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OPTIMAL RAINWATER HARVESTING TANK SIZING FOR DIFFERENT TYPES OF RESIDENTIAL HOUSES: PILOT STUDY IN KUCHING, SARAWAK

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Abstract

This study investigated the potential of installing rainwater harvesting system (RWHS) for non-potable water uses of single-storey residential houses including terraced intermediate, terraced corner, semi-detached and detached houses. The selected study area in Kuching, Sarawak, Malaysia. The analysis was carried out using daily Mass Balance model and cross-checked with Tangki NAHRIM software. Input data are 10 years daily rainfall, which observed data from years 2011 to 2017 are collected from Department of Irrigation and Drainage (DID) Sarawak, and rainfall data from years 2018 to 2020 were forecasted by Statistical Downscaling Model (SDSM). Results show that RWHS is able to supply about 40% of the total monthly household water usage. Optimum tank size for terraced intermediate, terraced corner, semi-detached and detached was found to be 2.00 m^3, 2.00 m^3, 2.05 m^3 and 2.10 m^3 respectively. Payback analysis revealed that the installation cost can be recovered within 6 to 8 years. With the current water rate of RM0.76/m^3 charged by Kuching Water Board, it is highly unlikely that RWHS is able to confer financial savings. However, RWHS should be installed as an alternative water supply source to satisfy growing water demands, reduce runoff peak and volume and achieve sustainable water usage practice in Kuching and its surrounding areas.

Keywords: Mass balance model, Rainwater harvesting system (RWHS), Tangki NAHRIM, Water demand, Water supply.

1. Introduction

Malaysia is striving towards achieving a developed nation status by the year 2020. The total population is expected to escalate to 30 million in 2020, and 55%-60% of them will live in cities and towns [1]. Rapid urbanization induced by population growth will lead to water shortages and it is expected to be more severe during peak usages and drought season [2]. In recent years, droughts, the rapid growth of population, economic development and rapid urbanization have caused water shortages Selangor, Negeri Sembilan and certain parts of Sarawak states.

The fastest-growing city in Sarawak is Kuching. Due to rapid urbanisation in last two decades, Kuching is facing great pressure on water supply, even though the state is blessed with abundant water resources from the densest river network in the country that is replenished by 4,000 mm of annual rainfall [3].

The situation will become worse by the year 2020 due to rapid population growth. General cleaning, gardening, hosing driveways, laundry, irrigation and cars washing do not require treated water. However, about 50% of daily water had been used for such purposes in Malaysia [1]. Hence, the most suitable water supply alternative is a rainwater harvesting system (RWHS) as it doesn’t involve centralized water treatment plant, electricity for pumping and distributing which are expensive.

To address the water shortage problem, the Malaysian government has taken several proactive measures including recycling and reusing grey or wastewater, raising water tariffs, raising awareness among the public and promoting the use of RWHS. In fact, RWHS was introduced in Malaysia since 1999 after a severe drought in 1998.

Hashim et al. [4] have found the most effective and sustainable method is using RWHS that has great potential in tackling water shortage, holistically combat water scarcity and reducing the dependency on treated water from dam reservoir.

The practice of RWHS is increasingly become an alternative system for about 100,000,000 people globally [5]. Since the 1980s, various studies were carried out to determine storage capacity and operating policy [6-9]. Most recent studies by Imteaz et al. [10] and Matos et al. [11] are focusing on water savings potentials, economic benefits of RWHS and reliability of RWHS by Mehrabadi et al. [12].

The Malaysian government has published “Guide to Rainwater Harvesting in Malaysia” as a reference for engineers who are involved in the design of RWHS [13]. However, this manual lacks comprehensive analysis and guidelines for determining the optimum tank size. Besides, previous researchers also found that it was difficult and complicated to determine the most cost-effective tank sizes due to variation in rainfall and economic considerations.

