A Thesis for the Degree of Master of Science

Rainwater Bank: A Self-sufficient Solution of Water Supply System in Bangladesh

우수저장고: 방글라데시 용수공급 시스템의 자급자족형 대안

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Abstract

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While fresh water availability has been decreasing all over the planet, rainwater usage is being suggested to promote potable water savings and to fight against water scarcity worldwide. Although small on-site rainwater harvesting has been practicing for long years to dry areas, establishing a common storage including personal rainwater tank to catch extra benefit for a community to increase the reliability in water supply system was ignored to fresh water threatened but high rainfall areas.

This study describes an alternative community-based rainwater-fed surface water supply scheme to provide fresh water to the affected regions. In this scheme, there is a common tank named as “Rainwater Bank” for a community. Individual houses are able to collect rainwater from the roof. The individual tanks overflow water to the connected common tank after filling up its capacity. Thus the common tank is acted as “Rainwater Bank” and supply water, when there is any deficit in any individual tank. The main objective of this study is to decrease the dependency on existing supply system by increasing the reliability with rain water harvesting and self-sufficient community water supply system. Standard operating policy was the basic for storage estimation techniques analyzed. Generating 100 sets of synthetic data with 30 years length, Rainwater Bank simulations are done. The behavior of statistical performance indices, namely, reliability (describe how likely a system is to fail), resilience (how quickly it recovers from failure) for evaluating the possible performance of Rainwater Bank systems are discussed. Several test cases have been assessed to determine the maximum reliability improvement/common tank capacity increase ratio with respect to inflow statistics and demand. It is found that water supply reliability can be improved from 64% to over 95% to the selected study site and 1200liter common tank is the best choice for 2 800liter sized individual tanks when individual tank size is assumed as equal to demand. Three types of "Rainwater Bank" systems are illustrated to find out the trend of common tank sizes. Tradeoff between individual tanks with or without common tank has also been discussed clearly. From this study, the RWHS engineers and decision makers can be benefitted for the evaluation and selection of alternative design and operating policies in Bangladesh.

Keywords: Rainwater bank, Common tank, Capacity determination, Bangladesh, Inflow generation.

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Chapter 1. Introduction

1.1 Problem statement

In recent years, the problem of decreased availability of potable water has led to increased awareness of the necessity to preserve water resources and explore additional sources of fresh water. The notion that water is a “dying supply” is felt most immediately from the fact that in many countries fresh water needs to be bought in bottled form, which was unimaginable just a few decades ago. The use value of water was never considered, but it is about time that even its exchange value is given due importance.

According to Rahman (2003), fresh water, a renewable but limited resource, is scarce in many areas of the developing world because of unplanned withdrawal of waters from rivers and underground aquifers causing severe environmental problems like arsenic contamination. That is why; the present study aims to highlight these important aspects and tries to find out a suitable solution.

Bangladesh, a South Asian country, is largely dependent on groundwater for domestic and irrigation purposes, because it is free from pathogens and has so far been available in adequate quantity in shallow aquifers. In rural areas, more than 97% of the populations rely on groundwater for their drinking water supply. For example; Dhaka, the capital city of Bangladesh, is one of the mega cities that face a severe shortage of safe drinking water. In Dhaka, 82% of the water supply is abstracted from groundwater, while three surface water treatment plants provide the remaining 18% (Haq and Khadakar, 2006). The country is now facing a major challenge in supplying safe potable water to the most of her people. The drinking water in Bangladesh is largely sourced from hand-pump tube wells, which has been badly polluted with arsenic in recent years. 59 of the country's 64 districts had arsenic presence in ground water. Table 1.1 is showing the magnitude of arsenic poisoning in Bangladesh. It is clearly noticeable that about half of the population of Bangladesh are at risk of drinking arsenic contaminated tube well water (Smith et al., 2000).

At the same time, the groundwater table (GWT) is also falling drastically due to extreme withdrawal of water. The 1991 National Survey on Water and Sanitation (Mitra, 1992) identified 64% of the population to live in areas under the shallow water table (SWT) while 25% were in areas under the low water table (LWT) and 11% in saline coastal areas. Though in 1986, only 12% of the country was affected by lowering of the water table, the affected area expanded to 35% in 1995 and by 2002, 42% of the country falls into the LWT area. Considering the existing situation, Uddin and Baten (2011) studied on the groundwater scenario of the capital city of Bangladesh. They stated that the capital city, Dhaka has been experiencing a sharp declination in the groundwater table with a drop of more than 20 meters during the last seven years corresponding to a rate of 2.81 meter per year. Figure 1.1 illustrates with an extrapolation of data prior to 2003 into the future. They predict that the groundwater table will decline to 120 meters by 2050. It has already receded by fifty meters over the past 40 years, bringing the current level to sixty meters below ground. Currently, the situation is so problematic that experts warn rapid depletion of Bangladesh's underground water table could jeopardize food and water security for millions throughout the country and also endanger the biodiversity of one of the world's largest mangrove forests within the next two decades.

Table 1.1 Magnitude of arsenic poisoning in Bangladesh (Smith et al. 2000)

Box 1. **Magnitude of arsenic poisoning in Bangladesh**	
Population of Bangladesh:	125 million
Total population in regions where some wells are known to be contaminated:	35–77 million
Maximum concentration of arsenic permitted in drinking-water according to WHO recommendations:	10 µg/l
Maximum concentration allowed in Bangladesh:	50 µg/l (similar to many countries worldwide)
Number of tube-wells sampled by the British Geological Survey (1998):	2022
– Proportion of wells with arsenic concentrations >50 µg/l:	35%
– Proportion of wells with arsenic concentrations >300 µg/l:	8.4%

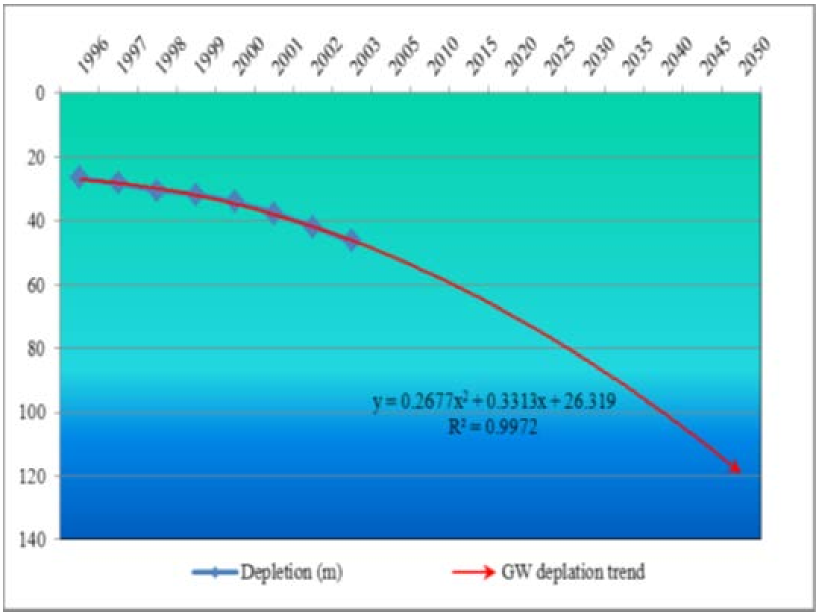

Figure 1.1 Groundwater depletion trend of Dhaka city, Bangladesh

1.2 Uniqueness of this study

In the depraved situation, increasing demand for water cannot be met as the groundwater abstraction is showing strong signs by running down in a rapid way which also cannot be replenished by the monsoon recharge to groundwater. However, treating surface water is much more technically complex and expensive than using groundwater. The large rivers nearest to the cities are so polluted by the indiscriminate discharge of domestic waste water and industrial effluent that treating surface water has become a great challenge for Water Supply and Sewerage Authority of Bangladesh nowadays.

Due to fast urban development, increasing water demand is putting continuous stress on existing water resources. Experts are now focusing on alternatives such as rainwater catchment systems as supplementary water sources with multi-purpose functions. Roofs represent an important percentage of the large impermeable areas which can offer a significant preference for rainwater collection. This study is also concentrating on rainwater collection system but the uniqueness is on the idea. Rather than small onsite rainwater harvesting system, this study is dealing with a common storage tank that is able to store water for whole of the year round with the onsite rain tanks for a small community. The combined system of common and individual network scheme is quite new and no study has been found until now that considers the reservoir of water with rainwater. We may find many dams that can hold large amount of surface water but how easy installing community based rainwater storage tank can perform better is the interesting output of this idea. Rainwater harvesting system can be seen in dry and arid areas of the world but how fresh water scarce heavy rain fed country like Bangladesh, can use rainwater to alleviate the problem and improve the water supply system of the country is the center of this study. Installing “Rainwater Bank” with the existing house tank the basic water demand for an average sized family can be fulfilled to better extent collecting rainwater only.

Moreover, one social development side-benefit of the idea is that a sense of self-concern and empowerment can be developed to those communities that are working according to the planned model. Sharing responsibility for new facilities and being actively involved in participatory baseline can benefit them in improving people's ability to analyze and take control of their living environments.

1.2 Objectives of the study

From the above discussions, it is easily understandable that Bangladesh is deeply suppressed by fresh water problem which needs an immediate solution. Realizing the acute problem, in this study 3 objectives have been thought to solve the difficulties:

- Firstly, the present study proposes a comparative evaluation of the reliability offered between the "Rainwater Bank" systems versus a single system of several individual rain barrels without a common tank in order to allow for informed choices tailored to specific situations.

- The key objective is to evaluate rain water supply reliability of a newly designed idea naming as "Rainwater Bank" to decrease the dependency on existing water supply systems in a community.

- Apart from studying the reliability of Rainwater Bank system, determining best choice for a suitable "Rainwater Bank" capacity for a particular number of houses for a particular area is also a target objective. To find out the suitable result sensitivity analyses are done. Three kinds of sensitivity tests are performed; a) sensitivity to mean inflow, b) sensitivity to standard deviation of inflow and c) sensitivity to individual tank size.

1.4 Thesis organization

This study is organized in the following manner. The background study related to the implementation of small on-site Rainwater Harvesting Systems (RHS) as alternative water supply sources in some countries; Bangladesh practice and literature on mass curve analysis; YAS/YBS rule, probabilistic method; standard operating policy; choices on reliability and resilience; optimization on water resource plan have been reviewed in Chapter 2. Methodologies applied on "Rainwater Bank" system and procedure of calculation and simulation are described in chapter 3. In Chapter 4, study site; data structure; assumptions and simulation cases have been discussed under Application. Results and discussions; sensitivity analyses of the case study; analyzing 3 cases; tradeoff between individual tanks with or without common tank are revealed in Chapter 5. Chapter 6 has been concluded with summary and future works.

Chapter 2. Literature Review

2.1 Rainwater harvesting system as an alternative water supply sources

Rainfall is the most directly accessible water supply source. Storages may be frequently needed for regulating the in-uniformly distributed characteristics of rainfall among the spatial and temporal aspects. Other than large reservoirs, small on-site Rainwater Harvesting Systems (RHS) have been successfully implemented as alternative water supply sources in some countries like Japan, Hong Kong, Singapore, Hawaii, and the United States (Chu et al., 1997; Thomas, 1998; Hatibu & Mahoo, 1999; Li et al., 2000). Rainwater harvesting systems capture rainwater in the hydrologic cycle by means of either natural aquifer recharge process or artificial facilities. With its easy structural installation, it has become one of the economical and practical measures for providing alternative options in water supply system. It may serve as a major water supply source in some rural or under-developed areas (Thomas, 1998; Liaw and Tsai, 2004), and can be a secondary water source for urbanized regions for miscellaneous household uses such as toilet flushing, lawn watering, cooling for air conditioning, or supplementary water source for landscape and ecological pools (Yusuf and Yusuf, 1999; Handia et al., 2003). Rainwater harvesting is a sustainable option to fresh water scarce small islands which are remote from the mainland (M. Han and J. Ki, 2000). In the UK, research has tended to focus on the potential to reduce reliance on potable mains supply at the single building scale (e.g. Dixon et al., 1999; Fewkes, 1999; Brewer et al., 2001). Mains supply water is to some degree substituted by harvested rainwater and so these systems are also a way of reducing pressure on the centralized water supply and distribution infrastructure (Schilling and Mantoglou, 1999; Coombes and Kuczera, 2003). Apart from storing water during rainfall period, it also can provide some flood detention capacity for flood attenuations in some regions (Becker and Raasch, 2003; Kumar et al., 2005). Thus rainwater harvesting system can be regarded as a sound strategy of alternative water sources for increasing water supply capacities (Hatibu and Mahoo, 1999; Motsi et al., 2004).

