can be calculated simply by replacing the database file (RainfallData.db) with the rainfall database of that particular area.

The software requires the following data for the reliability analysis:

i. Rainfall data
ii. Percent loss
iii. Catchment area
iv. Daily demand
v. Tank capacity

For economic analysis it requires the following data:

i. Water price
ii. Installation cost
iii. Operation and maintenance cost

iv. Project life
v. Rate of return

3.6.3 Output data

The second tab of the software displays the results of the reliability analysis. The results of the economic analysis are displayed in the third section.

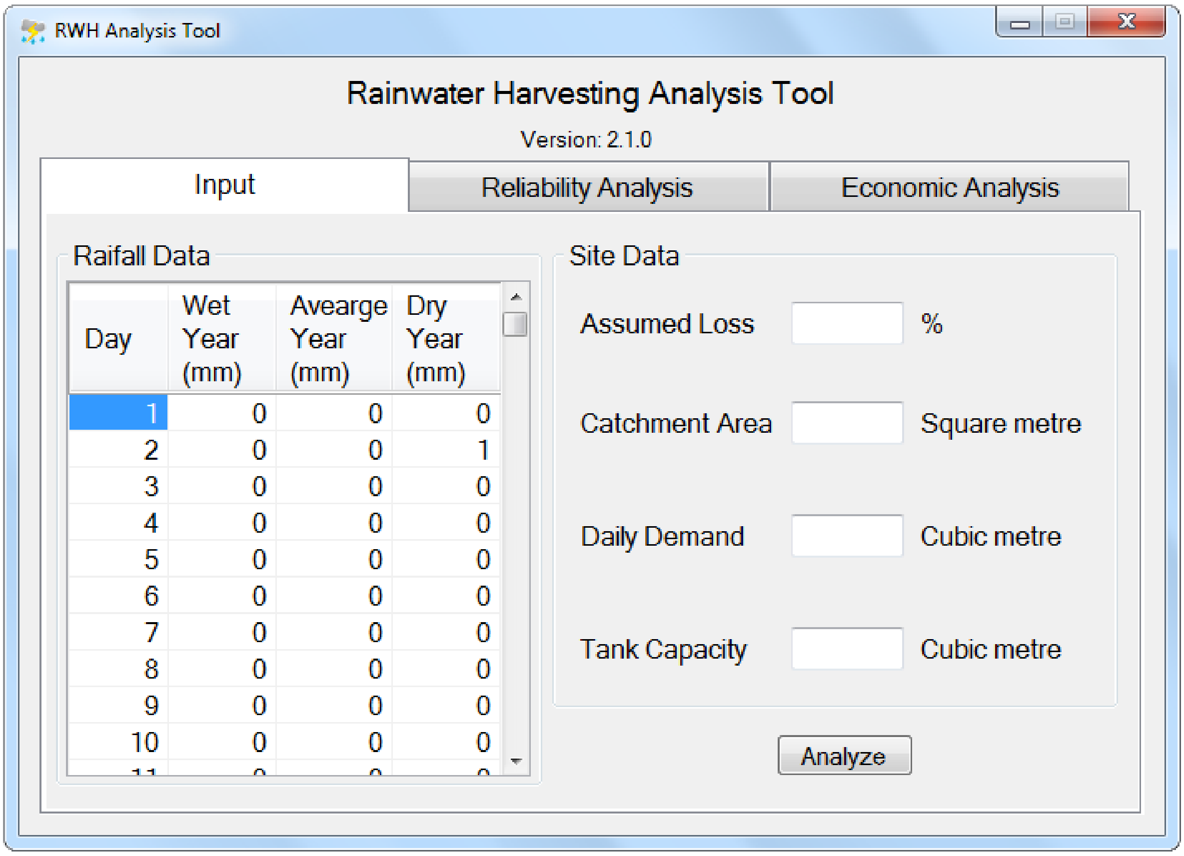


Figure 3.2: Rainwater harvesting analysis tool user interface (Input section)

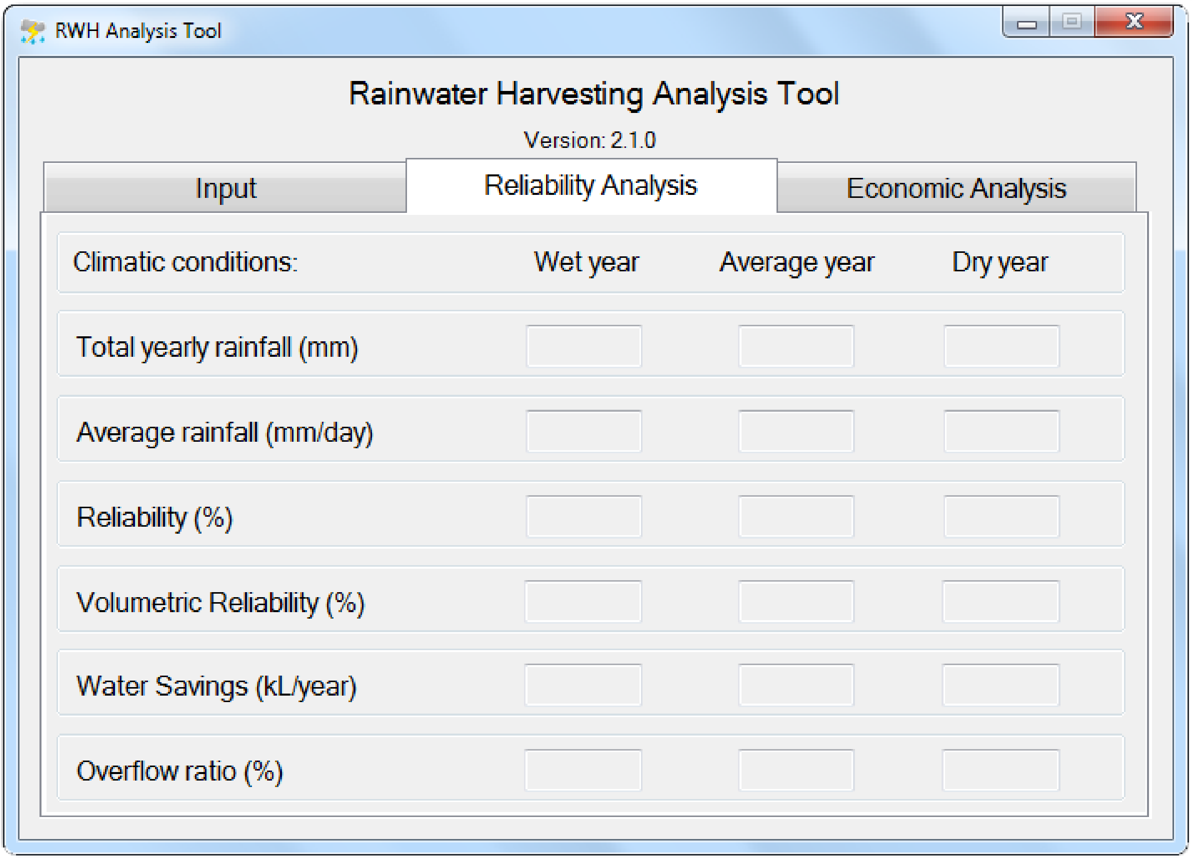


Figure 3.3: Rainwater harvesting analysis tool user interface (Reliability analysis section)

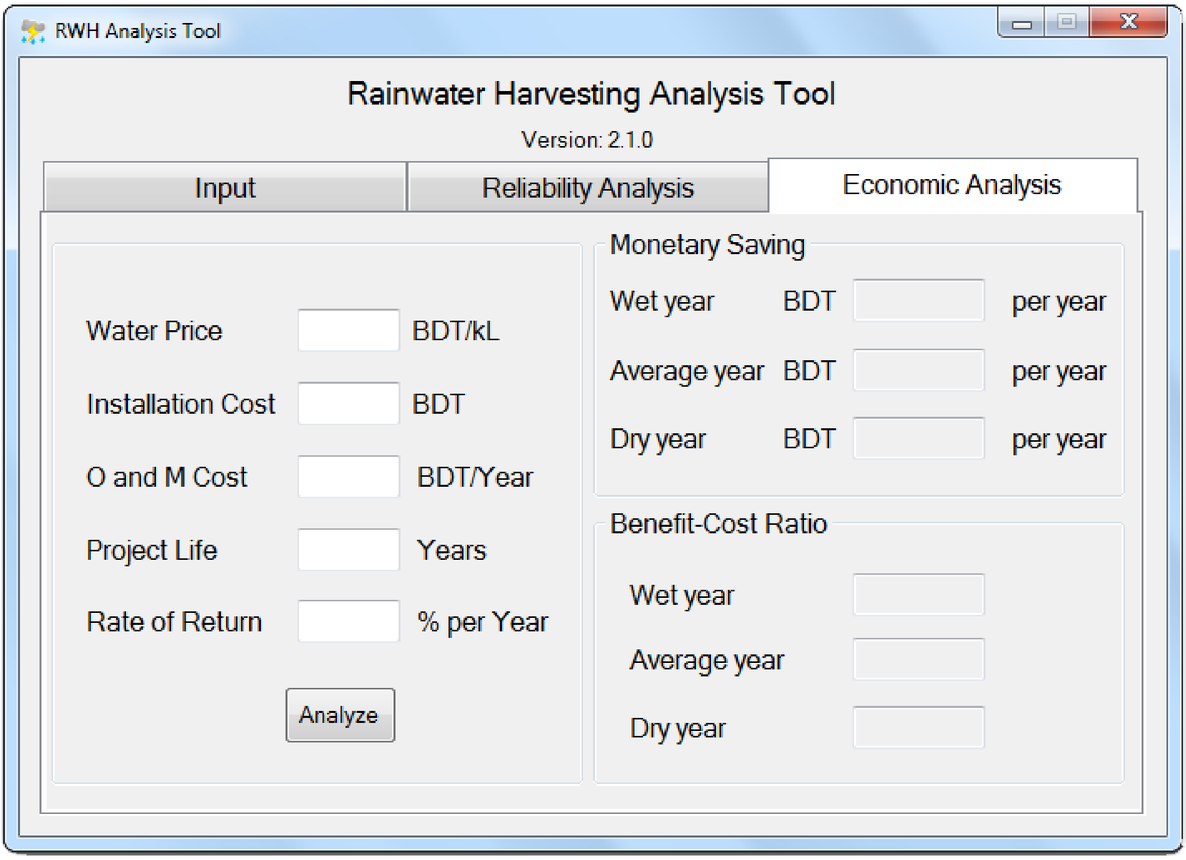


Figure 3.4: Rainwater harvesting analysis tool user interface (Economic analysis section)

CHAPTER 4
STUDY AREA AND DATA

4.1 Study area

Dhaka, the capital of Bangladesh is the 19th mega city of the world with a population of over 14 million. With the rapid growth of urban population the city is unable to cope with changing situations due to their internal resource constraints and management limitations (Tabassum et. al., 2013). In a city like Dhaka where the water table is falling rapidly & concrete surfaces and landfill dumps are taking the place of water bodies due to increased population and water demand as well, RWH is the most reliable solution as an alternative to reduce the stress on the conventional water supply.

About 75% of total demand of water in Dhaka is supplied by DWASA, and the rest comes from privately owned tube wells. At present DWASA can yield about 2092.69 million liters (ML) per day in which about 1840.04 MLD is collected from 586 deep tube wells (DTW), and the remaining 252.65 MLD is supplied by two surface water treatment plants (Rahman, et al., 2014).

This overreliance on groundwater is leading to the water table depletion. As can be seen from figure 1, the groundwater table of Dhaka is dropping down at a rate of 1-3 m per year and it is estimated that by 2050 it will drop down about 120 m.

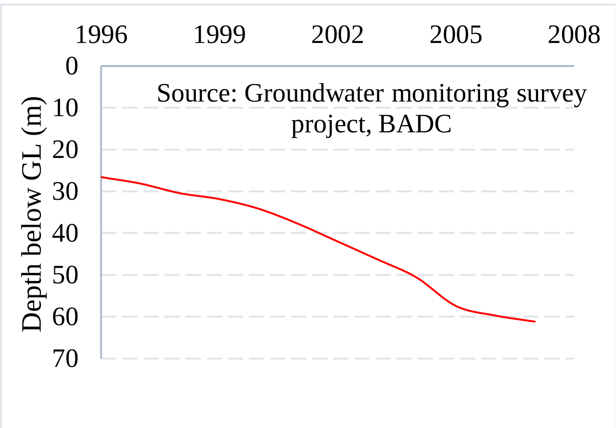


Figure 4.1: Groundwater table depletion of Dhaka city over the years.

