ORIGINAL ARTICLES

Sizing the Rainwater Tanks by Simulation of Daily Behavior Eerformance For Non-Portable Usage

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ABSTRACT

This study simulates the performance of the rainwater harvesting tank installed in the Faculty of Engineering, Universiti Putra Malaysia (UPM), Serdang in the state of Selangor. The study initially determines the coefficient of the roof runoff. Rainfall records were collected then analyzed to determine rainfall distribution and drought severity. The water demand was then monitored using constant critical daily demand in the modeling (36-years simulation). The behavior of water recharge and consumption were modeled with different type of tank sizes, then the failure probability was determined for the reliability of the tanks. The size of tank selections is related to the rainwater collecting area and to the degree of failure. Results are expressed as a regression equation to provide a design graph to the user to set up rainwater harvesting tank in this area.

Key words: Rainwater harvesting, tank simulation, tank sizing, statistical distribution, tank reliability, regression equation.

Introduction

Roof catchment systems so called rainwater harvesting are used for collecting runoff which is stored in tanks. The size and shape of the tanks and the roof areas vary considerably. Local designs for collection and storage have evolved from experience and largely they are not optimal.

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 design of rainwater roof catchment system is very simple if the standard deterministic method such as mass curve analysis is adopted. The most important aspect of the design is the uncertainty of parameters. The design of a rainwater roof catchment systems deals with a number of uncertain factors should incorporate. The major parameters involved in rainwater catchment systems design are the collection area, water demand pattern, storage capacity, and system reliability.

In order to determine the capacity of the storage (based on amount of rainwater could be collected) the major factor is to establish the surface runoff. The hydraulics of roof runoff is dependent on several factors relating to the type of materials used and the geometry of the roof and its collection systems (Kennedy et al., 2001).

2.0 Rainwater Storage Approaches:

The analysis of rainfall characteristics is the core of the hydrological design of rainwater harvesting system. The importance is such aspects as rainfall amount distribution, length of wet and dry spells, and drought severity among others. As with all engineering systems, rainwater harvesting system design requires a basic data set. This data generally includes rainfall, target demand and system size (Haggen, 1993).

2.1 Simulation models:

Models have been developed which use rainfall, catchment area and yield to determine storage requirements. Such models varied from simple deterministic types (Hoey and West, 1982) to probabilistic (Kok, et al, 1982) and stochastic models (Leung and Fok, 1982). In the United Kingdom a model was also developed (Fewkes and Ferris, 1982) where the rainwater was only used for toilet flushing.

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Computerized methods in optimizing storage volumes have also been reviewed (Schiller and Latham, 1982), the storage volume being determined by different methods based primarily on the classical mass curve analysis (Rippl, 1983), yield after storage model (Jenkins, et al, 1978) or a statistical method (Ree, et al, 1971).

In another simulation model (Morris, et al, 1984), the storage required to deliver a constant flow rate at each rainfall station was determined. A special feature of this model was the dual model of withdrawal with and without rationing.

Nanyang Technological University (NTU) has studied the feasibility of collecting the roof water from the north spine of the Nanyang Technological University (NTU) campus and to utilize it for non-potable uses and a simple input-output simulation model was used (Appan, 1982) with a minor addition in the output side. Herrmann and Schmida (1999) studied the development and performance of rainwater utilization system on the basis of a long-term simulation of 10 years rain data. The simulations were done by the hydrological based precipitation runoff model RW1N.

2.2 Modeling of System Performance:

Chilton et al. (1999) described a prototype rainwater recovery system that has been fitted with a monitoring system, which has been used to record the water usage and estimate the rainwater recovered for use in the supermarket over approximately an 8-month period. The results are used to calculate the collection efficiency of the system compared to potential gains determined from local rainfall data.

