RAINWATER HARVESTING POTENTIAL IN BANGLADESH

A Project Report

By

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ABSTRACT

In Bangladesh, surface water was the principal source for drinking water ever upto recent past. However, during the recent decades, due to the intensive development programs, the ground water is utilized for drinking purpose in most rural areas. Unfortunately, recent investigations have demonstrated almost countrywide occurrence of high arsenic levels in the tubewell water. Today, Bangladesh seems to be one of the most arsenic affected countries in the world. Bangladesh is a tropical country and receives heavy rainfall during the rainy season. In the present context, rainwater harvesting is being seriously considered as an alternative option for water supply in Bangladesh.

The objective of this research is to study the potential of the rainwater harvesting system in Bangladesh. Ninety seven percent of rural population has access to tubewell water and ground water is still good for all type of uses except drinking. Therefore, the main emphasis is given on the rainwater harvesting as a source of drinking water. The research includes a literature review on rainwater harvesting systems, costs and water quality.

In performing the study, frequency analysis is undertaken on annual rainfall data from 25 stations of Bangladesh Meteorological Department (BMD). The most appropriate probability distribution for each location is determined and used to estimate the reliability of the system of that location. Based on this, design curves are developed to estimate the reliability of the system for any consumption rate at different areas in Bangladesh.

Mass curve analysis is used to determine required storage volumes for every location. Based on statistical analysis of required storage volumes, design curves are developed for estimation of storage tank volumes covering the need for drinking water of different household sizes. These curves can be applied at field level by non professionals.

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CHAPTER ONE
INTRODUCTION

1.1 INTRODUCTION

Rural water supply in Bangladesh is based on groundwater, as it is free from pathogenic microorganisms and available in adequate quantity in shallow aquifers. In Bangladesh, except in coastal and hilly areas, a remarkable success has been achieved by providing 97 percent of the rural population with tubewell water. In the coastal belt, high salinity in surface and ground water and in the hilly areas, absence of good ground water aquifers as well as difficulties in tubewell construction in stony layers are the main constraints for the development of a dependable water supply system. At present, the success achieved in hand tubewell based rural water supply is on the verge of collapse due to the presence of arsenic in ground water in access of acceptable levels in the shallow aquifers. Provision of arsenic contamination free water is urgently needed to mitigate arsenic toxicity and to protect the health and well being of the rural population living in acute arsenic problem areas. The people, particularly the women, living in the problem areas have to walk long distances to fetch water from an available source (Ahmed, 1993).

Bangladesh is a tropical country and receives heavy rainfall during the rainy season. In the coastal districts, particularly in the offshore islands of Bangladesh, rainwater harvesting for drinking purpose is a common practice on a limited scale for a long time.

In some areas having a high salinity problem, about 36 percent of the households have been found to practice rainwater harvesting in the rainy season for drinking purpose (Hussain and Ziauddin, 1989). The protected ponds replenished by rainwater each year are main sources of water supply in the coastal area. Since various uses and unhygienic practices are increasingly polluting the pond water, an alternative source of good quality water supply is needed to maintain the service coverage. In the present context, rainwater harvesting is being seriously considered as an alternative option for water supply in Bangladesh.

A rainwater based water supply system requires determination of the capacity of the storage tank and catchment area for rainwater collection in relation to the water requirement, rainwater intensity and distribution. The main advantages of a rainwater system are that the quality of rainwater is comparatively good, it is independent and therefore suitable for scattered settlement and the owners/users can construct and maintain the system. On the other hand, the availability of rainwater is limited by the rainfall intensity and availability of a suitable catchment area. The mineral free rainwater may not be liked by many and the poorer section of the people may not have a roof or catchment area suitable for rainwater harvesting.

1.2 RATIONALE OF THE STUDY

Today there is a rapid increase in interest in rainwater harvesting (RWH) for water supply, as development assistance groups devote more and more attention to small-scale, locally implemented projects for meeting basic human needs. This high level of interest should not be surprising. As an option for development of water resources, RWH presents a number of advantages. It is a way to increase the quality of water available to households on an incremental basis; it does not require vast quantities of resources. In combination with sanitation or other projects, RWH planning and construction can serve as the focus for community organized efforts. RWH relies and build upon local skills and experiences in construction, water consumption, and rainfall patterns. Finally, RWH may be the only way to increase availability of water where ground water is contaminated with high arsenic concentration and surface water is polluted with unhygienic practices. Ninety seven percent of rural population has access to tubewell water and ground water is still good for all type of uses except drinking. Therefore, the main emphasis is given to examine the potentiality of RWH as an alternate source of drinking water.

1.3 OBJECTIVES OF THE STUDY

The main objectives of the study are:

i) Comparison of two different frequency distributions commonly used for rainfall analysis and selection of the most appropriate approach for such a distribution for a particular place.

ii) Estimation of the reliability of a rainwater harvesting system as a source of water, mainly for drinking purpose for a particular place.

iii) Preparation of Reliability-Demand curve for every location.

iv) Determination of the required storage volume for different places.

v) Development of the required storage volume curve for different degrees of security.

vi) Development of the general required storage volume-demand curve for every location.

vii) Development of cost-storage volume relationship to examine suitability of the system.

1.4 SCOPE OF THE STUDY

The following tasks will be carried out to achieve the objectives stated above:

i) Literature review of different rainwater harvesting systems practiced in different countries for drinking purposes in detail.

ii) Collection of related rainfall data from Bangladesh Meteorological Department for designing a rainwater harvesting system for long-term use.

iii) Frequency analysis of annual rainfall data from 25 stations of BMD for a period of 31 years (1965 to 1995) and selection of a suitable probability distribution function for every individual station.

iv) Reliability calculation of a rainwater harvesting system as a source of water for each station, based on the demand for drinking water for different household sizes with a common size of roof.

v) Development of the Reliability–Demand curve in general for every station which will enable the calculation of the reliability of the rainwater harvesting system for a particular demand with a particular roof catchment area.

vi) Determination of the required storage volume by mass curve analysis. At the same time introduction of the "degree of security" approach for more cost-effective designing of the storage volume with the help of statistical analysis.

vii) Development of Required Storage Volume-Household Size curve for drinking water purposes, and Required Storage Volume-Demand curve in general for every station.

viii) Establishment of an equation to observe how cost of the system varies with demand.

1.5 ORGANIZATION OF THE THESIS

This report presents the analysis, results and findings of the study in six chapters as shown below.

Chapter One presents a brief introduction to the study along with its objectives and scopes.

Chapter Two compiles all relevant literature on different components of the rainwater harvesting system with cost of different storage tanks, water quality protection., design procedure for the storage tank volume and different statistical methods for analyzing the rainfall data.

Chapter Three describes the methodologies for this study with design procedure for the storage tank volume and different statistical methods for analyzing the rainfall data.

Chapter Four provides a description of the analysis process adopted in this study.

Chapter Five presents the results of the analysis accompanied by discussions.

Chapter Six summarizes the whole study and provides some guidelines for further research in this area.

CHAPTER TWO

LITERATURE REVIEW

2.1 INTRODUCTION

Rainwater harvesting and storage do not constitute a new technology. It has been used for domestic and agricultural purposes, runoff control, air-conditioning etc. for a long time. Historical sources mention the use of rainwater for potable water supply some 4000 years ago in the Negev desert. Interest in the use of rainwater as an alternative or supplemental source of water for domestic water supply has been stepped up recently. It particular in developing countries where due to a number of problems, availability of adequate and potable water within easy reach is not always assured. Also, the cost of supplying water to the people through pumping, gravity or other schemes is higher than can be afforded. The rainwater harvesting is considered as a possible answer to the global water use problem, especially where surface and groundwater are limited.

Rainwater harvesting is not a common practice in Bangladesh. Only 35.5 percent households have been found to use rainwater as drinking water source during the rainy seasons in coastal areas, having high salinity problems (Hussain & Ziauddin, 1989). Rainwater is considered as a potential source of pollution for water in the context of groundwater arsenic contamination.

Rainwater harvesting is the process of the interception of rainwater from the air and conveying it towards a reservoir from which the water is withdrawn for consumption. It requires adequate provisions for interception, collection and storage of the water.

Rainwater is collected as it runs from roofs, or as surface runoff flowing on natural ground, roads, yards, or specially prepared ground surface catchments. Rock catchment systems can also be possible where unjoined rock outcrops provide suitable catchment surfaces. The runoff is channeled along stone and cement gutters constructed on the rock surface into reservoirs contained by concrete dams (Gould, 1991). Depending on circumstances, rainwater is collected from roofs or while running over ground surfaces. As the rainwater collected from roofs is usually quite clean, this water is best used for drinking and cooking purposes. Additional water needed for washing and watering a vegetable garden can be taken from less clean sources such as underground tank collecting surface runoff (Hofkes, 1981). The rooftop rainwater harvesting system seems suitable for Bangladesh, as the system will be designed only to supply drinking and cooking water.

In this study, an attempt was made to calculate the required storage volume for rainwater harvesting system in different parts of Bangladesh. The different low-cost materials used for storage tank construction in the other countries were reviewed and some materials are selected on the basis of cost, availability of local materials, skills, performances etc. The costs of these materials were estimated in the context of Bangladesh. The costs of different guttering materials were also estimated. The constraints of implementation of a rainwater harvesting system in rural Bangladesh was identified and steps to overcome these constraints were also discussed too.

2.2 THE MAIN TYPES OF RAINWATER CATCHMENT SYSTEMS

Rainwater catchment systems can be classified according to the type of catchment surface being utilized e.g. roof, ground and rock catchments.

Roof Catchment System

This is the most common type of catchment used for harvesting rainwater. The system consists of three main components: a roof which acts as a catchment surface, a gutter and downpipe, and a tank.

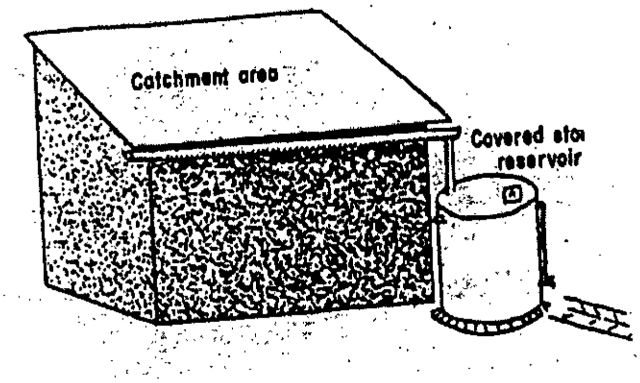


Figure 2.1: Roof catchment system (Gould, 1991).

Ground Catchment System

This is cheaper than roof catchment and is normally employed where suitable roof surface is available. The main advantage, the availability of large area for water collection. Ground surface is normally not efficient for collecting rainwater unless covered with cement or some other material to reduce its infiltration capacity. This may, however, increase the cost of the system.

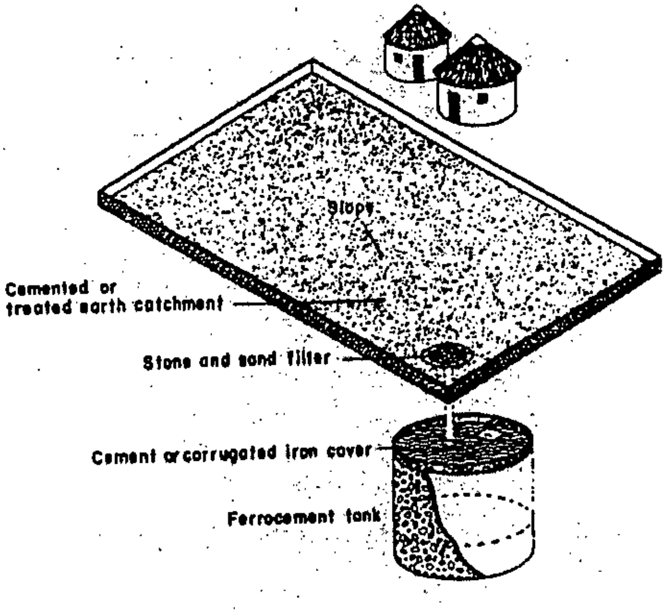


Figure 2.2: Ground catchment system (Gould, 1991).

Rock Catchment System

This is generally constructed for communal supplies in areas where unjointed massive rock outcrops provide a suitable catchment surface. The runoff is channeled along stone and cement gutters, constructed on the rock surface, into reservoirs contained by concrete dams. If the dams lie above the settlements, water can be supplied to stand posts through a gravity fed pipe network.

As ground catchment systems and rock catchment systems are beyond the scope of this work, they are not considered further in this thesis. Concentration will be given to the roof catchment system only.

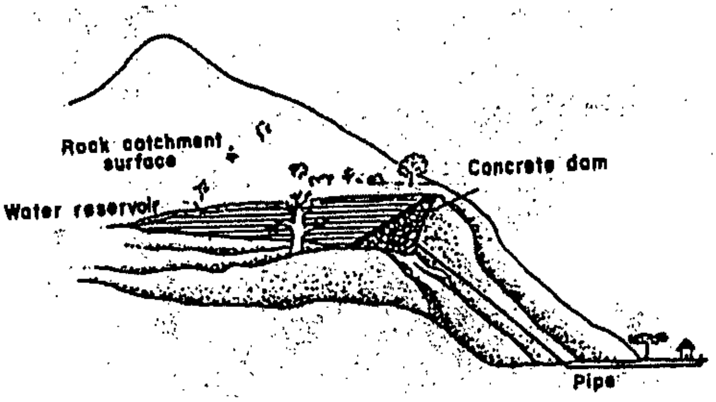


Figure 2.3: Rock catchment system (Gould, 1991).

2.3 COMPONENTS OF ROOF RAINWATER HARVESTING SYSTEM

A typical rainwater harvesting system mainly consists of the following components (adapted from Hasse, 1989; CWSSP, 1995; Michaelides & Young, 1985; Hofkes, 1981; Lee & Visscher, 1992 and Skinner & Franceys, 1992).

Suitable roof catchment

The roof of a domestic dwelling is the most common form of rainwater catchment for domestic water supply. The roofing surface should be smooth dense (hard inorganic) since this is less likely to catch and hold wind-blown dust and debris. Roofs of galvanized metal (corrugated plates or galvanized iron) are preferable. Lead roofs and roofs with asbestos cement sheeting are unsuitable because of health concerns. Thatched roofs pose problems as the runoff is lower and generally of low quality. It is also more difficult to fix gutters to thatched roofs. They can be used with a surface cover by plastic sheet when no other alternative is available.

The size of the roof will depend on the size of the house. The quantity of rainwater that can be collected through roof catchment will largely be determined by the effective area of roof and local rainfall. The greater the area of the roof catchment, the smaller the storage volume with same rainfall distribution.

The shape of any given catchment area has considerable influence on the catchment possibilities. Therefore different types of roofs provide different catchment possibilities. The most common roof types are: a flat roof, a single pitch roof, a double pitch roof, a hip roof and a tent roof. The single pitch roof is the most appropriate as the entire roof area can be drained into a single gutter on the lower side and one or two down-pipes can be provided depending on the area.

Gutter & down pipe system

The gutter and down-pipe are collecting and conveying systems. The gutter is fixed with the roof catchment in a gentle slope and connected to the down-pipe that ends up with the inlet of the storage tank. This connection can be made from locally available materials like bamboo and wood. However, GI and PVC provide better results. Sizing of this installation depends on the roof area. It is necessary to make the joints leak-proof to reduce water losses, a major problem with many of the locally produced gutters.

Flushing system

This arrangement is required to catch the first flush or bypass for flushing the roof. It prevents the contamination that results from the first flush, which is mixed with leaves, birds dropping, and other dirt. For small systems, simply fixing a small length of flexible hose at the end can do this. When the roof is being flushed the flexible hoses should be taken out of the storage tank inlet, and directed to a drain. Once the roof is clean this could be inserted back into the storage tank.

Filter

The sand filter is put before the storage tank to purify the collected rainwater. Installation of a filter will certainly improve the water quality, but it will also increase the cost of the system. This filter system is not common in the rainwater harvesting system. Cloth and netting are used as screens instead of a filter to reduce the cost of the system.

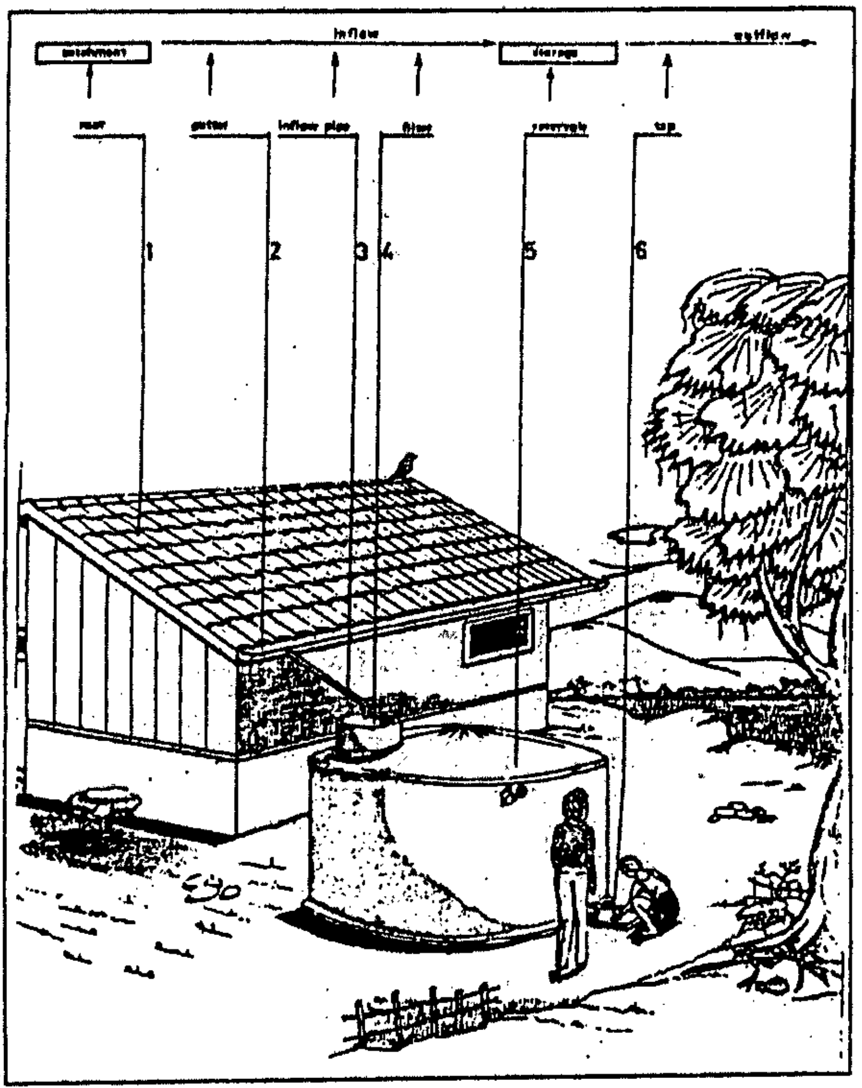


Figure 2.4: Components of a rainwater harvesting system (Ferdausi, 1999).

Storage tank

This is the most important component of the rainwater harvesting system. Safe storage of rainwater throughout the year is the main objective of the storage tanks. The size of the rainwater storage depends on demand, amount and distribution of rainfall, catchment area and type.

A variety of materials have been used in different parts of the world for rainwater storage tanks. These are mainly: ferrocement tanks, bamboo reinforced ferrocement tanks, earthen molded ferrocement tanks, cement mortar jars, bricks tanks, brick block tanks, earthen jars, plastic vessels etc. The different types of storage tanks are discussed in Section 2.4.

Device to extract water from the tank

The device for extraction of water from the tank depends on the position of storage tank. A tap fitted at the bottom of the tank is the easiest method for extraction of water in case of ground and elevated tanks. For under ground tanks, the withdrawal can be done by installing a hand pump.

2.4 TYPES OF STORAGE TANKS

The storage tanks constructed from different materials are described below.

Corrugated Iron tank

This is an industrial product manufactured in different countries. The advantages of this tank is the fast installation and the low capital cost. However, this system has a limited lifetime (8 to 15 years). Repainting is also necessary every 5 years and the quality of the paint may adversely affect the quality of stored water. The corrugated iron tank is also vulnerable to manual force (Hasse, 1989). The carrying cost of a manufactured tank may also be a concern in a rural context.

PVC tank

Several industrial producers offer different types of PVC foil water storage tanks. The foil is fixed inside a reinforcement mesh framework or galvanized sheet cylinders. The cost of the tank varies with the quality of the raw materials used. This type of tank is not suitable for long-term use due to the influence of ultraviolet rays on the PVC foil (Hasse, 1989).

Clay ring tank

Good quality of clay is readily available in many parts of Africa, Asia and Latin America. Clay can be used to build suitable rainwater storage containers of a limited volume. Hard-baked tiles or rings are preferred as building material for water storage tanks. A simple glazing technique is useful in improving the impermeability of clay pot or barrel walls (Hofkes, 1981). However, there is no evidence available on successful operation and maintenance of this type of tank in long term use.

Earthen jars (Motka)

Different sizes of earthen jars are readily available in rural Bangladesh. These types of jars are called 'Motka'. Motka are generally used in the rural areas for storage of food grains. These earthen jars are also used for short-term storage of rainwater by the people of coastal areas (Hussain, 1992). The main disadvantages of these jars are that safe water abstraction is difficult, they are very vulnerable to manual force and can only be produced in limited size.

Cement jars

About 9 million of cement jars were constructed and distributed during the 1980s in the mainly northeast part of Thailand. Construction and maintenance of the jars was easy. The use of jars for rainwater collection was also found cost-effective comparing to the other sources of water. The design is ideal for small tanks and can be used for tanks up to 2 m^3 with wire reinforcement or up to 0.5 m^3 without it. The construction procedure involves the use of a reusable form- work. This can be made using a hessian sack filled with sand, straw, sawdust, rice husks etc. for smaller jars up to 0.5 m^3. For larger jars, up to 2 m^3, reinforcement is required and either a basket or a specially made cement block form-work, made from about 90 curve bricks, can be used (Gould, 1991).

Concrete ring jars

This design is particularly suitable for medium size tanks up to 6 m^3 although larger tanks can be built too. It is an attractive option in areas where aggregate and hardcore are cheap or freely available and where wire-mesh and steel reinforcement bars, needed for standard ferrocement designs, are expensive (Gould, 1991).

Ferrocement tank

There are a number of different ferrocement designs available and up to 200 m^3 or more can be built using ferrocement. The ferrocement tank with a factory made mould has considerable advantages where a series of tanks are to be built with the same size. However, this technology can only be chosen if a factory or experienced workshop provides the facilities for bending corrugated sheets and welding them neatly together. The mould can be used 10-15 times depending on the experience and careful handling of the staff. Repairing of damage is relatively easy in this system. The estimated life expectancy is 15 to 20 years. The structure must be kept moist throughout the year (Hasse, 1989).

Bamboo reinforced ferrocement tank

Bamboo has been introduced as reinforcement material by Asian Institute of Technology (AIT). However, 6 mm diameter mild steel is also used for the mail skeletal. The construction procedure is similar to the wire framed ferrocement tank. A study shows that the tanks constructed with bamboo reinforcement work efficiently upto 5 years of operation (Chembi & Nimityongskul, 1989). However, the construction requires skills specifically for handling the bamboo mesh from breakage.

Soil-cement block tank

This type of low-cost tank was studied by AIT. The estimated cost of 8.2 m^3 tank is \$135.19 and the cost of 16.25 m^3 tank is \$189.25. The interlocking soil-cement blocks were produced through compression of lateritic soil mixed with 10% - 15% of cement and water (Iterbeke & Jacobus, 1988). However, a field study shows that this system has leakage problems, which has made this type of tank unsuccessful (Gould, 1991).

The reinforced brickwork tank

Brick tanks are common throughout the world and have a long history. A variety of design exists and these vary according to the type and availability of bricks. The reinforced brick tank is more expensive than the ferrocement tank, although the cost per m^3 reduces with the increased capacity. It costs twice as much as a ferrocement tank. For this reasons, this tank should be chosen where the capacity needed is above 30 m^3. The life of the structure is expected to be 20 years and more (Hasse, 1989).

2.5 WATER QUALITY PROTECTION

Rainwater has virtually no bacterial content. With few exceptions, the quality of rainwater prior to interception is more consistent than that of other water sources. Some typical examples of the composition of rainwater are given in Table 2.1. A general characteristic of rainwater is its low content of dissolved solids. In this respect calcium and magnesium are of particular interest. Recently it has been recognized that there is an inverse relationship between deaths from heart diseases and the concentration of calcium and magnesium in drinking water. This problem may particularly count for rural areas in developing countries where alternative supply of calcium and magnesium through food may be inadequate (IWACO BV, 1981).

Table 2.1: Typical examples of rainwater composition (IWACO BV, 1981).

SL. No.	*Parameter*	*Amazon area, Brazil*	*North Carolina, USA*	*West Java, Indonesia*
1	Specific conductance, µS/cm	40		25
2	pH	6.5		5.6
3	Chloride (Cl^-), mg/l	1.9	0.6	3
4	Nitrate (NO_3^-), mg/l	0.1	0.6	1
5	Sulfate (SO_4^{2-}), mg/l	3	2.2	4
6	Iron (Fe), mg/l	0.6		Nil
7	Manganese (Mn), mg/l			Nil
8	Calcium (Ca^{++}), mg/l	4.3	0.65	2
9	Magnesium, (Mg^{++}), mg/l	1.1	0.15	1

During collection of the water:

- Contamination from the catchment surface materials.
- Contamination by human beings and large animals (e.g. transmission of infection diseases)
- Remains of dead animals, birds etc.
- Accumulation of dirt, leaves, excrements of birds, small animals etc.

During storage of the water

- Entry and mixing with polluted groundwater (in case of ground storage).
- Entry of dirt, leaves, excrements of birds and small animals etc.
- Algae growth.
- Corrosion of the reservoir material.
- Transmission of disease organisms by insects or birds.

Reduction or elimination of the effects of these sources of pollution can be obtained by the following measures:

Catchment and collection

- The catchment structure must be non-toxic to the human beings.
- The surface should be smooth dense (hard inorganic) since this is less likely to catch and hold wind-blown dust and debris. It is preferable for a roof to be galvanized metal (corrugated plates or galvanized iron).
- Regular cleaning of the catchment surface, gutters and down-pipe to remove accumulated dirt etc.
- Diverting the first runoff, which contains most accumulated dirt etc.
- Placing a wire mesh over the top of the down-pipe to prevent entering of dirt etc. and possible clogging.
- Providing the catchment an even slope to prevent the formation of pools. A steeper slope will further stimulate the removal of solid waste.
- Proper selection of the location of the catchment to reduce the accumulation of dirt etc.
- Filtration of the water before entering the reservoir.

Storage

- Application of watertight materials and construction of above ground reservoirs to prevent the inflow of groundwater.
- Always covering the tank to reduce the algae growth and to prevent entry of insects, dirt, leaves, excrement of birds etc. Covering the ventilation hole with mosquito netting.
- Regular cleaning of the reservoirs to remove sediments at the bottom.
- Disinfection of water by boiling and chemical disinfectants.

However, chemical disinfection is discouraged due to dangers of health risks from over chlorination. One safe and simple method for improving the quality of lightly contaminated water is exposure of small quantities (1-3 liters) to the UV radiation in strong sunlight. This will destroy virtually all pathogenic bacteria in relatively clear, lightly polluted water.

2.6 COSTING OF STORAGE TANKS

A storage tank is the most expensive component of a rainwater harvesting system. The roof is assumed to be present since it must be available for a household. The cost of the gutters or the down-pipes, which direct water to the tank, is considered very little, compared to the cost of storage tank. The cost of the storage tanks mainly depends on the size and material of the rainwater storage tank. Different studies were carried out to reduce the cost of the storage using different low cost materials. The cost of different types of storage tanks used in the different parts of the world and Bangladesh is summarized in Table 2.2, 2.3 and 2.4. The cost of the storage tank generally decreases with the increase of the size.

Table 2.2: Cost of rainwater storage tanks in Asia (Lee & Visshher, 1990).

SL. No.	*System*	*Volume* (m^3)	*Cost (\$)*	*AEC \$/*m^3	*Country*
1	Reinforced cement jar	2	25	0.17	Thailand
2	Concrete ring	11.3	250	0.29	Thailand
3	Wire framed ferrocement	2	67	0.37	Philippines
4	Wire framed ferrocement	4	125	0.35	Philippines

AEC: Annual equivalent cost.

Table 2.3: Cost of rainwater storage tanks in Africa (Lee & Visshher, 1990).

SL. No.	*System*	*Volume (m^3)*	*Cost ($)*	*AEC $/$m^3$*	*Country*
1	Small jar standing	1	25	0.42	Togo
2	Ferrocement standing	5.5	180	0.36	Kenya
3	Cement stave & rooftop	6	627	1.74	Togo
4	Ferrocement ball	7	168	0.27	Kenya
5	Polyethylene & rooftop	7	750	1.87	Botswana
6	Basket standing	8	250	0.35	Kenya
7	Ferrocement standing	9	221	0.27	Kenya
8	Granary standing	10	167	0.28	Togo
9	Round hut standing	10	222	0.37	Togo
10	Ferrocement standing	10	250	0.28	Kenya
11	Brick standing	10	500	0.83	Botswana
12	Ferrocement standing	10	750	1.25	Botswana
13	Ferrocement standing	13.5	630	0.52	Kenya
14	Ferrocement standing	20	925	0.77	Tanzania
15	Ferrocement standing	21	534	0.28	Kenya
16	Ferrocement standing	25	1111	0.49	Kenya
17	Ferrocement standing	30	1073	0.39	Kenya
18	Masonry standing	50	3500	0.78	Kenya
19	Ferrocement ground tank	70	1750	0.28	Kenya
20	Ferrocement ground tank	75	1937	0.29	Kenya
21	Ferrocement ground tank	78	872	0.12	Kenya
22	Ferrocement ground tank	80	2000	0.27	Kenya

AEC: Annual equivalent cost.

Table 2.4: Cost of rainwater storage tanks in Bangladesh (Sher, 1995).

SL. No.	*System*	*Volume (m^3)*	*Cost (Tk)*	*Cost ($)*
1	Ferrocement jar	1	2000	50
3	Ferrocement jar	2	3200	80
4	Ferrocement tank	3.2	4800	120

AEC: Annual equivalent cost.

AEC is calculated by assuming that the tanks are filled three times each year over two rainy seasons, that all water is used and that the tanks last for 30 years.

From the tables, it is clear that rainwater storage is an expensive option compared to groundwater abstraction by handpump. The AEC for a handpump is estimated 0.006 $\$/m^3$ (Ferdausi, 1999), whereas the lowest AEC for rainwater storage is 0.12 $\$/m^3$ for Africa and 0.17 $\$/m^3$ for Asia. However, the estimated cost for groundwater abstraction is based on arsenic-free groundwater. The cost of the arsenic treatment will increase the AEC cost for groundwater.

Gutters and Down-pipes

As stated in the Section 2.3, different materials can be used as gutters and down-pipes and the requirement of the amount of materials depends on the roof size. Table 2.5 gives the costing of gutters and down-pipes.

Table 2.5: Cost of gutters and down-pipes (Ferdausi, 1999).

Materials	*Unit*	*Qty*	*Unit Cost (Tk.*)*	*Total cost (Tk.*)*
Bamboo made				
Material cost	No.	2	60	120
Accessories	-	L.S.	-	100
Labor	self			0
Total cost				***220***
Wood made				
Material cost	cft	0.5	600	300
Accessories	-	L.S.	-	200
Labor	man day	2	70	140
Total cost				***640***
PVC pipes				
Material cost	meter	8	50	400
Accessories	-	L.S.	-	200
Labor	man day	2	70	140
Total cost				***740***
G.I. pipes				
Material cost	meter	8	225	1800
Accessories	-	L.S.	-	300
Labor	man day	2	70	140
Total cost				***2240***

* 48.5 Tk. = 1 US$

The bamboo made gutters and down-pipes have a short life span. They can work properly during rainy season. Again, leakage is a major concern in case of bamboo and wood made gutters and down pipes. The cost of G.I. pipes is very high comparing to other materials. PVC pipes are very cheap and readily available in the rural areas of Bangladesh. The PVC pipes should be used as gutters and down-pipes for rainwater harvesting system in rural areas of Bangladesh.

Storage Tanks

From the review of Section 2.4, some potential materials for storage tanks have been selected. These can be applied in different sizes in rural Bangladesh. No fixed design or materials are selected on the basis on literature review, as these technologies require field-testing in the rural context of Bangladesh. Cost of some storage tanks are presented in Table 2.6.

Table 2.6: Cost of storage tanks (Ferdausi, 1999).

Materials	*Capacity (m^3)*	*Total cost (Tk.*)*	*Per m^3 Cost (Tk.*)*
Ferrocement- molded tank	3.2	7170	2240
Ferrocement- wire framed tank	10	14040	1404
Ferrocement- bamboo reinforced tank	4.5	6660	1480
Cement jars	2.0	2800	1400
Cement ring tank	5.0	6330	1266
Brick reinforcement tank	5.0	16500	3300

* 48.5 Tk = 1 US$

Though the cost of the tanks decreases with the size of the tank, the cement ring tank seems to be the least expensive storage tank for rural Bangladesh. The main advantage of the tank is the familiarity of the construction process. Cement rings are used and constructed widely in the rural Bangladesh for sanitary latrine construction. The ferrocement is not a common technology in Bangladesh and it requires an extensive training before construction.

The cost of earthen jars was not compared to the cost of other materials due to uncertainties regarding its applicability. However, several jars could be used together for long-term water storage. Adequate measures, should be taken for water storage and water collection. The average cost of 0.3 m^3 earthen jars varies from Tk. 250 to 350, i.e., approximately Tk. 1000/m^3.

2.7 RAINFALL IN BANGLADESH

Bangladesh is a tropical country and receives heavy rainfall due to the southern wind from Bay of Bengal. However the rainfall distribution is not uniform over the country.

The normal varies from 1500 mm to 3000 mm. The spatial distribution of normal rainfall in Bangladesh is shown in Figure 2.5. The distribution shows that relatively higher rainfall occurs in the eastern part of the country and highest rainfall occurs in the north-eastern region and eastern part of the coastal area. The low rainfall, less than 1500 mm per year, occurs in the western part of Bangladesh.

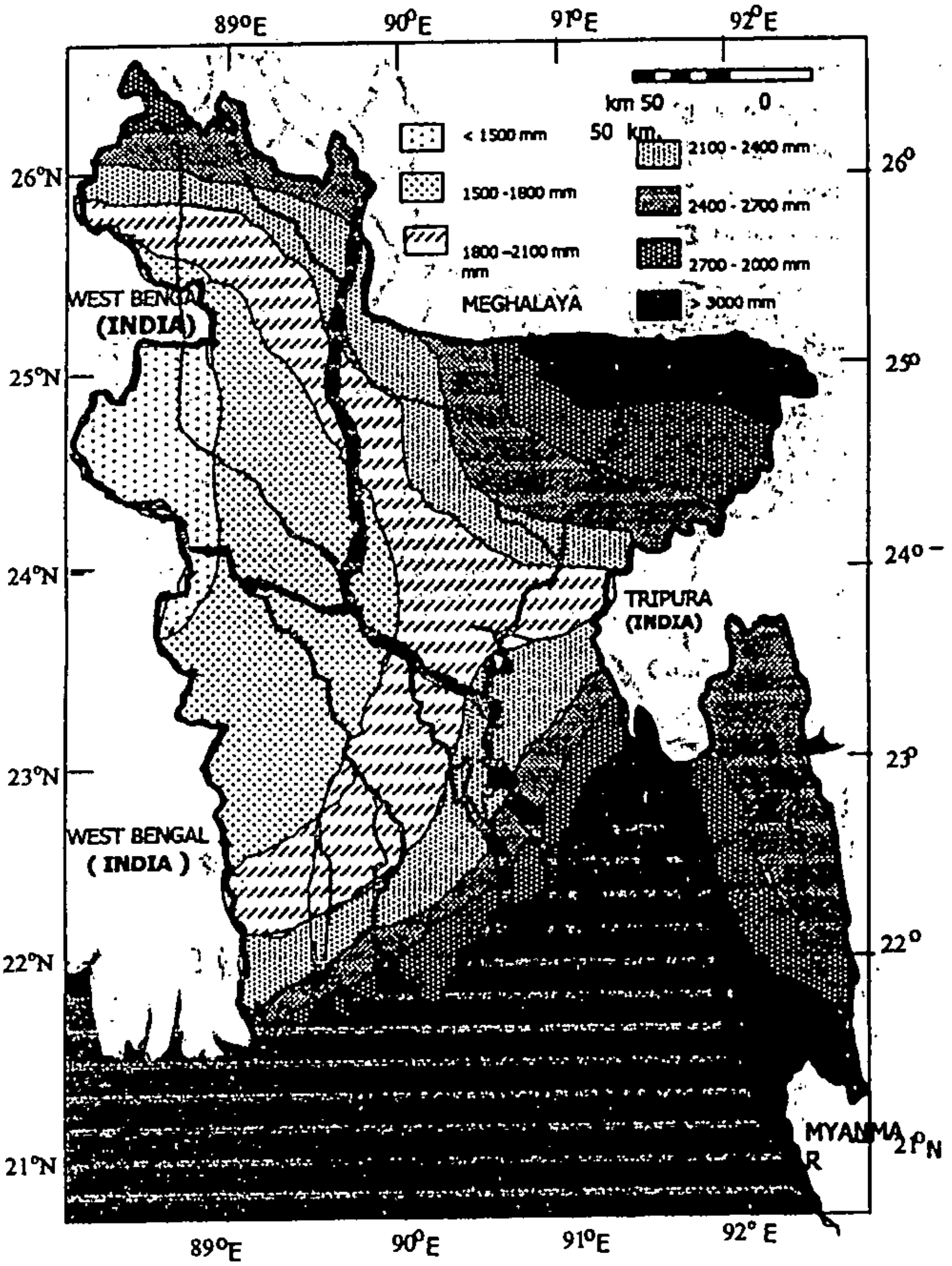


Figure 2.5: Variations of average annual rainfall in Bangladesh.

2.8 HOUSEHOLD SIZE IN BANGLADESH

Household size is one of the important parameter in designing a rainwater harvesting system specifically by using the mass curve analysis method. It is related to the total water demand, storage volume and catchment area. The household size of Bangladesh is given in Table 2.7 and 2.8.

Table 2.7: Distribution of household by number of persons (BBS, 1997).

Person per household	*Household*		*Population*	
	Number	*Percentage*	*Number*	*Percentage*
1	477582	2.5	477852	0.5
2	1411930	7.4	2823860	2.7
3	2421613	12.7	7264839	7.0
4	3164239	16.6	12656965	12.1
5	3233789	17.0	16168945	15.5
6	2746566	14.4	16479396	15.8
7	2019973	10.6	14139811	13.6
8	1344665	7.1	10757320	10.3
9	840881	4.4	7567929	7.3
10+	1358975	7.2	15848627	15.2

Table 2.8: Distribution of household in different locality (BBS, 1997).

Person per household	*Rural area total*	*Municipality area total*	*Other urban area total*	*National total*
1	375624	56253	45975	477582
2	1143415	148748	119767	1411930
3	1972379	246812	202422	2421613
4	2576286	321459	266494	3164239
5	2636293	324733	272763	3233789
6	2243825	271538	231203	2746566
7	1654229	196870	168874	2019973
8	110847	131560	112258	1344665
9	685583	84397	70901	840881
10	425107	55347	44595	525049
11+	660972	99873	73081	833926

2.9 ROOFING MATERIALS IN BANGLADESH

Different types of roofing materials are used in Bangladesh. These include cement concrete, tiles, C.I./metal sheet, straw with or without polythene covering, Bamboo with polythene covering. The different types of roofing materials are given in Table 2.9.

Table 2.9: Dwelling households by materials of roof (BBS, 1997).

Locality	*Straw/bamboo polythene*	*Tiles/C.I./metal sheet*	*Cement*	*Total household*
Rural area	7966388	7362318	145860	15474566
Municipality area	449828	970999	516763	1937590
Other urban area	572136	917508	118689	1608333
Bangladesh total	8988352	9250825	781312	19020489

CHAPTER THREE
METHODOLOGY

3.1 INTRODUCTION

The objective of this research is to study the potential of the rainwater harvesting system in Bangladesh. In performing the study, frequency analysis is undertaken on annual rainfall data from 25 stations of Bangladesh Meteorological Department (BMD). The most appropriate probability distribution for each location is determined and used to estimate the reliability of the system of that location. Based on this, design curves are developed to estimate the reliability of the system for any consumption rate at different areas in Bangladesh.

3.2 METHODOLOGIES

The methodologies for this the study are:

i) Different types of frequency distributions are used for analysis of rainfall data in different countries of the world. For many years, the most commonly adopted approach for this purpose in Bangladesh has been the Extreme Value Type I (EV I), even though there was no reasonable basis in favor of such an approach (Mamtaz, 1993). In this study, selection of an appropriate technique of frequency analysis will form the basis of all subsequent analyses and therefore a comparison between two commonly used frequency distribution approaches (Normal and Log-normal) will be chosen at the outset of the analytical works. The comparison will involve data (annual rainfall from 1965 to 1995; and monthly rainfall from 1975 to 1995) from 25 stations of Bangladesh Meteorological Department (BMD), which will cover more or less whole Bangladesh.

ii) The reliability of a rainwater catchment system is defined as the probability of the system (i.e. the supply of rainwater) exceeding or equaling the demand (consumption). On the other hand, the risk is the probability of the demand exceeding the supply. In this study, the reliability will be calculated on the basis of the most appropriate frequency distribution for a particular place for the purpose of drinking water. The demand will be considered on the basis of literature available and assumed constant within a particular level of variation.

iii) The reliability of a rainwater harvesting system for a particular area can be calculated on the basis of annual rainfall data available for that area, considering a fixed catchment area and a fixed consumption rate. In the present study, an attempt will be made to develop a Reliability-Demand curve, which will enable to determine the reliability of the rainwater harvesting system with any catchment area for any water demand.

iv) There are a number of methods that can be used to determine the tank volume, namely the dry season demand method, the mass curve analysis method and the A_c-V_c method. Although mass curve analysis method is the most simple and accurate method, it still has one disadvantage: it can not be applied to a specific area disregarding catchment area and household size like the A_c-V_c method (Ferdausi, 1999). In this study, attempts will be made to eliminate this disadvantage and only the mass curve analysis will be used for analysis purpose. Moreover, though successful use of the technique requires approximately 10 years of data (UNDP/World Bank, 1990), 20 years of data will be used to increase accuracy.

v) A rainwater harvesting system basically provides for the catchment, collection and the storage of rainwater. In designing such a system, the objective should be to obtain the most economical combination of the storage tank volume and catchment area. According to the mass curve analysis, the design volume will be the maximum required volume among several years. In reality, this volume will be needed only once in several years and increases the cost of the system considerably. In this study, a special attempt will be made to make the system more economical by introducing the probability concept in designing.

vi) In this study, general Required Storage Volume-Demand curves will be provided for different locations so that the storage volume can be determined from the curve for any demand with any catchment area for a particular degree of security. To make designing easier, another curve of required storage volumes for different household sizes will be prepared.

vii) Though there is not much data available regarding the cost of storage tank, still attempt will be made to establish an equation with cost and storage volume on the basis of limited data. This equation will be used to determine cost in order to measure the suitability of the system.

3.3 DESIGN PROCEDURE

A rainwater harvesting system basically provides for the catchment and collection, and the storage of rainwater. In designing such a system the objective should be to arrive at the most economical combination of the storage tank volume and catchment area. There are cases where the available catchment area is fixed (e.g. roof of the house), and then the most suitable size of storage tank may have to be determined.

In other instances, the conditions for determining the most economical combination of catchment and storage volume will be more flexible. Sometimes, experiences with rainwater harvesting system in the area may be wide enough to serve as a basis for decision making. However, more often than not this is not the case, and then the proper method to establish the optimal tank volume, in conjunction with the required size of catchment area, should be based on a systematic analysis of rainfall records, construction cost and other data. The systematic analysis, proposed here, uses monthly rainfall data.

The basis of the design is provided by any record of monthly rainfall measured at one or more rain gauge stations, which can be regarded as representative for the area under consideration. If no such rainfall records are available, either because there are no gauge stations in the area or the rainfall records are too short or unreliable, it may be possible to use the records from existing neighboring stations around the area. This however, may introduce serious errors in the analysis (Hofkes, 1981). Shorter time intervals (e.g. weekly totals) will yield more accurate results but do increase the amount of calculations over one period with both a time interval of one week and one month. it is shown that only a limited increase in accuracy is obtained by using data of shorter duration (IWACO BV, 1981). Besides that, monthly rainfall data are generally included in periodical publications of meteorological institutes and are more easily accessible than weekly rainfall records.

The amount of water yielded per month by a catchment may be computed as,

$$Yield = \frac{f * A * R}{1000} m^3 / month \tag{3.1}$$

where, A = catchment area (m^2)

R = monthly rainfall (mm)

f = catchment efficiency factor or runoff coefficient

Runoff coefficient

The rainfall received by a catchment area (whether a roof or ground surface) is only partly discharged toward the storage tank. A portion of the rainwater serving to wet the surface of the catchment area, is held in depressions and then lost by evaporation or infiltration in the ground. This amount is represented as a fraction called the runoff coefficient. This is not a precise value, but is estimated on the basis of the roof, the condition of gutter and piping, and the evaporation expected from the roof and tank. Approximate runoff coefficients values are:

Table 3.1: Runoff coefficient for different catchments (Hofkes, 1981).

SL. No.	*Type of catchment*	*f*
1	Uncovered catchment surface	
1.a	Completely flat terrain	0.3
1.b	Sloping 0 – 5%	0.4
1.c	Sloping 5 – 10%	0.5
1.d	Sloping more than 10%	0.5 and more
2	Covered catchment surface	
2.a	(roof) tiles	0.8 – 0.9
2.b	Corrugated sheets	0.8 – 0.9
2.c	Concrete bitumen	0.7 – 0.8
2.d	Plastic sheets	0.7 – 0.8
3	Brick pavement	0.5 – 0.6
4	Compacted soil	0.4 – 0.5

A short low-intensity rainstorm after a long dry period is likely to evaporate for the greater part, so that the useful runoff would be very small. Conversely, during a long period of heavy rain, the runoff coefficient might be very high. However, the runoff coefficient is taken as constant for the simplicity of calculation (Hofkes, 1981).

3.4 DIFFERENT METHODS FOR DESIGN

There are a number of methods that can be used to determine the tank volume.

Dry Season demand Versus Supply

This approach considers the length of the dry period as a design constraint. The tank is designed so that it accommodates the household during the dry season. For this reason, the method is most appropriate where there is a definite wet/dry period during the year. The method to determine the rainwater storage tank is to multiply the days of the longest dry period by the amount of water required per day.

$$Storag\ volume = \frac{D * N * Dp}{1000} m^3 \tag{3.2}$$

where, D = demand per capita per day in liter

N = no. of family members

Dp = duration of dry period in days

This method gives only a rough estimate of the storage required. It does not take into account the variation of rainfall, catchment area and runoff coefficient. A better method of tank sizing involves the mass curve analysis method.

Mass Curve Analysis Method

This method involves analysis of rainfall data using the mass curve technique. Successful use of this method requires a minimum of 10 years of raw data. This includes tabulating the monthly rainfall (mm), monthly supply (liters), cumulative supply (liters), monthly demand (liters), monthly amount stored (liters) and total amount stored (liters). The required tank volume (given in the seventh column) can be determined when the table is filled out. The least amount stored during the dry season is subtracted from the largest amount stored during the wet season. This difference represents the storage volume required for that particular year. The difference between the largest and least amounts stored in each year is calculated. The largest difference yields the tank size.

This method also can be applied graphically. However, a more accurate result is obtained from the tabulated calculations.

3.5 PROBABILITY DISTRIBUTION IN RAINFALL ANALYSIS

The Normal Distribution

Normal distribution is also known as Gaussian distribution. The normal distribution has a probability density function given by

$$f_X(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right] \qquad -\propto < x < \propto \tag{3.3}$$

where μ and σ are the parameters of the distribution N(μ, σ), which are also the mean and standard deviation, respectively, of the variate.

A Gaussian distribution with parameters μ = 0 and σ = 1.0 is known as standard normal distribution N(0,1) and the density function is

$$f_S(s) = \frac{1}{\sqrt{2\pi}} e^{-(1/2)s^2} \qquad -\infty < s < \infty \tag{3.4}$$

Φ(s) is the distribution function of the standard normal variate S, where S has N(0, 1) distribution. With the table of Φ(s), the probability of a normal variate X with distribution N(μ, σ) is

$$P(a < X \le b) = \frac{1}{\sigma\sqrt{2\pi}} \int_a^b \exp\left[-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right] dx = \Phi\left(\frac{b-\mu}{\sigma}\right) - \Phi\left(\frac{a-\mu}{\sigma}\right) \tag{3.5}$$

The normal distribution is applicable if

1. The variable is continuous,
2. Consecutive values are independent, and
3. Probabilities are stable.

The main limitation for normal distribution for describing hydrologic variables is that it varies over a continuous range ($-\infty$ to $+\infty$), while most hydrologic variables are non-negative, and that it is symmetric about the mean, while hydrologic data tend to be skewed.

The Logarithmic Normal Distribution

A random variable X has a logarithmic normal (or simply log-normal) probability distribution if lnX is normal. In this case the density function of X is

$$f_X(x) = \frac{1}{\sigma\sqrt{2\pi}\zeta x} \exp\left[-\frac{1}{2}\left(\frac{\ln x - \lambda}{\zeta}\right)^2\right] \qquad 0 \le x < \infty \tag{3.6}$$

The probability that X will assume values in an interval (a, b) is

$$P(a < X \le b) = \int_a^b \frac{1}{\sqrt{2\pi}\zeta x} \exp\left[-\frac{1}{2}\left(\frac{\ln x - \lambda}{\zeta}\right)^2\right] dx = \Phi\left(\frac{\ln b - \lambda}{\zeta}\right) - \Phi\left(\frac{\ln a - \lambda}{\zeta}\right) \tag{3.7}$$

Chow (1954) has provided a theoretical justification for the use of the log-normal distribution for hydrologic data analysis. The causative factors for many hydrologic variables act multiplicatively rather than addetively and so the logarithms of these factors will satisfy the basic conditions of normal distribution. The hydrologic variable will then be the product of these causative factors. The log-normal distribution has the advantage over the normal distribution that it is bounded by x > 0 and that the log-transportation tends to reduce the positive skewness commonly found in hydrologic data.

3.6 EMPIRICAL DETERMINATION OF DISTRIBUTION MODELS

The probabilistic characteristics of a random phenomenon are sometimes difficult to discern or define, such that the appropriate probability model needed to describe these characteristics is not readily amendable to the theoretical deduction or formulation. In particular, the functional form of the required probability distribution may not be easy to derive or ascertain. Under certain circumstances, the basis or properties of the physical process may suggest the form of the required distribution.

Nevertheless, there are occasions when the required probability distribution has to be determined empirically (that is, based entirely on available data). For example, if the frequency diagram for a set of data can be constructed, the required distribution model may be determined by visually comparing a density function with the frequency diagram. Alternatively, the data may be plotted on probability papers prepared for specific distributions (Ang & Tang, 1975).

3.7 PROBABILITY PLOTTING

The linearity, or lack of linearity, of a set of sample data plotted on a particular probability paper, can be used as a basis for determining whether the distribution of the variate is the same as that of the probability paper. The plotting position of each data point is determined as follows.

> If there are N observations $x_1, x_2, \ldots, x_N$, the m^th^ value among the N observations (arranged in increasing order) is plotted at the cumulative probability m/(N+1).

If the data points plot approximately on a straight line on one of these papers, the distribution corresponding to this paper may be an appropriate distribution model.

The Normal Probability

The normal probability paper is constructed on the basis of the standard normal distribution function as follows. One axis (in arithmetic scale) represents the values of the variate X. On the other axis are two parallel scales; one in arithmetic scale represents values of the standard normal variate s, whereas the other shows the cumulative probability $\Phi_S(s)$ corresponding to the values of s. A normal variate X with distribution $N(\mu, \sigma)$ would then be represented on this paper by a straight line passing through $\Phi_S(s) = 0.50$ and $X = \mu$. The value of X on this line corresponding to $\Phi_S(s) = 0.50$ is the estimate of the mean value μ_x, whereas the slope of the straight line is the estimate of the standard deviation σ_x; thus $\sigma_x \cong x_{.84} - \mu_x$.

The Log-Normal Probability

The logarithmic probability paper can be obtained from the normal probability paper by simply changing the arithmetic scale for values of the variate X to a logarithmic scale. In this case, the standard normal variate becomes

$$S = \frac{\ln(X / x_m)}{\zeta} \tag{3.8}$$

$$\zeta = \frac{1}{s}\ln\left(\frac{x_p}{x_m}\right) = \ln\left(\frac{x_{.84}}{x_m}\right) \tag{3.9}$$

where x_m is the median of X. If the plotted data points yield a straight line, this line represents the particular log-normal distribution. Accordingly, the median x_m is simply the value of the variate on this line corresponding to $\Phi_S(s) = 0.50$; whereas the parameter ζ is given by the slope of the line, that is,

3.8 TESTING VALIDITY OF ASSUMED DISTRIBUTION

When a theoretical distribution has been assumed, perhaps determined on the basis of the data plotted on a given probability paper, the validity of the assumed distribution may be verified or disproved statistically by goodness-of-fit tests. Moreover, when two or more distributions appear to be plausible probability distribution models, such tests can be used to delineate the relative degree of validity of the different distributions. Two such tests are commonly used for these purposes-the chi-square (χ^2) and the Kolmogorov-Smirnov (K-S) tests.

In a study by Akhter (1992), it is found that the chi-square test is a reliable tool for checking the goodness-of-fit of rainfall data with a given probability distribution function in Bangladesh.

Chi-square Test

Consider a sample of n observed values of a random variable. The chi-square goodness-of-fit test compares the observed frequencies $n_1, n_2, ..., n_k$ of k values (or in k intervals) of the variate with the corresponding frequencies $e_1, e_2, ..., e_k$ from an assumed distribution. The basis for appraising the goodness of this comparison is the distribution of the quantity

$$\sum_{i=1}^{k} \frac{(n_i - e_i)^2}{e_i}$$

which approaches the chi-square (χ_f^2) distribution with ($f = k-1$) degrees of freedom as $n \rightarrow \infty$. However, if the parameters of the theoretical model are unknown and must be estimated from the data, the above statement remains valid if the degree of freedom is reduced by one for every unknown parameter that must be estimated.