Therefore, this study is carried out to determine the most appropriate and optimum size of a rainwater harvesting tank for various types of single-storey residential houses in Kuching city. Analyses were conducted using the Daily Mass Balance model and counter checked with Tangki NAHRIM software.

In addition, an economic analysis was performed to compare the cost-effectiveness of RWHS with conventionally treated water supplied by the Kuching Water Board (KWB).

2. Study Area

Kuching city, located in East of Malaysia (refer Fig. 1), is the fourth largest city of Malaysia, covers a geographical area of 1,863 square kilometres located within the humid tropical rainforest zone. Out of the estimated population of 617,887 persons for Sarawak, about 25% of them are densely populated in Kuching City (2010 census).

Fig. 1. Kuching city location in Malaysia.

The sole water source supply for Kuching people is the Kuching Water Board (KWB). KWB draws freshwater from Sarawak Kiri River, upstream of Sarawak River Basin to Kuching and its surrounding areas, covering suppling boundary of 730 km^2 [14]. KWB has long relied on its Batu Kitang Water Treatment Plant (BKWTP) to supply 95% of water need for Kuching city and its surrounding areas, where else the balance of 5% is produced by Matang water treatment plant.

Sarawak River system is rich with fresh water. In recent years, Kuching city is facing great pressure on water supply due to rapid population growth, subsequently led to increasing of water demand.

Similar to other metropolitan cities, the rapidly growing population will cause public water supply may not be adequate to satisfy the ever-increasing domestic water demands in the nearest future and the water supply problem may become acute.

Hence, there is a need to investigate alternative ways of increasing water supply sources. With Sarawak annual rainfall of 4500 mm, the most suitable alternative water source is rainwater harvesting.

This can be evidenced with the delivering over 600 rainwater harvesting tanks for rural schools and villages (refer to Fig. 2) throughout Sabah and Sarawak by Weida (M) Bhd. [15], a local rainwater harvesting tanks manufacturer.

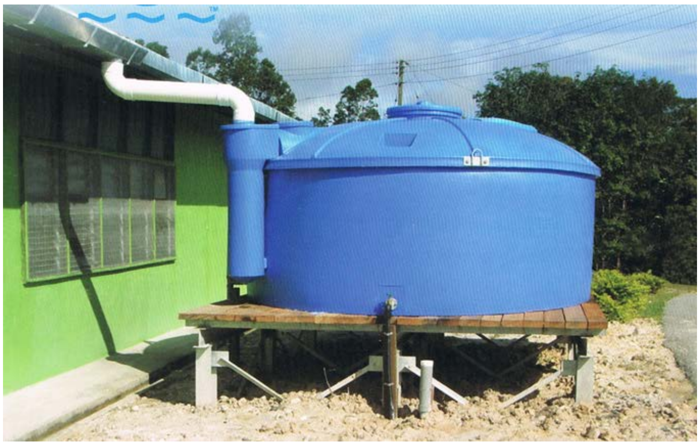


Fig. 2. Rainwater harvesting tank supplied by Weida (M) Bhd.

3. Methodology

Schematic diagram of the methodology is presented in Fig. 3. There are 4 main parameters that will determine the most appropriate and optimum size of rainwater harvesting tank namely rainfall pattern, household size, catchment area, water demand and usage. The possible impacts of each parameter are discussed as follows:

- **Rainfall pattern** - to study the rainfall pattern for a specific area, 10 years latest rainfall data is needed. Rainfall pattern is important to convince RWHS is an alternative source of domestic water supply [16]. Therefore, historical daily rainfall data for Kuching City in the period of 2010 to 2017 was acquired from the Department of Irrigation & Drainage (DID) Sarawak. Whereas, rainfall data from 2018 to 2020 was forecasted using Statistical Downscaling Model (SDSM).
- **Household size** - four main factors are considered for RWHS design. They are total water demand, water consumption and storage volume. The actual average household size in Sarawak is 4.47 persons. However, for design calculation purpose, the average household size was rounded up to 5 [17].
- **Catchment area** - the roof catchment area is referring to the horizontal plane only under the eaves. The average roof catchment area different types of houses in Kuching are: i) terraced intermediate = 101.5 m^2 (14.5 m × 7 m); ii) terraced corner = 135.8 m^2 (14 m × 9.7 m); iii) semi-detached = 152.25 m^2 (14.5 m × 10.5 m) and detached houses = 196 m^2 (14 m × 14 m). Roof runoff flow into RWHS is calculated using Eq. (1).

