A Computer-assisted Method for Optimum Design of Rainwater Harvesting Systems

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ABSTRACT:

Rainwater harvesting systems may function as a major alternative or supplementary source of water where the resource is limited, unusable or inaccessible. A computer-assisted mathematical model is presented for design and analysis of rainwater harvesting systems. The computer program determines the required minimum size of the storage tank for a given collection area, water demand and predicted rainfall amounts considering a computational time step of one day. Since the storage tank is the most expensive component of a system, minimization of the size of the tank would significantly reduce the cost. Results indicate that a storage tank smaller than that determined by traditional design methods would be sufficient to satisfy the specified demand. The computer program also produces a set of system performance curves for design and analysis of the system at various levels of reliability and security. These curves also estimate the feasible ranges of system components at a given level of system performance.

Keywords: Rainwater harvesting, Roof collection, Alternative water source.

1. INTRODUCTION

Providing safe water to the people for drinking and other domestic purposes is a major concern in the developing countries. The majority of the people in the developing countries are exposed to health hazards of consuming water from groundwater and surface water sources contaminated by microbial, chemical or physical contaminants. In many countries, arsenic contamination of groundwater makes the source unavailable for drinking. In coastal areas, both surface and groundwater may become unsuitable for drinking because of salinity. Dry seasons occur even in monsoon areas. Seasonal variation in water availability during the dry season sometimes restricts utilization of water from surface water or groundwater sources; surface water bodies dry up and groundwater levels fall, sometimes below the suction limit of tube wells. In some areas, inaccessibility to sources prohibits the availability of surface water.

A central water distribution system is often difficult and very expensive to install, especially in the rural areas. In such situations, alternative sources for drinking and domestic purposes can be considered. Ahmed *et al.* (2005) explored the feasibility and risk of several options including rainwater harvesting systems to mitigate arsenic contamination of groundwater. Rainwater harvesting systems were found to be a reasonable option. Rahman *et al.* (2003) conducted a technical and social evaluation of rainwater harvesting systems in Bangladesh. The design of the storage tank required to support a family for 8 to 10 months of the year was adopted from available regional models in other countries including Nepal, Thailand and Sri Lanka. International initiatives such as the Water Harvesting Program of United Nations Environmental Program (UNEP) aim to provide safe drinking water to the underprivileged people. This program suggests that in the present situation of water supply system in the developing countries, rooftop water collection systems can be considered to be the most appropriate technology for providing

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safe drinking water after filtration and necessary treatment. However, there is also a concern about the quality of water collected from a rooftop collection system. Although rainwater itself is free from pathogens, contamination by bird droppings, dirt and atmospheric fallout of heavy metals on the roof, and microbial growth in the storage tank may significantly deteriorate the water quality if proper treatment and maintenance are not carried out. Also, many essential minerals indicated in the WHO guideline are absent in rainwater.

Rainwater harvesting systems can be designed to operate as a sole source of water or as a supplementary source in conjunction with other sources. Although collected rainwater can be used to recharge the local groundwater for future use, collection in a storage tank is more feasible and manageable in developing countries. However, successful operation of a fully reliable year-round system largely depends on many factors including the size of the collection area, capacity of storage tank, amount and distribution of rainfall, and water demand from the system. The harvesting system may be designed for a small individual household or a larger school building or community center with the collection area and demand from the system varying in each case. Since the most expensive component of a rainwater harvesting system is the storage tank, the basic principle of designing the system is to determine the minimum storage volume required to satisfy the demand, with minimum wastage or spillage of water from the tank. If a relatively large storage tank is constructed, the wastage would be minimized, but at a higher cost of construction. On the other hand, if a relatively small tank is constructed to reduce cost, the storage capacity may not be sufficient to meet water demand during the dry periods. At the same time, because of a lower capacity, water would be wasted by spillage during periods of relatively high-intensity rainfall. Therefore there is a need to optimize the storage tank capacity based on available rainfall and collection area.