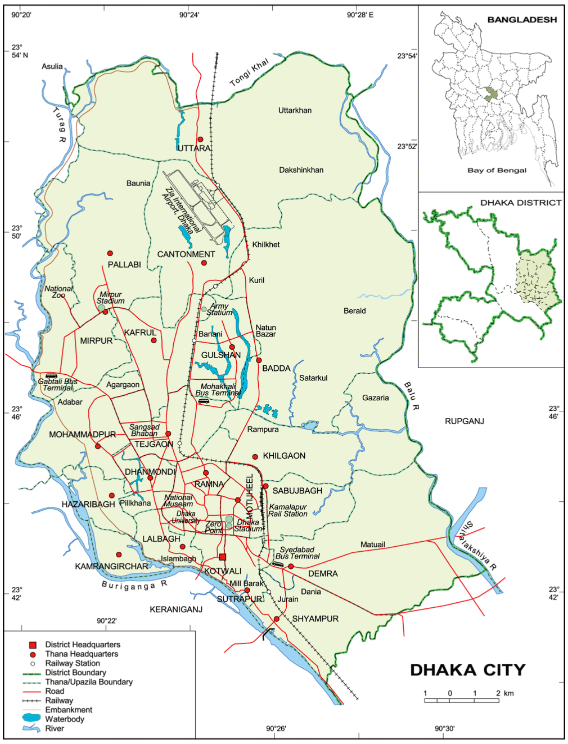


Figure 4.2: Study area: Dhaka city

Surface water bodies surrounding Dhaka city have lost their potential as a source of water supply because of high level of pollution. Not only the scarcity of fresh water but also water logging is an acute problem for the inhabitants of Dhaka city that disrupts the traffic movement and create health, hygiene and environmental problem in the life of city dwellers. In September 11th to 16th, 2004 heaviest ever rainfall (341mm) occurred in Dhaka City and its devastating impact paralyzed the city life. On May 22, 2006 the city experience 38 mm rainfall in 3 hours and caused huge water logging problem (Tabassum et. al., 2013).

In a situation like this if alternative water sources are considered, rainwater harvesting can be an effective solution if it is combined with the supply water.

4.2 Rainfall data

Historical 20-year (1988-2007) rainfall data for Dhaka city area was collected from Bangladesh Meteorological Department. To investigate the reliability this 20-year rainfall data was analyzed to find the three different climatic conditions i.e. Wet year, Average year and Dry year. Years corresponding to maximum and minimum annual rainfall were considered wet year and dry year respectively. The average year was considered the year having annual rainfall close to the average annual rainfall over 20 years' period. Selected years and corresponding annual rainfall amounts are shown in Table 1.

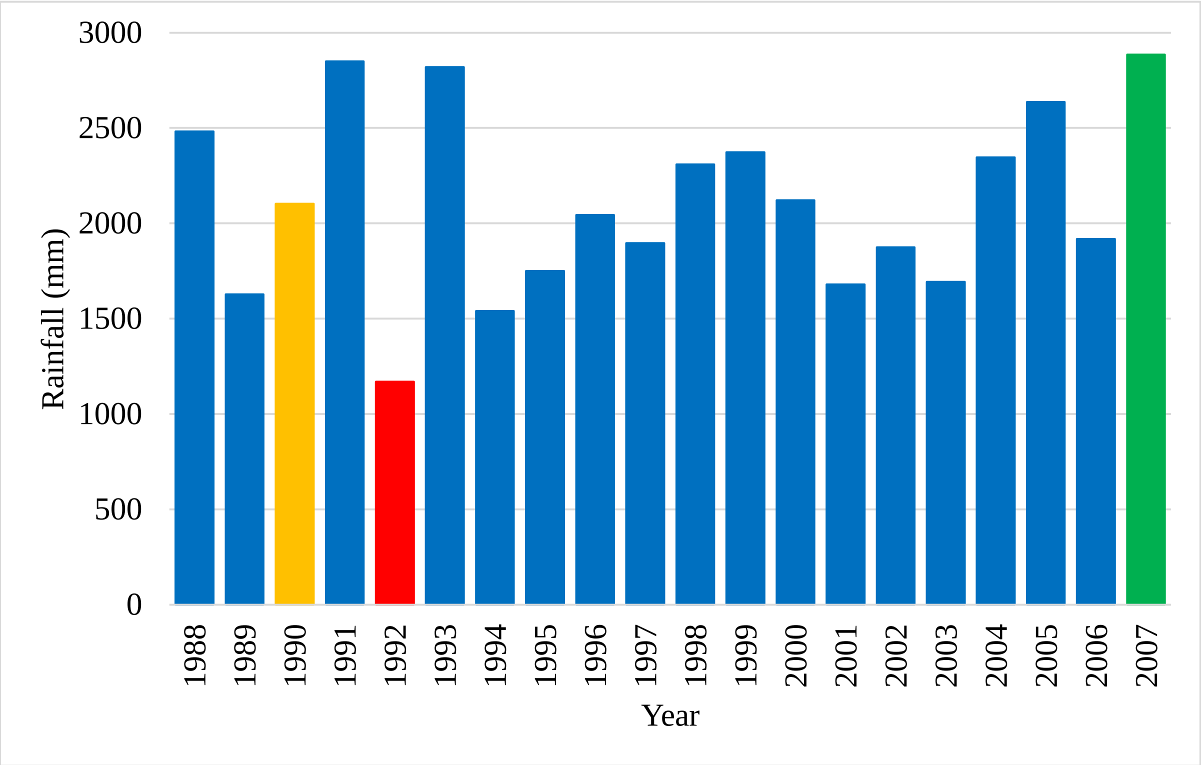


Figure 4.3: Rainfall in Dhaka City from 1988 to 2007.

Table 4.1: Annual rainfall for Dry, Average and Wet year

Year	Annual rainfall (mm)
Dry year (1992)	1169
Average year (1990)	2103
Wet year (2007)	2885

4.3 Runoff co-efficient

Runoff co-efficient is the factor which accounts for the fact that all the rainwater falling on a catchment cannot be collected. So rainfall will be lost as evaporation and retention on the surface itself. It decides how much rainwater can be harvested. Runoff co-efficient differs depending upon the nature of the catchment area. Table 4.4 shows runoff coefficients for various surfaces.

Table 4.2: Runoff coefficients for various surfaces.

Type of surface	Runoff co-efficient
Roof catchment	
-Tiles	0.8-0.9
-Corrugated metal sheets	0.7-0.9
Ground surface coverings	
-Concrete	0.6-0.8
-Brick pavement	0.5-0.6
Untreated ground catchments	
-Soil on slopes less than 10%	0.0-0.3
-Rocky natural catchments	0.2-0.5

In this study, only rooftop catchment area of the multistoried residential buildings have been considered for calculating the runoff. So, for this study the runoff coefficient was considered as 0.8-0.9 to account for several losses (leakage, spilling and evaporation).

4.4 Water demand

Daily water demand is the daily per capita water demand for drinking, cooking, bathing, washing, cleaning and flushing purposes. Assessment of daily water demand is a complex phenomenon. The total consumption of water per person is greatly influenced by availability of water, distance of the water source, price of the water, quality of the water, climatic conditions etc.

Previously different authors and organizations estimated the daily water demand for Dhaka city area. According to the Centre for science and Environment (CSE) water requirement for different purposes are shown in Table 4.2.

Table 4.3: Water consumption in urban areas according to CSE.

Use	Consumption (lpcd)
Drinking	5
Cooking	5
Bathing (including ablution)	55
Washing clothes	20
Washing utensils	10
Cleaning the house	10
Flushing the toilet	30
Total for urban areas	**135**

Table 4.4: Estimated daily water demand for Dhaka city.

Water demand (lpcd)			Reference
I.	Single Family Dwelling with Garden & Car washing	200-260	*Bangladesh National Building Code 2011*
II.	Big Multi-Family Apartment /Flat (> 2500 sft)	150-200	
III.	Moderate Apartment (< 2000 sft)	135-180	
IV.	Small Apartment (< 1500 sft)	120	
I.	City Corporation areas	180	*Ahmed & Rahman, 2001*
II.	Zila town	120	
I.	Dhaka, Bangladesh	95	*Yepes & Dianderas, 1996*
I.	High rise buildings	240	*Haque et al, 2007*
II.	Multi-storied buildings	140	
I.	Residential buildings	150	*DWASA*
I.	Residential buildings	140	*Rahman et al, 2011*

I.	Dhaka	90	*Bangladesh Water Utilities Data Book, 2006–07*

Table 4.3 shows estimated daily water demand for Dhaka city area by different authors and organizations. For this study a range of 120-180 lpcd has been selected as most of the recent estimated values lies within this range.

4.5 Catchment area

The roof of the dwelling is the common form of the rainwater catchment area. This study is concerned with the rainwater harvesting in the multistoried residential buildings of Dhaka city having a plot size 3 to 5 katha i.e. 200-334 m^2. The catchment area was considered as 60-70% of the plot size.

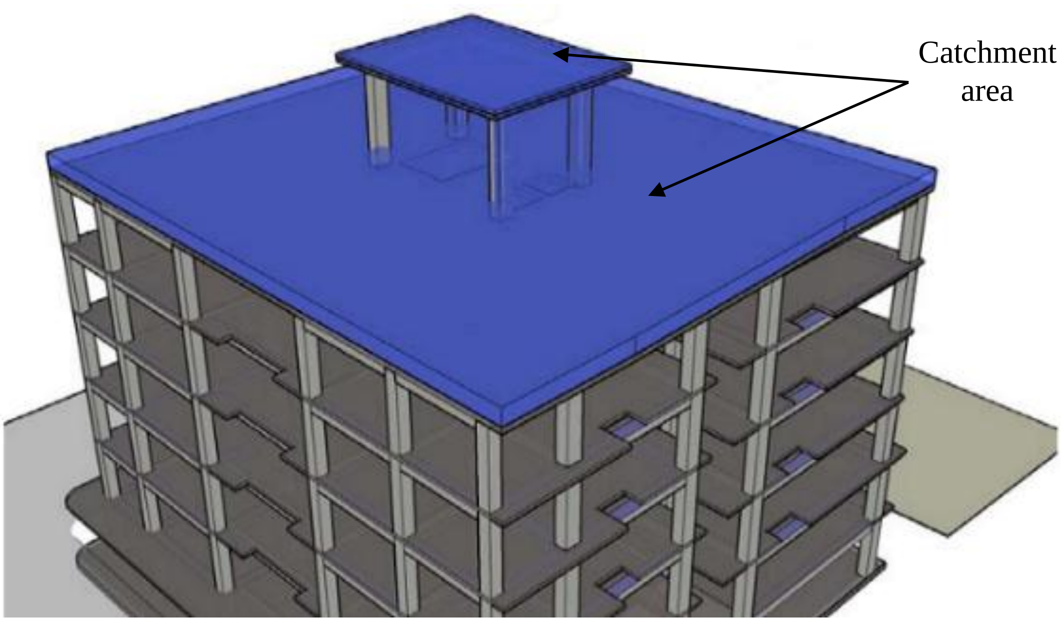


Figure 4.4: Catchment area of the rainwater harvesting system.

CHAPTER 5
RESULTS AND DISCUSSION

5.1 Introduction

Reliability and economic analysis were performed under three different climatic conditions (wet, average and dry year) for two different scenarios. For a plot size of 5 katha (334 m^2) a catchment area of 200 m^2 and for a 3 katha (200 m^2) a catchment area of 140 m^2 has been considered. It has been assumed that 50 people live in a 6 storied residential building having a plot size of 334 m^2 and 30 people live in a 6 storied residential building having a plot size of 200 m^2.

5.2 Reliability analysis

Both time based and volumetric reliability relationships were obtained for the two scenarios.

5.2.1 Time based reliability

The following graphs represent the relationship between time based reliability and tank volume for different catchment sizes and daily water demand.

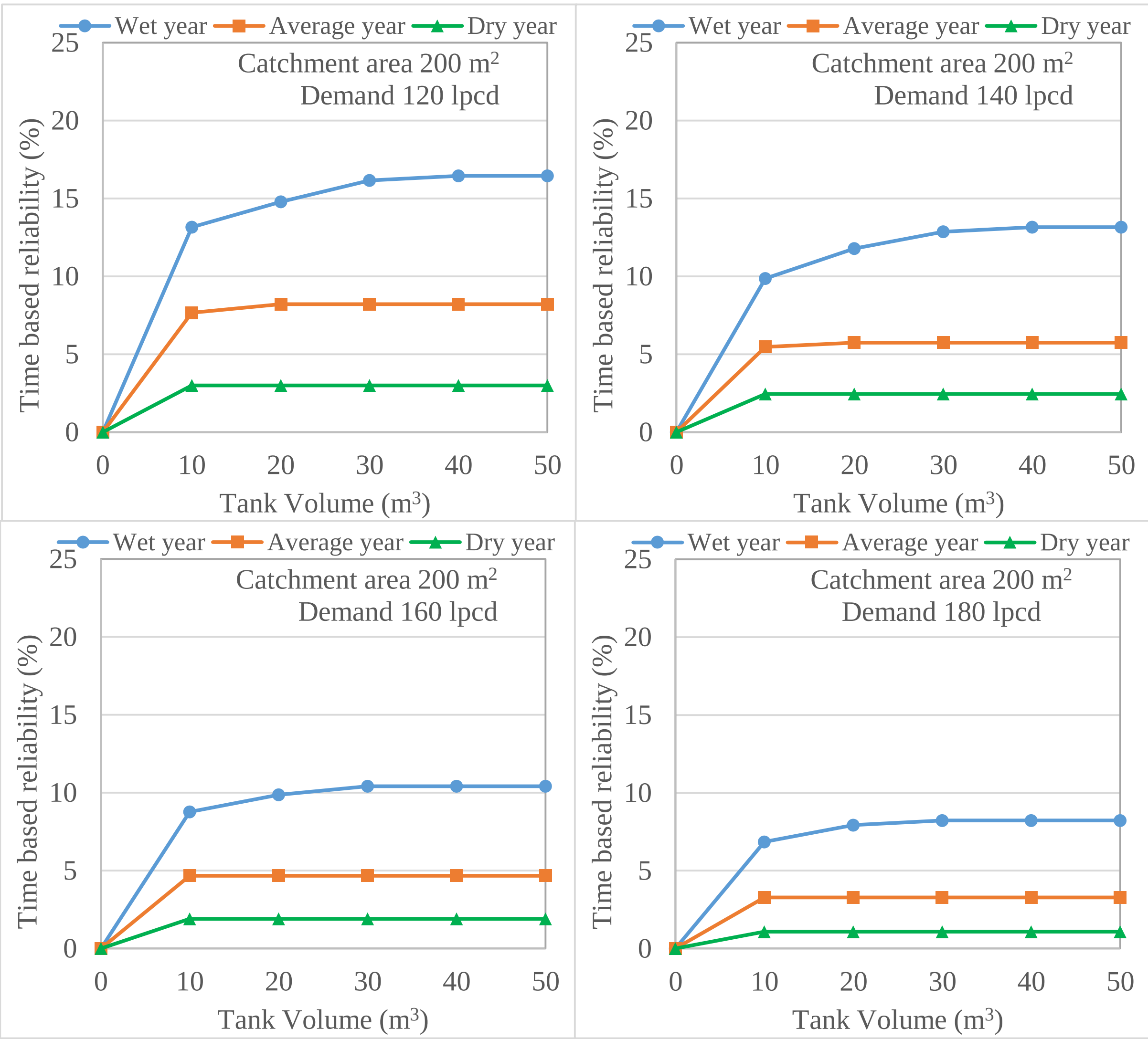


Figure 5.1: Reliability curves for a catchment size of 200 m^2 with varying tank volume.

