EMPIRICAL MODEL SIMULATING RAINWATER HARVESTING SYSTEM IN TROPICAL AREA

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ABSTRACT

Rainwater harvesting is the technique of capturing the rainfall to meet some water needs in both urban and rural areas. The volume of rainwater collected from rainwater harvesting system varies from place to place and depends mainly on the climatic condition. Typically, the rainwater harvesting system is composed of the catchment (roof), gutter, rainwater pipe, and storage tank. Reliability of a rainwater harvesting system mainly depends on the collected volume in rainwater storage tank and it is also used to check whether the collected volume of rainwater can meet a specific water demand (either for potable or non-potable uses). In the present study, a rainwater harvesting system is installed at the Faculty of Engineering, University Putra Malaysia. The system is tested using data from 24 different rain events. The collected data include rain depth and rainwater volume. It is found that the rainwater volume ranges form 0.027 m^3 to 4.03 m^3. The actual data are used to produce an empirical model for predicting the collected rainwater volume. Calibration and validation processes are conducted to the proposed model and T-test shows that the model prediction is within 95% level of confidence. Furthermore, the water consumption for toilet flushing is monitored using water meter. Reliability of the installed rainwater harvesting system for toilet flushing is computed. It is found that the system reliability ranges from 26.61 % to 100 % depending on daily water demand and recorded rainwater depth.

Keywords: Rainwater harvesting, system modeling, assessment, reliability

1. INTRODUCTION

Rainwater harvesting is the technique of collection and storage of rainwater from roofs during rain events for future use. This technique is appropriate in many countries such as United Kingdom, Germany, China, Japan, Thailand, Sri Lanka, India, Australia, Brazil and United States of America. The technique is relevant in areas with sufficient rainfall for collection but experiencing water shortage due to either limited availability of conventional water resources or high water demand. It can also be used in arid regions to overcome water shortage.

Rainwater can be used to meet part of domestic water demand including both potable and non-potable. In urban areas, at a household level, rainwater can be used for flushing toilets, watering gardens and washing floor and these uses are known as non-potable. While in rural areas, it becomes the main source of water for potable uses which include drinking, bathing, and cooking. In rural areas it is recommended to treat the collected rainwater prior to use particularly if it is intended to be used for drinking.

A simplified rainwater harvesting system consists of a storage tank which is usually connected to a rooftop through a pipe. Rooftops are constructed from various types of materials such as concrete slab, plastic corrugated sheets, metal corrugated sheets, corrugated cement tiles and corrugated clay tiles. The collection areas of rainwater harvesting systems are buildings' roof. The size of the roof varies from one type of building to another. Small roof size or catchment usually is found in houses and large size is found in super markets and airports. The size of catchment has a direct influence on the collected rainwater volume from a catchment. The intensity of the rainfall is also another factor affecting the collected volume of rainwater. Many rainwater harvesting systems installed in many countries including Malaysia but the main concern is the reliability of these systems. The reliability depends solely on collected

rainwater volume and the nature of water consumption (for potable and non potable uses). The collected rainwater volume depends largely on the climatic condition while the water consumption depends primarily on social and cultural habits of the community. In brief, the reliability will determine whether the system is successful and economically feasible or not.

Shaaban et al. (2002) tested the usage of rainwater harvesting installed in a house located in Kuala Lumpur, Malaysia and based on the experiment he recommended the rainwater to be used for washing clothes and flushing toilets only. Ruslan (2003) proposed a computer software to determine the reliability of rainwater tank. Ghisi and Ferreira (2006) studied the reliability of rainwater harvesting for 26 cities in Brazil. Gould and Nissen-Peterson (1999) gave the runoff coefficients for various materials used for roofing. Rahman and Fatima (2006) reviewed the materials of rainwater storage tank.

In Malaysia, it is recommended to use rainwater harvesting technique in rural areas (with housing and public buildings) but there is a lack of real data to help the designer do proper sizing for the system. In this study, an empirical model is proposed for sizing the tank for rainwater harvesting system. The model is calibrated and validated using actual data. Data for water consumption in a student toilet is used to check the reliability of the rainwater harvesting system.