2.2 Methods applied on rainwater harvesting researches

Jenkins et al. (1978) developed an essential mass balance equation to describe the behaviour of the RWHS in terms of yield after spillage (YAS) and yield before spillage (YBS) rules. Fewkes and Wam (2000) developed regression equations for a water-saving efficiency curve based on storage period, defined as storage capacity divided by average daily water demand. Liaw and Tsai (2004) tried to optimize storage volume of an RWHS in Taiwan. Villarreal and Dixon (2005) showed the contribution of RWHS for potable water, irrigation, and car washing with water saving efficiency concept with a case study at Ringdansen, Sweden. Water-saving efficiencies were estimated for surface areas of 20,000, 40,000, and 60,000 m^2. The concept of RWHS is very similar to that of reservoir systems, and various methodologies have been applied to estimate the size of RWHS. Storm water basins or reservoir systems, and various methodologies have been applied to estimate the size of RWHS.

Another group of researchers applied a probabilistic concept whilst simultaneously estimating RWHS factors. To consider a deficit rate, for a specific tank storage, normal distribution (Rahman and Yusuf, 2000; Surendran et al., 2005) and log-normal distribution (Xu and Goulter, 1999; Surendran et al., 2005) were applied. Su et al. (2009) studied RWHS storage capacities and deficit rates for grey water reuse in the city of Taipei, Taiwan. They applied a standard operation policy for simulation and used normal distribution as a deficit rate distribution under different

RWHS storages. Using these data, they presented economic and optimal RWHS volume. Also, they produced an exceedance probability curve and probability density functions with storage and deficit rates. Seo et al. (2011) investigated and quantified the influence on required storage reduction when multiple rain barrels are linked. They used the concept on homogeneous users (same mean and variance in water demand) and heterogeneous users (different means and variances in water demand) taking account of six cities in the USA for storage–reliability–yield analysis. The result indicates that required total storage can be reduced by connecting multiple rain barrels.

This research differs significantly from previous researches because these studies have only considered variability of rainfall characterization in a single RWHS storage, except Seo et al. (2011), considering uncertainty of water demand to show the influence of linked RWHS in terms of statistics. All the studies here came up with singular rainwater tank and small demand. No concept of individual and common tank network system was found. At the same time, every study neglected the significant amount of spilled water.

2.3 Rainwater harvesting practices in Bangladesh

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 (Ferdausi and Bolkland, 2000).

Being a tropical country, Bangladesh receives heavy rainfall during the rainy season with an average annual rainfall of 95 inches (BBS, 1997). This amount makes rain water harvesting an obvious solution for the arsenic contamination whereas 50%

area of the country is suffering from arsenic contamination making it a nationwide problem (Rahman et al., 2003). Dhaka receives an annual rainfall of 71-80 inches which can easily be an answer to the vertical recharge for the aquifers (Kabir and Faisal, 1999). The aquifer hydrology is almost entirely controlled by excessive abstraction of water in the area. The pattern of water-level change in the city of Dhaka from the 1980s onward largely follows the patterns of change in groundwater abstraction (Hoque et al., 2007).

The economic condition as well as absence of water supply facility has prompted the low income groups to harvest the rain water for household and essential uses which is evident in the fact that 52 indigenous methods has been practiced by the tribal people of Bangladesh (Kabir and Faisal, 1999). Although these methods are small scale, area specific, labor intensive and paced with slow rural life, they involve significant low cost while maintaining ecological balance and sustainability. Quality of rainwater is also a big concern. Different important physical, chemical and bacteriological parameters were tested throughout the storage period of 4 months. The test results were compared with the Bangladesh water quality standards. The tests have revealed slightly higher pH value (8.1 to 8.3) and enormity of color beyond the acceptable range. Although the presence of total coliform was detected after three months, traditional filtering of that stored rainwater showed a promising solution to mitigate potable water shortages in Bangladesh (Islam et al. 2010). Akbar et al. (2007) conducted the research on community water supply for the urban poor. His model is applicable to those cities where there is a little or no problem with water availability but where the poor still do not have good access to potable water. This paper suggested that engagement of the private sector can be utilized to empower local communities.

Feasibility studies were done by Islam et al. (2011) and Alam et al. (2012) in two megacities of Bangladesh. Both the studies found that the low-cost rainwater harvesting technique was feasible and acceptable to the slum dwellers as the only potential alternative source of safe drinking water. A sensitivity analysis was performed to check the important parameters toward the implementation of the system as well. The results showed that cost was the most sensitive parameter (48.1%), the second highest sensitive parameter was roof area (25.9%) and the lowest sensitive parameter was demand (2.2%) (Islam et al. 2011).

Chapter 3. Methodology

3.1 Overview

The key objectives of this study are to improve water supply reliability and to determine the best choice of "Rainwater Bank" i.e. common tank size for a community. To meet the purpose a mass-balance equation is incorporated into the Rainwater Bank model to simulate the common tank operation with assumed individual tank sizes and numbers. Standard operating policy is the basic for storage estimation techniques analyzed. The overall research procedure is presented as flow chart in Figure 3.1.

Input variable include monthly average rainfall data and given parameters are roof area, roof runoff coefficient, per capita water consumption per day and the size of the population using the storage system. For this experimental evaluation demand is taken only from individual houses, demand variability is not considered here. Historical precipitation has been used for the basic reference. Generation of inflow data is based on those observed historical data. Lognormal distribution is assumed for the inflow data and purely random AR (0) and auto correlated AR (1) models have been used for the new generated data. The yield from each tank is taken as decision variable. By assuming fixed demand, estimation of the size of the common water tank is being analyzed checking individual tank capacity as double and equal of demand. Sensitivity tests with mean and standard deviation changes have also been done for these 2 types of individual tank sizes. The behavior of performance indices, namely, reliability (describe how likely a system is to fail) and resilience (how quickly it recovers from failure) for evaluating the possible performance of Rainwater Bank systems are discussed. Finally, three types of "Rainwater Bank" schemes are investigated to find out the pattern of common tank sizes.

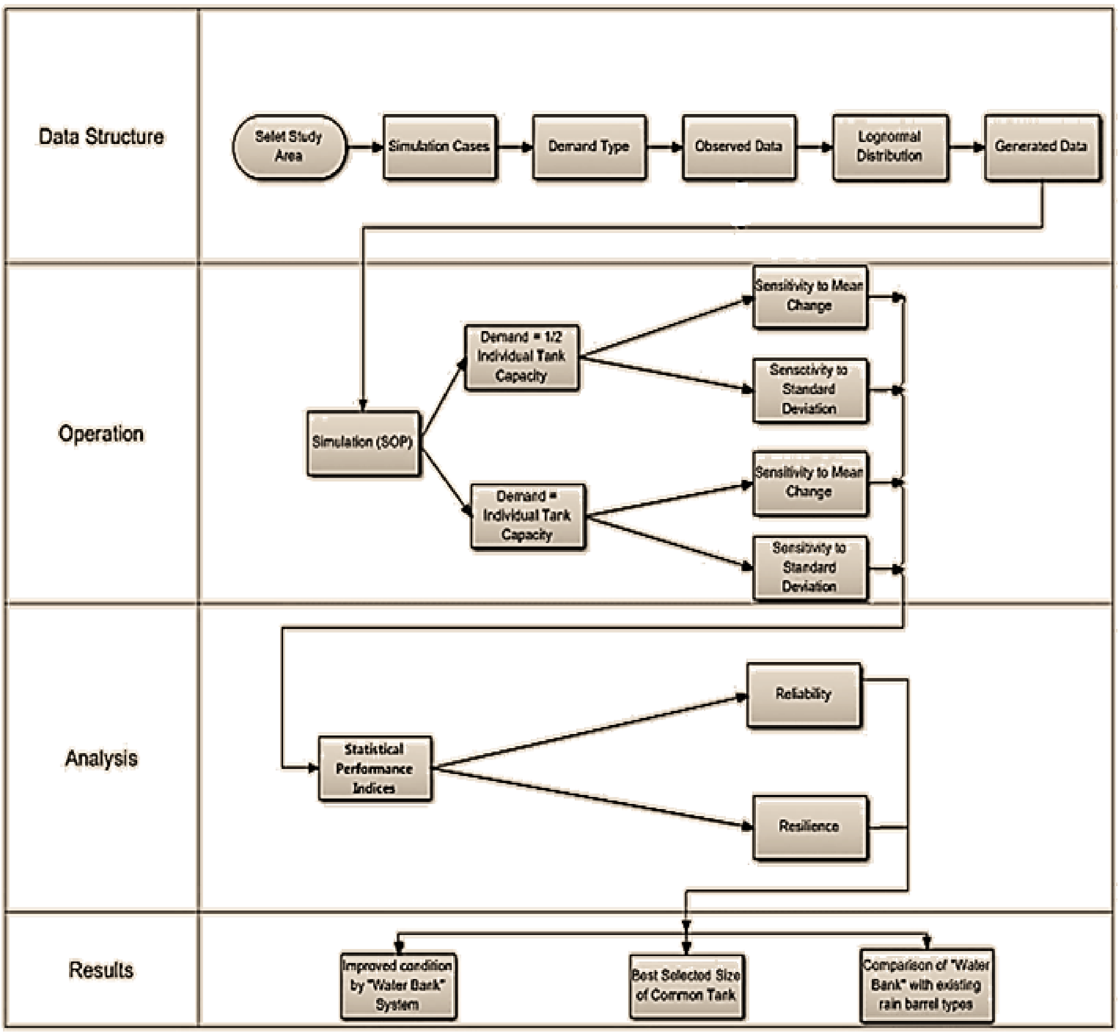

Figure 3.1 Flow chart of research procedure

3.2 “Rainwater Bank” systems

This study proposes a new community-oriented water supply system based on rainwater harvesting. The applicability of the system for a community has been investigated. Community will grab rainwater, will use it, will store it, and will maintain their supply system. This study reveals that by applying this plan a community can store rain water for the year round by a common storage named as “Rainwater Bank”, by avoiding dependency on groundwater abstraction and at the same time, fulfilling community demand.

The “Rainwater Bank” has been planned as follows: there is individual rain water storage tank in each house. As illustrated in Figure 3.2, individual houses are able to collect rain water from the roof. The individual tanks overflow water to the connected common tank after filling up its capacity. Thus the common tank is able to act as water bank and supply water, when there is any deficit in any individual tank. In this way, the common tank backs up and stores water throughout the year round for a community.

Community operation and maintenance, along with community participation and control, is essential to the successful implementation, operation and maintenance of any rainwater project, eventually which encourages demand management. Demand management strategies are unlikely to succeed without strict individual self-discipline and community-control/recommendations agreed by the community themselves regarding effort to promote water conservation. Evidences show that combined public-private sector approaches for rainwater harvesting initiatives can work effectively in certain circumstances (Gould, 2007).

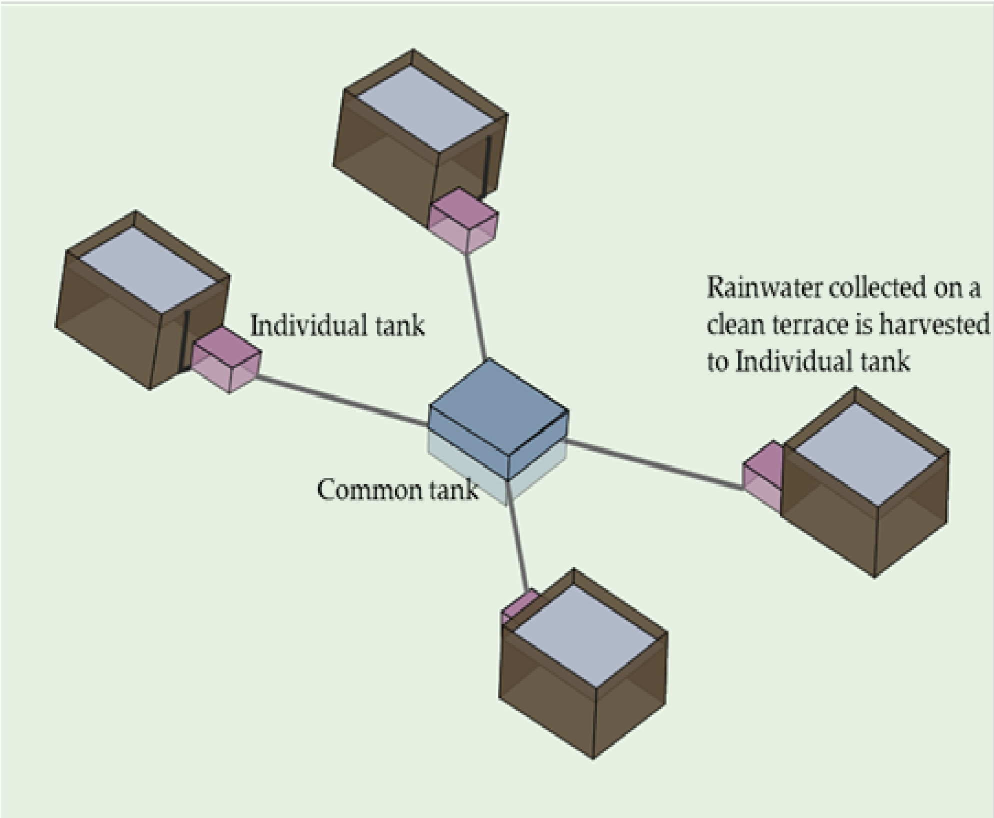

Figure 3.2 Schematic diagram of "Rainwater Bank" system

3.3 Simulation model

The physical process of a system can be described through repeated system operations with preset parameters and an array of input data. System behaviors can be better understood through this simulation process. System simulation can be used to evaluate alternatives. The impacts of alternatives can be revealed to the decision makers through the what-if studies. Satisfied solutions instead of optimal ones are achieved through system simulation (Rajasekaram et al., 2003).