On this basis, if an assumed distribution yields

$$\sum_{i=1}^{k} \frac{(n_i - e_i)^2}{e_i} < c_{1-\alpha,f} \tag{3.10}$$

where $c_{1-\alpha,f}$ is the value of the appropriate (χ_f^2) distribution at the cumulative probability ($1-\alpha$), the assumed theoretical distribution is an acceptable model, at the significance level α. Otherwise, the assumed distribution is not substantiated by the data at the α significance level.

3.9 RELIABILITY COMPUTATIONS USING DEMAND-SUPPLY ANALYSIS

The reliability of a rainwater catchment system is defined as the probability that the capacity of the system (i.e. the supply of rainwater) exceeds or equals the demand (consumption). On the other hand, the risk is the probability of the demand exceeding the supply. Considering the random variables D and S which represents the demand and supply, respectively, the reliability of a rainwater catchment system can be expressed mathematically as

$$\alpha = P(D \leq S) \tag{3.11}$$

The relationship between reliability (α) and risk (α') is

$$\alpha' = P(L > R) = 1 - \alpha \tag{3.12}$$

Method of Using Safety Margin

The safety margin (SM) is defined as the difference between the supply and demand, that is, SM = S – D. The reliability of the system can be expressed in terms of safety margin as

$$\alpha = P(S - D \geq 0) = P(SM \geq 0) \tag{3.13}$$

Using the safety margin for computing reliability requires knowing the probability distribution of SM. If that is the case, the reliability can be obtained by $\alpha = 1 - F_{SM}(0)$ in which $F_{SM}()$ is the CDF of the safety margin SM. In case of normal distribution, the distribution of SM is normally distributed with the mean μ_{SM} and variance σ_{SM}^2 if the demand and supply are both normal random variables. The reliability (α) can be obtained as

where Φ( ) is the standard normal CDF.

$$\mu_{SM} = \mu_S - \mu_D \tag{3.14}$$

$$\sigma_{SM} = \sqrt{\sigma_S^2 + \sigma_D^2 - 2Cov(D,S)} = \left(\sigma_S^2 + \sigma_D^2 3\right)^{\frac{1}{4}} \tag{3.15}$$

Method of Using Safety Factor

$$\alpha = P\left(\frac{SM - \mu_{SM}}{\sigma_{SM}} \geq \frac{-\mu_{SM}}{\sigma_{SM}}\right) = \Phi\left(\frac{\mu_{SM}}{\sigma_{SM}}\right) \tag{3.16}$$

The safety factor (SF) is defined as the ratio of supply to demand, S/D. Because safety factor SF is the ratio of two random variables, consequently, it is also a random variable. The reliability then can be written as P(SF ≥ 1). In case of log-normal distribution, reliability can be obtained as

$$\alpha = 1 - \Phi\left\{\frac{-\ln\left[\frac{\mu_S}{\mu_D}\sqrt{\frac{1+\Omega_D^2}{1+\Omega_S^2}}\right]}{\sqrt{\ln\left[\left(1+\Omega_D^2\right)\left(1+\Omega_S^2\right)\right]}}\right\} \tag{3.17}$$

where $\Omega_D = \sigma_D / \mu_D$ and $\Omega_S = \sigma_S / \mu_S$ are coefficients of variation of demand and supply.

CHAPTER FOUR

ANALYSIS OF DATA

4.1 INTRODUCTION

In Bangladesh, rainfall data are available from two agencies: Bangladesh Meteorological Department (BMD) and Bangladesh Water Development Board (BWDB). In this study, rainfall data are collected from BMD. Missing data are calculated by the normal ratio method. Rainfall patterns for different places will be examined using these data. Data of household sizes and roof materials are collected from Bangladesh Bureau of Statistics (BBS). Tests have been performed to determine the best-fit probability distribution for annual rainfall data to calculate the reliability of the rainwater harvesting system. Required storage volumes are calculated on the basis of the mass curve analysis. Required storage volumes for different years are statistically analyzed to determine the most cost-effective storage volume.

4.2 DATA AVAILABILITY IN BANGLADESH

Rainfall data are collected in Bangladesh mainly by two agencies; Bangladesh Meteorological Department (BMD) and Bangladesh Water Development Board (BWDB).

These agencies maintain two separate networks of rain gauge stations all over the country. Originally, the stations are equipped with manual rain gauges where reading had to be recorded by an operator. BMD has a total of 25 rain gauge stations operational since as early as 1948 and BWDB has a denser network of 294 stations all over the country (Mamtaz, 1993). At a later stage some automatic rainfall recording set-ups (auto chart) were installed by both BMD and BWDB. The auto charts record rainfall continuously on graph papers continuously from which rainfall for any duration can be extracted.

4.3 SELECTION OF DATA

In this study, monthly rainfall data are used for analysis. Shorter time intervals (i.e. daily, weekly data) increase only slightly the accuracy of the results, but do increase the amount of calculations considerably (Section 3.3).

Monthly rainfall data as well as annual rainfall data of 21 years (1975 to 1995) for 25 stations have been collected from BMD. Locations of these stations are denoted in Figure 4.1. To make the reliability calculations more accurate, annual rainfall data of another 10 years (1965 to 1974) have also been collected from Statistical Yearbook of Bangladesh (BBS, 1975). BMD is also the source of these data.

4.4 ESTIMATION OF MISSING DATA

It is necessary to have data sets of consecutive years for the subsequent statistical analysis. The missing data are filled out for one or two years with the help of rainfall recorded at the surrounding stations by the following methods.

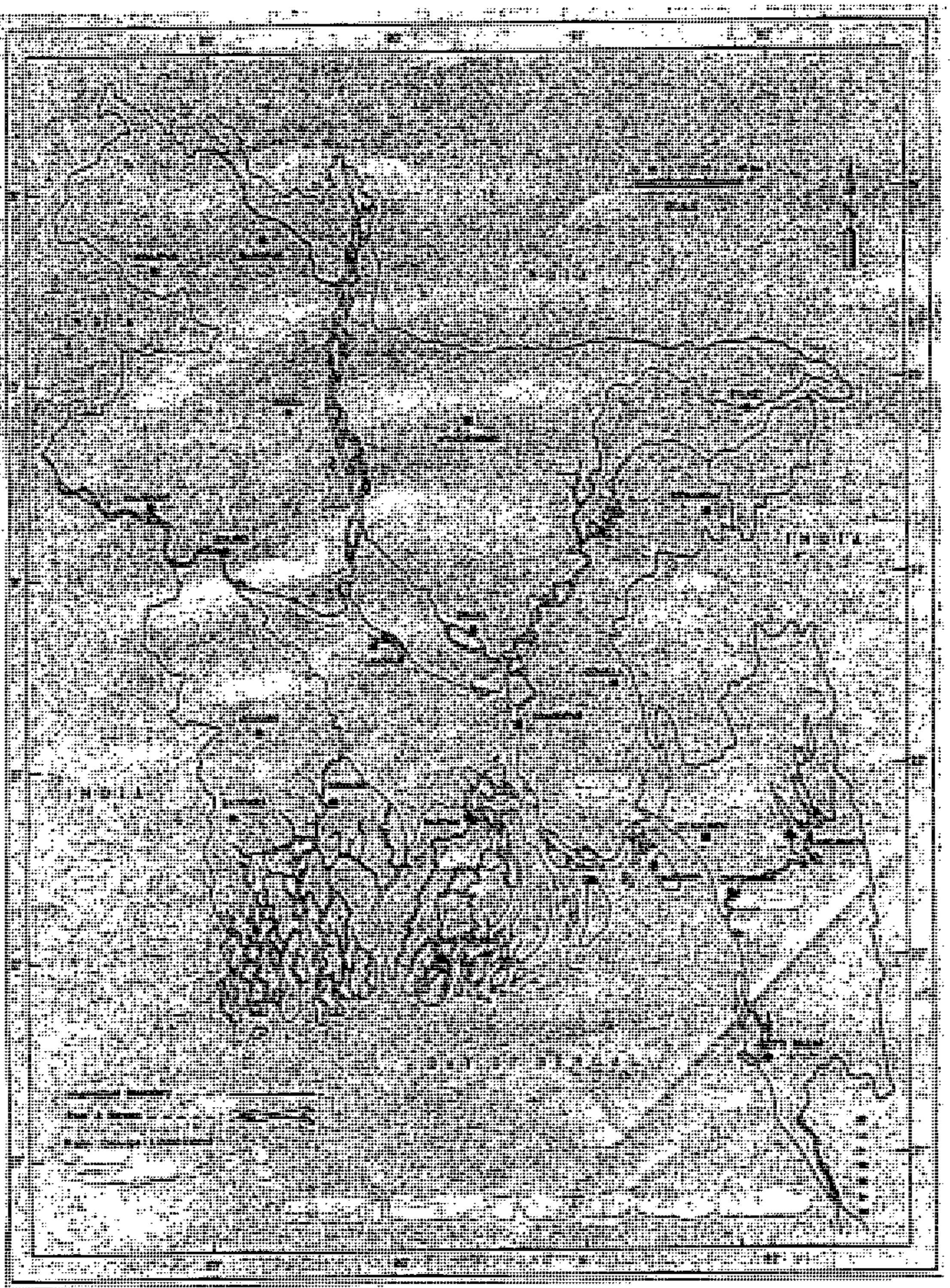


Figure 4.1: Location of BMD rain gauge stations.

Arithmetic Average Method

If the normal annual rainfall at each of the surrounding stations is within 10 percent of the rainfall of the station with missing records, a simple arithmetic average of the rainfall of the surrounding stations can be used to estimate the missing rainfall, i.e.

$$P_X = \frac{1}{3}[P_A + P_B + P_C] \tag{4.1}$$

where, P_X = The missing record, and

P_A, P_B, P_C = Rainfall at the surrounding stations.

Normal Ratio Method

If the normal annual rainfall at any of the surrounding stations vary from that of the station in question by more than 10 percent, this method is adopted. The missing record is estimated by the weighted average of the rainfall at the surrounding stations as follows:

$$P_X = \frac{1}{3}\left[P_A \frac{N_X}{N_A} + P_B \frac{N_X}{N_B} + P_C \frac{N_X}{N_C}\right] \tag{4.2}$$

where, P_X = The missing record, and

N_X/N_A, N_X/N_B and N_X/N_C = Ratios of the normal annual rainfall of the surrounding stations.

Normal Ratios

It is observed from the data that the variation of the normal annual rainfall among different stations is not always within 10% of the rainfall of that station. In this study, the missing data are calculated by the normal ratio method.

Normal ratios for surrounding stations are calculated on the basis of the average of 21 years annual rainfall since 1975 to 1995 (shown in Table 4.1). The calculation of the missing monthly rainfall data of Dhaka for the month of Jan., 1983 and Dec., 1983 is shown in Appendix A.

Table 4.1: Normal ratios for different stations of BMD

Sl. No.	*Station*	*Normal Ratios for Surrounding Stations*		
1	Barisal	Bhola (0.89)	Khulna (1.23)	Chandpur (0.98)
2	Bhola	Barisal (1.15)	Khulna (0.89)	Hatia (1.10)
3	Bogra	Rangpur (0.74)	Mymensingh (0.82)	Rajshahi (1.21)
4	Chandpur	Comilla (1.14)	Dhaka (1.08)	Barisal (1.09)
5	Chittagong	Sandwip (0.91)	Sitakunda (1.26)	Rangpur (1.20)
6	Comilla	Dhaka (0.96)	Chadpur (0.92)	Feni (0.71)
7	Cox's Bazar	Chittagong (1.28)		
8	Dhaka	Faridpur (1.14)	Chandpur (0.97)	Comilla (1.05)
9	Dinajpur	Rangpur (0.83)	Bogra (1.33)	
10	Faridpur	Dhaka (0.90)	Chandpur (0.86)	Jessore (1.14)
11	Feni	Comilla (1.49)	Chandpur (1.52)	Sitakunda (1.00)
12	Hatia	Sandwip (0.90)	Bhola (1.22)	
13	Ishurdi	Faridpur (0.80)	Bogra (1.01)	Rajshahi (1.05)
14	Jessore	Faridpur (0.89)	Khulna (0.94)	Satkhira (0.97)
15	Khepupara	Barisal (1.31)	Hatia (1.39)	Bhola (1.18)
16	Khulna	Jessore (1.08)	Satkhira (1.06)	Barisal (0.83)
17	Mymensingh	Bogra (1.52)	Dhaka (1.14)	Srimangal (0.59)
18	Rajshahi	Ishurdi (0.97)	Bogra (0.96)	
19	Rangamati	Sitakunda (0.79)	Chittagong (0.87)	
20	Rangpur	Dinajpur (1.25)	Bogra (1.54)	
21	Sandwip	Hatia (1.51)	Sandwip (1.28)	Chittagong (1.11)
22	Satkhira	Khulna (0.98)	Jessore (1.05)	
23	Sitakunda	Feni (1.05)	Sandwip (0.94)	Chittagong (1.03)
24	Srimangal	Sylhet (0.59)		
25	Sylhet	Srimangal (1.93)		

The figure in parenthesis indicates normal ratio

4.5 RAINFALL PATTERNS IN BANGLADESH

Rainwater is available in adequate quantity in Bangladesh during the rainy season. A 21-year rainfall pattern based on the mean rainfall intensity recorded in 25 stations for the period 1975 to 1995 is shown in Figure 4.2 with maximum and minimum annual rainfall. It appears that the average yearly rainfall in the country during 1975-95 is 2426 mm which varied from 1797 to 2867 mm. This means 1.80 to 2.87 m^3 of rainwater was available per m^2 of catchment area each year for development of a rainwater based water supply system.

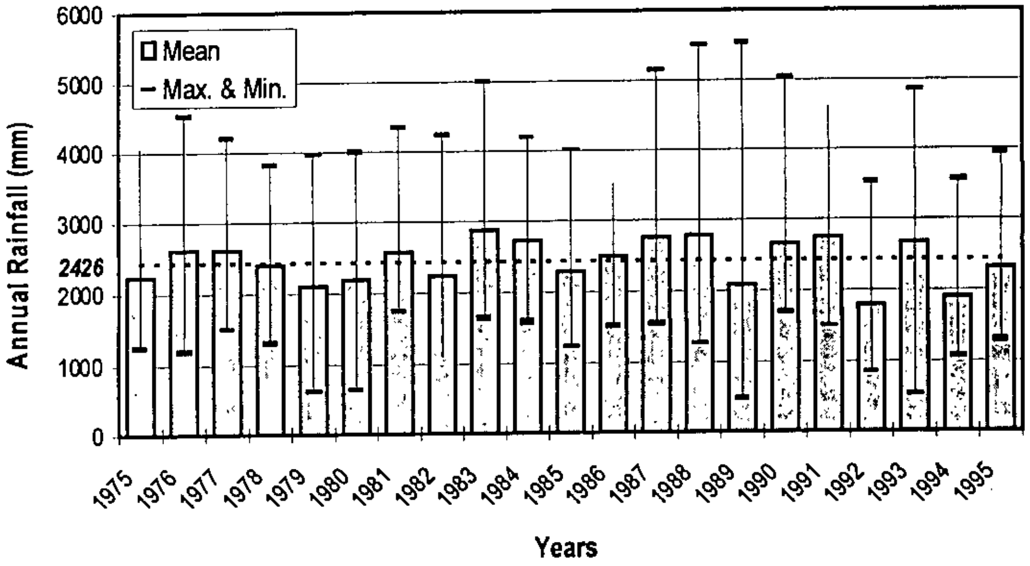


Figure 4.2: Variations of annual rainfall in Bangladesh.

To facilitate the analysis on zonal basis, an attempt has been made to divide the country in rainfall zones. Based on the average annual rainfall, Bangladesh can be divided into seven different rainfall zones (Figure 2.5). Table 4.2 shows the location of 25 rain gauge stations in seven different zones according to the average annual rainfall for each zone.

Table 4.2: Rain gauge stations in different zones.

Zones	*Average annual Rainfall (mm)*	*Rain gauge stations*
Zone I	< 1500	Rajshahi
Zone II	1500 – 1800	Ishurdi, Jessore, Satkhira
Zone III	1800 - 2100	Bogra, Dinajpur, Faridpur, Khulna
Zone IV	2100 - 2400	Barisal, Chandpur, Comilla, Dhaka, Rangpur, Mymensingh
Zone V	2400 - 2700	Bhola, Khepupara, Rangamati, Srimangal
Zone VI	2700 - 3000	Chittagong, Feni, Hatia
Zone VII	> 3000	Cox's Bazar, Shandip, Sitakunda, Sylhet

However, in designing a rainwater harvesting system, the monthly rainfall has more significance than the average annual rainfall. The monthly rainfall distribution for Dhaka with maximum and minimum monthly rainfall is shown with the monthly average rainfall for the country in Figure 4.3. The monthly rainfall distribution for other stations are shown in Appendix B.

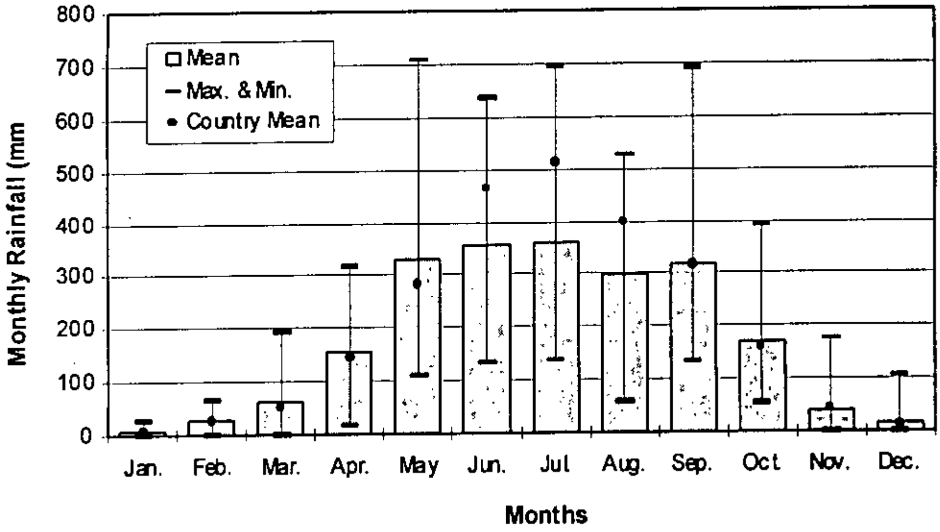


Figure 4.3: **Average monthly rainfall distribution for Dhaka (1975-1995).**

Figure 4.3 shows that the heavy rainfall in Dhaka concentrates only from April to October. The rainfall from November to March is inadequate to meet the demand during the dry period. Consequently, rainwater has to be collected during the rainy season and stored for use throughout the year. Rainwater harvesting for long-term use was not considered as a potential source due to the unavailability of suitable catchment areas and the inconvenience of storing water over 5 months during the dry season. Hand tubewells were comparatively more suitable. However, at present rainwater harvesting in Bangladesh is considered as a potential alternative source given the recent groundwater contamination with arsenic.

4.6 HOUSEHOLD SIZE IN BANGLADESH

The distribution of household and population by number of persons per household is shown in Figures 4.4 and 4.5 based on the population census of 1991 (Table 2.7 & 2.8). It is observed that the average size of a household is 5.48 persons and 67% of the population has a household size between 4 and 8 persons. The average household size is taken as 6 persons per household for several calculations of storage capacity.

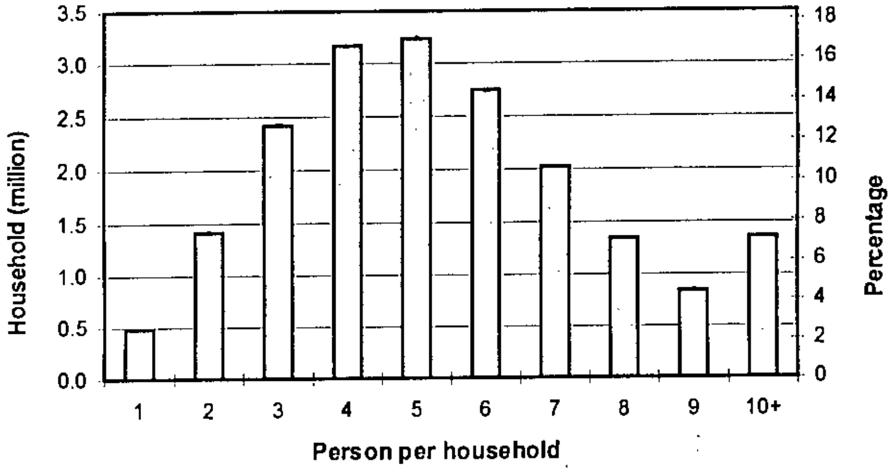


Figure 4.4: Distribution of households by persons per household.

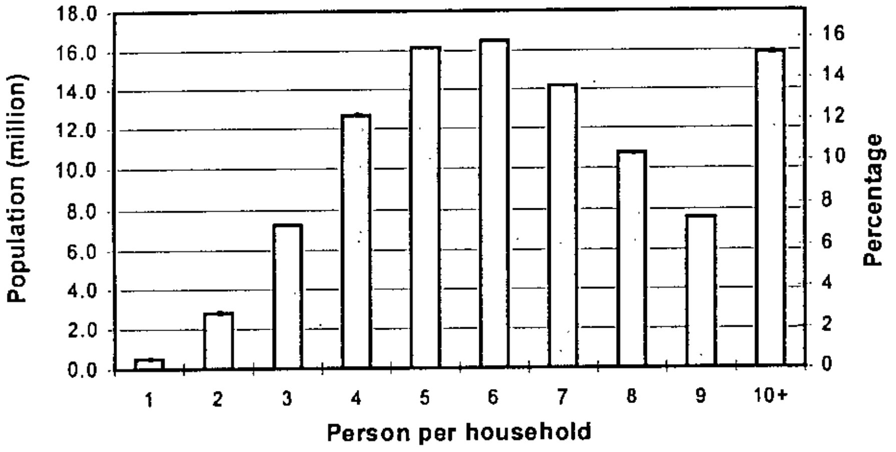
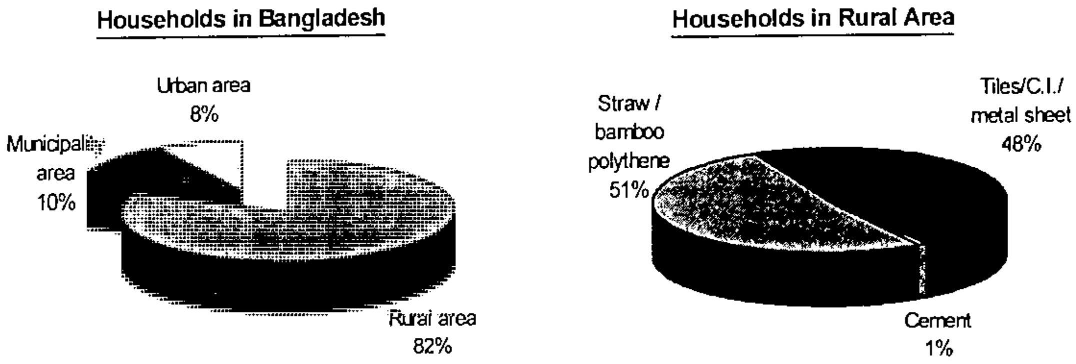


Figure 4.5: Distribution of population by persons per household.

4.7 ROOFING MATERIALS IN BANGLADESH

Based on the population census of 1991 (Table 2.9), a pie chart is shown in figure 4.6 to describe the percentage of different roofing materials for rural areas. It is seen that about 82% of the total households are located in rural areas. Among these, 48% of the households have tiles, C.I./metal sheet as roofing materials which are very suitable as roof catchment area. However, BBS reported in 1995 that 58% of the households in rural areas have tiles, C.I./metal sheet. This shows that the number of households having roofs of tiles, C.I./metal sheet are increasing, which is an advantage for rainwater harvesting.



Households in Bangladesh

Households in Rural Area

Figure 4.6: Dwelling households by materials of roof.

4.8 SELECTION OF A PROBABILITY DISTRIBUTION FOR ANNUAL RAINFALL DATA

Annual rainfall data are used to determine the reliability of rainwater option as the source of drinking water for a particular area. For the calculation of reliability the data need to be fitted with a probability distribution. Two types of probability distributions were applied on the observed data, i.e., the Normal Distribution and Log-normal Distribution. To determine the appropriate probability distribution for the data for a particular station, annual rainfall data of 31 years (1965-1995) were plotted on normal and log-normal probability paper. Figures 4.7 and 4.8 show the annual rainfall of Dhaka, plotted as normal and log-normal probability with corresponding R^2 values. The calculation for Dhaka is shown in Appendix C.

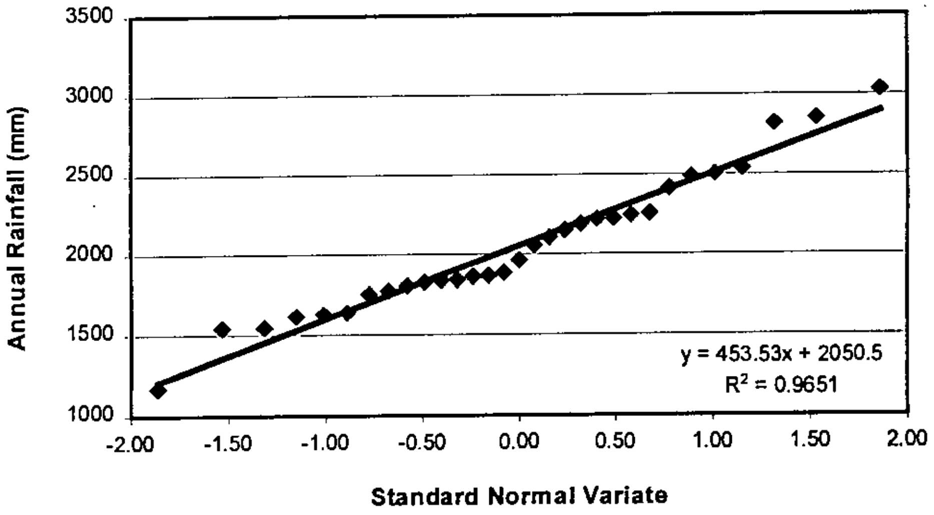


Figure 4.7: Annual rainfall plotted for normal probability (1965-1995).

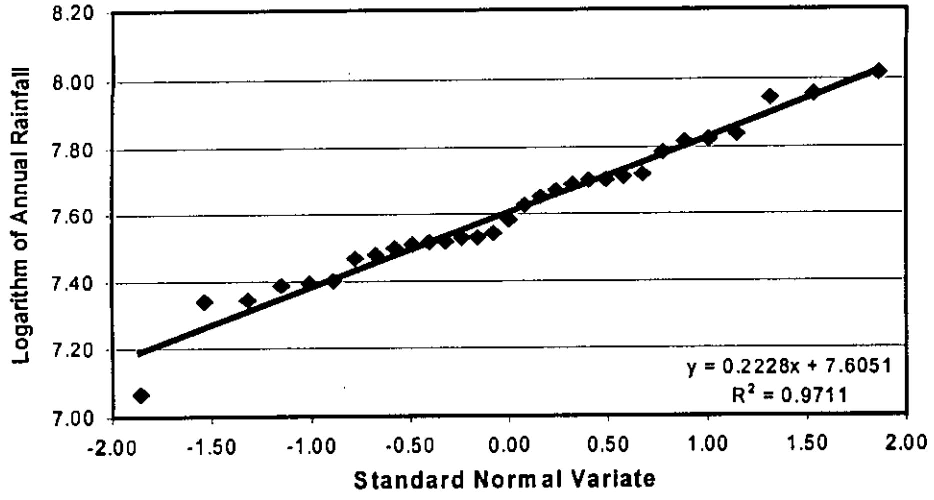


Figure 4.8: Logarithm of annual rainfall plotted for log-normal probability (1965-1995).

From the R^2 values of 0.9651 (normal distribution) and 0.9711 (log-normal distribution) from Figures 4.7 and 4.8, it appears that log-normal distribution is more appropriate for the annual rainfall distribution of Dhaka. The goodness-of-fit can also be verified by a statistical test i.e. the chi-square test. The best fit probability distribution of annual rainfall for different stations with corresponding R^2 and chi-square test values are shown in Table 4.3. Chi-square test calculations are done at the significance level $\alpha = 5\%$. Chi-square test calculations for Dhaka are shown in appendix D.

Table 4.3: Values of R^2 and chi-square test for annual rainfall data (mm) of different stations.

Sl. No.	*Station*	*R^2-value*		*Chi-square test*		*Suitable distribution*
		Normal	*Log-normal*	*Normal*	*Log-normal*	
1	Barisal	0.9733	0.9417	4.76	7.50	Normal
2	Bhola	0.9532	0.8263	6.79	22.43	Normal
3	Bogra	0.9538	0.8184	10.07	22.89	Normal
4	Chandpur	0.9079	0.9579	12.06	4.29	Log-normal
5	Chittagong	0.9187	0.9051	5.90	6.12	Normal
6	Comilla	0.9565	0.8711	8.56	18.76	Normal
7	Cox's Bazar	0.9164	0.7923	3.40	4.66	Normal
8	Dhaka	0.9651	0.9711	7.13	6.11	Log-normal
9	Dinajpur	0.9035	0.8631	8.75	11.64	Normal
10	Faridpur	0.9736	0.9821	6.32	5.31	Log-normal
11	Feni	0.9808	0.9317	4.45	8.59	Normal
12	Hatia	0.8643	0.6485	16.93	50.03	Normal
13	Ishurdi	0.9355	0.9792	15.96	8.76	Log-normal
14	Jessore	0.9838	0.9651	2.27	2.33	Normal
15	Khepupara	0.9404	0.9610	6.47	5.81	Log-normal
16	Khulna	0.8508	0.9167	62.16	12.84	Log-normal
17	Mymensingh	0.9790	0.9534	4.66	5.45	Normal
18	Rajshahi	0.9754	0.8686	4.10	10.45	Normal
19	Rangamati	0.8694	0.8701	19.45	8.58	Log-normal
20	Rangpur	0.9666	0.9459	4.01	6.55	Normal
21	Sandwip	0.9448	0.8707	4.83	8.50	Normal
22	Satkhira	0.9625	0.8463	4.25	20.26	Normal
23	Sitakunda	0.9091	0.7009	6.86	9.15	Normal
24	Srimangal	0.9744	0.9316	3.31	5.95	Normal
25	Sylhet	0.9626	0.9122	6.58	9.46	Normal

Chi-square test value, $c_{.95,6} = 12.6$

4.9 CALCULATION OF RELIABILITY

Reliability of rainwater as a source of water for a particular area is completely dependent on the rainfall distribution of that area, per capita consumption, household size and above all the catchment area. Reliability is calculated from the best fit annual rainfall distribution by considering different consumption rates with different household sizes for different catchment areas. To make it more realistic, it was assumed that the demand can vary within a variation limit of 10%. The calculation of reliability for a household size of 6 persons with 3 lpcd (liter per capita per day) consumption rate (for drinking water) for a roof size of 30 m^2 is shown in Appendix E for Dhaka. Figure 4.9 shows the variation of reliability for different household sizes with different consumption rates for a particular catchment area of 30m^2 at Dhaka. At the same time Figure 4.10 shows the effect of the catchment size for different levels of demand at Dhaka. Figures for other places are shown in Appendix F.

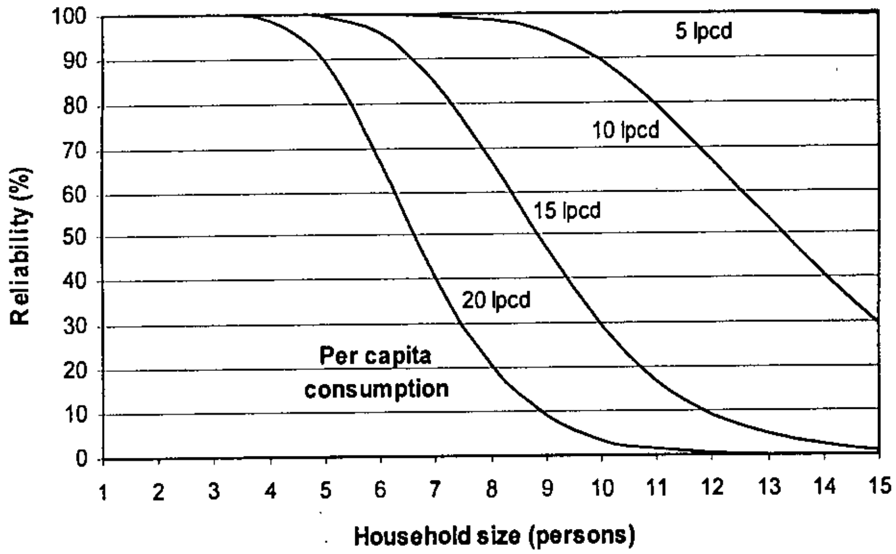


Figure 4.9: Relationship between reliability and household size for different consumption rates at Dhaka.

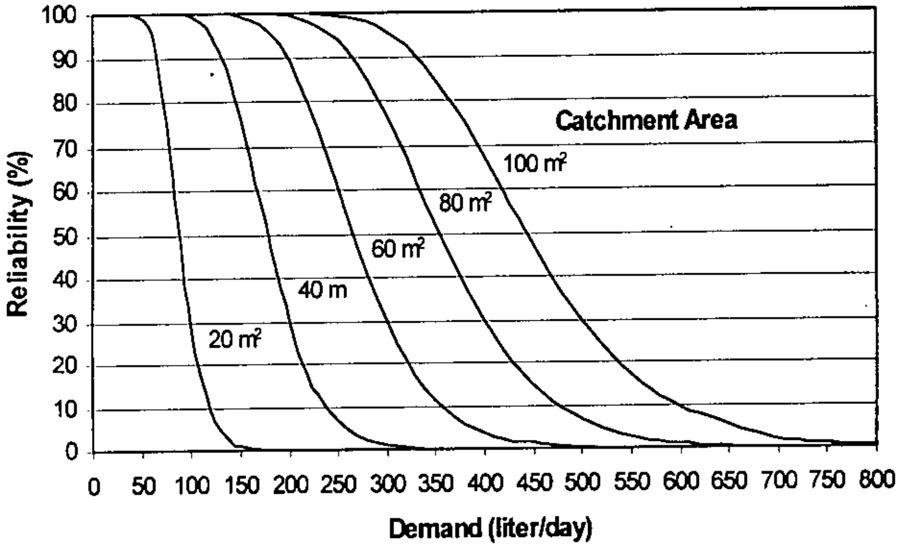


Figure 4.10: Rclationship between reliability and demand for different catchment areas at Dhaka.

4.10 MASS CURVE ANALYSIS FOR REQUIRED STORAGE VOLUME

As storage volumes calculated by mass curve method gives more accurate result (Ferdausi, 1999), storage volumes of 25 locations (as shown in Figure 4.1) were calculated, using the 21 years rainfall data (1975-95). The calculation is based on the technique described in section 3.4. The mass curve analysis for Dhaka is shown in Appendix G. The following assumptions were made for this calculation.

- The family size is 6.
- The demand is 3 liter per capita per day.
- The demand is the same for every month of the year.
- The demand is constant from year to year.
- The rainfall pattern in future will be similar.
- The runoff coefficient is 0.75 (explained in section 4.11).
- The evaporation from the roof and the tank is included in the runoff co-efficient.

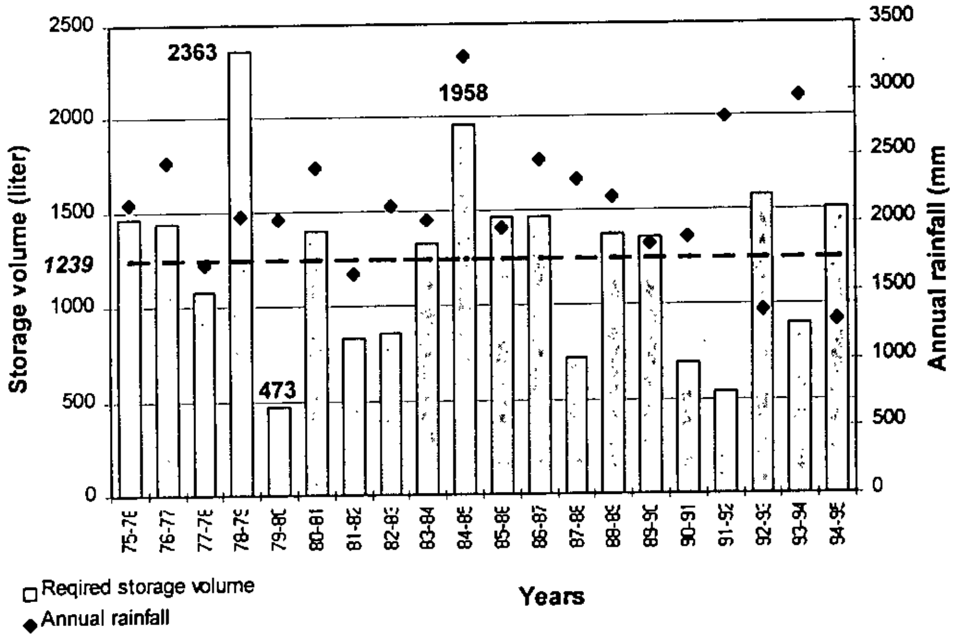
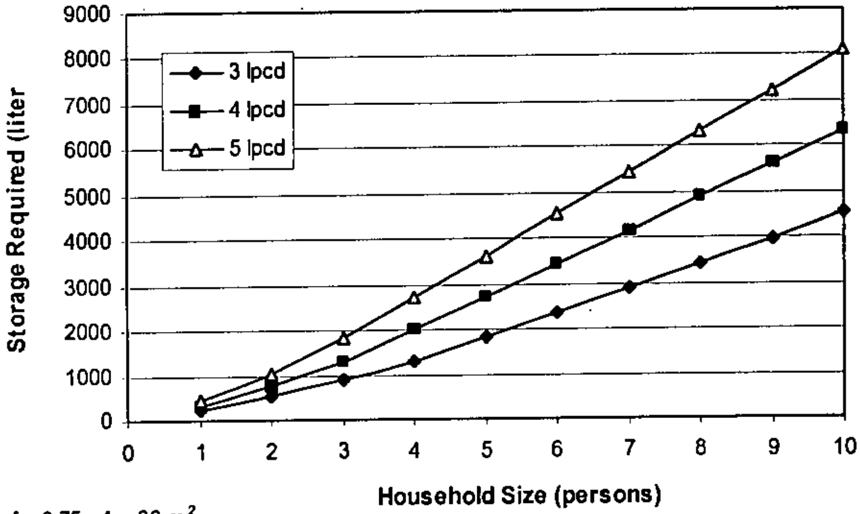


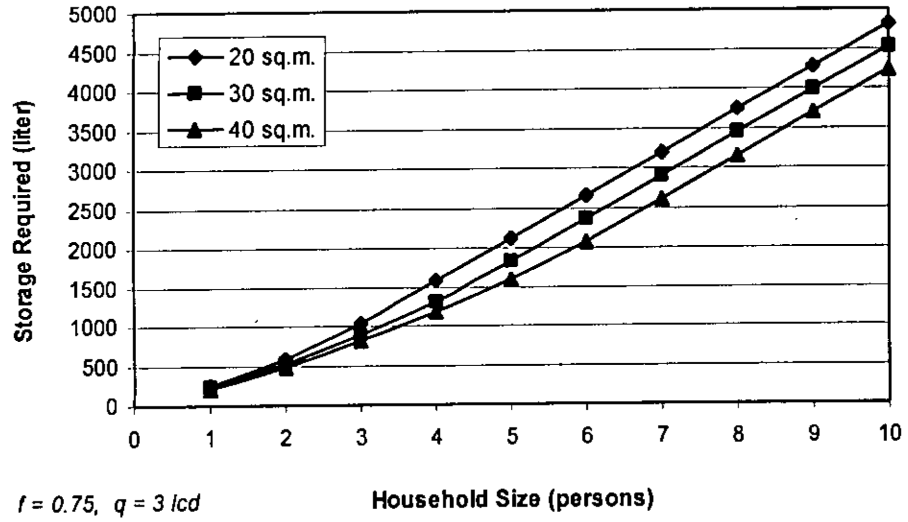
Figure 4.11: Storage volume requirement for different years for Dhaka.

The storage volume required for different years with a given annual rainfall are shown in Figure 4.11. From the figure it is observed that the maximum storage volume required is 2363 liters for the year 1978-79. According to the mass curve analysis this is considered as the design volume. The minimum storage volume is 473 liters for the year 1979-80. It is interesting to note that maximum and minimum storage volumes do not coincide with minimum and maximum annual rainfall. The required storage volume depends not upon the total amount of rainfall, but upon the monthly rainfall distribution over the year, especially during the dry months. It is seen that the average required storage volume is 1239 liters. If the maximum value (2363 liters) is ignored, which means that shortage of storage capacity is accepted for once every twenty years, the second largest storage volume of 1958 liters for the year of 1984-85 can be considered as the design volume. This will reduce the tank size with almost 17% of its original size and makes the system less expensive. For this reason the concept of degree of security is introduced in the Section 4.13.



$f = 0.75$, $A = 30\, m^2$

Figure 4.12: Storage volume and household size relationship for different consumption rates at Dhaka.



$f = 0.75$, $q = 3$ lcd

Figure 4.13: Storage volume and household size relationship for different catchment areas at Dhaka.

Figures 4.12 and 4.13 show the variation of storage volumes for different consumption rates and catchment areas for Dhaka. From Figure 4.13, it is seen that the storage volume curves for different catchment sizes become parallel when the household size exceeds more than 4 persons per household and maintain a constant difference of storage volume of 193 liters. It can be concluded that the storage volume requirement for Dhaka decreases 19 liters for an increase of every m^2 of catchment area when household size is more than 4 persons per household. Storage volume-demand relationships for different roof areas for different places are shown in Appendix H.

4.11 SELECTION OF A COMMON RUNOFF COEFFICIENT

In Section 3.3, the runoff coefficient for different catchment areas has been presented. From Section 4.7 it is seen that mainly three types of roofs exist. For roofs with tiles, C.I./metal sheets and cement, the runoff coefficient $f = 0.80$ can be used. For roofs made of straw/bamboo covered with polythene, the runoff coefficient can be $f = 0.70$. Figure 4.14 shows the effect of these coefficients with an average value of $f = 0.75$ for Dhaka for a consumption rate of 3 liter/capita/day.

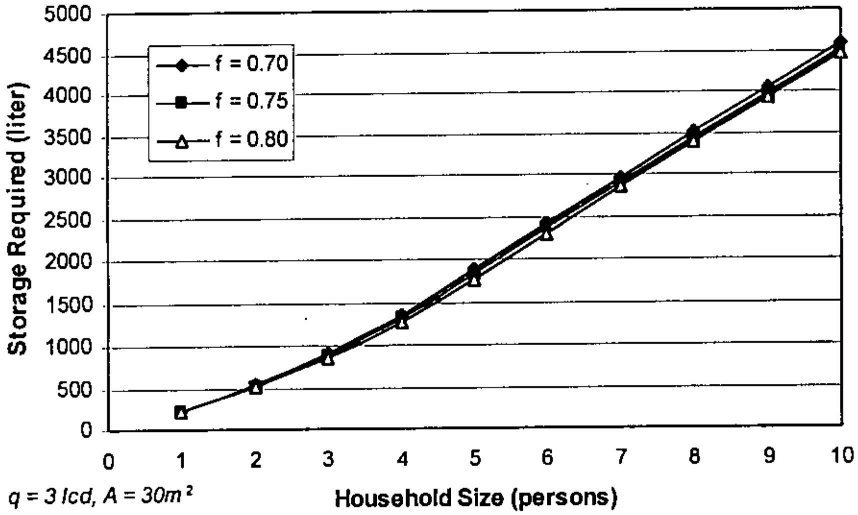


Figure 4.14: Effect of runoff coefficients (roofs) for Dhaka.

From the Figure 4.14, it can be concluded that the effect of different runoff coefficients is relatively small. So an average value of f = 0.75 can be used for all calculations of storage volume requirements.

4.12 SELECTION OF A PROBABILITY DISTRIBUTION FOR STORAGE VOLUMES CALCULATION

The required storage volumes calculated for different years from the mass curve analysis are tested to fit in the normal and log-normal distribution as in Section 4.8 for different years. Storage volumes for different years are plotted on a normal and log-normal probability paper. Figures 4.15 and 4.16 show the required storage volumes for 20 years (from 1975-76 to 1994-95) for 6 consumers of Dhaka with a consumption rate of 3 liter/capita/day for 30 m^2 of catchment area on a normal and log-normal paper. Calculations are shown in Appendix I.

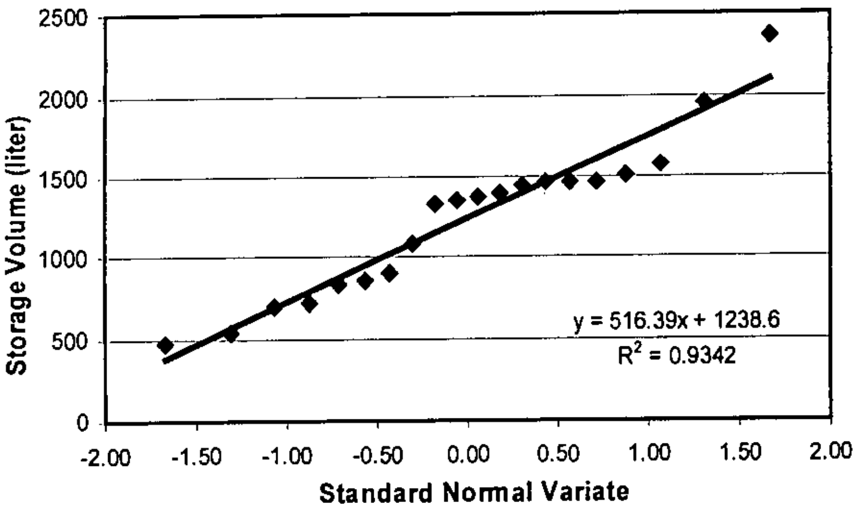


Figure 4.15: Required storage volume plotted on normal probability paper.

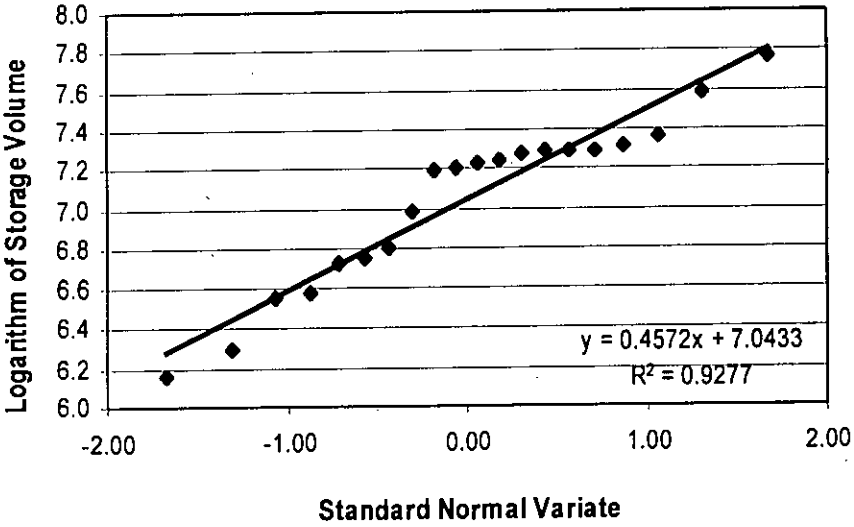


Figure 4.16: Logarithm of required storage volumes plotted on log-normal probability paper.

From the R^2 values of 0.9342 (normal distribution) and 0.9277 (log-normal distribution) from Figures 4.15 and 4.16, it appears that the normal distribution is more appropriate for the required storage volume distribution of Dhaka. The goodness-of-fit can also be verified by the chi-square test. In Appendix J, Chi-square test calculation is done at the significance level $\alpha = 5\%$ and the test results for the normal and log-normal distributions are 13.90 and 16.59 respectively, where the Chi-square value is 16.90. In this case normal distribution should be used for the probability (degree of security) calculation.

4.13 CALCULATION OF DEGREES OF SECURITY

As described in Section 4.10 (Figure 4.11), the design storage volume for 6 consumers with a drinking water consumption rate of 3 lpcd at Dhaka by mass curve analysis is 2363 liters. This is also the maximum required storage volume. The average required storage volume is 1239 liters. If the value of the maximum storage volume (2363 liters) is ignored, which means that shortage of storage capacity is allowed once in every twenty years (90%), the second largest value of storage volume of 1958 liters can be used as the design volume. This will reduce the storage volume and will make the system less expensive. For this reason, the concept of degree of security is introduced with statistical analysis for designing the storage volume. Attempts have been made to establish security levels with the help of the probability distribution. Figure 4.17 shows the degree of security for different storage volumes for 6 consumers (3 lpcd, 30 m^2 catchment area) at Dhaka. Calculations are shown in Appendix K.

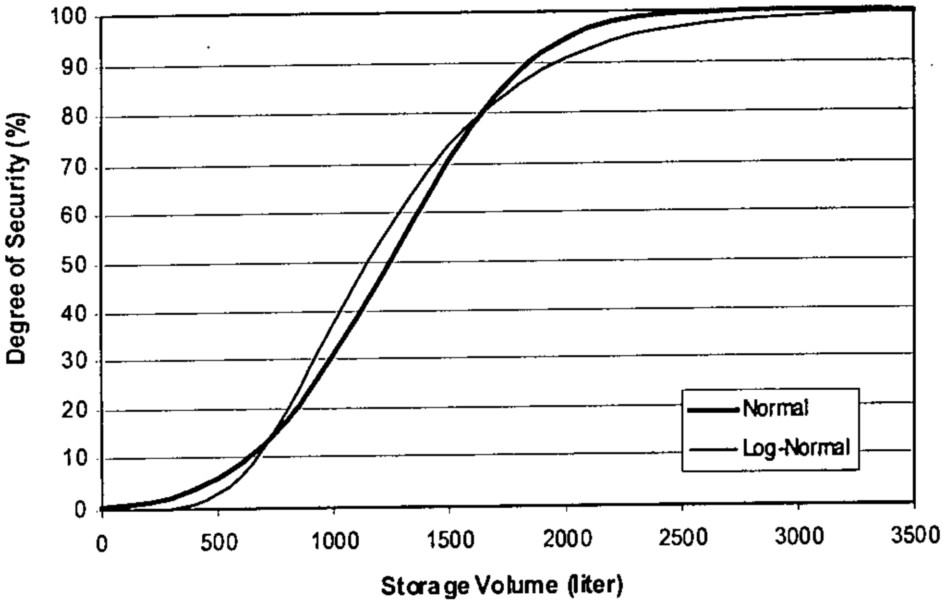


Figure 4.17: Degree of security for different storage volumes for Dhaka.

Figure 4.17 shows that the storage volumes for a degree of security of 99%, 90% and 80% are 2346, 1849 and 1639 liters respectively. Allowing a shortage of storage volume once in every ten years, the tank volume can be reduced to 1849 liters from 2346 liters, which is a reduction of almost 22% of its original requirement. This reduction will be more significant for the reservoirs with higher demands. This can be concluded from Figure 4.18, where storage volumes for different consumers are plotted, taking into account different degrees of security.

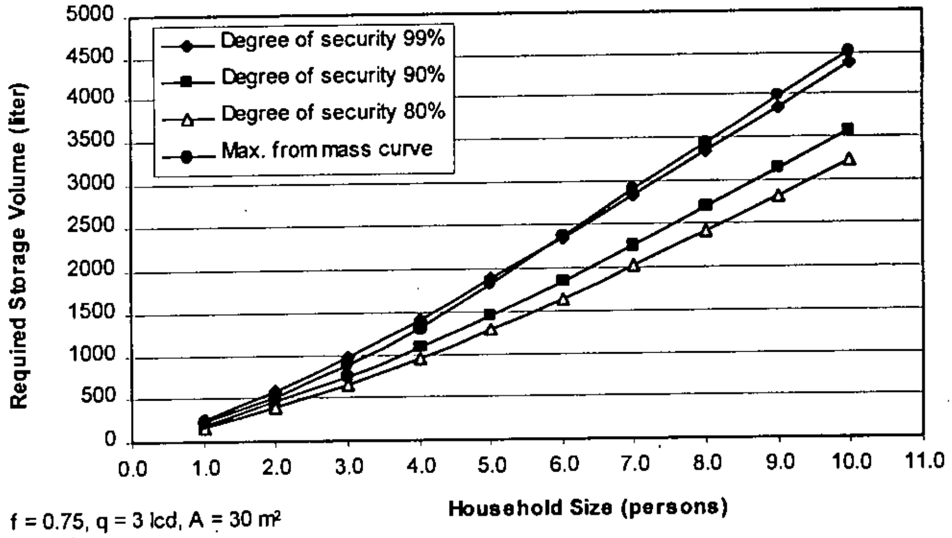


Figure 4.18: Storage volumes for different degrees of security levels for Dhaka.

4.14 COST OF STORAGE TANKS

As rainwater harvesting is a new approach for Bangladesh, there is not much data available regarding the material and construction cost for storage tanks. Moreover costs vary for different types of storage tanks. On the basis of Section 2.6, an attempt has been made to establish a relationship between cost and storage volume. Data from Table 2.4 and Table 2.6 are plotted in Figure 4.19 to establish an equation. As the system is more focused on the rural area, expensive options like ferrocement wire-framed tank and brick reinforcement tank are disregarded. Though this relationship will not be very accurate, still it will be very helpful to give an idea regarding the costs.

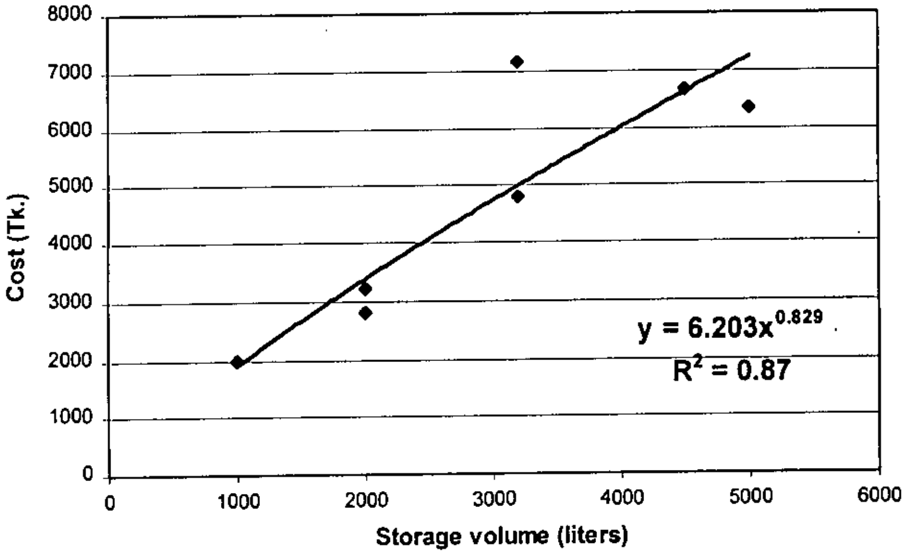


Figure 4.19: Cost-storage volume relationship for Bangladesh.