2. SYSTEM DESCRIPTION AND METHODOLOGY

In this study, a rainwater harvesting system is installed at a selected site at the Faculty of Engineering, Universiti Putra Malaysia. The system is composed of roof (catchment), gutter, PVC pipe and storage tank. The roof (catchment) size is 150 m^2 and it is made of corrugated steel sheets and sloped towards the gutter. The gutter is made of steel and fixed tightly with the roof and its dimensions are 140 mm x 140 mm (width x depth). The diameter of the PVC pipe is 100 mm and it contains a piece of flexible hose and this arrangement can be used to collect samples of rainwater for quality monitoring. The pipe is connected to the storage tank from the top. The storage tank is made of steel and contains drain and depth monitoring scale. The dimensions of the tank are 0.85 m x 4.0 m x 1.2 m (width x length x depth) and its maximum capacity is 4.08 m^3. A graduated scale is used to calculate the tank volume while the drain is used to empty the tank after rain in order to prepare the tank for the next rain event. Figure 1 shows the general view of the tank and Figure 2 shows the arrangement used to measure the water depth in the tank. Figures 3 and 4 show the roof and the gutter while Figure 5 shows the plastic pipe connections.

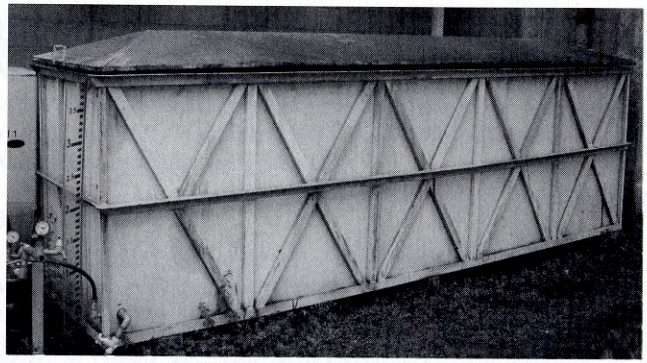


Figure 1: General view of the storage tank.

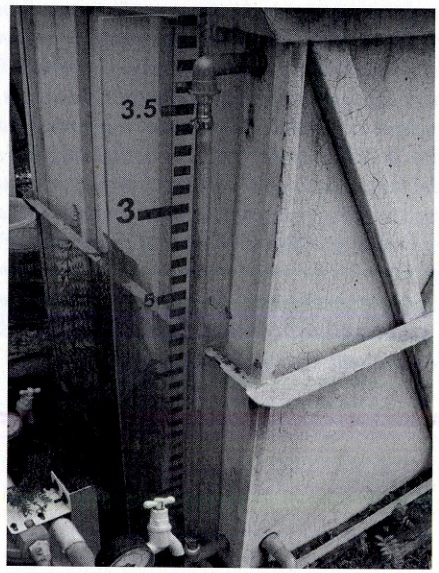


Figure 2: The scale for measuring water depth in the tank.

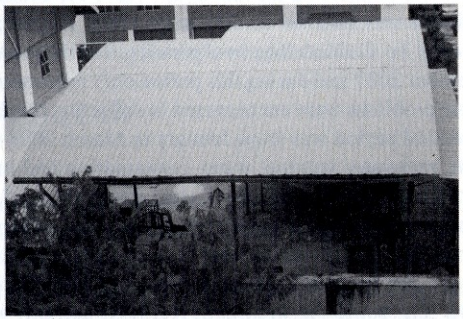
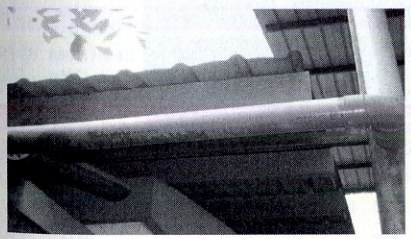


Figure 3: The rainwater catchment comprises of a 100 m^2 roof.

Figure 4: Picture of 140 mm x 140 mm gutter.



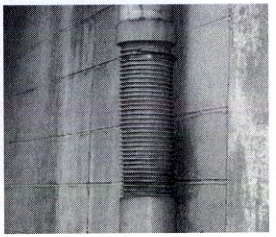


Figure 5: Rain pipe connections and example of a flexible hose.

Beside the collection of rainwater volume in the tank, a rain gage is installed near the location of the system to get the rainfall record (Figure 6). Rainfall record for the period of the study is used to build a model simulating the system as well as to compute runoff coefficient for roof (catchment).

A meter is installed in one of the student wash rooms in order to get daily water consumption for toilet flushing (Figure 7). Data are collected continuously for 3 months (from January to March 2008). Furthermore, the number of students using the washroom is also monitored for one week. This type of data is needed for conducting reliability assessment to the system. The methodology of the study can be summarized in the flowchart shown in Figure 8. Shaaban et al. (2002) installed a rainwater harvesting system at a house located in Taman Wangsa Melawati, Kuala Lumpur, Malaysia. The main objective of the system is to monitor the rainwater quality. The methodology and the objectives of the present study are quite different from this work.