In the mass balance investigation, rainfall is regarded as inflow and yield and spill as outflows. Time series of monthly rainfall are converted to inflow and routed through the individual tank with a specified individual storage capacity K^i and demandD_t^i. Decisions on releases or yields are based on the standard operation rule (SOP) that the demand will be met as far as the storage is available. In that scenario, the yield for individual tank meets demand as long as storage of individual tank is greater than demand otherwise it meets only the amount that it has as residual. If the accessible water of individual tank is larger than the maximum storage capacity, spill occurs with an amount equal to the difference between the residual storage and tank capacity. Otherwise, there will be no overflow. That surplus water is regarded as inflow to common tank.

For Individual Tanks,

The yields are estimated as:

$$Y_t^i = \begin{cases} D_t^i, & if \quad S_{t-1}^i + Q_t^i - O_t^i \geq D_t^i \\ S_{t-1}^i + Q_t^i - O_t^i & Otherwise \end{cases} \tag{3.1}$$

Overflows from individual tanks were estimated as,

$$O_t^i = \begin{cases} S_{t-1}^i + Q_t^i - K^i, & if\ positive \\ 0 & Otherwise \end{cases} \tag{3.2}$$

Amount of storage water in the tank at time t can be determined as,

$$S_t^i = S_{t-1}^i + Q_t^i - O_t^i - Y_t^i \tag{3.3}$$

where $S_{t-1}^i =$ Storage content at individual reservoir at time t-1 (liter), $Y_t^i =$ Yield from individual reservoir at time t (liter) and Q_t^i is flow into the individual tank during time interval t (liter). The amount of water in the individual tank was assumed to be half of tank capacity at the beginning of each simulation.

For Common Tank,

Common tank demand, $D_t^c = Individual\ tank\ demand - Individual\ yield$

$$D_t^c = D_t^i - Y_t^i \tag{3.4}$$

Inflow to common tank, $Q_t^c = \sum_{i=1}^{n} O_t^i$, where n=1,2,3… (3.5)

$$\text{Yield, } Y_t^c = \begin{cases} D_t^c, & if \quad S_{t-1}^c + Q_t^c \geq D_t^c \\ S_{t-1}^c + Q_t^c & Otherwise \end{cases} \tag{3.6}$$

Storage water in the tank,

$$S_t^c = minimum\ of \begin{cases} S_{t-1}^c + Q_t^c - Y_t^c \\ or \\ K^c - Y_t^c \end{cases} \tag{3.7}$$

Q_t^c = Flow into the common tank during time interval t (liter)

S_{t-1}^c = Storage content at common tank at time t-1 (liter)

K^c = Common rain water tank capacity (liter)

Y_t^c = Yield from common tank at time t (liter)

S_t^c = Active common tank capacity (liter)

3.4 Performance indices

A number of indicators can be used to describe the likely performance of water supply systems. Simple and commonly used measures are statistical performance indices, namely, reliability and resilience.

Reliability

The oldest and widely used theory in water resources systems is reliability. According to Hashimoto et al. (1982), the reliability of a system can be described by the frequency or probability α that a system is in a satisfactory state:

$$\alpha = \text{Prob}\ [X_t \in S] \tag{3.8}$$

where X_t is a system's output state at time t. t takes on discrete values 1, 2, 3,… and S is the set of all satisfactory outputs.

The most widely accepted and applied definition is occurrence reliability (Kjeldsen, T.R and Rosbjerg, D.,2004), which can be estimated as:

$$Rel = 1 - \frac{\sum_{j=1}^{M} d(j)}{T} \quad (3.9)$$

where d(j) is the duration of the j th failure event, M is the number of failure events, and T is the total number of time intervals.

That is, the reliability is simply one minus risk or probability of failure. But reliability or risk does not describe about how fast a system can recover and come back to a satisfactory level, nor does it indicates the severity or likely consequences of a failure. Resilience can qualify the possible severity of failures for a system performance evaluation.

Resilience

Resilience shows the rapidity performance of a system from unsatisfactory state to satisfactory state. If system recovery is slow, this may have adverse effect for system design. Hashimoto et al. (1982) defines resilience as:

$$\gamma = \frac{\rho}{1-\alpha} \quad (3.10)$$

where γ is resiliency and ρ is the ratio of total number of events when the condition moves from satisfactory to unsatisfactory state divided by the total number of time intervals.

Alternatively, resilience may also be defined as equal to the inverse of the mean value of the time the system spends in an unsatisfactory state, i.e.:

$$\gamma = \left\{\frac{1}{M}\sum_{j=1}^{M} d(j)\right\}^{-1} \quad (3.11)$$

where d(j) is the duration of the jth failure event and M is the total number of failure events.

Chapter 4. Application

4.1 Assumptions

To meet the goals of the simulation and quality of the data several simplifications are made in this study. For example Table 4.1 shows that the average water consumption in Bangladesh is 88lpcd. So, in case of fixing demand, 90lpcd of water demand is presumed as basic needs for a day for all the year round.

Assuming the total water demand for a house as follows,
Drinking water requirement = 3 lpcd
Sanitation services = 22 lpcd
Bathing = 20 lpcd
Cooking and kitchen = 15 lpcd
Cleaning and miscellaneous = 30 lpcd
Thus, The total per capita water consumption = 90 lpcd
Size of the house = 5
Total water demand in a day = 5*90 = 450 l/day

For the interpretation of the simulation this study approximates an average roof area of the individual household to be around 100 m^2 for 5 numbers of persons. This approximation is important in the implementation stage while utilizing the results of the study, since the study is performed for a range of situations where the individual households as well as the community level uses are considered.

Roof runoff coefficient (f) is assumed to be 0.8 (applicable for corrugated sheets) throughout the study. Hofkes (1981) showed typical values of the roof runoff coefficients which has been presented as Table 4.2. Yusuf (1999) showed insignificant difference among the end results for variation of this parameter in the range of 0.75 – 0.85.Though the runoff coefficient is often cited as an important design parameter, it is here assumed as 0.8 to reduce the number of parameters in the simulation.

The first rainfall after a dry period usually collects most of the contaminants from the roof. A system is, therefore, necessary to divert the contaminated first flow of rainwater from roof surfaces. Some devices and good practices are necessary to divert the first foul flush of rainwater. Automatic devices that prevent the first 20–25 liters of runoff from being collected in storages can be recommended. Here 20-25 liters of first flush are discarded from the simulation. Similarly, no system loss or losses due to evaporation are assumed in the behavioral analysis.

Additionally, individual demands and individual tank sizes are assumed constant with the increasing number of individual nodes. Finally, only gravitational flow to the Rainwater Bank is being anticipated. There are no motor pumps to generate the flow and no system inefficiencies are present in operational circumstance. To fetch water from the common tank manual bucket system has been assumed for a small community.

Table 4.1 Water consumption in 11 cities, Bangladesh (Bangladesh Water Utilities Data Book, 2006–07)

	Dhaka	Chittagong	Rajshahi	Bagerhat	Chandpur	Chapai Nawabganj	Chuadanga	Gazipur	Jessore	Manikganj	Narsingdi	Average (11)
Water coverage(%)	83.3	34.2	84.5	42.2	72.0	36.1	68.3	14.8	68.0	36.2	70.3	55.4
Water availability (hours)	23	8	12	2	20	11	7	10	9	20	7	11.7
Consumption/ capita/day (lpcd)	90.4	69.7	88.2	61.5	55.3	33.5	86.7	33.9	72.3	263.5	113.2	88.0
Production/capita/ day (m^3/day/c)	0.159	0.130	0.132	0.084	0.067	0.054	0.093	0.075	0.107	0.326	0.168	0.127
Unaccounted-for water (%)	37.2	33.3	25.5	3.3	16.3	15.9	2.7	52.0	28.2	7.2	25.4	22.5

Table: 4.2 Typical values of roof runoff coefficients

Type of catchment	**f**
Uncovered catchment surface	
Completely flat terrain	0.3
Slopping 0–5%	0.4
Sloping 5–10%	0.5
Sloping more than 10%	0.5 and more
Covered catchment surface	
(Roof) tiles	0.8–0.9
Corrugated sheets	0.8–0.9
Concrete bitumen	0.7–0.8
Plastic sheets	0.7–0.8
Brick pavement	0.5–0.6
Compacted soil	0.4–0.5

4.2 Study Site

Sylhet, the north-eastern division of Bangladesh which is bearing highly from Arsenic (As) contamination in groundwater has been selected as study target. The feasibility of “Rainwater Bank” is being examined throughout the study. Figure 4.1 is showing the map of Bangladesh which is surrounded by India to her three directions and south part is towards the Bay of Bengal. Figure 4.2 is showing the severity of groundwater contamination by arsenic in Bangladesh and my study site Sylhet is on the severe zone of arsenic contamination. Figure 4.3 is the map of Sylhet division. The city is mainly dependent on groundwater supply system with 28 groundwater stations and only 1 surface water station. Demand is approximately 69000 cubic meters for 8 million subscribers. But present water coverage in Sylhet city is only 25000 cubic meters with the reliability of 64%. For that reason, this water stressed major urban center and one of the administrative capitals of Bangladesh has been taken as the study area.

4.3 Data

4.3.1 Precipitation

The 30 years’ rainfall data of Sylhet division has been collected from Bangladesh Meteorological Department (BMD). The area is within the monsoon climatic zone, with annual average highest temperatures of 23 °C (Aug–Oct) and average lowest temperature of 7 °C (Jan). Nearly 80% of the annual average rainfall of 3,334 mm occurs between May and September (Monthly average for Sylhet, BGD, MSN Weather). The amount of rainfall that the area takes undoubtedly is a good source to alleviate fresh water problem within this region. Figure 4.4 shows long-term monthly average rainfall in Sylhet division.

Figure4.1 Map of South Asia

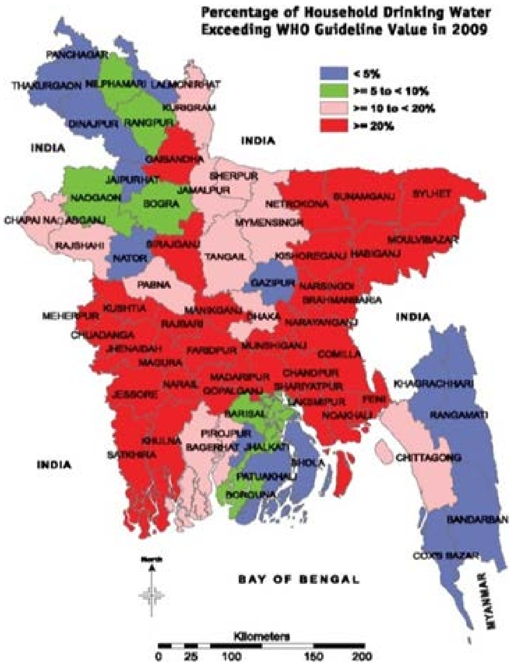

Figure 4.2 Map showing groundwater contaminations by arsenic in Bangladesh

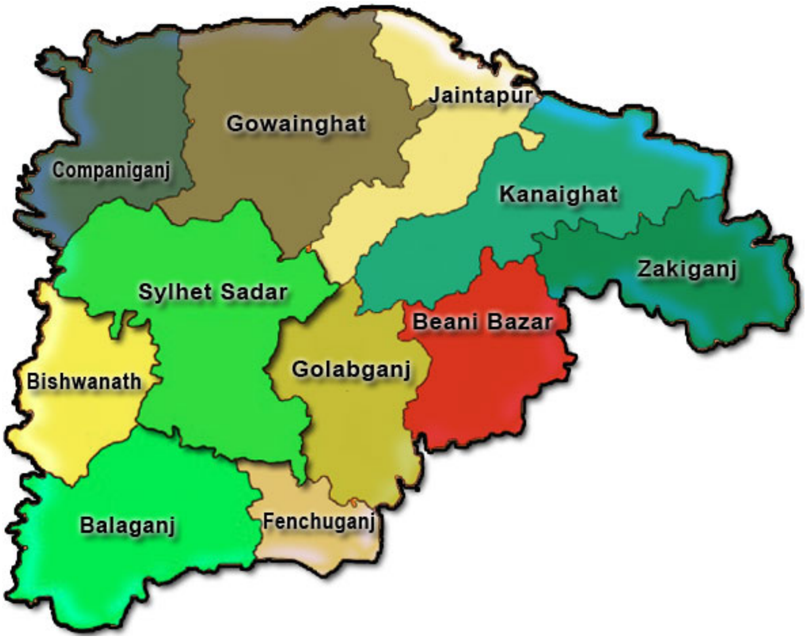

Figure 4.3 Map of the study site (Sylhet divisions)

