Effect of roof size on the rainwater harvesting tank sizes and performances using Tangki NAHRIM 2.0

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Abstract. Global warming and increasing population have direct impacts on water demand all over the world. Usage of potable water in Malaysia is high if compared with other countries and the source of potable water is mainly surface water. Rainwater harvesting is one of the popular alternatives to water resources around the world. However, even Malaysia is a country with an abundance of rainfall, rainwater harvesting is still unpopular. Different size of houses has different roof sizes which will subsequently require different sizes of rainwater tanks. This study utilized Tangki NAHRIM 2.0 (TN2); a web application to determine the optimal tank size for a rainwater harvesting system for five different roof sizes for non-potable demand. TN2 simulation uses a daily water balance model with rainfall input from a built-in database by adopting the yield-after-spillage (YAS) convention. The optimum rainwater tank sizes for five different roof sizes are found to be between 2.6 m³ and 3.8 m³ with water-saving efficiency values between 59% to 76.2% and 30.9% to 53.9% for storage efficiency. A bigger tank size offers higher watersaving efficiency but with lower storage efficiency. The output will be useful for the application of RWHS to residential houses.

1. Introduction

The increasing population around the world has increased the water demand in all sectors of production. In addition to that, climate change is increasing the frequency and intensity of both droughts and storms events everywhere. Nowadays, river contamination has been a rising issue that disrupts water supplies as Malaysia is dependent on the river for the source of water supply. River contamination will jeopardize the long-term sustainability of water supplies. Malaysia's domestic water consumption is between 209 to 228 liters per capita per day, (lcd) is high if compared to the amount advised by WHO which is only 165 lcd [1]. Furthermore, Stec et al. (2019) [2] discovered that over 50% of water consumption for household usage is for non-potable usage. One of the ways to achieve a green infrastructure is through RWHS. RWHS supplements water supply and reduces flooding through reduction of surface runoff into the drains and rivers, helps alleviate combined sewer overflows (CSOs), and decreases water withdrawals from surface water in long term [3].
Rainwater harvesting is one of the popular alternatives to water resources around the world. Malaysia is a country with an abundance of rainfall. However, the application of rainwater harvesting in Malaysia is still considered low. Through a literature search, study and application of Rainwater Harvesting System (RWHS) for residential houses is still limited compared to government buildings [4]. For example, Hashim et al. (2013) [5] simulated a model for a large-scale RWHS and found that the optimal size storage tank is 160 m$^3$ of 60% reliability for a 20,000 m$^2$ roof area. Hamid et al. (2011) [6] found that for a student hostel roof area of 3000 m$^2$, a 40 m x 35 m storage tank with a 5-meter depth could result in a reduction of 6500 m$^3$ of treated water used each year. This results in an annual water bill savings of about RM10460. Another research on RWHS for institutional application was conducted by Al-Saffar et al. (2016) [7] where the study area is at the Infrastructure University Kuala Lumpur (IUKL) Bangi Campus using Tangki Nahrim 1.0 (TN). The selected tank sizes were 75 m$^3$ and they offer 81% and 93% water saving efficiency for two academic blocks. Potential application of RWHS for non-potable use of residential houses in Kuching, Sarawak using TN by Kuok Kuok et al. (2020) [8] found that the optimal size of RWHS tank for double-story dwellings in Kuching is 2m$^3$. A recent study by Goh et al. (2021) [9] found that the optimum RWHS tank size for a 100 m$^2$ roof size in Kuala Lumpur is 3 m$^3$ where 90% of the non-potable demand can be served by the rainwater.

One of the important components of RWHS is the size of the roof or the catchment area. Yet the different size of the house has different roof sizes which will subsequently require different size of the rainwater tank. According to Gurung et al. (2012) [10] tanks account for 30% of the whole-of-life costs and they are the costliest individual component of the RWHS. Hence, the selection of the incorrect size of rainwater tank will lead to wastage of resources if oversize and poor system performance if undersized. Thus, this study focuses on determining the optimum rainwater harvesting tank sizes under various residential roof sizes. The output will be useful for the application of RWHS to residential houses.

2. Study Area
The study area is Kundang Estate located in Rawang, Selangor, Malaysia. There were five types of houses considered in this study. The house size varies from 20’ x 70’, 24’ x 70’, 30’ x 70’, 33’ x 70’, and 45’ x 70’. The house sizes are considered equal to the roof sizes. The nearest rainfall station is station ID: 3315041 Taman Desa Kundang which is located about 6.1km from the study area.

![Figure 1. Location of Taman Desa Kundang Rainfall Station (Source: TN2.0)](image)

The yearly rainfall variability rainfall from 2008 until 2017 is depicted in Figure 3a, with an average rainfall amount of 2,546 mm. While Figure 3b depicts the average monthly fluctuation from 2008 until 2017 with highest rainfall amount in November, owing to the North-East Monsoon and a modest peak
in June during the inter-monsoon season. High yearly and month rainfall amount shows that the area is fit for rainwater harvesting [9]. Hence, the performance of the rainwater harvesting tank is directly affected by the rainfall intensity of the location.