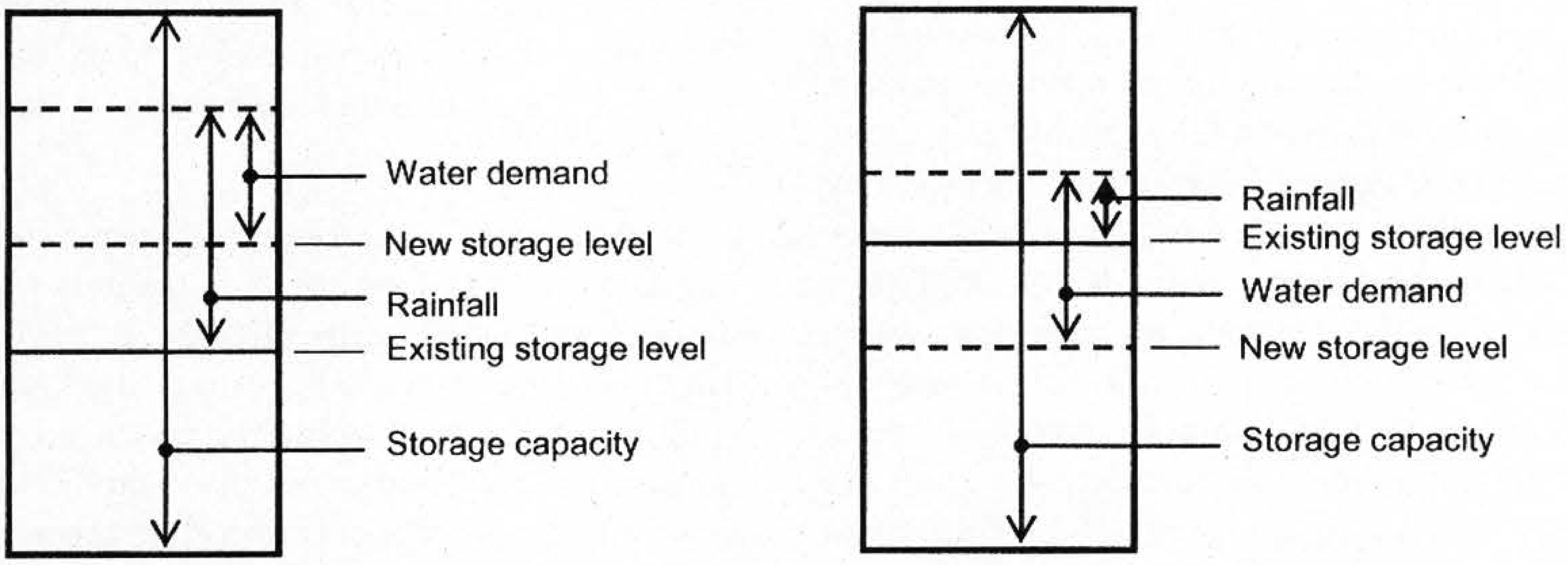
Feasibility of a rainwater harvesting system also depends on water demand. In extreme situations, the minimum quantity of water needed for survival depends on many factors including climate and culture. White *et al.* (1972) found that the minimum quantity of water for survival in a tropical area is between 1.8 and 3.0 liter/day/person. Feachem *et al.* (1978) reported large differences in drinking water consumption in different countries. For example, in Papua the minimum rate was found to be 0.54 liter/day/person, whereas in Uganda the rate was 3.4 liter/day/person. Diamant (1982) suggested that a drinking water consumption rate of 2.0 liter/day/person can be considered as a reasonable design value under grave water supply situations. However, the daily household consumption rate is much higher due to other domestic usage. Rahman *et al.* (2003) estimated the average water demand for drinking and cooking in the rural areas of Bangladesh to be 7.5 liter/day/person.

In most traditional design methods, the storage tank capacity is determined based on monthly rainfall amounts and an assumed efficiency of the system. However, the size of the storage tank can be reduced if the water balance based on water demand and predicted variability in rainfall can be determined more precisely over shorter periods of time. Such a method would ensure that for a given frequency of rainfall, the storage capacity would be just enough to satisfy the cumulative demand while accounting for the storage required for anticipated dry days, and minimizing spillage from the tank. This can be achieved easily and more accurately with a mathematical model aided by a computer program. This program will also give options for selecting different levels of system performance and demand for a specified rainfall frequency by generating design curves that will help select the required minimum storage capacity.