$$Q = I_{eff} \times C \times A \tag{1}$$

$$I_{eff} = \text{Daily rainfall - First flush} \tag{2}$$

where, Q is the daily runoff (L), C is the run-off coefficient, A is the roof area connected to the tank (m^2), I_{eff} is the daily effective rainfall (mm) calculated using Eq. (2). First flush is needed to wash away the dust, bird and animal droppings, leaves and debris from the surrounding areas that accumulated on the roof surface.

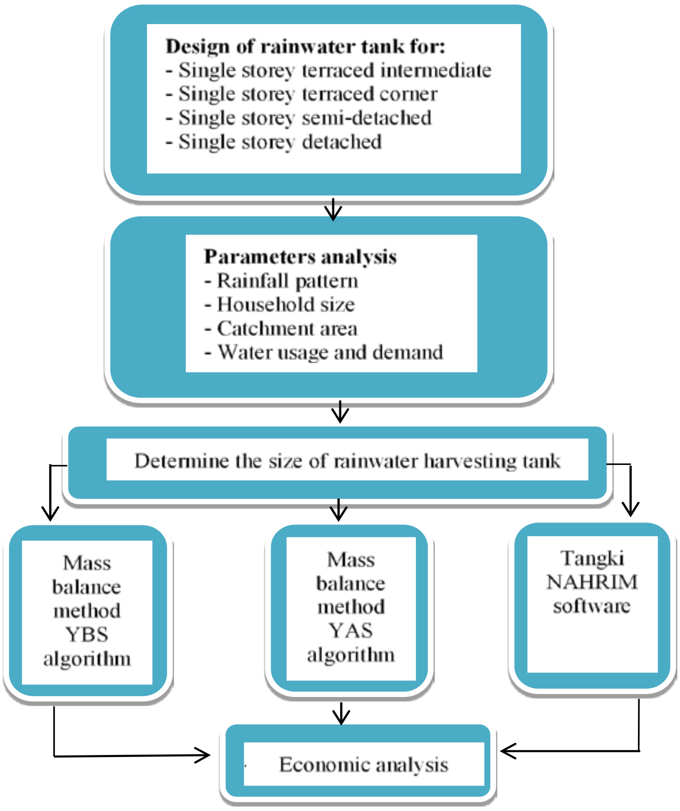


Fig. 3. Methodology framework.

- Water usage or demand in this study, water usage or demand is estimated based on the approximation for a family of five. Average water consumption rate for toilet flushing, general cleaning, sprinkled or handheld hose drip system, hosing paths /driveways and car washing using a running hose is tabulated in Table 1, according to guidelines provided in Urban Stormwater Management Manual 2nd edition (MSMA2). Data provided in Table 1 is utilized to estimated average daily water usage for different types of single-storey houses in Kuching City as presented in Table 2.

Table 1. Average water consumption rate [18].

Use (appliance)	Type	Average consumption
Toilet flushing	Single flush	9 liters per flush
General cleaning	-	10 liters per minute
Sprinkled or handheld hose drip system	-	10 liters per minute
Hosing paths/driveways	-	10 liters per minute
Washing car with a running hose	-	10 liters per minute

Table 2. Average daily water usage (liters) for different types of single-story houses.