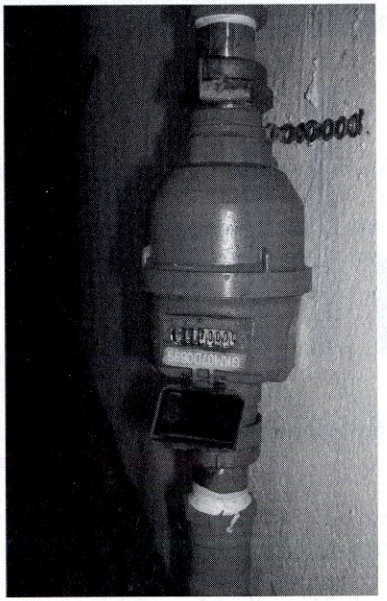


Figure 6: The rainwater gauge.

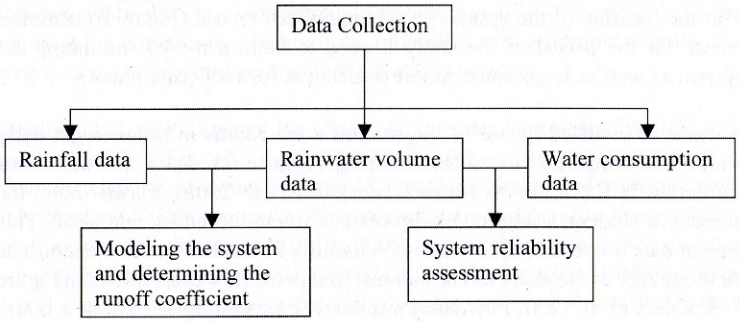


Figure 7: The flow meter.

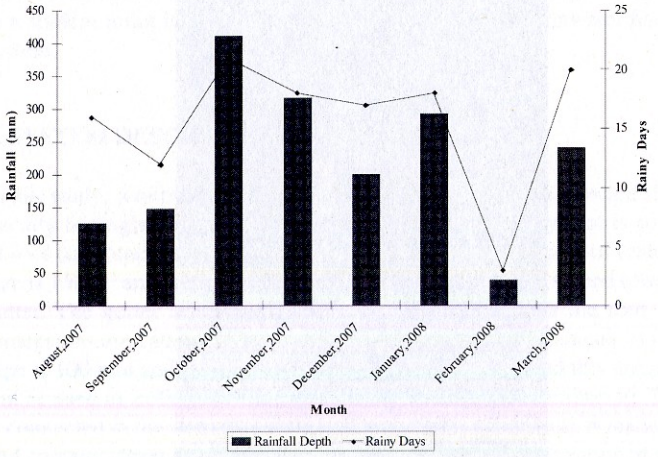


Figure 8: The methodology of the present study.

3. RESULTS AND ANALYSIS

In this study, data were collected for 8 months (from August 2007 to March 2008) and it could be divided into two periods. The first period was from August to December 2007 and during this period only rainwater was collected. This was because problems were encountered in collecting the data of rainwater volume. The second period was from January to March 2008 and focused on data for rainfall, rainwater volume, water consumption and number of toilet users. In order to eliminate the effect of areal distribution of rainfall, a rain gauge was installed nearby the location of rainwater harvesting system. Figure 9 shows total monthly rainfall and number of rainy days at the site of rainwater harvesting system for the studied period. The maximum recorded monthly rainfall was 412 mm while the minimum recorded monthly rainfall was 40 mm. The maximum number of rainy days was 21 and it occurred in October 2007 while the minimum number of rainy days was 3 and it occurred in February 2008. Thus, the average monthly rainfall depth was 223 mm while the average rainy days were 16.

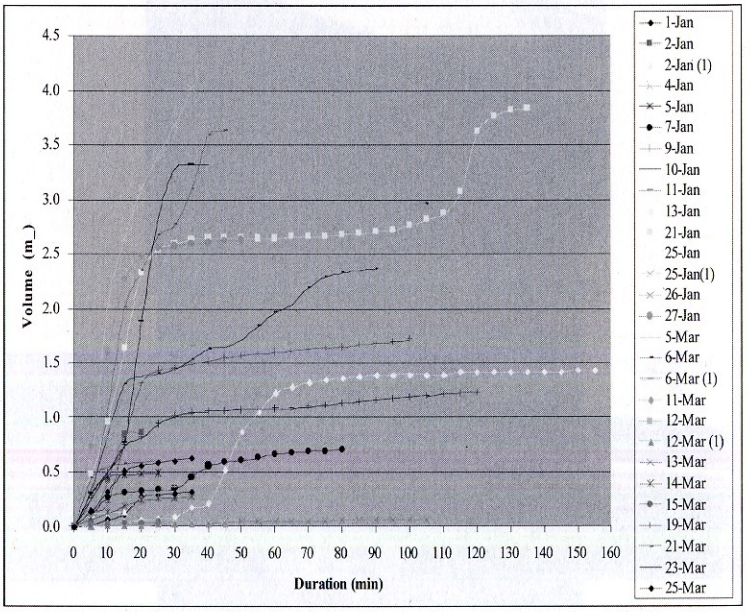


Figure 9: Monthly rainfall (mm) and rainy days from August 2007 to March 2008.