Fawkes (1999) described results from field testing a rainwater collector installed in a U.K. house. He found that the capacity of the storage tank is critical in the design of such systems. A set of dimensionless curves were produced which enables the storage capacity required to achieve a desired performance level with the known roof area and demand pattern are known. The data collected in his study was used to assess the desirable characteristics of a rainwater collection sizing model. The rainfall and WC usage data collected during the twelve month monitoring period was used as input into the system simulation model. The algorithm for the model used a yield after spillage (YAS) operating rule (Latham and Schiller, 1987)

Butler (1993) in his survey of domestic water usage also observed that the variation of WC usage on different weekdays was low. The system investigated is adequately modeled using average demand data, but this observation may not be universally applicable to other systems depending upon the nature of the demand time series.

Coombes and Kuczera (2003) studied the performance rainwater tanks with mains water tickle top up used to supplement mains water supply for domestic toilet, laundry, hot water and outdoor uses was evaluated for some cities in Australia. The PURRS (Probabilistic Urban Rainwater and wastewater Reuse Simulator) model developed by Coombes and Kuczera (2001) was employed to continuously simulate the performance of rainwater tanks using synthetic pluviograph rainfall generated by the DRIP (Disaggregated Rectangular Intensity Pulse) event based rainfall model by Heneker et al. (2001).

Tai and Pearce (1987) studied the use of rainwater for households in South Australia without mains water supply and a dependent upon rainwater as the sole source of supply, graphic results as depicted by iso-demand curves have been produced using a combination of tank sizes and roof areas.

2.3 Rainwater Catchment System Design Methods:

The major parameters involved in rainwater catchment system design are the collection area, water demand pattern, rainfall pattern, storage capacity and system reliability.

The major item of uncertainty is the rainfall regime, which must be analyzed in order to determine both the minimum collection area and the size of the tank. Ngigi (1999) has proposed an extensive investigation of rainfall characteristics such as rainfall amount, rainfall distribution, and length of wet and dry spells and severity of drought among other factors for rainwater catchment system design purposes. The reliability of rainfall distribution and its effect on rainwater catchment system design are only mentioned but not taken into account in the design method adopted. Scott et al. (1992) in their development of cistern sizing reference map have used rainfall amounts without any specific consideration of the rainfall distribution. Waweru (1998) did a research in runoff harvesting potential for crop production in Kitui, Kenya uses a rainfall probability to determine design rainfall based on rainfall amounts only.

Latham Schiller and (1987) in their comparison of commonly used hydrologic design methods, noted that the major constraint in the design process is cost which is directly related to the size of the tank. Waweru (1999) studied the importance aspects influencing the Rainwater catchment System design by analyzing the rainfall amount and rainfall distribution on the probability exceedence approaches.

The dimensioning of artificial storage tanks as an integrated part of Rainwater Harvesting System (RHS) has been verified by using statistical equations. An approach was worked by Walther and Thanasekaran (2001) using common rainfall data.
2.4 Catchment Area and Storage Capacity:

In most cases, empirical formulae have been developed to determine the design parameters (catchment area and storage capacity) for RWCS (Ndiritu, 1992). However, Ngigi (1999) found out that most of them are site specific, and hence inadequate without modifications to suit a certain locality. In addition, most of the empirical equations ignore one important input parameter rainfall distribution which is very critical in determining the design parameters. Another limitation of most of these empirical formulae is that they do not give the reliability levels in design. Ndiritu (1992) indicated that such formulae assume that the averages represent the rainfall series adequately, and thereby ignore the annual variability of rainfall.

Ngigi, (1999) cited that the mass curve analysis is more appropriate in that it considers all the input parameters. The mass curve analysis can also be used to monitor water management, by giving the tank volume at any time, provided that water inflows and outflows records are taken continuously.

Dominguez et al., (2001) shows the significant volumes from a rainwater harvesting system could be obtained if we use the roofs of large buildings in urban centers; on the other hand, a technical-economic analysis is done to evaluate the size of the rainwater storage. Under this approach, the temporal variability of the rainfall is considered by modeling the mass balance equation for the storage tank. The approach maximizes the water input and minimizes the construction costs of the cistern.

2.5 Sizing of Rainwater Storage Tanks:

The major constraint in the design process of the RWCS (RainWater Cistern System) is cost (Latham and Schiller, 1987), which is directly related to the size of the cistern. Its capacity not only influences the system costs but also the water supply capability of the system.