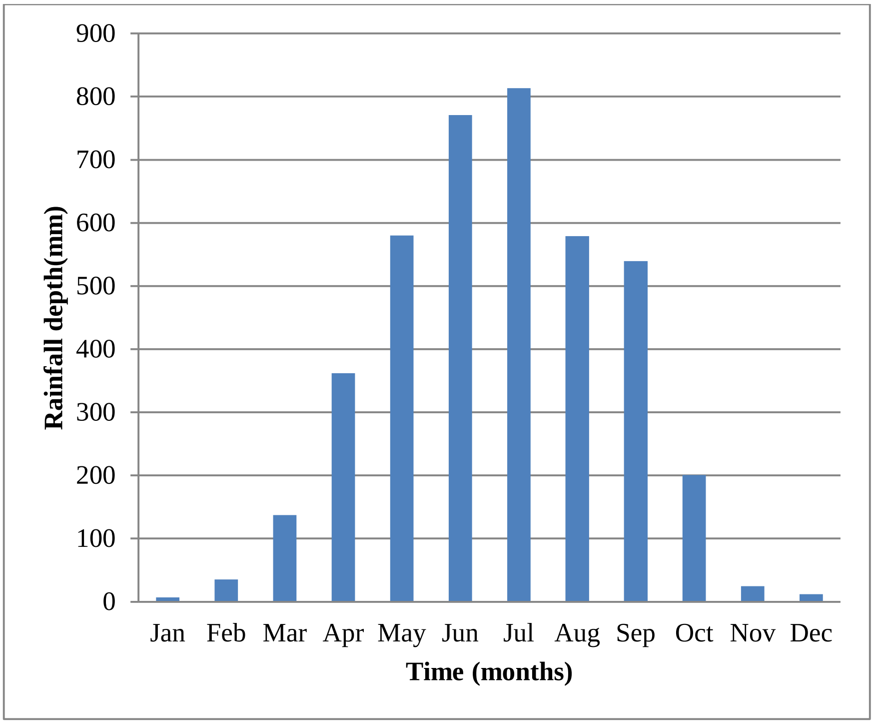

Figure 4.4 Monthly mean rainfall hyetograph of Sylhet city (1978-2008)

4.3.2 Flow

Inflows of water are calculated following the basic equation:

$$Q_t^i = A * f * \mathrm{R}_t \tag{4.1}$$

where, A is the roof area (m^2), roof runoff coefficient (a character of the roofing material and slope) is denoted as f, R_t is the monthly average rainfall depth (m) and Q_t^i is flow into the individual tank during time interval t (liter).

According to Hirsch et al. (1979), one drawback to this approach is its inflexibility. It cannot readily provide estimates of performance in the face of rising demands for water. Another drawback is that it provides only one of the many types of information that may be desired. It cannot provide information on the distribution of severity of failures, nor can it provide estimates of the expectation or variance of net benefits. Furthermore, it fails to extract certain important information from the data. If the historical record shows no failures but several 'near misses,' it would give a $\bar{P}$ value of 1.00, a very misleading estimate. It is also shown by the author that it is operationally superior to base the specification of marginal distributions of monthly stream flows on transformed values of historical stream flow data rather than on the data itself.

The historical series are taken in this study to produce a realistic synthetic generated data. The inflow data are assumed to follow a log-normal distribution, that's why the generated events have to be so distributed and whose parameters are μ_{lnx} & σ_{lnx},

$$\mu_{lnx} = \ln \mu_x - \frac{1}{2}\sigma_{lnx}^2 \tag{4.2}$$

$$\sigma_{lnx} = \sqrt{ln\left[1 + \frac{\sigma_x^2}{\mu_x^2}\right]} \tag{4.3}$$

$x_p = e^{z_p \cdot \sigma_{lnx} + \mu_{lnx}}$ (4.4)

And, $C_v = \frac{\sigma_x}{\mu_x} = \sqrt{e^{\sigma_{lnx}^2} - 1}$ (4.5)

To see the appropriateness of the distribution, Kolmogorov-Smirnov test is done which is used to investigate the hypothesis for a sample data which comes from a hypothesized continuous distribution.

Table 4.3 illustrates that p-value is greater than the level of significance (α) in 5 values. So, the null hypotheses are acceptable. Hence, the lognormal distribution is appropriate for this study.

4.4 Generation of inflow series

4.4.1 Purely random AR (0)

When the observed flow data are analyzed, lag-one autocorrelation $\boldsymbol{\emptyset_1}$ are found in the month of September-October and October-November as 0.6 and 0.57 respectively and insignificant values for the rest of the months as illustrated in Table 4.4. So, for the month of October and November flow data are generated using AR (1) model and for the rest of the months $\emptyset_1 = 0$. Therefore, purely random generation has been done using the mean and standard deviation obtained from lognormal distribution. One hundred sequences of 10 months' of 30 years' data have been generated following the equation:

$y_t = \mu + \varepsilon_t$ (4.6)

Where ε_t is an uncorrelated normal random variable referred as noise with mean 0 and variance σ_ϵ^2. For purely random generation variance $\sigma_\epsilon^2 = \sigma_y^2$, as $\emptyset_1 = 0$. μ and σ_y^2 are the lognormal mean and variation of each month except October and November.

Table 4.2 Kolmogorov-Smirnov Test

Lognormal [#40]					
Kolmogorov-Smirnov					
Sample Size Statistic P-Value Rank	360 0.03105 0.86735 6				
α	0.2	0.1	0.05	0.02	0.01
Critical Value	0.05655	0.06446	0.07157	0.08001	0.08586
Reject?	No	No	No	No	No

Table 4.3 Lag 1 auto-correlation in observed data

Lag 1 auto-correlation	Jan-Feb	Feb-Mar	Mar-Apr	Apr-May	May-Jun	Jun-Jul	Jul-Aug	Aug-Sep	Sep-Oct	Oct-Nov	Nov-Dec	Dec-Jan
$\emptyset_1$	0.039	-0.004	0.071	-0.023	-0.057	-0.120	-0.015	-0.002	0.602	0.573	-0.035	-0.255

4.4.2 Auto-correlated AR (1)

Flows of October and November have been generated by using AR (1) model. The AR (1) model takes the simple form

$$y_t = \mu + \emptyset_1(y_{t-1} - \mu) + \varepsilon_t \qquad (4.7)$$

Following equation (4.8), monthly σ_ϵ^2 can be determined as

$$\sigma_y^2 = \frac{\sigma_\epsilon^2}{\mathbf{1-\emptyset_1}^2} \qquad (4.8)$$

Here μ and σ_y^2 are the lognormal mean and variation for October and November and $\emptyset_1$ is lag 1 auto-correlation coefficient for the month of October and November. Now to generate data for October and November firstly σ_ϵ^2 (October) and σ_ϵ^2 (November) are determined following equation 4.8. $\emptyset_1$ is used as 0.6 for October and 0.57 for November. After that, for these two months one hundred sequences of ε_t, each of 30 years in length have been generated randomly using mean 0 and standard deviation σ_ε . And then new generation is being done following equation 4.7 where $\emptyset_1$ for October and November are assumed as constant for each generation. Thus 100 sets of these 2 months' 30 years' length data are generated using AR (1) model.

4.5 Simulation Cases

4.5.1 Number of individual tanks

Three types of systems have been assumed here.1common tank +2individual tanks, 1 common + 3 individual tanks and 1 common + 4 individual tanks system. Figure

4.5 (a), (b) and (c) are showing schematic diagrams of the three cases. Taking same data sensitivity analyses are done on these three systems to find out the best choice of common tank.

4.5.2 Simulation by altering individual tank size

Assuming fixed demand two types of scenarios have been analyzed to see the worst condition and size differences of common tank respective to individual tank. Firstly, individual tank capacity is taken as equal to demand and secondly, individual tank capacity as double of demand. Sensitivity analyses are done to these two scenarios. Statistics that are done to these two operations for 3 types of "Rainwater Bank" systems are illustrated in section 4.4.3.

4.5.3 Statistics of inflow series

Using the inflow sequences, operation of the "Rainwater Bank" system has been simulated. The simulation results are then used to compute several performance indices in order to see the "Rainwater Bank" behavior with rainwater harvesting and to evaluate the best fitted size of common tank. Several test cases have been assessed to determine the maximum reliability improvement/common tank capacity increase ($\frac{\Delta \boldsymbol{R}}{\Delta \boldsymbol{K_c}}$) ratio with respect to inflow statistics and demand. Sensitivity tests are done as follows: (a) When individual tank capacity = demand; behavior of reliability and resilience changing mean inflow and standard deviation. (b) When individual tank capacity = double of demand; behavior of reliability and resilience changing mean inflow and standard deviation.

All these analyses are done for the cases of 2 individuals + 1 common, 3 individuals + 1 common and 4 individuals + 1 common tanks combinations.

Figure 4.5(a) Scheme 1: 2 Individuals + 1 Common tank system

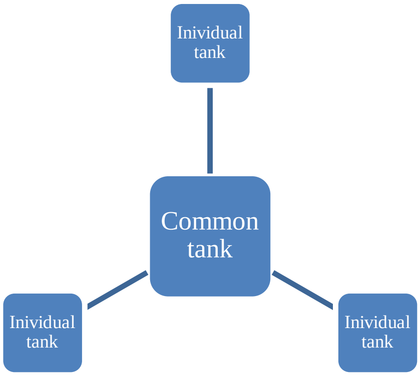

Figure 4.5(b) Scheme 2: 3 Individuals + 1 Common tank system

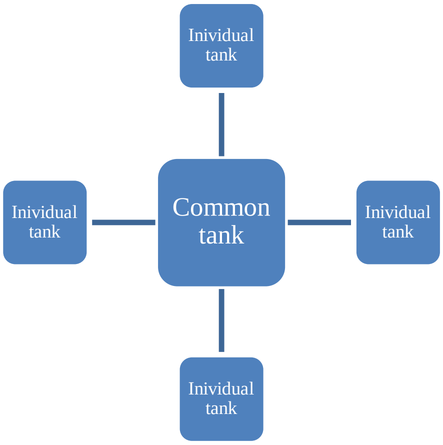

Figure 4.5(c) Scheme 3: 4 Individuals + 1 Common tank system

Chapter 5. Simulation Results

Bangladesh receives heavy rainfall during monsoon. Monsoon usually lasts from April to October and occasional rainfall in November. Sylhet city receives notable amount of rainfall during April to September. Simulation shows that if rainwater is harvested and preserved, basic water demand can easily be met for the entire year.

5.1 Tradeoff between individual tanks with or without common tank

Alam et al. (2012) already showed the cost benefits of rainwater harvesting in Sylhet city. 25 liter of water per day for drinking and cooking for a family was considered taking economic life span of a Ferro cement tank of 15 years. Table 5.1 is showing cost comparison among three systems for that respective case study.

The cost of rainwater harvesting system was estimated to be Tk. 1.5 per 25 liters, i.e. 0.02 USD whereas conventional system water rate is 0.05 USD and private water supply system costs 0.09 USD for 25 liters demand. Conventional system also includes 77 USD/connection fees (for every 5 years). That means, water collected by rainwater harvesting system is almost three times cheaper than that of conventional water supply system and almost 4.5 times cheaper than that of private water supply system.

Realizing the advantage of rainwater harvesting, the research has been started by analyzing the tradeoff between rain barrel systems and rain barrel with common tank combinations, i.e. proposed “Rainwater Bank” system. First of all, this study tries to find out the likely consequence for a community whether we should consider 1 common and several (n_i) individual tanks or only several more scattered individual tanks without a common tank.

Figure 5.1 presents the schematic diagram of the two systems and attempts to illustrate the tentative comparison of those two systems in terms of reliability. Table 5.2 is describing the reliability increment by increasing individual tank size on behalf of per capita water demand necessary for 5 persons and Table 5.3 is depicting the rise of reliability through “Rainwater Bank” system for 2 individual + 1 common tank combinations. Visibly, it can be comprehended that with 2800 liter (2*800 K (I) + 1200 K(C)) “Rainwater Bank” system we can have more (97.31) reliability than (2*1500) 3000 liter individual tanks for the same demand. For individual tank 1500 liter tank capacity is almost 4times of the demand. That means we will have higher efficiency in combined (common+individual) system with optimum individual tank size.

On the other hand, constructing a large individual tank for 1/4th demand is not recommended due to hygienic concern. It may keep empty during the no-monsoon period. As the simulation in this study is routed through the year round, storage facility for the dry period is supporting by the common tank.