The volume of rainwater collected in the tank of the rainwater harvesting system was recorded for every rain event for a period of 3 months (from January 2008 to March 2008). The volume of rainwater collected in the tank can be determined using the following formula:

$$V_R = D \, x \, L \, x W \tag{1}$$

where, V_R is the rainwater volume collected in the tank, D is the depth of water in the tank of the system, L is the tank length and W is the tank width.

For every rain event, the value of V_R was determined. Depending on the rainfall intensity and duration, it was found that the volume of rainwater collected in the tank varied and ranged between 0.027 m^3 and 4.026 m^3. The maximum volume was collected on the 4th January while the minimum volume was collected on 12th March 2008. From the rainfall record, it was found that the shortest duration of rain was 15 minutes which was recorded on 25th January 2008 and rainwater volume collected from this event was 0.136 m^3. On the other hand, the longest duration of rain was 150 minutes (2 hour 30 minutes) which was recorded on 13th January 2008 and the rainwater volume collected from this event was 1.438 m^3. Figure 10 shows the variation of the collected volume of rainwater with the duration of the rainfall for various events. Hindia et al. (2002) installed a rainwater harvesting system at a school in Zambia, Africa to monitor rainwater quality. They used a tank with a size of 10 m^3 but they justified that the amount was enough for one year since the consumption was 10 liters per capita per day.

The Calibration and Validation of Governing Models

The collected data (volume of the rainwater, rainfall depth, duration and roof area) can be used to determine the runoff coefficient of the roof (catchment). The rational formula described below is used for this purpose.

$$Q = \frac{CIA}{360} \tag{2}$$

where C is the coefficient of runoff (dimensionless), Q is the collected runoff (m^3/s), I is rainfall intensity (mm/hr) and A is the roof area (hectare).

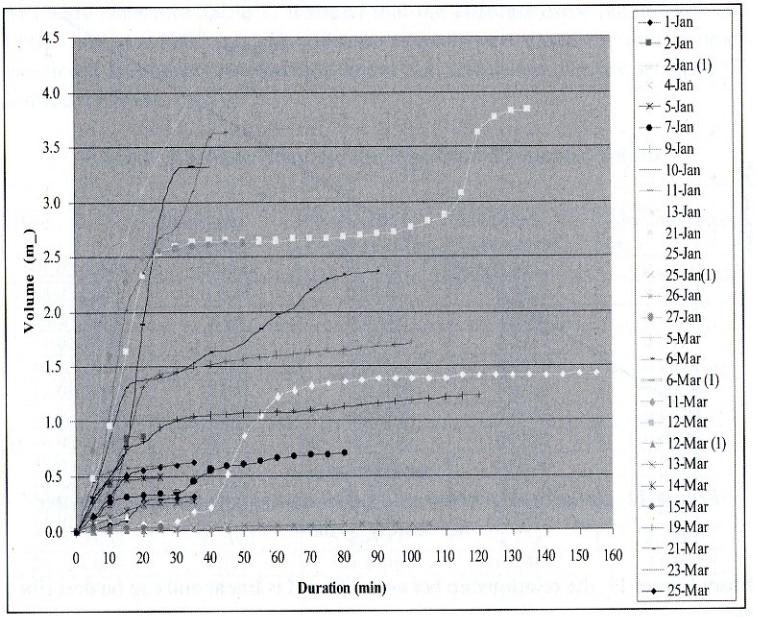


Figure 10: Variation of rainwater volume with time for various rain events.

For a given system, the size of the roof area is known and value of C depends on the type of roof material. So, Equation (2) can be written in the following general form:

$$Q = KI \tag{3}$$

where K is a constant and its value can be determined from the graphical relationship between Q and I.

For the system employed in the present study and based on the collected data, the graphical relationship between of runoff and rainfall is shown in Figure 11.