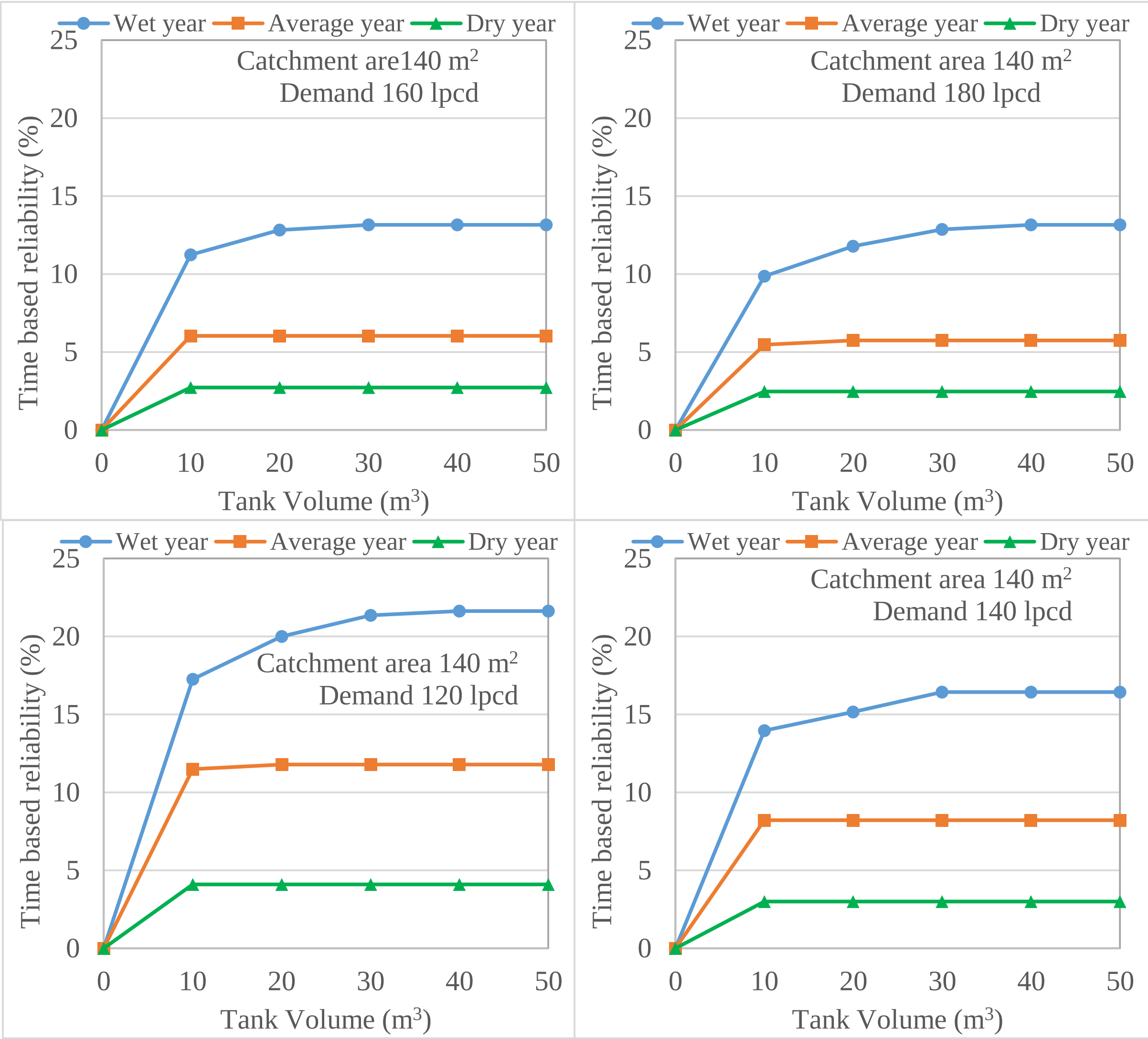


Figure 5.2: Reliability curves for a catchment size of 140 m^2 with varying tank volume.

Figure 5.1 and 5.2 shows the reliability relationships with the tank sizes and water demand. For both the cases reliability increases up to a tank volume of 30 m^3 for the wet year and beyond that reliability does not increase with the increasing tank volume. But in case of average and dry conditions tank size have no significant impact on reliability.

The following graphs represent the relationship between time based reliability and water demand for different catchment sizes and tank volumes.

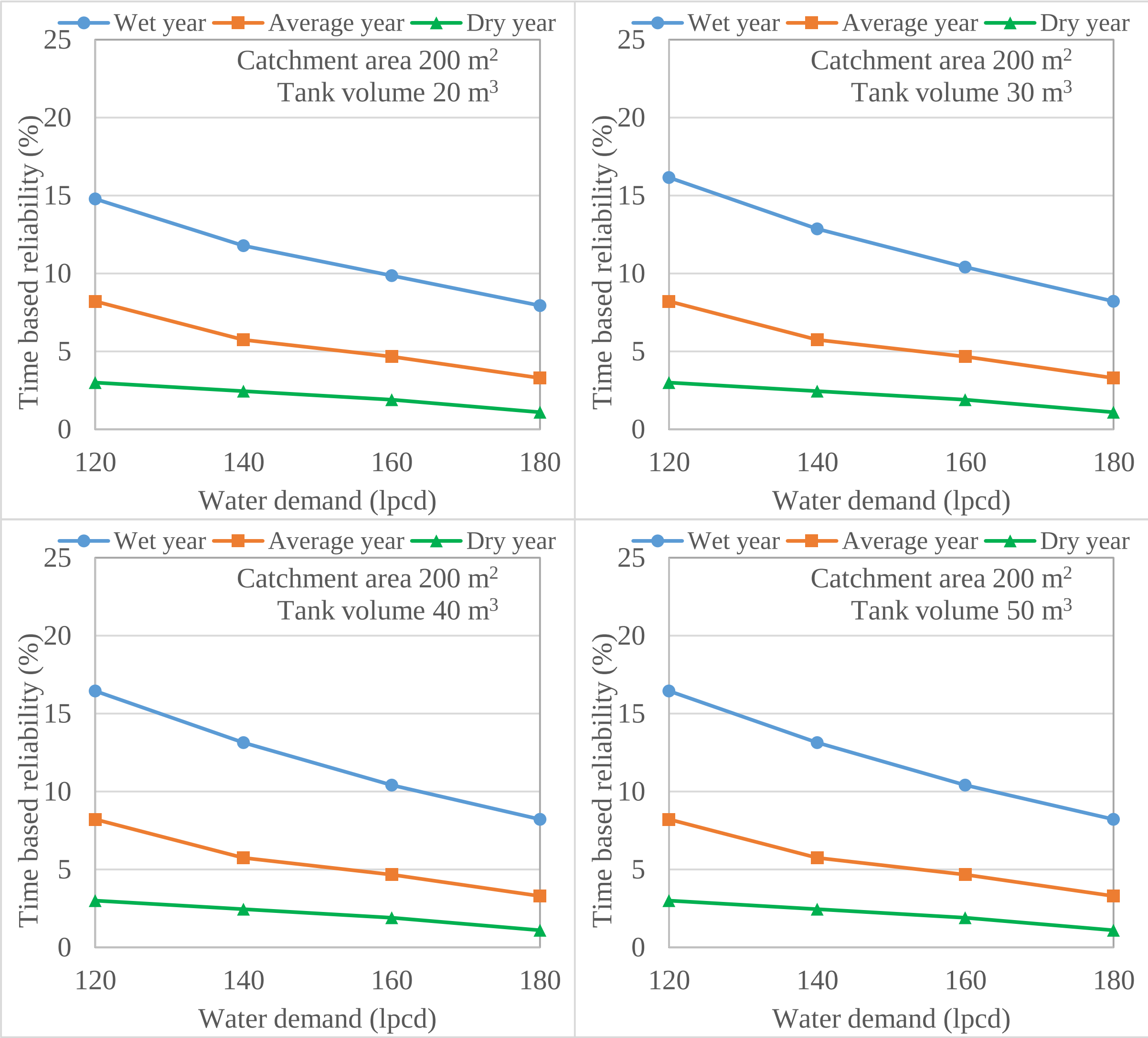
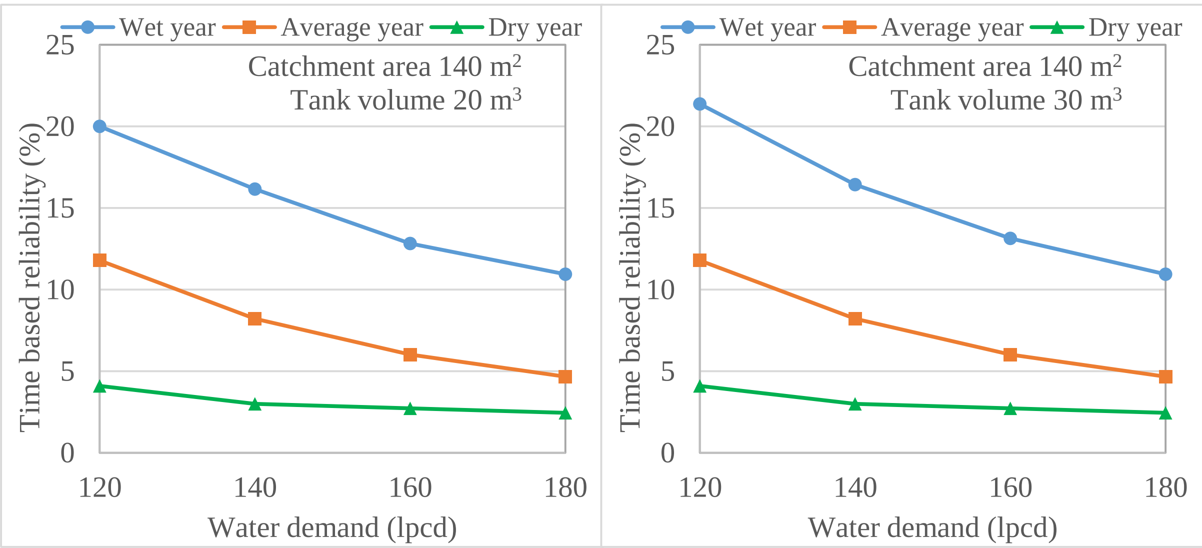


Figure 5.3: Reliability curves for a catchment size of 200 m^2 with varying water demand.



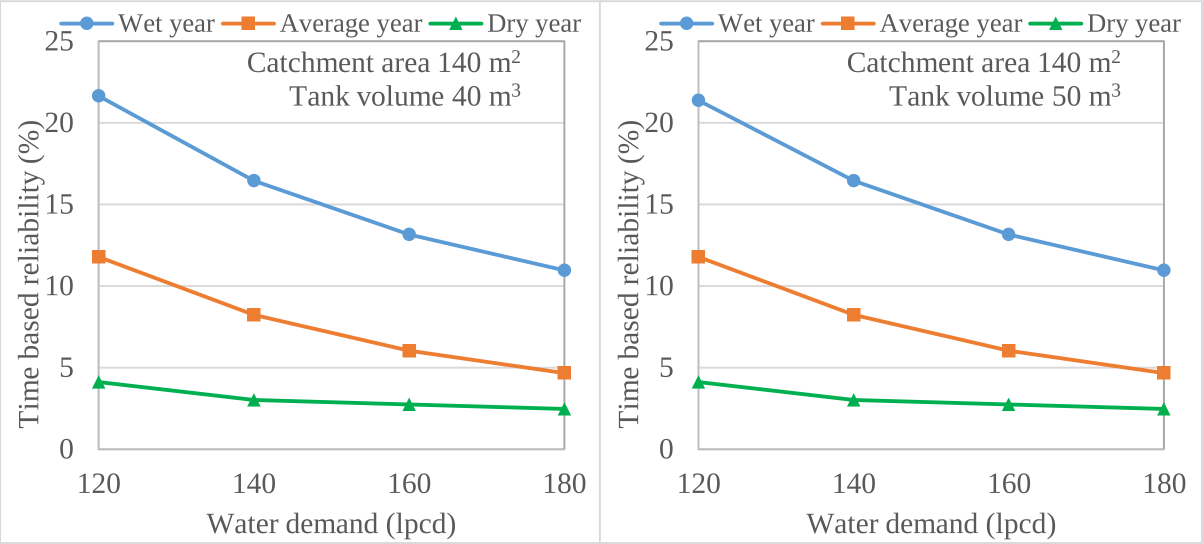


Figure 5.4: Reliability curves for a catchment size of 140 m^2 with varying water demand.