Chu et al. (1999) established a relationship between water releases. Storage capacity and roof top catchments area were established under different water demand conditions and were very useful and essential for planner in selecting and optimizing a rainwater catchments system design. An estimated storage volume of detention tank was simulated from the hyetograph was done by Zaizen et al., (1999) and the analysis of water balance was carried out by determining the estimated volume to be utilized.

2.6 Probability Approach:

An approach based on statistical tools like probability of rainfall, return periods, storage equation have been developed by Walther and Thanasekaran (2001) to dimension a rainwater harvesting system which are more cost-effective. Statistical approaches are used to predict the probability of high rainfall amounts as well as the return periods. According to that information the engineer can theoretically forecast how often a flooding will take place during a certain time range. Similar approaches can be used for the estimation of tank-sizes (Walther and Thanasekaran, 2001).

The determination of the tank size is related to the rainwater abstraction coefficient, the ratio of the cultivated area to the rainwater collecting area and the failure probability. The results are expressed as a regression equation to provide a convenient way for farmers to set up cistern systems in this area (Lee et al., 2000).

Verma and Sarma (1990) developed a computer based procedure to design a tank for rainwater harvesting and cost computing and volume of available water at the time of irrigation for planning water harvesting tank and found the economy measures, the tank should be of the largest size within the limits set by other factors.

Rugumayo et al., (2003) examined some of the probability distributions to be compared to the rainfall in order to determine amount water to be collected in state of the determination of the effectiveness of the rainfall in meeting crop water requirements.

3.0 Methodology:

A rainwater tank with the maximum storage of 3.35 m³ was installed at the Civil Engineering Laboratory Building, Faculty of Engineering Universiti Putra Malaysia (UPM). Rainwater was collected from a whole roof (metal) area which has a total plan area of 150 m². Rainwater is collected from the roof by gravity via a gutter to 100 mm diameter down pipe into a mild steel tank. The diagram of the rainwater harvesting system is shown in Plate 1.
Plate 1: Rainwater Harvesting System for this model.

Simulation of system operation was first made by monitoring the water consumption in the Civil Engineering Laboratory building toilets which consists the 4 rooms both for men and women from the upper tank of the toilet.

3.1.1 Fundamental of designing rainwater tank:

The type and size of the catchment determines the amount of rainwater that can be harvested and hence the storage capacity for a certain design rainfall amount. A reliable Rainwater Harvesting System (RHS) requires optimal combination of catchment and storage systems in order to maximize the overall reliability at a lowest cost. The design of a RHS requires the determination of the optimal size of the catchment which would yield an adequate water to satisfy the anticipated demand.

The water demand hence becomes an input parameter, equivalent to $Q_y$ in Equation (1). This would then dictate the capacity of the storage system, and subsequently the cost of the whole RHS. The water yield of a RHS depends on rainfall characteristics: amount $P$, reliability, and distribution, and on the catchment characteristics: type, size $A$, and runoff coefficient $C$. The water yield, $Q_y$ is given by:

$$ Q_y = CAP $$

Furthermore, determination of the optimal size of the storage capacity of RHS is a prerequisite because the storage tank is the key and usually the most expensive component. The storage requirement is taken as the volume of water that would be stored to meet the water requirements throughout the critical dry spell. Storage capacity depends on the water demand, length of the dry period, water use strategies and the available tank sizes. Therefore, the anticipated water demand dictates the size of the required storage capacity, while the amount of expected rainfall, and the size and type of catchment will determine whether this demand can be satisfied.

3.1.2 Mass Curve Analysis:

The mass curve analysis is more appropriate in that it considers all the input parameters. It is also not site specific, and hence has a wide application. The mass curve analysis is used to monitor water management, by giving the tank volume at any time, provided that water inflows and outflows records are taken continuously. This is important, especially for regulating water utilization, in case of unexpected drought. The mass curve analysis can be presented empirically by the following equation adopted from Ngigi (1999).

$$ V_T = \sum_{i=1}^{n} \left( Q_t - V_{i,t} + L_t \right) $$

where; $V_T$ is storage capacity at time $t$, $Q_t$ is water demand at time $t$, $V_{i,t}$ is volume of inflow at time $t$, and $L_t$ is losses from the system (can also due to overshoot from the gutter) during time $t$. 
Based on the mass curve, an adequate size of rainwater tank can be obtained when the accumulative water demand equals to the accumulative collected rainwater volume. However, the effectiveness of the mass curve analysis depends on the accuracy of determining the starting month of the hydrological year the beginning of the rainy season and/or the end of the dry.