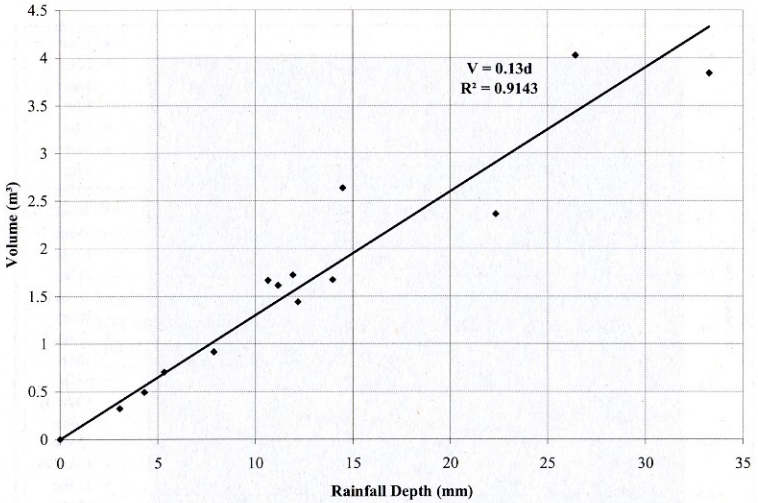


Figure 11: Relationship between rainfall and runoff for the rainwater harvesting system.

From Figure 11, the relationship between Q and I is linear and can be described as:

$$Q = 0.0000346I \tag{4}$$

From Equation (4), it can be concluded that the value of K is equal to 0.0000346 and the value of K can be described as

$$K = \frac{CA}{360} \tag{5}$$

After substituting the values of A and K in Equation (5), the value of C is found to be 0.83. The value of runoff coefficient, C for the system in the present study is in agreement with the value proposed by Zhu and Liu (1998). The values of runoff coefficient for roof catchment of sheet metal as recommended by Zhu and Liu (1998) range from 0.8 to 0.85. The value of C indicates that type of roof material used in the rainwater harvesting system is corrugated metal. It is recommended that similar studies to find values of C for the common types of roof materials used in Malaysia are carried out.

Based on Equations (2) and (4) the following general model can be proposed to simulate the relationship between the rainwater volume and the rainwater depth for a rainwater harvesting system.

$$V_R = \phi d \tag{6}$$

In the present study, the collected data is divided into two equal parts. The first part is used to calibrate the model while the second part is used to validate the model.

From Figure 12, the value of ϕ is found to be 0.13. Thus, Equation (6) can be written as:

$$V_R = 0.13d \tag{6}$$

The coefficient of determination for the model described in Equation (6) is found to be 0.91. The model is very essential for designers involved in sizing the tank of rainwater harvesting system for housing and public buildings in Malaysia.

Using the second part of the data, the proposed model is used to predict the rainwater volumes. Then the predicted volumes are compared with the recorded volumes (Figure 13). Generally, both predicted and recorded volumes are in agreement.

The absolute error (E_A) between the predicted rainwater volume (V_p) and the recorded rainwater volume (V_m) is determined using the following equation:

$$E_A = V_p - V_m \tag{7}$$

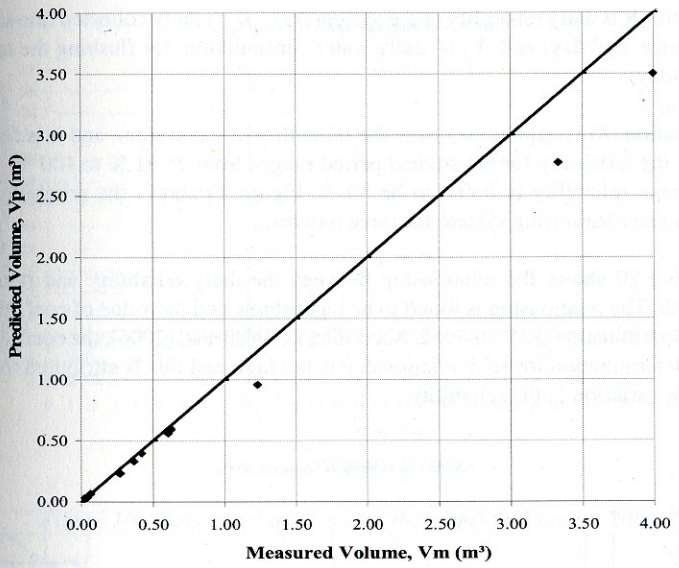


Figure 12: Relationship between the rainwater volume and rainwater depth for the studied system.

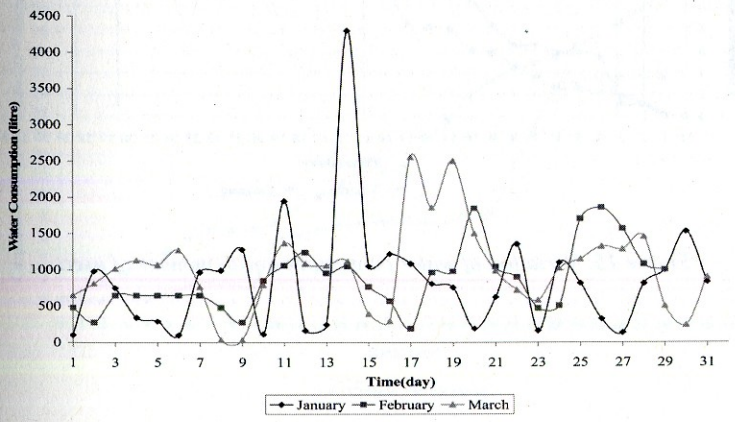


Figure 13: Comparison between the predicted and observed rainwater volumes.

