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Performance of small and large scales rainwater harvesting systems in commercial buildings under different reliability and future water tariff scenarios

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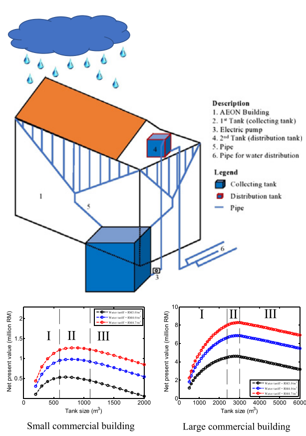
HIGHLIGHTS

- A framework of design of RWHS for commercial buildings was proposed.
- Reliability of RWHS in relation to tank size and water consumption was determined.
- Economic performances of RWHS under different water tariff scenarios were examined.
- RWHS for large building is more benefit compared to the small building.

GRAPHICAL ABSTRACT



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ABSTRACT

A rainwater harvesting system (RWHS) was proposed for small and large commercial buildings in Malaysia as an alternative water supply for non-potable water consumption. The selected small and large commercial buildings are AEON Taman Universiti and AEON Bukit Indah, respectively. Daily rainfall data employed in this work were obtained from the nearest rainfall station at Senai International Airport, which has the longest and reliable rainfall record (29 years). Water consumption at both buildings were monitored daily and combined with the secondary data obtained from the AEON's offices. The mass balance model was adopted as the simulation approach. In addition, the economic benefits of RWHS in terms of percentage of reliability (R), net present value (NPV), return on investment (ROI), benefit-cost ratio (BCR), and payback period (PBP) were examined. Effects of rainwater tank sizes and water tariffs on the economic indicators were also evaluated. The results revealed that the percentages of reliability of the RWHS for the small and large commercial buildings were up to 93 and 100%, respectively, depending on the size of rainwater tank use. The economic benefits of the proposed RWHS were highly influenced

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Rainfall
Roof area

by the tank size and water tariff. At different water tariffs between RM3.0/m^3 and RM4.7/m^3, the optimum PBPs for small system range from 6.5 to 10.0 years whereas for the large system from 3.0 to 4.5 years. Interestingly, the large commercial RWHS offers better NPV, ROI, BCR, and PBP compared to the small system, suggesting more economic benefits for the larger system.

1. Introduction

Water is one of the most valuable resources in the world. Because of its vital role in life, the water demand has dramatically increased due to the population growth and change in precipitation patterns associated with climate change (Bocanegra-Martínez et al., 2014; Gerland et al., 2014). In addition, there are several highly-populated regions in the world where the water scarcity becomes a central public issue. Moreover, approximately 5 to 20% of the global population is projected to live under the absolute water scarcity (<500 m^3/person/year) (Schewe et al., 2014). Therefore, the aforementioned facts have motivated researchers and policy makers to develop alternative water resource strategies in meeting the water demands (Biagini et al., 2014; Pandey, 2001; Rockström and Falkenmark, 2015).

In industries, several strategies for water reuse, recycling, and regeneration have been proposed in order to meet their water demand and reduce consumption (Ng et al., 2010). Beside traditional source, the future water requirement must explore alternative resources in order to overcome water scarcity (Bocanegra-Martínez et al., 2014). In this context, a new strategy such as the implementation of the rainwater harvesting system (RWHS) is crucially needed. It is well established that the performance of this system depends on the rainfall pattern, roof area, and the tank use (Morales-Pinzón et al., 2014). In UK, the installation of RWHS in a supermarket became more attractive by optimizing the parameters (Chilton et al., 2000). Another study found that the higher and more consistent rainfall pattern such as in Sydney provides the shortest payback period compared to other Australian cities such as Melbourne, Perth, and Darwin (Zhang et al., 2009). Therefore, the implementation of RWHS becomes more attractive because it has other benefits including mitigating storm water runoff (Palla et al., 2017), providing non-potable water (Campisano et al., 2017; Hashim et al., 2013; Lopes et al., 2017), water use for agro-forestry (Liang and van Dijk, 2011; Terêncio et al., 2018; Terêncio et al., 2017), and more importantly the cost saving (Amos et al., 2018; García-Montoya et al., 2016; Lian et al., 2016; Morales-Pinzón et al., 2015).