Figure 5.3 and 5.4 shows the reliability curves with varying daily water demand for different scenarios. For both the cases reliability decreases significantly with the increasing water demand. Reliability decreases by about 5-10% for an increase in water demand of about 60 lpcd, which signifies that the rainwater harvesting system becomes inefficient with a high water demand.

5.1.2 Volumetric reliability

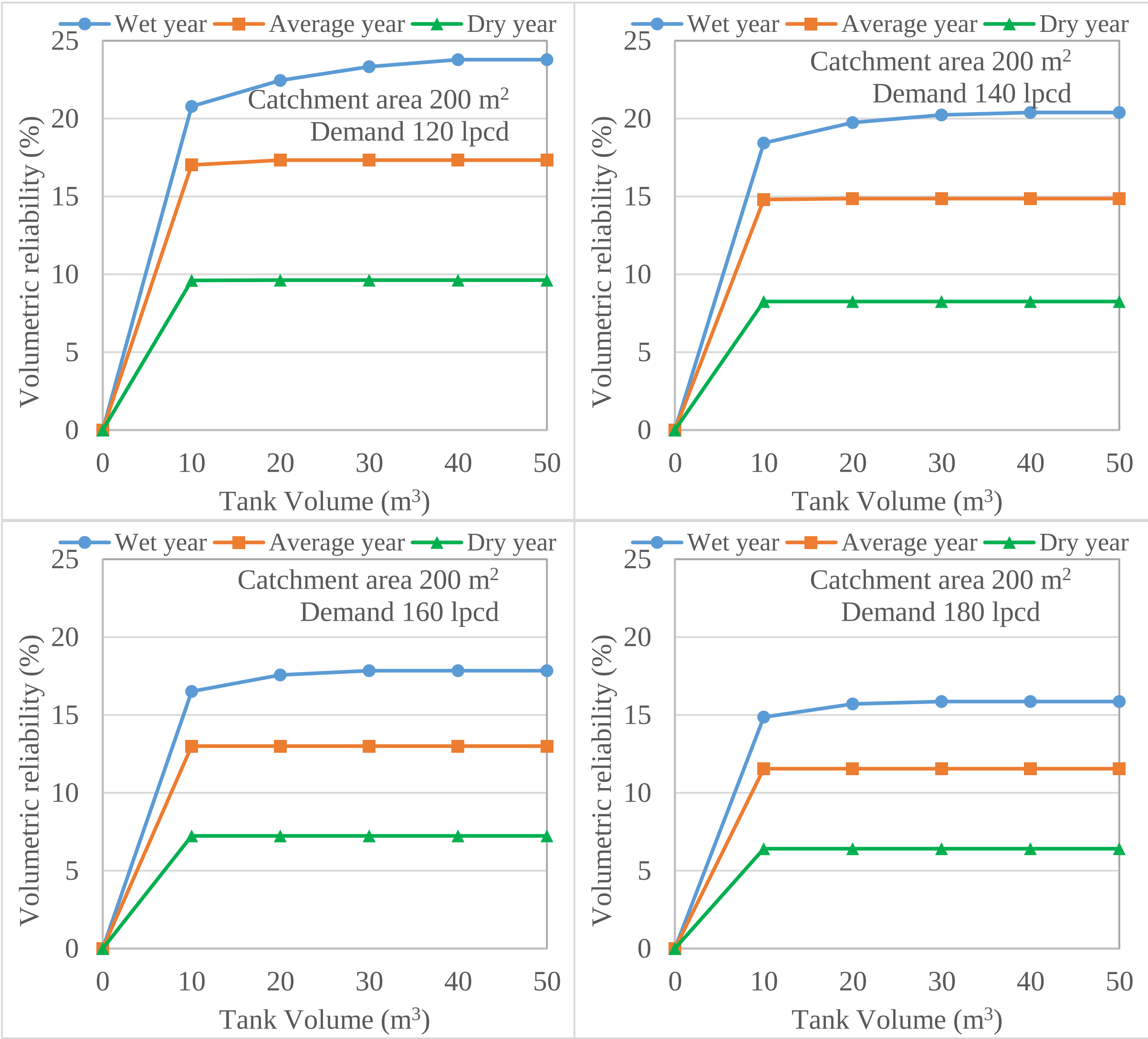
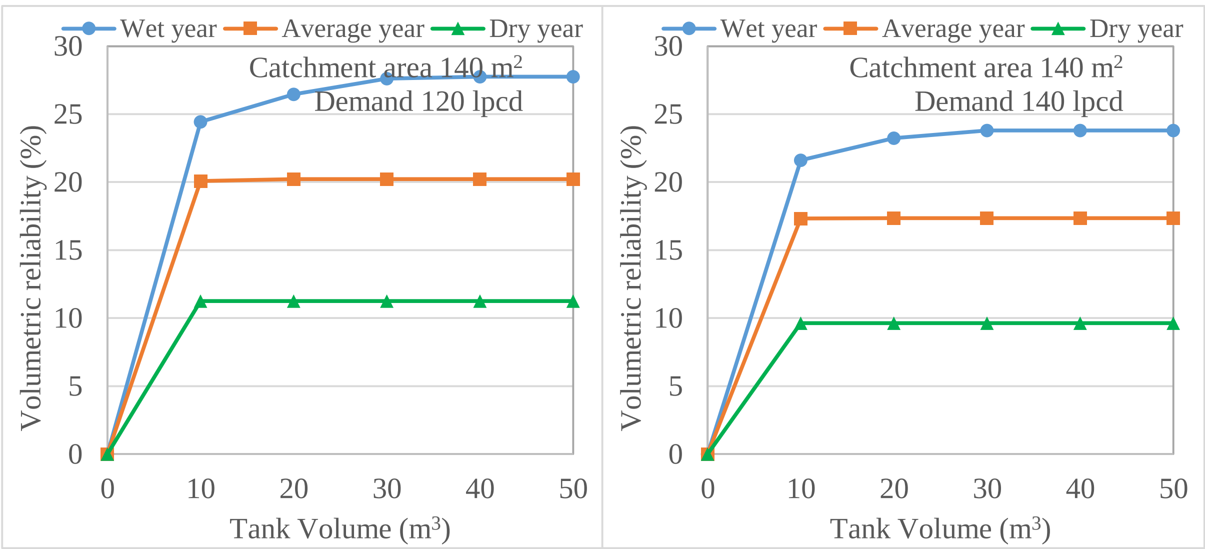


Figure 5.5: Volumetric reliability curves for a catchment size of 200 m^2 with varying tank sizes.



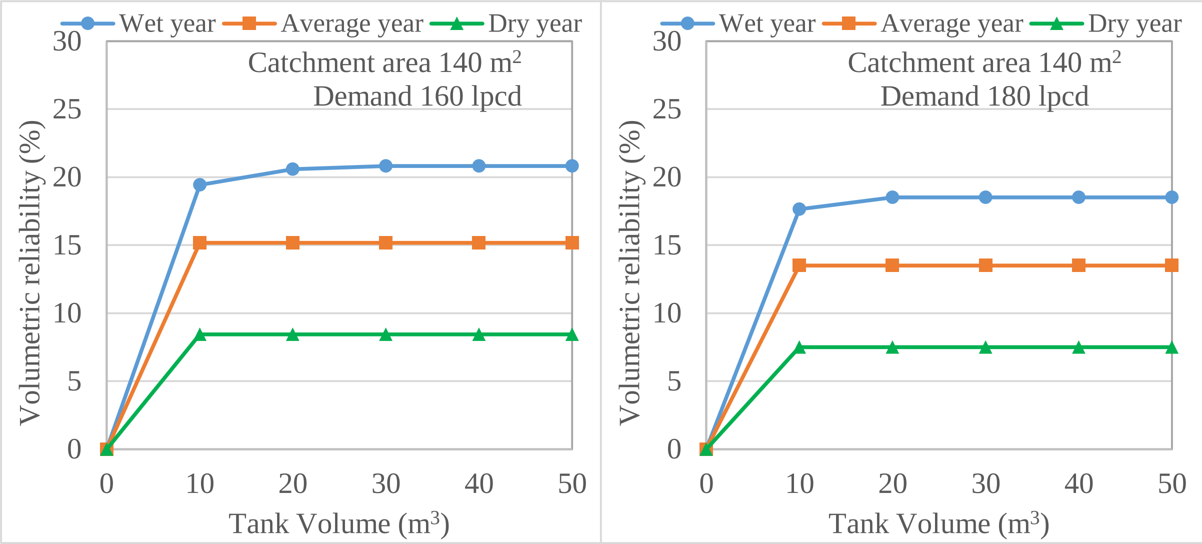


Figure 5.6: Volumetric reliability curves for a catchment size of 140 m^2 with varying tank sizes.

Figure 5.5 and 5.6 both shows the relationships between the volumetric reliability and tank volumes for different catchment sizes and water demand. The effect of tank size on the volumetric reliability is same as the time based reliability. It can be observed that the value of volumetric reliability is higher than the time base reliability for the same scenarios. Where the time based reliability varies from 3-17% for a catchment size of 140 m^2, volumetric reliability varies from about 10-24% for the same catchment size. This is primarily because of the water demand considered for this study includes domestic water use such as drinking, toilet, kitchen sink, bath, washing machine, wash basin, outside use, shower, dishwasher, leaks etc. which is very high for a city like Dhaka in compared to the other areas of Bangladesh. Whereas, the number of days when the rainfall runoff exceeded this demand is less.

The following graphs represent the relationship between volumetric reliability and water demand for different catchment sizes and tank volumes.

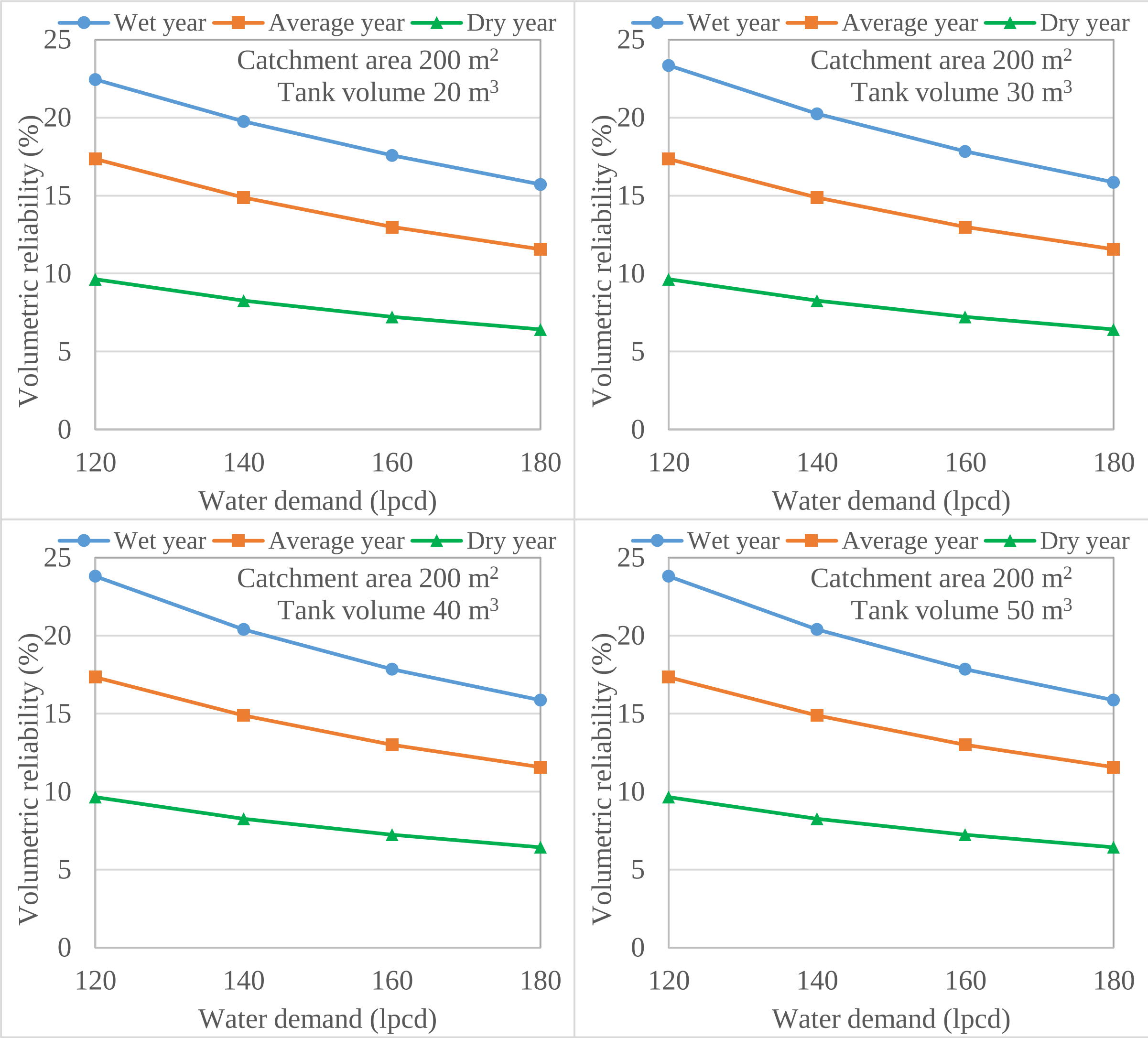
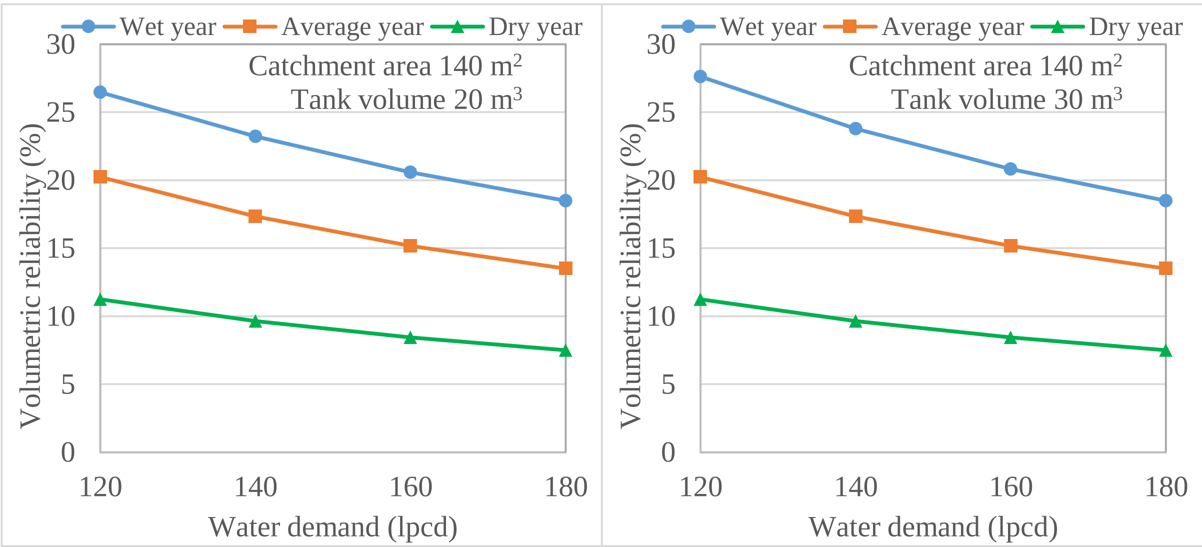