Usage	Terrace intermediate	Terrace corner	Semi-detached	Detached
Toilets (single flush type) (liters)	135	135	135	135
General cleaning (liters)	80	80	107	133
Gardening (handheld hose) (liters)	20	40	40	40
Washing car with a running hose (liters)	40	40	40	40
Hosing paths/driveways (liters)	20	27	27	40
Total	**295**	**322**	**348**	**388**

3.1. Sizing of rainwater tank

3.1.1. Mass balance method

For the mass balance method, the volume of inflow water from the roof, household water demand and water tank storage need to be analysed for each time-step [19]. The analysis is repeated with different tank sizes until finding the optimum tank size, which is storing sufficient water to meet the required water demand while minimizing the days of overflow and the days of the empty tank.

The calculation processes for calculating inflow, water demand and storage volumes are discussed below:

- **Determine inflow volume**

Inflow volume is calculated using Eq. (3).

$$\text{Volume} = R_c \times V_r \times A/1000 \quad (3)$$

where, R_c is the runoff coefficient, V_r is rainfall volume and A is the roof catchment area. R_c value used in this study is 0.8 for roof tile and acceptable R_c values for other roof materials can be found in Table 3.

Table 3. R_c values for different roof materials [16].

Roof materials	R_c
Galvanised iron	> 0.9
Tile	0.6-0.9
Asbestos	0.8-0.9
Organic (Thatch, Cadjan)	0.2

- **Water demand volume**

In this study, a set of questionnaires was prepared to collect the local experience in water usages. It was found that water demand for terraced intermediate is 59 litres/day/house, a terraced corner is 64 litres/day/house, semi-detached is 70 litres/day/house and detached houses is 78 litres/day/house.

- **Tank volume**

The optimum size of the rainwater tank is determined by fulfilling the water demand with minimum days of water spillage and empty tank. Two methods available for calculating spillage are yield-before-spillage algorithm (YBS) and the yield-after-spillage algorithm (YAS).

- **YBS Algorithm**

The optimistic approach is adopted for YBS model, with the basic concept that rainwater harvested will be supplied for daily consumption. Water is assumed to be drawn from storage before it overflows the tank. The surplus will be spilt if remain at the end of the time step. The balance water will be stored and to be used in the following days [18]. Figure 4 presents the schematic diagram of the YBS algorithm.

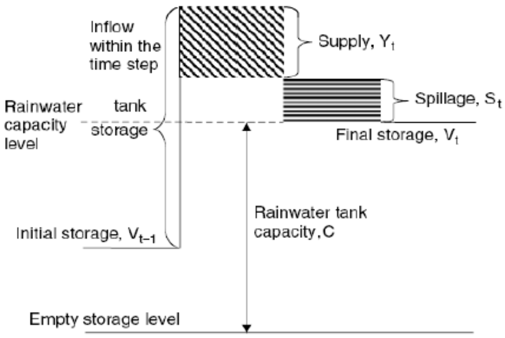


Fig. 4. Schematic diagram of YBS operating rule for a single-time step [20].

- **YAS Algorithm**

Conservative approach is adopted for the YAS model with the basic concept that rainwater is only harvested until the storage tank is full. Once the storage tank is full, the harvested rainwater will overflow the tank due to the limited storage tank capacity and only then the harvested rainwater will be supplied for daily usage. Therefore, the storage volume of harvesting tank adopting YAS algorithm is much lower compared to the one that adopts YBS algorithm. Schematic diagram of the YAS algorithm is presented in Fig. 5.

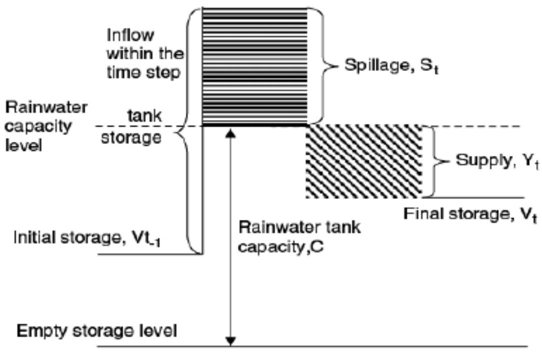


Fig. 5. Schematic diagram of YBS operating rule for a single time step [20].