Numerous studies have been conducted to verify the suitability of RWHS. For instance in the Australian continent, the use of the RWHS in the Victoria region can save up to 40% of the potable water use (Muthukumaran et al., 2011). In the European continent, an evaluation of the RWHS in Spain reported that the sloping smooth roofs may harvest up to about 50% more rainwater than flat rough roofs (Farreny et al., 2011b). Alternatively, the performance of the RWHS in Porto and Almada, Portugal for toilet flushing, laundry, and irrigation has also been evaluated. Their study reported that the proposed system was able to save the water in the range of 17% to 95%. In the American continent, the RWHS was also conducted to assess the potential for non-potable water savings for car washing at petrol stations in the City of Brasilia, Brazil (Ghisi et al., 2009). Their study found that increasing the rainwater tank size enhanced the reliability of the rainwater use notably in meeting the water demand. In the Asian continent, the RWHS was evaluated as a new option for water supply in Banda Aceh, Indonesia from two perspectives, namely, technical and social (Song et al., 2009). From the technical perspective, their study found that the system was reliable and useful in terms of the construction material, maintenance, and water saving. In addition, from the social perspective, their study found some problems such as the public awareness that need to be solved before the system can be fully implemented in the area. Focusing in Malaysia, implementation of the RWHS is still limited mostly to government buildings.

Considering the aforementioned advantages, it is also potential to implement the RWHS for commercial buildings. This is because the commercial buildings generally offer large catchment areas and high water consumption. Another motivation for establishing RWHS is due to high commercial water tariff compared to domestic water tariff. Aligning the research necessity, several investigations have been conducted. For instance, a prototype of RWHS was installed in a supermarket at Thamesmead, South London for toilet flushing (Chilton et al., 2000). Their proposed system was ratified to have a collection efficiency of 57.4% and a payback period of 12 years. Alternatively, the performance of RWHS was also evaluated for the Dolce Vita Braga, a new commercial building located in Braga, Portugal for toilet flushing, pavement washing, and irrigation (Matos et al., 2013). By several simulations, their investigation found that the proposed system was the best configuration for pavement washing and garden irrigation. In another study on the economic benefit, their proposed system was found to have payback periods from 2 to 6 years and approximately 1 year when the discount rates of 10% and 5% were considered, respectively (Matos et al., 2015). Another evaluation of the performance of the RWHS was also carried out in the Green Square North Tower, a twelve-storey commercial office building in Brisbane, Australia and their system offered a moderate reliability with minimal energy requirements (Cook et al., 2014). A commercial RWHS was compared with a municipal water supply system using the life cycle impact assessment (LCIA) indicators and found that a 50% auxiliary commercial RWHS outperformed the municipal water supply system for various LCIA categories (Ghimire et al., 2017). The RWHS with wall-mounted tanks was studied using the computational fluid dynamic procedure by modifying its inlet designs for shop lots in Malaysia (Foo et al., 2017). Their study successfully demonstrated the streamline and pressure zonation characteristics in the rainwater tanks and recommended an inlet design of 120 mm pipe. A comparative evaluation was also carried out to assess the performance of the commercial RWHS in Sonae Sierra's shopping centers in Portugal and Brazil (Sousa et al., 2017). The fastest payback period was found for the Brazilian study due to relatively lower investment costs and higher water tariff. Therefore, it is timely to evaluate the performance of commercial building RWHS in Malaysia by considering its reliability and economic advantages.

In closing the research gap, the present work aims to evaluate the performance of the RWHS for AEON Taman Universiti and AEON Bukit Indah as a small and a large commercial building models, respectively. Therefore, this paper is organized as follows. First, the description the catchment areas of the buildings is discussed. Next, the water consumption and daily rainfall data are described. This is followed by description on methodologies in terms of simulation model and economic evaluations. In addition, findings from the present work are then presented in detail and ends up with conclusions and suggestions for future works.

2. Materials and method

2.1. Catchment area

It is noted that there are various commercial buildings in Malaysia. Since the benefits of RWHS are more promising for large scales (commercial buildings) compared to small scales (houses) as the former has higher roof top area, higher water consumption, and higher water tariff, some recent studies have more focused on the implementation of RWHS for commercial buildings. However, a clear comparison analysis of the rainwater harvesting benefits for different commercial building sizes is still lacking. In this respect, AEON mall provides the best option since the building design is similar throughout the country. At present, there are only two types of AEON mall building design, which are small and large types.

The catchment areas considered in this work are AEON Taman Universiti (1°32′33.1″N 103°37′44.1″E) and AEON Bukit Indah (1°28′ 54.9″N 103°39′21.5″E), Malaysia. AEON Taman Universiti, a shopping mall, is located at Taman Universiti, a university town near Johor Bahru City in Malaysia. In addition, AEON Bukit Indah is also a shopping mall in the fast-expanding township of Bukit Indah, Iskandar Puteri, Johor Bahru, Malaysia. AEON Taman Universiti and AEON Bukit Indah are categorized as a small and a large commercial building, respectively. Their characteristics and daily water consumptions are presented in Table 1. Because the AEON building design is quite standard, the present study provides a good opportunity to apply the finding to other AEON buildings throughout the country.