CHAPTER FIVE

RESULTS AND DISCUSSIONS

5.1 INTRODUCTION

In this chapter monthly rainfall patterns for different places of Bangladesh are examined to have an idea about the rainfall distribution of that area. Results of frequency analysis of annual rainfall data are presented for further reliability calculations. Reliability charts are presented to show the reliability of the rainwater harvesting system for drinking purposes for different places of Bangladesh. Generalized curves are developed as well to measure the reliability of the system for different purposes. A chart for required storage volumes for drinking water collection for different places is presented for an average catchment area to study the feasibility of the rainwater harvesting system in a financial context. Design curves are developed to determine required storage volumes for drinking requirement with different degrees of security. Generalized design curves are also developed to determine storage volumes for different consumption purposes.

5.2 MONTHLY RAINFALL PATTERNS IN BANGLADESH

From Figure 4.3 and Appendix B, it can be concluded that the average monthly rainfall distributions for individual places do not vary much compared to the average monthly rainfall distribution for the whole country. These figures also show that the heavy rainfall only concentrates from April/May to October when an adequate quantity of rainwater is available. The rainfall from November to February/March is inadequate to meet the demand during the dry period. But it is possible to recuperate this shortage by storing water during the rainy season. Rainwater has to be stored during rainy seasons, so that it can be used throughout the year.

5.3 FREQUENCY ANALYSIS OF ANNUAL RAINFALL DATA

Two types of frequency distributions – Normal and Log-normal – are undertaken on the annual rainfall data in this study. On the basis of a graphical comparison (R^2 value of Figure 4.7 and 4.8, Appendix C, and Table 4.3) and the Chi-square test (Table 4.3), normal distribution is found to be the more appropriate distribution for annual rainfall analysis in Bangladesh. Among 25 stations, annual rainfall data of 18 stations satisfy the normal probability distribution, and annual rainfall data of the remaining 7 stations satisfy the log-normal distribution. In general, normal distribution is more appropriate, but calculations for reliability are done on the basis of the best fit distribution for every station to obtain more accurate results.

5.4 RELIABILITY OF THE RAINWATER HARVESTING SYSTEM FOR DRINKING PURPOSE

For the calculation of the reliability of the rainwater harvesting system as a source of drinking water, some common parameters have been chosen. In a limited field survey in Chuadanga, it is seen that the maximum number of households with a metal sheet roof have a roof area within 40 to 60 m^2 (Ferdausi, 1999). Considering a safety margin, it was assumed that the average roof area for households in village areas varies between $20m^2$ to $30m^2$. Based on a survey conducted by the government of Thailand, the minimum requirement for drinking water alone is 4 liters per person per day (UNDP-World Bank, 1990). For Bangladesh it is assumed to be 3 liters per person per day. The drinking water demand is not constant throughout the year. It is assumed to be more during the dry season than during the winter season. So a variation level of 10% for drinking water is considered in the reliability calculation. Reliabilities (in percentage) of the rainwater harvesting system for different places for the consumption rate of 3 lpcd and 4 lpcd with 20 m^2 and 30 m^2 of catchment area are presented through Table 5.1 to 5.4.

Table 5.1: Reliability of the rainwater harvesting system for different household sizes for a consumption rate of 3 lpcd with a catchment area of 20 m^2.

Sl. No.	*Station*	*Household Size (person)*									
		1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
1	Barisal	100.00	100.00	100.00	100.00	100.00	99.99	99.99	99.97	99.95	99.91
2	Bhola	99.99	99.99	99.98	99.98	99.96	99.94	99.91	99.87	99.81	99.72
3	Bogra	99.98	99.97	99.95	99.92	99.86	99.78	99.65	99.46	99.17	98.77
4	Chandpur	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
5	Chittagong	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.99
6	Comilla	100.00	99.98	99.96	99.94	99.90	99.85	99.77	99.65	99.48	99.24
7	Cox's Bazar	100.00	100.00	99.99	99.99	99.99	99.99	99.98	99.97	99.96	99.95
8	Dhaka	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
9	Dinajpur	99.90	99.86	99.79	99.69	99.56	99.38	99.14	98.81	98.38	97.82
10	Faridpur	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.99
11	Feni	100.00	100.00	99.99	99.99	99.99	99.98	99.97	99.96	99.95	99.93
12	Hatia	99.99	99.99	99.98	99.97	99.96	99.94	99.92	99.89	99.85	99.80
13	Ishurdi	100.00	100.00	100.00	100.00	100.00	100.00	99.99	99.96	99.86	99.60
14	Jessore	100.00	100.00	100.00	99.99	99.98	99.97	99.93	99.86	99.74	99.51
15	Khepupara	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
16	Khulna	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.98	99.92	99.77
17	Mymensingh	99.98	99.97	99.95	99.93	99.90	99.86	99.80	99.72	99.62	99.47
18	Rajshahi	99.92	99.86	99.76	99.60	99.36	98.99	98.46	97.70	96.65	95.23
19	Rangamati	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.99	99.96
20	Rangpur	99.97	99.95	99.93	99.89	99.84	99.77	99.67	99.54	99.36	99.12
21	Sandwip	100.00	100.00	100.00	100.00	100.00	100.00	99.99	99.99	99.98	99.98
22	Satkhira	100.00	99.99	99.99	99.98	99.95	99.91	99.84	99.71	99.51	99.18
23	Sitakunda	99.73	99.67	99.60	99.52	99.42	99.30	99.17	99.00	98.82	98.60
24	Srimangal	99.97	99.96	99.94	99.92	99.89	99.85	99.80	99.73	99.64	99.52
25	Sylhet	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Min. Reliability		*99.73*	*99.67*	*99.60*	*99.52*	*99.36*	*98.99*	*98.46*	*97.70*	*96.65*	*95.23*

Table 5.2: Reliability of the rainwater harvesting system for different household sizes for a consumption rate of 3 lpcd with a catchment area of 30 m^2.

Sl. No.	*Station*	*Household Size (person)*									
		1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
1	Barisal	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.99	99.99
2	Bhola	99.99	99.99	99.99	99.99	99.98	99.98	99.97	99.96	99.94	99.92
3	Bogra	99.99	99.98	99.97	99.96	99.94	99.92	99.88	99.84	99.78	99.70
4	Chandpur	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
5	Chittagong	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
6	Comilla	99.99	99.98	99.98	99.97	99.96	99.94	99.92	99.89	99.85	99.80
7	Cox's Bazar	100.00	100.00	100.00	100.00	99.99	99.99	99.99	99.99	99.99	99.98
8	Dhaka	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
9	Dinajpur	99.92	99.89	99.86	99.81	99.76	99.69	99.61	99.51	99.38	99.23
10	Faridpur	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
11	Feni	100.00	100.00	100.00	100.00	99.99	99.99	99.99	99.99	99.98	99.98
12	Hatia	99.99	99.99	99.99	99.98	99.98	99.97	99.96	99.96	99.94	99.93
13	Ishurdi	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
14	Jessore	100.00	100.00	100.00	100.00	100.00	99.99	99.99	99.98	99.97	99.95
15	Khepupara	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
16	Khulna	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
17	Mymensingh	99.98	99.98	99.97	99.96	99.95	99.93	99.92	99.89	990.86	99.83
18	Rajshahi	99.93	99.90	99.86	99.79	99.71	99.60	99.45	99.25	98.99	98.66
19	Rangamati	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
20	Rangpur	99.97	99.96	99.95	99.94	99.92	99.89	99.86	99.82	99.77	99.71
21	Sandwip	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.99
22	Satkhira	100.00	100.00	99.99	99.99	99.98	99.98	99.96	99.94	99.91	99.87
23	Sitakunda	99.75	99.71	99.67	99.63	99.58	99.52	99.46	99.38	99.30	99.21
24	Srimangal	99.97	99.97	99.96	99.95	99.94	99.92	99.90	99.88	99.85	99.82
25	Sylhet	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Min. Reliability		*99.75*	*99.71*	*99.67*	*99.63*	*99.58*	*99.52*	*99.45*	*99.25*	*98.99*	*98.66*

Table.5.3: Reliability of the rainwater harvesting system for different household sizes for a consumption rate of 4 lpcd with a catchment area of 20 m^2.

Sl. No.	*Station*	*Household Size (person)*									
		1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
1	Barisal	100.00	100.00	100.00	100.00	99.99	99.97	99.94	99.88	99.75	99.52
2	Bhola	99.99	99.99	99.98	99.96	99.92	99.87	99.78	99.64	99.43	99.11
3	Bogra	99.98	99.96	99.92	99.84	99.70	99.46	99.06	98.41	97.44	96.00
4	Chandpur	100.00	100.00	100.00	100.00	100.00	100.00	99.99	99.95	99.83	99.51
5	Chittagong	100.00	100.00	100.00	100.00	100.00	100.00	99.99	99.99	99.98	99.96
6	Comilla	99.98	99.97	99.94	99.89	99.80	99.65	99.41	99.03	98.45	97.60
7	Cox's Bazar	100.00	100.00	99.99	99.99	99.98	99.97	99.96	99.94	99.91	99.88
8	Dhaka	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.98
9	Dinajpur	99.89	99.81	99.69	99.51	99.23	98.81	98.21	97.36	96.22	94.69
10	Faridpur	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.97	99.86	99.52
11	Feni	100.00	100.00	99.99	99.99	99.98	99.96	99.94	99.91	99.86	99.79
12	Hatia	99.99	99.98	99.97	99.96	99.93	99.84	99.84	99.76	99.64	99.48
13	Ishurdi	100.00	100.00	100.00	100.00	100.00	99.96	99.80	99.26	97.97	95.54
14	Jessore	100.00	100.00	99.99	99.98	99.95	99.86	99.68	99.28	98.52	97.17
15	Khepupara	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
16	Khulna	100.00	100.00	100.00	100.00	100.00	99.98	99.88	99.57	98.82	97.36
17	Mymensingh	99.98	99.96	99.93	99.89	99.82	99.72	99.57	99.35	99.03	98.58
18	Rajshahi	99.90	99.79	99.60	99.25	98.66	97.70	96.22	94.04	91.00	86.97
19	Rangamati	100.00	100.00	100.00	100.00	100.00	100.00	99.98	99.93	99.81	99.53
20	Rangpur	99.96	99.94	99.89	99.82	99.71	99.54	99.29	98.92	98.39	97.66
21	Sandwip	100.00	100.00	100.00	100.00	99.99	99.99	99.98	99.97	99.96	99.93
22	Satkhira	100.00	99.99	99.98	99.94	99.87	99.71	99.41	98.86	97.91	96.37
23	Sitakunda	99.71	99.63	99.52	99.38	99.21	99.00	98.75	98.43	99.06	97.60
24	Srimangal	99.97	99.95	99.92	99.88	99.82	99.73	99.60	99.42	99.18	98.85
25	Sylhet	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Min. Reliability		*99.71*	*99.63*	*99.52*	*99.25*	*98.66*	*97.70*	*96.22*	*94.04*	*91.00*	*86.97*

Table 5.4: Reliability of the rainwater harvesting system for different household sizes for a consumption rate of 4 lpcd with a catchment area of 30 m^2.

Sl. No.	*Station*	*Household Size (person)*									
		1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
1	Barisal	100.00	100.00	100.00	100.00	100.00	100.00	99.99	99.98	99.97	99.96
2	Bhola	99.99	99.99	99.99	99.98	99.97	99.96	99.94	99.91	99.87	99.82
3	Bogra	99.98	99.97	99.96	99.93	99.90	99.84	99.76	99.63	99.46	99.21
4	Chandpur	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
5	Chittagong	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
6	Comilla	99.99	99.98	99.97	99.95	99.93	99.89	99.84	99.76	99.65	99.50
7	Cox's Bazar	100.00	100.00	100.00	99.99	99.99	99.99	99.98	99.98	99.97	99.96
8	Dhaka	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
9	Dinajpur	99.91	99.87	99.81	99.74	99.64	99.51	99.33	99.10	98.81	98.43
10	Faridpur	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
11	Feni	100.00	100.00	100.00	99.99	99.99	99.99	99.98	99.97	99.96	99.95
12	Hatia	99.99	99.99	99.98	99.98	99.97	99.96	99.94	99.92	99.89	99.86
13	Ishurdi	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.99	99.96	99.88
14	Jessore	100.00	100.00	100.00	100.00	99.99	99.98	99.96	99.93	99.86	99.76
15	Khepupara	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
16	Khulna	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.99	99.98	99.93
17	Mymensingh	99.98	99.97	99.96	99.94	99.92	99.89	99.85	99.80	99.72	99.63
18	Rajshahi	99.92	99.87	99.79	99.68	99.50	99.25	99.89	99.39	99.70	96.78
19	Rangamati	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.99
20	Rangpur	99.97	99.95	99.94	99.91	99.87	99.82	99.76	99.63	99.46	99.21
21	Sandwip	100.00	100.00	100.00	100.00	100.00	100.00	99.99	99.99	99.99	99.99
22	Satkhira	100.00	100.00	99.99	99.98	99.97	99.94	99.90	99.83	99.71	99.54
23	Sitakunda	99.74	99.69	99.63	99.56	99.48	99.38	99.27	99.15	99.00	99.84
24	Srimangal	99.97	99.96	99.95	99.93	99.91	99.88	99.84	99.79	99.73	99.65
25	Sylhet	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Min. Reliability		*99.74*	*99.69*	*99.63*	*99.56*	*99.48*	*99.25*	*99.27*	*99.10*	*98.81*	*96.78*

From Tables 5.1 to 5.4, the minimum reliabilities are 95.23%, 98.66%, 86.97% and 96.78% respectively. All these minimum values are for the household size of 10 persons for Rajshahi, confirm to Section 4.5 (Figure 2.5), ranking that Rajshahi (Zone I) has the minimum annual rainfall. Except the reliability for 4 lpcd with a catchment area of 20 m^2 (86.97%), all are more than 90%, which indicates the suitability of a rainwater harvesting system for Bangladesh. Even for Rajshahi, if the catchment area is increased to 22 m^2 for the consumption rate of 4 lpcd, it will become a reliable water source (90.68%). It is mentioned in section 4.7 that 67% of the total population has a household size in between 4 to 8 persons with an average of 6 persons. Tables 5.1 to 5.4 show that the minimum reliabilities for the household size of 6 persons are 98.99%, 99.52%, 97.70% and 99.25% respectively, which is quite high. So rainwater harvesting appears to be a reliable source of drinking water.

5.5 DEVELOPMENT OF A GENERAL RELIABILITY-DEMAND CURVE

Section 4.9 shows that the reliability of the rainwater harvesting system as a source of water for a particular area is completely dependent on the rainfall distribution of that area, per capita consumption, household size and the catchment area. The reliability of a rainwater harvesting system for different places for drinking purpose has presented in Tables 5.1 to 5.4. These do not represent the reliability of the system for other demands like cooking, bathing, washing etc. In this section an attempt has been made to develop a general reliability curve which will enable to determine the reliability of the rainwater harvesting system for a particular area for different ratios of demand and catchment area. The advantage of the ratio of demand and catchment area is that the reliability can be measured from the curve for any combination of demand and catchment area. This type of general reliability curve for Dhaka is shown in Figure 5.1. Calculations are shown in Appendix L. General reliability curves for other places are presented in Appendix M.

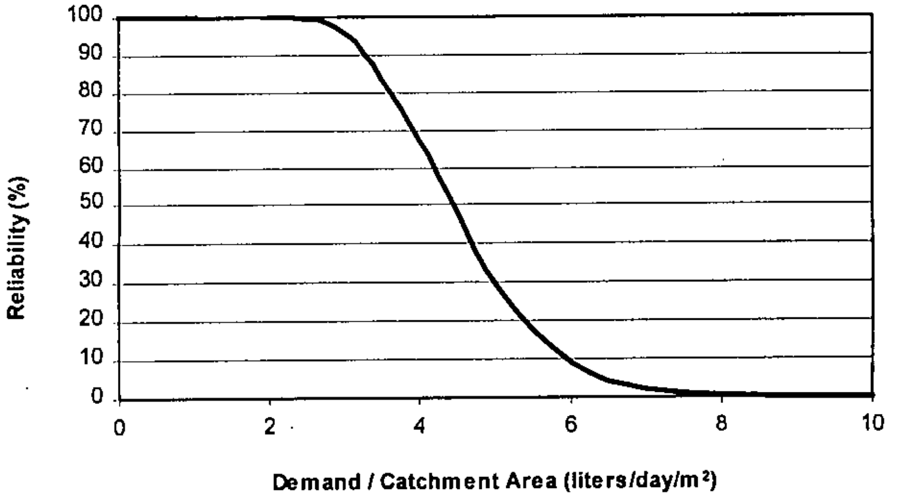


Figure 5.1: General reliability demand curve for Dhaka.

On the basis of Section 4.5 (Table 4.2) and Appendix L, reliabilities for different places are averaged within seven zones and presented in Figure 5.2. It is seen from the graph that for a given demand-catchment area ratio, reliability increases with the increase of zone numbers, which is very obvious. As for example, for a fixed demand-catchment ratio of 3, a rainwater harvesting system of Rajshahi (Zone I) is 53% reliable, whereas the rainwater harvesting system of Sylhet and Cox's Bazar (Zone II) is 98% reliable. That means, while the system of Rajshahi has the chance to fail almost 5 years out of 10 years, the system for Sylhet and Cox's Bazar have almost no chance to fail. This also proves the reality that for a fixed demand with a fixed catchment area, the rainwater harvesting system can not be improved with increasing the storage capacity, unless otherwise the catchment area is increased.

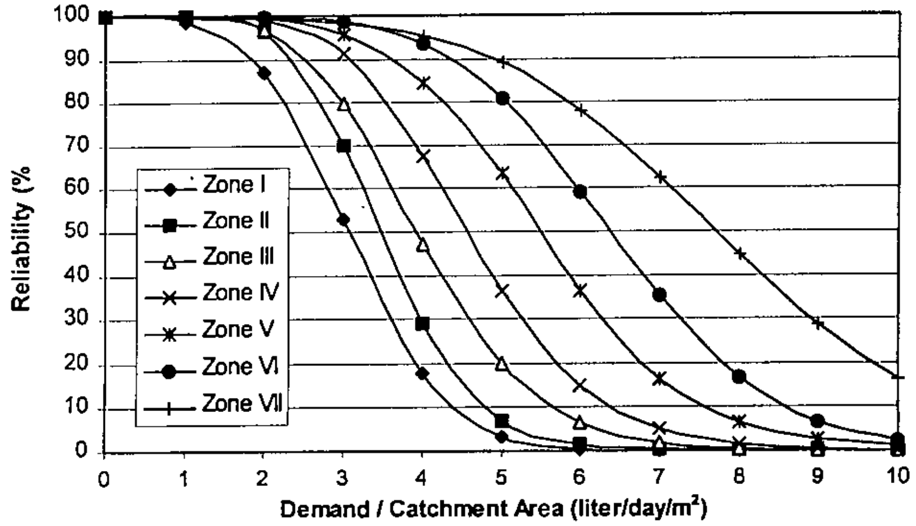


Figure 5.2: General reliability demand curves for different zones.

5.6 DEVELOPMENT OF A DESIGN CURVE FOR REQUIRED STORAGE VOLUMES FOR DIFFERENT DEGREES OF SECURITY

From Figures 4.12 and 4.13, it can be concluded that the required storage volume calculated from the mass curve analysis depends on household size, consumption rate and catchment area. A small reduction (Section 4.13) of the security level (10%) can reduce the required storage volume to a considerable amount which makes the system less costly. Figure 4.18 shows the required storage volumes for drinking water for different household sizes for different degrees of security for a catchment area of 30 m^2. An attempt was made to develop a more generalized design curve which people can use to design their storage tank for drinking water purposes for their roof size, taking into account different degrees of security. Figure 5.3 shows the general design curve for drinking water for Dhaka. General curves for other places are shown in Appendix N.

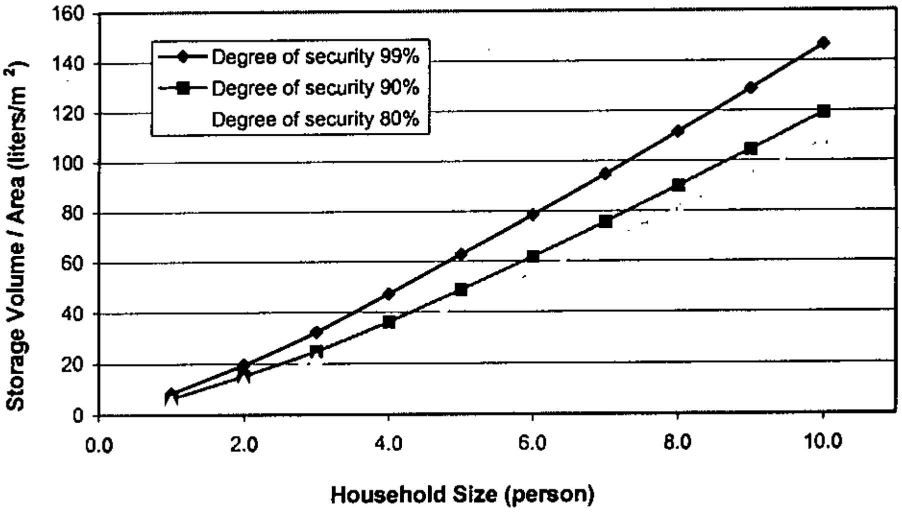


Figure 5.3: Design curve for required storage volumes for drinking water with different degrees of security for Dhaka.

5.7 DEVELOPMENT OF A GENERALIZED DESIGN CURVE FOR ALL PURPOSES

A design curve (Figure 5.3) was developed on the basis of the demand for drinking water. As adequate rainwater is available in Bangladesh, storage volumes can be designed also for other demands like cooking, bathing, washing etc. To serve this purpose a generalized design curve has been developed for different demands with different catchment areas. Figure 5.4 shows the generalized design curve for Dhaka. Generalized curves for other locations are shown in Appendix O.

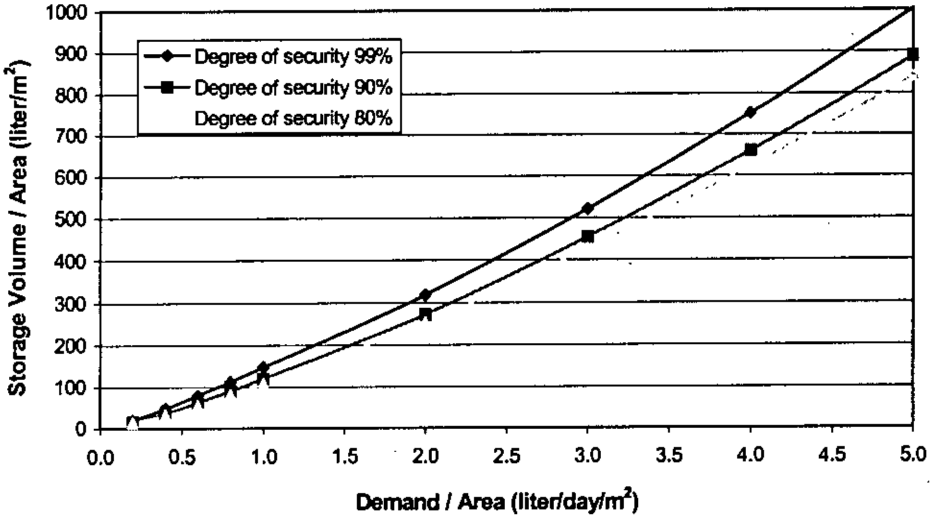


Figure 5.4: Generalized design curve for required storage volumes for Dhaka.

5.8 USE OF DIFFERENT DESIGN CHARTS AND CURVES

Considering a family of 6 persons in Barisal with a roof size of 30 m^2, the reliability and the required storage volumes will be determined mainly for drinking water by using the design charts and curves. Possibilities for other uses will be examined too.

Reliability

First of all, it should be checked whether the rainwater harvesting system will serve the demands of this family for drinking water, and for drinking and other purposes considering the rainwater distribution of Barisal. It is assumed that the consumption rate for drinking water is 3 liters per capita per day. From Table 5.2, it can be determined that the reliability of the rainwater harvesting system for 6 persons with a consumption rate of 3 lpcd for a catchment area of 30 m^2 at Barisal is 100%.

If a consumption rate of 20 lpcd (120 liter/day for the family) is considered for cooking and some washing in addition to drinking water, the reliability is approximately 65% (Appendix M, Figure M.1) for a demand-area ration of 4 liters/day/m^2 (120 liters per day / 30 m^2). The rainwater harvesting system will cover only 65% of the demand.

Required Storage Volume

The required storage volume for drinking water is shown in Appendix N. Figure N.1 shows the storage volume-area ratios for 6 persons: 83, 47 and 44 for 99%, 90% and 80% of security respectively. The storage volumes needed are 2,490, 1,410 and 1,320 liters respectively for a catchment area of 30 m^2. If a storage tank of 1,410 liters will be constructed for this family instead of 2,490 liters, the tank volume will be insufficient once in every ten years. But this will make the system less costly.

In case the consumption rate is 20 lpcd, the storage volume-area ratios are 790, 700 and 670 (liter/m^2) for 99%, 90% and 80% security respectively for a demand-area ratio of 4 liter/day/m^2 (Appendix O, Figure O.1). The required storage volumes will be 23,700, 21,000 and 20,100 liters respectively. By increasing the catchment area to 60 m^2, these volumes can be reduced to 19,200, 18,000 and 15,600 liters respectively.

5.9 EFFECTS OF DEGREE OF SECURITY UPON COST OF STORAGE TANKS.

In Section 4.14, an equation was developed to estimate the cost of different storage tanks. Section 4.13 shows how to make the system less costly with degree of security approach. Here, in Figure 5.5, an attempt has been made to observe the effect of degree of security upon cost of storage tanks for drinking purposes at Dhaka. It is seen that for a household size of 10 persons, a rainwater system with 99% security will cost around Tk. 6,650, where as a system with 90% security will cost Tk. 5,470.

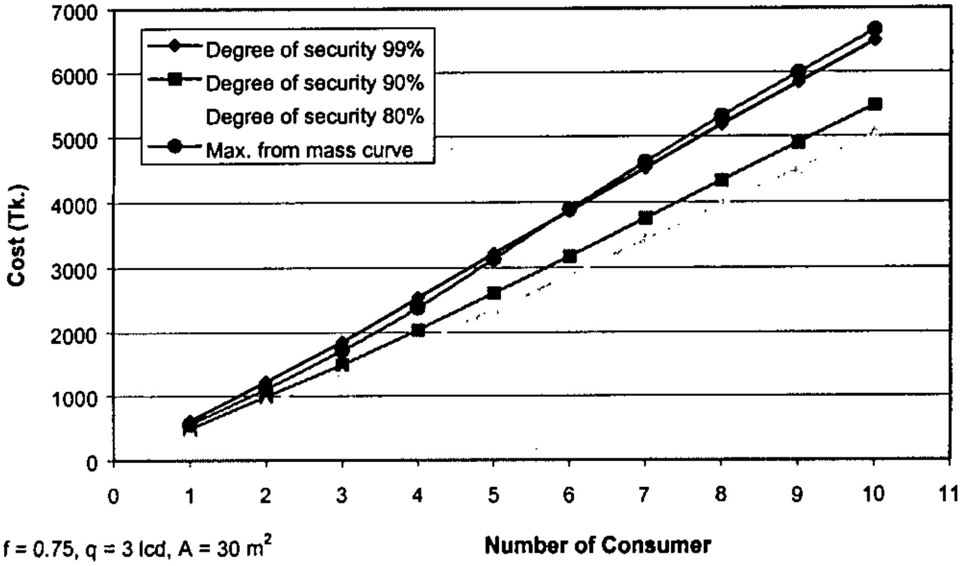


Figure 5.5: Effect of degree of security upon cost for storage tanks for Dhaka.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

The rainwater harvesting in rural Bangladesh seems a viable alternative drinking water source. There is adequate rainfall during the rainy season distributed from April/May to October. It appears that the average yearly rainfall in the country during 1975-95 is 2426 mm ranging from 1797 to 2867 mm. This means 1.80 to 2.87 m^3 of rainwater was available per m^2 of catchment area each year for development of a rainwater based water supply system. There is a regional variation of rainfall. The distribution shows that relatively higher rainfall occurs in the eastern part of the country and highest rainfall occurs in the north-eastern region and eastern part of the coastal area.

For statistical analysis, two types of frequency distributions- normal and log-normal were undertaken on the annual rainfall data. Normal distribution was found to be the more appropriate distribution for annual rainfall distribution of these stations. It is very important to identify the reliability of the rainwater harvesting system for a particular place prior to implementing it. If the source has relatively less reliability for a demand-catchment area ratio, increase of the tank capacity will not help it unless the roof area is increased, which is not always an easy option.

Reliability calculation for drinking water shows that the minimum reliability for drinking water is at Rajshahi, which confirms its position in Zone I (rainfall<1500 mm). Average reliability of each zone also shows that reliability increases with the increase of zone no.

In designing a rainwater harvesting system, the monthly rainfall has more significance than the average yearly rainfall. It is observed that the storage volume completely depends on monthly rainfall distribution over the year, especially during the dry months. It is also observed that due to high storage volume requirement for one or two dry years, the storage volume requirement can become high, which ultimately make the system expensive. To eliminate this problem, attempts have been made to establish security levels with the help of the probability distribution. It was observed that allowing some shortage in storage capacity can reduce the storage volume and make the system less expensive.

For storage volume calculations, rainfall distribution has more effect than the total amount of rainfall. It is also observed that the required storage volumes calculated by the mass curve analysis for different runoff coefficients (for roofs with metal sheet and bamboo covered with polythene) do not show significant differences.

The water quality of rainwater is very high and the stored water quality is also very satisfactory when proper attention is taken. This water is free from two extreme contaminants i.e., arsenic and fecal coliform (with due care). The major advantage of the rooftop rainwater harvesting system is that the system is independent and suitable for scattered settlements. Each household can use their own separate water storage system. It is very convenient for the users especially for the women to collect water from their house premises. It saves the time of collecting water from a distance source. As the system is household based, strong community cohesion is not a very prerequisite factor for rainwater harvesting.

The operation of the rainwater harvesting is easier than any other water supply system. No specialized skills are necessary to operate the system. It does not require any pumping device to abstract the water. The system also requires very little maintenance work. The maintenance work is mainly cleaning the catchment area, gutters, down-pipe, storage tank etc. The storage tank can require plastering or other maintenance work, normally once in five years if the storage tank is constructed properly.

The success of the rainwater harvesting system depends on the interest, enthusiasm and active support of the users. Groundwater is the major source of water supply for nearly two decades in Bangladesh. People may have negative attitudes towards rainwater. The rainwater harvesting program can only be implemented when people have the willingness to use the system. Failure to involve the community in the planning, design, siting and construction of the rainwater harvesting system is commonly a cause of failure of the system in many countries.

One of the important steps towards achieving a successful and suitable rainwater harvesting system is to create awareness of the technology among its potential users. This can be achieved through mass media, workshop and grass root level formal and informal meetings.

The community must be involved in the planning, design, siting and construction of the rainwater harvesting. Women should be consulted about the technologies and implementation strategies and their involvement must be ensured in the program.

Training activities are required both at the project management and at the community level. The training will be towards program sustainability, community involvement, design procedure, site selection, construction of system, operation and maintenance of the system.

6.2 RECOMMENDATIONS

In this study, all the analysis were done based on rainfall data of 25 stations of BMD which cover whole Bangladesh, but are not very evenly distributed for the whole country. It would be better if analysis could be done based upon the rainfall data of the 294 stations of BWDB in addition to the BMD stations, specially for calculating missing data and required storage volume. It would also be easier to find out the borderline of the different zones for rainwater distribution with denser gauge stations.

In general the quality of rainwater is quite high. But research can be done to monitor the water quality on a regular basis to detect the effect of time on stored water.

In Chapter 2, different types of storage tanks are discussed which are used in other countries. Research can be done to find out the most suitable water tank for Bangladesh. Their performances can be monitored for a long time. Construction of different storage tanks will also give an idea about the real cost of storage tanks in Bangladesh.

The average catchment area was assumed to be between 20 m^2 and 30 m^2. A survey can be done in different places to find a more logical average catchment area.

A survey work can be done to determine the acceptance of low mineral rainwater compared to other water. Because of lack of dissolved minerals, rainwater is tasteless for drinking purposes.

Above all, in this study, charts and curves are developed for designing rainwater storage tanks based upon statistical analysis of past rainfall data. Validity of these procedures can be judged by observing the performance of real storage tanks designed by these methods.

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Appendix A: CALCULATION OF MISSING DATA OF MONTHLY RAINFALL OF DHAKA

Table A.1: Calculation for Normal Ratios.

Year	*Dhaka*	*Faridpur*		*Chadpur*		*Comilla*	
	Annual rainfall (mm)	*Annual rainfall (mm)*	*Ratio*	*Annual rainfall (mm)*	*Ratio*	*Annual rainfall (mm)*	*Ratio*
1975	2145					1813	1.18
1976	2238					1965	1.14
1977	1861					2125	0.88
1978	2251						
1979	1837					1461	1.26
1980	2218	2072	1.07			2093	1.06
1981	1865			2801	0.67	2198	0.85
1982	1805	1410	1.28	3224	0.56	2185	0.83
1983		2251		3681		2286	
1984	3028	2544	1.19	3772	0.80	2439	1.24
1985	2053	1482	1.39	2662	0.77	1641	1.25
1986	2500	2319	1.08	2069	1.21	1992	1.26
1987	2187	1993	1.10				
1988	2482	2183	1.14	1964	1.26	2249	1.10
1989	1627	1438	1.13	1527	1.07	1439	1.13
1990	2103	1985	1.06	1956	1.08	2211	0.95
1991	2850	2156	1.32	2346	1.21	2914	0.98
1992	1169	1336	0.88	1349	0.87	1240	0.94
1993	2819	2256	1.25	2276	1.24	2864	0.98
1994	1540	1344	1.15	1572	0.98	1384	1.11
1995	1751	2006	0.87	2009	0.87	2102	0.83
Average			1.14		0.97		1.05

Table A.2: Calculation for Missing Data.

Month	*Faridpur*	*Chadpur*	*Comilla*	*Missing Data*
Jan, 1983	4	10	14	10
Nov, 1983	0	56	17	24

Appendix B: AVERAGE MONTHLY RAINFALL DISTRIBUTION FOR DIFFERENT PLACES OF BANGLADESH

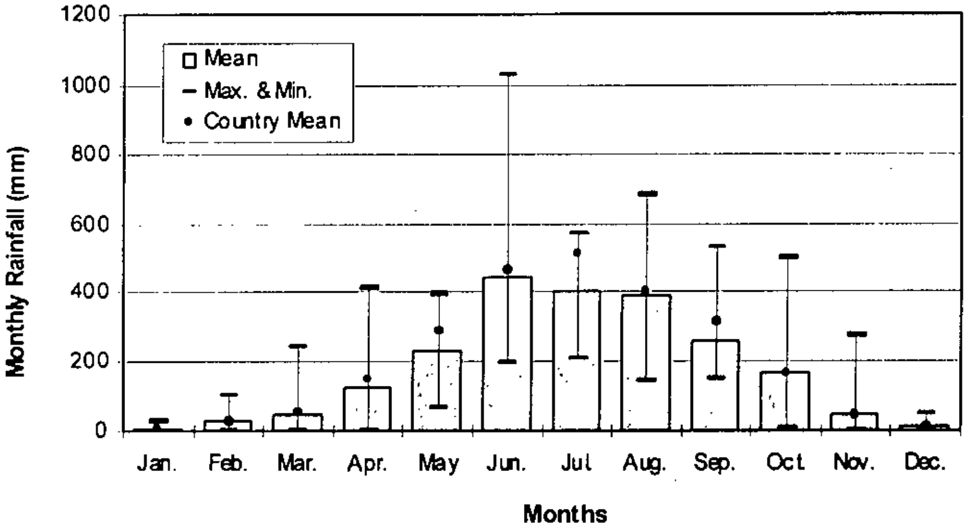

Figure B.1: Average monthly rainfall distribution for Barisal (1975-1995).

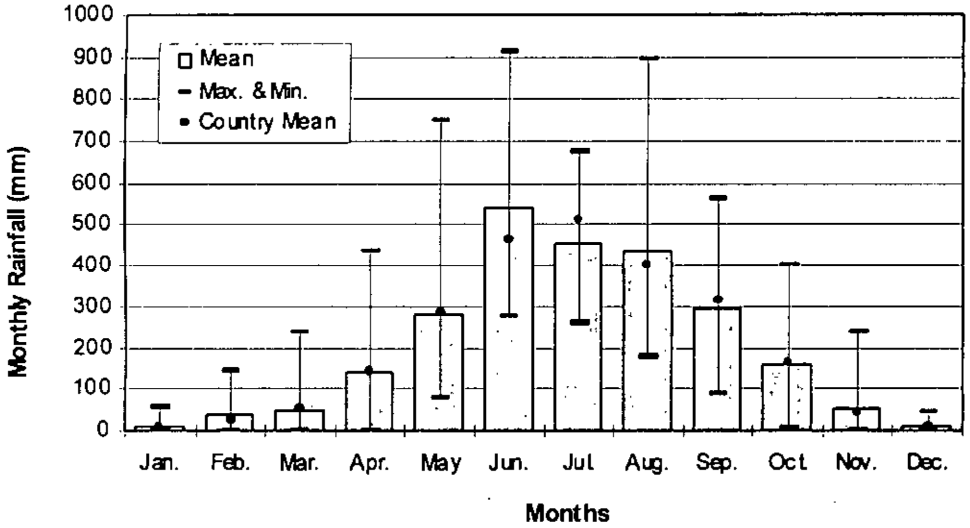

Figure B.2: Average monthly rainfall distribution for Bhola (1975-1995).

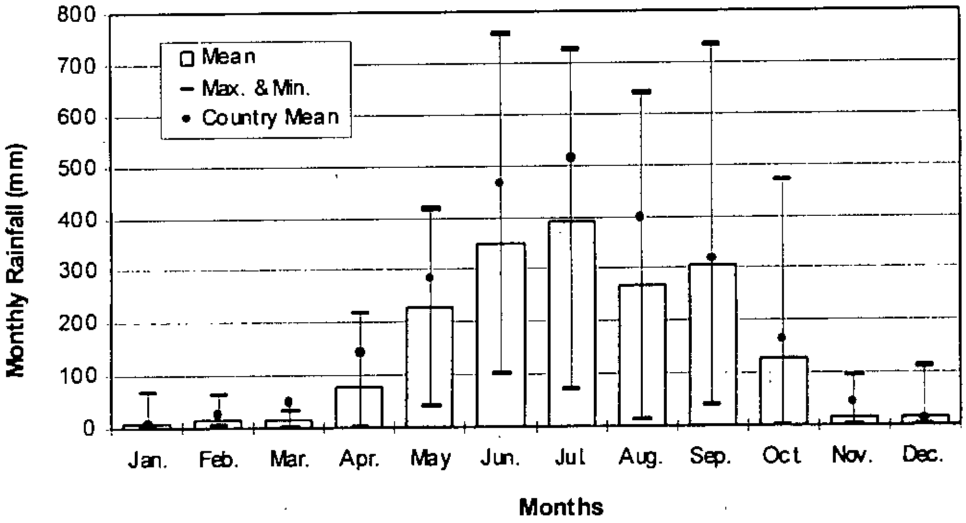

Figure B.3: Average monthly rainfall distribution for Bogra (1975-1995).

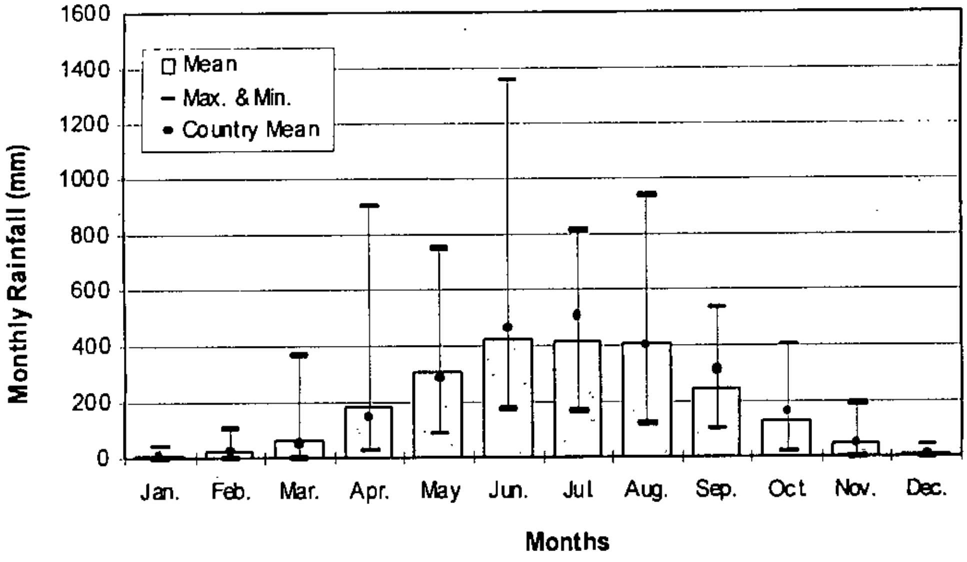

Figure B.4: Average monthly rainfall distribution for Chandpur (1975-1995).

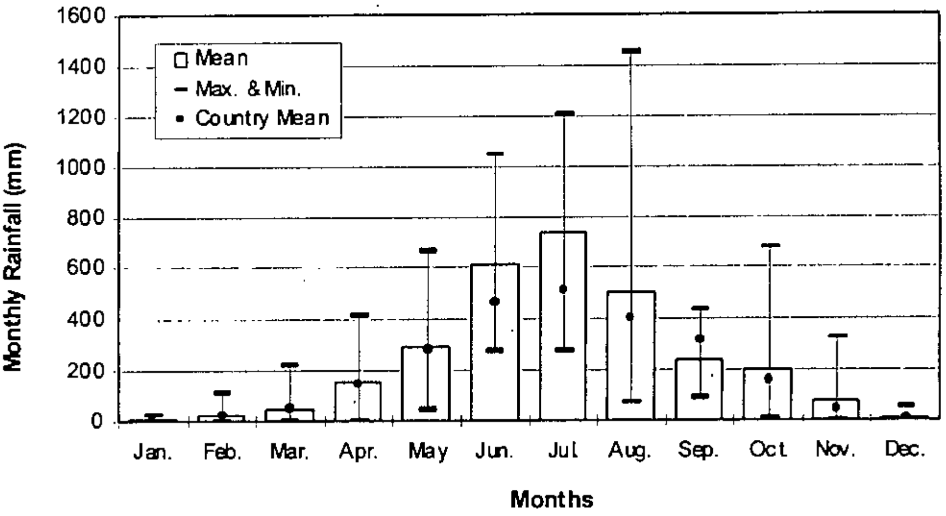

Figure B.5: Average monthly rainfall distribution for Chittagong (1975-1995).

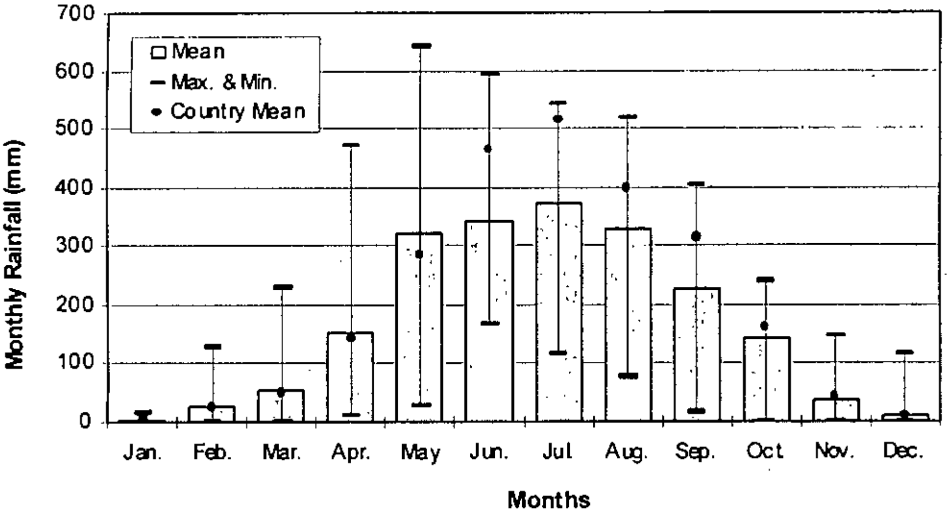

Figure B.6: Average monthly rainfall distribution for Comilla (1975-1995).

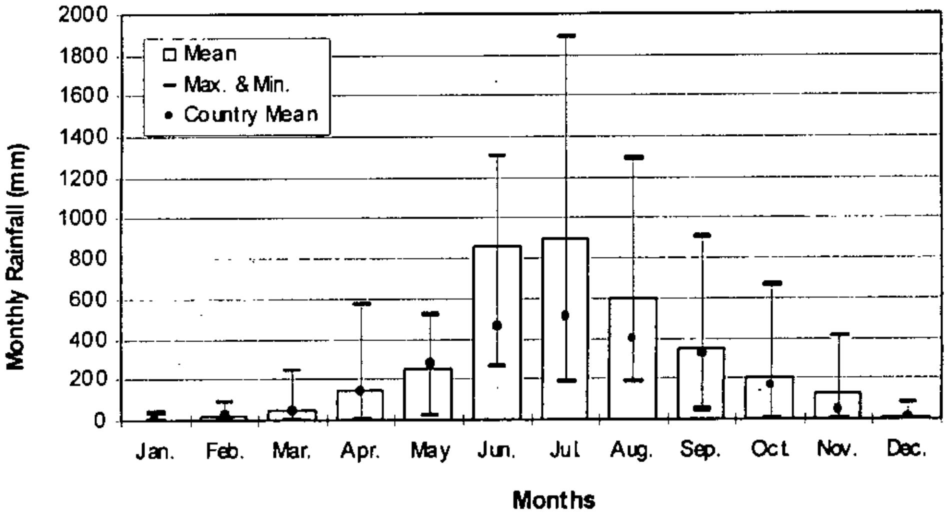

Figure B.7: Average monthly rainfall distribution for Cox's Bazar (1975-1995).

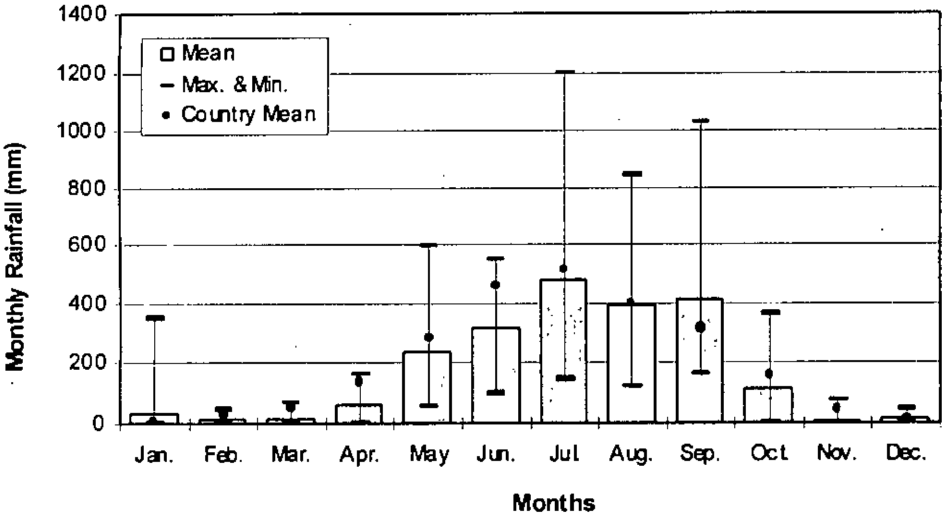

Figure B.8: Average monthly rainfall distribution for Dinajpur (1975-1995).

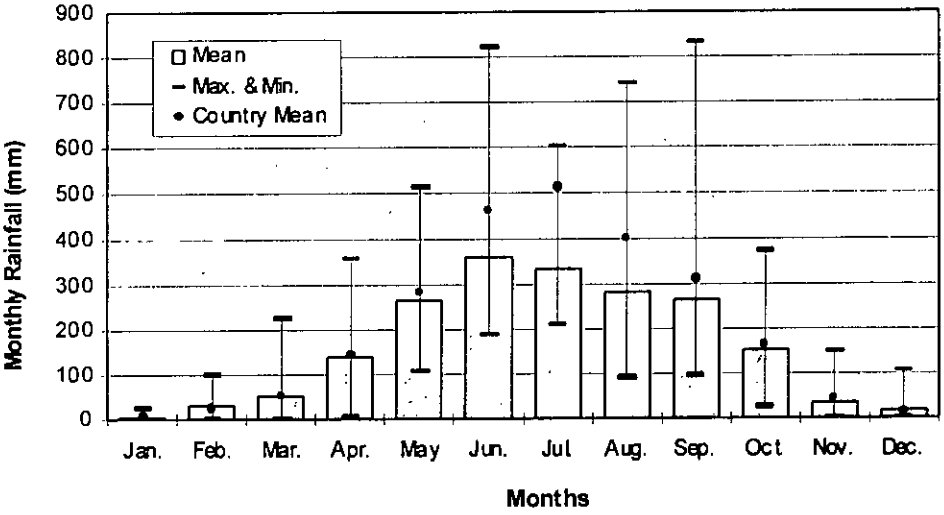

Figure B.9: Average monthly rainfall distribution for Faridpur (1975-1995).

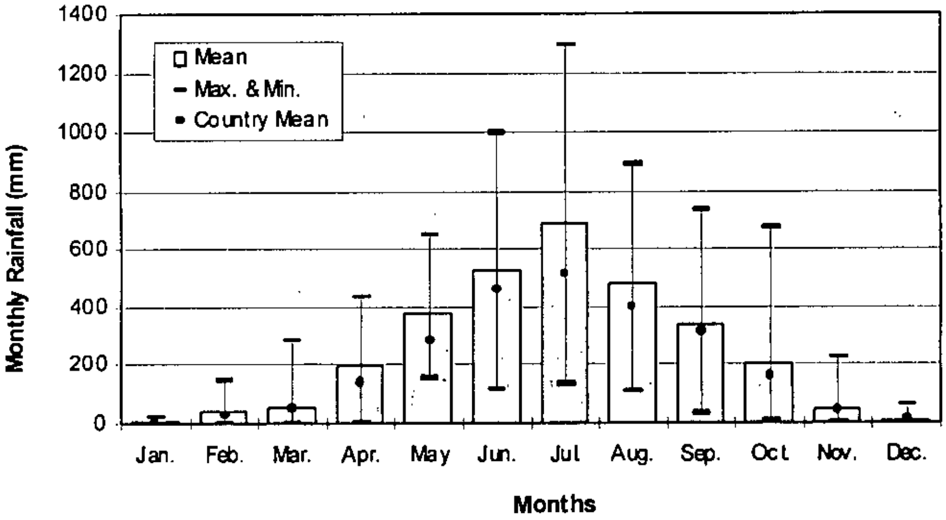

Figure B.10: Average monthly rainfall distribution for Feni (1975-1995).

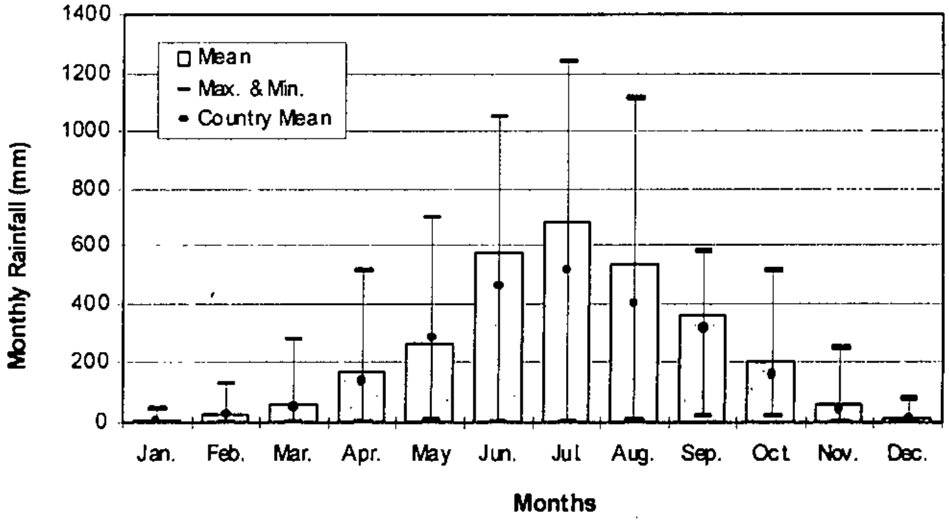

Figure B.11: Average monthly rainfall distribution for Hatiya (1975-1995).

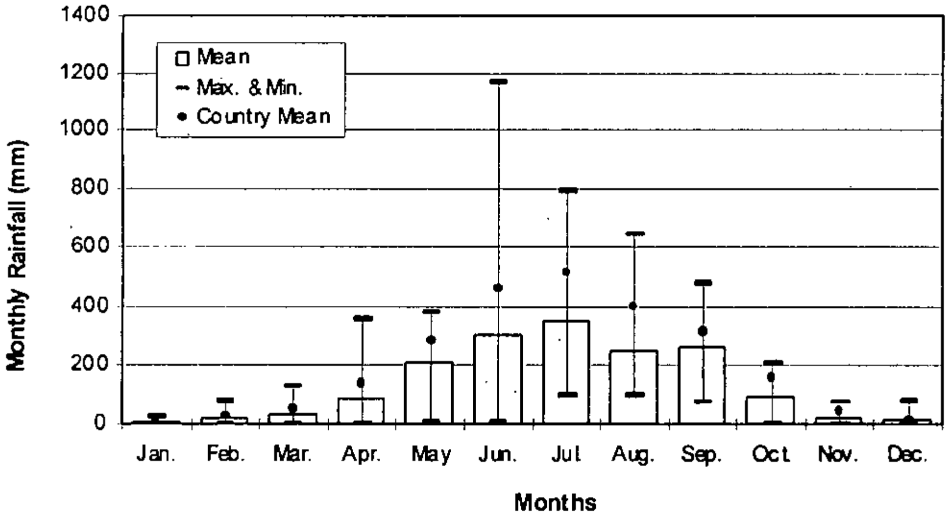

Figure B.12: Average monthly rainfall distribution for Ishurdi (1975-1995).