Meanwhile, the reliability of the rainwater tank, which is defined as the total rainwater supply over the tank-water demand is computed using Eq. (4).

$$E_T = \frac{\sum_t^T \mathrm{Y}_t}{\sum_t^T \mathrm{D}_t} \times 100 \quad (4)$$

where Y_t is the yield of the supplied rainwater and D_t is the household demand over a specific time period.

3.1.2. TANGKI NAHRIM rainwater harvesting simulation software

The sizing of the rainwater tank was also analysed with Tangki NAHRIM rainwater harvesting simulation software. Tangki NAHRIM software is developed by the National Hydraulic Research Institute of Malaysia (NAHRIM). Tangki NAHRIM is able to estimate the optimum tank size by considering three factors namely; a) rainfall volume and pattern, b) roof catchment area and c) water demand. The input data into Tangki NAHRIM model are: i) daily rainfall, ii) roof area, iii) the percentage of losses from roof runoff, iv) daily water demand and v) tank size volume. The output generated by Tangki NAHRIM are; i) the total amount of rainwater captured, ii) rainwater volume delivered per day, iii) reliability of the system, iv) percentage of rainwater utilization, v) storage efficiency, vi) number of days with no rain and vii) empty tank.

3.2. Economic assessment of RWHS

The economic assessment was being carried out based on Payback Period Analysis, which is the time required to get the equivalent return from the investment of constructing RWHS system.

$$Pay\ back\ Period = \frac{Total\ Cost}{Value\ of\ WaterSaved} \quad (5)$$

where the total cost is the money spent on installing RWHS, the value of water saved is defined as the water rate charged by KWB × total volume of water supplied by RWHS.

4. Results and Discussion

In order to find the optimal configuration of the SDSM model, SDSM was calibrated with observed rainfall data over 1961 -1990, and rainfall data over 1991 - 2010 were utilized to validate the model. Predictors used for model calibration and validation are NCEP reanalysis data category SRES A2a including r850, Shum, r500, temp and mslp.

Model parameters to be investigated are model transformation, data transformation, conditional selection, variance inflation, bias correction, optimisation algorithm and criteria for stepwise regression.

Through model validation, the optimal results yielded a coefficient of correlation (*R*) to 0.92, Root mean square error (RMSE) to 1.91, mean absolute error (MAE) to 1.71 and correlation of efficiency (E) to 0.97 with the following configuration:

- Fourth root model transformation
- Conditional selection: the fixed threshold at 0.5

- Variance inflation of 15
- Bias correction of 1
- Ordinary least squares Optimisation algorithm
- AIC Stepwise regression

The optimal configuration obtained will be utilised to estimate future rainfall in 2020. Simulation results show by the year 2020, the monthly average rainfall will increase by 5%. The increment of 5% rainfall intensity is utilized to determine the inflow and tank volumes.

The highest percentage of non-potable household water usage is constituted from toilet flushing, followed by general cleaning. The reliability of rainwater tanks for single-storey houses with different roof catchment area and house types are presented in Figs. 6 to 9. Results show that for all the cases 100% reliability is achievable with a tank size ranging from 4~5 m^3 depending on the type of house.

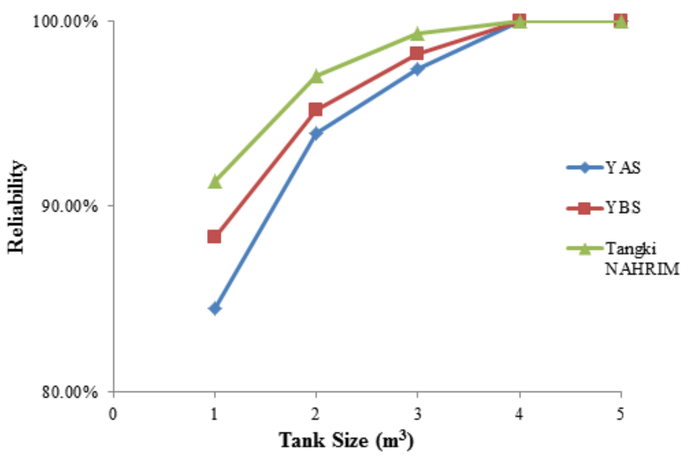


Fig. 6. Reliability vs. tank size for single storey terrace intemediate.