Table 5.1 Cost comparison between rain water harvesting (RWH), conventional water supply system and private water

Rainwater harvesting technique cost:	Conventional water supply system cost	Private water supply system cost:
Total construction cost Tk. 6,000.	Connection cost = Tk. 7,000/connection	Pump installation cost = Tk. 6,000
Maintenance cost Tk. 200/year (including cleaning by chlorine and repairing if any leakage detected)	Water use rate = Tk. 0. 15 to Tk. 0.25/l	
Economic life = 15 years Therefore, total cost =[6,000 + (200 × 14)] = Tk. 8,800	Total cost (Tk. 0. 15 × 25 l × 365 days × 15 years) + 7,000 = Tk. 28,352	Total cost = {Tk 0.14[a] × 25 l × 365 days × (5 × 3) years} + 6,000 × 3 = Tk. 37,929
Annual payment = (8,800/15) = Tk. 587	Annual payment = (28,352/15) = Tk. 1890.	Annual payment = (37,929/15) = Tk. 2529.
Cost/l = [8,800/(25 lit × 365 days × 15 Years)] =Tk 0.06/l Cost/l = Tk. 0.06 (Cheapest)	Cost/l = Tk. 0.15 (3 times costlier than RWHT)	Cost/l = (37,929/26 lit × 365 days × 15 Years) = Tk 0.27/l Cost/l = Tk. 0.27 (Costliest, 4.5 times costlier than RWHT)

[a]The cost of electric bill per liter

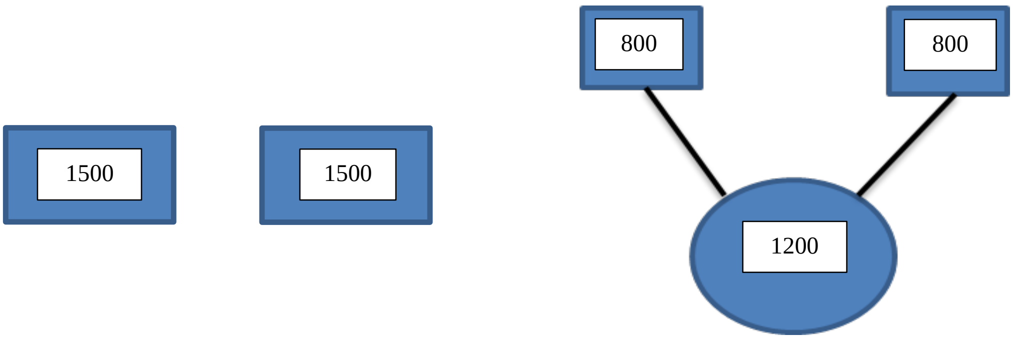

Figure 5.1 Individual tank system vs "Rainwater Bank" system

Table 5.2 Reliability performance with increasing individual tank size

Capacity (I)	Reliability(I)
800	85.75
1000	91.94
1300	94.6
1500	95.1

Table 5.3 Reliability performance with increasing common tank sizes

Capacity(I)	Capacity(C)	Combined capacity(C+2I)	Reliability
800	1000	1800	94.89
800	1200	2000	97.31
800	1400	2200	97.58

5.2 Determining the best size for a common tank with 2 individual tanks

Apart from studying the reliability of "Rainwater Bank" system, best choice for a suitable water bank capacity is also one of the targets in this study. Storage capacity investigations are verified changing mean and standard deviations of the inflows. 4 types of standard deviation are used to see the variations as well.0.72, 0.74, 0.76, 0.78 for mean=13.4. And for each case CVs are 0.83, 0.86, 0.91, 0.89.Taking the individual tank size 800liter, 6 different common tank sizes are examined to find out the satisfactory size for 3 different schemes. Here system with 2 individual and 1 common tank combinations has been elaborated.

5.2.1 Sensitivity to mean and standard deviation when individual tank capacity = double of demand

Sensitivity to mean and standard deviation changes for the inflow derived from rainfall has been observed routing the inflows to the whole "Rainwater Bank" model. The possible role of changes in mean and variability is an important ambiguity that can have possible impacts in selecting common tank capacity. Taking individual tank capacity = double demand, 6 sizes are examined as 800, 1000, 1200, 1400, 1600, 1800 liter. Figure 5.2 is showing storage-reliability relationship changing mean inflow and Figure 5.3 is showing for changing standard deviation when mean is kept fixed. Both the graphs are depicting a significant rise in reliability for 1600liters common tank capacity for all varieties of inflows. Table 5.4 and 5.5 are showing the maximum $\frac{\Delta R}{\Delta K_c}$ ratio for different common tank sizes.

Resilience is also showing similar behavior as reliability as shown in Figure 5.4 and 5.5. It can be seen that significant increase in resilience for 1600liters common tank size for all varieties of inflows. So, it is verified that 1600liters common tank is the best designed capacity for 2 individual houses when individual tank volume is two times of demand capacity.

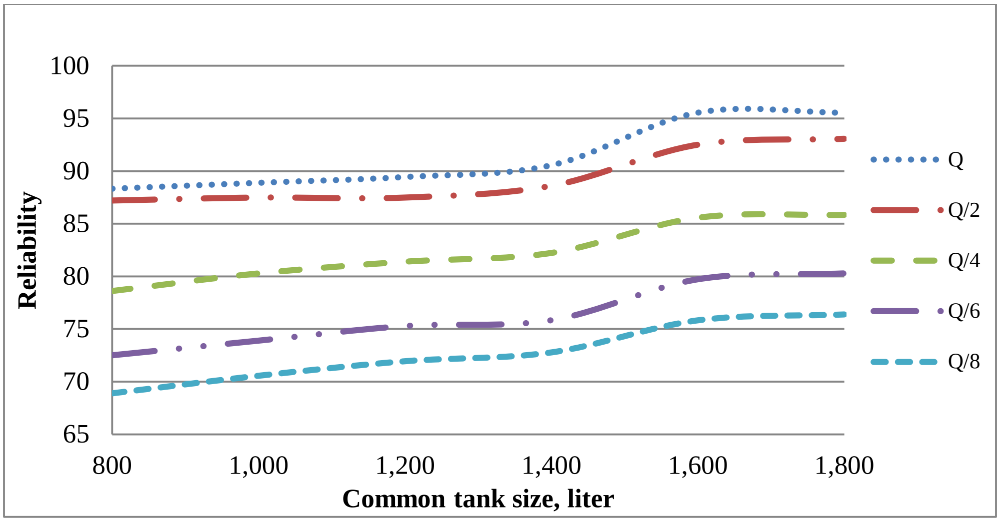

Figure 5.2 Storage-reliability relationships changing mean inflow [K(I) =2*Demand]

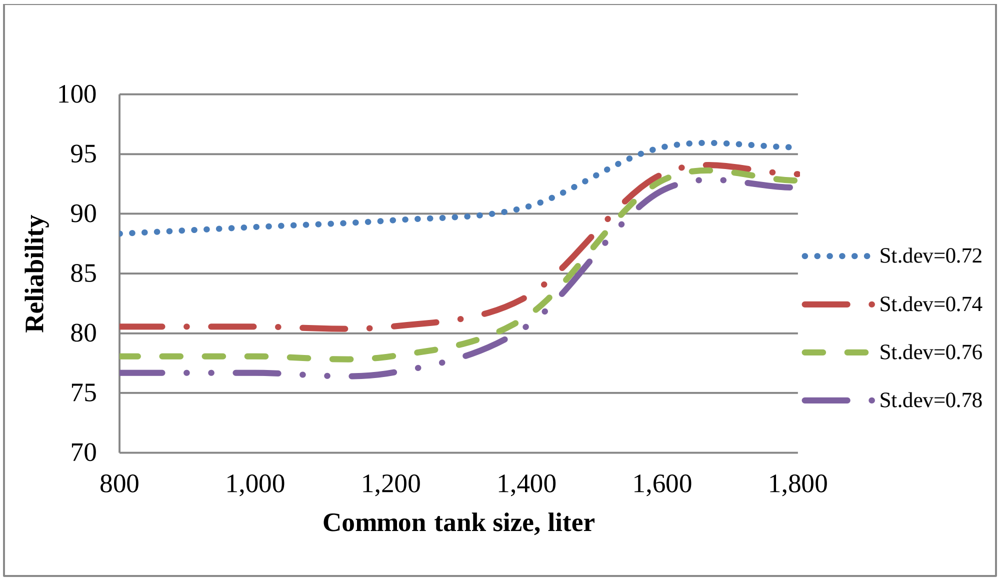

Figure 5.3 Storage-reliability relationships changing standard deviation [K (I) =2*Demand]

Table 5.4 Max $\Delta R/\Delta K(c)$ ratios for selected common tank size with changing mean inflows [K (I) =2*Demand]

Mean Inflow	**Coefficient of variation (CV)**	**Individual tank capacity, K(I)**	**Selected common tank size, K (c)liter**	**Max $\Delta R/\Delta K(c)$**
Q/1	0.83	2*800	**1600**	0.95
Q/2	0.83	2*800	**1600**	0.67
Q/4	0.83	2*800	**1600**	0.61
Q/6	0.83	2*800	**1600**	0.67
Q/8	0.83	2*800	**1600**	0.61

Table 5.5 Max $\Delta R/\Delta K(c)$ ratios for selected common tank size with changing standard deviations [K (I) =2*Demand]

Standard deviation	**Coefficient of variation (CV)**	**Individual tank capacity, K(I)**	**Selected common tank size, K (c)liter**	**Max $\Delta R/\Delta K(c)$**
0.72	0.83	2*800	**1600**	0.95
0.74	0.86	2*800	**1600**	2.1
0.76	0.89	2*800	**1600**	2.28
0.78	0.91	2*800	**1600**	2.3

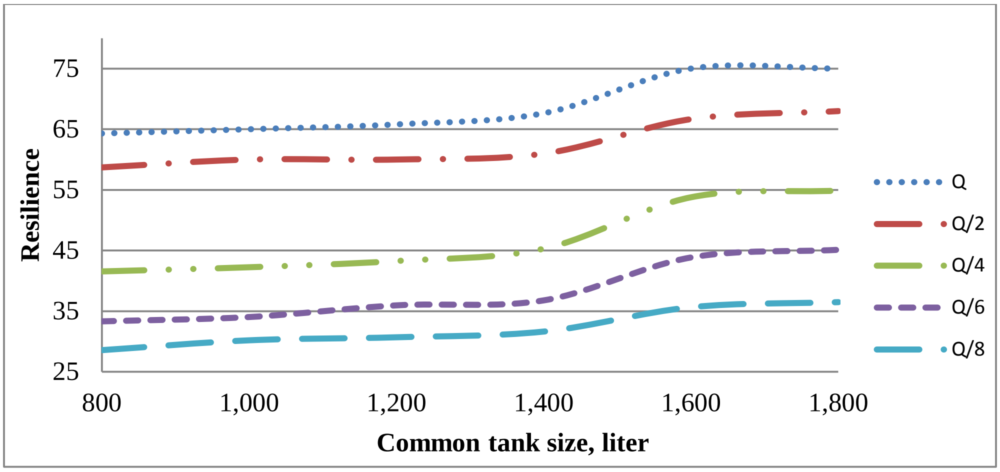

Figure 5.4 Storage-resilience relationships changing mean inflow [K (I) = 2*Demand]

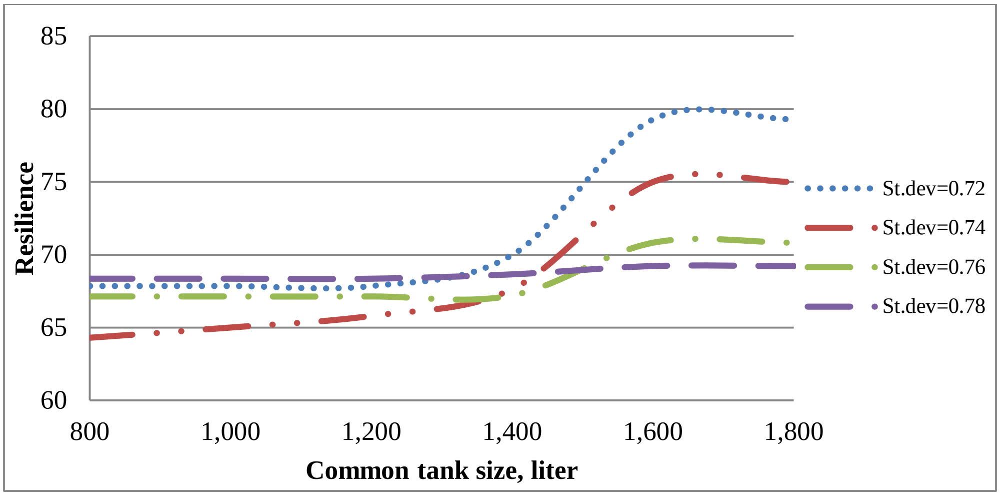

Figure 5.5 Storage- resilience relationships changing standard deviation [K (I) = 2*Demand]

5.2.1.1 Reliability and resilience curves for selected common tank size when individual tank capacity = 2*demand

It can be seen from Figure 5.6 and 5.7 that reliability and resilience increase with increasing mean inflows but decrease by growing standard deviation. Reliability plays between 79.72 to 95.56 with mean flow changes but 91.94 to 93.33 with standard deviation variation. In the same way, resilience varies from 43.84 to 75.0 in case of mean flow variations but 69.23 to 75 for altering standard deviation. Clearly, changes on mean inflows impact more on "Rainwater Bank" system than changes of standard deviations.