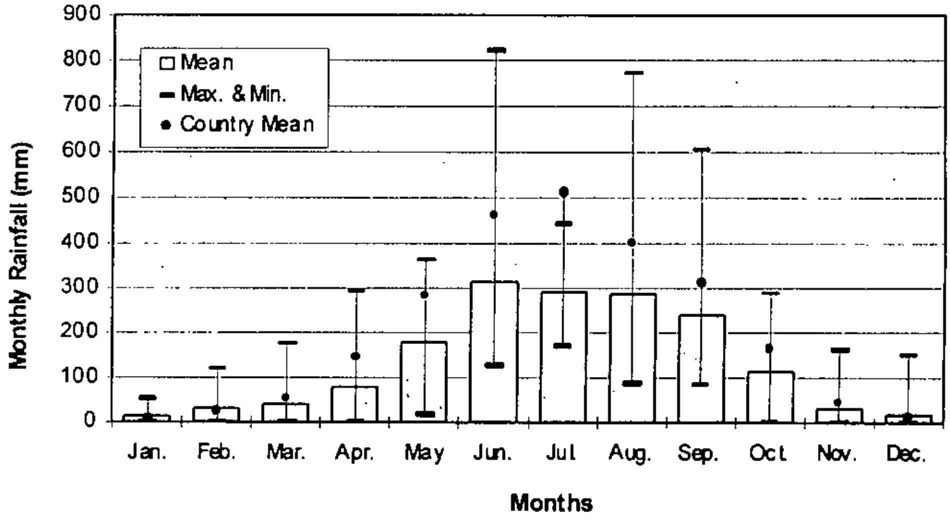

Figure B.13: Average monthly rainfall distribution for Jessore (1975-1995).

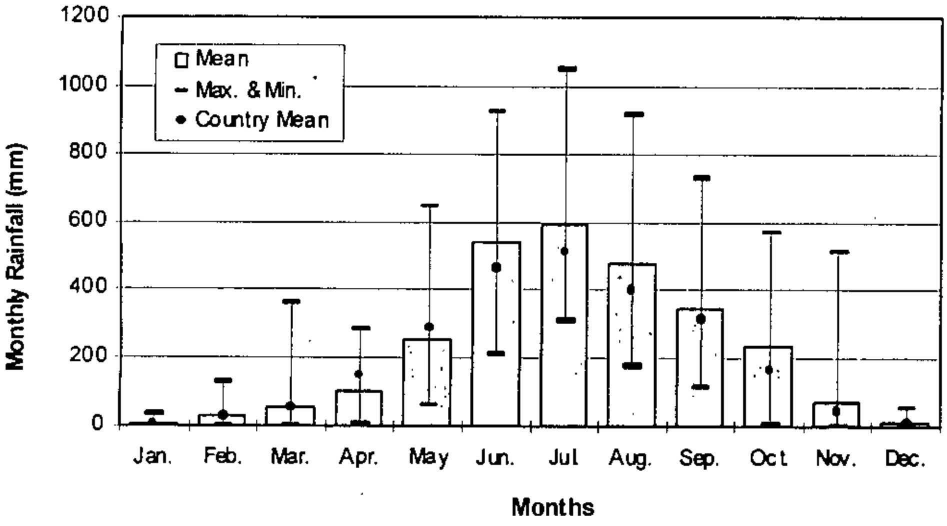

Figure B.14: Average monthly rainfall distribution for Khepupara (1975-1995).

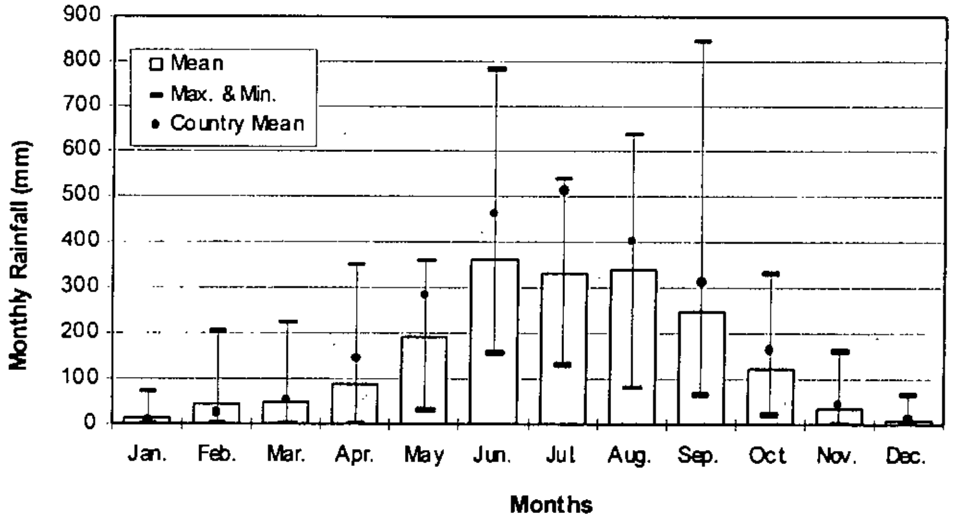

Figure B.15: Average monthly rainfall distribution for Khulna (1975-1995).

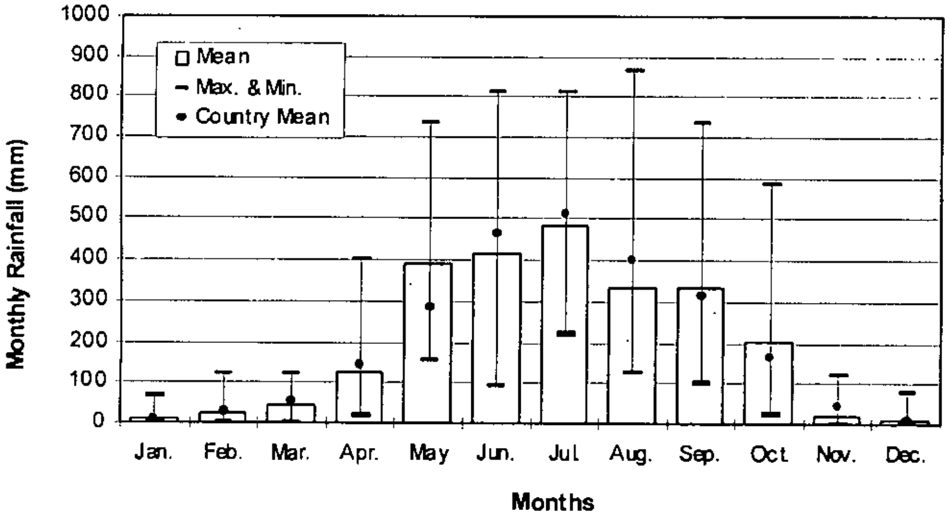

Figure B.16: Average monthly rainfall distribution for Mymensingh (1975-1995).

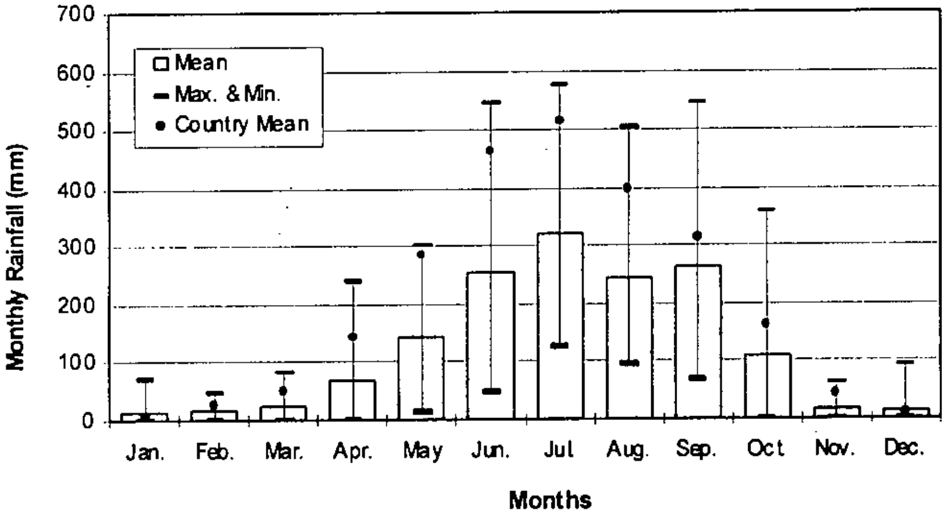

Figure B.17: Average monthly rainfall distribution for Rajshahi (1975-1995).

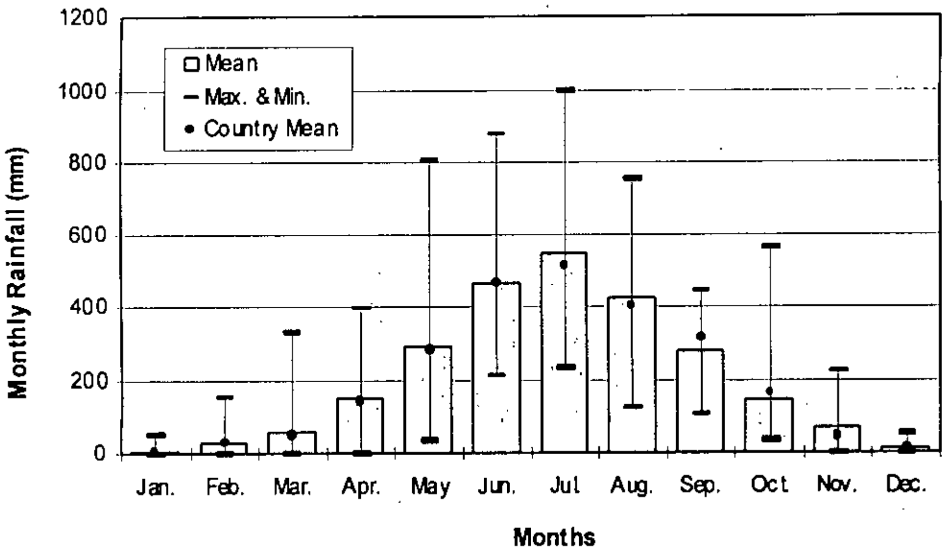

Figure B.18: Average monthly rainfall distribution for Rangamati (1975-1995).

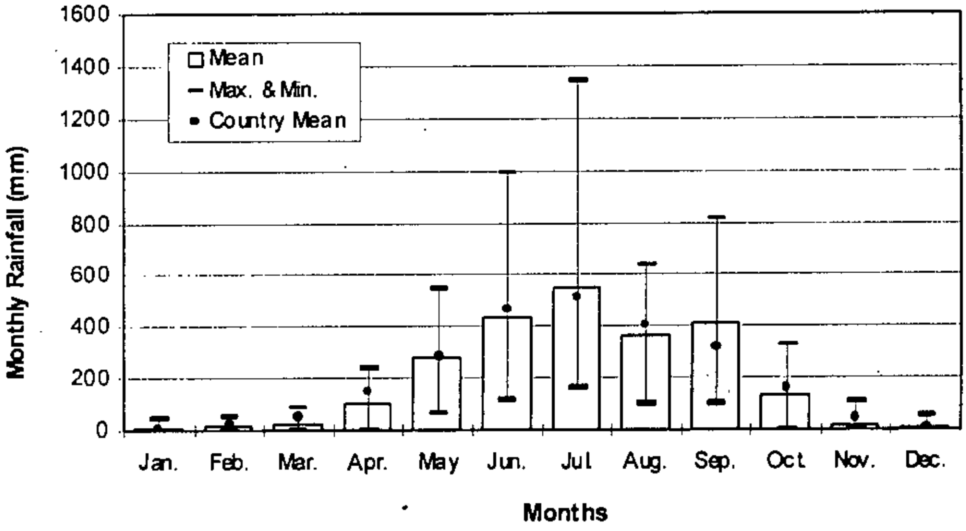

Figure B.19: Average monthly rainfall distribution for Rangpur (1975-1995).

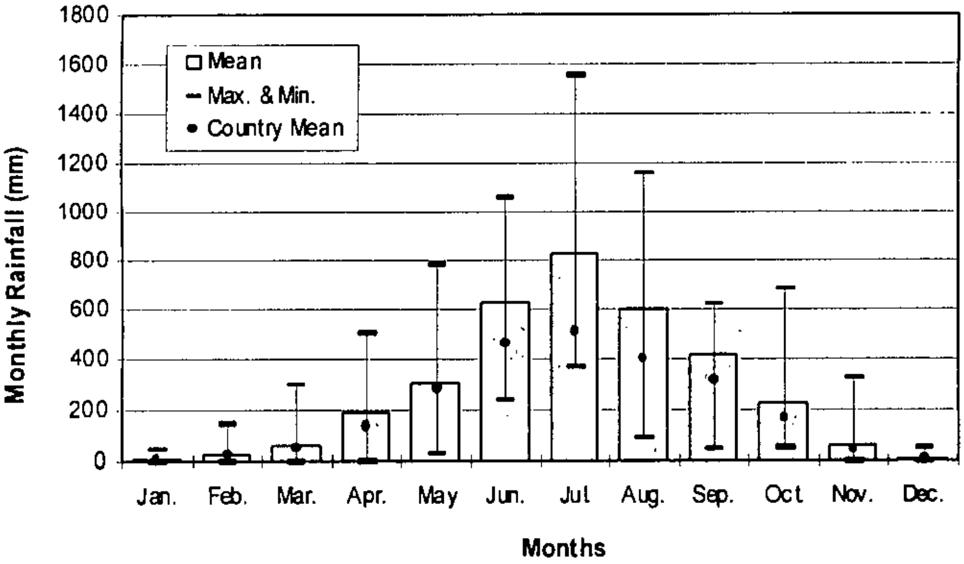

Figure B.20: Average monthly rainfall distribution for Sandwip (1975-1995).

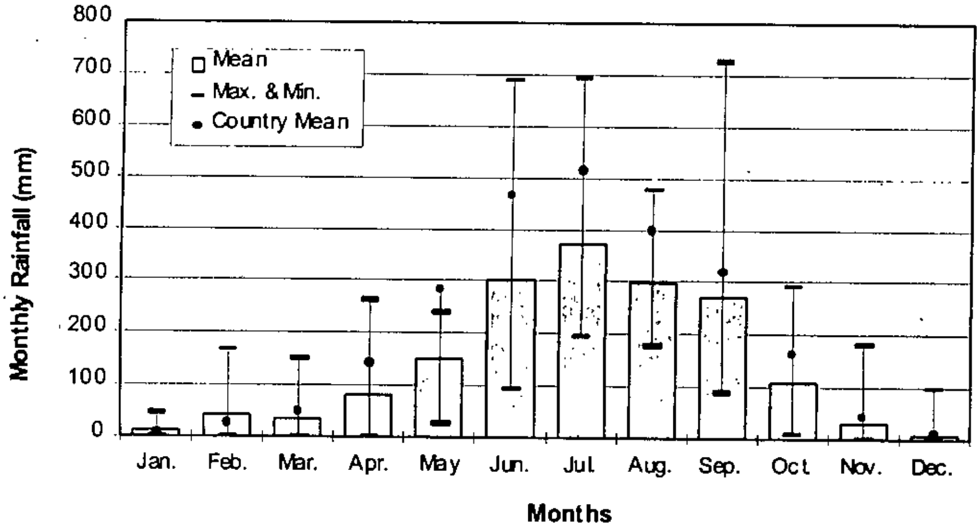

Figure B.21: Average monthly rainfall distribution for Satkhira (1975-1995).

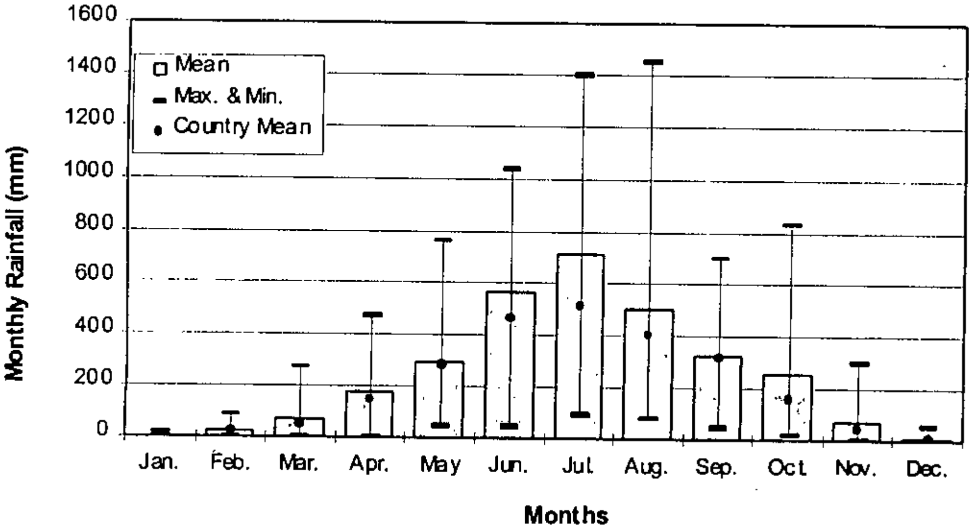

Figure B.22: Average monthly rainfall distribution for Sitakunda (1975-1995).

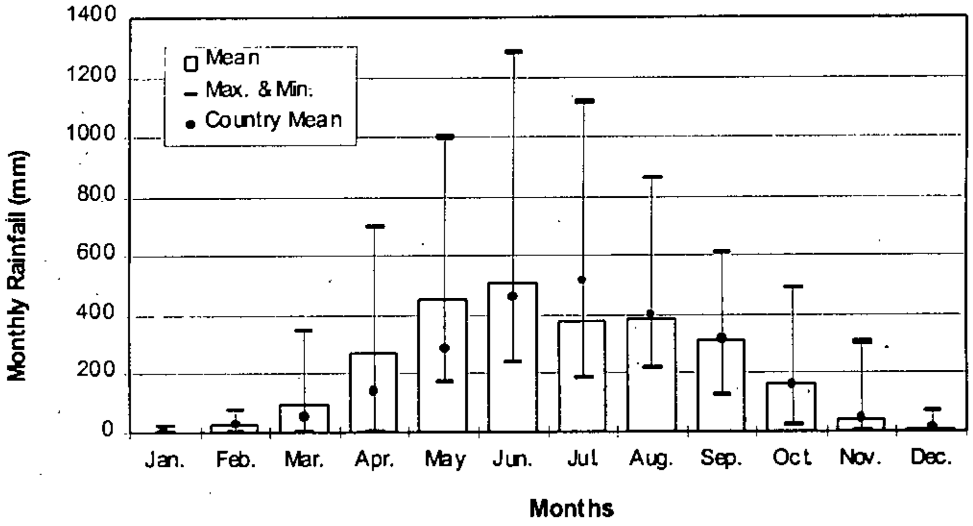

Figure B.23 Average monthly rainfall distribution for Srimangal (1975-1995).

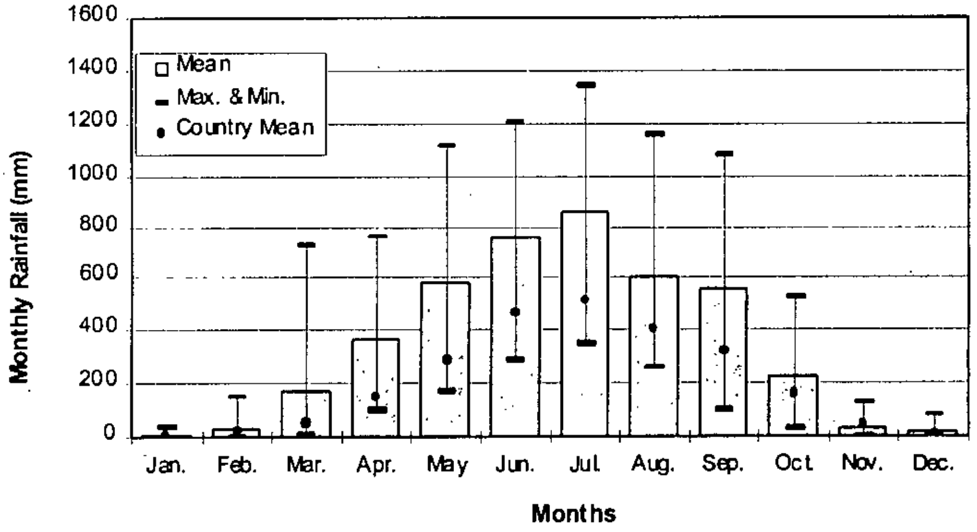

Figure B.24: Average monthly rainfall distribution for Sylhet (1975-1995).

Appendix C: CALCULATION OF NORMAL AND LOG-NORMAL DISTRIBUTIONS OF ANNUAL RAINFALL DATA OF DHAKA

Table C.1: Calculation of Normal and Log-Normal Distribution of Annual Rainfall Data.

Sl. No. m	*Year*	*Annual rainfall (mm)*	*Annual rainfall* (mm)*	*ln (x)*	*m/(N+1) =* $\phi_s(s)$	*s*
1	1965	1547	1169	7.06	0.03	-1.86
2	1966	1637	1540	7.34	0.06	-1.53
3	1967	1885	1547	7.34	0.09	-1.32
4	1968	1840	1614	7.39	0.13	-1.15
5	1969	1614	1627	7.39	0.16	-1.01
6	1970	1962	1637	7.40	0.19	-0.89
7	1971	1770	1751	7.47	0.22	-0.78
8	1972	1825	1770	7.48	0.25	-0.67
9	1973	2533	1805	7.50	0.28	-0.58
10	1974	2215	1825	7.51	0.31	-0.49
11	1975	2145	1837	7.52	0.34	-0.40
12	1976	2238	1840	7.52	0.38	-0.32
13	1977	1861	1861	7.53	0.41	-0.24
14	1978	2251	1865	7.53	0.44	-0.16
15	1979	1837	1885	7.54	0.47	-0.08
16	1980	2218	1962	7.58	0.50	0.00
17	1981	1865	2053	7.63	0.53	0.08
18	1982	1805	2103	7.65	0.56	0.16
19	1983	2408	2145	7.67	0.59	0.24
20	1984	3028	2187	7.69	0.63	0.32
21	1985	2053	2215	7.70	0.66	0.40
22	1986	2500	2218	7.70	0.69	0.49
23	1987	2187	2238	7.71	0.72	0.58
24	1988	2482	2251	7.72	0.75	0.67
25	1989	1627	2408	7.79	0.78	0.78
26	1990	2103	2482	7.82	0.81	0.89
27	1991	2850	2500	7.82	0.84	1.01
28	1992	1169	2533	7.84	0.88	1.15
29	1993	2819	2819	7.94	0.91	1.32
30	1994	1540	2850	7.96	0.94	1.53
31	1995	1751	3028	8.02	0.97	1.86

* Tank volumes are in ascending order.

Appendix D: CHI-SQUARE TEST OF NORMAL AND LOG-NORMAL DISTRIBUTIONS OF ANNUAL RAINFALL DATA OF DHAKA

Table D.1: Calculation for Normal Distribution.

Interval (mm)	x_i *(mm)*	n_i *(observed)*	n_ix_i	$n_ix_i^2$	s	$\phi(s)$	$P(x)$	e_i *(theoretical)*	$\Sigma(n_i-e_i)^2/e_i$
1000-1250	1125	1	1125	1265625	-1.92	0.03	0.03	0.86	0.02
1250-1500	1375	0	0	0	-1.32	0.09	0.06	2.01	2.01
1500-1750	1625	5	8125	13203125	-0.73	0.23	0.14	4.31	0.11
1750-2000	1875	10	18750	35156250	-0.14	0.44	0.21	6.56	1.80
2000-2250	2125	7	14875	31609375	0.45	0.67	0.23	7.12	0.00
2250-2500	2375	4	9500	22562500	1.04	0.85	0.18	5.51	0.41
2500-2750	2625	1	2625	6890625	1.63	0.95	0.10	3.03	1.36
2750-3000	2875	2	5750	16531250	2.22	0.99	0.04	1.19	0.55
3000-3250	3125	1	3125	9765625	2.81	1.00	0.01	0.41	0.85
Total		31	63875	136984375			1.00	31.00	**7.13**

Mean, μ = 2060.48

Sta. dev., σ = 423.12

Table D.2: Calculation for Log-Normal Distribution.

Interval (mm)	x_i *(mm)*	$x_i' = \ln(x_i)$	n_i *(observed)*	n_ix_i'	$n_ix_i'^2$	s	$\phi(s)$	$P(x')$	e_i *(theoretical)*	$\Sigma(n_i-e_i)^2/e_i$
1000-1250	1125	7.03	1	7.03	49.36	-2.33	0.01	0.01	0.30	1.60
1250-1500	1375	7.23	0	0.00	0.00	-1.45	0.07	0.06	1.99	1.99
1500-1750	1625	7.39	5	36.97	273.30	-0.70	0.24	0.17	5.24	0.01
1750-2000	1875	7.54	10	75.36	567.97	-0.05	0.48	0.24	7.39	0.92
2000-2250	2125	7.66	7	53.63	410.89	0.53	0.70	0.22	6.80	0.01
2250-2500	2375	7.77	4	31.09	241.66	1.04	0.85	0.15	4.65	0.09
2500-2750	2625	7.87	1	7.87	61.98	1.50	0.93	0.08	2.57	0.96
2750-3000	2875	7.96	2	15.93	126.84	1.93	0.97	0.04	1.22	0.50
3000-3250	3125	8.05	1	8.05	64.76	2.32	0.99	0.03	0.84	0.03
Total			31	235.92	1796.77			1.00	31.00	**6.11**

Mean, μ = 7.61

Sta. dev., σ = 0.21

Degree of freedom, f = 6

Significance level, α = 5%

Chi-square value, $C_{.95,6}$ = **12.6**

Appendix E: CALCULATION OF THE RELIABILITY OF THE RAINWATER HARVESTING SYSTEM AS A SOURCE OF DRINKING WATER FOR DHAKA

Table E.1: Calculation of the Reliability for a Household Size of 6 persons with a Catchment Area of 30 m^2.

Catchment area (m^2)	*Household size (person)*	*Consumption rate (lpcd)*	*Demand (m^3/yr.)*	*Year*	*Annual rainfall (mm)*	*Supply (m^3/yr.)*	*Supply (m^3/yr.)*	*Reliability (%)*
30	6	3	***Mean***	1965	1547	37.13	***Mean***	100.00
			μ_D =	1966	1637	39.28	μ_S =	(Normal
			6.57	1967	1885	45.25	49.21	distribution)
				1968	1840	44.16		
			Standard	1969	1614	38.75	***Standard***	100.00
			Deviation	1970	1962	47.09	***Deviation***	(Log-
			σ_D =	1971	1770	42.48	σ_S =	normal
			0.657	1972	1825	43.79	10.18	distribution)
				1973	2533	60.80		
			Coefficient	1974	2215	53.16	***Coefficient***	
			of	1975	2145	51.48	***of***	
			Variation	1976	2238	53.71	***Variation***	
			C.O.V. =	1977	1861	44.66	C.O.V. =	
			0.10	1978	2251	54.02	0.21	
				1979	1837	44.09		
				1980	2218	53.23		
				1981	1865	44.76		
				1982	1805	43.32		
				1983	2408	57.79		
				1984	3028	72.67		
				1985	2053	49.27		
				1986	2500	60.00		
				1987	2187	52.49		
				1988	2482	59.57		
				1989	1627	39.05		
				1990	2103	50.47		
				1991	2850	68.40		
				1992	1169	28.06		
				1993	2819	67.66		
				1994	1540	36.96		
				1995	1751	42.02		

Appendix F: DEMAND RELIABILITY RELATIONSHIP FOR DIFFERENT ROOF AREAS FOR DIFFERENT PLACES OF BANGLADESH

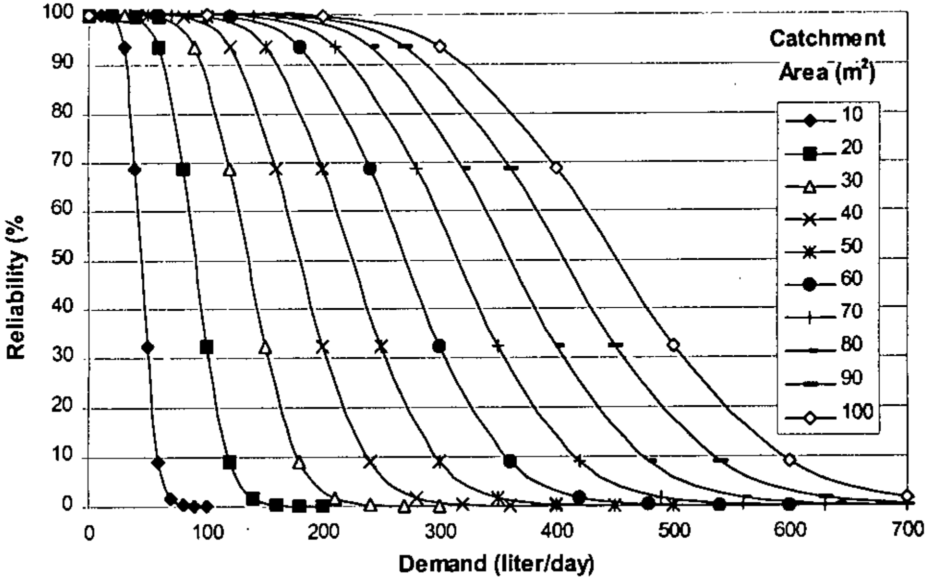

Figure F.1: Demand reliability relationship for different roof areas for Barisal.

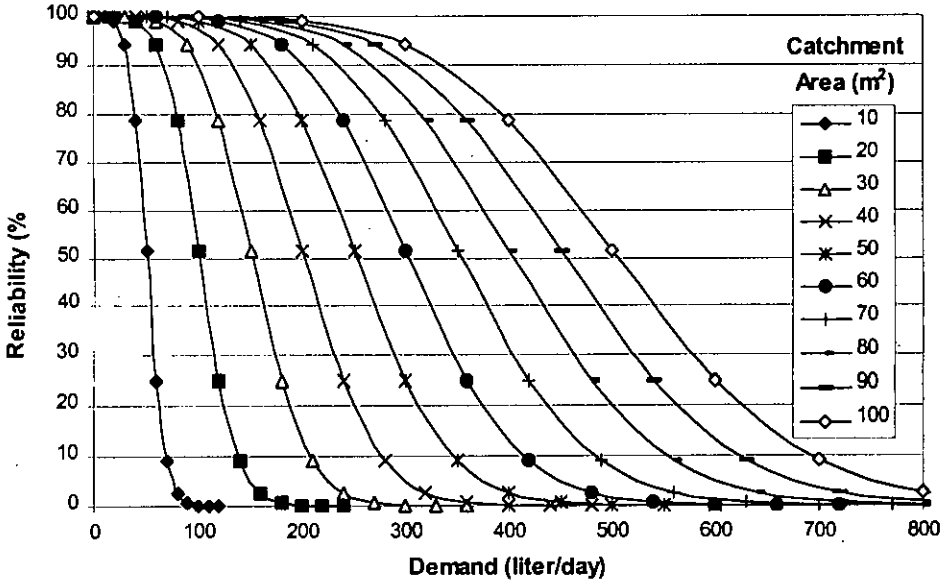

Figure F.2: Demand reliability relationship for different roof areas for Bhola.

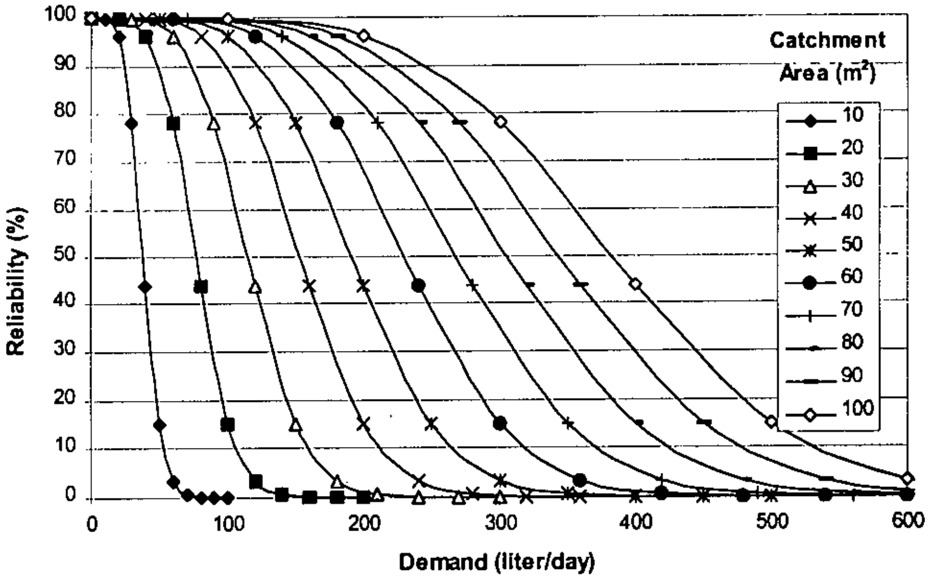

Figure F.3: Demand reliability relationship for different roof areas for Bogra.

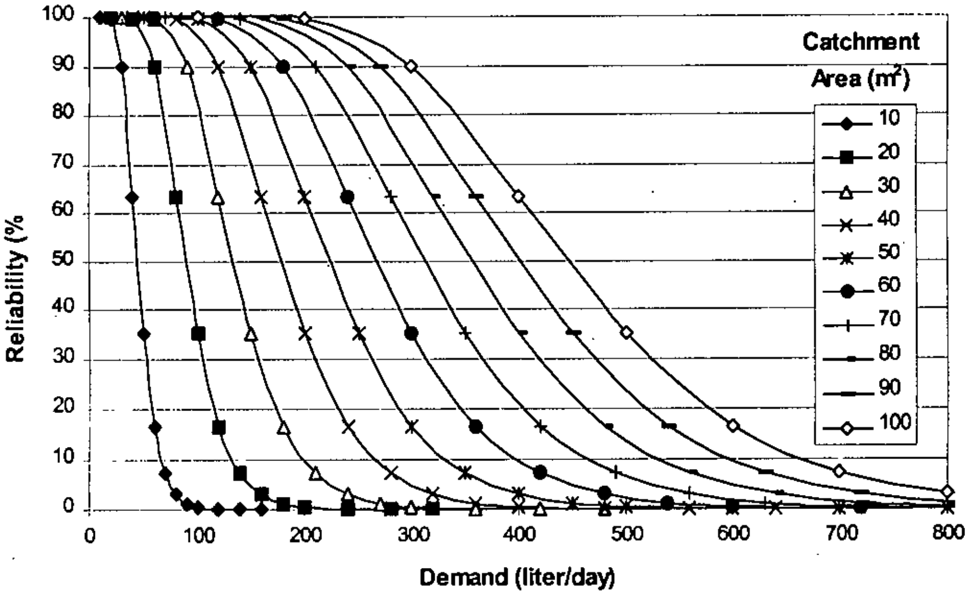

Figure F.4: Demand reliability relationship for different roof areas for Chandpur.

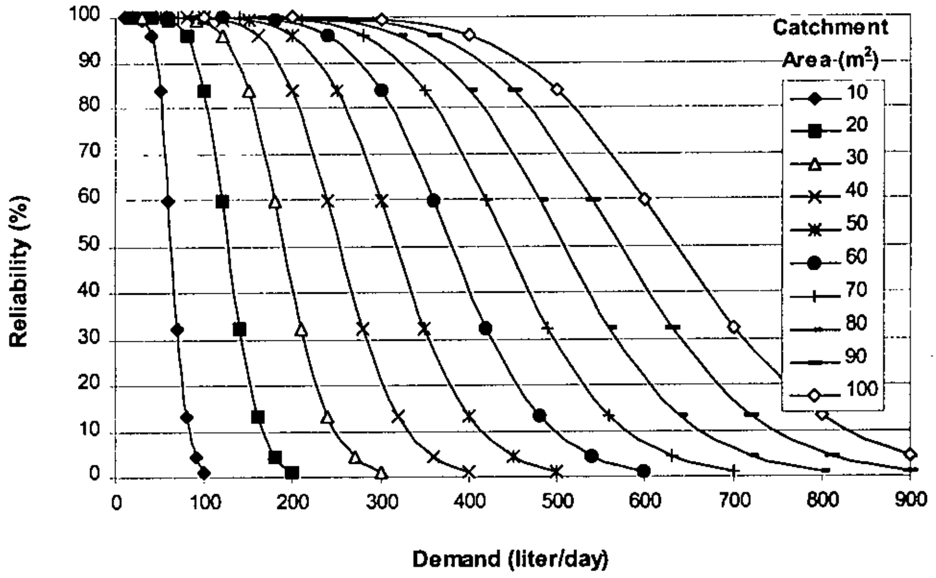

Figure F.5: Demand reliability relationship for different roof areas for Chittagong.

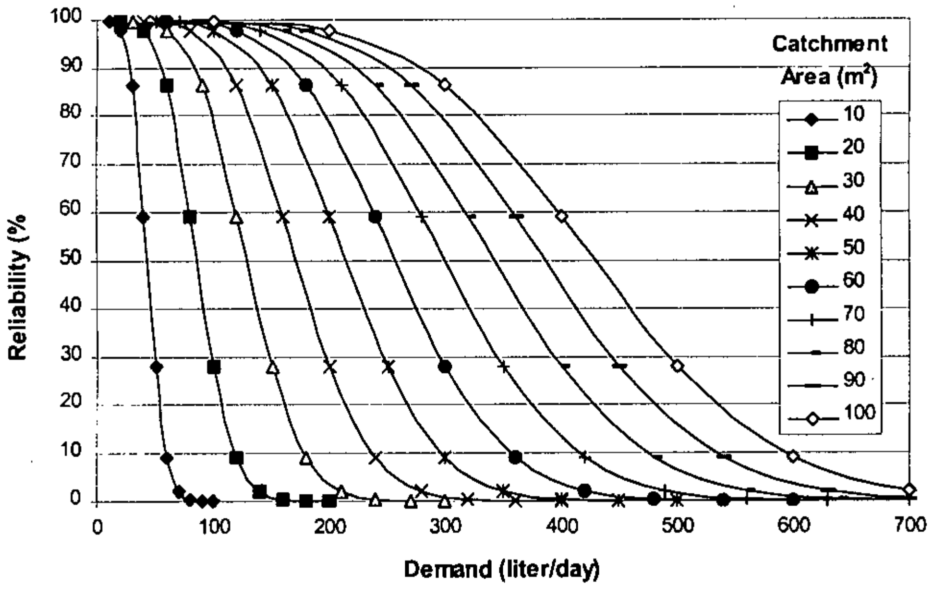

Figure F.6: Demand reliability relationship for different roof areas for Comilla.

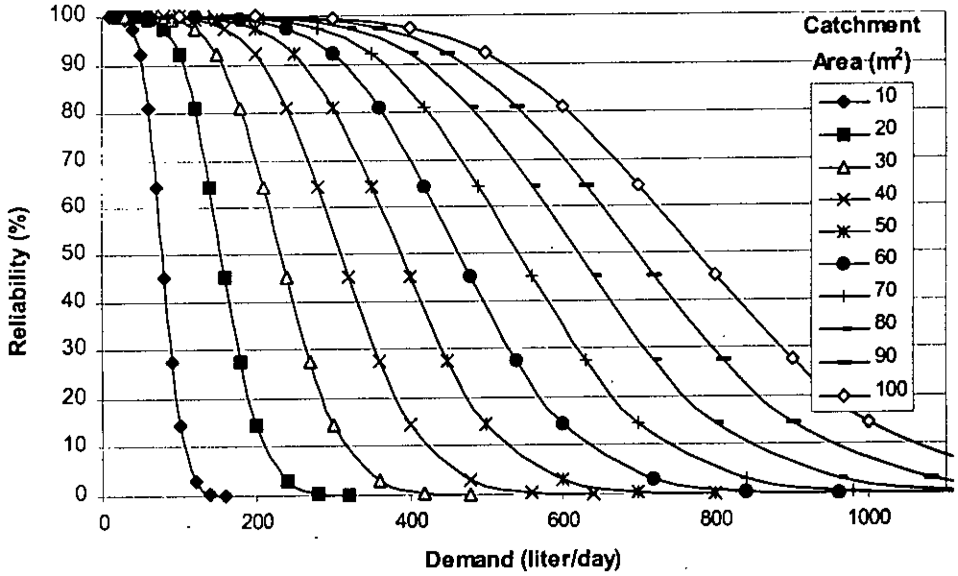

Figure F.7: Demand reliability relationship for different roof areas for Cox's Bazar.

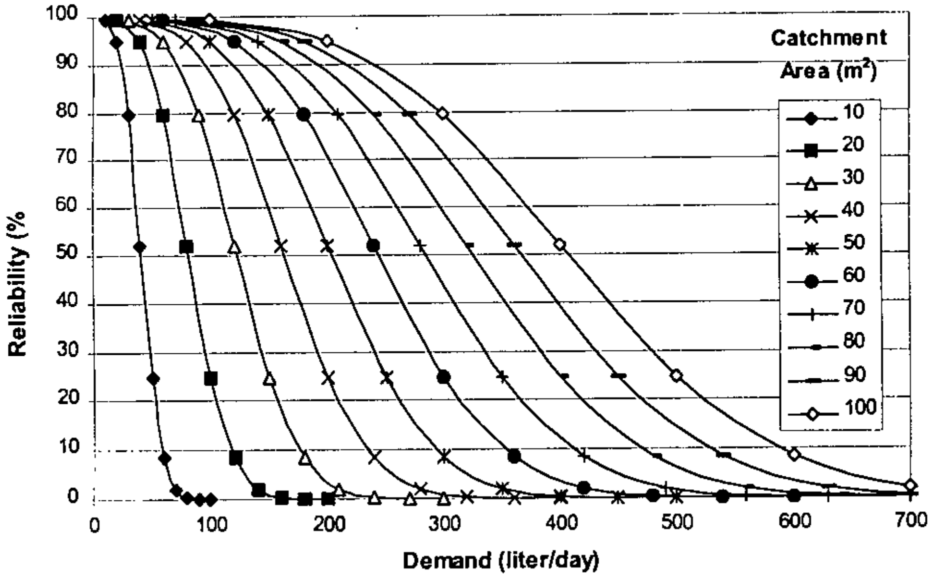

Figure F.8: Demand reliability relationship for different roof areas for Dinajpur.

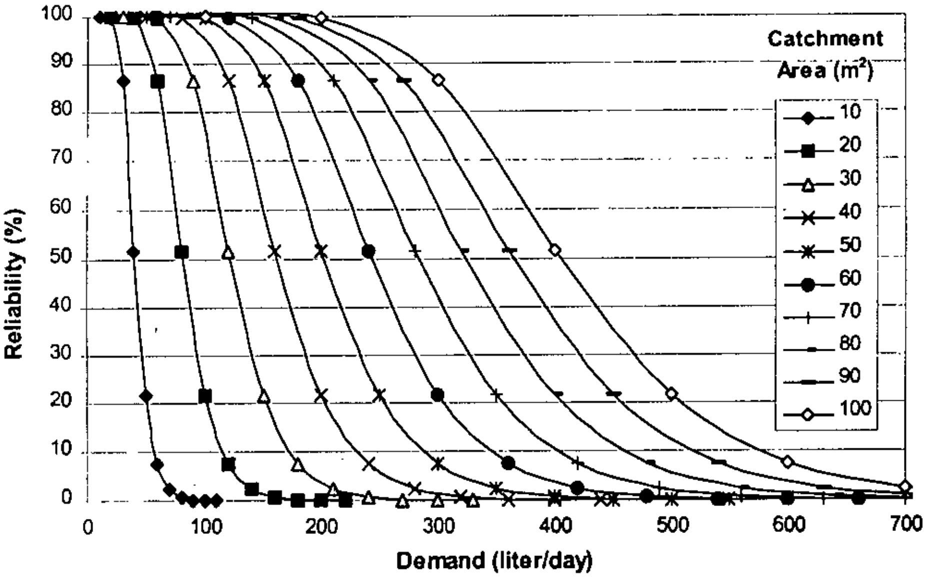

Figure F.9: Demand reliability relationship for different roof areas for Faridpur.

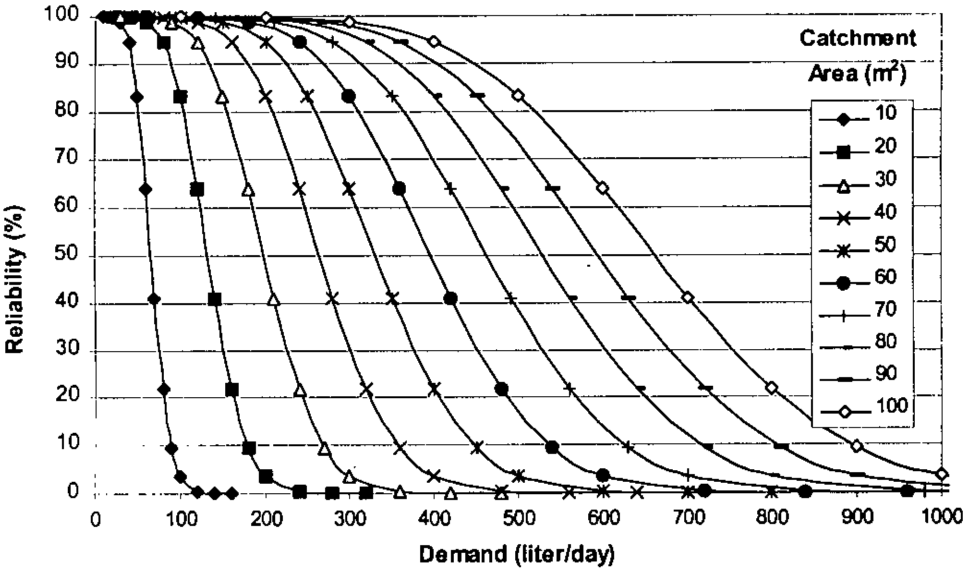

Figure F.10: Demand reliability relationship for different roof areas for Feni.

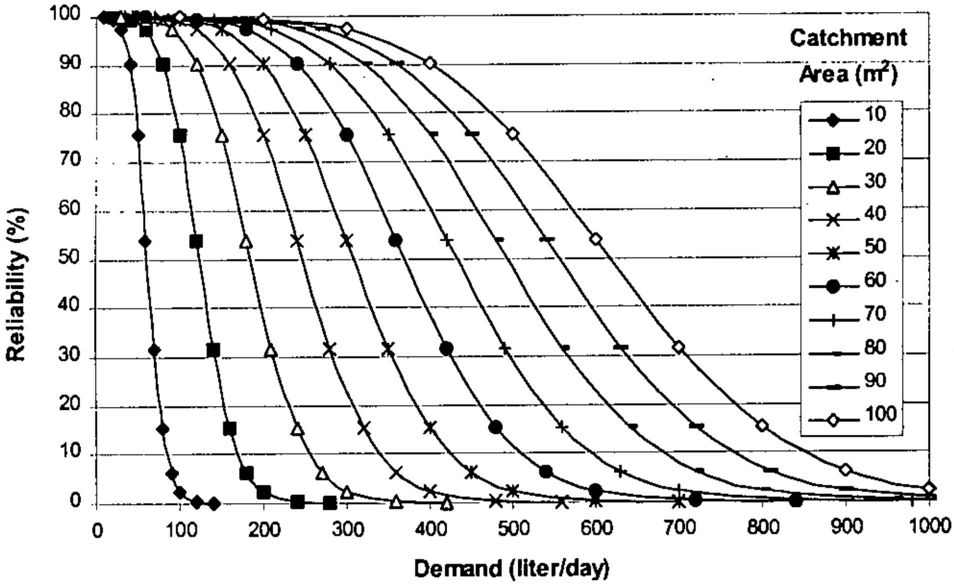

Figure F.11: Demand reliability relationship for different roof areas for Hatia.

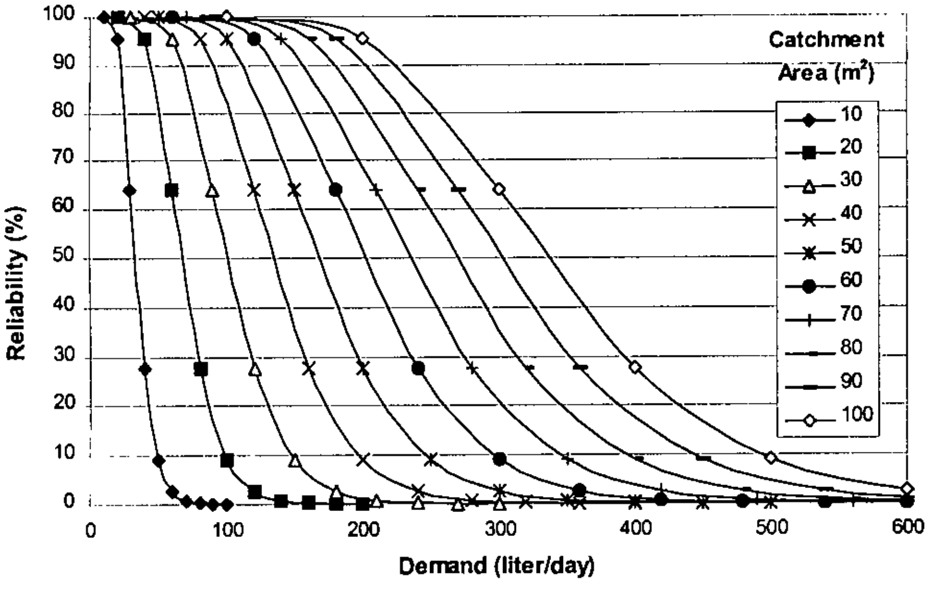

Figure F.12: Demand reliability relationship for different roof areas for Ishurdi.

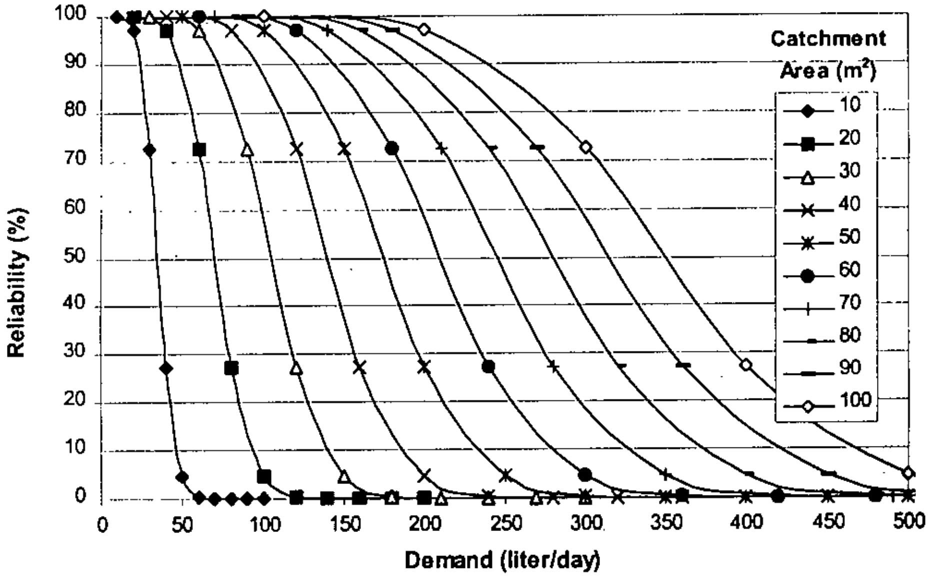

Figure F.13: Demand reliability relationship for different roof areas for Jessore.

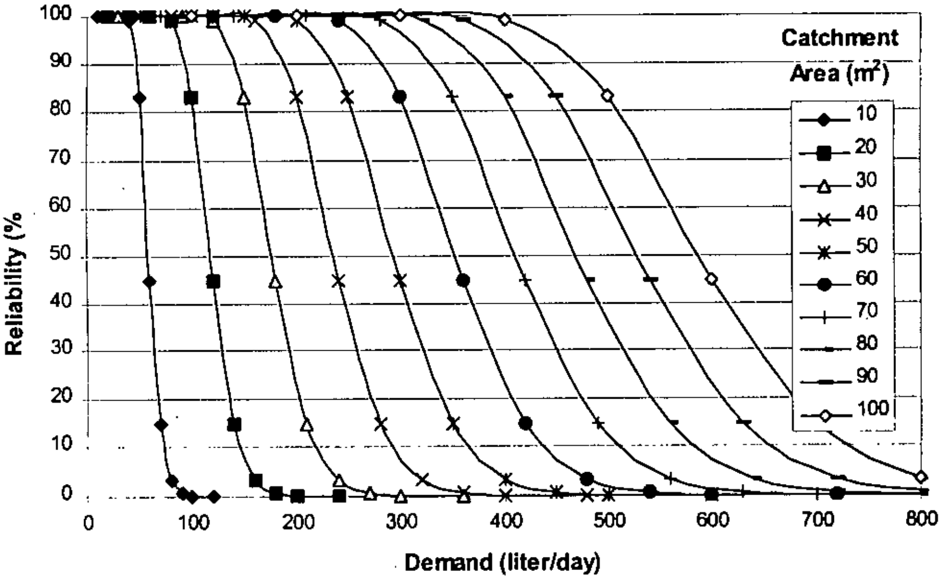

Figure F.14: Demand reliability relationship for different roof areas for Khepupara.