Figure 2a. Annual rainfall pattern at Kundang Figure 2b. Average monthly rainfall pattern at Station from 2008 until 2017 with an average Kundang Station from 2008 until 2017 annual rainfall of 2546 mm.

3. Methodology

TN2.0 is the upgraded version of a web application developed by the National Hydraulic Research Institute of Malaysia (NAHRIM). It is designed and developed to calculate the optimal tank size for RWHS with built-in rainfall data for Malaysia. TN2.0 applies an R-based water balance model. There are two types of water balance models which can be either Yield Before Storage (YBS) or Yield After Storage (YAS). The YBS model provides a strategic approach, with the rainwater harvested being used for everyday use and the balance being stored in a storage tank for use the next day. While the YAS model adopts a conservative approach in which rainwater is collected first and then channeled to the tank, with the excess rainwater being overflowed. The tank will be used to draw the daily consumption. TN2.0 adopts the YAS algorithm.

Simulation for TN2.0 involves the subsequent data which are: i) daily rainfall, ii) roof area, iii) roof coefficient (depends on the type of roof material), iv) first flush (a basic device that diverts the first influx of water away from a rainwater catchment system) v) daily water demand, and vi) range of rainwater tank volume. The household normal family size in Selangor is 3.9 people [11]. Nonetheless, for planning reasons, all family size was gathered to 4. Only non-potable demand was considered in this study which includes single flush toilet flushing, general cleaning, gardening, washing 2 cars, and pathways. The average water consumption rate was according to the guidelines established in the Urban Stormwater Management Manual 2nd edition (MSMA2).

| Use (appliances) | Average Consumption | Average daily water usage (liters) |
|------------------|---------------------|----------------------------------|
|                  |                     |                                  |

Table 1. Average daily water usage (litres) for 4 persons
| Activity                                | Water Consumption (litres) |
|-----------------------------------------|----------------------------|
| Single Flush Toilet                     | 9                         |
| General Cleaning                        | 20                        |
| Gardening                               | 20                        |
| Washing 2 car with running horse        | 20                        |
| Hosing path/driveways                  | 20                        |
| **Total**                               | **662.3**                 |

Source: Type of usage and average consumption from MSMA2[12]

The estimated average daily water usage for various types of double-story houses in Kundang Estate is shown in Table 1. The daily non-potable demand for four persons in a house is 662.3 l/day. The sizes of RWHS were varied from 1 m$^3$ to 10 m$^3$ at first before the tank sizes were reduced between 1 m$^3$ to 4 m$^3$ to be more precise. The roof coefficient and first flush were assumed to be 0.9 for a zinc/metal roof and 1 mm respectively [7] [9].

3.1 YAS Algorithm
YAS and YBS were two models developed by Jenkins et al. (1978) by looking into the temporal and volumetric performance [13]. YAS refers to the usage of rainwater was after excess rainwater was released algorithm while YBS refers to the usage of rainwater before the excess rainwater was released. According to Fewkes et al. (2000) [14], YAS was found to provide a conservative estimate of yield, while YBS produced the other way around. Thus, YAS was recommended in preference to YBS [14]. Figure 5 shows a schematic diagram of the YAS algorithm.

![Figure 3. Schematic diagram of YAS operating rule for a single-time step Source: Mitchell 2007 [15]](image)

3.2 Performance Measures
Water-saving efficiency or also known as volumetric reliability is the main performance indicator of a RWHS. It refers to the amount of water demand satisfied by the system in comparison to the overall demand and it is the commonly used indicator for RWHS [16 - 17]. If the yield can meet the demand most of the time, it indicates that the water-saving efficiency is excellent, then the user can consider raising the water demand for other purposes. Equation 1 shows the formula for water-saving efficiency:

$$E_{WS} = \frac{\sum_{i=1}^{n} Y_i}{D_i} \times 100$$

Equation (1)

where $n$ is the entire time interval in the simulation.
Another less popular indicator is storage efficiency or well known as detention efficiency. Storage efficiency refers to the amount of runoff retained by the tank over the amount of tank rainfall intake. Storage efficiency is also described as the fraction of roof runoff that may be used and is not wasted due to leakage. Equation 2 shows the storage efficiency formula.

\[
E_S = \left[1 - \frac{\sum_{i=1}^{n} Q_{ri}}{Q_{ri}} \right] \times 100
\]

Equation (2)

where \(Q_S\) represents the spillage or overflow. Size of the tank is said to be efficient if the storage efficiency approaches unity or when the overflow loss is almost zero. A high volume of spillage implies a low storage efficiency. Storage efficiency can be improved by either increasing the tank size or the water demand [9].