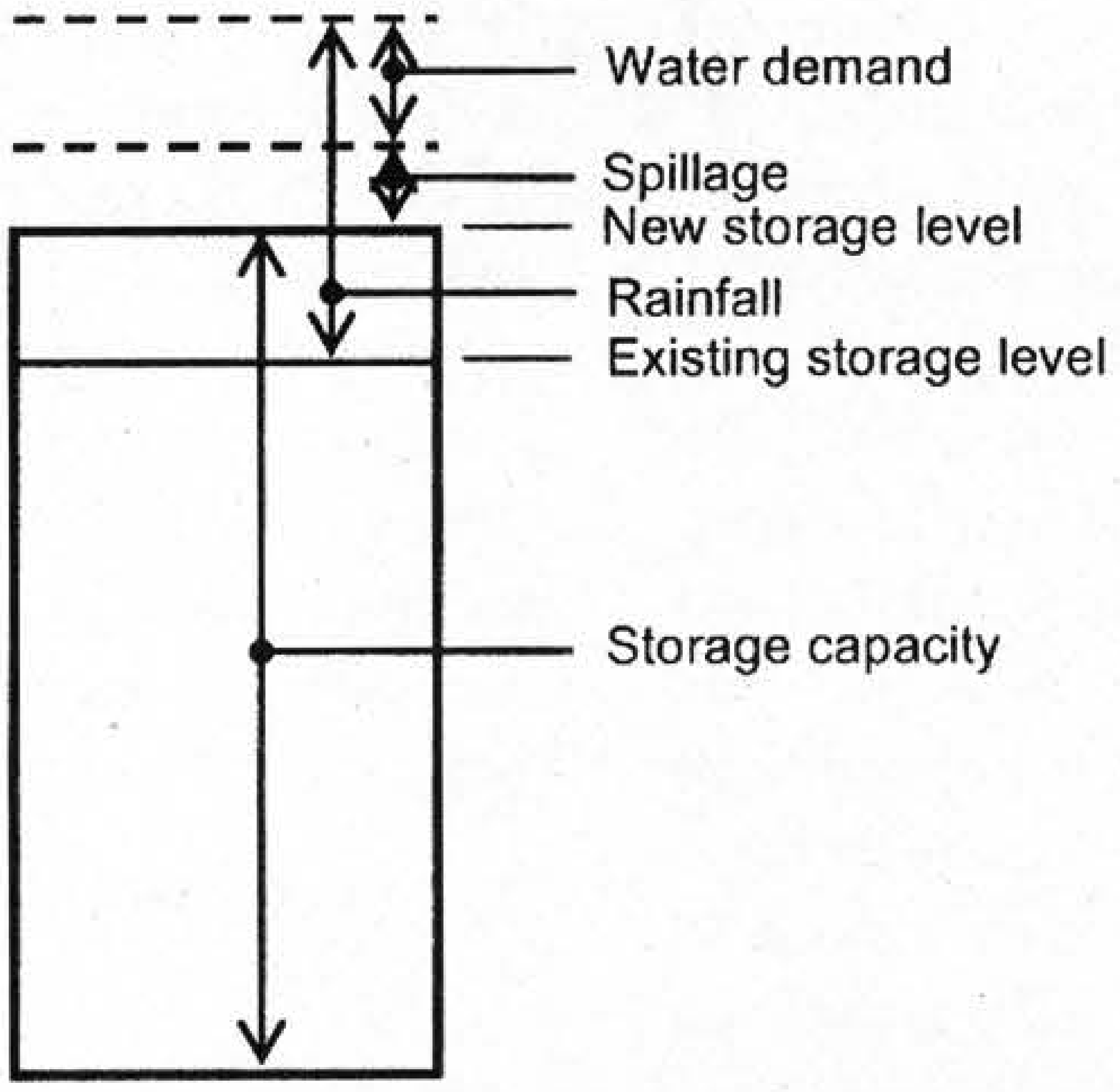
2. CONCEPTUAL AND MATHEMATICAL BASIS

The performance of a rainwater harvesting system depends on four factors: (1) rainwater collection area, (2) storage capacity, (3) amount and distribution of rainfall, and (4) water demand. Of these factors, collection area, storage volume and demand, to some extent, can be controlled. Rainfall, being entirely a natural phenomenon, has to be predicted using a suitable statistical interpretation of the previous rainfall records. Consumption of water may vary during different parts of the year. The highest demand of water may occur during the driest period of the year. In these cases, consumption may be kept to a minimum or, if possible, the system may be kept inoperative during certain periods if the size of the storage tank has to be minimized. A computer program is developed to establish a functional relationship among all these factors and possibilities.

There are a number of methods to compute the minimum storage volume required for a rainwater harvesting system. Some of these methods are: the mass curve based on historical data (Grover, 1971), the yield after storage (YAS) mathematical model (Jenkins *et al.*, 1978), rationing and stocking model (Perrens, 1975), and statistical method (Ree *et al.*, 1971). Fig. 1 shows a schematic representation of a rainwater harvesting system. When a rainfall event occurs, rain falling on a collection area passes to a storage tank while water is withdrawn from the tank in response to the demand. The amount of water in excess of the storage capacity spills. Any water that is not withdrawn remains in the tank. In this model, it is assumed that collection and withdrawal take place concurrently over a time



(a) rainfall amount exceeds demand. **(b) demand exceeds rainfall amount.**



(c) spillage occurs from the system.

Figure 1: Schematic representation of a rainwater harvesting system.

interval of one day. If the available water from rainfall and previous storage is not sufficient to meet the demand, actual yield from the system is less than the demand and the system runs dry for that time interval. On the other hand, if the available water is more than the demand, the yield is equal to the demand and the excess water is stored in the tank after spillage, if any. This sequence of events is repeated in successive time intervals throughout the year.

The present model is more realistic than the previous models in the sense that yield from the system takes place during storage. The mathematical basis of this model can be presented as,

$$Y_i = \min(D_i, S_{i-1} + R_i) \tag{1}$$

$$S_i = \min(S_{i-1} + R_i - Y_i, S) \tag{2}$$

where, Y_i = yield from the system during the i-th interval, D_i = demand from the system during the i-th interval, S_i = water in storage at the end of the i-th time interval, R_i = rainfall during the i-th interval, and S = storage tank capacity. All variables have consistent units of volume.

Eq. 1 indicates that during a time interval yield cannot be less than zero or more than the specified demand, although yield can be less than the specified demand for the time interval. If the actual yield is less than the specified demand, it is counted as one failure of the system. The storage capacity is increased in steps by a specified increment from an initially assumed relatively low value until there is no failure of the system. The storage thus computed corresponding to no failure is specified as the design storage capacity that satisfies the specified demand.

Performance of the system under different operating conditions can be evaluated by the following equations:

$$P = \frac{N_d}{N} \times 100\% \tag{3}$$

$$Q = \frac{\sum_{i=1}^{N} Y_i}{\sum_{i=1}^{N} D_i} \times 100\% \tag{4}$$

where, N_d = number of time intervals for which $Y_i = D_i$, N = total number of time intervals in the period of records, P = system security, or percent of times (or days in a year) the system fully satisfies the demand, and Q = system reliability, or percent of specified annual demand satisfied by the annual cumulative yield. A higher P and Q indicate a higher system security and a higher system reliability, respectively. Since system security accounts for only those time intervals during which the demand is fully satisfied, it is a more stringent representation of the system performance, whereas system reliability is a more accurate overall indication of the system performance in satisfying the demand.