Equation (7) is used to verify the model accuracy and the values of absolute errors are shown in Table 1. It found that the absolute error ranges between 0.0014 m^3 to 0.5583 m^3. In addition, t-test is performed for two samples (predicted and observed) and it is found that tested samples are within 95% confidence level.

Table 1: Absolute Error for the Predicted Rainwater Volume

Date	Rainwater Depth (mm)	Predicted Volume (m^3)	Recorded Volume (m^3)	Absolute Error (m^3)
05.03.2008	3.048	0.3962	0.3962	0.0254
06.03.2008	4.318	0.5613	0.5613	0.0439
06.03.2008	2.54	0.3302	0.3302	0.0370
11.03.2008	1.778	0.2311	0.2311	0.0341
12.03.2008	0.254	0.0330	0.0330	0.0024
12.03.2008	0.254	0.0330	0.0330	0.0058
13.03.2008	0.508	0.0660	0.0660	**0.0014**
14.03.2008	1.778	0.2311	0.2311	0.0409
15.03.2008	0.254	0.0330	0.0330	0.0078
19.03.2008	7.366	0.9576	0.9576	0.2732
21.03.2008	26.924	3.5001	3.5001	0.4949
23.03.2008	21.336	2.7737	2.7737	**0.5583**
25.03.2008	4.572	0.5944	0.5944	0.0346

Water consumption for flushing toilet was monitored using the water meter for the period of three months (from January 2008 to March 2008). Figure 14 shows the variation of daily water consumption. Through the monitoring period, it was found that the maximum and minimum daily water consumptions were 4.3 m^3 and 0.036 m^3 respectively. From the collected data it was found that the average daily water consumptions was 0.85 m^3 for month January 2008 while the average daily consumptions for February and March 2008 were 0.88 m^3 and 1.02 m^3 respectively. For a selected day, water consumption for flushing toilet was monitored and the variation of the consumption was shown in Figure 15. This observation was carried out from 8 am to 8 pm on the 5th March 2008. The total measured volume of water consumed was 1.07 m^3 and the total number of students using the toilet was 101.

Figure 16 shows the mass curve for demand (water consumption for toilet flushing) and supply (rainwater volume collected in the tank) for the month of January 2008. During the month of January, there were 5 days where the demand met the supply and this meant that the collected rainwater volume is enough to meet the demand. Also, there were 3 periods during the month

where the water demand exceeded the water supply and this meant that the collected rainwater volume was not enough to meet the volume needed to flush the toilet but it contributed to fulfill part of the demand. Based on this result, a dual system is very helpful to make use of rainwater and reduce the demand on public water supply. The total water demand throughout the month was 26.39 m^3 whereas the total water supply from rainwater is 23.4 m^3. It indicated that the rainwater volume could meet 89% of the demand for that month. The mass curves for months of February 2008 and March 2008 are shown in Figures 17 and 18. In February 2008, only 18.5% of the demand could be met but in March 2008 the supply was 21% greater than the demand and this meant that there was surplus of water for the following month.

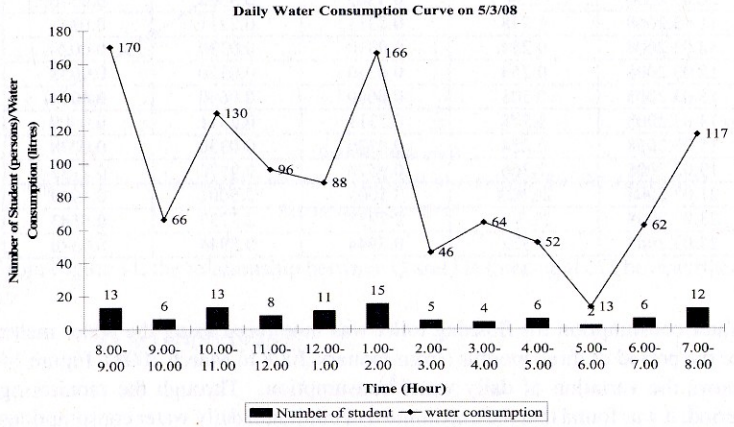


Figure 14: Variation of daily water consumption for flushing toilet.