4. Results and Discussion

4.1 Optimum Tank Size

Figures 4a to 4e show the simulation results for the five sizes of houses where they illustrated the watersaving and storage efficiency curves versus the range of tank capacities under similar daily non-potable demand. The graph grows linearly, it signifies that the larger the tank, the more water may be retrieved, depending on the desired water-saving efficiency.
Figure 4a to 4e. Water-saving and storage efficiencies versus tank sizes for a) 130 m$^2$, b) 156 m$^2$, c) 195 m$^2$, d) 215 m$^2$ and e) 292 m$^2$ roof sizes

Judgment of the optimum tank size for each house was made mainly based on the shape of watersaving and storage-efficiency curves. Increment of tank sizes offers increment of both efficiencies until the percentage of efficiencies increased were not very significant with the increment of tank size [9]. It can be seen when the graphs started to be flattened. Based on the observation, the optimum tank size for each house was found to be 2.6 m$^3$, 2.8 m$^3$, 3.2 m$^3$, 3.4 m$^3$, and 3.8 m$^3$ with water-saving efficiency values between 59% to 76.2% and 30.9% to 53.9% for storage efficiency. 59% water-saving efficiency implies that the rainwater can serve 390.8 liters out of 662.3 liters of the daily non-potable demand.

4.2 Effect of Roof Size on Optimum Tank Size

Figure 5 demonstrates the relationship between roof size and tank size. Roof size 130 m$^2$ requires the smallest size of rainwater harvesting tank which is only 2.6 m$^3$. The largest area of the roof needs the biggest size of a tank which is 3.8 m$^3$. The roof size is the catchment area of the system which varies. This indicates that the roof size and the rainwater tank size have a linear relationship. Hashim et al. (2013) [5] stated that the greater the roof dimension is, a lot of quantity of water can be stored which subsequently requires a bigger tank size.

Figure 5. Roof sizes versus tank sizes
4.3 Effect of tank size on water-saving and storage-efficiencies

Figure 6 illustrates the plot of tank size versus water-saving and storage efficiencies. Water-saving efficiency is increasing corresponding to the increment of the roof size area. Tank size 2.6 m$^3$ provides the lowest water-saving efficiency of 59%. The biggest roof size offers a higher water-saving efficiency value of 76.2% for equal daily water demand.

![Figure 6. Tank sizes versus storage and water-saving efficiencies](image)

A smaller roof area can only gather a small volume of rainwater. With the increase in the roof area, the inflow increases which will increase the reliability of the tank in terms of volume. For a particular tank size, the reliability increases as the catchment area increases [18]. However, storage efficiency shows an opposite trend to water-saving efficiency. The storage will be less efficient if a bigger rainwater tank is used. The storage efficiency decreased from 53.9% to 30.9% as the tank size increased from 2.6 m$^3$ to 3.8 m$^3$. Storage efficiency is a combined function of spillage and roof runoff volume where decreasing spillage volume increases storage efficiency. Low storage efficiency implies that a major percentage of the rainfall that the roof may gather drains out. As the water demand is low while the rainfall volume is high, the spillage will increase and subsequently reduce the storage efficiency [9]. This is in line with the rainfall pattern in the western part of Peninsular Malaysia, which is influenced by the inter-monsoon seasons and characterized by high-intensity convective storms.

5. Conclusion

This study applied TN2.0; a web-based program to determine the optimum tank size for five different roof sizes of a residential house in Selangor under similar daily demand. TN2.0 uses ten years of daily rainfall data for its simulation. It has been found that the optimum RW tank sizes for non-potable demand five different roof sizes of houses of 130 m$^2$, 156 m$^2$, 195 m$^2$, 215 m$^2$ and 292m$^2$ are 2.6 m$^3$, 2.8 m$^3$, 3.2 m$^3$, 3.4 m$^3$ and 3.8 m$^3$, respectively. A bigger roof size requires a bigger optimum tank size. The optimum rainwater tank sizes for five different roof sizes are found to be between 2.6 m$^3$ and 3.8 m$^3$ with water-saving efficiency values between 59% to 76.2% and 30.9% to 53.9% for storage efficiency. As the tank size increase, the water-saving efficiency will be increased for the same demand. However, under similar demand, the storage efficiency is decreasing for a bigger rainwater tank.

This study focuses on the application of TN2.0 to residential houses, future applications of TN2.0 should be adopted for commercial and industrial buildings. It is recommended that subsequent work can be extended to see the effect of spatial rainfall patterns on the rainwater tank sizes and performances. Future research can investigate the effect of roof technologies on tank efficiency. Hotter temperatures on the roof of course will affect the collection of rainwater. Another potential factor to be explored is the performance of the tank under variation of water demand. The demand variation can be either daily, weekly, or number of users.
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