3.1.3 Sensitivity of Runoff coefficient:

The sensitivity of the RCS model to rainfall losses will be constructed. The depression storage loss was set to zero and the sensitivity of the RCS model investigated using constant proportional losses or runoff coefficients ranging from 0.8 to 1.0. The selection of a runoff coefficient of 0.8 (Fawkes, 1999) maintains the accuracy of the RCS model. The overall runoff coefficient for the trial period was estimated using the relationship:

$$C = \frac{V_T}{R_T A}$$

(3)

where $C$, $V_T$, $R_T$ and $A$ are previously defined. The value of $V_T$ was equated to the total volume of rainwater collected and $R_T$ to the total rainfall level during the trial.

Rainfall loss during collection occurs due to absorption by the roofing material and wind effects around the roof are neglected.

3.1.4 System performance modeling:

The data collected in this study was used to assess the desirable characteristics of a rainwater collection sizing model. The rainwater collection sizing (RCS) model consists of two parts:

1. Provision of rainfall supply and toilet demand patterns must be known from collected data
2. Simulation the real system operation. In this study, the water consumptions at the laboratory building of the Department of Civil Engineering, UPM were monitored, which consist of four toilets rooms for men and women.

3.1.5 Demand and Availability:

The first step of dimensioning the system is to evaluate the real demand of the users. A number of tables are available indicating the daily consumption for various kinds of users or throughout the water consumption in the location will be used. In general the consumption depends on the degree of availability of water (Walther and Thansekaran, 2001).

The amount of water which can be collected is calculated from the size of the catchment area and the amount of rainwater. A rough estimation is obtained from Equation (1) where $P$ is daily modified rainfall.

3.1.6 Maximal storage theory:

A first estimation of the maximal demand has been made, which can be covered by the catchment area. In the case that the collection area can meet the consumption, the size of the tank can be directly calculated. An optimized system should follow two basic assumptions:

- The water-level of the tank should never become 0
- The water-level of the tank should never overflow

To meet these requirements, as far as possible, a number of statistical approaches are available.

3.1.7 Storage function of the tank:

Optimum tank size is equal to the volume of the runoff that can be collected form the catchment (roof). In fact, the size of the tank will be much less as the rainfall is distributed over the whole length of a year. Significant dimensioning parameters are either the length of drought periods or the amount of consumption. To call back the ideal assumptions mentioned above the water level should never go below zero, this means the tank becomes empty and it should never overflow which is equal to the loss of un-recharged rainwater. To estimate the amount of stored water in the tank there are two important functions to be dealt with. These are the functions for the consumption and for the recharge.
If the integral of these two functions are applied, the intersection gives information about the amount of water, which is really stored in the tank. Then the number of empty days can be calculated, indicating the most important dimensioning factor for the tank-size. In the optimal case the water level is always pending between the zero and the overflow level, without cutting these marks. If these requirements are fulfilled, the size of the tank could be selected. To get this kind of information, a matrix has to be developed to construct the functions of the rainfall recharge and the daily demand of water. Such a matrix could be designed as shown in Table 1.

Table 1: Various parameters included in the matrix used to calculate the storage.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>Daily Rainfall (mm)</td>
<td>Modified Rainfall (mm)</td>
<td>Recharge (m³)</td>
<td>Consumption (m³)</td>
<td>Tank Filling (m³)</td>
<td>Accumulated Recharge (m³)</td>
<td>Accumulated Consumption (m³)</td>
<td></td>
</tr>
</tbody>
</table>

The data given in columns 1, 2 and 5 are collected from the rainfall station water consumption monitoring. In this study a 36 year daily rainfall data have been used and the constant daily consumption which is 0.1 m³ per day has been used in this simulations. In column 3 the rainfall will be modified according to the amount of rain, which really results in a recharge which is the 5 mm rainfall and above because during a preliminary observation the rainfall less than 5 mm just only enough to wet the catchment surface. Column 4 is to be calculated from the size of the collection area and the efficiency C (Equation (1)). The last three columns 6-8 are logical equations, which calculate the amount of water in the tank as well as the accumulated amount of water for recharge and consumption.