Data concerning rainwater volume and water consumption (mainly for flushing toilet) was used to assess the reliability of the rainwater harvesting system. The following equation is proposed to determine the daily reliability of the system

$$R = \frac{V_a}{V_d} x100 \qquad (8)$$

where R is daily reliability of the system (%), V_a *is d*aily collected rainwater volume (m^3/day) and V_d is daily water consumption for flushing the toilet (m^3/day).

Equation (8) is applied to assess the reliability of the system and it is found that the reliability for the studied period ranges from 26.61 % to 100 %. The average reliability is found to be 80 %. Figure 19 shows the reliability of rainwater harvesting system for three months.

Figure 20 shows the relationship between the daily reliability and rainfall depth. The relationship is found to be logarithmic and the value of coefficient of determination (R^2) is 0.4962. According to Ghisi et al. (2006), the coefficient of determination for such relationship is not high and this is attributed to the wide variation in the reliability.

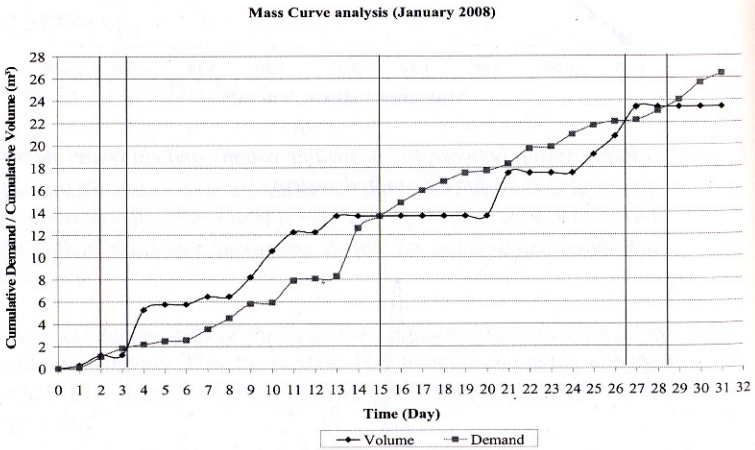


Figure 15: Variation of water consumption with number of users.

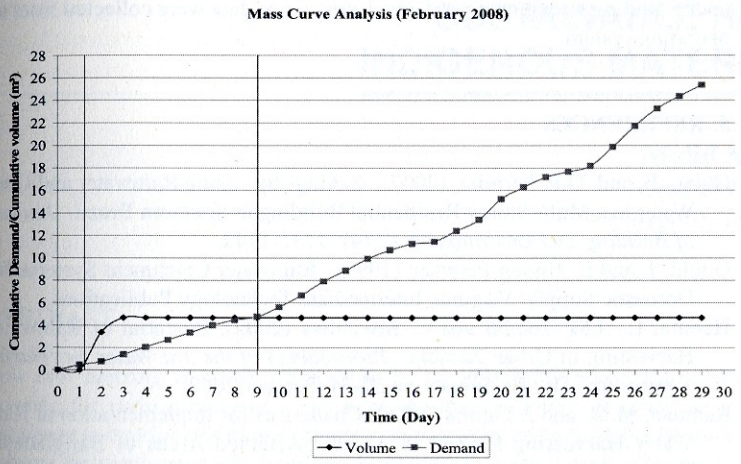


Figure 16: Mass curve analysis for the month of January 2008.

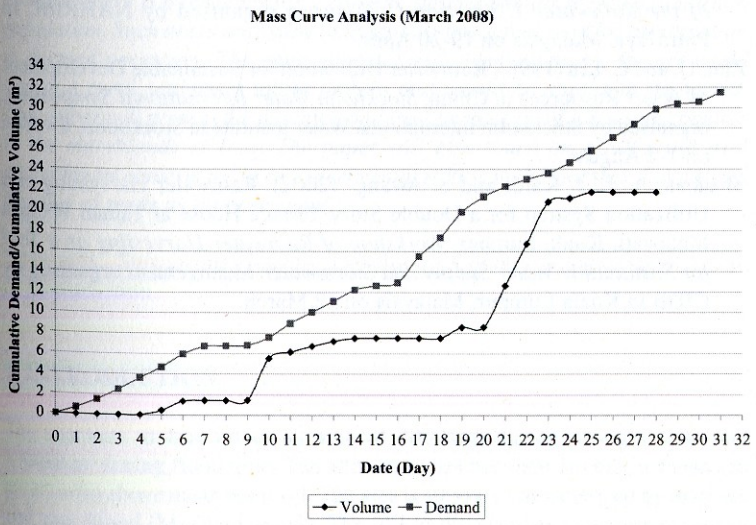


Figure 17: Mass curve analysis for the month of February 2008.