Figure 5.7: Volumetric reliability curves for a catchment size of 200 m^2 with varying water demand.



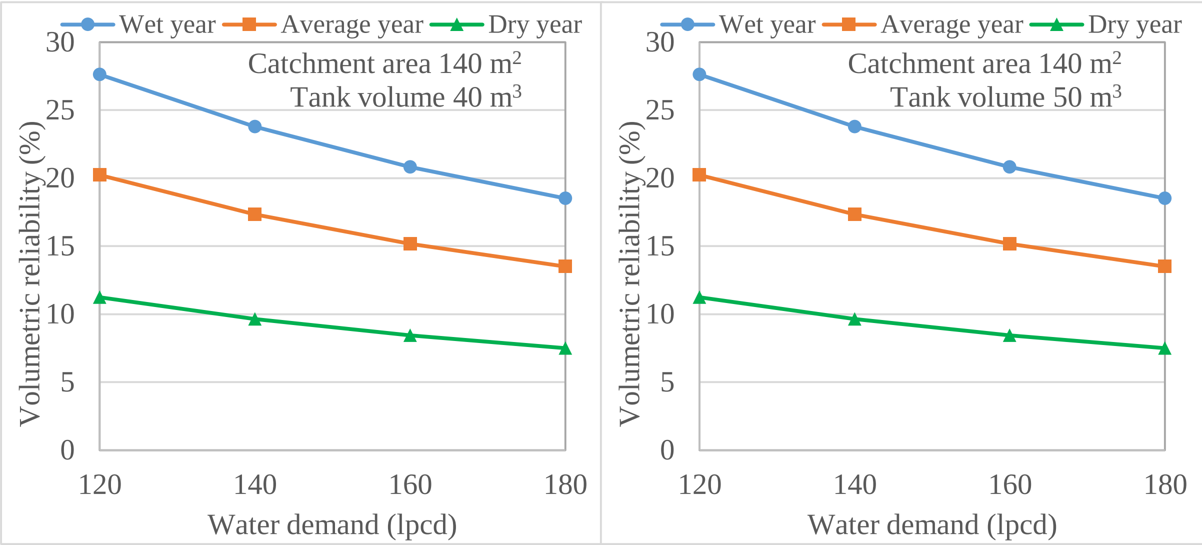


Figure 5.8: Volumetric reliability curves for a catchment size of 140 m^2 with varying water demand.

Figure 5.7 and 5.8 shows the relationship between volumetric reliability water demands for different catchment sizes and tank volumes. The effect of water demand on the volumetric reliability is same as the effect of water demand on the time based reliability i.e. reliability decrease with the increasing water demand. For an increase in water demand by 60 lpcd, the reliability decreases by about 8-10%.

5.1.3 Overflow ratio

Figure 5.9 and 5.10 shows the overflow ratio relationships with the varying tank size and water demand. For the tank sizes varying from 30 m^3 to 50 m^3 no spilled water was found. So the overflow ratios remain zero with increasing water demand and tank volume. This indicates that the existing underground reservoirs capacities are sufficient to prevent the overflow of the harvested rainwater.

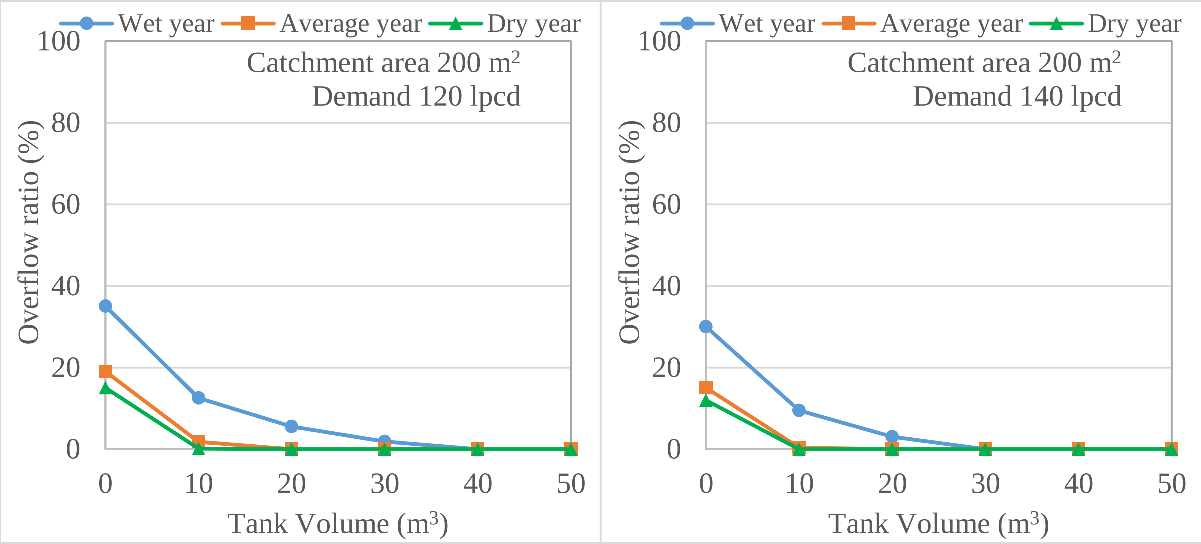


Figure 5.9: Overflow ratios for varying tank volume.

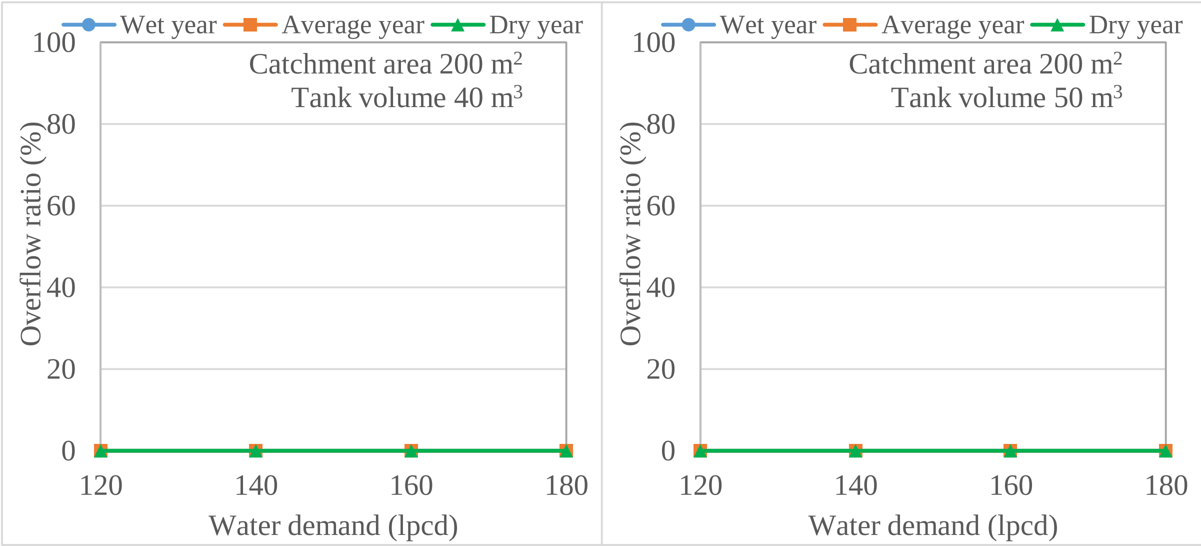


Figure 5.10: Overflow ratios for varying water demand.

5.1.4 Water use pattern

Figure 5.11, 5.12 and 5.13 shows the monthly water use pattern during the wet, average and dry year. As can be seen that rainfall is available from May to October and more than 60% of the demand can be satisfied during June to August in the wet years.

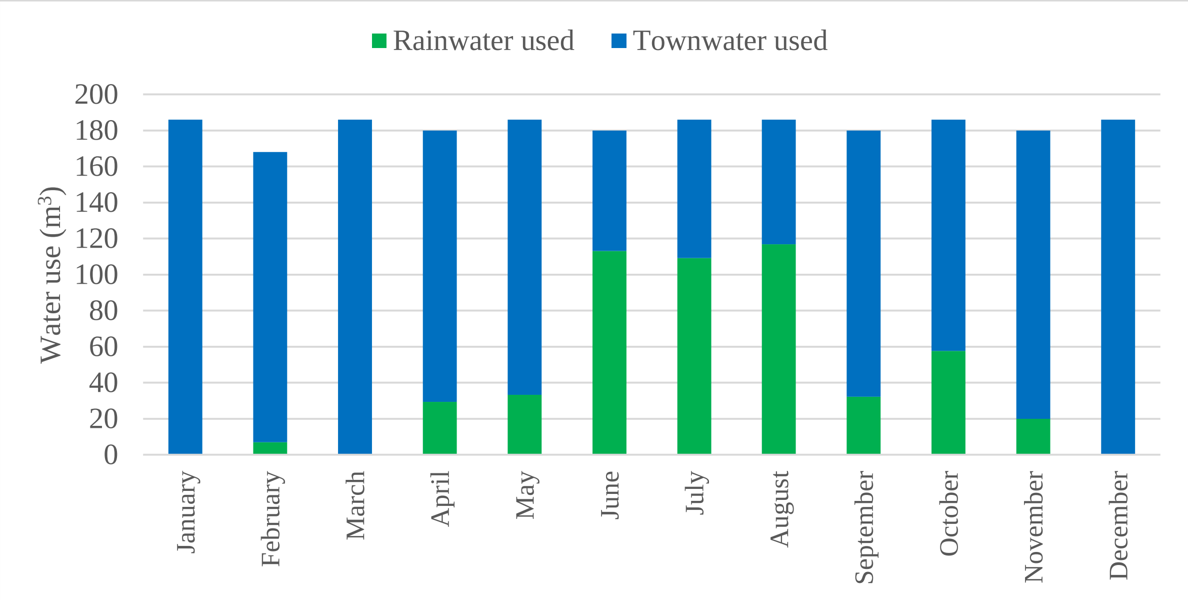


Figure 5.11: Monthly water use pattern in a wet year for a catchment area of 200 m^2, tank volume of 40 m^3 and water demand of 120 lpcd.