5.2.2 Sensitivity to mean and standard deviation when individual tank capacity= demand

Taking individual tank capacity = demand, 6 sizes are examined as 1000, 1200, 1400, 1600, 1800, 2000 liters. Figure 5.8 is showing storage-reliability relationship changing mean inflow and Figure 5.9 is showing for changing standard deviation when mean is kept fixed. Both the graphs are depicting a significant change in reliability for 1200liters common tank capacity for all varieties of inflows. But it is noticeable that after 1200liters point reliability increases gradually with increased common tank sizes for changing mean inflow but mild increase for changing standard deviation. Here, it was also established that changes of mean inflow a more effect on "Rainwater Bank" system rather than standard deviation. So, it can be stated that 1200liter common tank size is the best choice for 2 800liter individual tank sizes as per $\frac{\Delta R}{\Delta K_c}$ ratio when individual tank capacity is equal to assumed demand. Table 5.6 and 5.7 show the maximum $\frac{\Delta R}{\Delta K_c}$ ratio for different common tank sizes.

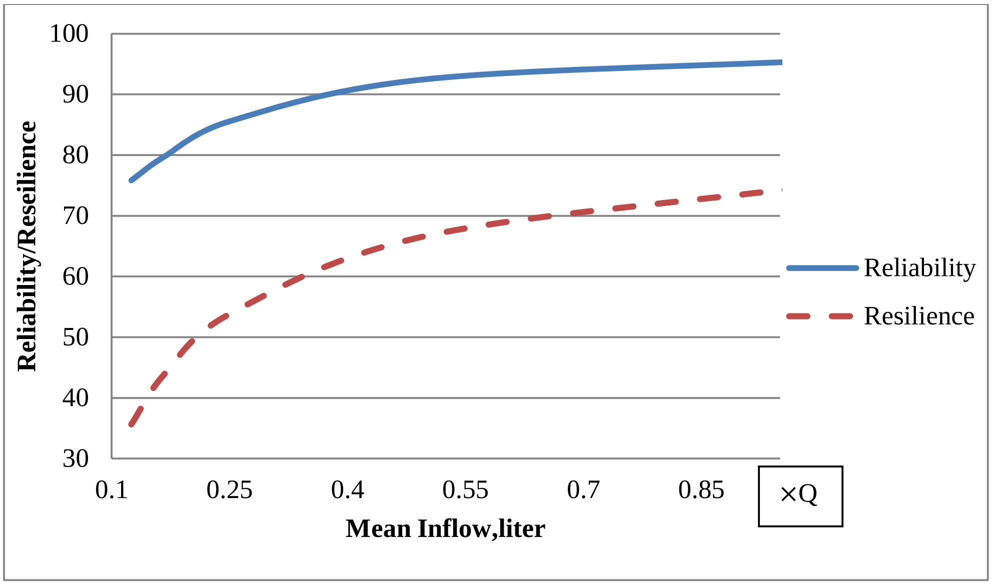

Figure 5.6 Behavior of 1600liter tank with reliability and resilience by changing mean inflow

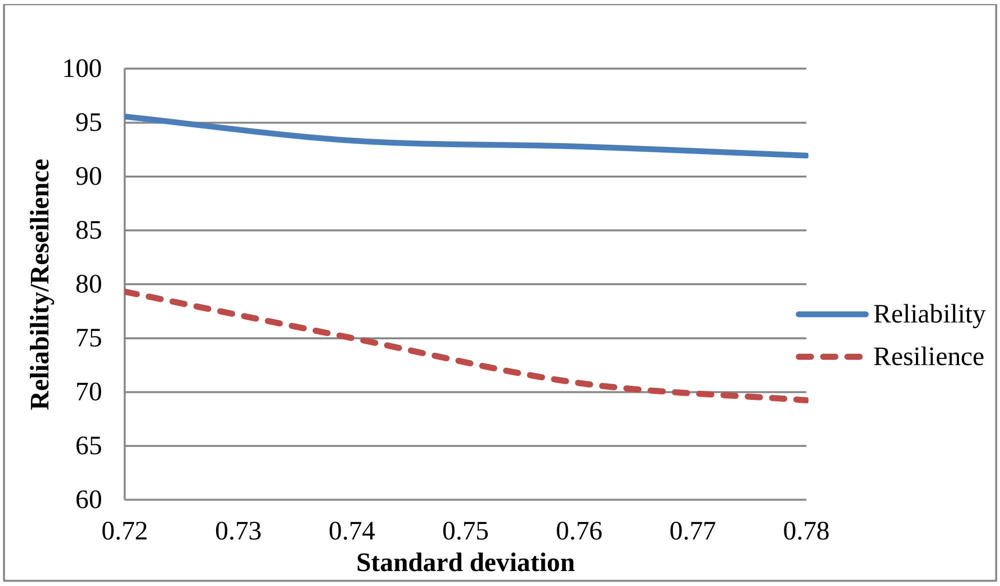

Figure 5.7 Behavior of 1600liter tank with reliability and resilience by changing standard deviation

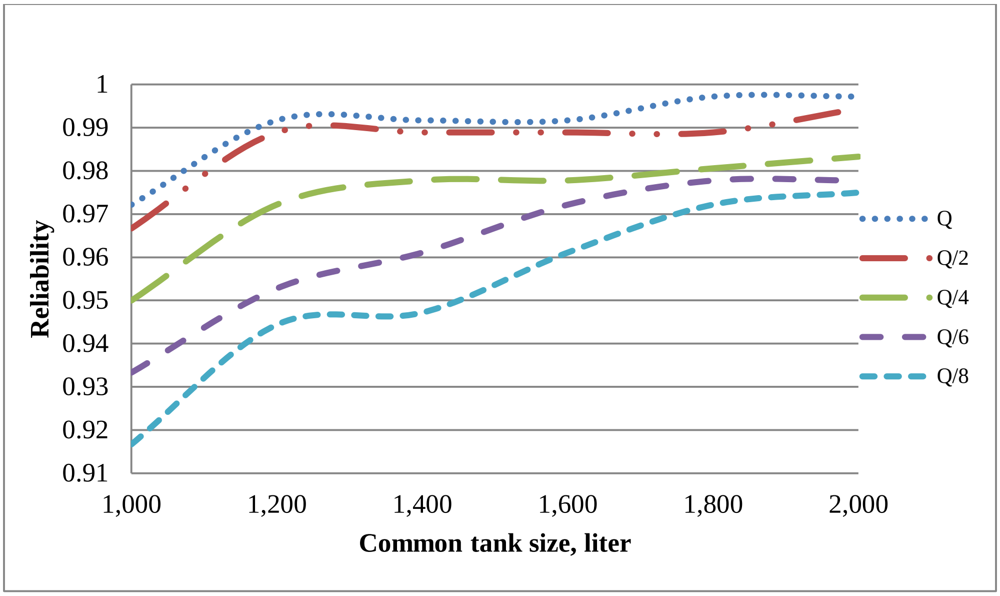

Figure 5.8 Storage-reliability relationships changing mean inflow [K (I) = Demand]

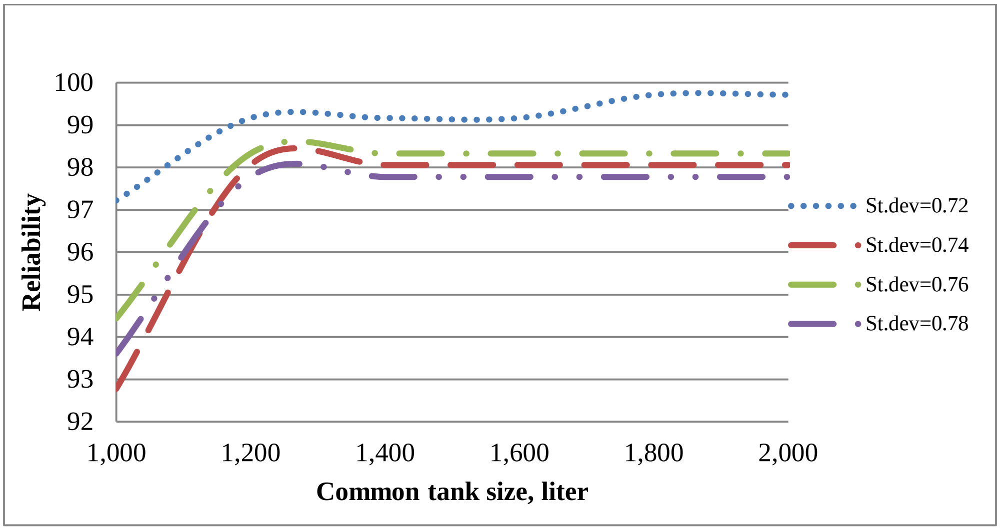

Figure 5.9 Storage-reliability relationships changing standard deviation [K (I) = Demand]

Table 5.6 Max $\Delta\boldsymbol{R}/\Delta\boldsymbol{K}(\boldsymbol{c})$ ratios for selected common tank size with changing mean inflows [K (I) = Demand]

Mean Inflow	**Coefficient of variation (CV)**	**Individual tank capacity, K(I)**	**Selected common tank size, K $(\boldsymbol{c})$liter**	**Max $\Delta\boldsymbol{R}/\Delta\boldsymbol{K}(\boldsymbol{c})$**
Q/1	0.83	2*800	**1200**	0.33
Q/2	0.83	2*800	**1200**	0.44
Q/4	0.83	2*800	**1200**	0.4
Q/6	0.83	2*800	**1200**	0.4
Q/8	0.83	2*800	**1200**	0.61

Table 5.7 Max $\Delta\boldsymbol{R}/\Delta\boldsymbol{K}(\boldsymbol{c})$ ratios for selected common tank size with changing standard deviations [K (I) = Demand]

Standard deviation	**Coefficient of variation (CV)**	**Individual tank capacity, K(I)**	**Selected common tank size, $\boldsymbol{K}(\boldsymbol{c})$liter**	**Max $\Delta\boldsymbol{R}/\Delta\boldsymbol{K}(\boldsymbol{c})$**
0.72	0.83	2*800	**1200**	0.33
0.74	0.86	2*800	**1200**	0.778
0.76	0.89	2*800	**1200**	0.834
0.78	0.91	2*800	**1200**	1.06

Interestingly, similar to individual tank capacity = 2*demand scenario, resilience is not showing similar performance for individual tank capacity = demand scenario as shown in Figure 5.10 and 5.11. When sensitivity tests to mean inflow and standard deviations are performed, significant fluctuations are noticed with changing common tank sizes whereas there should have rising curves of resilience with increased common tank sizes. The reason can be described like that: in this case, reliability is already showing very nice results with increased common tank sizes, there are very small failure events here and resilience is always worthy in low reliability cases. It shows that if there are continuous successive failure events how quickly the system can come back to the satisfactory level is the measure of resilience. But if there are few single failure events resilience may show fluctuating behavior because failure events are already recovering fast. That is why, satisfactory results have found for larger individual tank capacity scenario whereas variations are seen here.