The results of columns 7 and 8 are the integral functions of the amount of water, which was either collected or pumped from the storage. The integral functions can be calculated for different tank-sizes and then visualized in form of a graph. The single graph shows the behavior of water storage depending on the amount of rains, which leads to the recharge and the consumption.

Figure 1 shows flowchart for the rainwater storage model used in this study and Figure 2 shows the logic of tank filling al equation to be filled in Table 1.

3.1.8 Harmonizing of the designing parameters:

After the consumption and the recharge were plotting, the efficiency (reliability) of different tank-sizes has to be validated. This can be done by using the number of days for empty and for full conditions.

Legend:

- C = Consumption
- R = Recharge
- S = Storage
- TF = Tank Filling
- Wt = Overflow

a. Schematic diagram for rainwater storage model

b. Flowchart for logical routes of tank filling
c. Logical routes for accumulated recharge

\[ \text{IF } (T_b + R - C) = S_{\text{max}} \]

\[ \text{Acc} R_0 + R \]

\[ \text{Acc} R_0 + T F - T_h + C \]

\[ \text{NO} \]

\[ \text{NO} \]

\[ \text{Acc} C_0 + C \]

\[ \text{Acc} C_0 + T F + R \]

d. Logical routes for accumulated consumption

**Fig. 1:** Flowchart for the rainwater storage model used in this study.

For that purpose two more columns have to be added which includes the following logical equations

### 3.1.9 Failure rate and reliability:

A common definition of failure probability is the ratio of the time that the tank is empty to the total time period applied in the analysis. This can be expressed as (McMahon, 1993).

Equation for empty tank

\[ P_f = \frac{n_F}{n} \]

Equation for full tank

\[ P_f = \frac{n_F}{n} \]

where \( P_f \) is the failure probability, \( n_F \) is the time that the tank is empty and \( n \) is the total time period used in the analysis. Consequently, a cistern system with a small tank may receive a large failure probability. On the other hand, a large tank preserves the cistern system in a low failure probability.

In order to maximize reliability of the tank, the maximum failure is determined for each year occurred in each tank sizes simulations. Consequently, the maximum failure for different size of tank can be expressed as:

\[ P_{\text{fd}} = \text{Max}[P_f] \]

where \( P_{\text{fd}} \) is the maximum failure (design failure) and \( \text{Max}[P_f] \) is the maximum quantity within the bracket.

### 3.2 Rainfall reliability:

Rainwater harvesting is an anticipatory response to drought. Catchment design requires a prudent definition of target drought. Target drought might be a normal dry season, two rainless weeks, etc. Definition is by both duration and depth of precipitation. Target drought is often a balance drawn from past hydrologic history, consequences of rainwater catchment system failure, social implications and public acceptance. Most of the numerous drought indices are inappropriate as catchment performance targets. Analysis must anticipate the variety of meteorological futures that a catchment might experience. Stochastic analysis improves understanding of probable catchment behavior and the risks associated with alternative catchment designs.
3.2.1 Rainfall data analysis:

The availability of water is directly linked with rainfall events for a number of constructions like weirs or water storages. For that kind of construction the engineer is interested in the probability of floods which cannot be stopped by a weir or which makes a water storage overflow. Statistical approaches are used to predict the probability of high rainfall amounts as well as the return periods. According to that information the engineer can theoretically forecast how often a flooding will take place during a certain time range. Similar approaches can be used for the estimation of tank-sizes.