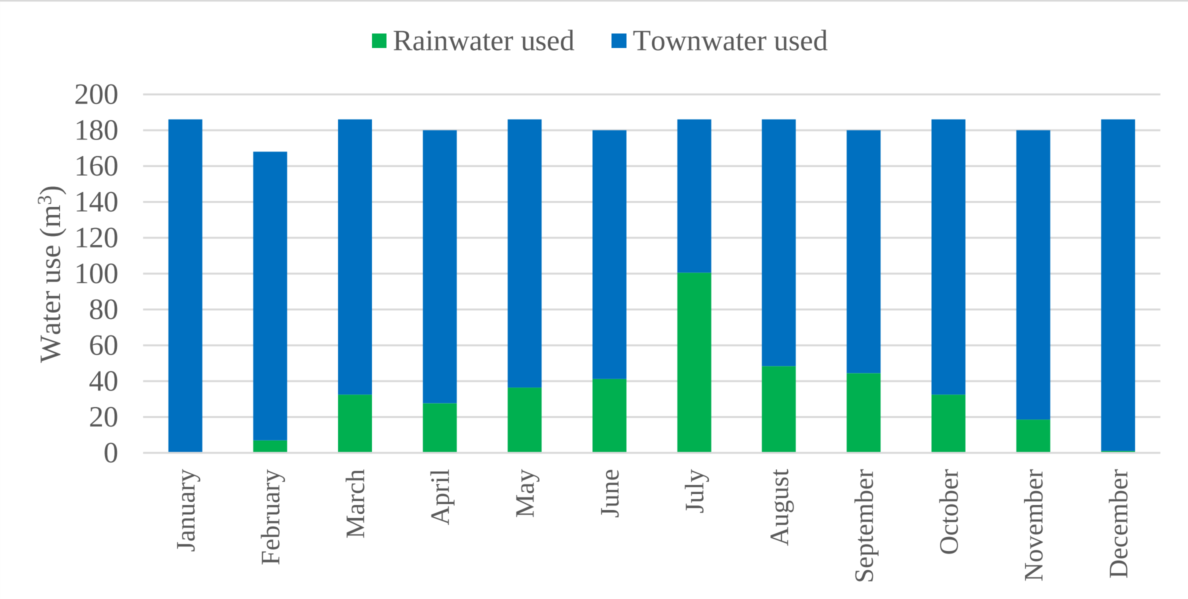


Figure 5.12: Monthly water use pattern in an average year for a catchment area of 200 m^2, tank volume of 40 m^3 and water demand of 120 lpcd.

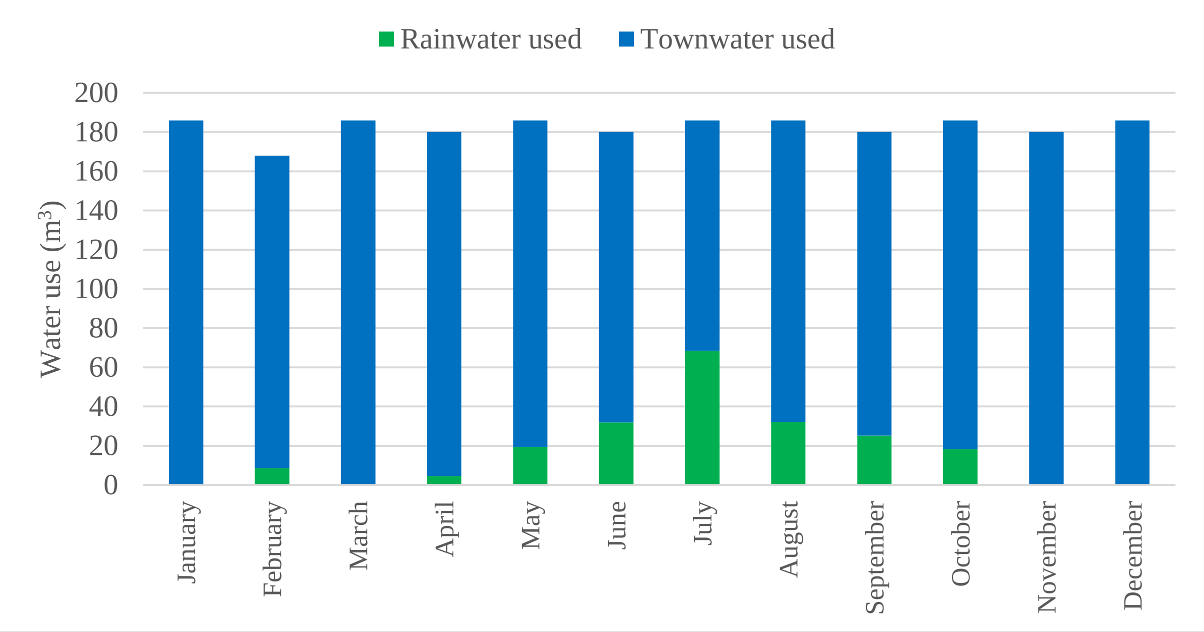


Figure 5.13: Monthly water use pattern in a dry year for a catchment area of 200 m^2, tank volume of 40 m^3 and water demand of 120 lpcd.

Figure 5.14, 5.15 and 5.16 shows the yearly town water and rainwater use pattern in three different climatic conditions. For all three climatic conditions the total town water used throughout the year is 3-5 times the rainwater used.

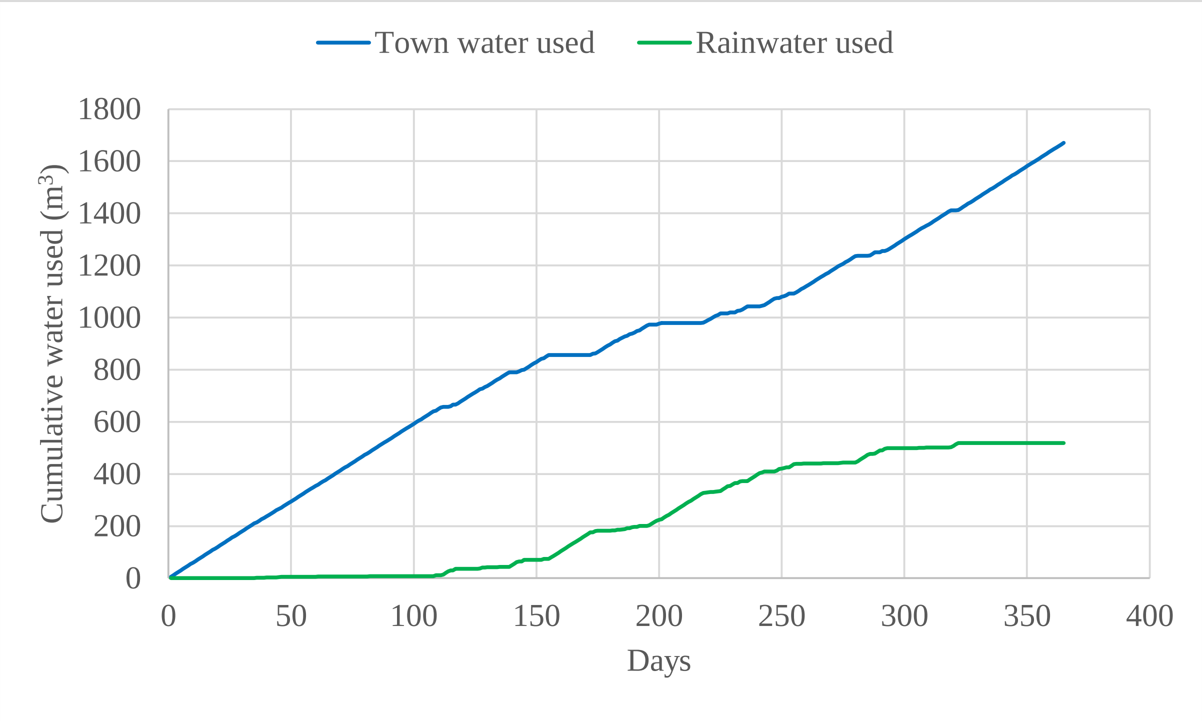


Figure 5.14: Yearly water use pattern in a wet year for a catchment area of 200 m^2, tank volume of 40 m^3 and water demand of 120 lpcd. (Wet year)

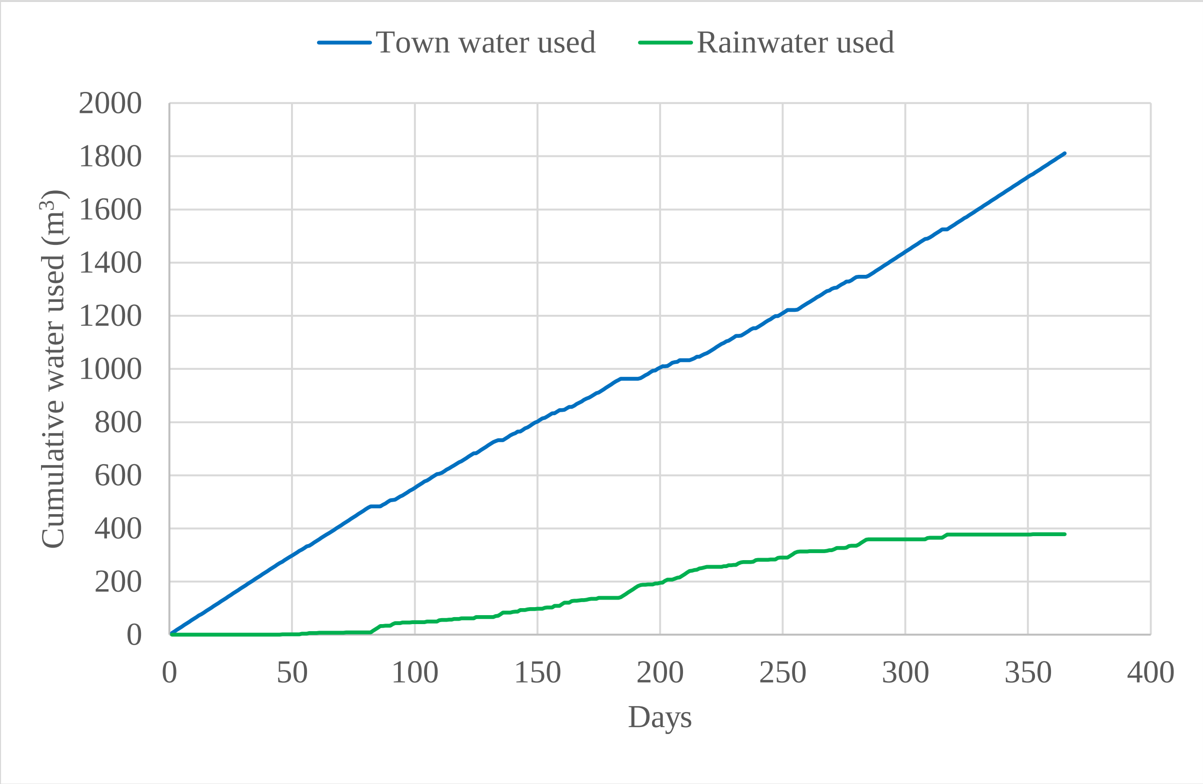


Figure 5.15: Yearly water use pattern in a wet year for a catchment area of 200 m^2, tank volume of 40 m^3 and water demand of 120 lpcd. (Average year)

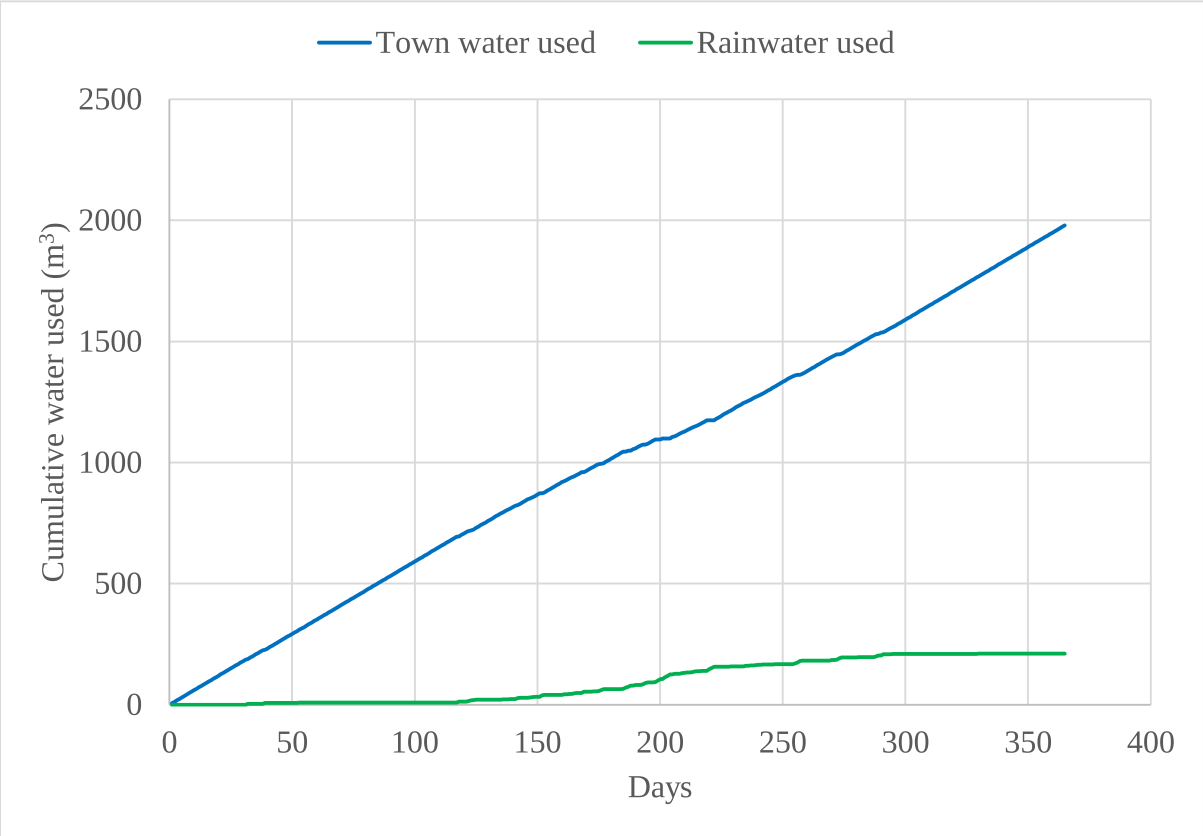


Figure 5.16: Yearly water use pattern in a wet year for a catchment area of 200 m^2, tank volume of 40 m^3 and water demand of 120 lpcd. (Dry year)

5.3 Sensitivity analysis

Figure 5.17, 5.18, 5.19 illustrates the water saving efficiency behavior as a function of the demand fraction with respect to four different runoff co-efficient. The results show that for all the four runoff co-efficient the behavior is same under three different climatic conditions i.e. as the demand fraction and loss increases the efficiency decreases.