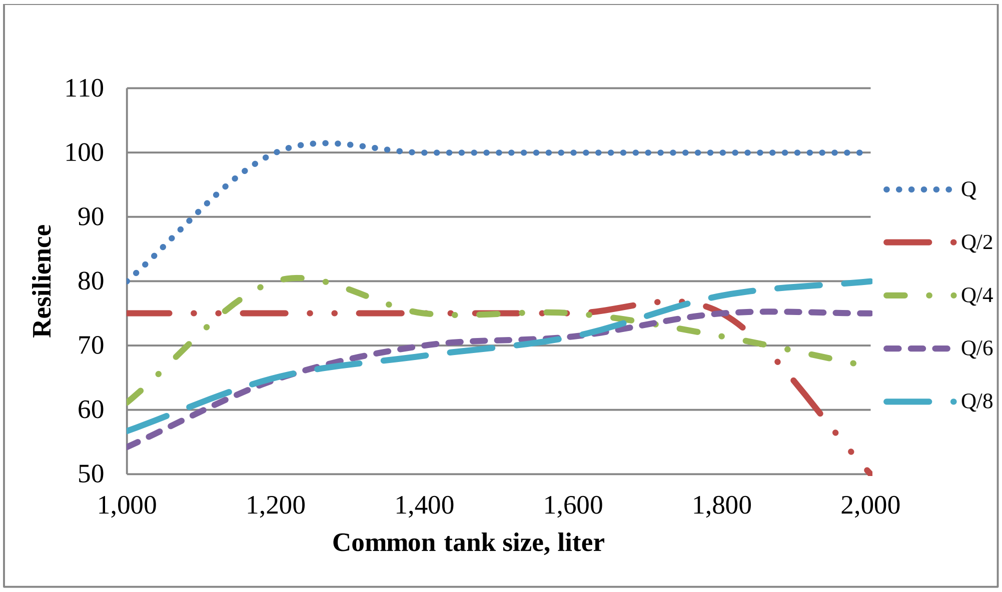

Figure5.10 Storage-resilience relationships changing mean inflow [K (I) = Demand]

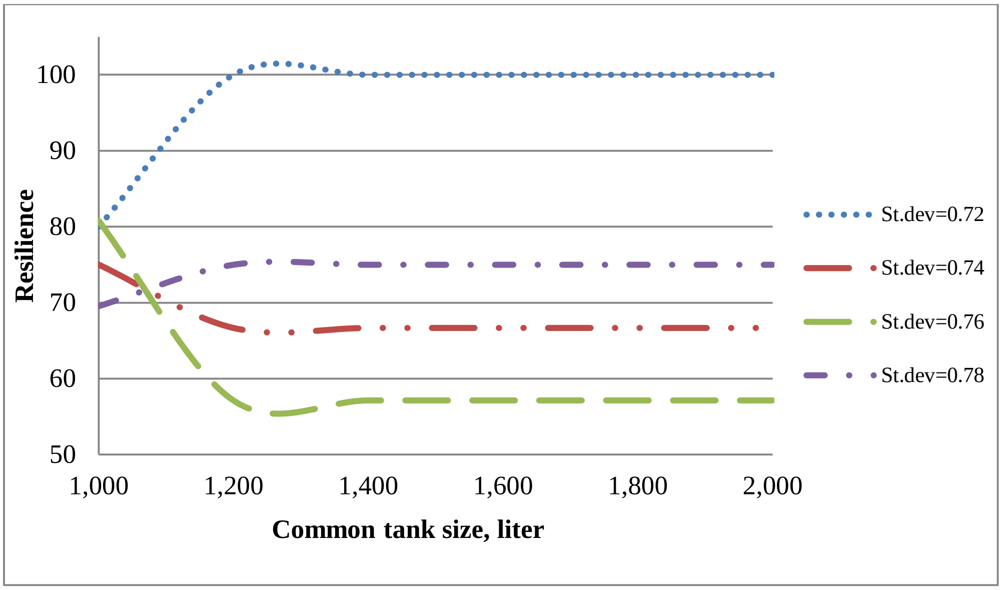

Figure 5.11 Storage- resilience relationships changing standard deviation [K (I) = Demand]

5.3 Analyzing the three types of “Rainwater Bank” systems

As per scheme 1, same analyses are done for scheme 2 and scheme 3 i.e. taking 3 individual and 4 individual tanks with a common tank combination. Considering both types of individual tank capacity and assuming same inflows as generated, best suitable size for common tank has been found out. It has been observed that 1600liter common tank size is the best for scheme 2, i.e. 3 individual + 1 common tank combinations and 2400liter common tank is best for 4 individuals + 1 common tank combination with individual tank capacity = demand scenario. However, for individual tank capacity = double of demand scenario, suitable common tank sizes are obtained as 2500 and 3200 liters respectively as per $\frac{\Delta R}{\Delta K_c}$ ratio. Some tables and figures showing reliability and resilience relationship with the selected common tank sizes for schemes 2 and 3 are displayed in the Appendix. Here Figure 5.12 is portraying the best sizes of common tanks with the increment of Individual house nodes as per schemes 2 and 3 for both the individual tank size variation. It is noteworthy that with these simulations any size of common tank is able to be calculated for particular demand and inflow series in any region of the world.

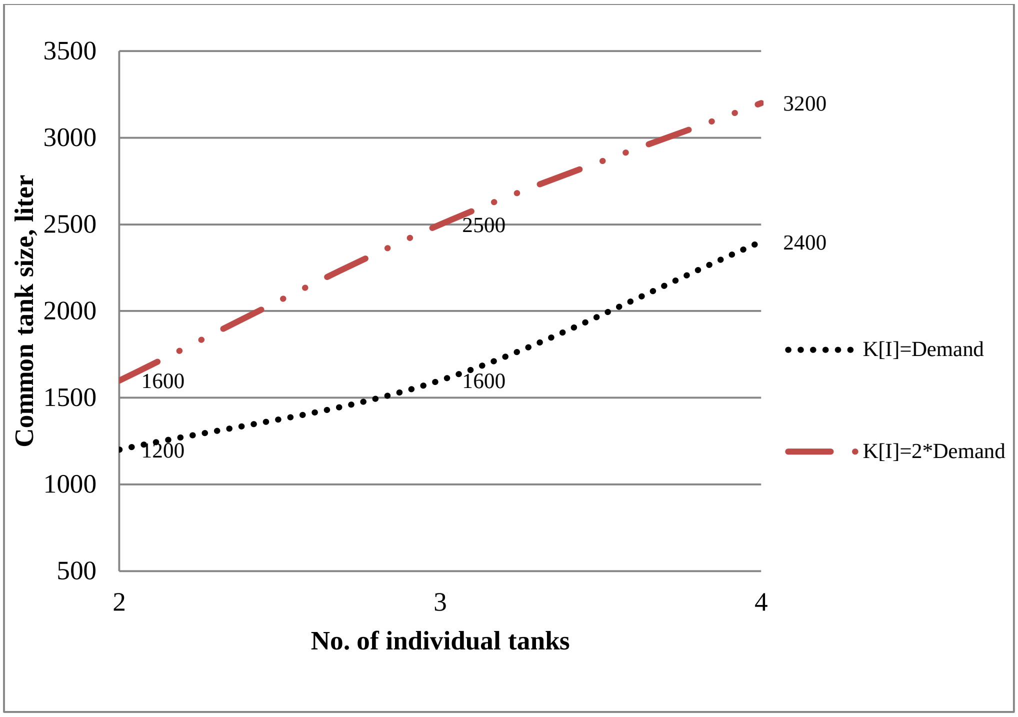

Figure 5.12 Best common tank sizes for 2 demand types of 3 "Rainwater Bank" systems

Chapter 6. Conclusion

6.1 Summary and conclusions

From this study, we are having some nice satisfactory results. First of all, it has been presented that individual tank does not have to be large enough to acquire better reliability. One common tank can serve for all the linked connections.

Secondly, the main target was to evaluate water supply reliability by means of rain water harvesting so that we can decrease the dependency on existing water supply system and we have seen that collecting rainwater in the common tank over the year round is promoting the reliability.

Lastly, suitable common tank sizes for different combinations of “Rainwater Bank” systems were also successfully determined by testing sensitivity to mean and standard deviation of inflows through altering the individual tank size by way of equal and double of demand. Since a simulation model is the core of this “Rainwater Bank” procedure, it permits a realistic representation of the system up to the desired details. The simulation model computes all the relevant quantities for each time step as well. Reliability alone cannot completely describe the strengths and weaknesses of a performance. In this study, the importance of resilience also has been highlighted. By monitoring the behavior of these two indices, decision on common tank size has been made.

In summary,

- “Rainwater Bank” system is better in efficiency than individual rain barrel systems.

- "Rainwater Bank" is promoting reliability in Sylhet metropolitan city from 64% to over 95% by only using rainwater.

- Finally, a comprehensive conclusion can be made that how small or big rain may it be occurred 1200 liter common tank size (i.e. 1.5 times of individual tank) is the best choice considering individual tank size equals to assumed demand and 1600 liter (i.e. 2 times of individual tank) is the best while individual tank size is twice of assumed demand for this respective case study.

  -Another important observation was noticed that changes on mean inflows impact more on "Rainwater Bank" system than changes of standard deviations.

  -From the sensitivity analysis it is clear that individual tank capacity is sensitive to common tank capacity.

Thus, it is the "Rainwater Bank" which is supporting the community for whole the year round. Nevertheless, it is recommended to test and evaluate approximate storage sizes in a real world situation based on average roof area and rain fall scenario to gain further information about relevant factors. "Rainwater Bank" system is easy to construct and operate. So, undoubtedly it's a better solution as alternative water supply system in fresh water cursed regions in the world.

Largely, following the methodology presented in this study, rainwater harvesting can also be considered in commercial, public and industrial buildings. The figures presented here characterize the general relationships among storage capacity, water availability, reliability and resilience. And hence, it can be stated that outputs of this study can be used successfully to assist in the evaluation and selection of alternative design and operating policies for RWHS engineers and decision makers in Bangladesh.

6.2 Future Study

In this study, “Rainwater Bank” system has been analyzed taking only 2, 3 and 4 individual nodes with common tank combination. But in future, “Rainwater Bank” scheme will need to be analyzed in large scale with several hundred individual tanks which can serve as applicable in real field.

Only one study site was taken for the analyses here. In future different characteristics of climatic zones and the average rainfall records for the whole country will need to be taken under consideration to establish a generalized solution for the entire state.

In future, it will also be revealed that how “Rainwater Bank” system can provide some flood detention capacity for mitigating rainfall induced flood in urban areas.

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Appendices

A: Reliability of “Rainwater Bank” system with 3 individuals and 1 common tank.

B: Reliability of “Rainwater Bank” system with 4 individuals and 1 common tank.

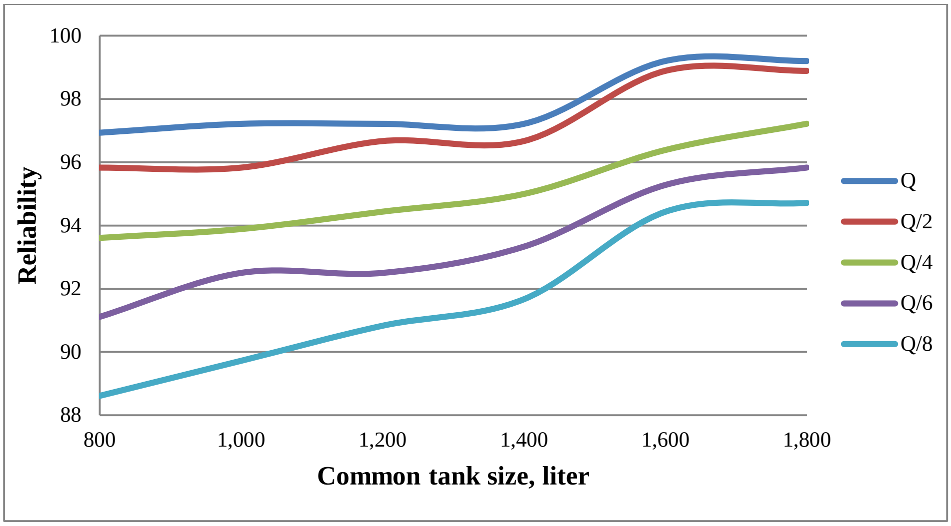

Figure A. 1 Storage-reliability relationships changing mean inflow [K(I)]=Demand]

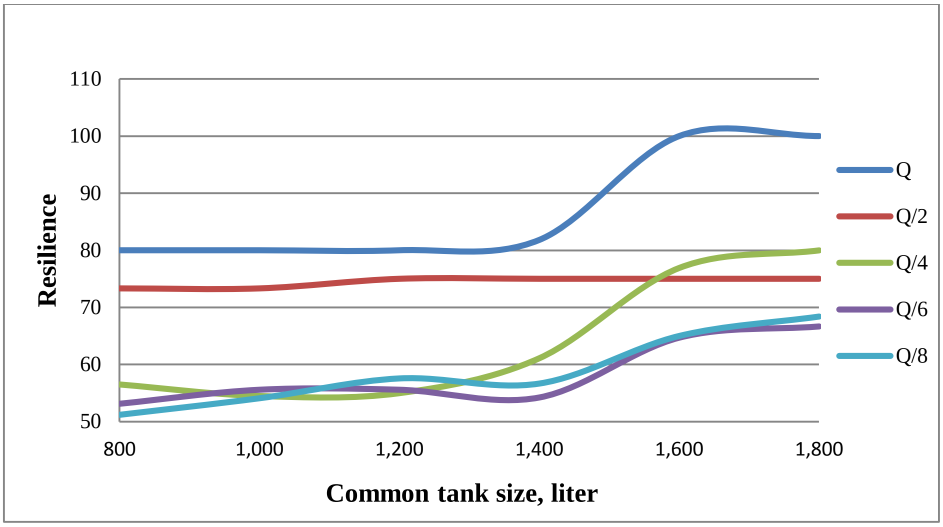

Figure A.2 Storage-resilience relationships changing mean inflow [K(I)]=Demand]