3.2.2 Probability distributions for rainfall data analysis:

In this study, three probability distributions are studied which are as follows:

Normal Distribution:

A random variable X is said to have three parameter probability density function (pdf) of a random variable X is given by:

\[
f(x) = \frac{1}{\sigma \sqrt{2\pi}} \exp \left[ -\frac{1}{2} \left( \frac{x - \mu}{\sigma} \right)^2 \right] \quad -\infty < x < -\infty
\]  

(6)

where \( \mu \) and \( \sigma \) are mean and standard deviation, respectively.

Lognormal Distribution:

A random variable X is said to have three parameter probability density function (pdf) of a random variable X is given by:

\[
f(x) = \frac{1}{\sigma \sqrt{2\pi}} \exp \left[ -\frac{1}{2\sigma^2} \left( \ln x - \mu \right)^2 \right] \quad x \geq 0
\]  

(7)

where \( \mu \) and \( \sigma \) are mean and standard deviation, respectively.

Extreme Value III / Weibull distribution:

A random variable X is said to have three parameter probability density function (pdf) of a random variable X is given by:

\[
f(x) = \alpha (x - \lambda)^{\alpha-1} (\beta - \lambda)^{-\alpha} \exp \left[ -\left( \frac{x - \lambda}{\beta - \lambda} \right)^{\alpha} \right] \quad x, \alpha, \beta > 0
\]  

(8)

The parameters of the distribution, namely \( \alpha \), \( \beta \) and \( \lambda \) are known as shape, scale, and threshold, respectively. For \( \alpha < 1 \), the probability distribution tends to infinity as \( x \to 0 \); for \( \alpha = 1 \), it becomes the exponential distribution, and for \( \alpha > 1 \), it resembles the gamma probability distribution.

A Kolmogorov-Smirnov test is used to check the fitness of the hypothetic distributions.

3.2.3 Length of dry spells:

The tank fails due to the long dry spells, thus, it is very important to study the distribution of the dry spells. The probability of having a day as a rainy day by \( p \) and dry by \( q=1-p \). A dry spell of length \( k \) is a sequence of \( k \) dry days bounded by wet days (consecutive dry day period). The lengths of dry spells are independent is assumed to be independent; a suitable distribution to fit the lengths is a truncated negative binomial distribution.

\[
f(k) = \binom{k + r - 1}{k} p^r q^k \frac{1}{1 - p^r}
\]  

(9)
Equation (9) can be reduced to the geometric distribution by putting $r = 1$. The reduced expression is (Shahin et al., 1993):

$$f(k) = pq^{k-1}$$

For $r \rightarrow 0$, one gets the logarithmic series distribution

$$f(k) = \frac{q^k}{k \ln p}$$

As a matter of fact the use of geometric distribution in the frequency analysis of dry-dry sequences for precipitation has been suggested earlier. Interchanging $q$ and $p$, Equation (11) can be written as

$$f(k) = p^{k-1}(1 - p)$$

where $f(k)$ is the probability of obtaining a sequence of $k$ dry days and $p$ is the distribution parameters.

### 3.2.4 Maximum annual dry length spells:

The recorded events are arranged in order of increasing magnitude $m$, with $m$ being 1 for the minimum event as well as $m$ being $n$ for the maximum event, and then the cumulative probability is given by (Haan, 1977).

$$P(X \leq x_T) = \frac{m}{n + 1} + \frac{1}{T}$$

where $P(X \leq x_T)$ is the cumulative probability of an event $X$ being less than or equal to $x_T$ so called Weibull plotting position formula. By using Equation (11), the data can be plotted to realize the minimum quantities for different return periods of drought based on available hydrologic records.

Chow (1964) showed that frequency analyses can be expressed in the following form:

$$x_T = \bar{x} + sK_T$$

where $x_T$ is the magnitude of the event having the $T$ year return period, $\bar{x}$ is the mean value of the hydrologic record, $s$ is the standard deviation of the hydrologic record and $K_T$ is a frequency factor.