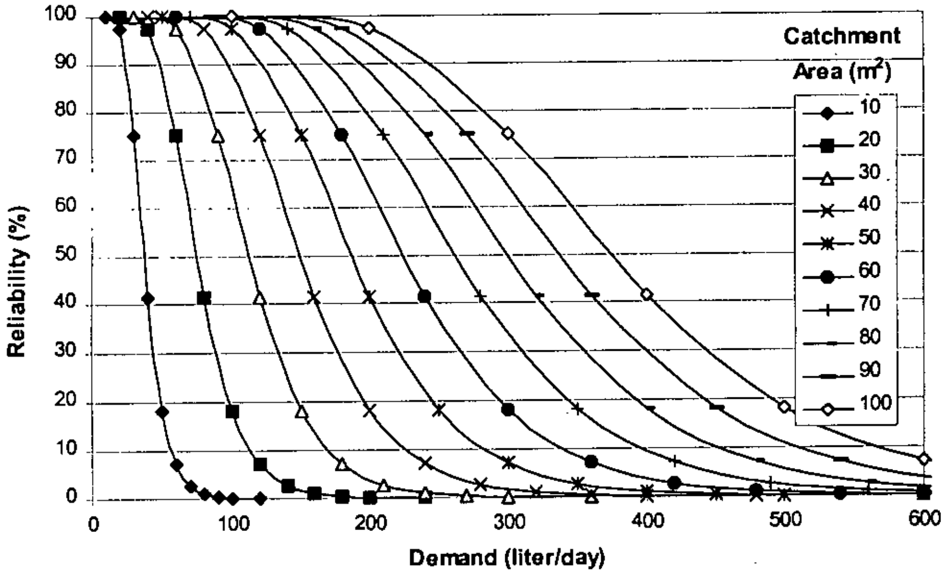

Figure F.15: Demand reliability relationship for different roof areas for Khulna.

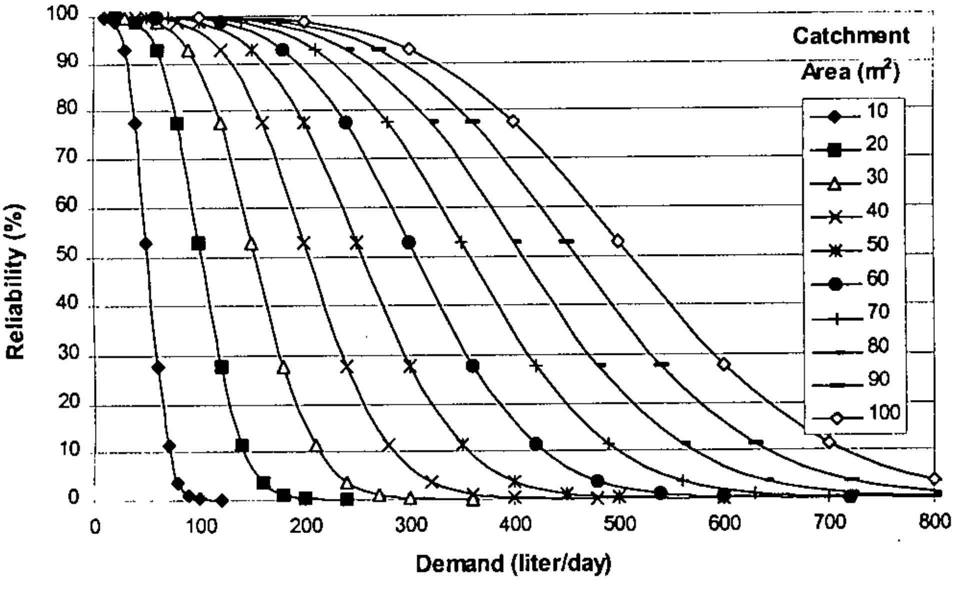

Figure F.16: Demand reliability relationship for different roof areas for Mymensingh.

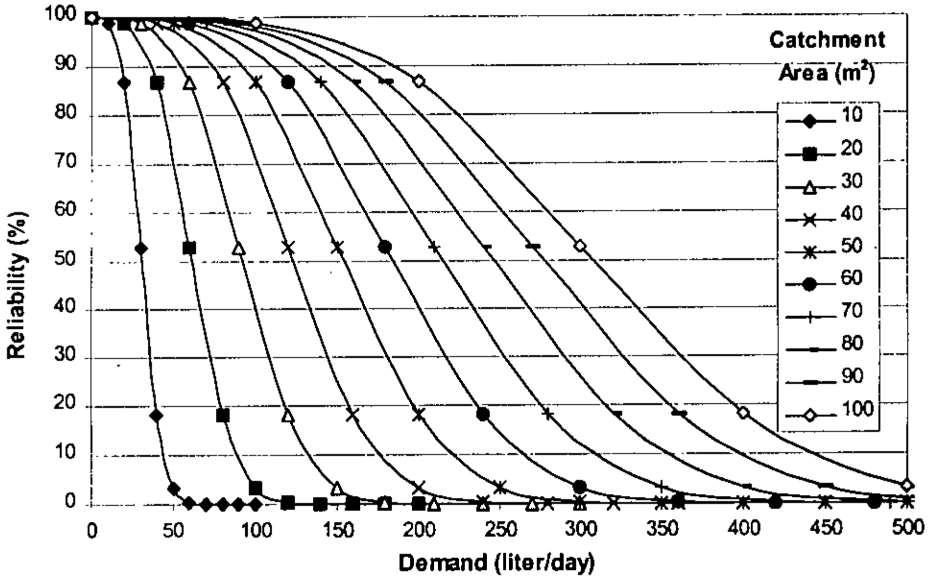

Figure F.17: Demand reliability relationship for different roof areas for Rajshahi.

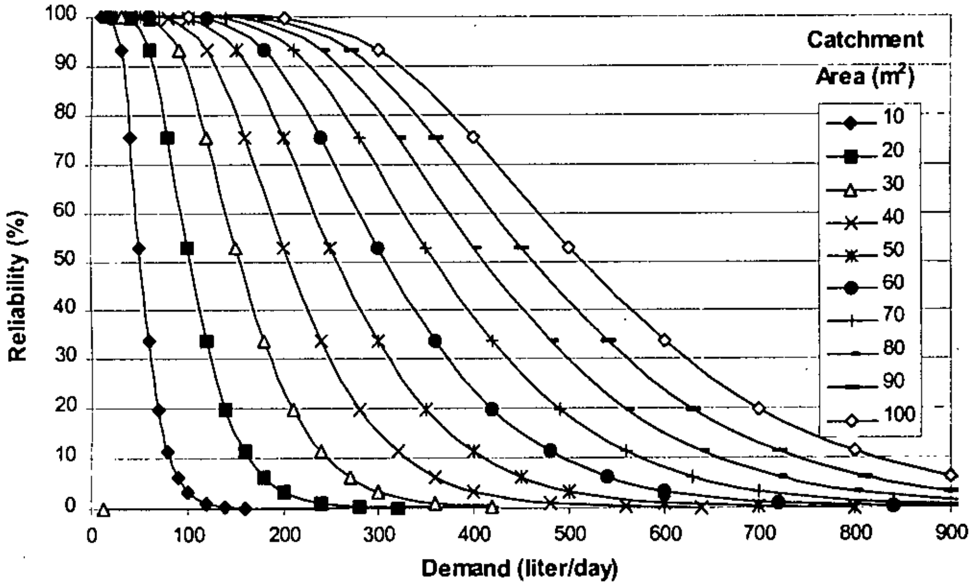

Figure F.18: Demand reliability relationship for different roof areas for Rangamati.

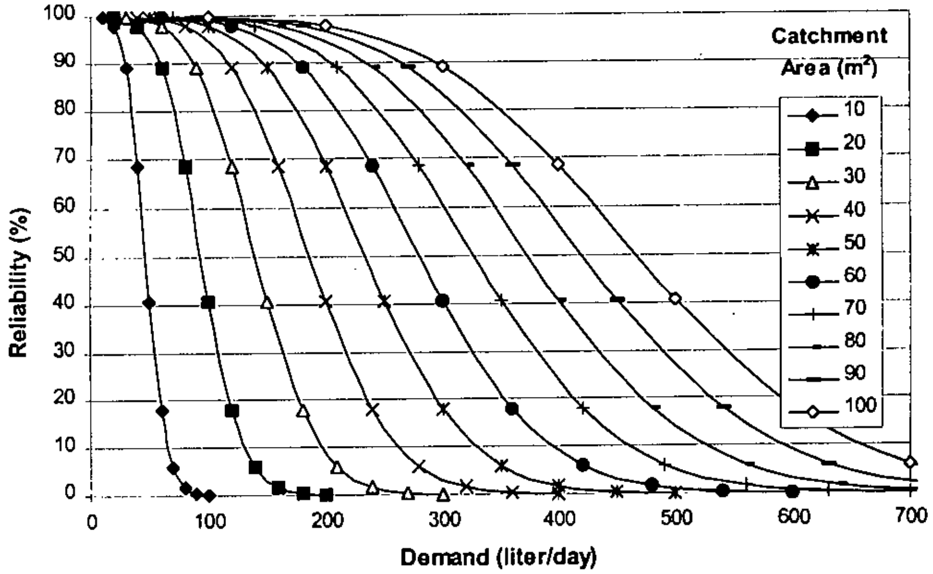

Figure F.19: Demand reliability relationship for different roof areas for Rangpur.

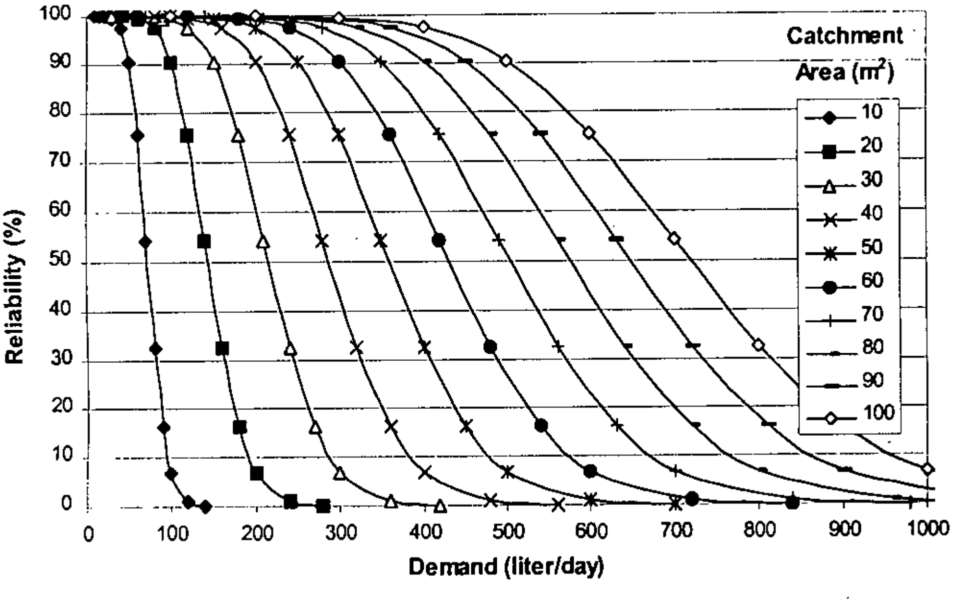

Figure F.20: Demand reliability relationship for different roof areas for Sandwip.

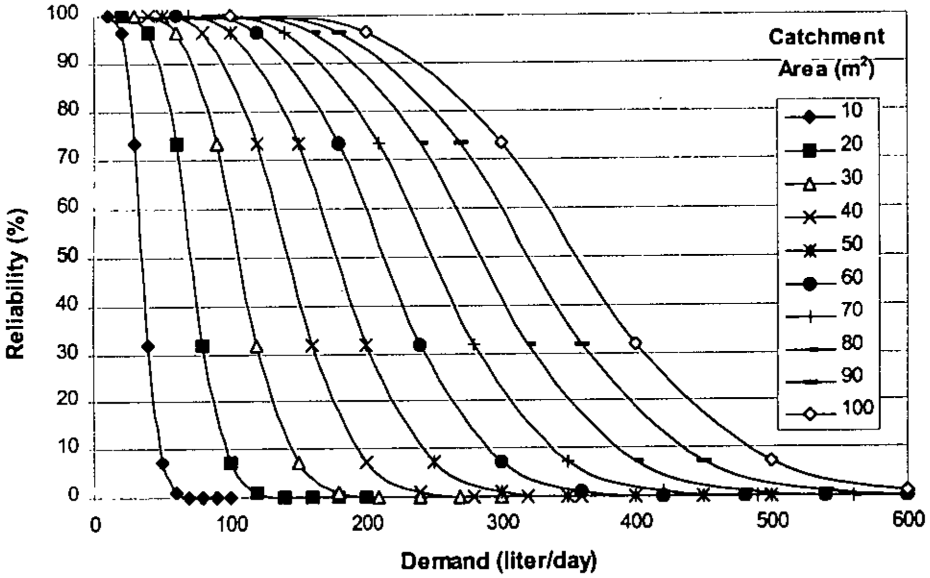

Figure F.21: Demand reliability relationship for different roof areas for Satkhira.

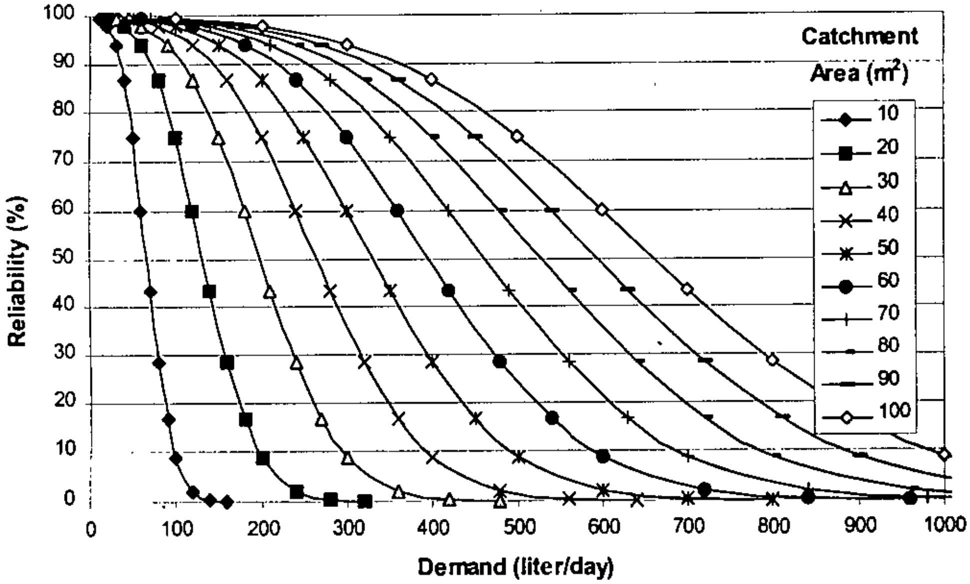

Figure F.22: Demand reliability relationship for different roof areas for Sitakunda.

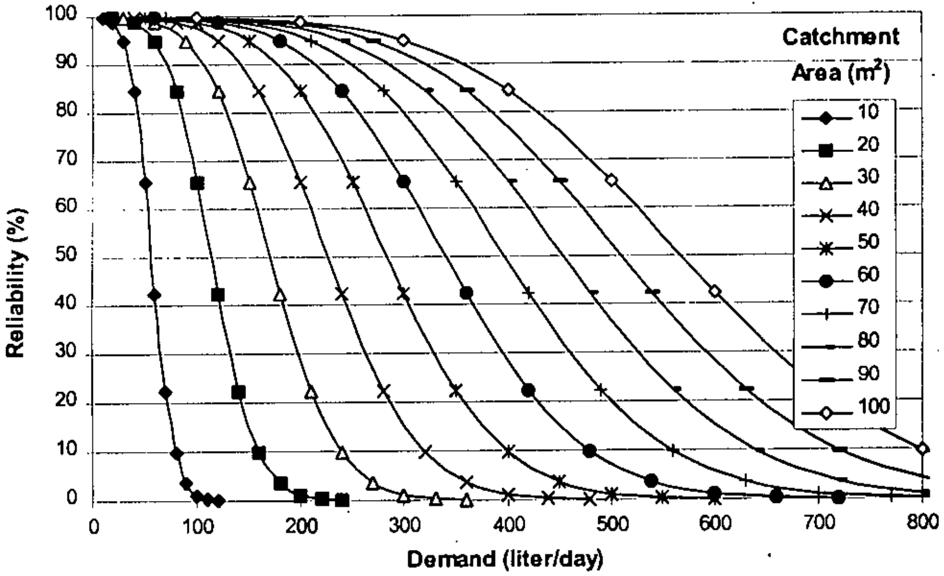

Figure F.23: Demand reliability relationship for different roof areas for Srimangal.

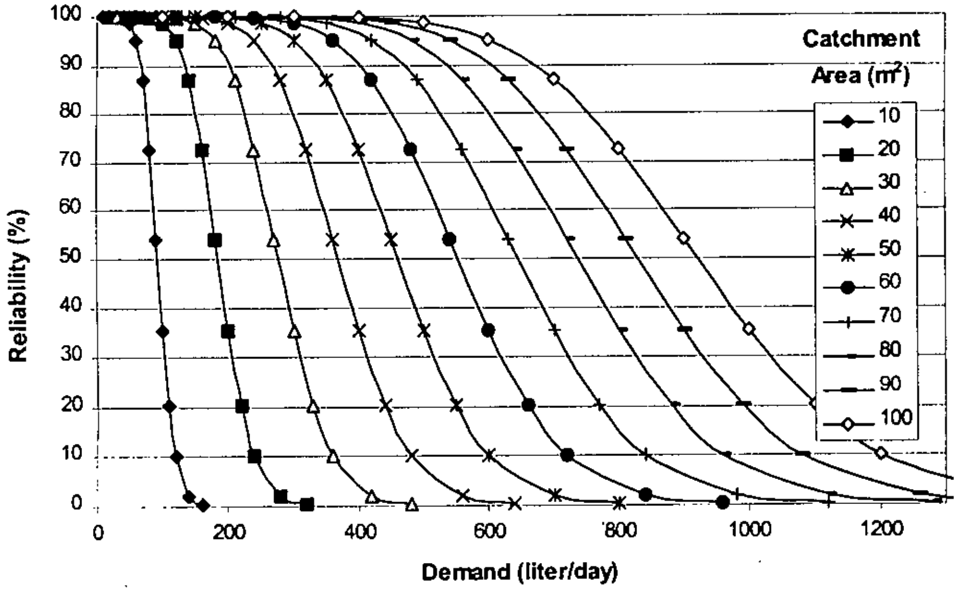

Figure F.24: Demand reliability relationship for different roof areas for Sylhet.

Appendix G: CALCULATION OF REQUIRED STORAGE VOLUME FOR DHAKA BY MASS CURVE ANALYSIS

Assumptions:
1. Average household size = 6 persons
2. Consumption rate for drinking water = 3 lpcd
3. Average catchment area = 30 m^2
4. Runoff coefficient = 0.75
5. Annual demand = 6.57 m^3
6. Average annual supply = 47.93 m^3
7. Required tank volume = 2363 liters

Table G.1: Mass Curve Analysis for Required Storage Volume.

SL. No.	*Year*	*Month*	*Monthly rainfall (mm)*	*Monthly supply (liters)*	*Cumulative supply (liters)*	*Monthly demand (liters)*	*Cumulative demand (liters)*	*Amount stored (liters)*	*Total amount stored (liters)*	*Required tank volume (liters)*
1	1975	Jan.	1							
2		Feb.	29							
3		Mar.	13							
4		Apr.	98							
5		May	317	7133	7133	540	540	6593	6593	
6		Jun.	235	5288	12420	540	1080	4748	11340	
7		Jul.	559	12578	24998	540	1620	12038	23378	
8		Aug.	307	6908	31905	540	2160	6368	29745	
9		Sep.	329	7403	39308	540	2700	6863	36608	
10		Oct.	232	5220	44528	540	3240	4680	41288	
11		Nov.	25	563	45090	540	3780	23	41310	41310
12		Dec.	0	0	45090	540	4320	-540	40770	-
13	1976	Jan.	0	0	45090	540	4860	-540	40230	39848
14		Feb.	7	158	45248	540	5400	-383	39848	=
15		Mar.	117	2633	47880	540	5940	2093	41940	**1463**
16		Apr.	34	765	48645	540	6480	225	42165	
17		May	459	10328	58973	540	7020	9788	51953	
18		Jun.	627	14108	73080	540	7560	13568	65520	
19		Jul.	346	7785	80865	540	8100	7245	72765	
20		Aug.	361	8123	88988	540	8640	7583	80348	
21		Sep.	165	3713	92700	540	9180	3173	83520	
22		Oct.	114	2565	95265	540	9720	2025	85545	
23		Nov.	8	180	95445	540	10260	-360	85185	85545
24		Dec.	0	0	95445	540	10800	-540	84645	-
25	1977	Jan.	0	0	95445	540	11340	-540	84105	84105
26		Feb.	66	1485	96930	540	11880	945	85050	=
27		Mar.	71	1598	98528	540	12420	1058	86108	**1440**
28		Apr.	255	5738	104265	540	12960	5198	91305	

29		May	381	8573	112838	540	13500	8033	99338	
30		Jun.	252	5670	118508	540	14040	5130	104468	
31		Jul.	306	6885	125393	540	14580	6345	110813	
32		Aug.	92	2070	127463	540	15120	1530	112343	
33		Sep.	131	2948	130410	540	15660	2408	114750	
34		Oct.	273	6143	136553	540	16200	5603	120353	
35		Nov.	10	225	136778	540	16740	-315	120038	120353
36		Dec.	24	540	137318	540	17280	0	120038	-
37	1978	Jan.	0	0	137318	540	17820	-540	119498	119273
38		Feb.	20	450	137768	540	18360	-90	119408	=
39		Mar.	18	405	138173	540	18900	-135	119273	**1080**
40		Apr.	194	4365	142538	540	19440	3825	123098	
41		May	454	10215	152753	540	19980	9675	132773	
42		Jun.	529	11903	164655	540	20520	11363	144135	
43		Jul.	320	7200	171855	540	21060	6660	150795	
44		Aug.	426	9585	181440	540	21600	9045	159840	
45		Sep.	192	4320	185760	540	22140	3780	163620	
46		Oct.	98	2205	187965	540	22680	1665	165285	
47		Nov.	0	0	187965	540	23220	-540	164745	165285
48		Dec.	0	0	187965	540	23760	-540	164205	-
49	1979	Jan.	3	68	188033	540	24300	-473	163733	162923
50		Feb.	13	293	188325	540	24840	-248	163485	=
51		Mar.	6	135	188460	540	25380	-405	163080	**2363**
52		Apr.	17	383	188843	540	25920	-158	162923	
53		May	114	2565	191408	540	26460	2025	164948	
54		Jun.	258	5805	197213	540	27000	5265	170213	
55		Jul.	267	6008	203220	540	27540	5468	175680	
56		Aug.	525	11813	215033	540	28080	11273	186953	
57		Sep.	382	8595	223628	540	28620	8055	195008	
58		Oct.	146	3285	226913	540	29160	2745	197753	
59		Nov.	55	1238	228150	540	29700	698	198450	199058
60		Dec.	51	1148	229298	540	30240	608	199058	-
61	1980	Jan.	3	68	229365	540	30780	-473	198585	198585
62		Feb.	32	720	230085	540	31320	180	198765	=
63		Mar.	54	1215	231300	540	31860	675	199440	**473**
64		Apr.	147	3308	234608	540	32400	2768	202208	
65		May	414	9315	243923	540	32940	8775	210983	
66		Jun.	323	7268	251190	540	33480	6728	217710	
67		Jul.	380	8550	259740	540	34020	8010	225720	
68		Aug.	269	6053	265793	540	34560	5513	231233	
69		Sep.	296	6660	272453	540	35100	6120	237353	
70		Oct.	300	6750	279203	540	35640	6210	243563	
71		Nov.	0	0	279203	540	36180	-540	243023	243563
72		Dec.	0	0	279203	540	36720	-540	242483	-
73	1981	Jan.	10	225	279428	540	37260	-315	242168	242168
74		Feb.	42	945	280373	540	37800	405	242573	=

75		Mar.	109	2453	282825	540	38340	1913	244485	**1395**
76		Apr.	274	6165	288990	540	38880	5625	250110	
77		May	272	6120	295110	540	39420	5580	255690	
78		Jun.	168	3780	298890	540	39960	3240	258930	
79		Jul.	356	8010	306900	540	40500	7470	266400	
80		Aug.	188	4230	311130	540	41040	3690	270090	
81		Sep.	320	7200	318330	540	41580	6660	276750	
82		Oct.	82	1845	320175	540	42120	1305	278055	
83		Nov.	9	203	320378	540	42660	-338	277718	278055
84		Dec.	35	788	321165	540	43200	248	277965	-
85	1982	Jan.	0	0	321165	540	43740	-540	277425	277223
86		Feb.	15	338	321503	540	44280	-203	277223	=
87		Mar.	81	1823	323325	540	44820	1283	278505	**833**
88		Apr.	104	2340	325665	540	45360	1800	280305	
89		May	154	3465	329130	540	45900	2925	283230	
90		Jun.	514	11565	340695	540	46440	11025	294255	
91		Jul.	136	3060	343755	540	46980	2520	296775	
92		Aug.	346	7785	351540	540	47520	7245	304020	
93		Sep.	258	5805	357345	540	48060	5265	309285	
94		Oct.	146	3285	360630	540	48600	2745	312030	
95		Nov.	51	1148	361778	540	49140	608	312638	312638
96		Dec.	0	0	361778	540	49680	-540	312098	-
97	1983	Jan.	10	225	362003	540	50220	-315	311783	311783
98		Feb.	61	1373	363375	540	50760	833	312615	=
99		Mar.	138	3105	366480	540	51300	2565	315180	**855**
100		Apr.	318	7155	373635	540	51840	6615	321795	
101		May	348	7830	381465	540	52380	7290	329085	
102		Jun.	300	6750	388215	540	52920	6210	335295	
103		Jul.	179	4028	392243	540	53460	3488	338783	
104		Aug.	437	9833	402075	540	54000	9293	348075	
105		Sep.	322	7245	409320	540	54540	6705	354780	
106		Oct.	253	5693	415013	540	55080	5153	359933	
107		Nov.	24	540	415553	540	55620	0	359933	359933
108		Dec.	18	405	415958	540	56160	-135	359798	-
109	1984	Jan.	13	293	416250	540	56700	-248	359550	358605
110		Feb.	1	23	416273	540	57240	-518	359033	=
111		Mar.	5	113	416385	540	57780	-428	358605	**1328**
112		Apr.	124	2790	419175	540	58320	2250	360855	
113		May	707	15908	435083	540	58860	15368	376223	
114		Jun.	637	14333	449415	540	59400	13793	390015	
115		Jul.	694	15615	465030	540	59940	15075	405090	
116		Aug.	311	6998	472028	540	60480	6458	411548	
117		Sep.	478	10755	482783	540	61020	10215	421763	
118		Oct.	58	1305	484088	540	61560	765	422528	
119		Nov.	0	0	484088	540	62100	-540	421988	422528
120		Dec.	0	0	484088	540	62640	-540	421448	-

121	1985	Jan.	8	180	484268	540	63180	-360	421088	420570
122		Feb.	1	23	484290	540	63720	-518	420570	=
123		Mar.	195	4388	488678	540	64260	3848	424418	**1958**
124		Apr.	176	3960	492638	540	64800	3420	427838	
125		May	300	6750	499388	540	65340	6210	434048	
126		Jun.	399	8978	508365	540	65880	8438	442485	
127		Jul.	262	5895	514260	540	66420	5355	447840	
128		Aug.	317	7133	521393	540	66960	6593	454433	
129		Sep.	306	6885	528278	540	67500	6345	460778	
130		Oct.	79	1778	530055	540	68040	1238	462015	
131		Nov.	0	0	530055	540	68580	-540	461475	462015
132		Dec.	10	225	530280	540	69120	-315	461160	-
133	1986	Jan.	22	495	530775	540	69660	-45	461115	460553
134		Feb.	0	0	530775	540	70200	-540	460575	=
135		Mar.	23	518	531293	540	70740	-23	460553	**1463**
136		Apr.	247	5558	536850	540	71280	5018	465570	
137		May	191	4298	541148	540	71820	3758	469328	
138		Jun.	304	6840	547988	540	72360	6300	475628	
139		Jul.	443	9968	557955	540	72900	9428	485055	
140		Aug.	171	3848	561803	540	73440	3308	488363	
141		Sep.	687	15458	577260	540	73980	14918	503280	
142		Oct.	237	5333	582593	540	74520	4793	508073	
143		Nov.	172	3870	586463	540	75060	3330	511403	511403
144		Dec.	3	68	586530	540	75600	-473	510930	-
145	1987	Jan.	4	90	586620	540	76140	-450	510480	509940
146		Feb.	0	0	586620	540	76680	-540	509940	=
147		Mar.	33	743	587363	540	77220	203	510143	**1463**
148		Apr.	230	5175	592538	540	77760	4635	514778	
149		May	109	2453	594990	540	78300	1913	516690	
150		Jun.	316	7110	602100	540	78840	6570	523260	
151		Jul.	526	11835	613935	540	79380	11295	534555	
152		Aug.	462	10395	624330	540	79920	9855	544410	
153		Sep.	363	8168	632498	540	80460	7628	552038	
154		Oct.	104	2340	634838	540	81000	1800	553838	
155		Nov.	7	158	634995	540	81540	-383	553455	553838
156		Dec.	33	743	635738	540	82080	203	553658	-
157	1988	Jan.	0	0	635738	540	82620	-540	553118	553118
158		Feb.	44	990	636728	540	83160	450	553568	=
159		Mar.	74	1665	638393	540	83700	1125	554693	**720**
160		Apr.	282	6345	644738	540	84240	5805	560498	
161		May	513	11543	656280	540	84780	11003	571500	
162		Jun.	580	13050	669330	540	85320	12510	584010	
163		Jul.	255	5738	675068	540	85860	5198	589208	
164		Aug.	169	3803	678870	540	86400	3263	592470	
165		Sep.	196	4410	683280	540	86940	3870	596340	
166		Oct.	213	4793	688073	540	87480	4253	600593	

167		Nov.	153	3443	691515	540	88020	2903	603495	603495
168		Dec.	3	68	691583	540	88560	-473	603023	-
169	1989	Jan.	0	0	691583	540	89100	-540	602483	602123
170		Feb.	32	720	692303	540	89640	180	602663	=
171		Mar.	0	0	692303	540	90180	-540	602123	**1373**
172		Apr.	85	1913	694215	540	90720	1373	603495	
173		May	228	5130	699345	540	91260	4590	608085	
174		Jun.	319	7178	706523	540	91800	6638	614723	
175		Jul.	347	7808	714330	540	92340	7268	621990	
176		Aug.	59	1328	715658	540	92880	788	622778	
177		Sep.	305	6863	722520	540	93420	6323	629100	
178		Oct.	240	5400	727920	540	93960	4860	633960	
179		Nov.	0	0	727920	540	94500	-540	633420	633960
180		Dec.	12	270	728190	540	95040	-270	633150	-
181	1990	Jan.	0	0	728190	540	95580	-540	632610	632610
182		Feb.	36	810	729000	540	96120	270	632880	=
183		Mar.	151	3398	732398	540	96660	2858	635738	**1350**
184		Apr.	154	3465	735863	540	97200	2925	638663	
185		May	202	4545	740408	540	97740	4005	642668	
186		Jun.	229	5153	745560	540	98280	4613	647280	
187		Jul.	567	12758	758318	540	98820	12218	659498	
188		Aug.	227	5108	763425	540	99360	4568	664065	
189		Sep.	247	5558	768983	540	99900	5018	669083	
190		Oct.	181	4073	773055	540	100440	3533	672615	
191		Nov.	103	2318	775373	540	100980	1778	674393	674393
192		Dec.	6	135	775508	540	101520	-405	673988	-
193	1991	Jan.	27	608	776115	540	102060	68	674055	673695
194		Feb.	8	180	776295	540	102600	-360	673695	=
195		Mar.	46	1035	777330	540	103140	495	674190	**698**
196		Apr.	53	1193	778523	540	103680	653	674843	
197		May	529	11903	790425	540	104220	11363	686205	
198		Jun.	320	7200	797625	540	104760	6660	692865	
199		Jul.	318	7155	804780	540	105300	6615	699480	
200		Aug.	345	7763	812543	540	105840	7223	706703	
201		Sep.	692	15570	828113	540	106380	15030	721733	
202		Oct.	392	8820	836933	540	106920	8280	730013	
203		Nov.	14	315	837248	540	107460	-225	729788	731633
204		Dec.	106	2385	839633	540	108000	1845	731633	-
205	1992	Jan.	1	23	839655	540	108540	-518	731115	731093
206		Feb.	47	1058	840713	540	109080	518	731633	=
207		Mar.	0	0	840713	540	109620	-540	731093	**540**
208		Apr.	25	563	841275	540	110160	23	731115	
209		May	153	3443	844718	540	110700	2903	734018	
210		Jun.	132	2970	847688	540	111240	2430	736448	
211		Jul.	386	8685	856373	540	111780	8145	744593	
212		Aug.	182	4095	860468	540	112320	3555	748148	

213		Sep.	158	3555	864023	540	112860	3015	751163	
214		Oct.	83	1868	865890	540	113400	1328	752490	
215		Nov.	2	45	865935	540	113940	-495	751995	752490
216		Dec.	0	0	865935	540	114480	-540	751455	-
217	1993	Jan.	0	0	865935	540	115020	-540	750915	750915
218		Feb.	52	1170	867105	540	115560	630	751545	=
219		Mar.	88	1980	869085	540	116100	1440	752985	**1575**
220		Apr.	113	2543	871628	540	116640	2003	754988	
221		May	556	12510	884138	540	117180	11970	766958	
222		Jun.	504	11340	895478	540	117720	10800	777758	
223		Jul.	421	9473	904950	540	118260	8933	786690	
224		Aug.	432	9720	914670	540	118800	9180	795870	
225		Sep.	417	9383	924053	540	119340	8843	804713	
226		Oct.	217	4883	928935	540	119880	4343	809055	
227		Nov.	19	428	929363	540	120420	-113	808943	809055
228		Dec.	0	0	929363	540	120960	-540	808403	-
229	1994	Jan.	13	293	929655	540	121500	-248	808155	808155
230		Feb.	54	1215	930870	540	122040	675	808830	=
231		Mar.	115	2588	933458	540	122580	2048	810878	**900**
232		Apr.	201	4523	937980	540	123120	3983	814860	
233		May	254	5715	943695	540	123660	5175	820035	
234		Jun.	266	5985	949680	540	124200	5445	825480	
235		Jul.	153	3443	953123	540	124740	2903	828383	
236		Aug.	246	5535	958658	540	125280	4995	833378	
237		Sep.	169	3803	962460	540	125820	3263	836640	
238		Oct.	55	1238	963698	540	126360	698	837338	
239		Nov.	14	315	964013	540	126900	-225	837113	837338
240		Dec.	0	0	964013	540	127440	-540	836573	-
241	1995	Jan.	8	180	964193	540	127980	-360	836213	835830
242		Feb.	31	698	964890	540	128520	158	836370	=
243		Mar.	0	0	964890	540	129060	-540	835830	**1508**
244		Apr.	88	1980	966870	540	129600	1440	837270	
245		May	264	5940	972810	540	130140	5400	842670	
246		Jun.	237	5333	978143	540	130680	4793	847463	
247		Jul.	354	7965	986108	540	131220	7425	854888	
248		Aug.	360	8100	994208	540	131760	7560	862448	
249		Sep.	205	4613	998820	540	132300	4073	866520	
250		Oct.	91	2048	1000868	540	132840	1508	868028	
251		Nov.	112	2520	1003388	540	133380	1980	870008	
252		Dec.	1	23	1003410	540	133920	-518	869490	

Appendix H: STORAGE VOLUME-DEMAND RELATIONSHIP FOR DIFFERENT ROOF AREAS FOR DIFFERENT PLACES OF BANGLADESH

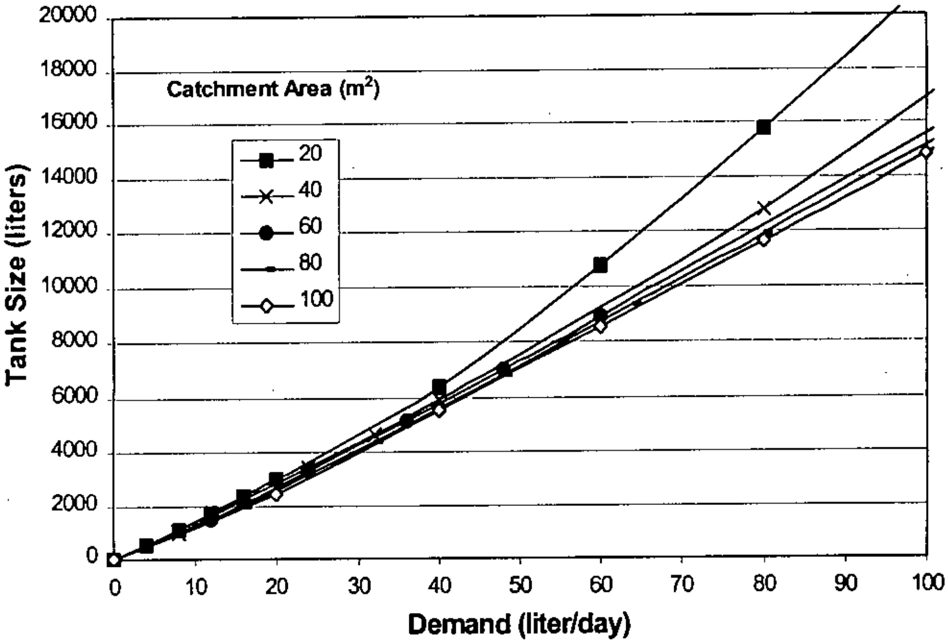

Figure H.1: Storage volume-demand relationship for different roof areas for Barisal.

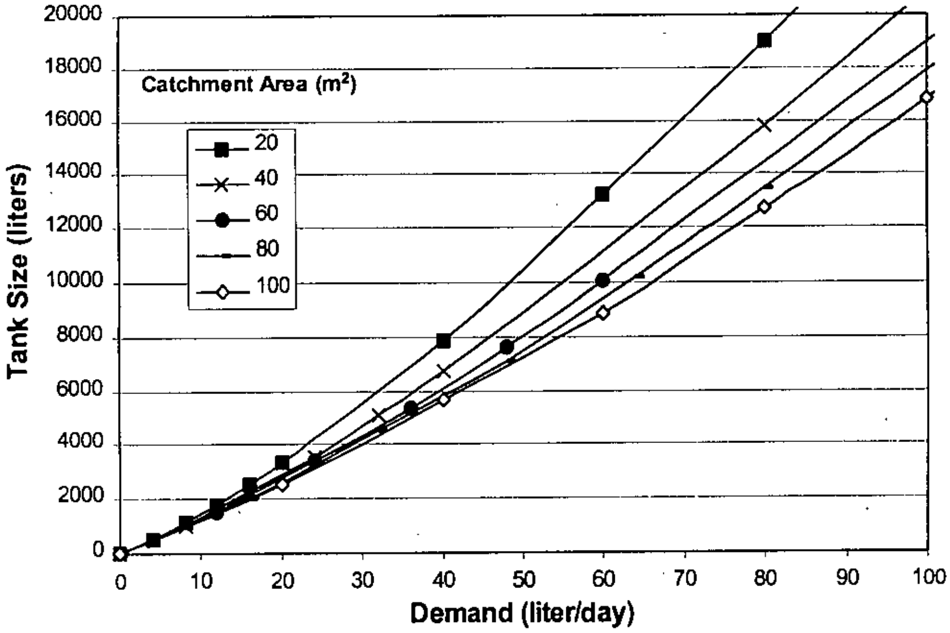

Figure H.2: Storage volume-demand relationship for different roof areas for Bhola.

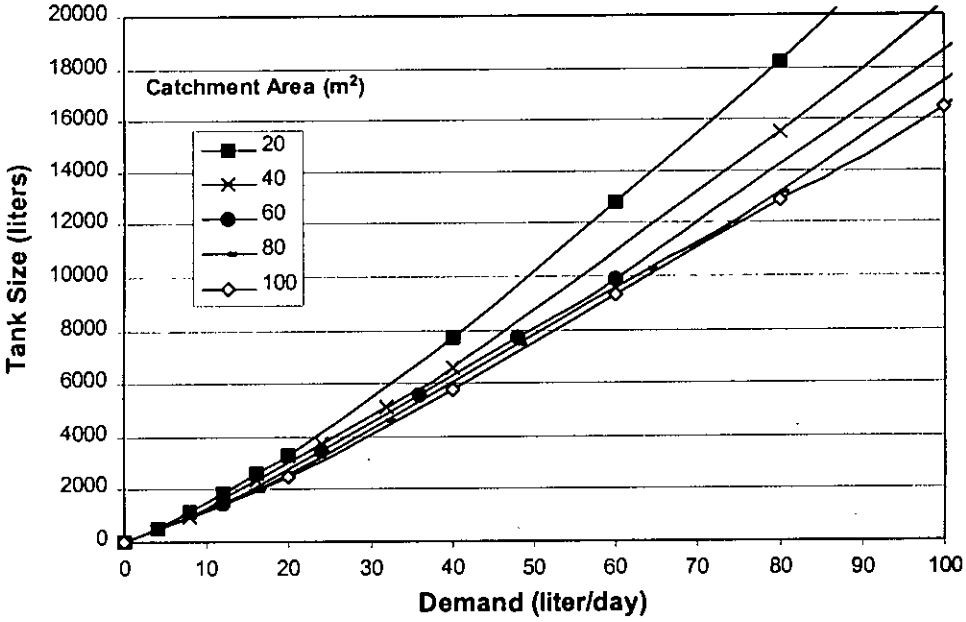

Figure H.3: Storage volume-demand relationship for different roof areas for Bogra.

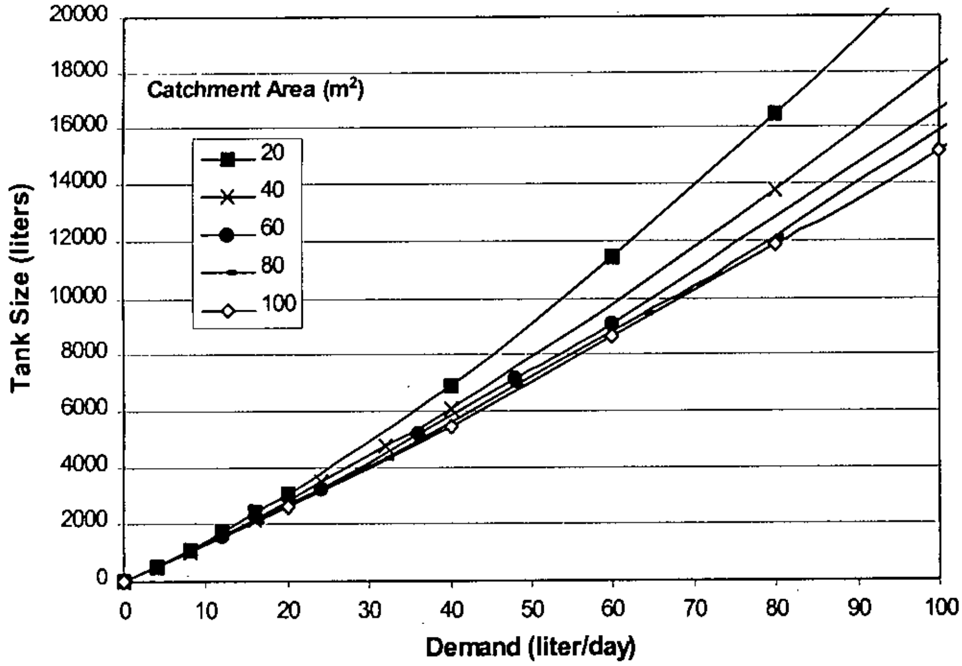

Figure H.4: Storage volume-demand relationship for different roof areas for Chandpur.

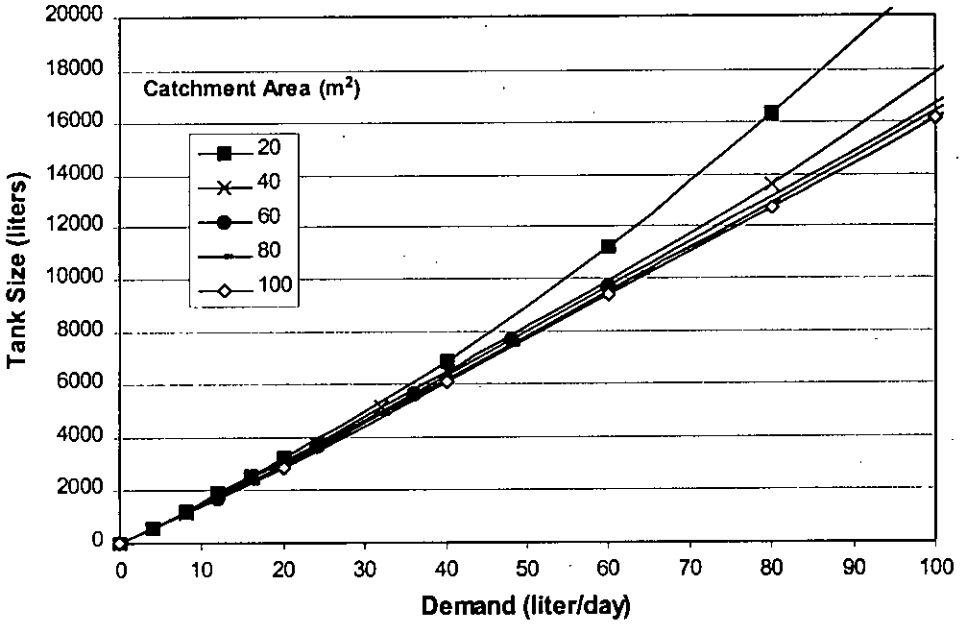

Figure H.5: Storage volume-demand relationship for different roof areas for Chittagong.

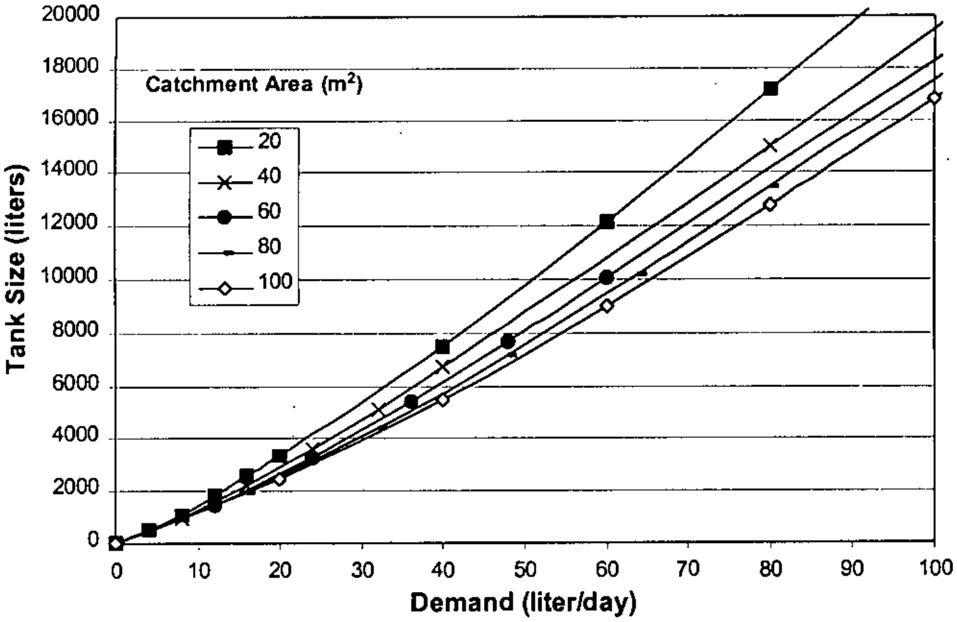

Figure H.6: Storage volume-demand relationship for different roof areas for Comilla.

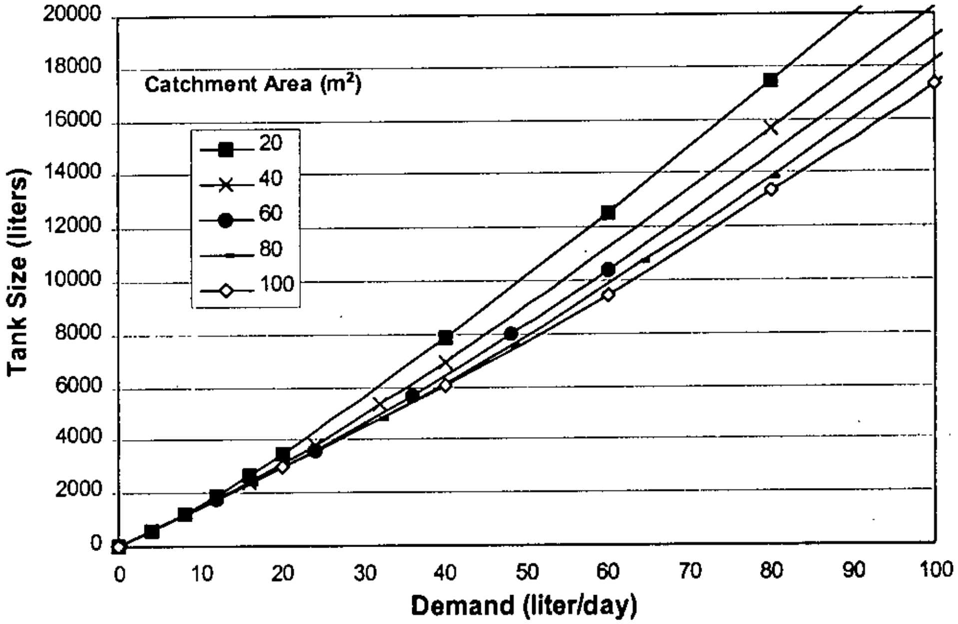

Figure H.7: Storage volume-demand relationship for different roof areas for Cox's Bazar.

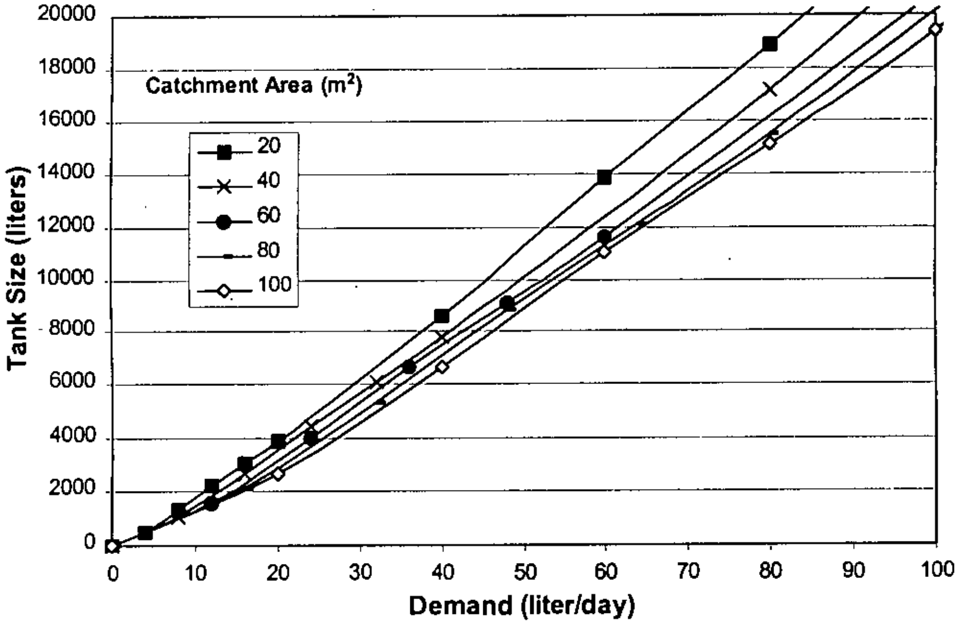

Figure H.8: Storage volume-demand relationship for different roof areas for Dinajpur.

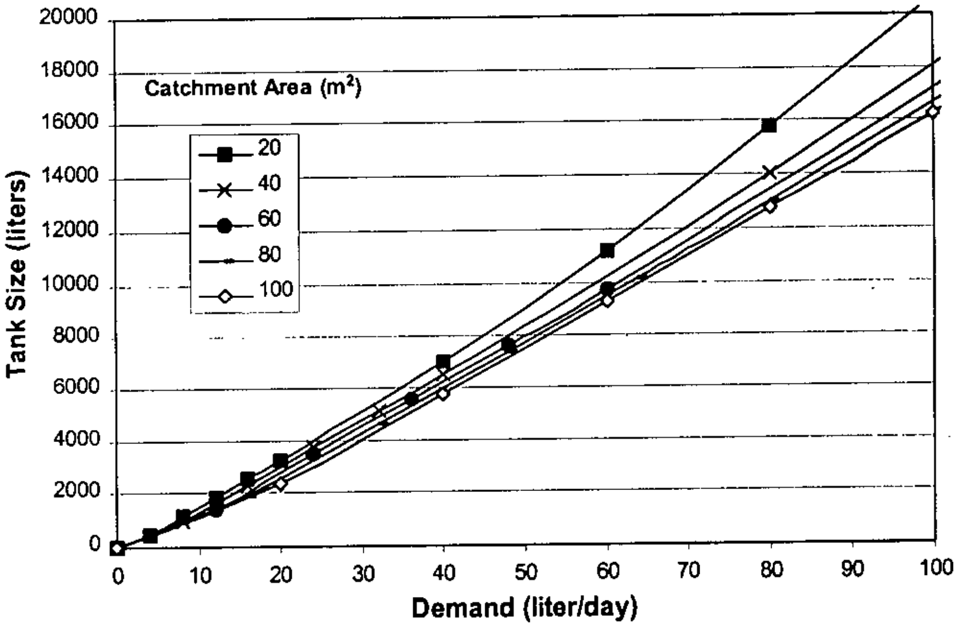

Figure H.9: Storage volume-demand relationship for different roof areas for Faridpur.

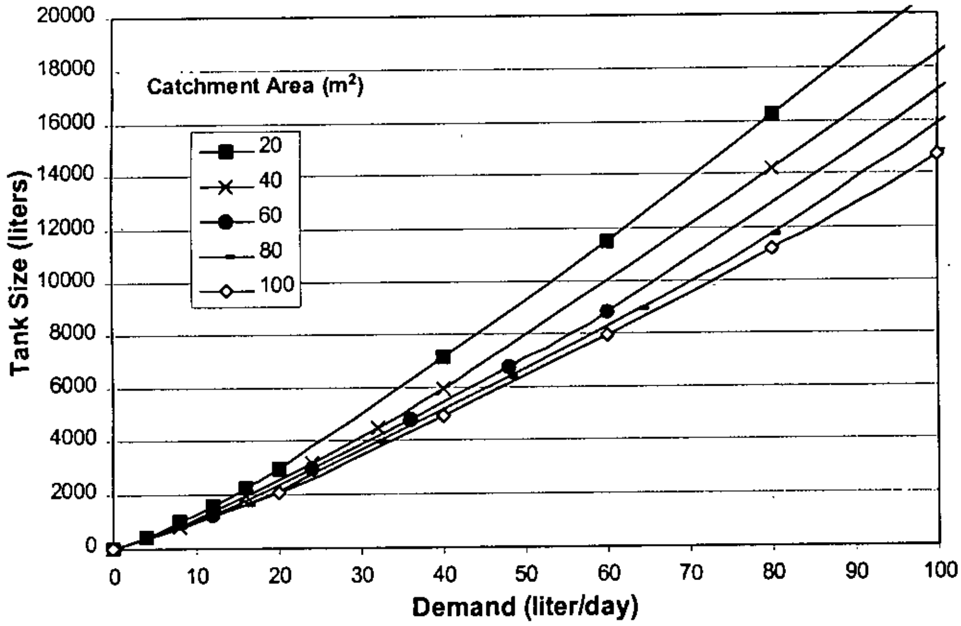

Figure H.10: Storage volume-demand relationship for different roof areas for Feni.