For a given rainfall record, the system performance is evaluated over a range of demand and storage capacity to define the system characteristics. These relationships can be plotted to generate system performance curves at various levels of operation of the system. Design storage capacity for a specified demand, and design demand that can be satisfied with a given storage capacity can be determined at different levels of reliability and security from this set of curves.

3. STRUCTURE OF THE COMPUTER PROGRAM

The structure of the computer program is presented by a general flowchart in Fig.2. The input file can be created manually following a specified format, or by another interactive program. The parameters are normalized by dividing the rainfall amount, water demand, yield, and storage each by the collection area, and the unit quantities are expressed as liter/day per m^2 of collection area. Similarly, unit storage is expressed as liter per m^2 of collection area. Design and analysis of the rainwater harvesting system are based on prediction of future rainfall amounts based on rainfall amounts and patterns observed in the past. Significantly different system performance may result if rainfall characteristics observed in the past are not reproduced in the future. A frequency analysis of historical rainfall records is performed in the program by the Gumbel method to predict the daily rainfall amounts for a specified return period. The Gumbel distribution is assumed to be suitable since Matin (1984) used daily rainfall data for 23 years from 68 stations in Bangladesh and found that the Gumbel distribution fits the daily maximum rainfall data better than other distributions.

Different losses including the 'first flush' volume are deducted from the predicted rainfall to determine the design rainfall amounts. The storage capacity required for a specified demand is computed using this design rainfall. The initially collected water after an antecedent dry period that contains roof washout impurities, or the first flush volume, is not stored in the system. In the program, demand from the system can be set to be constant round the year, or the seasonal variation in demand can be specified over four different periods of the year. With this option, the system can be kept inoperative for a certain period of the year by specifying a zero demand for that period.

The months of installing and starting the system, for which maximum yield is obtainable, can be estimated by the program. The program also produces a set of data to generate a mass curve from which periods of low yield may be visually determined. Design demand may be reduced for these periods to design a 100% reliable and secured system.

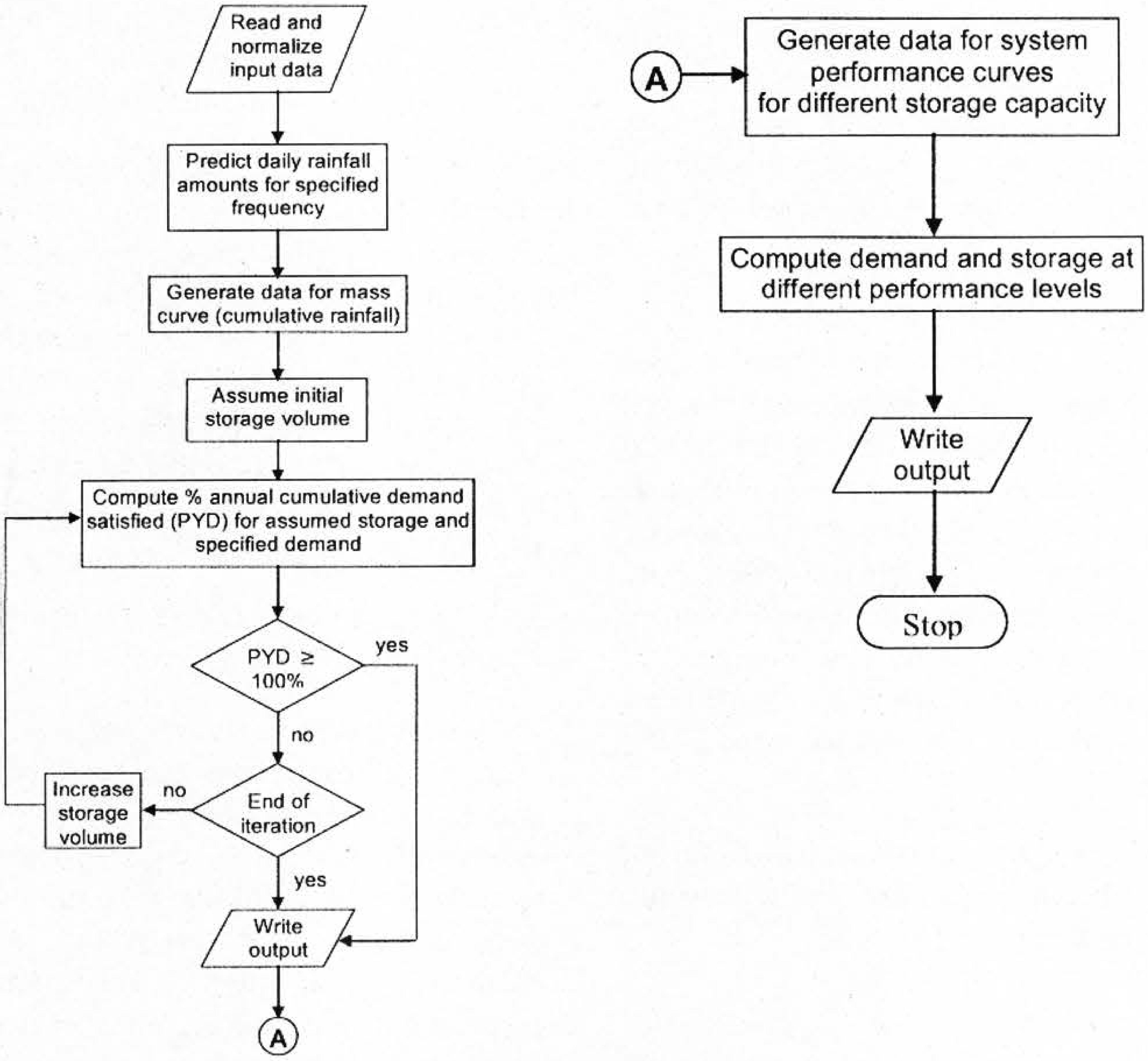


Figure 2: General flowchart of the computer program.