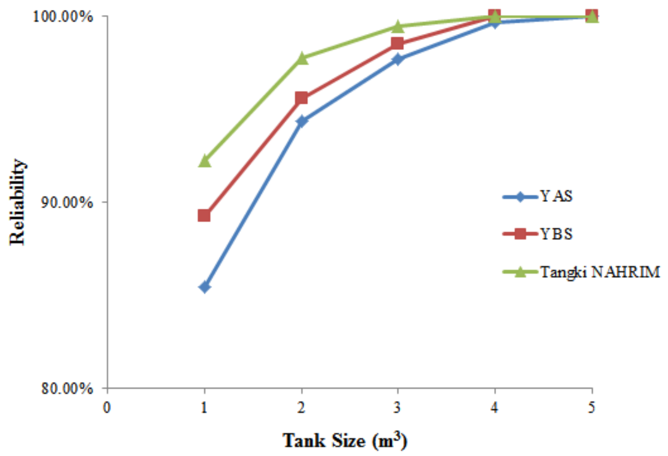


Fig. 7. Reliability vs. tank size for single storey terrace corner.

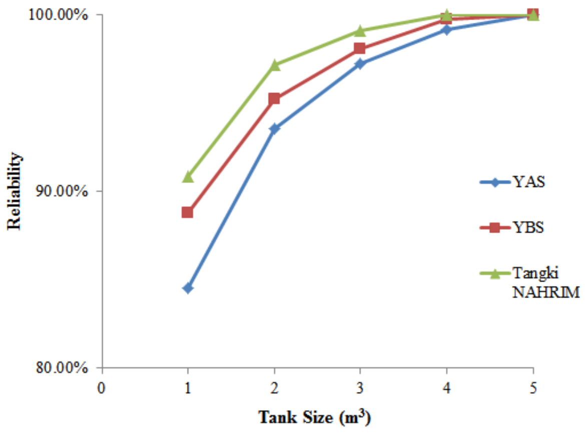


Fig. 8. Reliability vs. tank size for single storey semi-detached.

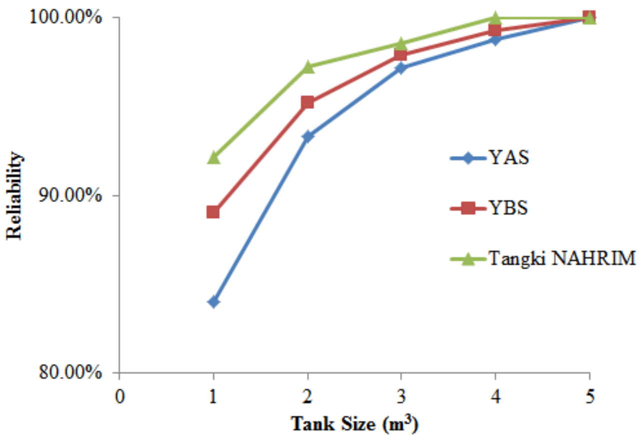


Fig. 9. Reliability vs. tank size for single storey detached.