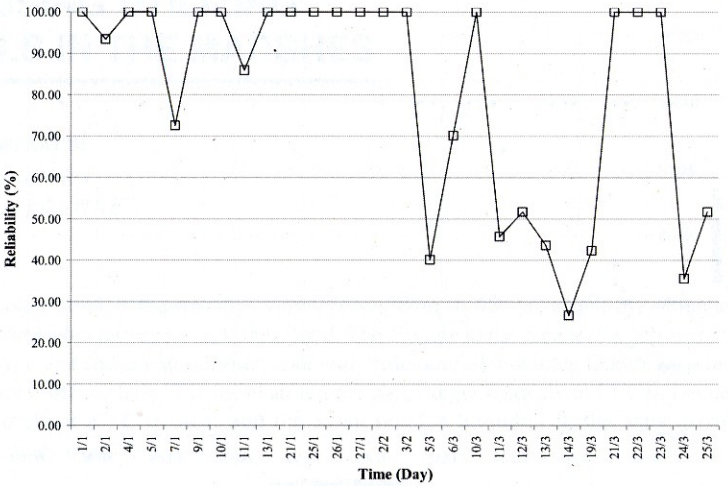


Figure 18: Mass curve analysis for the month of March 2008.

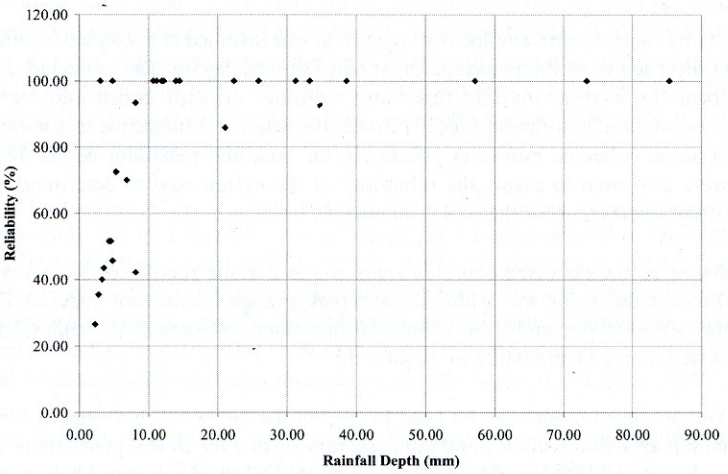


Figure 19: Reliability of the system for the period of study.

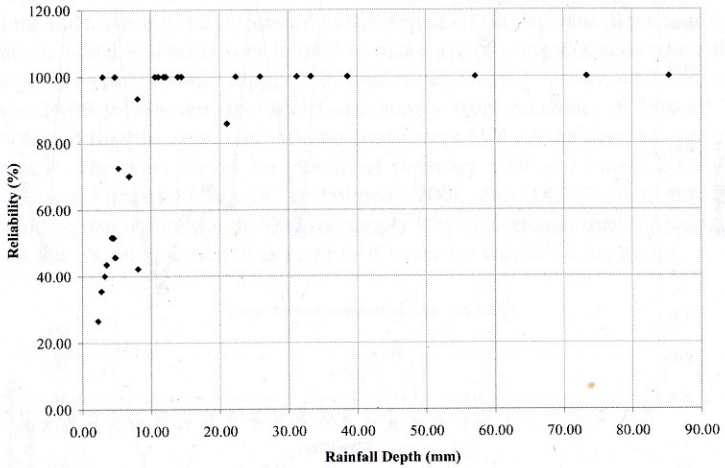


Figure 20: Correlation between reliability and rainfall depth.

4. CONCLUSION

In this study, a rainwater harvesting system was installed at a selected location at the Faculty of Engineering, Universiti Putra Malaysia. The collected data from the system include rainwater volume, rainfall depth and water consumption for toilet flushing. The data were used to simulate the relationship between collected rainwater volume in the tank and rainwater depth. They were also used to assess the reliability of the system and to determine the runoff coefficient for the roof (catchment).

Based on the collected data this study found that the runoff coefficient was 0.83 and this value was within the acceptable range for the roof material. For the period of the study, the volume of rainwater collected in the tank of the system ranged from 0.027 m^3 to 4.03 m^3.

The proposed model can be used to predict the collected rainwater volume with reasonable accuracy and the t-test reveals that the model predictions are within the 95% level of confidence. The reliability of rainwater harvesting system is determined and it ranges between 18.5% and 100% depending on the rainfall pattern and water consumption. The findings contribute new understanding to engineers and developers since data were collected from an operating system.

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