4. CASE STUDY

The computer program was used to design and analyze the feasibility of a rainwater harvesting system in Khepupara, a coastal township in Bangladesh. The average annual rainfall in Khepupara is 1725 mm. Approximately 95% of the annual rainfall occurs during April to October. The distribution of monthly rainfall is given in Table 1. The average daily rainfall is shown in Fig. 3.

Table 1: Distribution of Monthly rainfall in Khepupara, Bangladesh.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall (mm)	1	12	14	49	125	350	439	344	246	110	27	7

Daily rainfall records for 24 years were used to predict the design rainfall for a 1:2 year frequency. A first flush volume of 2.5 mm was selected to account for the losses including the first flush volume. Assuming an average water demand of 7.5 liter/day/person for cooking and domestic purposes in an individual household, the total demand for a family of 6 is 45.0 liter/day (Rahman *et al.*, 2003). Considering very low rainfall availability periods, the system would be kept inoperative from December to February, by specifying a zero demand during this time. For this setting, the system would remain closed for 90 days. Although different water demand from the system may be assigned in the program during four different periods of the year, a constant demand of 45.0 liter/day was assumed for the period of 9 months during which the system would operate. Therefore, for this operating period, the system reliability would be about 75%, or in other words, 75% of the cumulative annual demand is to be satisfied by the system. Fig. 4 shows the results of several program runs. Fig. 4 indicates that increasing the collection area beyond about 40 m^2 will not significantly reduce the required storage capacity. On the other hand, for any collection area less than about 20 m^2, a relatively large storage tank will be required to satisfy the demand. From this plot the storage capacity requirement for a given collection area can be determined for the specified demand and system reliability. Similar curves can be plotted from the results to determine storage capacity requirements at other levels of system reliability.

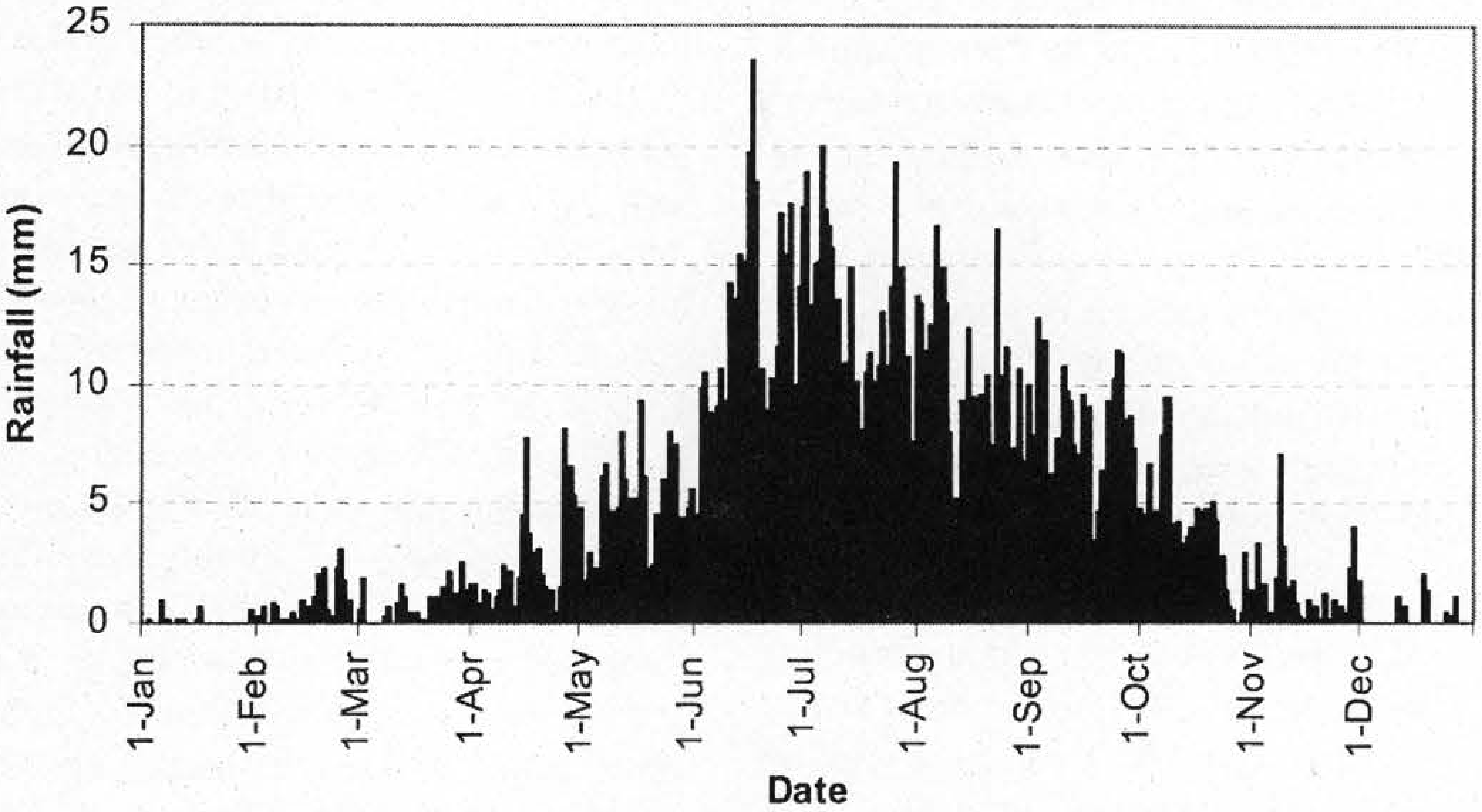


Figure 3: Average daily rainfall in Khepupara, Bangladesh.