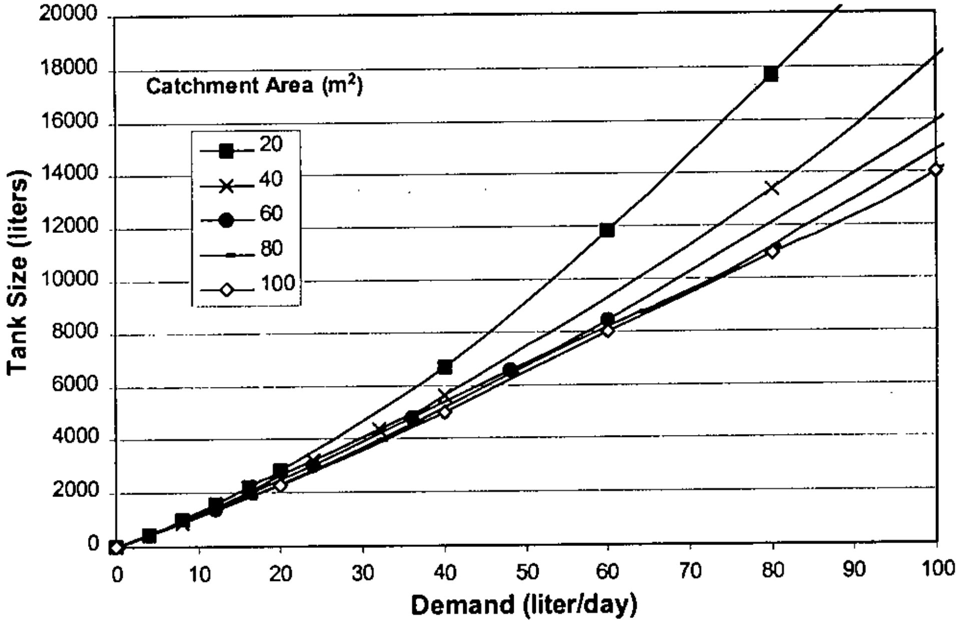

Figure H.11: Storage volume-demand relationship for different roof areas for Hatia.

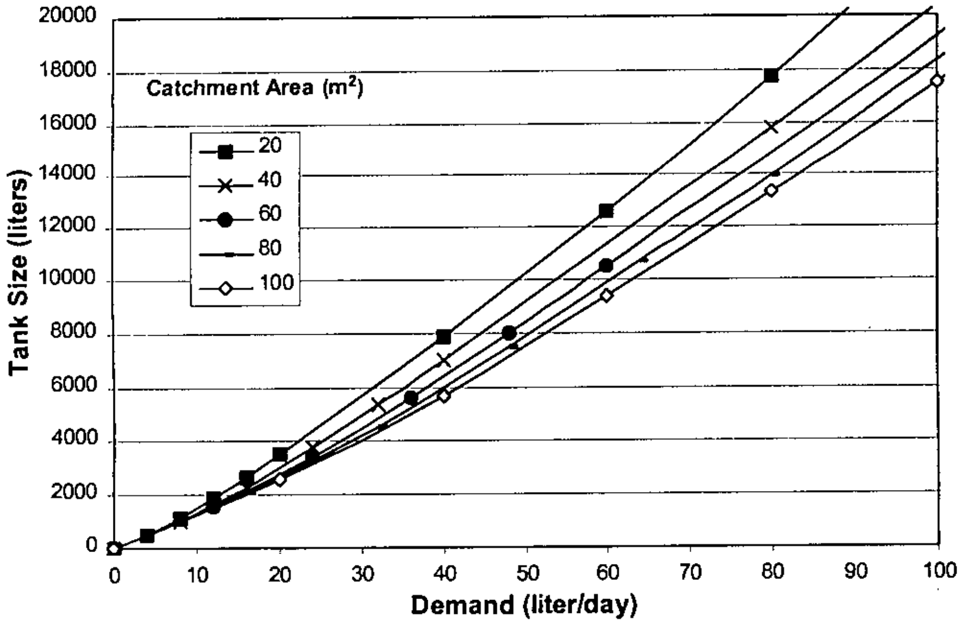

Figure H.12: Storage volume-demand relationship for different roof areas for Ishurdi.

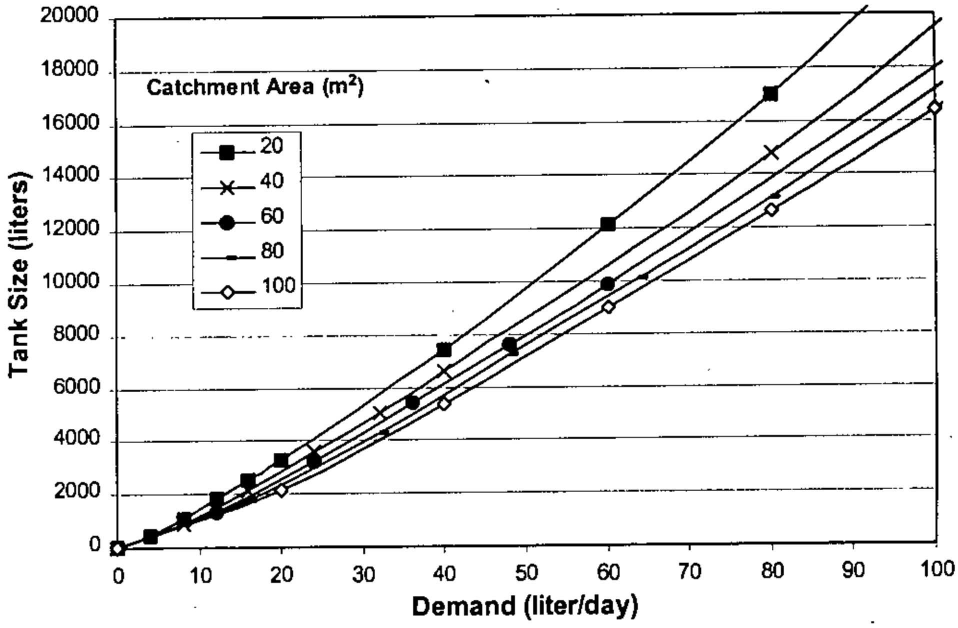

Figure H.13: Storage volume-demand relationship for different roof areas for Jessore.

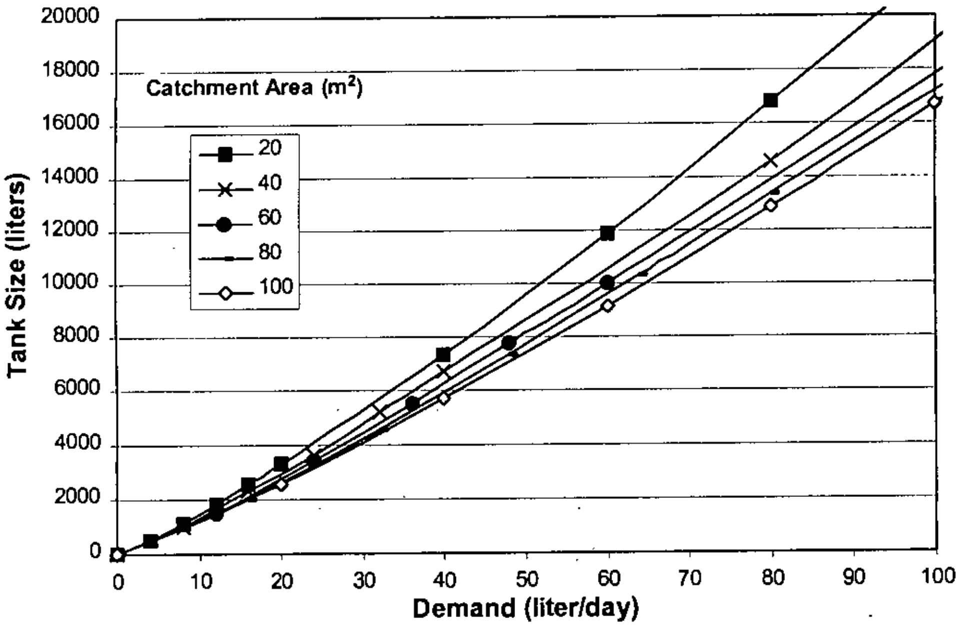

Figure H.14: Storage volume-demand relationship for different roof areas for Khepupara.

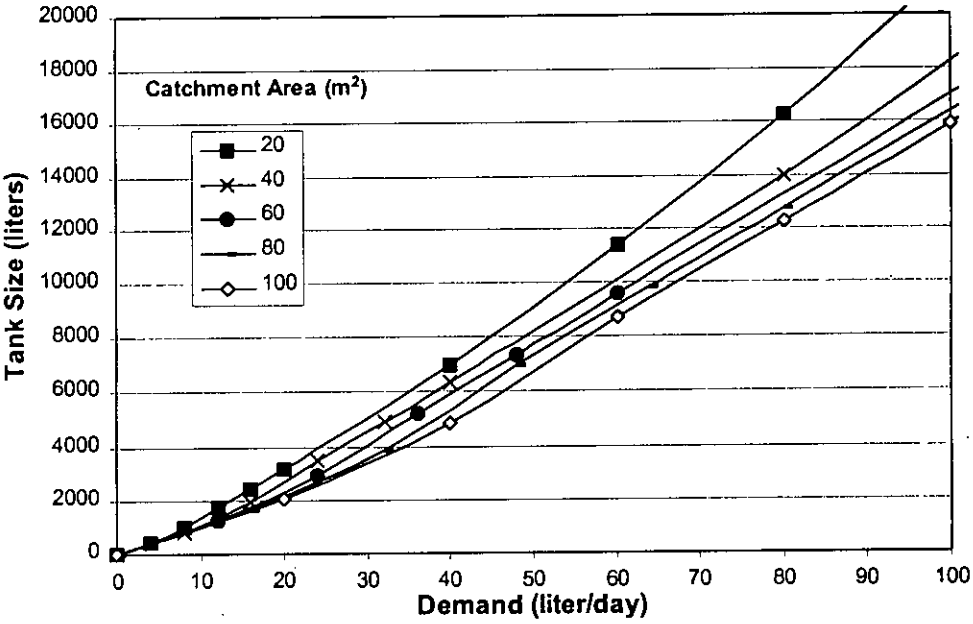

Figure H.15: Storage volume-demand relationship for different roof areas for Khulna.

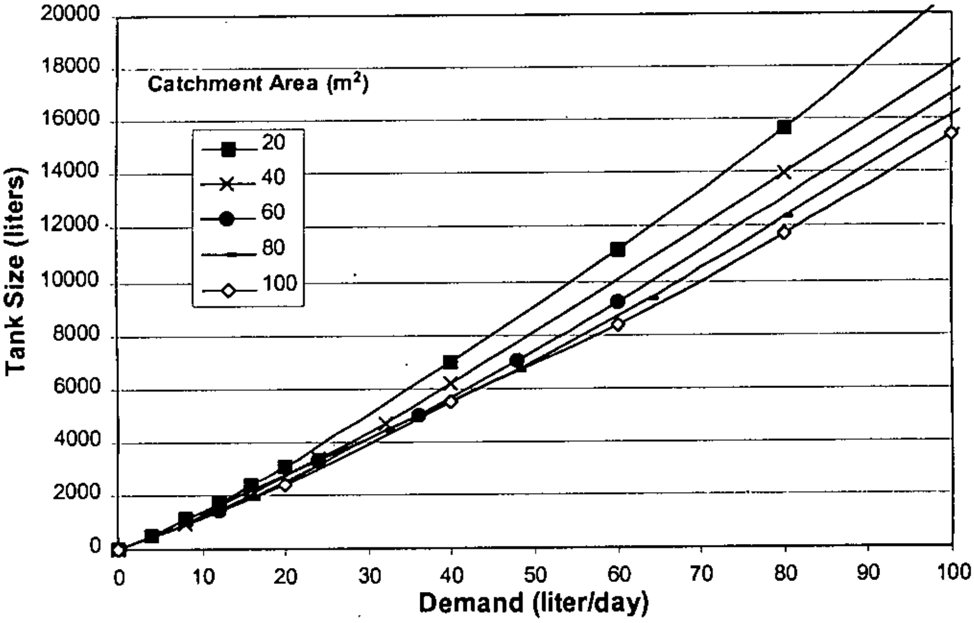

Figure H.16: Storage volume-demand relationship for different roof areas for Mymensingh.

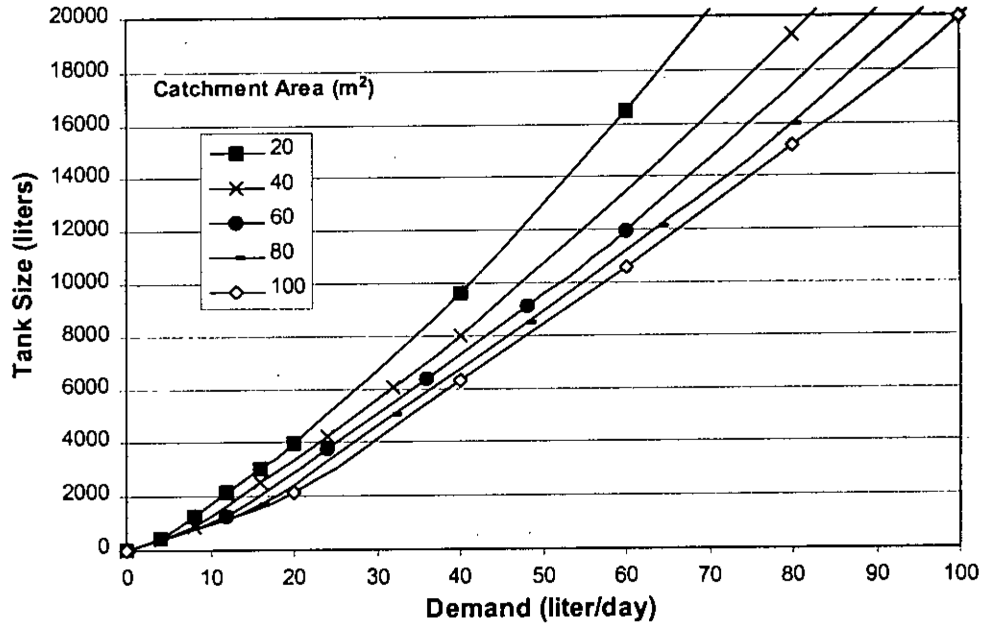

Figure H.17: Storage volume-demand relationship for different roof areas for Rajshahi.

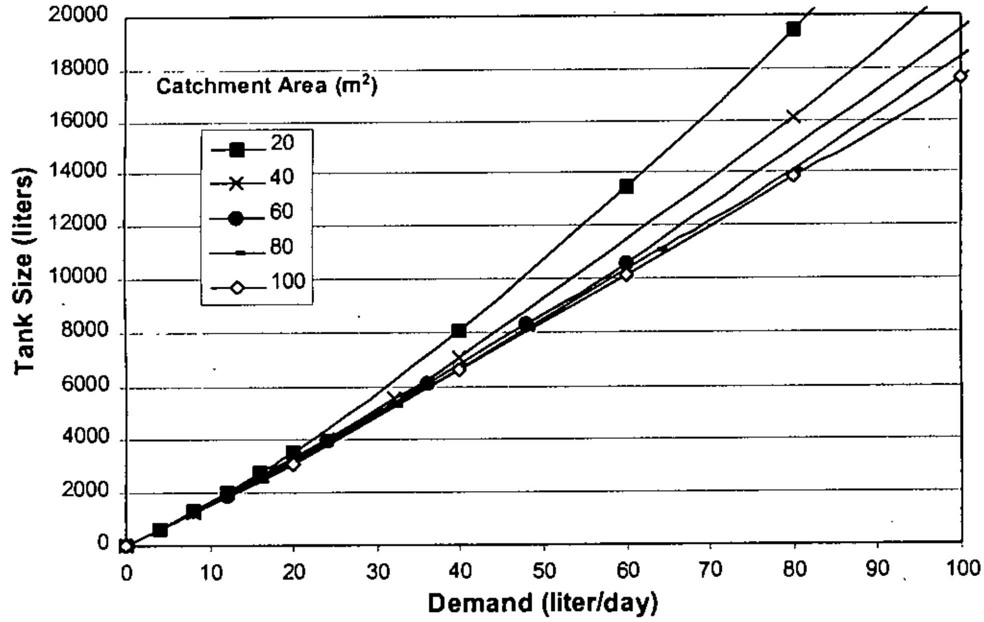

Figure H.18: Storage volume-demand relationship for different roof areas for Rangamati.

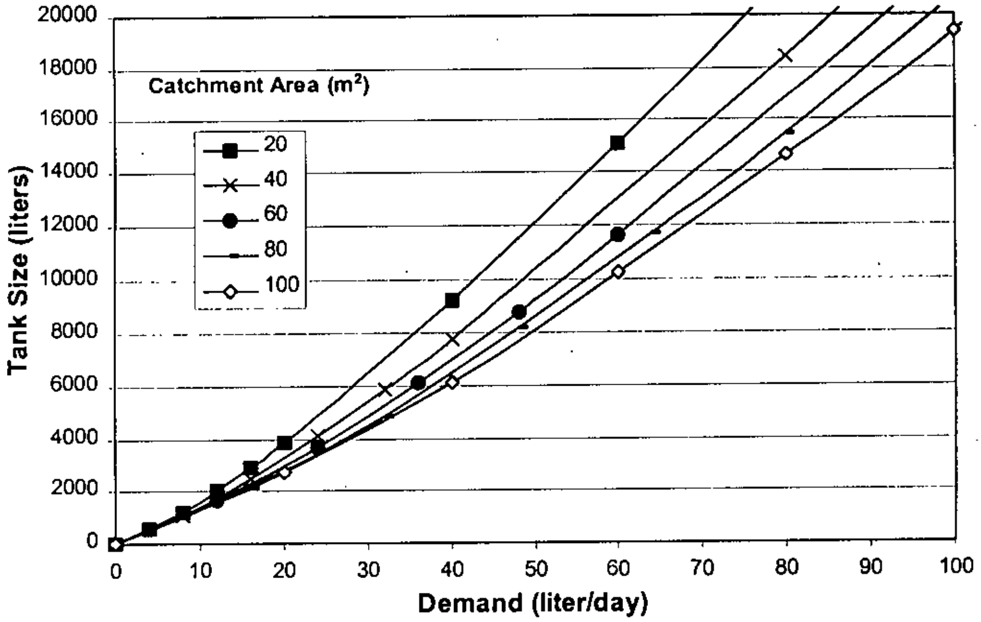

Figure H.19: Storage volume-demand relationship for different roof areas for Rangpur.

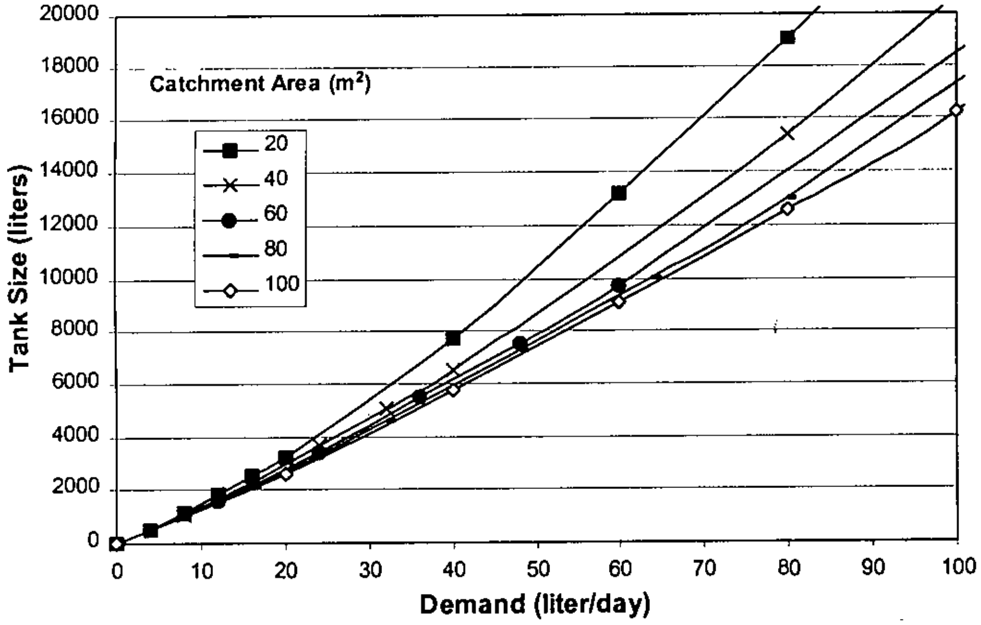

Figure H.20: Storage volume-demand relationship for different roof areas for Sandwip.

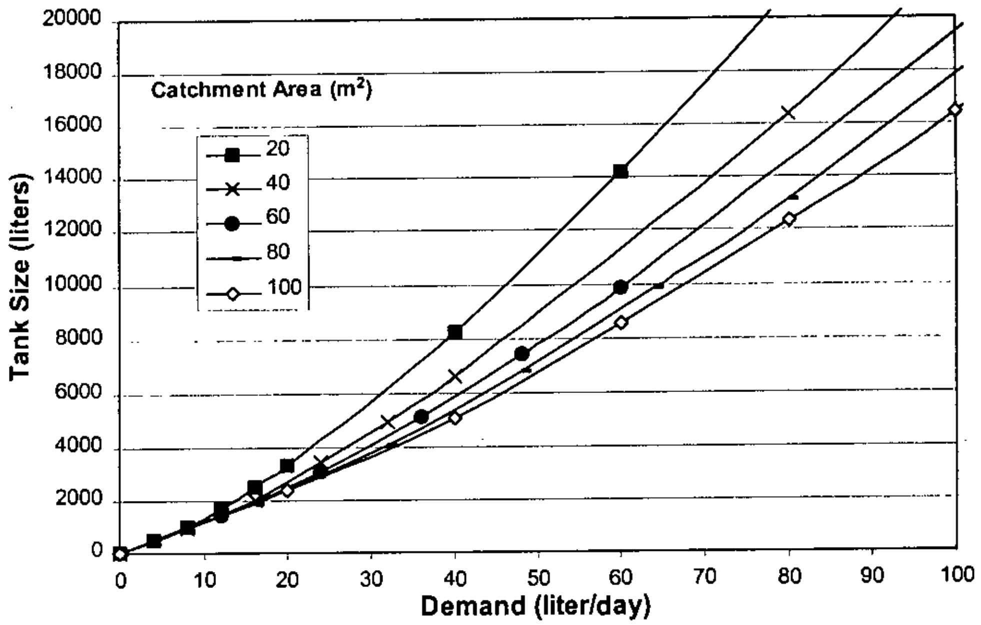

Figure H.21: Storage volume-demand relationship for different roof areas for Satkhira.

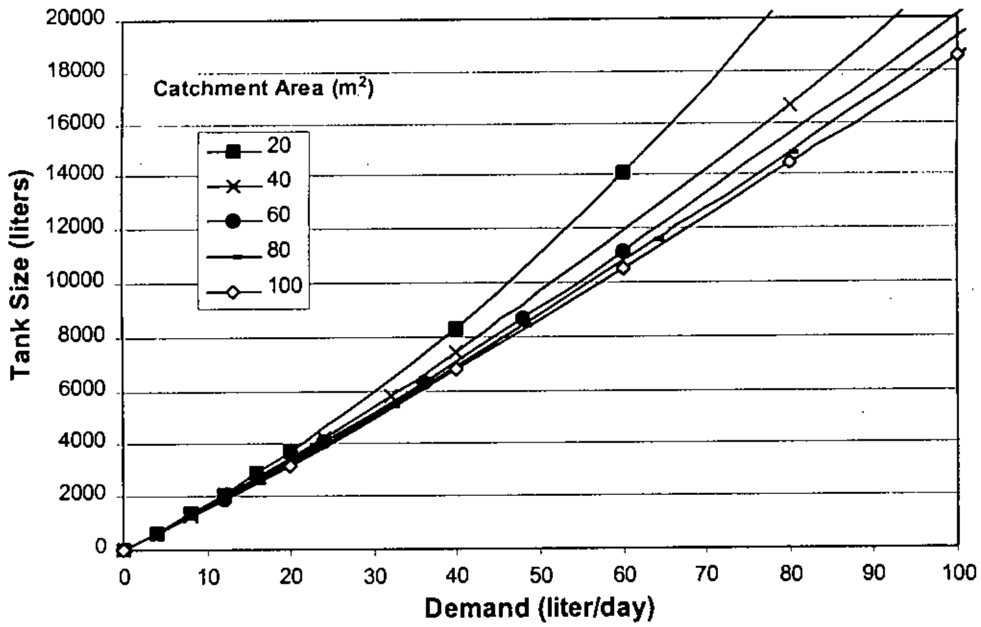

Figure H.22: Storage volume-demand relationship for different roof areas for Sitakunda.

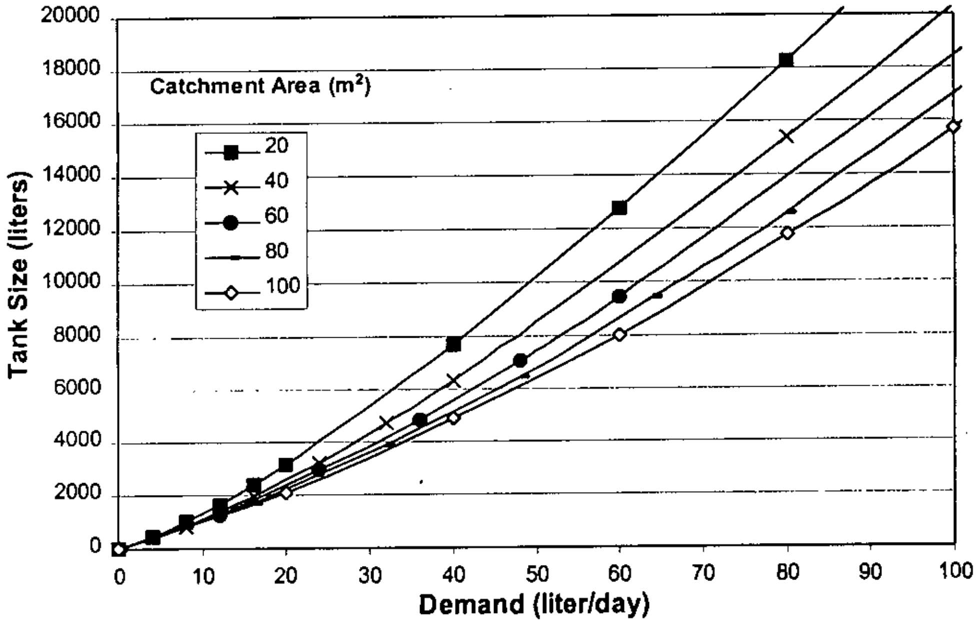

Figure H.23: Storage volume-demand relationship for different roof areas for Srimangal.

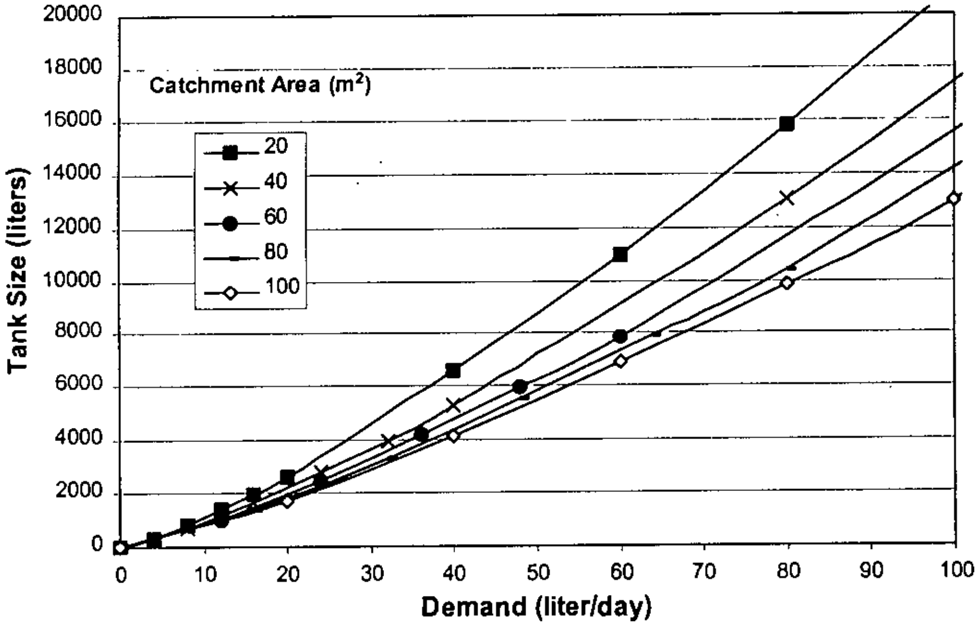

Figure H.24: Storage volume-demand relationship for different roof areas for Sylhet.

213		Sep.	158	3555	864023	540	112860	3015	751163	
214		Oct.	83	1868	865890	540	113400	1328	752490	
215		Nov.	2	45	865935	540	113940	-495	751995	752490
216		Dec.	0	0	865935	540	114480	-540	751455	-
217	1993	Jan.	0	0	865935	540	115020	-540	750915	750915
218		Feb.	52	1170	867105	540	115560	630	751545	=
219		Mar.	88	1980	869085	540	116100	1440	752985	**1575**
220		Apr.	113	2543	871628	540	116640	2003	754988	
221		May	556	12510	884138	540	117180	11970	766958	
222		Jun.	504	11340	895478	540	117720	10800	777758	
223		Jul.	421	9473	904950	540	118260	8933	786690	
224		Aug.	432	9720	914670	540	118800	9180	795870	
225		Sep.	417	9383	924053	540	119340	8843	804713	
226		Oct.	217	4883	928935	540	119880	4343	809055	
227		Nov.	19	428	929363	540	120420	-113	808943	809055
228		Dec.	0	0	929363	540	120960	-540	808403	-
229	1994	Jan.	13	293	929655	540	121500	-248	808155	808155
230		Feb.	54	1215	930870	540	122040	675	808830	=
231		Mar.	115	2588	933458	540	122580	2048	810878	**900**
232		Apr.	201	4523	937980	540	123120	3983	814860	
233		May	254	5715	943695	540	123660	5175	820035	
234		Jun.	266	5985	949680	540	124200	5445	825480	
235		Jul.	153	3443	953123	540	124740	2903	828383	
236		Aug.	246	5535	958658	540	125280	4995	833378	
237		Sep.	169	3803	962460	540	125820	3263	836640	
238		Oct.	55	1238	963698	540	126360	698	837338	
239		Nov.	14	315	964013	540	126900	-225	837113	837338
240		Dec.	0	0	964013	540	127440	-540	836573	-
241	1995	Jan.	8	180	964193	540	127980	-360	836213	835830
242		Feb.	31	698	964890	540	128520	158	836370	=
243		Mar.	0	0	964890	540	129060	-540	835830	**1508**
244		Apr.	88	1980	966870	540	129600	1440	837270	
245		May	264	5940	972810	540	130140	5400	842670	
246		Jun.	237	5333	978143	540	130680	4793	847463	
247		Jul.	354	7965	986108	540	131220	7425	854888	
248		Aug.	360	8100	994208	540	131760	7560	862448	
249		Sep.	205	4613	998820	540	132300	4073	866520	
250		Oct.	91	2048	1000868	540	132840	1508	868028	
251		Nov.	112	2520	1003388	540	133380	1980	870008	
252		Dec.	1	23	1003410	540	133920	-518	869490	

Appendix I: CALCULATION OF NORMAL AND LOG-NORMAL DISTRIBUTIONS OF REQUIRED STORAGE VOLUMES FOR DHAKA

Table I.1: Calculation for Normal and Log-Normal Distributions of Required Storage Volumes.

Sl. No. m	*Year*	*Tank Volume (liter)*
1	1975-1976	1463
2	1976-1977	1440
3	1977-1978	1080
4	1978-1979	2363
5	1979-1980	473
6	1980-1981	1395
7	1981-1982	833
8	1982-1983	855
9	1983-1984	1328
10	1984-1985	1958
11	1985-1986	1463
12	1986-1987	1463
13	1987-1988	720
14	1988-1989	1373
15	1979-1990	1350
16	1990-1991	698
17	1991-1992	540
18	1992-1993	1575
19	1993-1994	900
20	1994-1995	1508

Tank Volume (liter)*	*ln (X)*	*m/(N+1) =* $\phi_s(s)$	*s*
473	6.158038	0.0476	-1.6684
540	6.291569	0.0952	-1.3092
698	6.547503	0.1429	-1.0676
720	6.579251	0.1905	-0.8761
833	6.724433	0.2381	-0.7124
855	6.751101	0.2857	-0.5659
900	6.802395	0.3333	-0.4307
1080	6.984716	0.3810	-0.3030
1328	7.191053	0.4286	-0.1800
1350	7.207860	0.4762	-0.0597
1373	7.224389	0.5238	0.0597
1395	7.240650	0.5714	0.1800
1440	7.272398	0.6190	0.3030
1463	7.287903	0.6667	0.4307
1463	7.287903	0.7143	0.5659
1463	7.287903	0.7619	0.7124
1508	7.318208	0.8095	0.8761
1575	7.362011	0.8571	1.0676
1958	7.579423	0.9048	1.3092
2363	7.767476	0.9524	1.6684

* Tank volumes are in ascending order.

Appendix J: CHI-SQUARE TEST OF NORMAL AND LOG-NORMAL DISTRIBUTIONS OF REQUIRED STORAGE VOLUMES OF DHAKA

Table J.1: Calculation for Normal Distribution.

Interval (*liters*)	*X* (*liters*)	*f* (*observed*)	fX	fX^2	*s*	$\phi(s)$	$P(X)$	*e* (*theoretical*)	$\Sigma(f-e)^2/e$
350-525	437.5	1	437.5	191406.25	-1.48	0.07	0.07	1.40	0.11
525-700	612.5	2	1225	750312.5	-1.11	0.13	0.06	1.26	0.43
700-875	787.5	3	2362.5	1860468.75	-0.75	0.23	0.09	1.89	0.66
875-1050	962.5	1	962.5	926406.25	-0.38	0.35	0.12	2.47	0.88
1050-1225	1137.5	1	1137.5	1293906.25	-0.02	0.49	0.14	2.84	1.19
1225-1400	1312.5	4	5250	6890625	0.35	0.64	0.14	2.85	0.46
1400-1575	1487.5	6	8925	13275937.5	0.71	0.76	0.13	2.52	4.81
1575-1750	1662.5	0	0	0	1.08	0.86	0.10	1.95	1.95
1750-1925	1837.5	0	0	0	1.44	0.93	0.07	1.32	1.32
1925-2100	2012.5	1	2012.5	4050156.25	1.80	0.96	0.04	0.79	0.06
2100-2275	2187.5	0	0	0	2.17	0.98	0.02	0.41	0.41
2275-2450	2362.5	1	2362.5	5581406.25	2.53	0.99	0.02	0.30	1.63
Total		20	24675	34820625			1.00	20.00	**13.90**

Mean, μ = 1233.75

Std. dev., σ = 480.01

Table J.2: Calculation for Log-Normal Distribution.

Interval (*liters*)	*X* (*liters*)	$X'=\ln(X)$	*f* (*observed*)	fX'	fX'^2	*s*	$\phi(s)$	$P(X)$	*e* (*theoretical*)	$\Sigma(f-e)^2/e$
350-525	437.5	6.08	1	6.08	36.98	-0.54	0.296	0.30	5.91	4.08
525-700	350.0	5.86	2	11.72	68.63	0.29	0.614	0.32	6.36	2.99
700-875	437.5	6.08	3	18.24	110.94	0.93	0.824	0.21	4.20	0.34
875-1050	525.0	6.26	1	6.26	39.23	1.45	0.927	0.10	2.06	0.55
1050-1225	612.5	6.42	1	6.42	41.18	1.90	0.971	0.04	0.88	0.02
1225-1400	700.0	6.55	4	26.20	171.67	2.28	0.989	0.02	0.35	37.74
1400-1575	787.5	6.67	6	40.01	266.84	2.62	0.996	0.01	0.14	249.89
1575-1750	875.0	6.77	0	0.00	0.00	2.92	0.998	0.00	0.05	0.05
1750-1925	962.5	6.87	0	0.00	0.00	3.20	0.999	0.00	0.02	0.02
1925-2100	1050.0	6.96	1	6.96	48.39	3.45	1.000	0.00	0.01	119.02
2100-2275	1137.5	7.04	0	0.00	0.00	3.68	1.000	0.00	0.00	0.00
2275-2450	1225.0	7.11	1	7.11	50.56	3.89	1.000	0.00	0.00	418.54
Total			20	129.01	834.43			1.00	20.00	**833.25**

Mean, μ = 6.45

Std. dev., σ = 0.35

Degree of freedom, f = 9

Significance level, α = 5%

Chi-square value, $C_{.95,9}$ = **16.9**

Appendix K: CALCULATION OF REQUIRED STORAGE VOLUMES FOR DIFFERENT DEGREES OF SECURITY FOR DHAKA

Table K.1: Calculation of Normal and Log-Normal Distributions of Required Storage Volumes.

SL. No.	*Year*	*Required tank volume (liters)*	*Ln (X)*	*Tank volume (liters)*	*Normal distribution*	*Log-normal distribution*
1	1975-1976	1463	7.29	1	0.47	0.00
2	1976-1977	1440	7.27	200	1.46	0.00
3	1977-1978	1080	6.98	400	3.91	0.65
4	1978-1979	2363	7.77	600	8.99	6.33
5	1979-1980	473	6.16	800	17.85	19.82
6	1980-1981	1395	7.24	1000	30.81	37.43
7	1981-1982	833	6.72	1200	46.77	54.40
8	1982-1983	855	6.75	1400	63.27	68.26
9	1983-1984	1328	7.19	1600	77.61	78.54
10	1984-1985	1958	7.58	1800	88.08	85.75
11	1985-1986	1463	7.29	2000	94.51	90.63
12	1986-1987	1463	7.29	2200	97.83	93.86
13	1987-1988	720	6.58	2400	99.26	95.99
14	1988-1989	1373	7.22	2600	99.79	97.37
15	1979-1990	1350	7.21	2800	99.95	98.27
16	1990-1991	698	6.55	3000	99.99	98.86
17	1991-1992	540	6.29	3200	100.00	99.24
18	1992-1993	1575	7.36	3400	100.00	99.50
19	1993-1994	900	6.80	3600	100.00	99.66
20	1994-1995	1508	7.32	3800	100.00	99.77
				Mean, μ =	1239	7.04
				Std. dev., σ =	476	0.42

Table K.2: Calculation of Required Storage Volumes (liters) for Different Degrees of Security.

Distribution	*Degrees of Security*		
	99%	90%	80%
Normal	129.14	112.24	91.62
Log-normal	3063.82	1969.32	1634.90

Appendix L: CALCULATION OF RELIABILITIES FOR DIFFERENT AMOUNT OF DEMANDS WITH DIFFERENT CATCHMENT AREAS FOR DHAKA

Table L.1: Calculation of Reliabilities for different catchment areas.

Demand (liters/day)	*Reliability (%) for Catchment Area of*				
	20 (m^2)	*40 (m^2)*	*60 (m^2)*	*80 (m^2)*	*100 (m^2)*
20	[redacted]	100.00	100.00	100.00	100.00
40	[redacted]	[redacted]	100.00	100.00	100.00
60	[redacted]	100.00	[redacted]	100.00	100.00
80	[redacted]	[redacted]	100.00	[redacted]	100.00
100	[redacted]	99.39	100.00	100.00	[redacted]
120	[redacted]	[redacted]	[redacted]	100.00	100.00
140	[redacted]	84.79	99.75	100.00	100.00
160	[redacted]	[redacted]	98.68	[redacted]	100.00
180	[redacted]	46.98	[redacted]	99.85	100.00
200	[redacted]	[redacted]	89.28	99.39	[redacted]
240		[redacted]	[redacted]	[redacted]	99.64
280		[redacted]	40.69	84.79	97.76
300		1.02	[redacted]	76.57	[redacted]
320		[redacted]	20.56	[redacted]	92.23
360		[redacted]	[redacted]	46.98	81.51
400		[redacted]	3.58	[redacted]	[redacted]
420		0.01	[redacted]	22.59	58.98
480			[redacted]	[redacted]	35.97
500			0.27	6.45	[redacted]
540			[redacted]	3.17	19.05
560			0.05	[redacted]	15.01
600			[redacted]	1.02	[redacted]
640			0.00	[redacted]	5.24
700				0.14	[redacted]
720				[redacted]	1.62
800				[redacted]	[redacted]
900					[redacted]
1000					[redacted]

Table L.2: Reliabilities for different Demand-Area Ratios.

Demand / Area (liters/day/m^2)	*Reliability (%)*
0	100.00
1	100.00
2	99.98
3	95.58
4	67.05
5	29.52
6	9.03
7	2.19
8	0.46
9	0.09
10	0.02

Appendix M: GENERAL RELIABILITY CURVES FOR DIFFERENT PLACES OF BANGLADESH

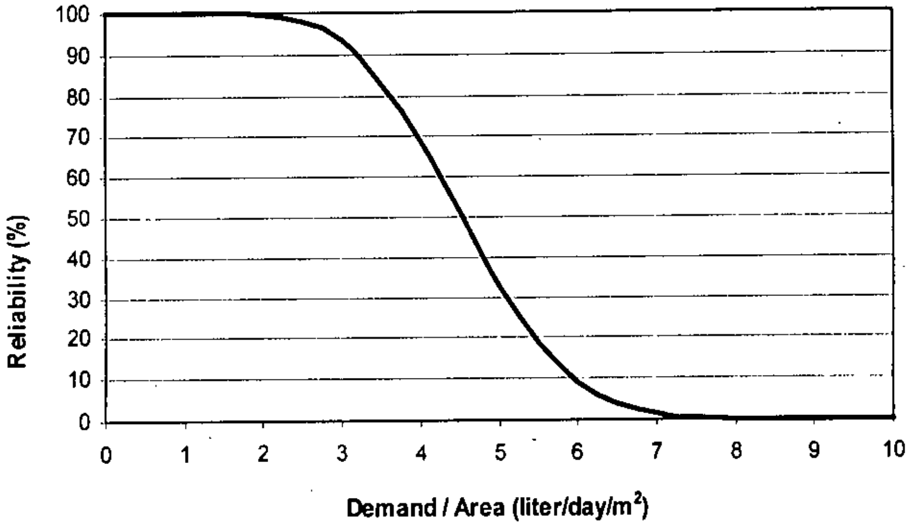

Figure M.1: General reliability curve for Barisal.

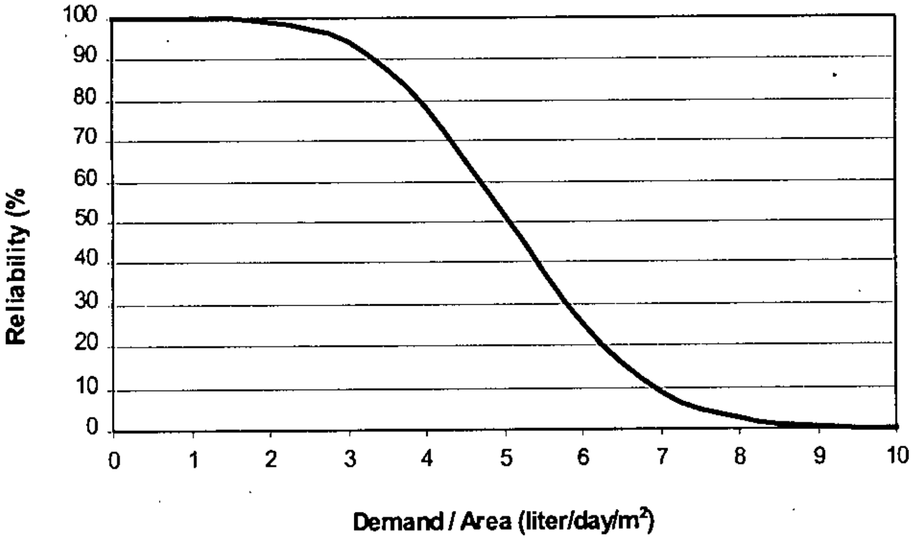

Figure M.2: General reliability curve for Bhola.

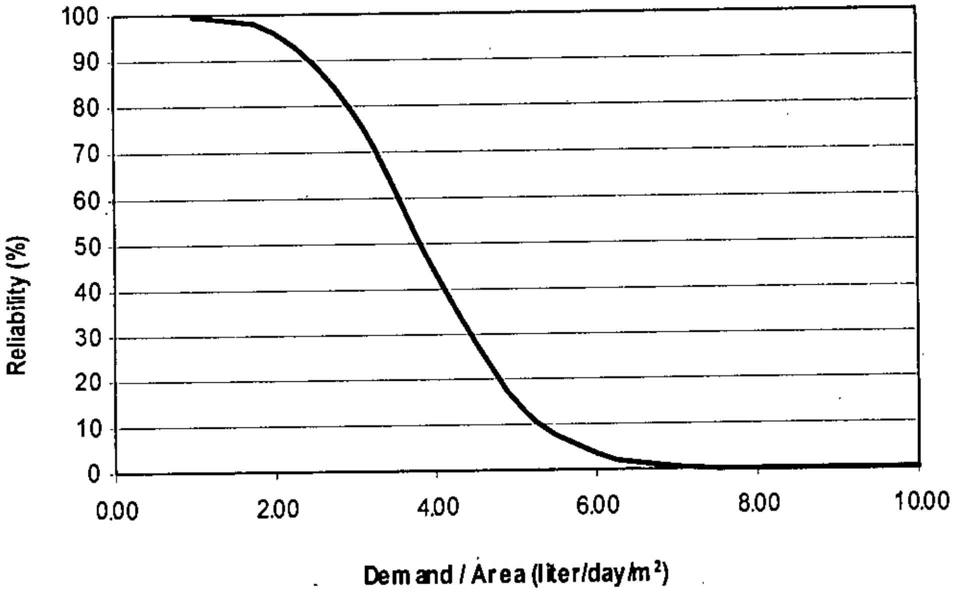

Figure M.3: General reliability curve for Bogra.

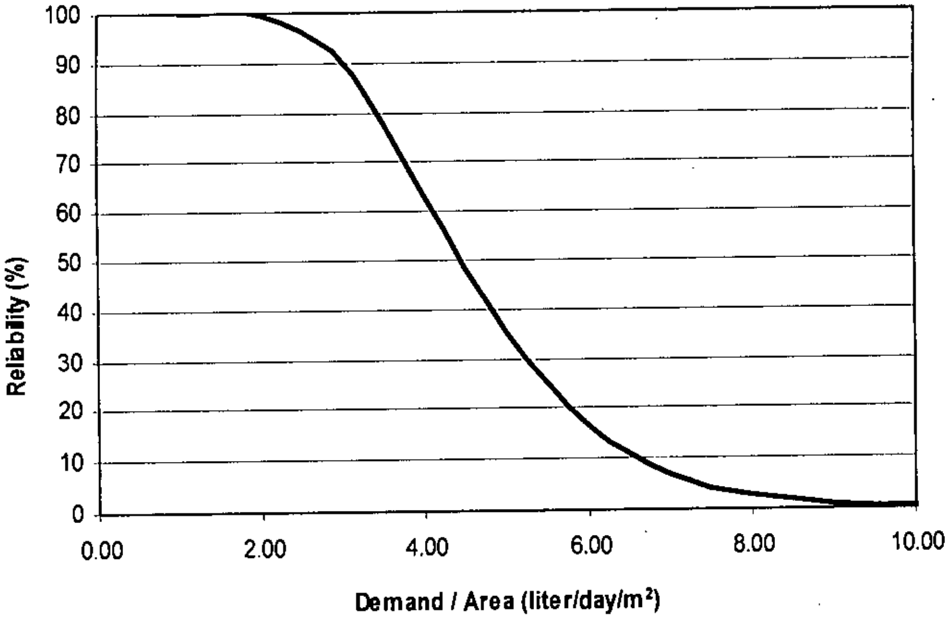

Figure M.4: General reliability curve for Chandpur.

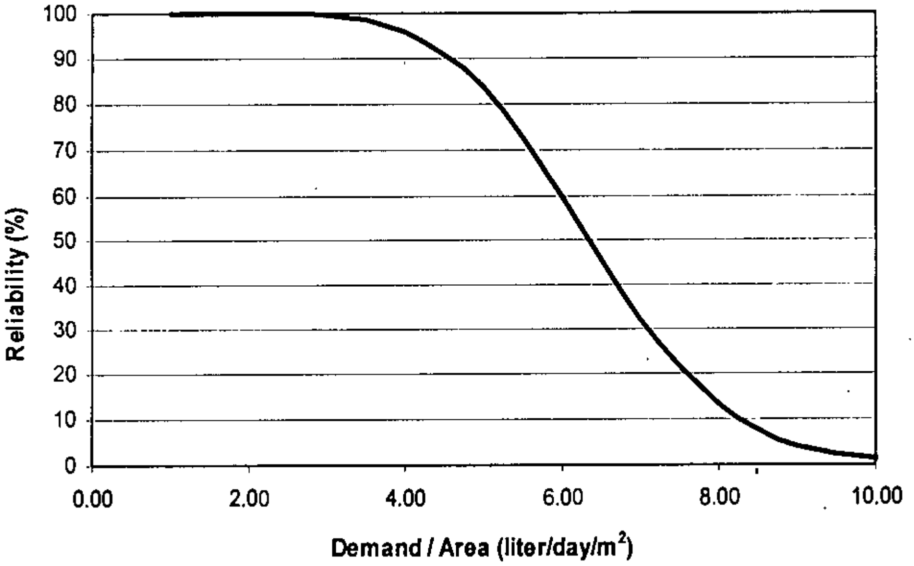

Figure M.5: General reliability curve for Chittagong.

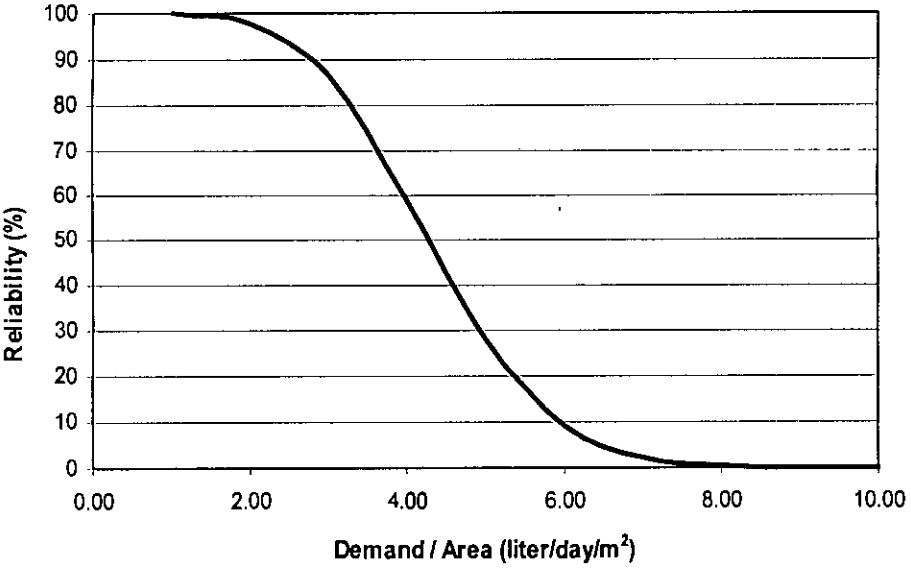

Figure M.6: General reliability curve for Comilla.

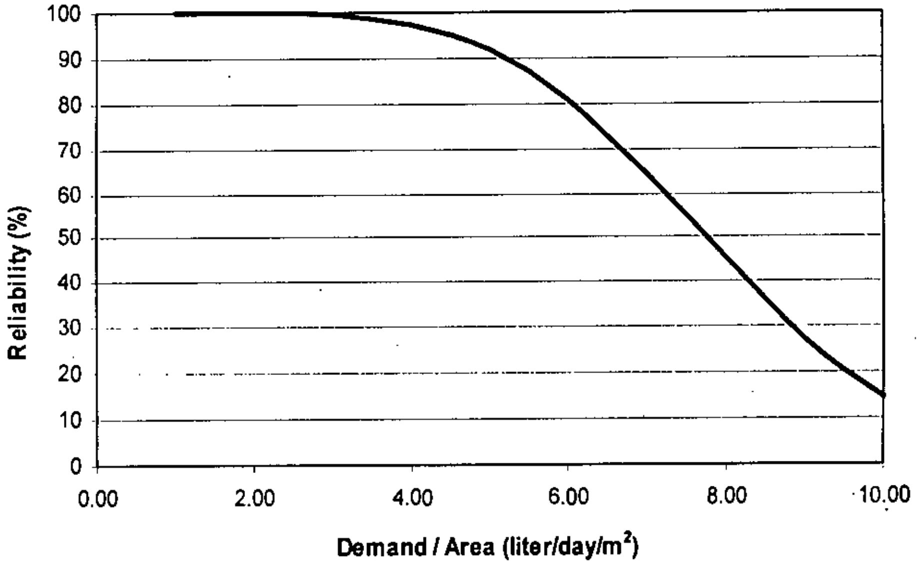

Figure M.7: General reliability curve for Cox's Bazar.