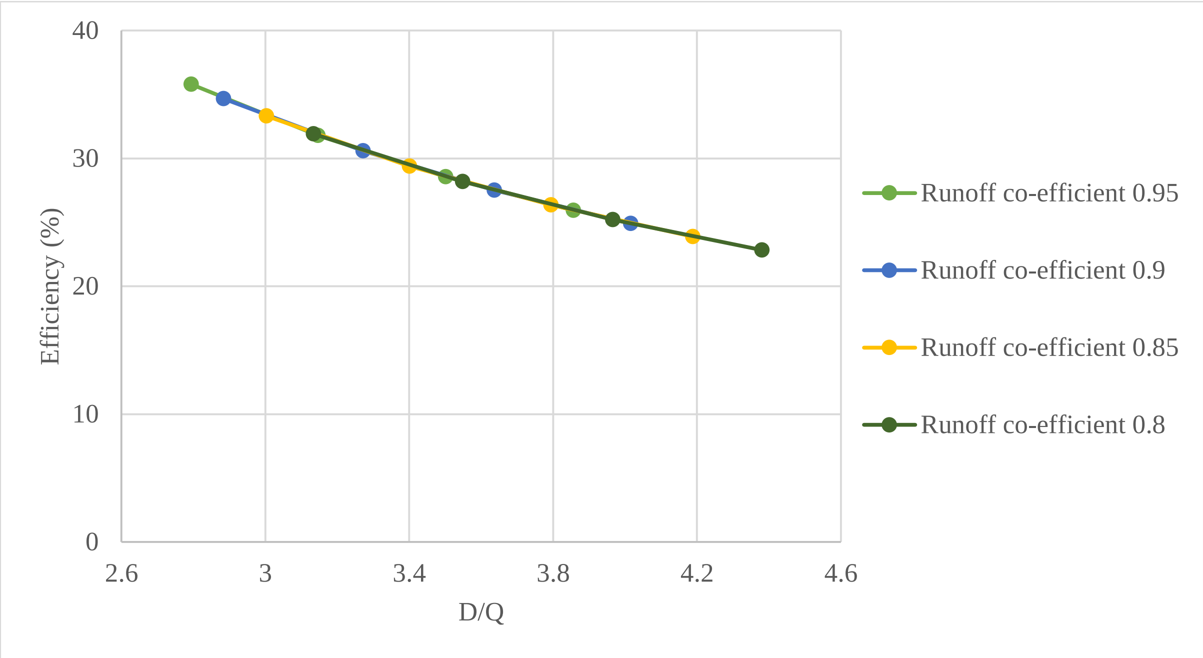


Figure 5.17: Efficiency vs. Demand fraction graph for the wet year.

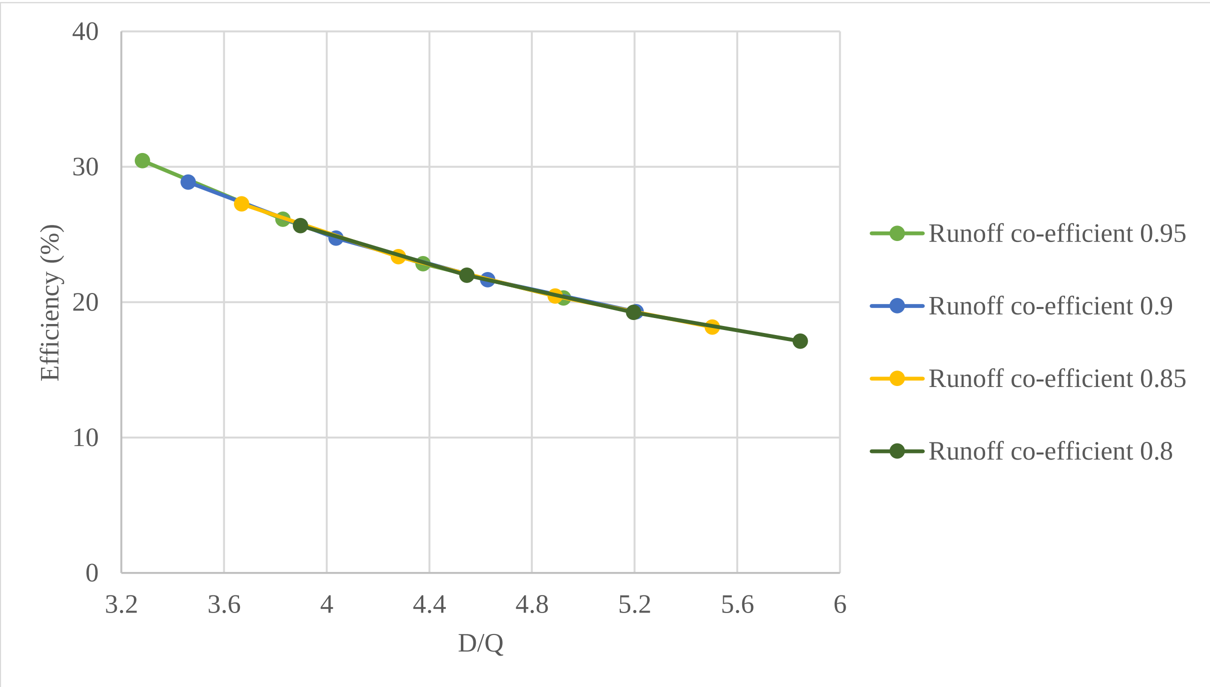


Figure 5.18: Efficiency vs. Demand fraction graph for the average year.

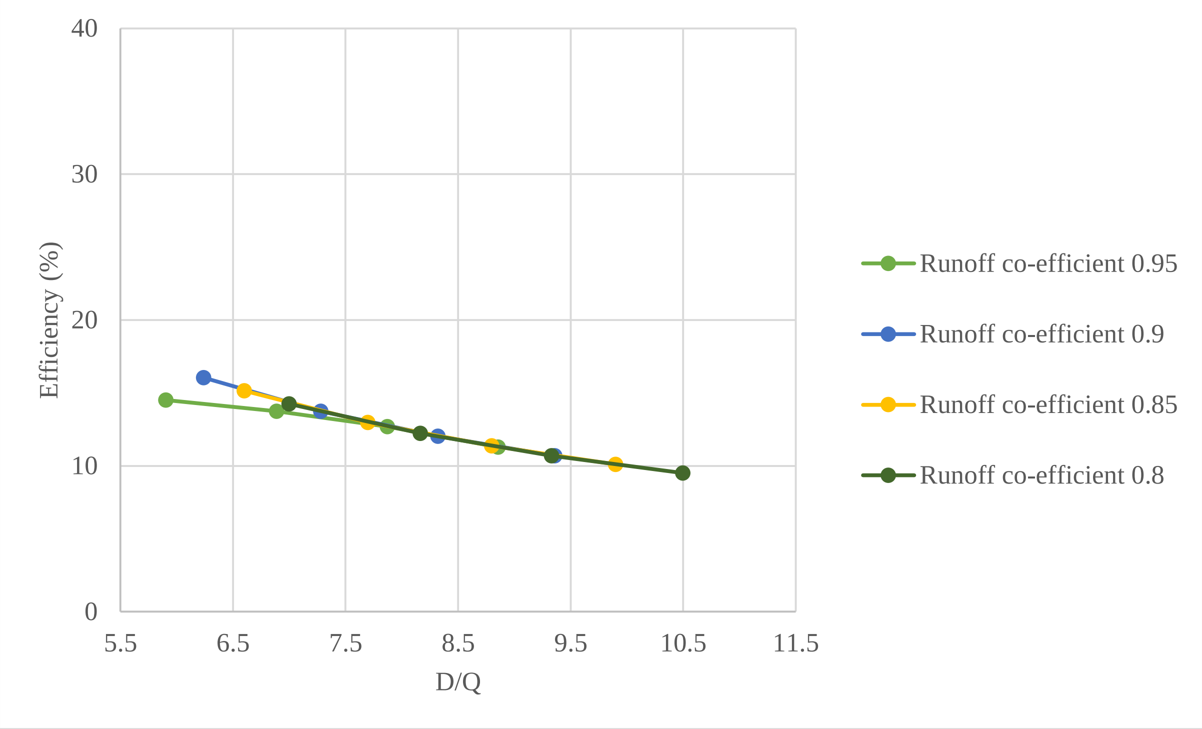


Figure 5.19: Efficiency vs. Demand fraction graph for the dry year.

Figure 5.20, 5.21, 5.22 illustrates the water saving efficiency behavior as a function of the storage fraction with respect to four different runoff co-efficient. Results show that the efficiency tends to increase with increasing storage fraction. Due to a 5% reduction in the loss, efficiency increases about 3-4%.

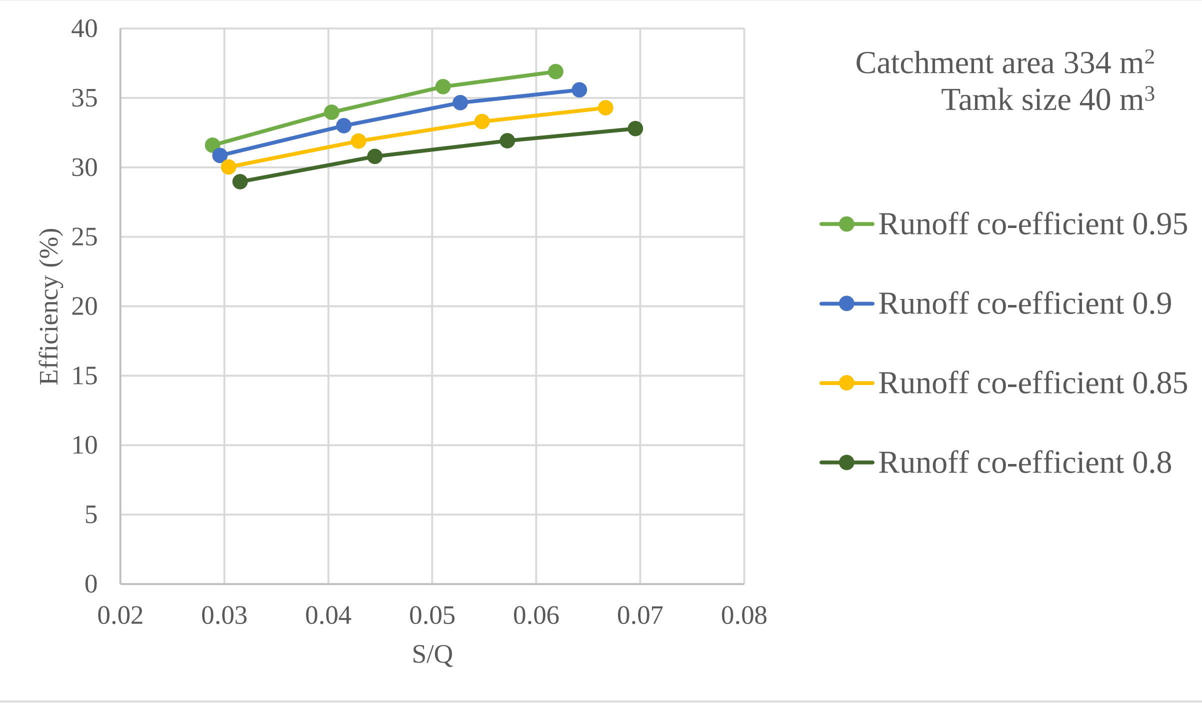


Figure 5.20: Efficiency vs. Storage fraction graph for the wet year.