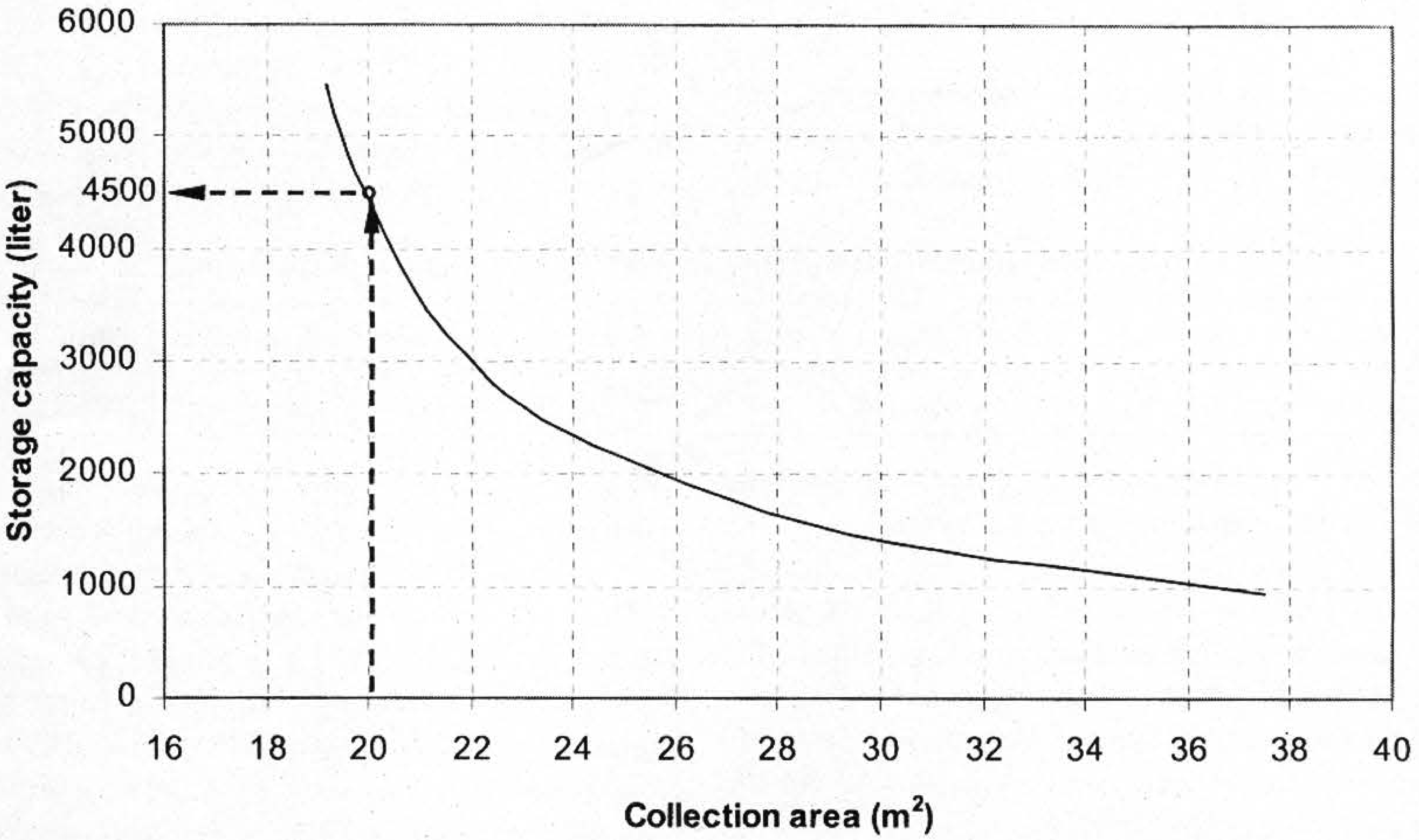


Figure 4: Results of computer program runs for a demand of 45 liter/day and a system reliability of 75%.

From Fig. 4, the storage capacity requirement for a collection area of 20 m^2 is found to be approximately 4500 liter. Rahman *et al.* (2003) found the storage capacity requirement to be 6500 liter by a water balance method using monthly rainfall amounts for the same demand, collection area and system reliability, and a similar rainfall distribution. Therefore, the present mathematical model indicates that the specified demand can be satisfied by a much smaller tank, requiring a lower cost for the system. The computer program thus can be used to determine the required storage capacity for a given set of conditions including amount and distribution of rainfall, available rainwater collection area, and annual variation in demand for a 100% reliable and secured system.