### Results and Discussion

#### 4.1 Rainfall data analysis:

Rainfall data from Bukit Jalil Station was collected for analysis. The rainfall data taken from this station is assumed to represent the rainfall occurred in the experimental site (UPM). The records of the Bukit Jalil station were collected from 1955 to 1999 but only 36 years data is being used in this study due to missing data for some years. The mean annual rainfall is 2447 mm with a standard deviation of 412 mm. The variation in the annual rainfall is shown in Figure 3.
In this area, the wettest month is June which contributes 4% of total monthly throughout the year (Figure 3). The monthly average rainfall depth is 204 mm. The analysis of daily rainfall data showed that the mean daily rainfall is 6.7 mm (Figure 4). As a flow duration curve describes the natural stream flow characteristics of a river, the daily rainfall duration curve in Figure 5 shows the percentage of time that the rainfall depth is equal to or less than the various depths during the study period. This figure resulted from the daily rainfall distribution which passes the Kolmogorov-Smirnov one sample test at 1% level of significance for lognormal distributions. As shown in Figure 4, more than 40% is considered as the fair day weather (no rain). A rainwater tank technique is designed to store water in rainy periods and alleviate water shortage in dry seasons.

![Fig. 4: Histogram of daily rainfall with fitted density.](image)

An analysis of the frequency of one-day precipitation has been made as shown in Figure 6. This analysis is made to study the probability of the one-day precipitation could recharge the tank for the most severe case. The maximum size of tank is 3.35 m³, this means that for the 0.1 m³/day consumption, for the minimum rainfall could occur (5 mm rainfall) the average number of days per year is 7 days only. A 5 mm rainfall contributes a 0.6 m³ for a 150 m² roof size and could only last for 6 days if there is no rainfall for the consecutive 6 days after the single precipitation of 5 mm.

![Fig. 5: Depth-duration curve (daily rainfall data).](image)

4.2 Length of wet and dry spell:

On the other hand, to realize the severity of the water shortage in this area, the length of wet and dry spell are examined. As mentioned previously, the tank will fail due to consecutive dry period after the recharge (rain). Table 2 shows the fraction length of spells for a consecutive day of dry and wet for 1 day, less than 5 and 10 days. For a maximum size of 3.35 m³, the tanks as a rule of thumb, would fail to the day 34 after the tank is full and there is no rain for a 33 consecutive days for to meet 0.1 m³ water demand per day. In this study periods, the probability of consecutives spells have been fitted in a geometric distribution. The 33 days consecutive of dry days has a probability of 2.3x10-6, which is very small. Thus, the probability of the maximum of tank will not fail is extremely small.
In order to realize frequency characteristics of the maximum dry spell sequence, a maximum dry spells sequence were plotted on Gumbell probability paper. Figure 7 shows the maximum consecutive time is 37 days in 40 years. Equation (14) yields to the following equation to estimate the annual maximum dry-day sequences:

$$x_T = 20.86 + 5.52K_T$$

(15)
The failure of the tank is calculated using Equation (5). In this analysis, the maximum size of tank gives 7 maximum days of empty tank and for 90% of the maximum size gives 14 days. Also, an 80% and 70% of maximum size both gives 18 and 23 days of emptiness, respectively, while for a 60% and 50% of the maximum size gives 29 and 44 day of emptiness, respectively. As the results show, the failure rate increases as the tank size is decreased.

For the analysis of the failures, the maximum failure is chosen as a measure to maximize the reliability of the tank. By maximizing the failure probability, the reliability of the size to be selected for a design will set to the most reliable sizes of tank.

Table 3 shows the maximum failure for different size of tank. The failures of tank are calculated using Equation (6). As shown in this table, the maximum failures are very small for sizes of 100% to 60%. For a size of 50% of the maximum size of tank, the maximum failure is 1% of the day in a year. This means that the sizes of tank are essential to meet the constant demand of 0.1 m³/day with a good rainfall reliability as well.