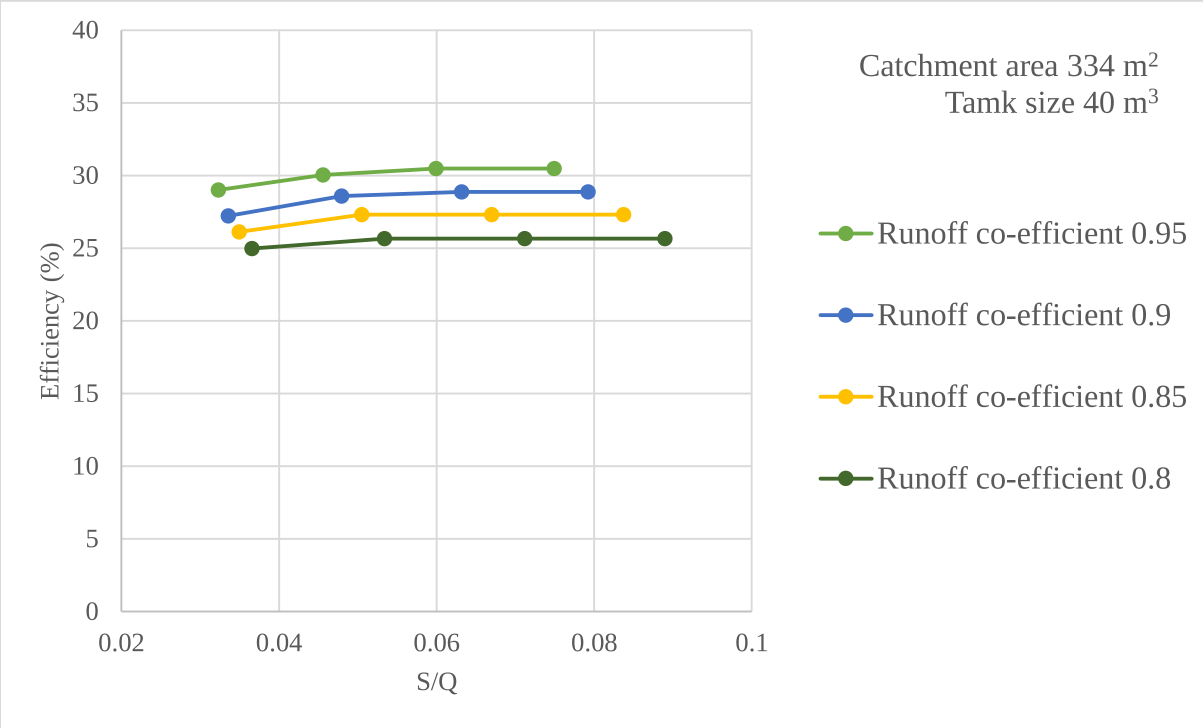


Figure 5.21: Efficiency vs. Storage fraction graph for the average year

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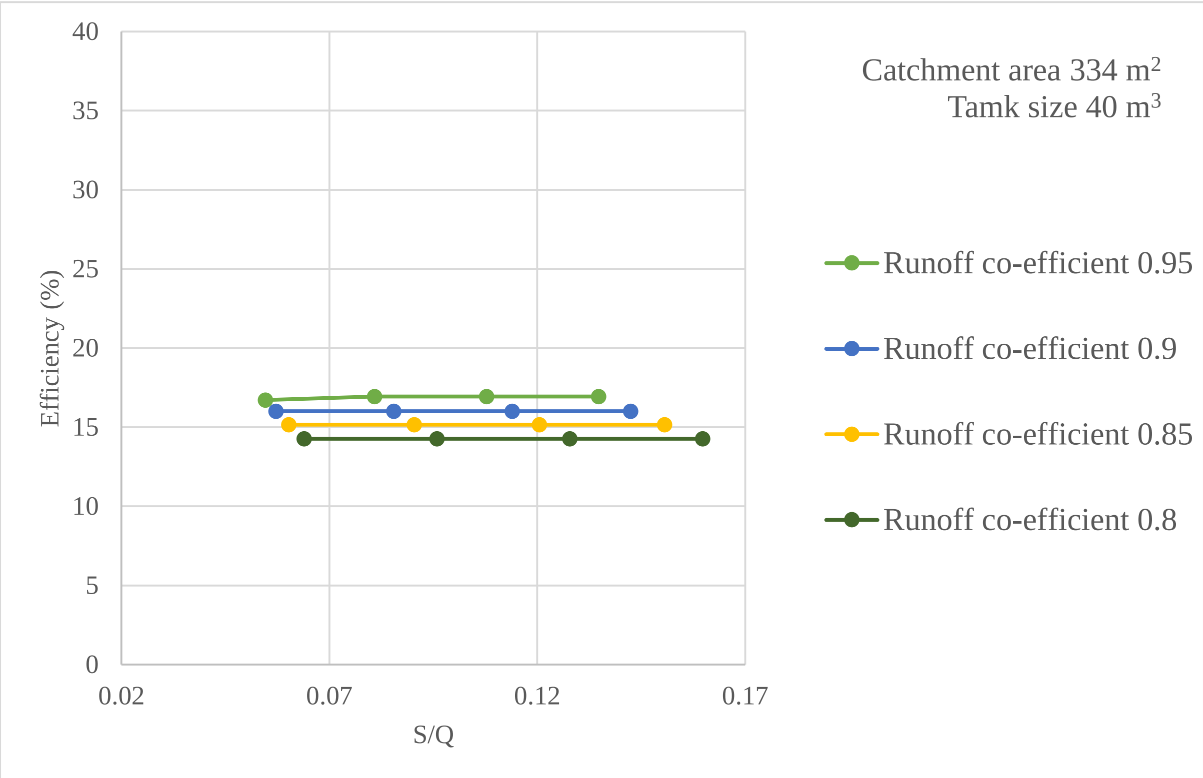

Figure 5.22: Efficiency vs. Storage fraction graph for the dry year.

5.4 Economic analysis

5.4.1 Economic savings

For different scenarios the economic savings are shown on the tables below. The water price has been taken as BDT 8 per kL of water (as per 2014 DWASA water price).

For a daily demand of 6 metre cube of water in an apartment with a tank size of 40 metre cube the monetary savings are shown in table 5.1 for different catchment sizes. It shows that the monetary savings increases with the increasing catchment sizes for all the climatic conditions provided that the daily water demand and tank size remain the same.

Table 5.1: Monetary savings for different catchment sizes.

Climatic conditions	**Catchment sizes (m^2)**		
	140	280	420
	Monetary savings (BDT/ year)		
Wet year	2908	5342	6807
Average year	2120	4203	6238
Dry year	1178	2339	3518

5.4.2 Monthly economic savings

Monthly economic savings pattern for a catchment size of 200 m^2, daily water demand of 6 m^3 and a tank size of 40 m^3 is shown in the figure 5.9. It can be observed that about 60-70% of the money can be saved during May to September.

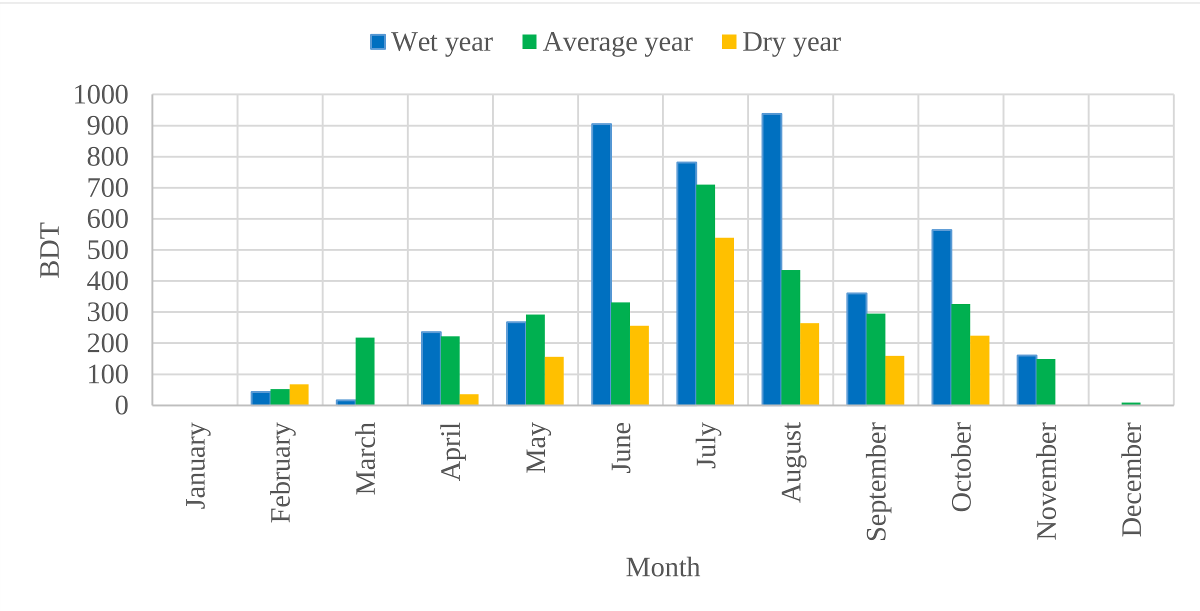

Figure 5.23: Monthly economic savings pattern.

5.4.3 Benefit cost ratio analysis

Considering the economic savings as benefits and installation, maintenance and operation costs as costs, the benefit cost ratios for different project life have been shown in table 5.2. The benefit cost ratios have been calculated for an apartment with a daily water demand of 6 m^3, catchment size of 200 m^2 and tank size of 40 m^3. Installation cost has been assumed as BDT 10,000, Operation and maintenance cost has been assumed as BDT 1500 per year and rate of return has been assumed as 12.5%. The values indicate that the rainwater harvesting systems becomes more economically efficient with greater project life.

Table5.2: Benefit cost ratios for different project life.

Climatic conditions	**Project life**		
	10	15	20
	Benefit-cost ratio		
Wet year	1.26	1.38	1.44
Average year	0.92	1.01	1.05
Dry year	0.51	0.56	0.58

CHAPTER 6
SUMMARY AND CONCLUSION

6.1 Introduction

Despite positive outcome from many studies, there remains a general community reluctance to adopt storm water harvesting on a wider scale. Part of the reason for this reluctance can be attributed to lack of information about the effectiveness of a storm water harvesting system and the optimum storage size required to satisfy the performance requirements under the specific site conditions (Imteaz et al., 2011). The research presented in this paper is undertaken in the light of current knowledge gaps to access the efficiency of a RWH system in Dhaka to provide guidance to water authorities to enhance the acceptance of a RWH system.

6.2 Summary of the main findings

This research investigated the reliability and water savings for the multistoried residential buildings of Dhaka city under three different climatic conditions. The study revealed that the current underground tank sizes of the residential buildings of the city are sufficient to prevent the overflow of the harvested rainwater and about 250-550 kL of rainwater can be harvested per year from a catchment area of 200 m^2 if RWH system is combined with the conventional water supply.

The reliability relationships with the varying tank sizes showed that both the time base and volumetric reliability increases up to a tank volume of 30 m^3 for the wet year and beyond that, reliability does not increase with the increasing tank volume. But in case of average and dry conditions tank size have no significant impact on reliability. For all the cases volumetric reliability was found 5-8% more than the time based reliability.

Both time based reliability and volumetric reliability decreased with the increasing water demand. For an increase of 60 lpcd in the water demand both the reliabilities decreased by about 8-10%.

The demand being high and the tank sizes being large no spilled water was found for tank sizes ranging from 30-50 m^3. So the overflow ratio relationships with the varying water demand and tank size remained zero. A negligible amount of spilled water was found in the wet years only when the catchment size exceeded 400 m^2.

The monthly water use pattern indicates that during June to August more than 50% of the water demand was met by the rainwater and during the months of April, May, September and October the amount dropped to 15-20%.

Yearly water use pattern for a catchment of 200 m^2, tank volume of 40 m^3 and water demand of 120 lpcd showed that around 1700 m^3 of town water and around 350 m^3 of rainwater was used throughout the year. No water was spilled during this evaluation period.

Economic savings showed that around BDT 4000 on average can be saved each year if rainwater harvesting system is integrated with the conventional water supply system. Benefit-cost ratios indicated that the project is economically beneficial in the wet and average years but in the worst case scenarios i.e. in dry years the project becomes a non-beneficial one.

For a reliable and sustainable rainwater harvesting system, reliability analysis should be performed to find out the optimum tank volume. Tank capacity is the key factor to maximize the rainwater storage. There are numerous optimum solutions with different combinations of storage volumes, roof sizes and rainwater demand. The proposed model can be used to predict the reliability and water savings with reasonable accuracy.

The present analysis indicates that a maximum of 25% reliability can be achieved if sufficient rainfall is available throughout the year. Though the reliability and the economic savings found is not much greater, it will have a significant impact if rainwater harvesting system is practised at a larger scale as it will reduce a certain portion of the pressure from the conventional water supply and it will also play a significant role in alleviating the water clogging problem.

6.3 Limitation of the study

This research was carried out only for the multistoried residential buildings having a plot size ranging from 200 to 334 m^2. It does not show the scenarios when the plot size will exceed this limit.

Water demand varies depending upon the type of the building, as this research is mainly concerned with the residential buildings it does not discuss about the reliability of rainwater harvesting system in the buildings which are used for different purposes such as stadium, shopping complex, office, school and colleges etc.

This study also does not cover the assessment of the quality of the harvested rainwater.

6.4 Recommendations for future study

Current research focuses on the applicability of rainwater harvesting system in the urban areas or in particular, Dhaka city. Future research should continue both for rural and urban areas of Bangladesh. The same analysis should performed for different cities of Bangladesh.

Rainwater harvesting have very good potential in different parts of the country where there are problems such as arsenic contamination, salinity, groundwater table depletion, shortage of potable water supply etc. All these factors should be brought under consideration to develop a suitable rainwater harvesting method that best suits the situation for a particular scenario.

Assessment of the quality of the harvested rainwater can also be brought under the research objectives as it plays an important role in the effectiveness of a rainwater harvesting project.

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