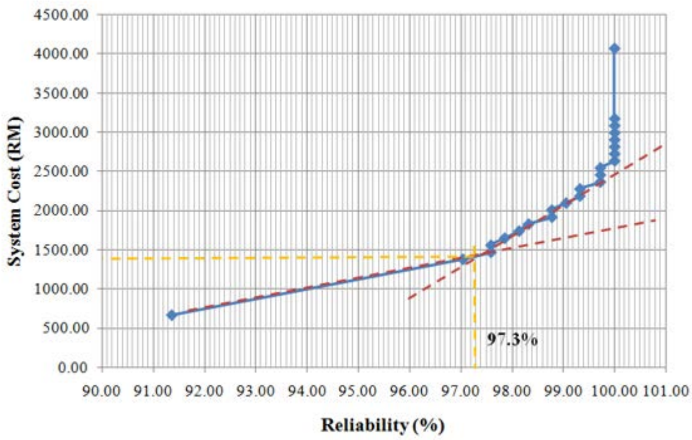
Simulation results also demonstrated that the reliability of RWHS adopting YBS algorithm is higher than YAS. Higher reliability means RWHS is able to supply more water to fulfil the ever-increasing water demand. This is because the YBS model is adopting an optimistic approach. Water is allowed to be drawn from the storage tank before it exceeds the maximum tank capacity. Rainwater harvested will simultaneously be supplied for daily used and the balance will be stored in the rainwater harvesting tank for the usage of following days. In contrast, YAS model adopts a conservative approach, where stored water will only be used after the tank is full.

When compared with the Tangki NAHRIM software, results show that Tangki NAHRIM simulation is closer to the YBS model results. From the results, it is conceivable that Tangki NAHRIM software adopted the YBS operating rule. For the bigger tank sizes, all the three models produced very close results. For a small tank size (i.e., 1 m^3) reliability results produced by the three models are noticeably different. Difference between YBS and YAS models are obvious as explained earlier; differences between YBS and Tangki NAHRIM software are insignificant and in the range of 2%.

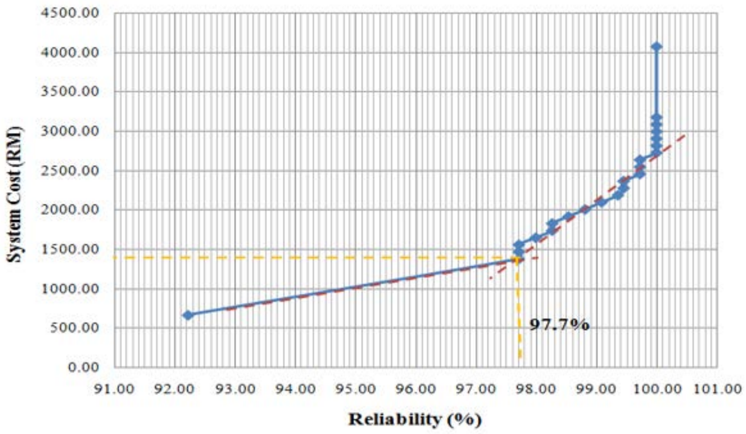
4.1. Optimum tank sizing

The optimum size of the storage tank is governed by two main factors namely reliability and the cost of RWHS. Optimum storage tank size can be determined by plotting system costs of different sized storage tanks versus the associated system reliability as shown in Fig. 10. There are two linear lines with different gradients presented on each graph; a) gentle slope; b) steep slope.

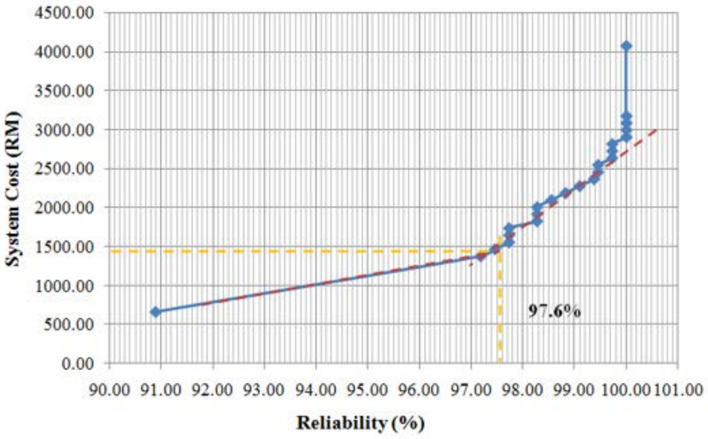
The gentle slope indicates a little increment of system cost will improve the system reliability significantly; whereas steep gradient means a large increment of system cost will not improve much of the system reliability. The optimum tank size is identified at the intersection or inflexion point between the gentle and steep gradient lines. For terraced intermediate, the rational reliability lies approximately 97.3% with the system cost of RM1400 (refer to Fig. 10(a)). Through calculation, the optimum tank size is found to be 2.0m^3 with annual water saving up to RM172.4 and payback period required is 8 years.