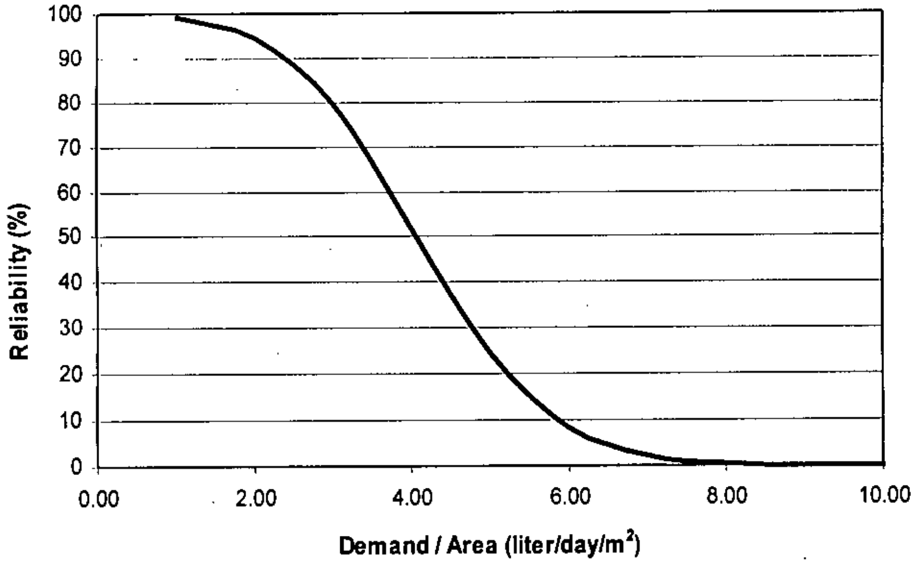

Figure M.8: General reliability curve for Dinajpur.

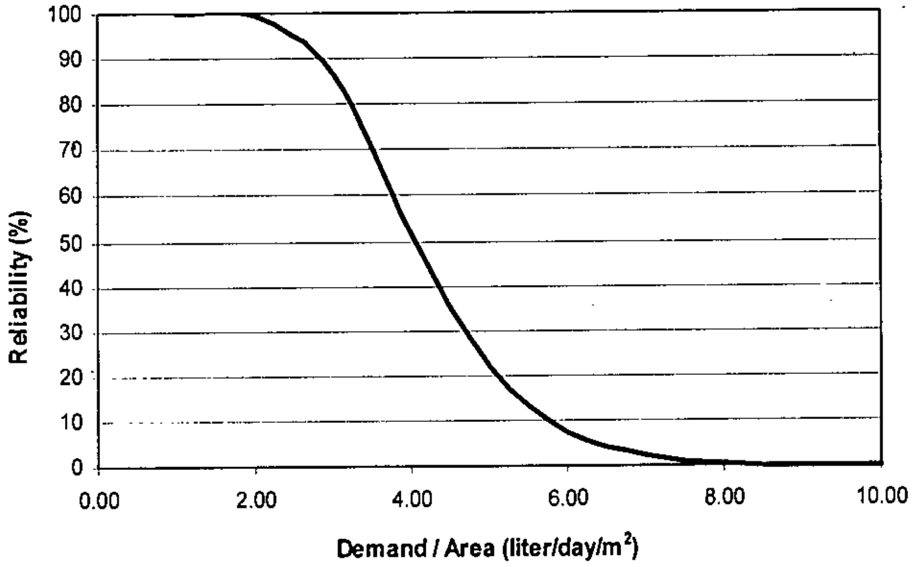

Figure M.9: General reliability curve for Faridpur.

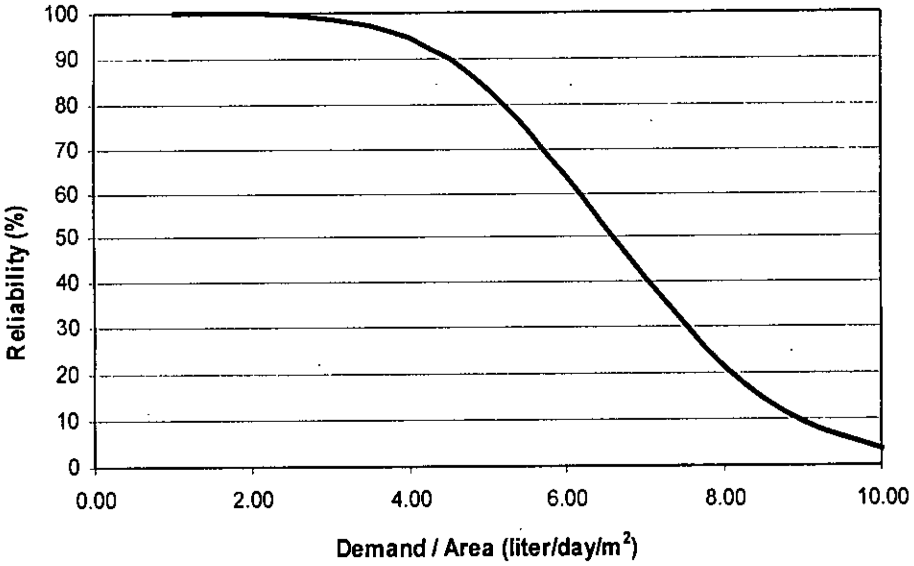

Figure M.10: General reliability curve for Feni.

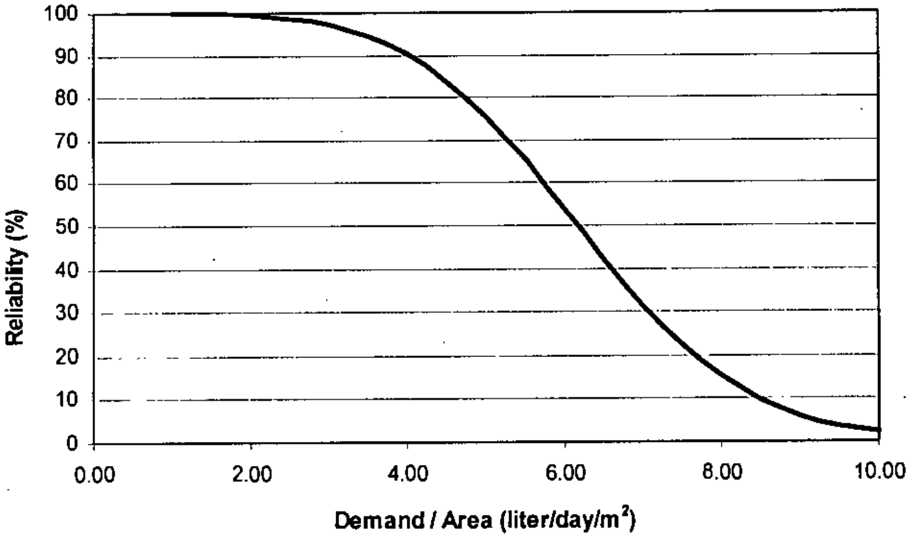

Figure M.11: General reliability curve for Hatiya.

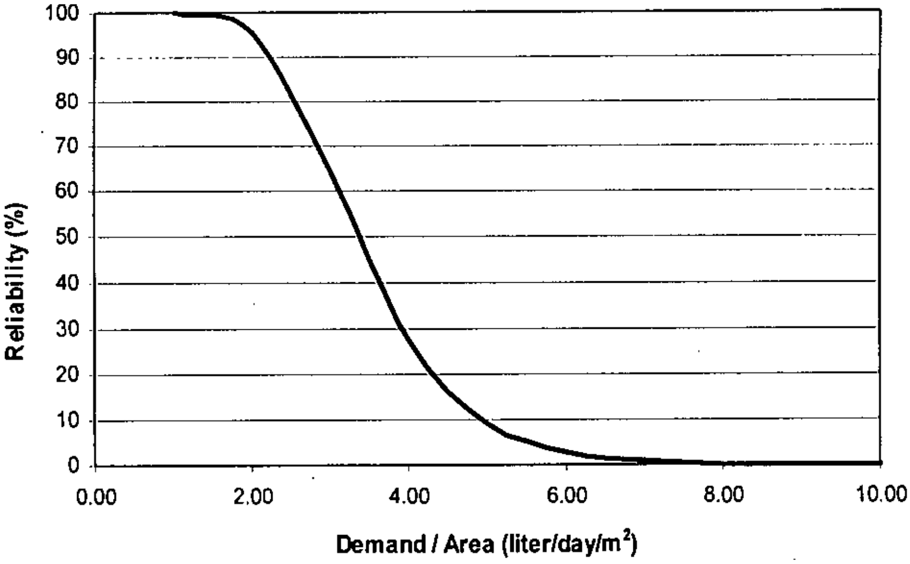

Figure M.12: General reliability curve for Ishurdi.

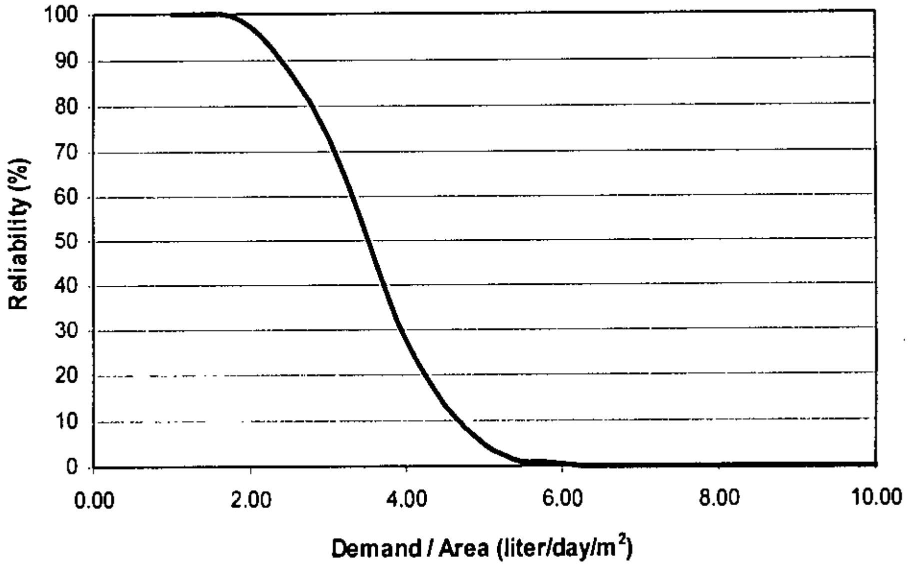

Figure M.13: General reliability curve for Jessore.

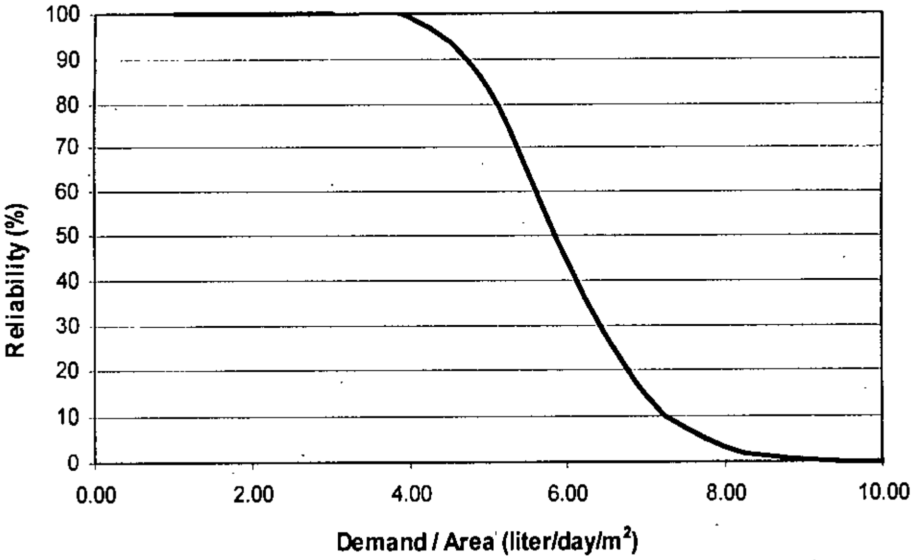

Figure M.14: General reliability curve for Khepupara.

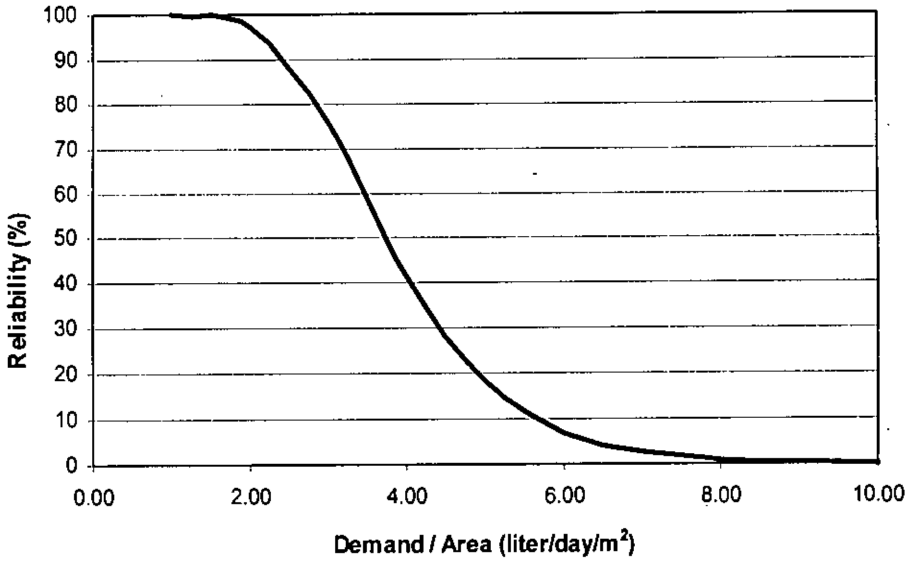

Figure M.15: General reliability curve for Khulna.

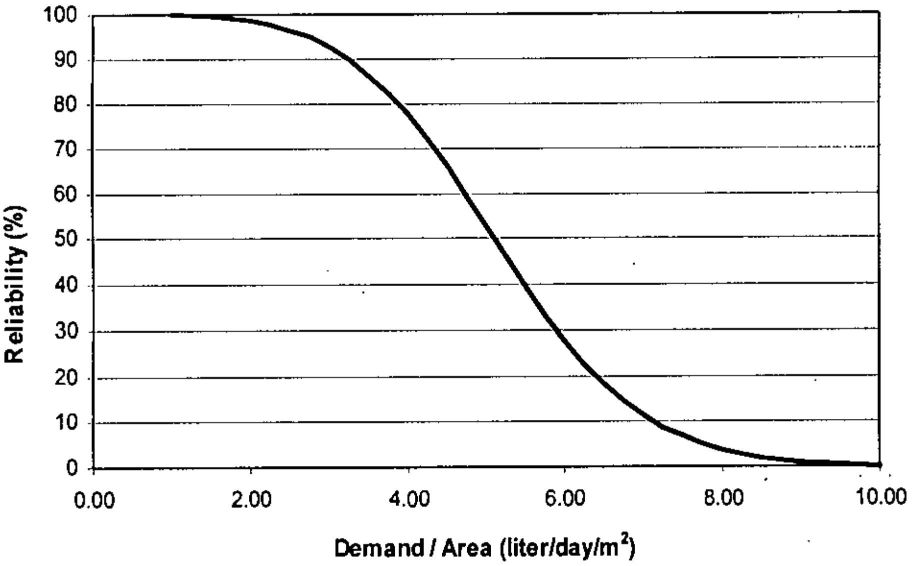

Figure M.16: General reliability curve for Mymensingh.

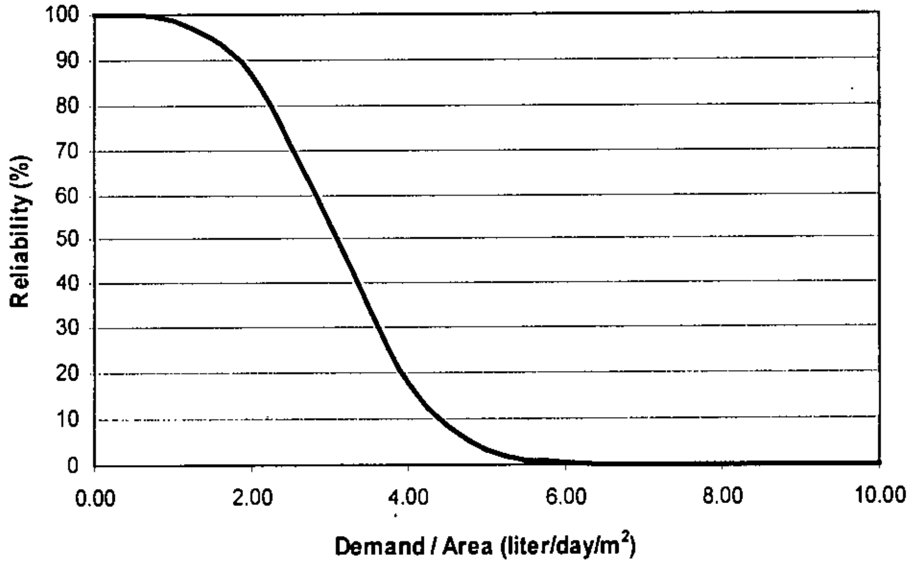

Figure M.17: General reliability curve for Rajshahi.

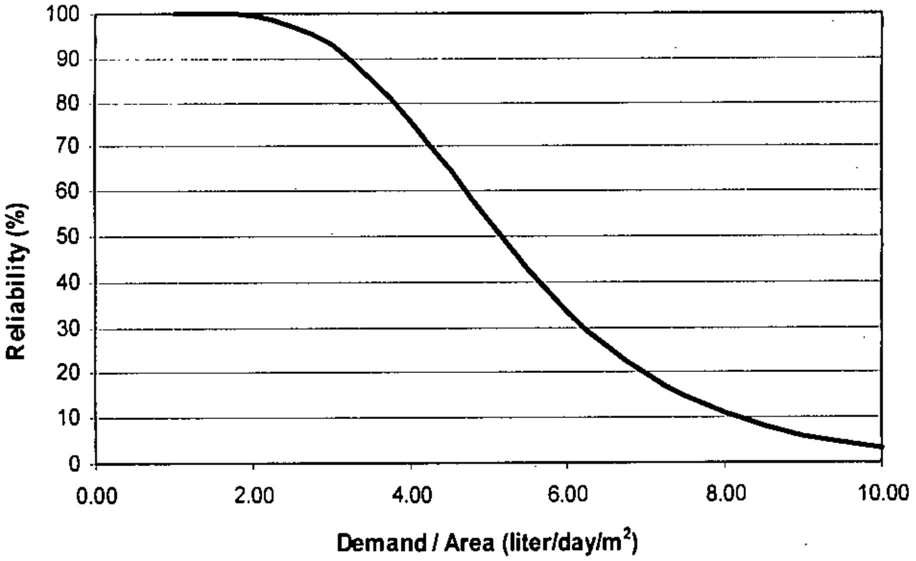

Figure M.18: General reliability curve for Rangamati.

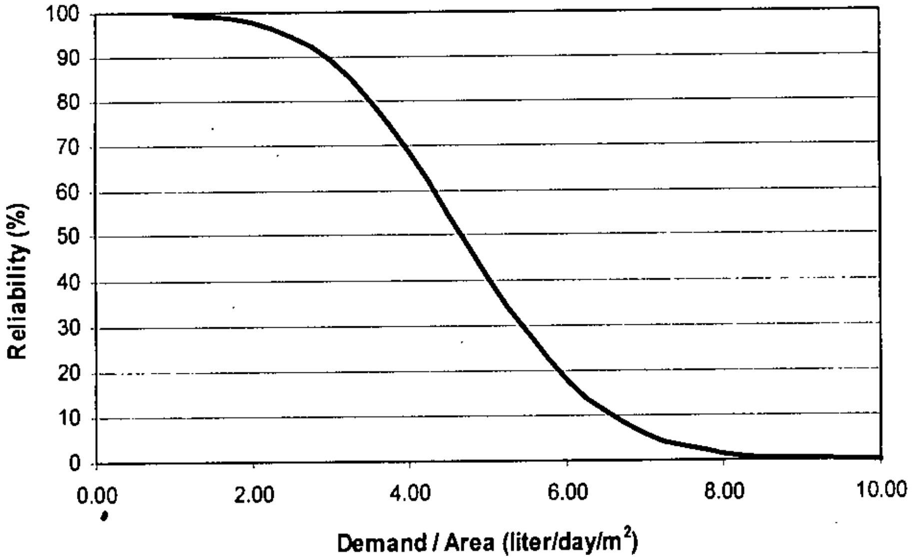

Figure M.19: General reliability curve for Rangpur.

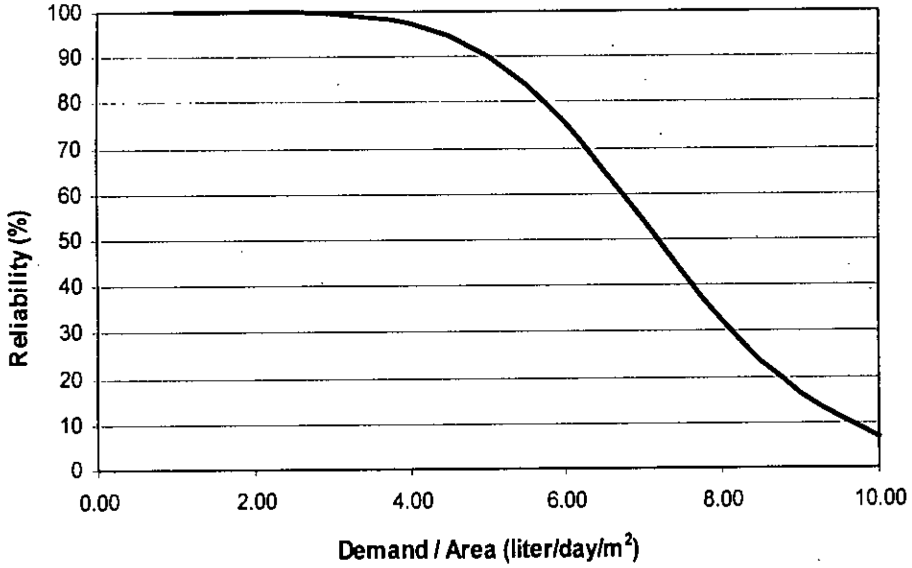

Figure M.20: General reliability curve for Sandwip.

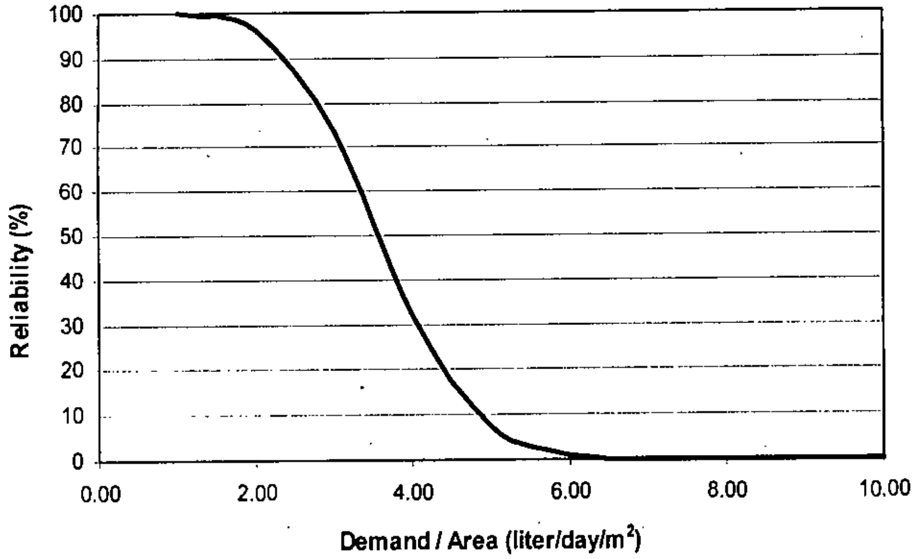

Figure M.21: General reliability curve for Satkhira.

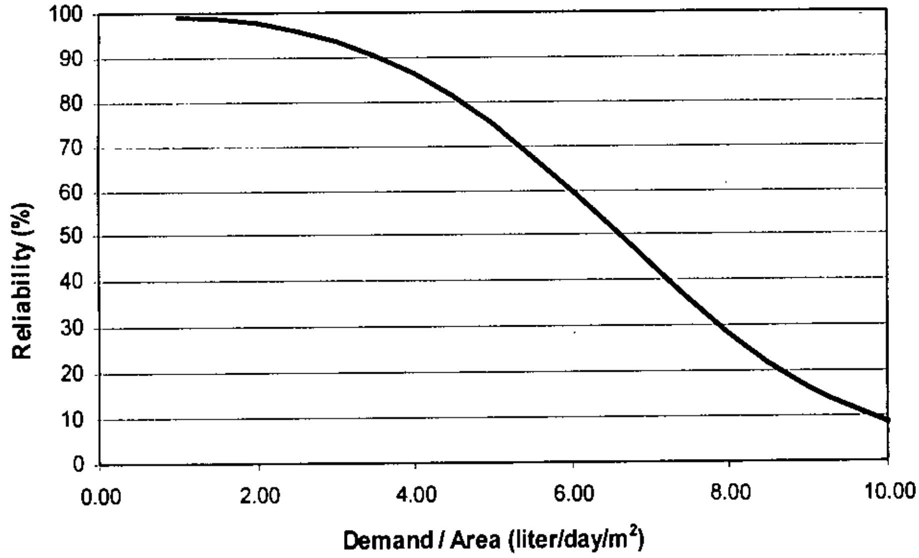

Figure M.22: General reliability curve for Sitakunda.

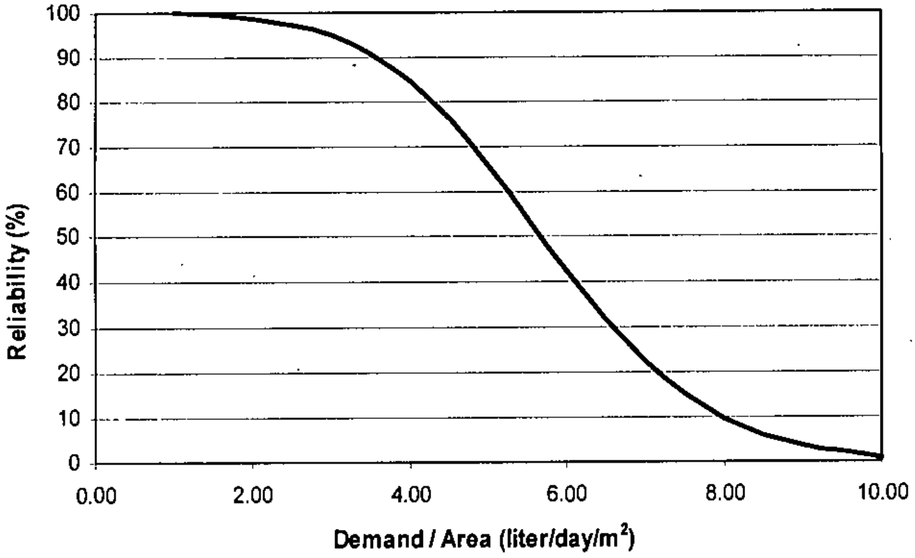

Figure M.23: General reliability curve for Srimangal.

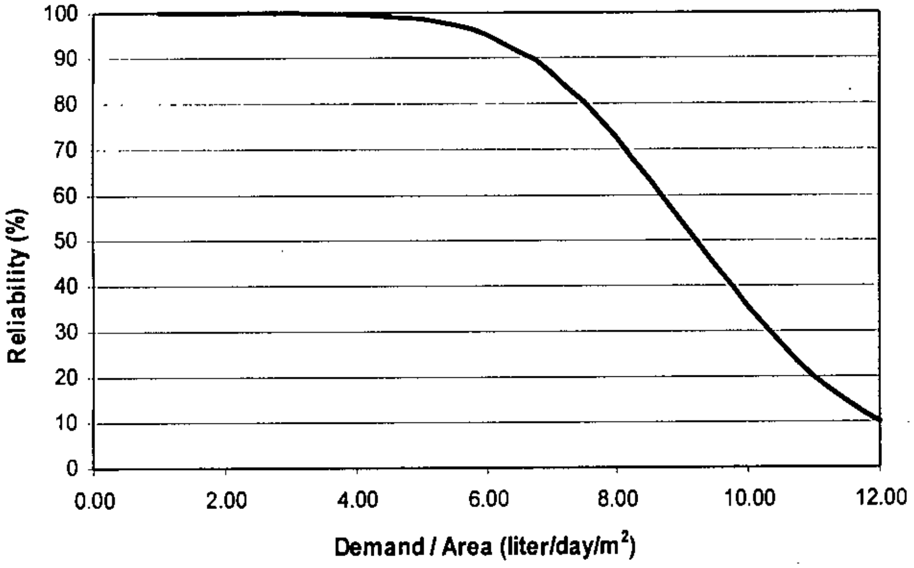

Figure M.24: General reliability curve for Sylhet.

Appendix N: DESIGN CURVES FOR REQUIRED STORAGE VOLUME FOR DRINKING WATER FOR DIFFERENT PLACES OF BANGLADESH

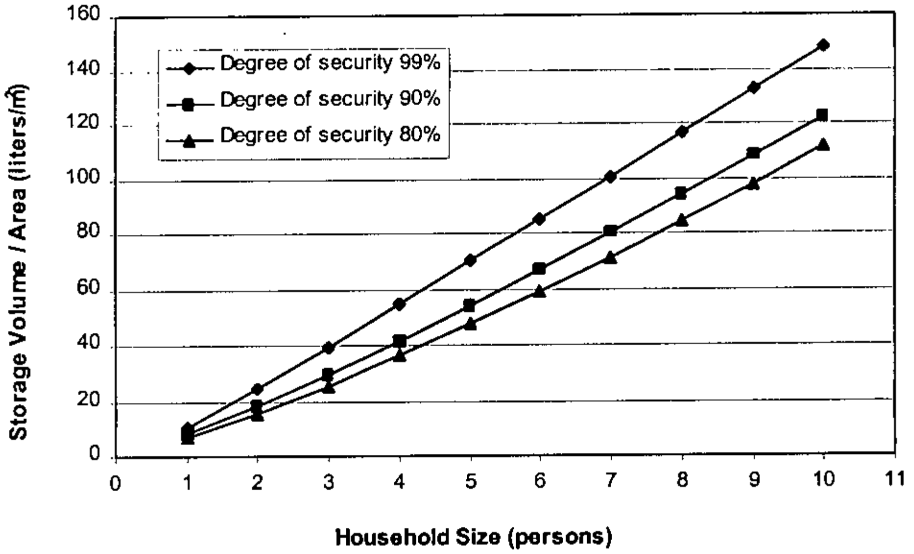

Figure N.1: Design curve for drinking water for Barisal.

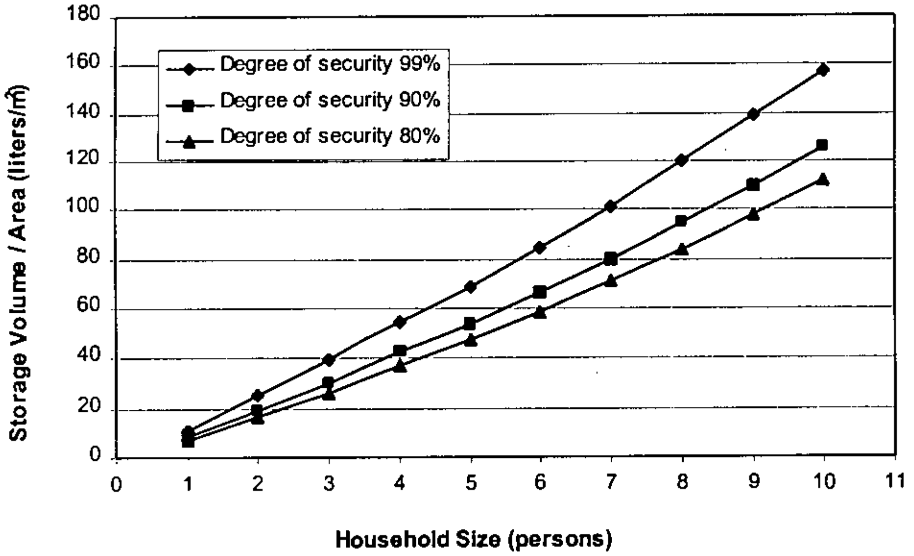

Figure N.2: Design curve for drinking water for Bhola.

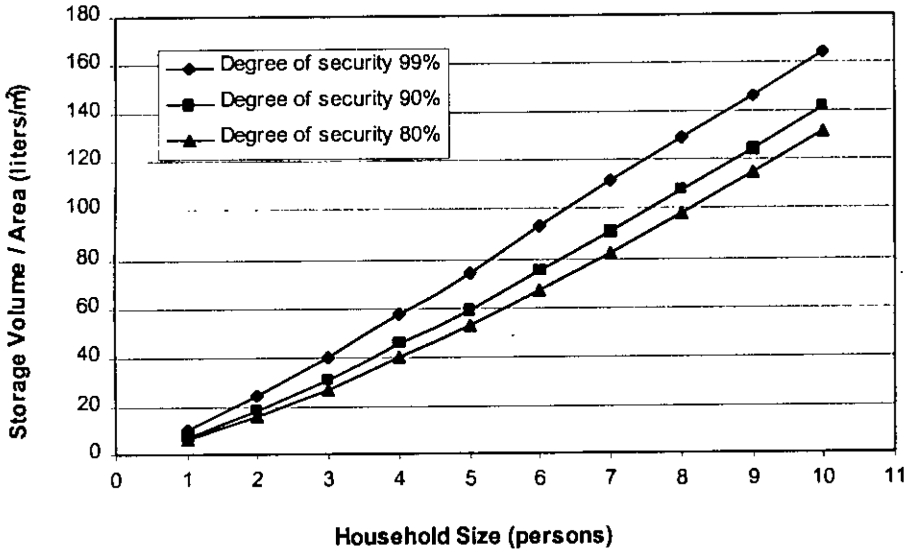

Figure N.3: Design Curve for Drinking Water for Bogra.

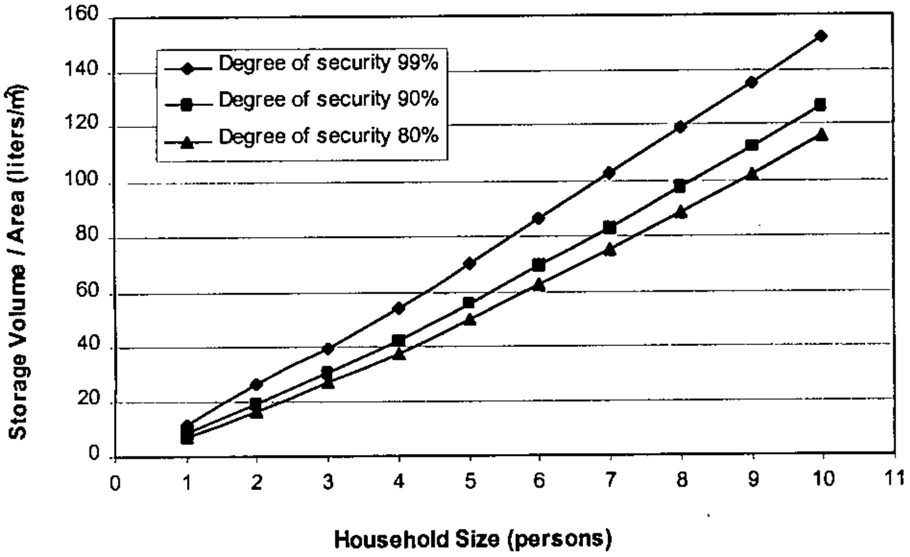

Figure N.4: Design curve for drinking water for Chandpur.

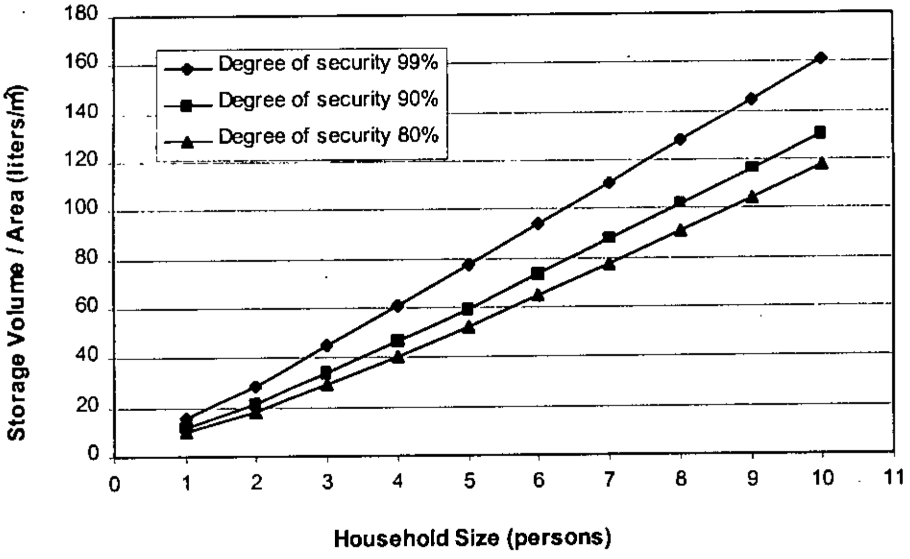

Figure N.5: Design curve for drinking water for Chittagong.

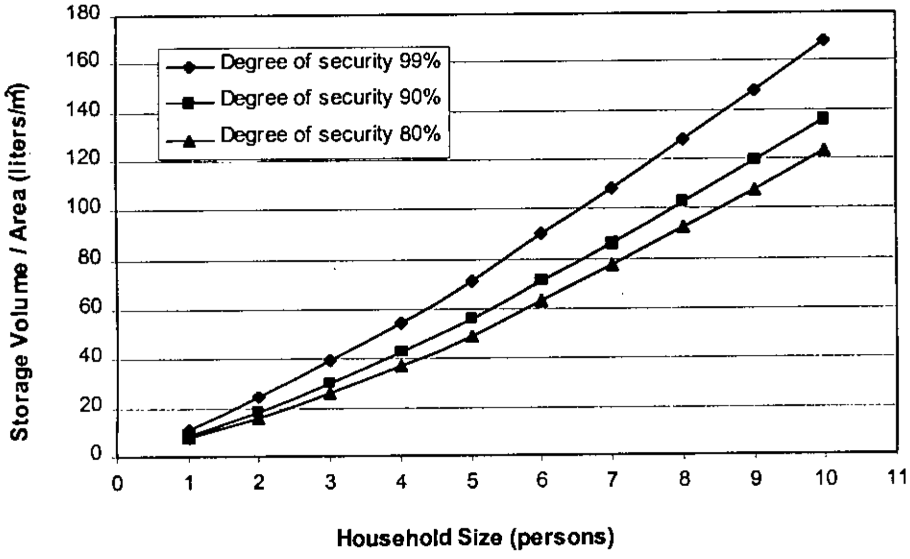

Figure N.6: Design curve for drinking water for Comilla.

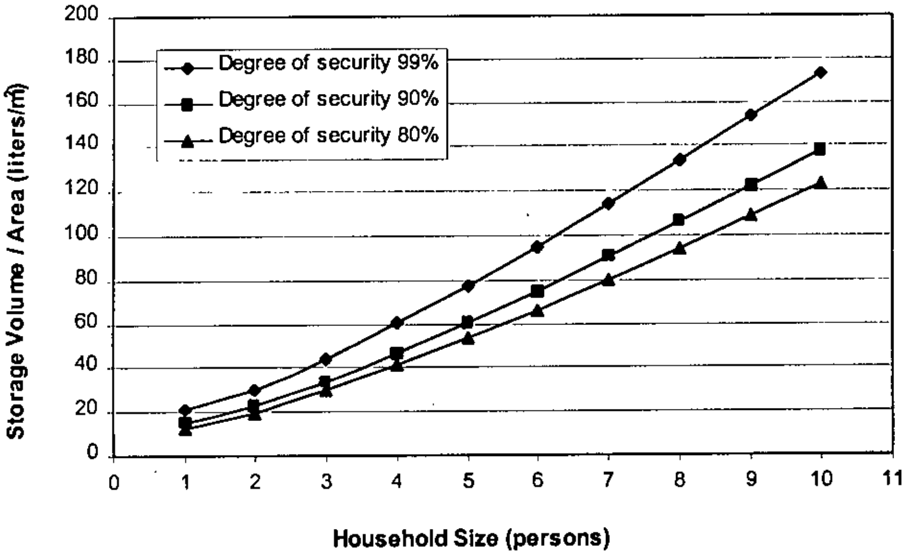

Figure N.7: Design curve for drinking water for Cox's Bazar.

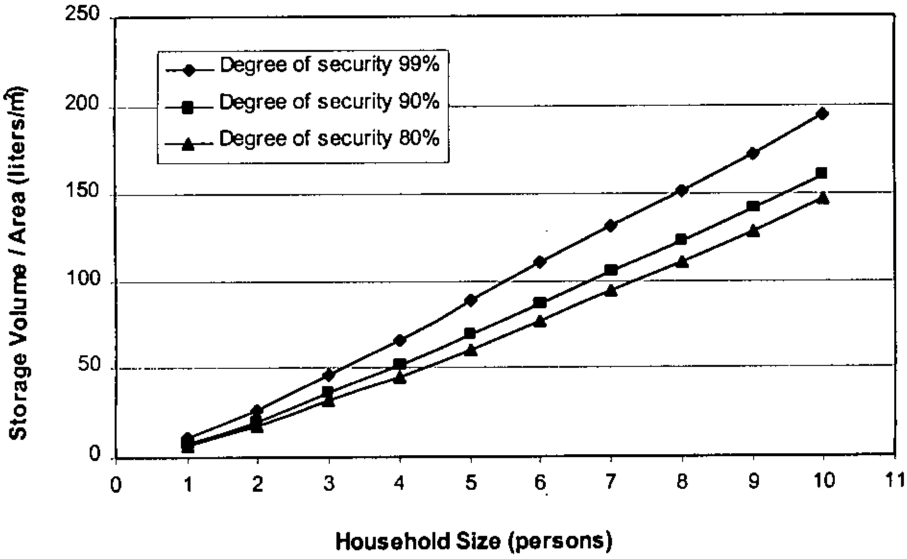

Figure N.8: Design curve for drinking water for Dinajpur.

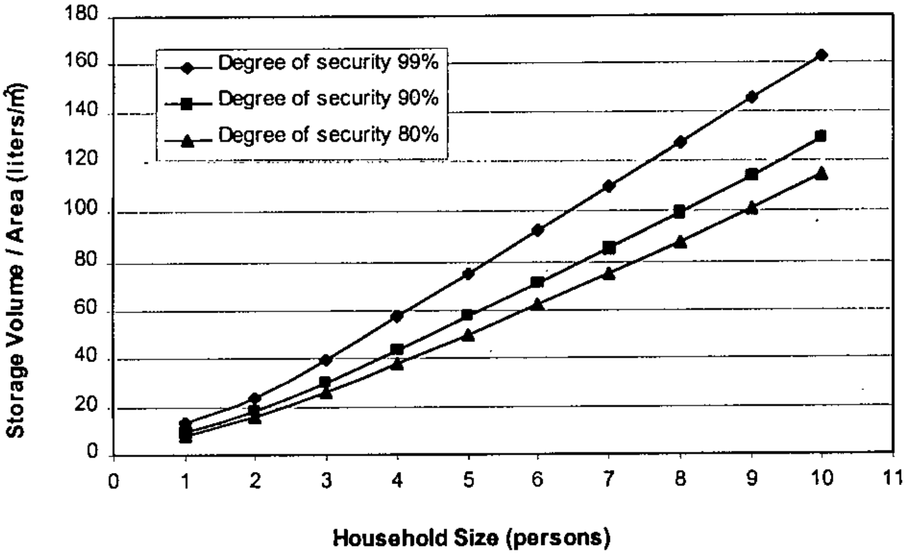

Figure N.9: Design curve for drinking water for Faridpur.

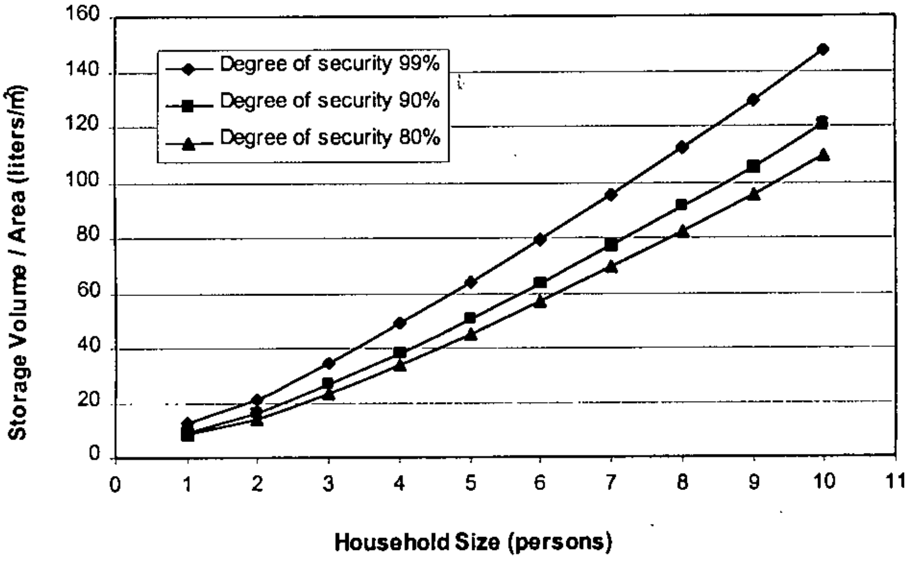

Figure N.10: Design curve for drinking water for Feni.

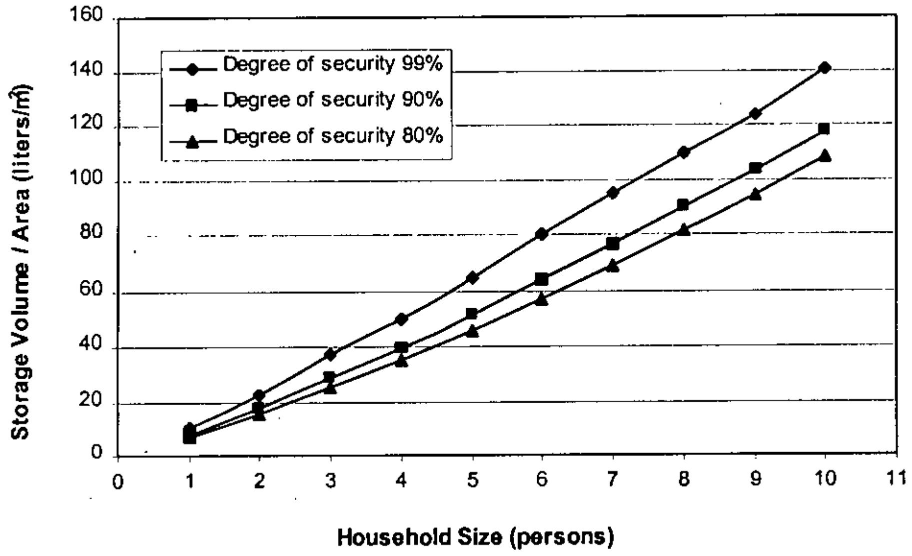

Figure N.11: Design curve for drinking water for Hatiya.

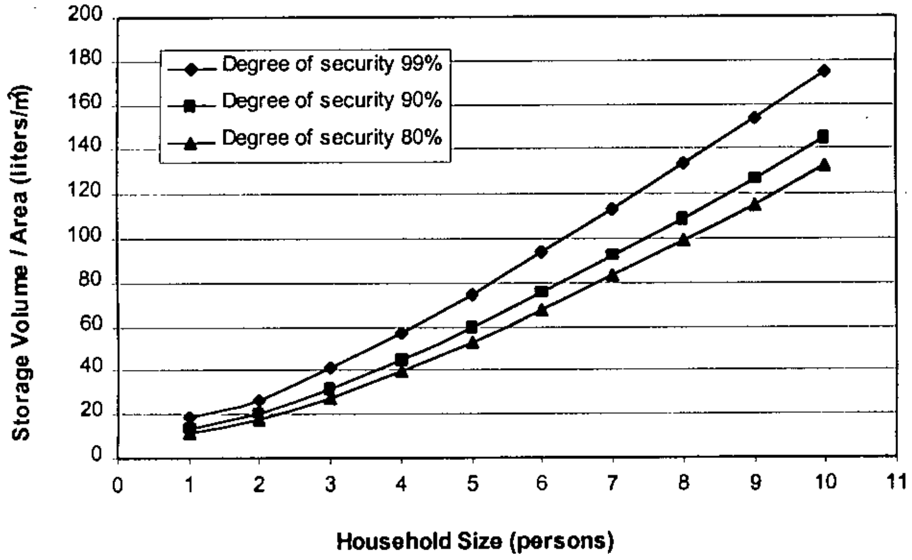

Figure N.12: Design curve for drinking water for Ishurdi.

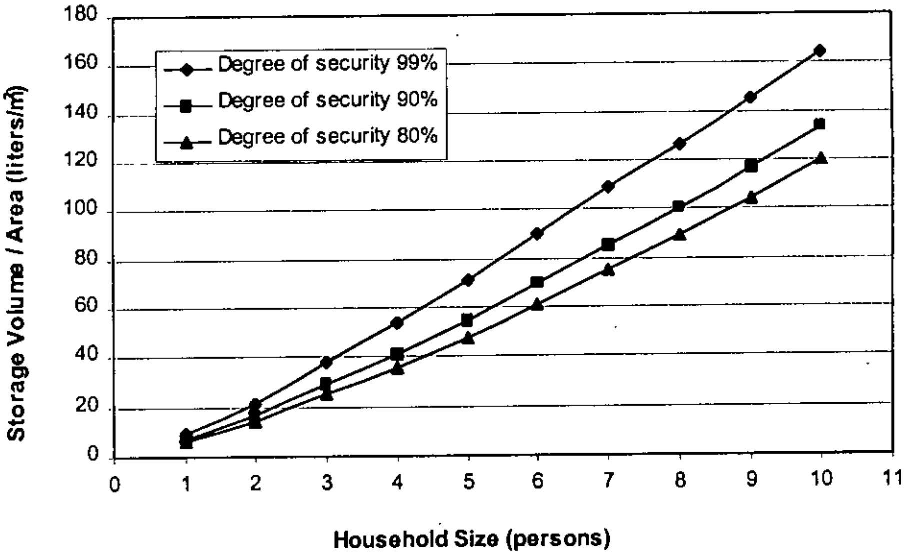

Figure N.13: Design curve for drinking water for Jessore.

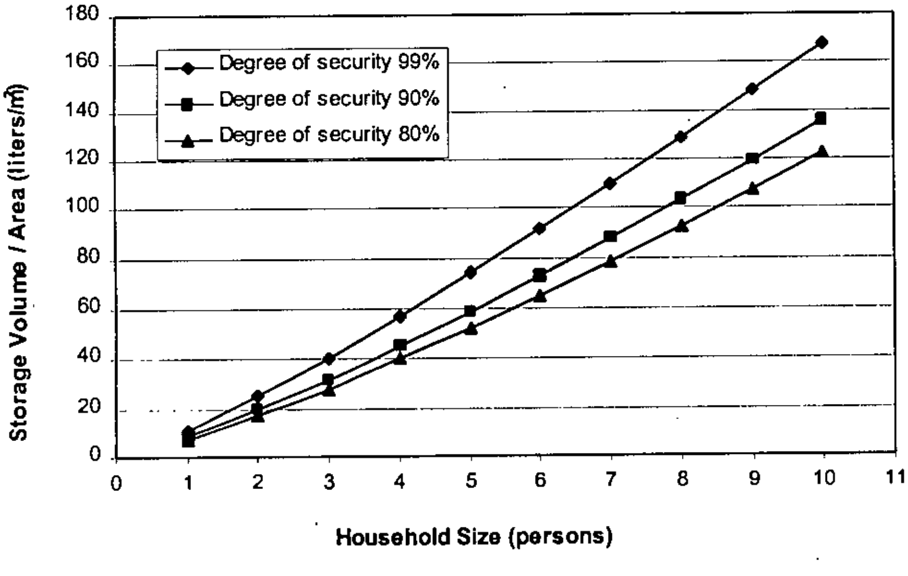

Figure N.14: Design curve for drinking water for Khepupara.

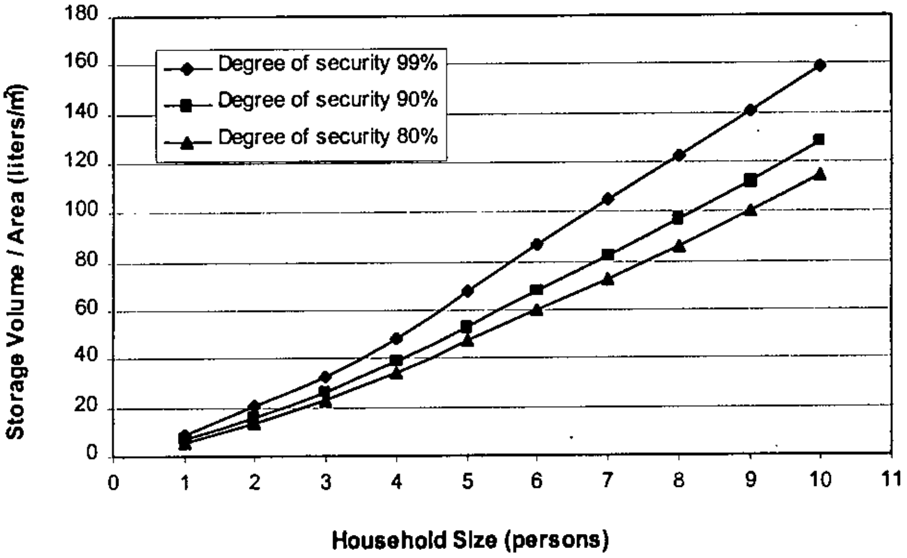

Figure N.15: Design curve for drinking water for Khulna.

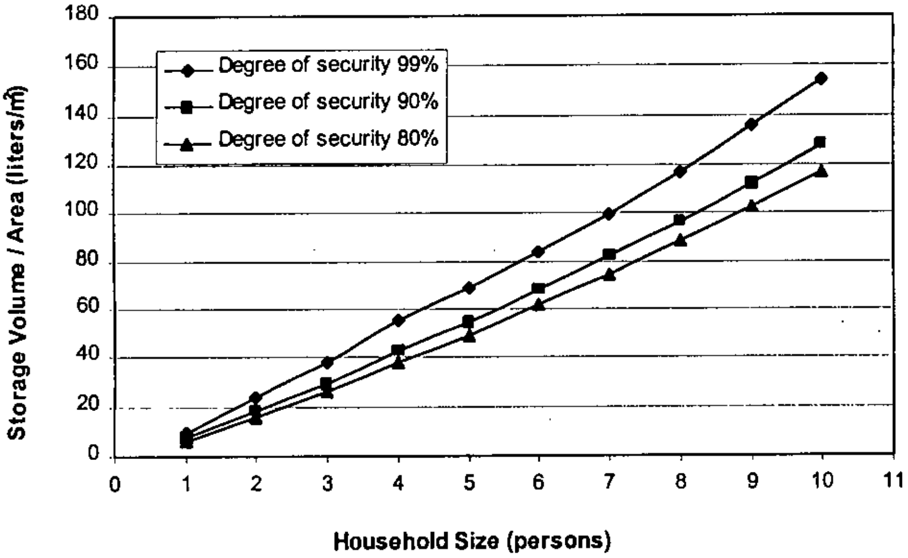

Figure N.16: Design curve for drinking water for Mymensingh.