<table>
<thead>
<tr>
<th>Tank Size (m²)</th>
<th>3.35</th>
<th>3.015</th>
<th>2.68</th>
<th>2.345</th>
<th>2.01</th>
<th>1.675</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Failure (%)</td>
<td>0.019178</td>
<td>0.038356</td>
<td>0.049315</td>
<td>0.063014</td>
<td>0.079452</td>
<td>0.120548</td>
</tr>
</tbody>
</table>

4.4 Storage/roof size ratio and degree of failure relationship:

The system reliability depends on the failure of the system and the size of tank depend on the catchment area as well as rainfall reliability and the water demand. The results gained from the simulations are used to correlate these two situations. From Table 3, the maximum failures are changed to be the degree of failure of the system. The ratio of the storage capacities to the roof area of 150 m² is determined and the relationship between storage capacity to roof area ratio and degree of failure is shown in Figure 8. This relationship yields to the following regression equation:

$$ \frac{S_c}{A_r} = 0.0254e^{-7.1965P_f} $$

where the value of coefficient of correlation, R² is 0.9716, where S_c/A_r is ratio of the storage capacity to roof area (m³/m²), and P_f is degree of failure. Equation (16) indicates that degree of failure inversely proportional to the ratio of the storage capacity to roof area exponentially.

Through that relationship the desired size of tank could be determined with the selections of area of roof/catchment and the degree of failure for the reliability of the systems. Table 4 shows the sizes of tank gained from Equation (16) which leads to the construction of design graph for a tank selection as shown in Figure 9. The design graphs are plotted for the roof area ranging from 50 to 300 m², and the degree of failure (in percent) ranging from 5 to 50% of degree of failure.

<table>
<thead>
<tr>
<th>Aroof m²</th>
<th>5</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
</tr>
</thead>
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<tr>
<td>50</td>
<td>0.8723</td>
<td>0.6087</td>
<td>0.2964</td>
<td>0.1443</td>
<td>0.0703</td>
<td>0.0342</td>
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<tr>
<td>100</td>
<td>1.7445</td>
<td>1.2174</td>
<td>0.5923</td>
<td>0.2887</td>
<td>0.1406</td>
<td>0.0684</td>
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<tr>
<td>150</td>
<td>2.6168</td>
<td>1.8261</td>
<td>0.8892</td>
<td>0.433</td>
<td>0.2108</td>
<td>0.1027</td>
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<tr>
<td>200</td>
<td>3.4891</td>
<td>2.4347</td>
<td>1.1856</td>
<td>0.5773</td>
<td>0.2811</td>
<td>0.1369</td>
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<tr>
<td>250</td>
<td>4.3613</td>
<td>3.0434</td>
<td>1.482</td>
<td>0.7216</td>
<td>0.3514</td>
<td>0.1711</td>
</tr>
<tr>
<td>300</td>
<td>5.2336</td>
<td>3.6521</td>
<td>1.7784</td>
<td>0.866</td>
<td>0.4217</td>
<td>0.2053</td>
</tr>
</tbody>
</table>

5.0 Conclusion:

The capacity of rainwater tank depends mainly on the size of roof, rainfall distribution, water demand, and the coefficient of the roof runoff. The method used to simulate the performance of the rainwater harvesting tanks in this study was selected as the best way by knowing the behavior of the capacity in tank as indicated in literatures that have been reviewed.

From this study, the size of 1.34 m³ (40% of maximum capacity 3.35m³) was selected as the optimum size which gives the 9.95% of failure. The maximum capacity (3.35m³) is sufficient to cover the daily demand during the study with the 8.43% of the volume collected could be recharged, but for a tank size of 1.34 m³, the recharge was only 7% means only 0.43% less, whereas the volume of the tank was reduced to 60% of maximum capacity. It is a fact that a storage tank, which is generously dimensioned, will decrease the risk of failure. Similarly, a too small dimensioned tank will overflow frequently during peak rainfalls. In both cases the
consumer will notice if the tank could be dimensioned in a better way or not. The size of the tank and the cost for the construction should be kept at the optimum. In addition the designer of the tank can give information up to which probability the demand can be covered during a year and if additional measurement are necessary.

Fig. 8: Relationship between storage capacity to roof area ratio.

Fig. 9: Design graph of tank size for different roof areas and degree of failure.

References


Hoey, P.J. and S.F. West, 1982. *Recent initiation in rainwater supply systems for South Australia*. Proceedings of the International Conference on Rainwater Cistern System (pp. 284-293), Honolulu, USA.