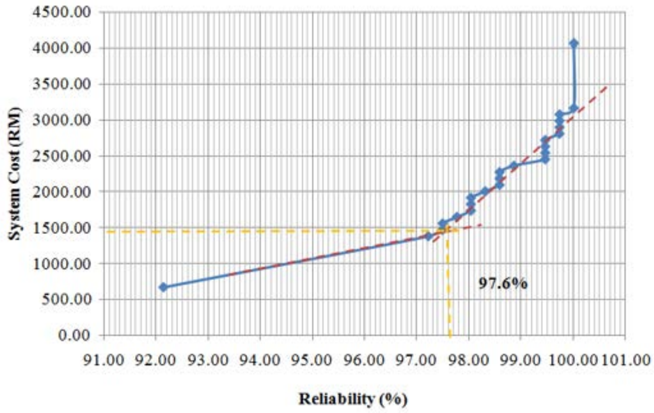
(a) Terrace intermediate.



(b) Terrace corner.



(c) Semi-detached.



(d) Detached.

Fig. 10. Annual cost vs. reliability for: (a) Terrace intermediate, (b) Terrace corner, (c) Semi-detached and (d) Detached.

5. Conclusions

Using recorded and forecasted daily rainfall data from 2010 to 2020, it has been found that the optimum tank size for single storey terraced intermediate, terraced corner, semi-detached and detached in Kuching city are 2.0 m^3, 2.0 m^3, 2.05 m^3 and 2.1 m^3 respectively. Tank sizes of 2.05 m^3 and 2.1 m^3 are not available in the market, hence the size of storage tank for single-storey houses in Kuching city can be standardized as 2.0 m^3.

The current water tariff charged by KWB for domestic rate is only RM0.48/m^3 for water usage from 1 m^3 to 1.5 m^3 per month, RM0.72/m^3 for water usage excess of 1.5 m^3 but not exceeding 50 m^3 within one month and RM0.76/m^3 for the excesses over 50 m^3 within one month. Generally, these domestic water rates are considered cheap and it is highly unlikely that the installation of RWHS will be financially viable in this region with these cheap costs of water. Therefore, Sarawak

State Government should provide subsidies for house owners who area installing RWHS as implemented in Germany, United Kingdom and Australia where state governments and local councils have offered cash rebates to support the installation of rainwater tanks in a household.

Meanwhile, taking into account the scarcity of water resources especially during drought season, together with the expected increase in water demand in Kuching city and its surrounding areas in coming years, it would be a waste if the government or public not fully utilize the available rainwater resources. It was observed that RWHS can satisfy about 34~44% of the total monthly household water usage for different types of single-storey houses in Kuching. RWHS can be utilized as an alternative water supply to satisfy growing water demand to ensure a sustainable living environment in Kuching city.

Besides, through rainwater harvesting, the surface run-off flowing into the drain will be reduced significantly and RWHS can be utilized to mitigate the floods. Hence, the size of the conveyance system at downstream can be reduced as less water will flow into natural waterways. Lastly, more efforts are needed to encourage the use and practice of rainwater harvesting, especially for existing houses. Incentives such as rebates or tax exemptions, education and raising awareness, guidelines and restrictions in the usage of piped water should be introduced and implemented in order to encourage rainwater harvesting practice. To encourage public participation in rainwater harvesting practice, Government agencies and the mass media should promote the benefits and importance of rainwater harvesting and utilization through campaigns or by social media.

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