The computer program also generates system performance curves for design and analysis of the system. For this case study, only the system reliability is discussed since it is a closer representation of the system performance. Fig. 5 shows the variation in system reliability, or the percent of annual cumulative demand satisfied by the system, for different levels of constant demand throughout the year. Demand and storage are expressed per m^2 of the collection area. The actual demand and storage for the system can be found from a given collection area in m^2. A system reliability less than 100% indicates that the system is unable to fully satisfy the cumulative annual demand for the given set of conditions. This plot can be used to determine the storage capacity requirement for a specified demand at a given level of system reliability. For example, for a 75% reliable system and a specified demand of 2.25 liter/day/m^2, the required storage capacity is approximately 225 liter/m^2. Thus for a collection area of 20 m^2, the actual storage capacity is 4500 liter. This plot would also help select the minimum storage capacity required for a 100% reliable system for a specified demand. For example, for a demand of 0.2 liter/day/m^2, the required storage capacity is 150 liter/m^2. Any storage tank larger than this size would also fully satisfy the annual cumulative demand, or be 100% reliable.

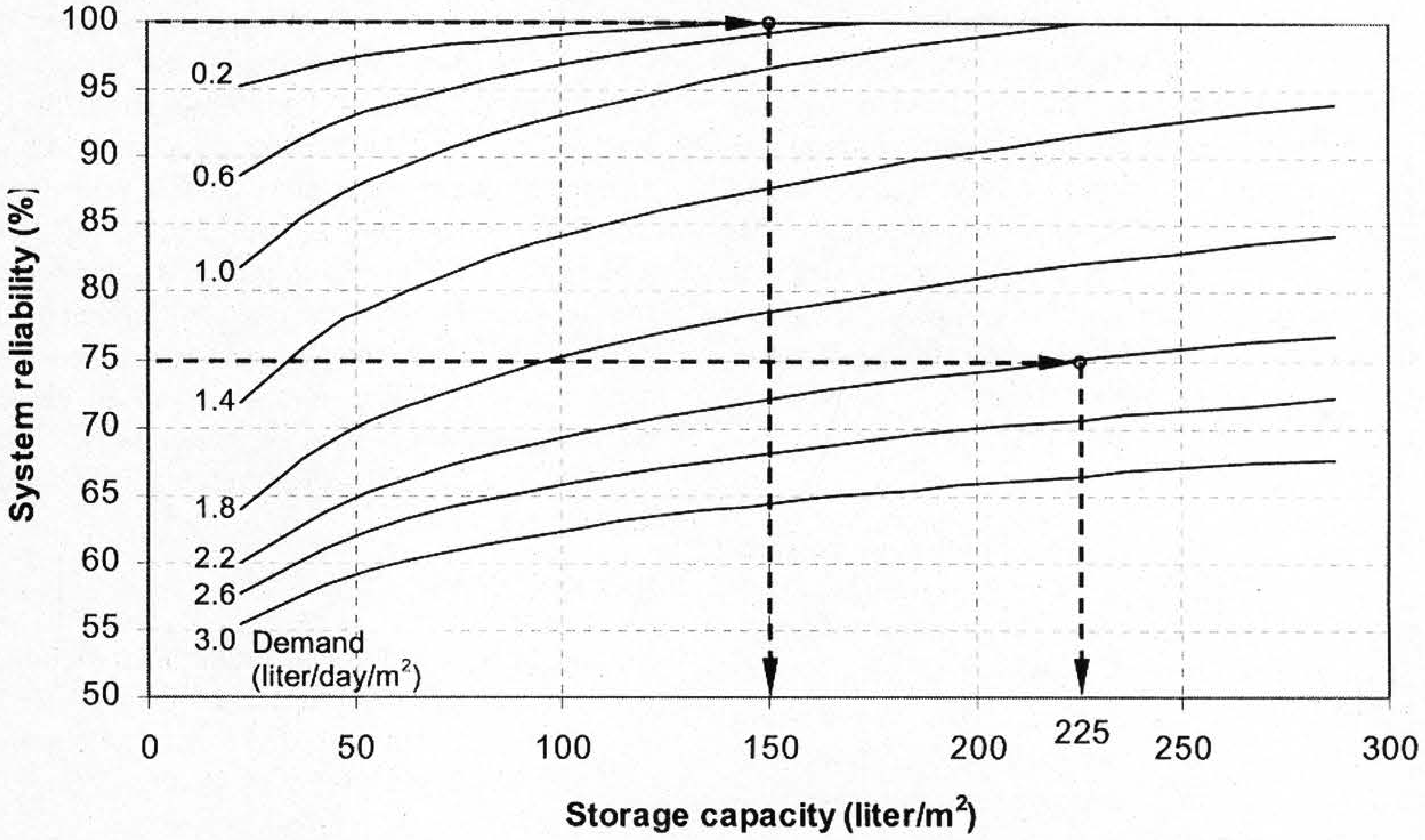


Figure 5: Variation in system reliability with storage requirement at various levels of demand.