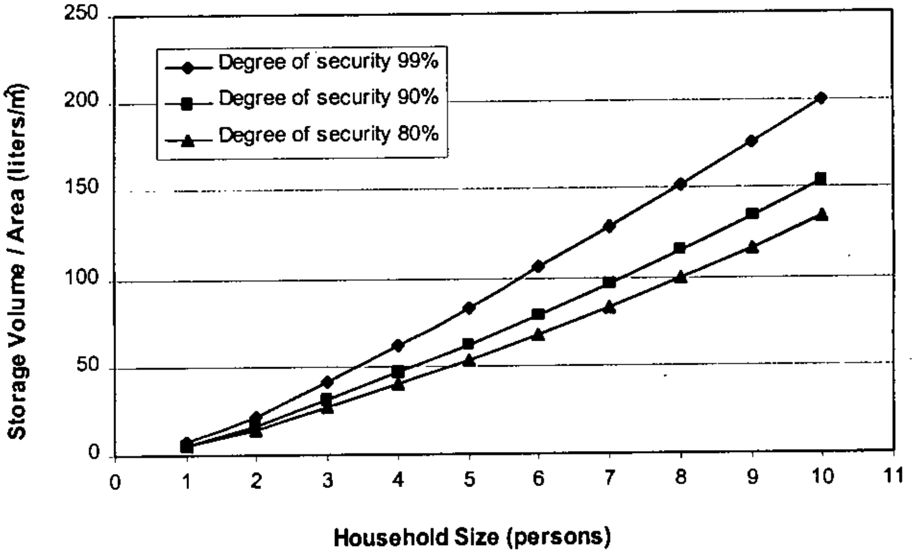

Figure N.17: Design curve for drinking water for Rajshahi.

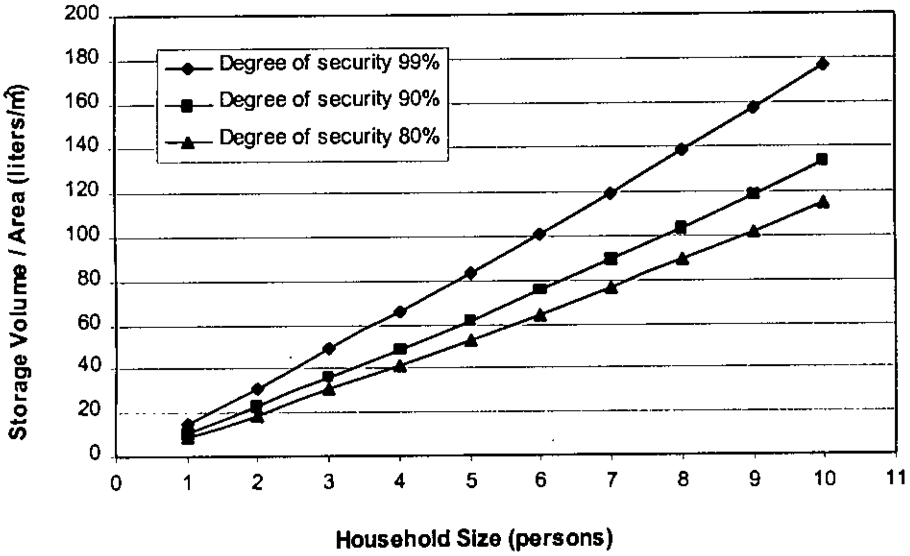

Figure N.18: Design curve for drinking water for Rangamati.

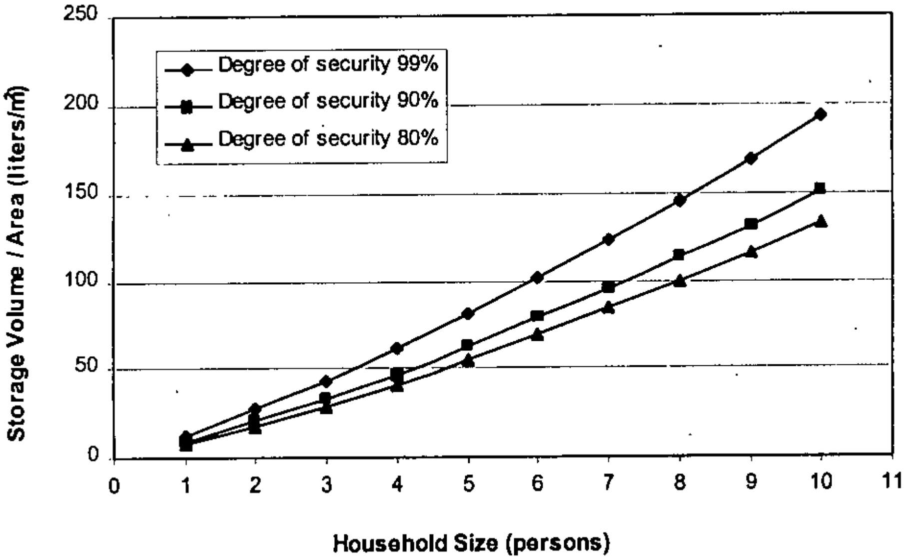

Figure N.19: Design curve for drinking water for Rangpur.

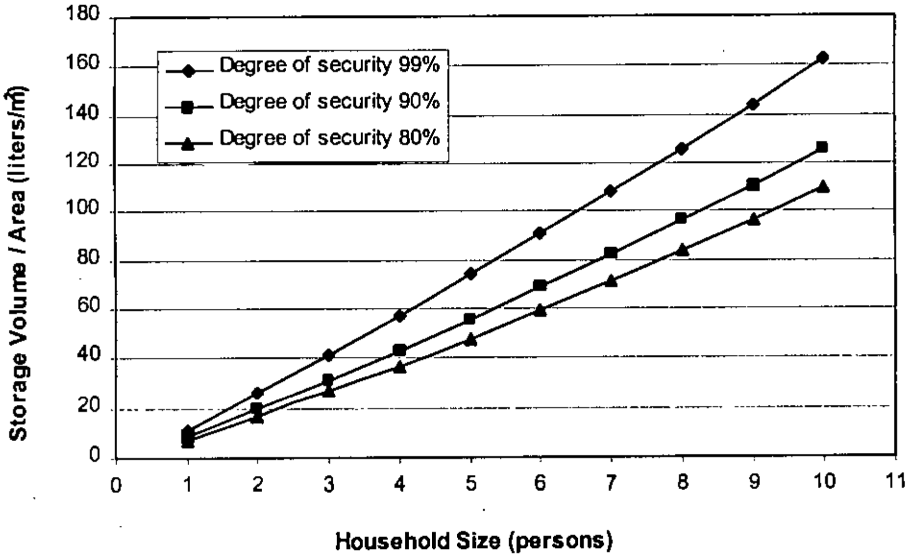

Figure N.20: Design curve for drinking water for Sandwip.

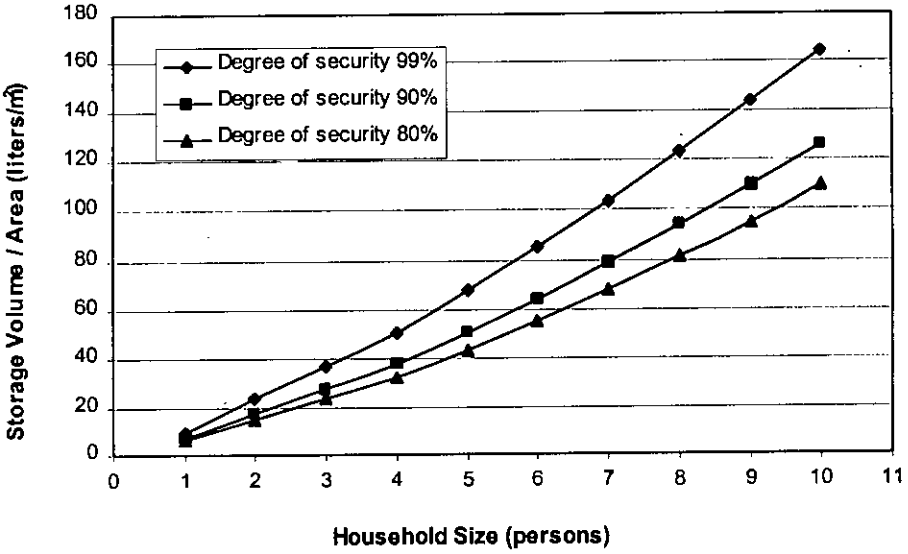

Figure N.21: Design curve for drinking water for Satkhira.

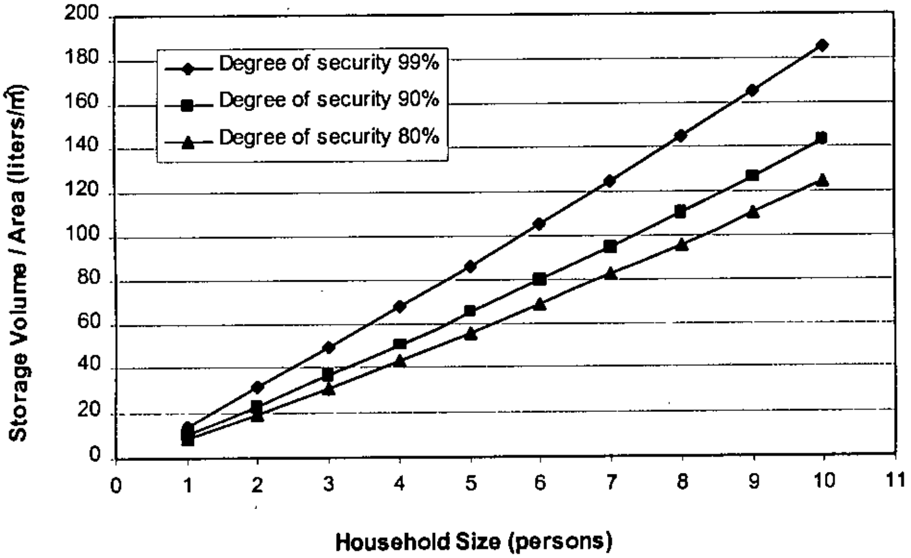

Figure N.22: Design curve for drinking water for Sitakunda.

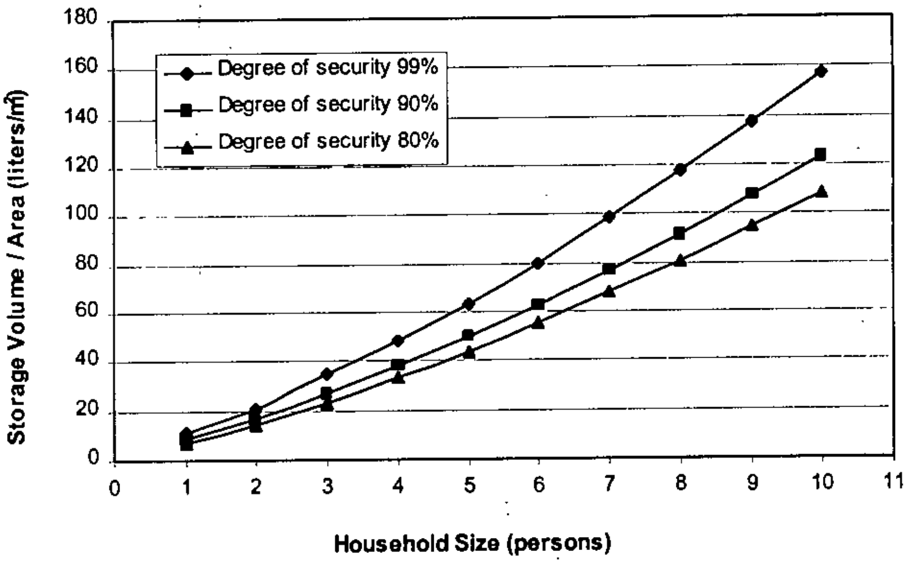

Figure N.23: Design curve for drinking water for Srimangal.

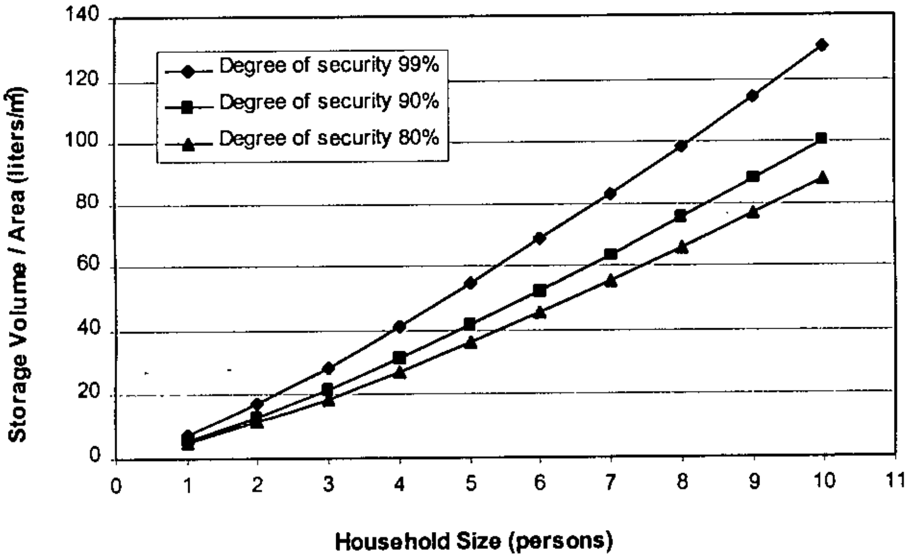

Figure N.24: Design curve for drinking water for Sylhet.

Appendix O: GENERAL DESIGN CURVES FOR REQUIRED STORAGE VOLUME FOR DIFFERENT PLACES OF BANGLADESH

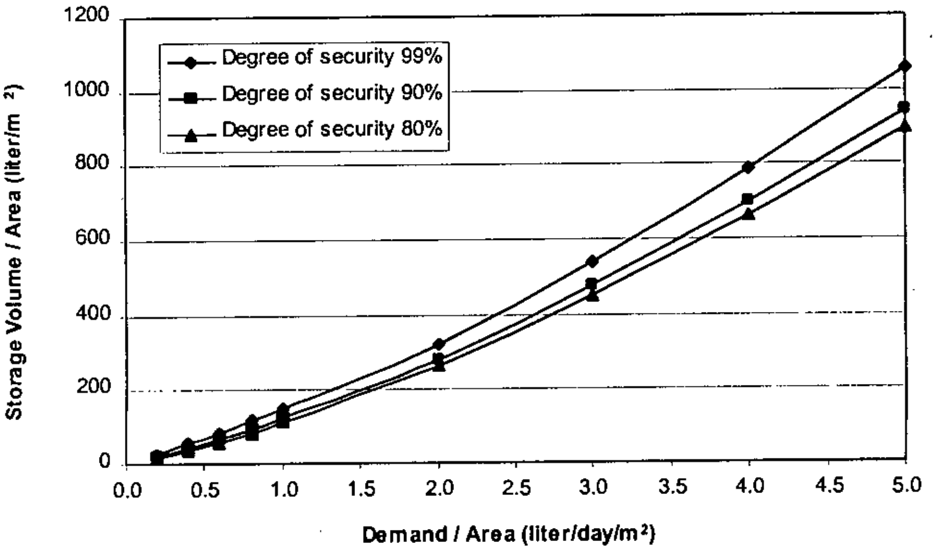

Figure O.1: General design curve for Barisal.

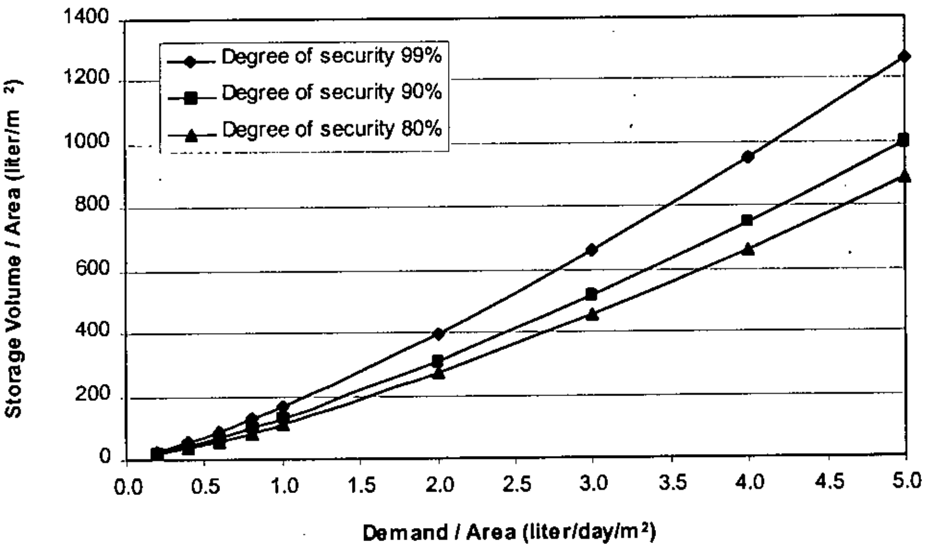

Figure O.2: General design curve for Bhola.

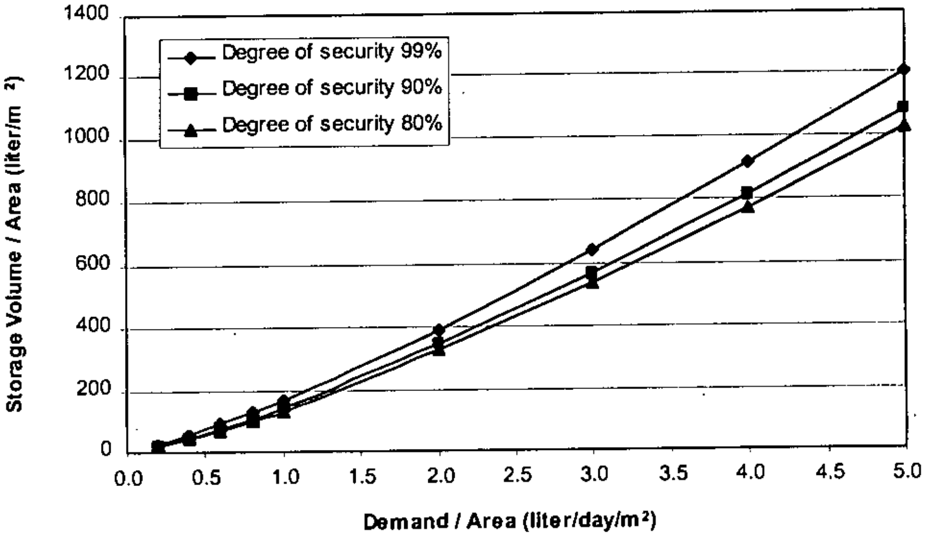

Figure O.3: General design curve for Bogra.

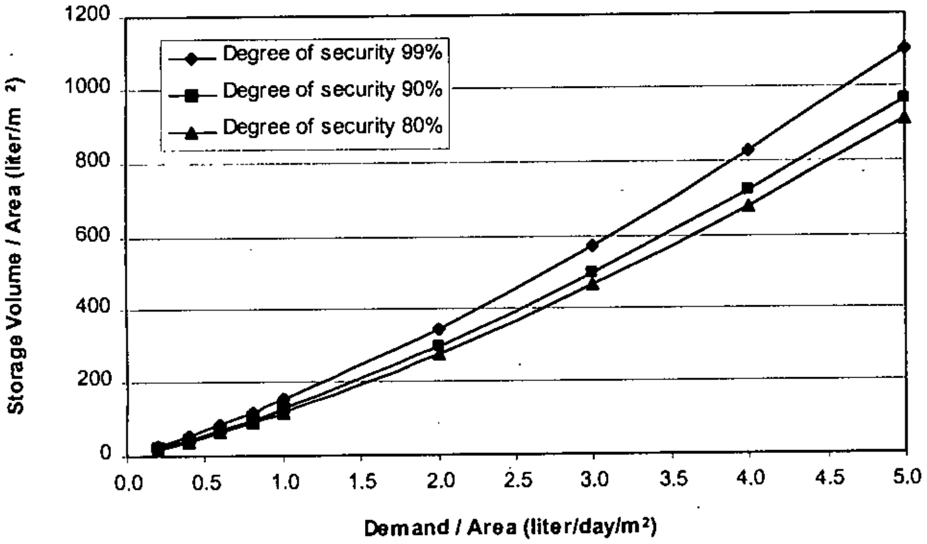

Figure O.4: General design curve for Chandpur.

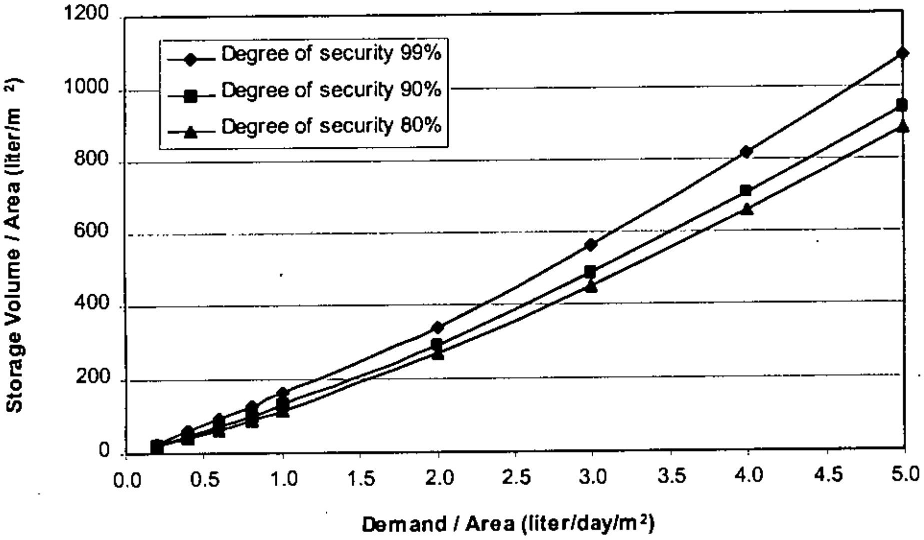

Figure O.5: General design curve for Chittagong.

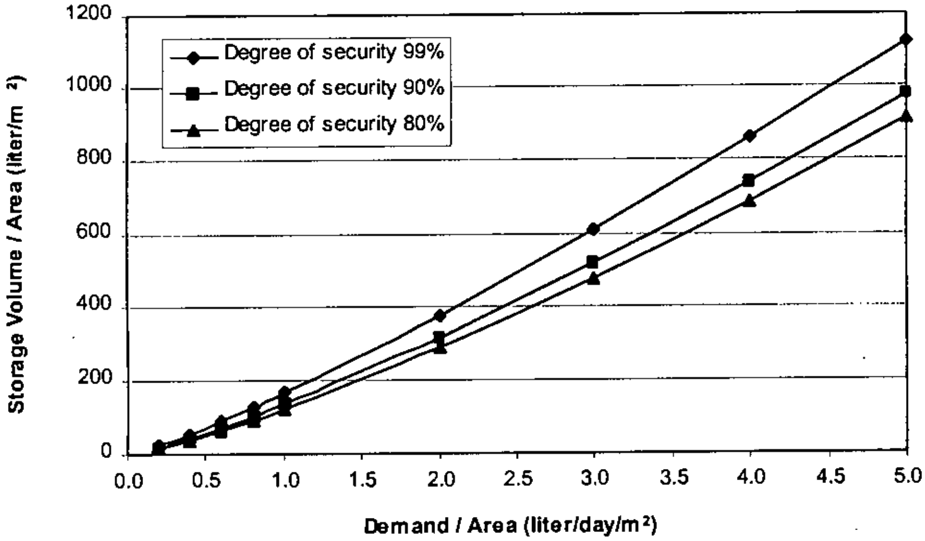

Figure O.6: General design curve for Comilla.

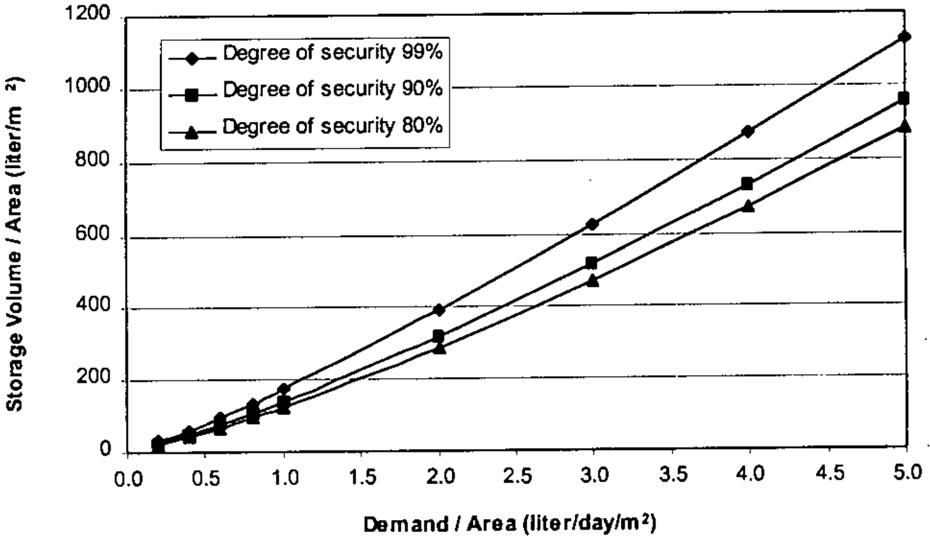

Figure O.7: General design curve for Cox's Bazar.

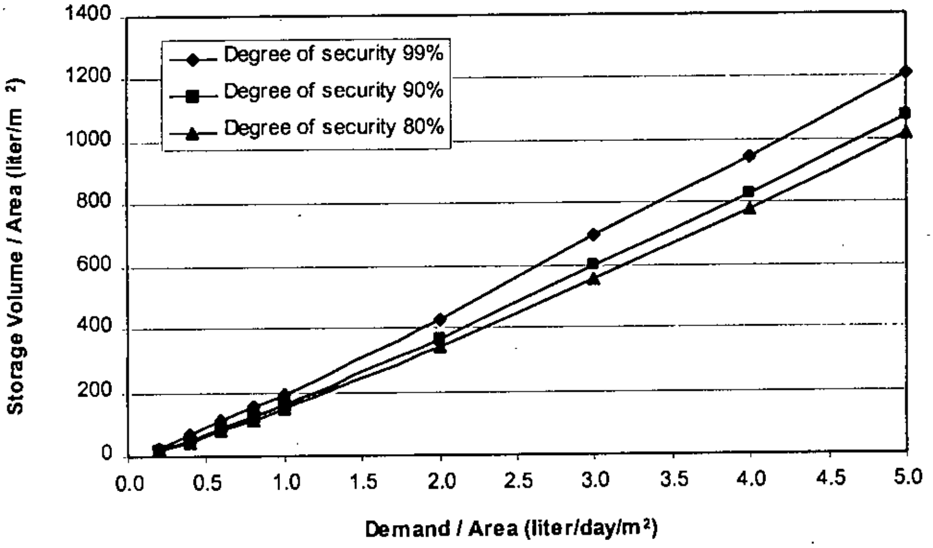

Figure O.8: General design curve for Dinajpur.

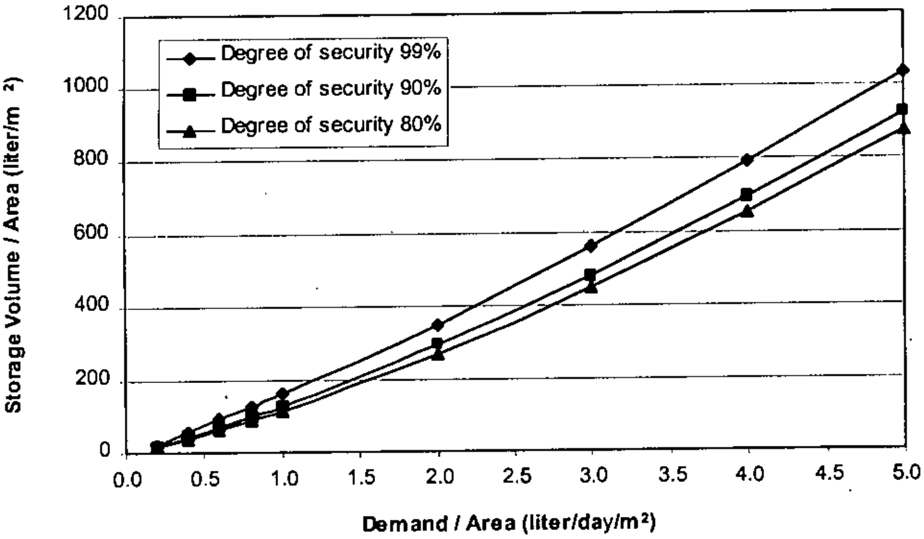

Figure O.9: General design curve for Faridpur.

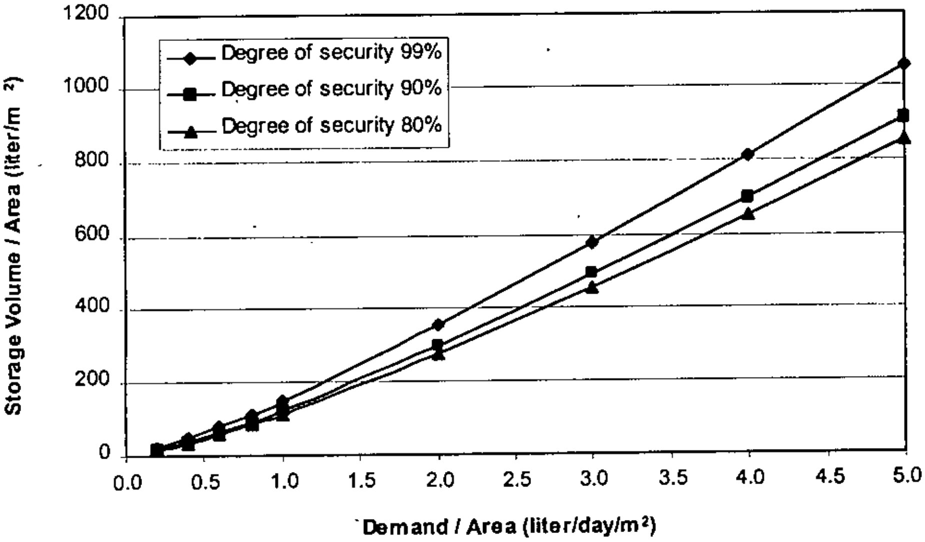

Figure O.10: General design curve for Feni.

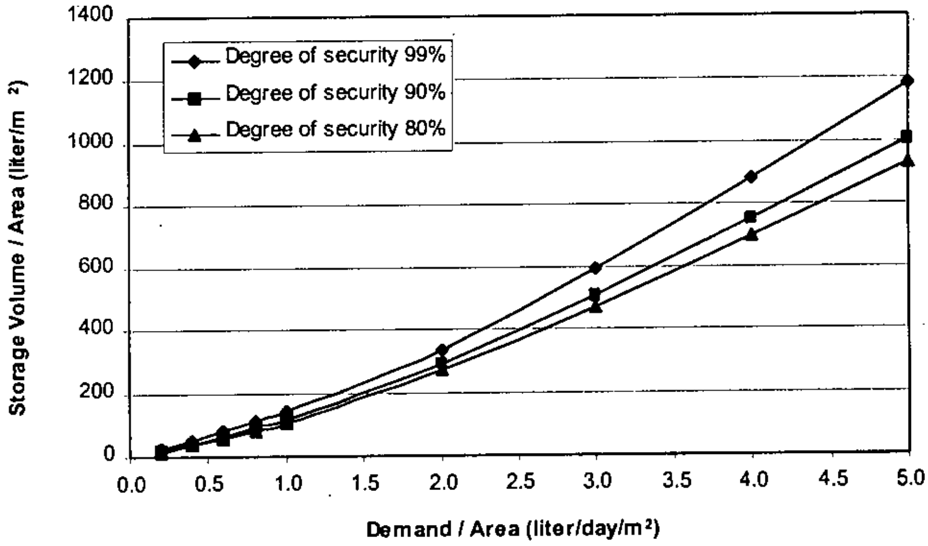

Figure O.11: General design curve for Hatiya.

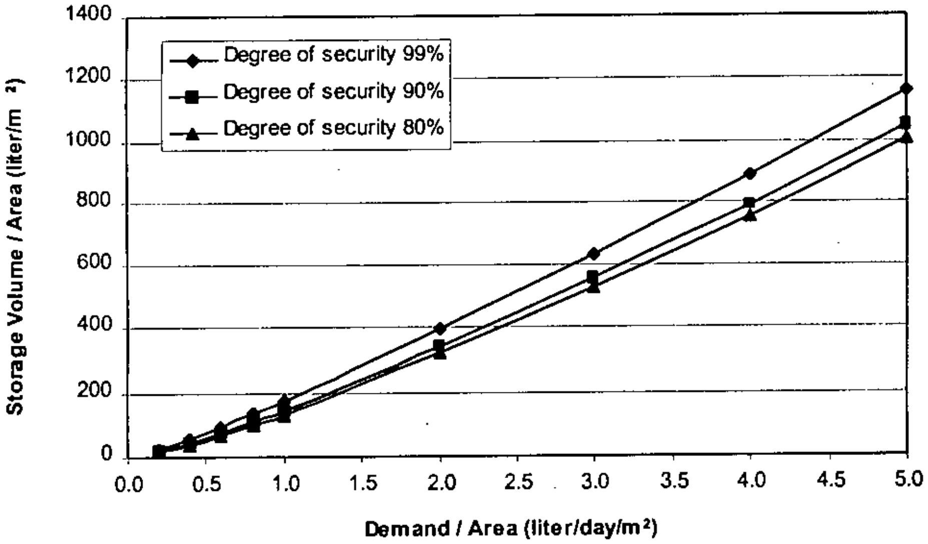

Figure O.12: General design curve for Ishurdi.

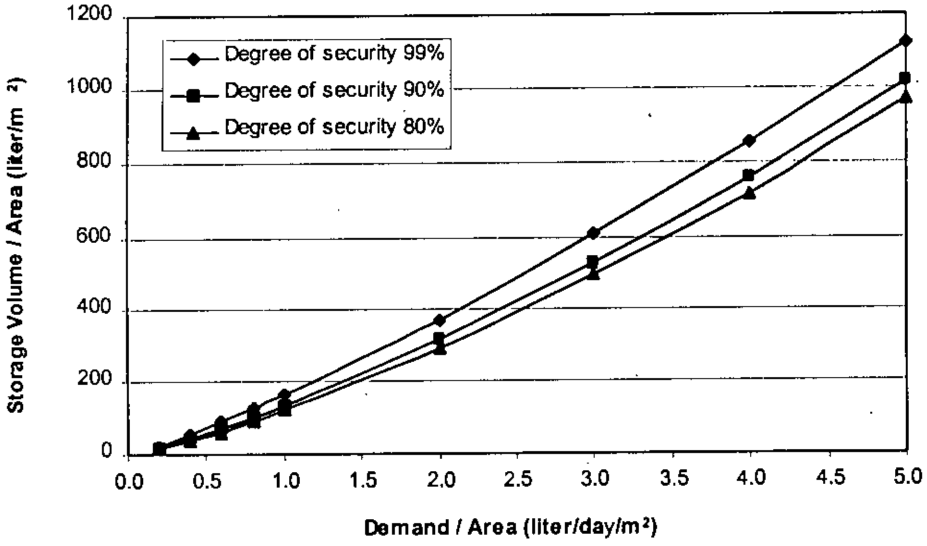

Figure O.13: General design curve for Jessore.

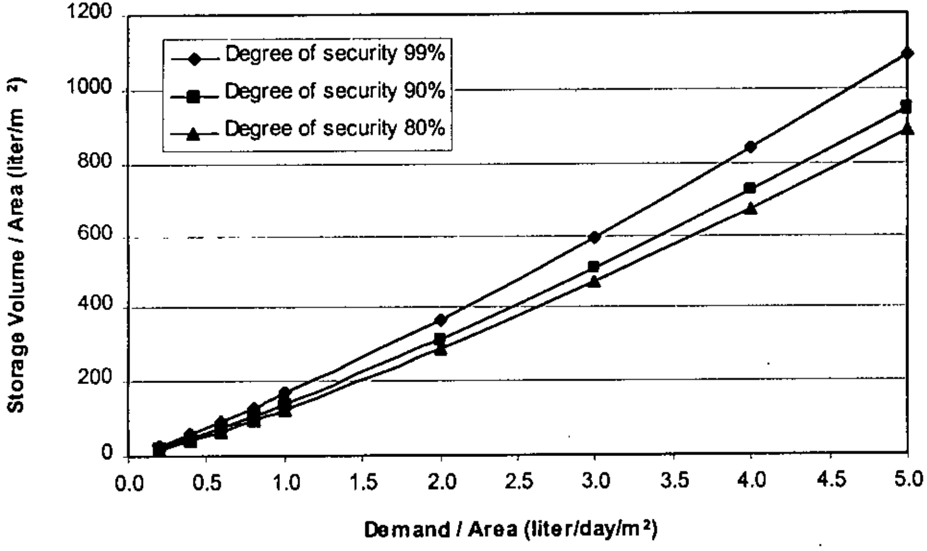

Figure O.14: General design curve for Khepupara.

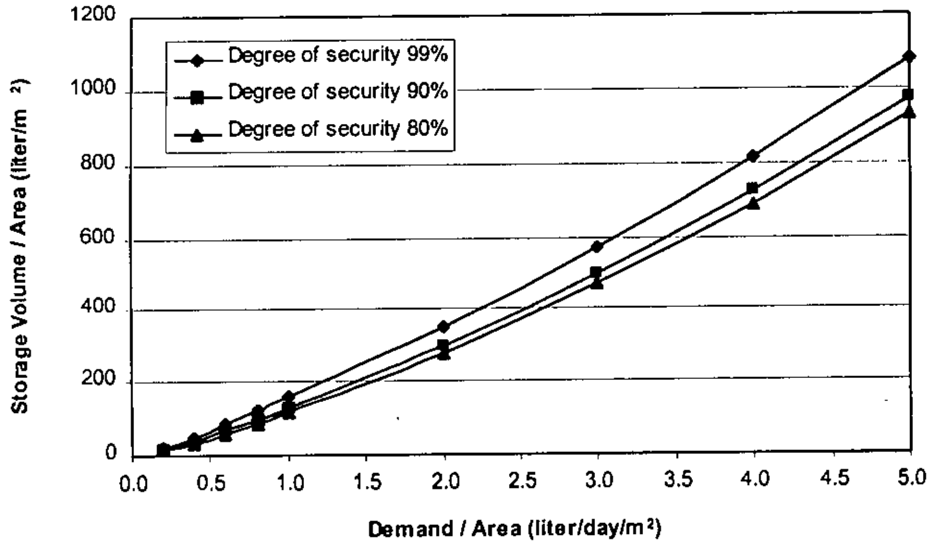

Figure O.15: General design curve for Khulna.

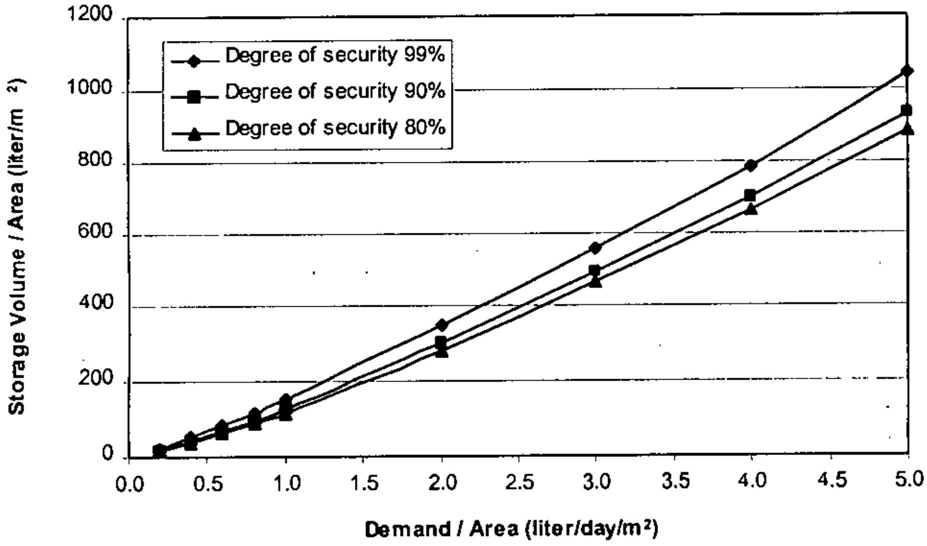

Figure O.16: General design curve for Mymensingh.

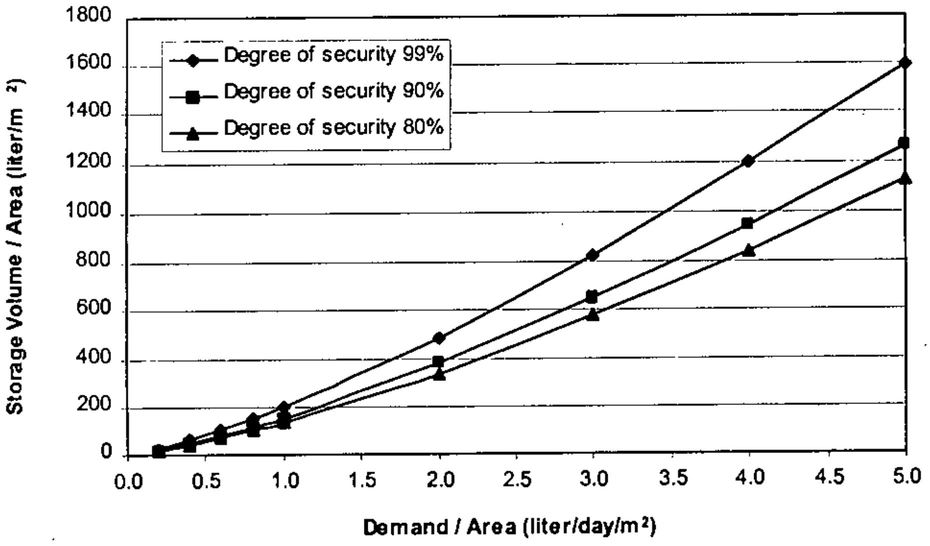

Figure O.17: General design curve for Rajshahi.

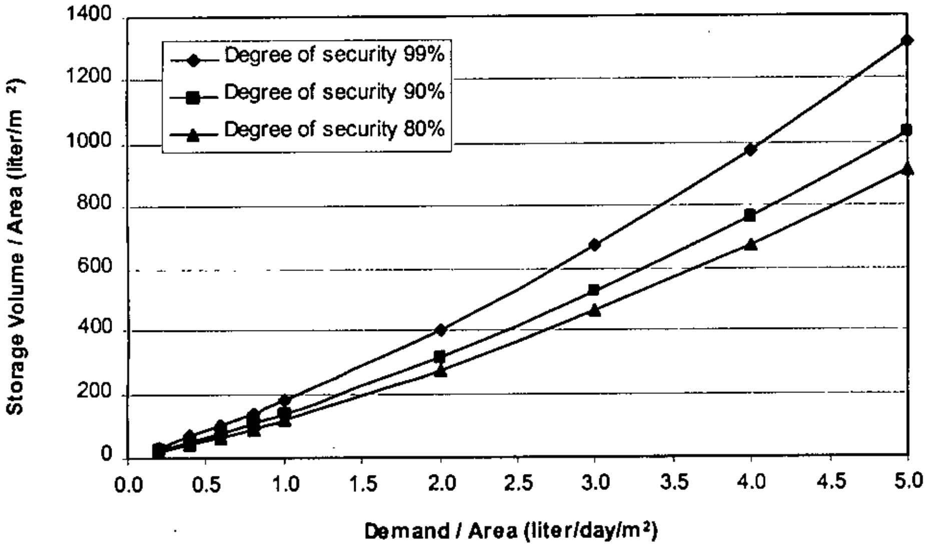

Figure O.18: General design curve for Rangamati.

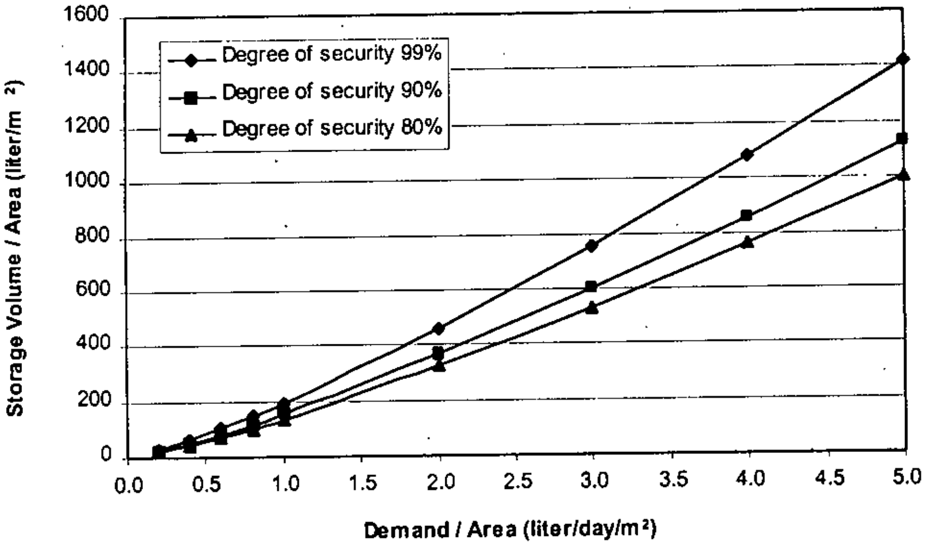

Figure O.19: General design curve for Rangpur.

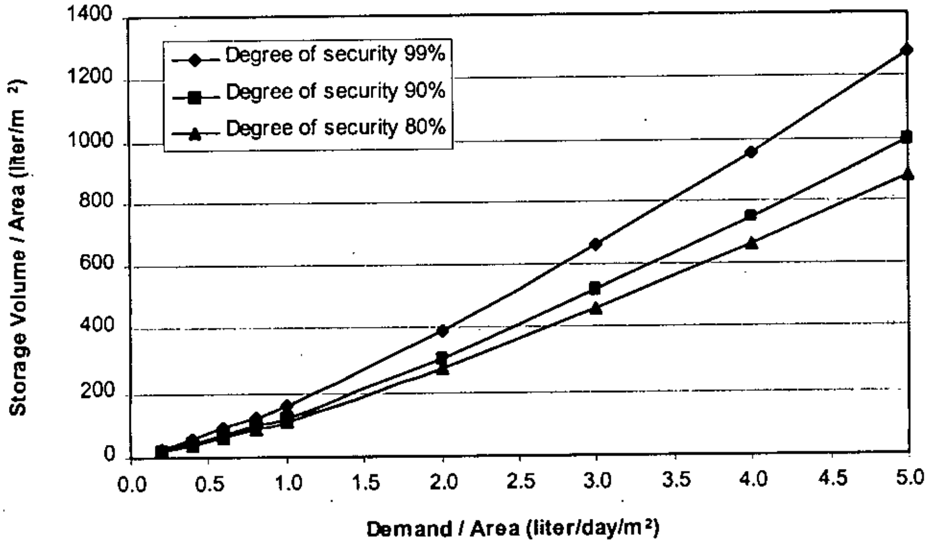

Figure O.20: General design curve for Sandwip.

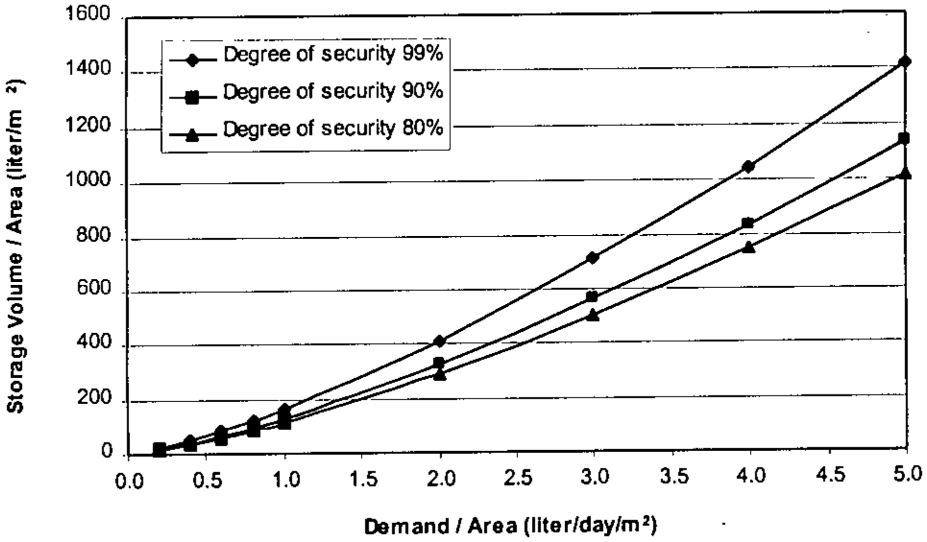

Figure O.21: General design curve for Satkhira.

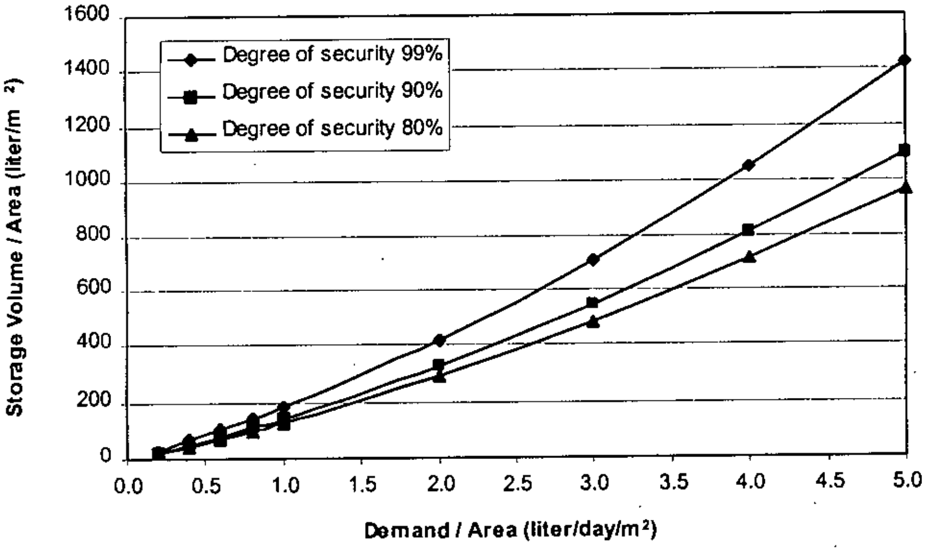

Figure O.22: General design curve for Sitakunda.

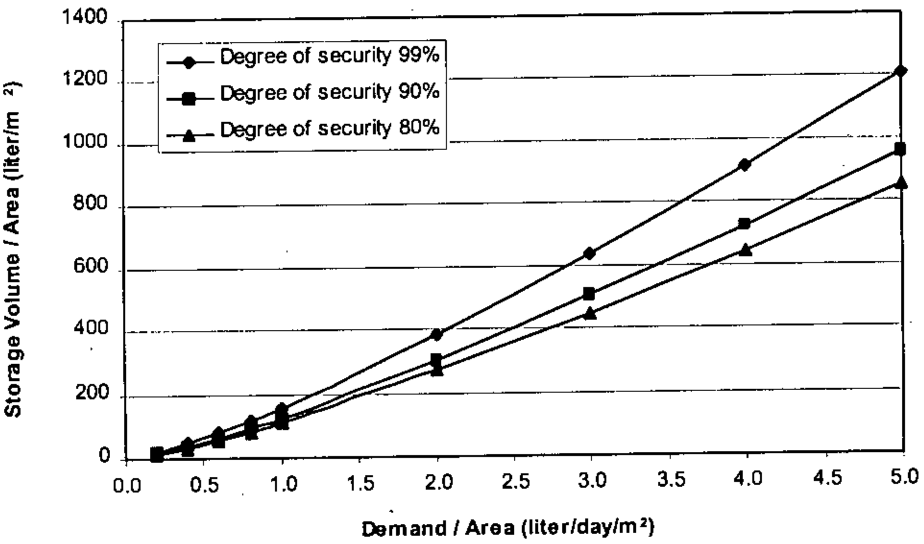

Figure O.23: General design curve for Srimangal.

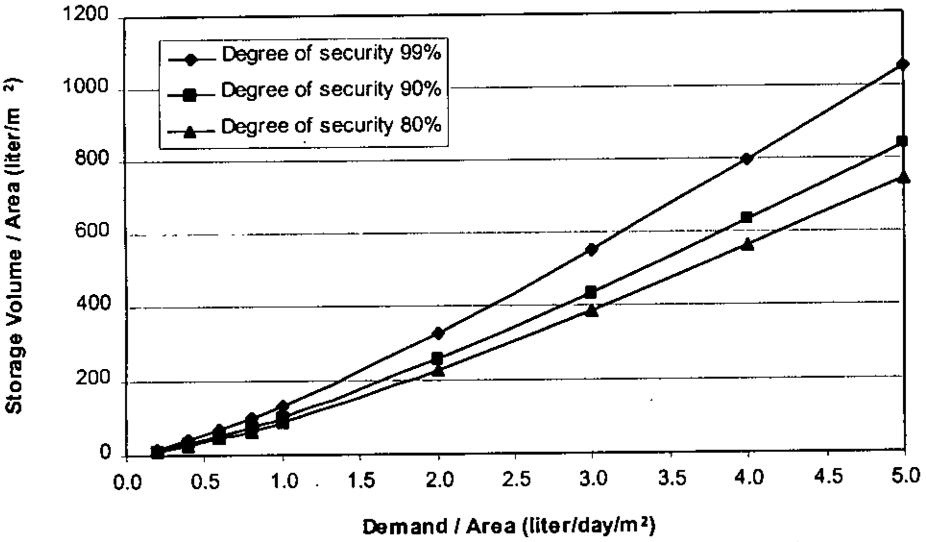

Figure O.24: General design curve for Sylhet.