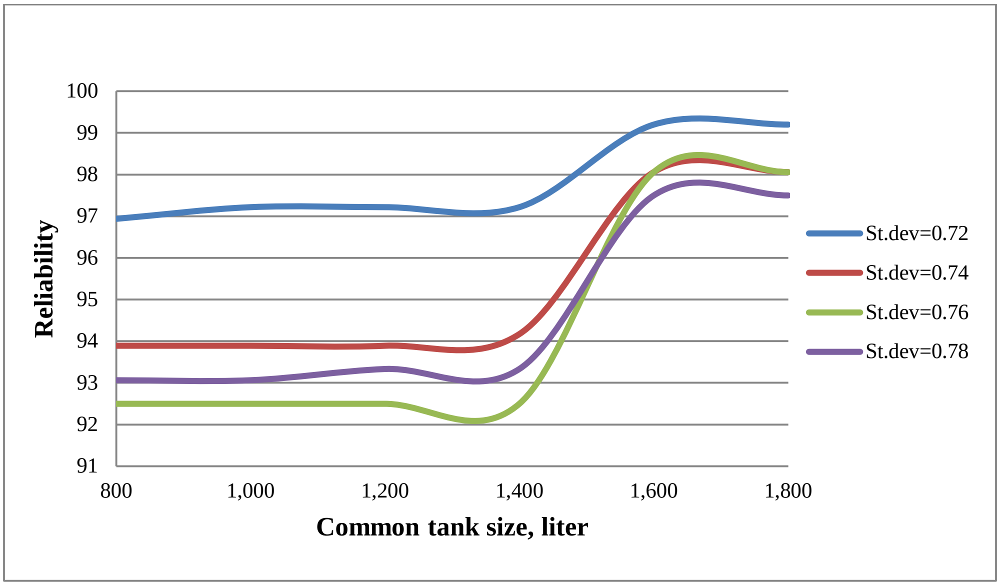

Figure A.3 Storage-reliability relationships changing standard deviations [K(I)]=Demand]

Table A.1 Max $\Delta R/\Delta K(c)$ ratios for selected common tank size with changing mean inflows [K(I)]=Demand]

Mean Inflow	Coefficient of variation (CV)	Individual tank capacity, K(I)	Selected common tank size, K (c)liter	Max $\Delta R/\Delta K(c)$
Q/1	0.83	3*800	**1600**	0.28
Q/2	0.83	3*800	**1600**	0.39
Q/4	0.83	3*800	**1600**	0.40
Q/6	0.83	3*800	**1600**	0.44
Q/8	0.83	3*800	**1600**	0.55

Table A.2 Max $\Delta R/\Delta K(c)$ ratios for selected common tank size with changing standard deviations [K(I)]=Demand]

Standard deviation	Coefficient of variation (CV)	Individual tank capacity, K(I)	Selected common tank size, K (c)liter	Max $\Delta R/\Delta K(c)$
0.72	0.83	3*800	**1600**	0.28
0.74	0.86	3*800	**1600**	0.78
0.76	0.89	3*800	**1600**	0.83
0.78	0.91	3*800	**1600**	1.11

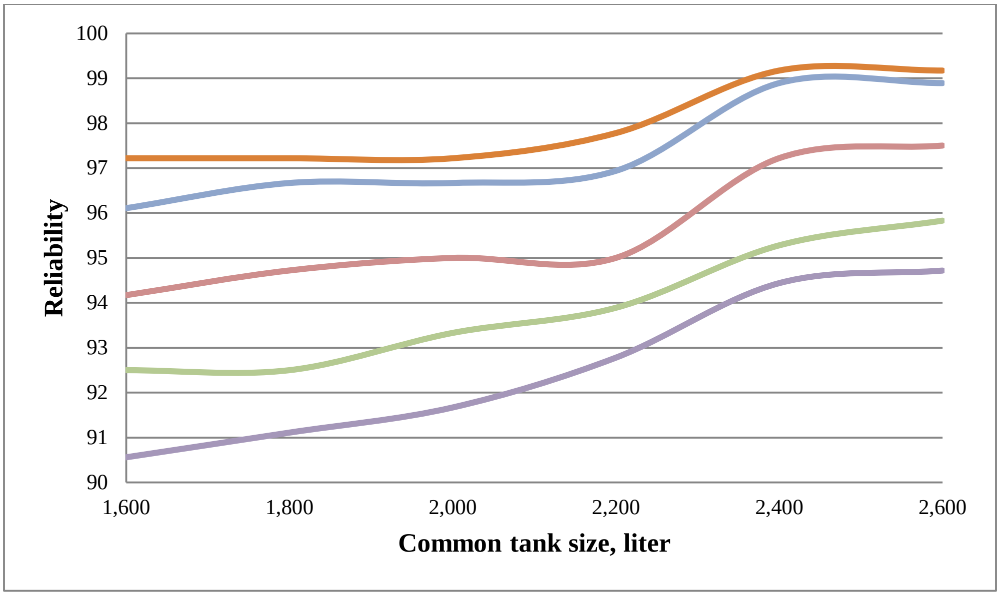

Figure B. 1 Storage-reliability relationships changing mean inflow [K(I) =Demand]

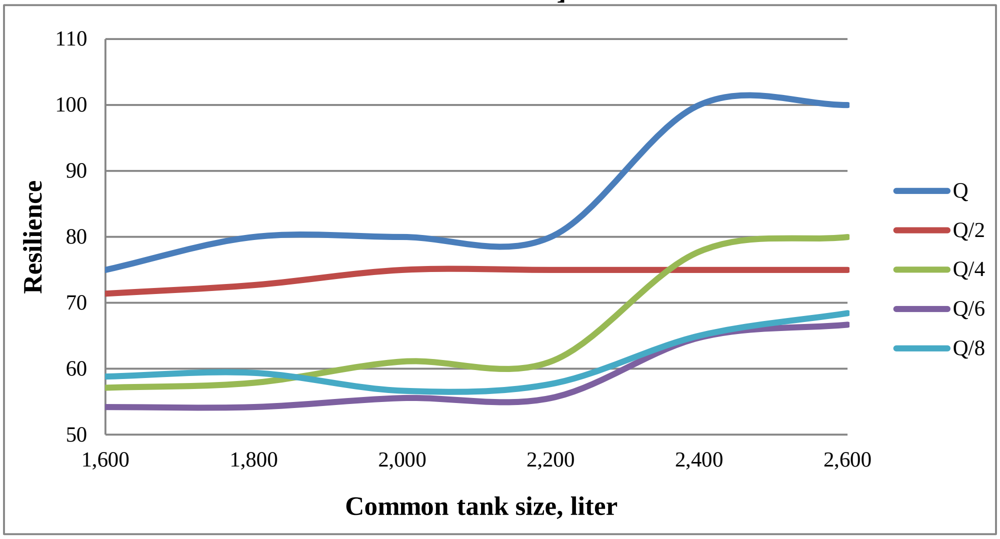

Figure B. 2 Storage-resilience relationships changing mean inflow [K(I) =Demand]

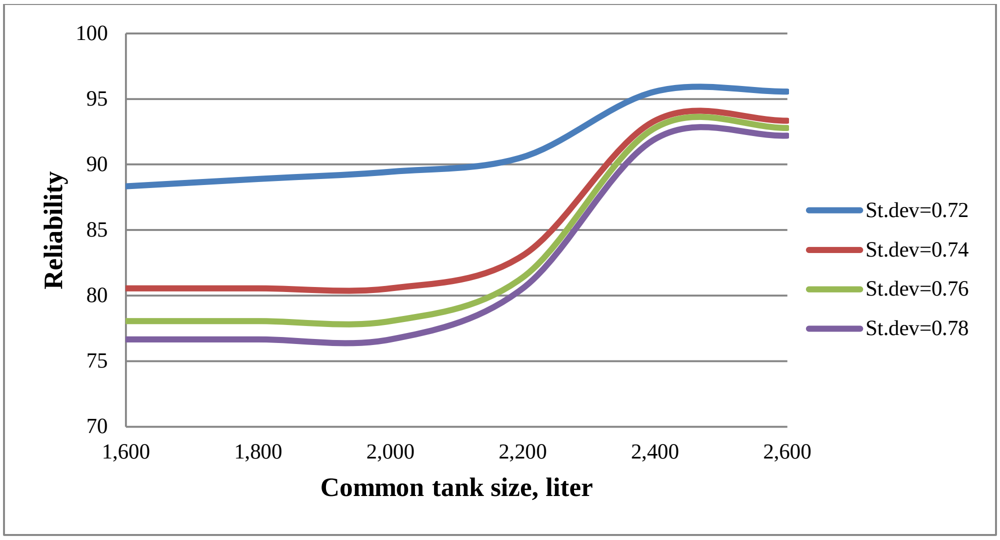

Figure B.3 Storage-reliability relationships changing standard deviations [K(I) =Demand]

Table B.1 Max $\Delta R/\Delta K(c)$ ratios for selected common tank size with changing mean inflows [K(I) =Demand]

Mean Inflow	**Coefficient of variation (CV)**	**Individual tank capacity, K(I)**	**Selected common tank size, K (c)liter**	**Max $\Delta R/\Delta K(c)$**
Q/1	0.83	4*800	**2400**	0.28
Q/2	0.83	4*800	**2400**	0.28
Q/4	0.83	4*800	**2400**	0.33
Q/6	0.83	4*800	**2400**	0.39
Q/8	0.83	4*800	**2400**	0.44

Table B.2 Max $\Delta R/\Delta K(c)$ ratios for selected common tank size with changing standard deviations [K(I) =Demand]

Standard deviation	**Coefficient of variation (CV)**	**Individual tank capacity, K(I)**	**Selected common tank size, K (c)liter**	**Max $\Delta R/\Delta K(c)$**
0.72	0.83	4*800	**2400**	0.28
0.74	0.86	4*800	**2400**	0.78
0.76	0.89	4*800	**2400**	0.85
0.78	0.91	4*800	**2400**	1.1

국문 초록

우수저장고: 방글라데시 용수공급 시스템의 자급자족형 대안

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건설환경공학부
아타시 보타차르지

전지구적으로 사용 가능한 담수(fresh water)의 양이 감소함에 따라, 우수(rainwater) 활용은 전 세계적인 물 부족에 맞서 식수(potable water)를 확보하기 위한 대안으로 제시되고 있다. 비록 강우량이 부족하고 건조한 지역에서는 예전부터 우수의 중요성을 인지하고 국지적으로 우수 집수(rainwater harvesting)를 시행해 왔지만, 강우량이 많으면서 담수가 부족한 지역에서는 우수의 활용에 대한 인식이 적었다. 이러한 지역에 공용의 우수저장고(common rainwater tank) 개념을 도입 및 설치하는 것은 개인의 우수저장고의 의존성을 높이는 것과 마찬가지로 공용 우수저장고에 대한 의존성을 높일 수 있고 이는 지역 사회에 큰 이익을 가져다 줄 수 있다.

본 연구에서는 영향 지역(affected area)의 원활한 담수 공급을 위한 대안으로서 지역 사회 기반의 우수 활용 물 공급 기법을 제시한다. 이 기법에서는, 우수저금통(rainwater bank)라고 하는 공용저장고가 소개된다. 개인의 주택에서는 그들의 지붕을 통해 개인저장고(individual tank)에 우수를 집수할 수 있고 개인저장고가 가득 찬 이후의 넘치는 물은 공용저장고로 흘러 들어간다. 따라서, 개인저장고에 결함이 생겼을 시에는 공용저장고가 우수 저장고로서의 기능을 수행하여 해당 주택에 부족한 물을 공급해 줄 수 있는 것이다. 본 논문의 주 연구목적은 우수 집수 시스템의 신뢰도를 높이고, 자급자족 가능한 지역사회 물 공급 시스템을 구축함으로써 기존 물 공급 시스템에 대한 의존성을 낮추는 것이라 할 수 있다.

여기서, 공용저장고 용량 추정을 위한 기법의 근간으로 표준 운영정책(standard operating policy)이 사용되었다. 우수저장고 모의실험은 30년 길이의 100개 임의 데이터를 사용하여 수행되었다. 우수저장고 시스템의 수행능력의 평가를 위해 시스템이 몇 번 실패하지 않을 것인지를 나타내는 신뢰도와 실패 시 얼마나 빨리 복구할 수 있는지를 나타내는 회복도(resilience)와 같은 통계적 성능 지수(statistical performance indices)들을 유입량 통계값(inflow statistics)과 수요량에 대한 최대 신뢰도 개선값을

공용저장고 용량 증가분으로 나눈 비율을 구하기 위한 여러 시험들이 수행되었고, 그 결과 선정 유역에 대하여 물 공급 신뢰도는 64%에서 95%까지 개선되었으며, 요구량에 따라 두 개의 개인저장고는 동일하다는 가정하였을 때 공용저장고의 용량은 1200리터, 개인저장고의 용량은 800리터로 산정되었다.

또한 1개의 공용저장고와 2개의 개인저장고, 1개의 고용 저장고와 3개의 개인저장고, 1개의 공용저장고와 4개의 개인저장고의 조합으로 공용저장고 용량에 대한 경향을 살펴보았다. 공용저장고를 사용했을 때와 사용하지 않았을 때의 개인저장고의 트레이드오프(tradeoff) 또한 명확하게 논의되었다.

따라서 본 연구의 결과는 방글라데시의 우수 집수 시스템을 연구하는 엔지니어들 혹은 의사결정자들이 대체설계 혹은 운영 정책계획 및 평가를 하는데 있어 도움을 줄 수 있을 것이다.

주 요 어: 우수저금통 (Rainwater bank), 공용저장고 (Common tank), 용량 결정 (Capacity determination), 방글라데시 (Bangladesh), 유입량 생성 (Inflow generation)

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