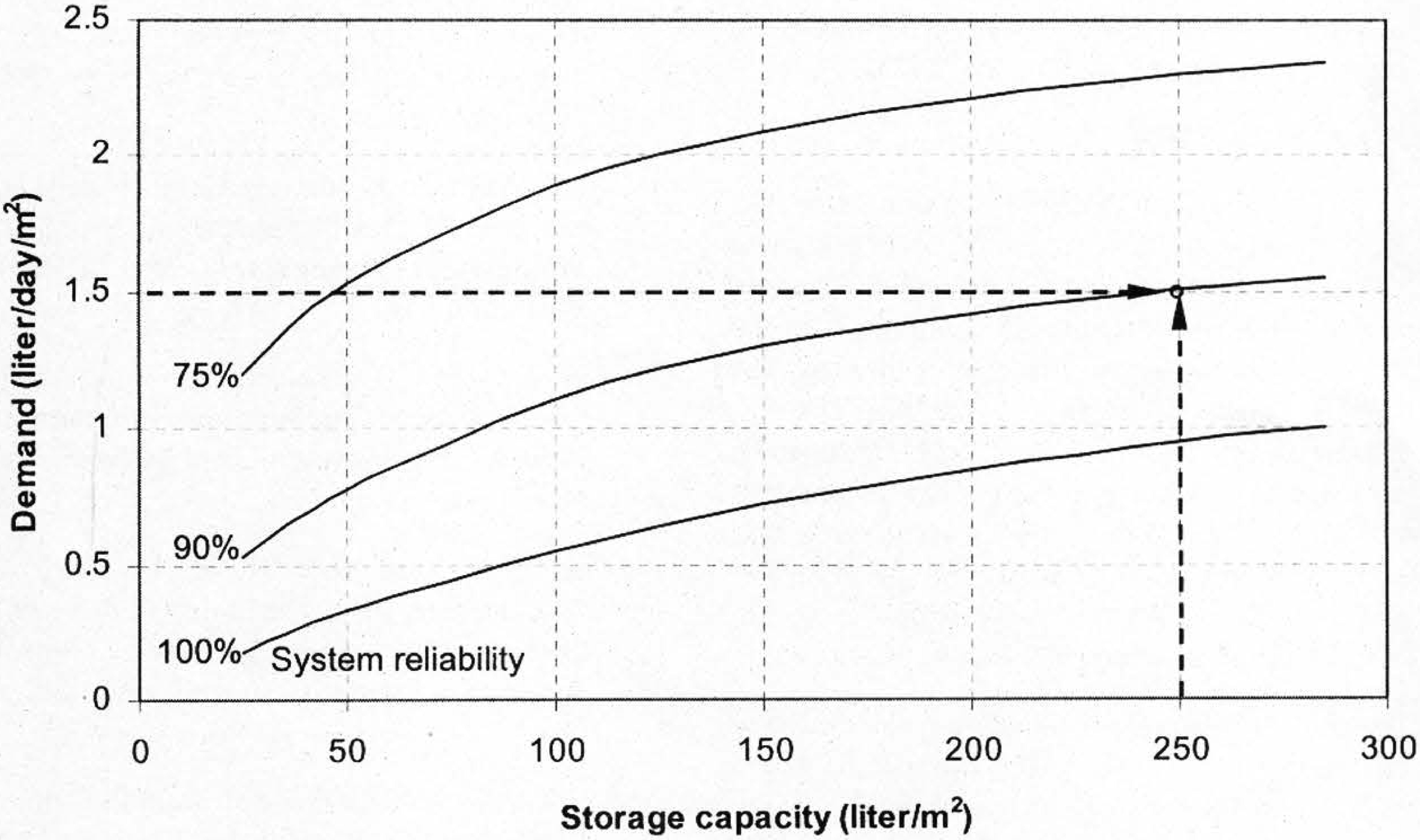


Figure 6: Storage capacity and demand at various levels of system reliability.

Fig. 6 shows the relationship between demand and storage at various levels of system reliability. The plot indicates that at a given level of system reliability, the system approaches a limiting demand which cannot be exceeded even if the storage capacity is increased. From this plot, the system reliability for a given storage and specified demand can be readily determined. For example, for a given demand of 1.5 liter/day/m^2 and a storage capacity of 250 liter/m^2, the system reliability is about 90%. From the results, similar curves can be plotted for system security.

Although the required minimum storage capacity for a 100% reliable and secured system, a given collection area, and a specified demand over four different periods of the year is readily available from a computer program run, the system performance curves would give the option and flexibility of selecting the size of a storage tank at various levels of system reliability and system security. These curves can be also used to determine the feasible ranges of design parameters including collection area and storage capacity for a given rainfall distribution.

5. CONCLUSION

Computation of the required minimum size of a storage tank is the most important part of designing a rainwater harvesting system. Since the storage tank costs the most among all components of the system, minimization of the size of the tank will significantly reduce the cost of the system. Minimization of the storage tank size can be achieved by considering predicted rainfall amounts and distribution, size of the collection area, and demand from the system over relatively short intervals of time throughout the year. The present method assumes a time interval of one day.

A computer program has been developed based on a mathematical model to serve as an inexpensive and easy-to-use tool for design and analysis of the rainwater harvesting systems. From the program, the required minimum storage capacity for a specified demand and a given collection area is readily available for a 100% reliable and secured system. System reliability has been defined as the percent of the annual demand satisfied by the system, whereas system security has been defined as the percent of time intervals in a year during which the demand is fully satisfied. Comparison with the traditional design methods shows that a smaller size of the storage tank determined by the present method is able to satisfy the specified demand. With the program-generated system performance curves, the designer has the flexibility of selecting various levels of system reliability and security for the design.

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