2.2. Water consumption and daily rainfall data

Water consumption was monitored daily for two years. The data were also combined with the secondary data from AEON database. Daily rainfall data from 1975 to 2003 were obtained from Senai International Airport station (1°38′17.2″N 103°40′10.3″E), which is located about 11 km and 15 km from AEON Taman Universiti and AEON Bukit Indah, respectively. Potential rainwater that can be harvested in the present catchments was estimated using the following formula:

$$PRH = A_{RT} \times RC \times RI \tag{1}$$

where *PRH* is the potential rainwater harvesting (m^3), *A* is the area of the rooftop (m^2), *RC* is the runoff coefficient (−), and *RI* is the daily rainfall (m).

2.3. Simulation model

In the simulation model, the mass balance computation for the storage capacity was adopted (Su et al., 2009). Volume of rainwater captured from the rooftop was regarded as inflow and the release for use and possible spill from the storage tank were considered as outflow. Release was carried out based on the demand and availability of the water. Rainfall data from 1975 to 2003 were employed as inflow into the storage tank, and the release was estimated using the following formula:

$$R_t = \begin{cases} D_t & \text{if } WI_t + WS_{t-1} \geq D_t \\ WI_t + WS_{t-1} & \text{if } WI_t + WS_{t-1} < D_t \end{cases} \tag{2}$$

R_t is the daily release (m^3), D_t is the daily demand (m^3), *WI* is the inflow (m^3), and WS_{t-1} is the tank storage at the end of the preceding day (m^3).

Table 1
Characteristics of the small and large scale commercial buildings.

Parameter	Large building	Small building
Rooftop area	95,760 m^2	16,506 m^2
Length of the proposed pipe system	890 m	446 m
Average daily water consumption	535.7 m^3	213.9 m^3
Number of downpipe	56	36
Cost of single pump	RM52300	RM38000
Distribution tank size	50 m^3	20 m^3
Rooftop area	95,760 m^2	16,506 m^2

2.4. Economic indicators

In this work, the economic benefits of the proposed RWHS were evaluated using several economic indicators, which are percentage of reliability (R), net present value (NPV), return on investment (ROI), benefit-cost ratio (BCR), and payback period (PBP) (Morales-Pinzón et al., 2014). These indicators are mathematically expressed as:

$$R(\%) = \frac{WR}{D} \times 100\% \tag{3}$$

$$NPV = \sum_{t=0}^{s} \frac{S_t P_t - I_t - M_t}{(1+r)^t} \tag{4}$$

$$ROI = \frac{\sum_{t=0}^{s} S_t P_t - I_t - M_t}{\sum_{t=0}^{s} I_t + M_t} \tag{5}$$

$$BCR = \frac{\sum_{t=0}^{s} \frac{S_t P_t}{(1+r)^t}}{\sum_{t=0}^{s} \frac{I_t + M_t}{(1+r)^t}} \tag{6}$$

$$PBP = N_{BCR} > 1 \tag{7}$$

where *R* is the reliability of the use of RWHS (%), *WR* is the water release (m^3), *D* is the water demand (m^3), S_t is the volume of water saved over a period of time *t* (m^3), P_t is the cost of water over a period of time *t* (RM/m^3), I_t is the investment required for a period of time *t* (RM), M_t is the maintenance costs over a period of time *t* (RM), *s* is the system life span (year), *t* is the system operation period (year), and *r* is the interest rate (%).

The propose RWHS design is shown in Fig. 1(a). It is noted from the figure that the small and large buildings have 36 and 56 downpipes, respectively (see Fig. 1(b) and (c). Roof water in the downpipes will be intercepted into the sloping pipe and channelled into the collecting tanks. In the proposed system, six components were considered to develop the system. Rooftop of the building is considered as the catchment area. The roof water will be conveyed trough pipe into collecting tank by gravity flow.

In this system, two collecting tanks are proposed, one at each side of the building. Fig. 1(a) illustrates the side view of the collecting tank location. In addition, electric pump is used to transfer the collected water into the 2nd tank (20 m^3 and 50 m^3 in volume for small and large buildings, respectively). Two electric pumps are required for each system. The collected water in the 2nd tank is distributed by gravity for non-potable water (toilet flushing, irrigation, and chiller system). In addition, the assumption and parameters involved in this simulation are listed in Tables 2 and 3. The operational cost assumed in this work was estimated using the following formula:

$$OC = \frac{Ws}{PFS} P_E E_t \tag{8}$$

where *OC* is the annual operation cost (RM), *Ws* is the water saved (m^3), *PFS* is the pump flow speed (m^3/min), P_E is the pump energy (W), and E_t is the electricity tariff (RM/W). In this analysis, *PFS* and P_E used are decided to be 15 m^3/h and 2.2 kW and 30 m^3/h and 4.0 kW, respectively, for small and large buildings, respectively.

Moreover, the initial investment was assumed to be obtained from a loan. Hence, annual year-end payment (annuity) needed to be paid can be estimated as:

$$A_{yp} = I_{nv} \left[\frac{r(1+r)^t}{(1+r)^t - 1} \right] \tag{9}$$

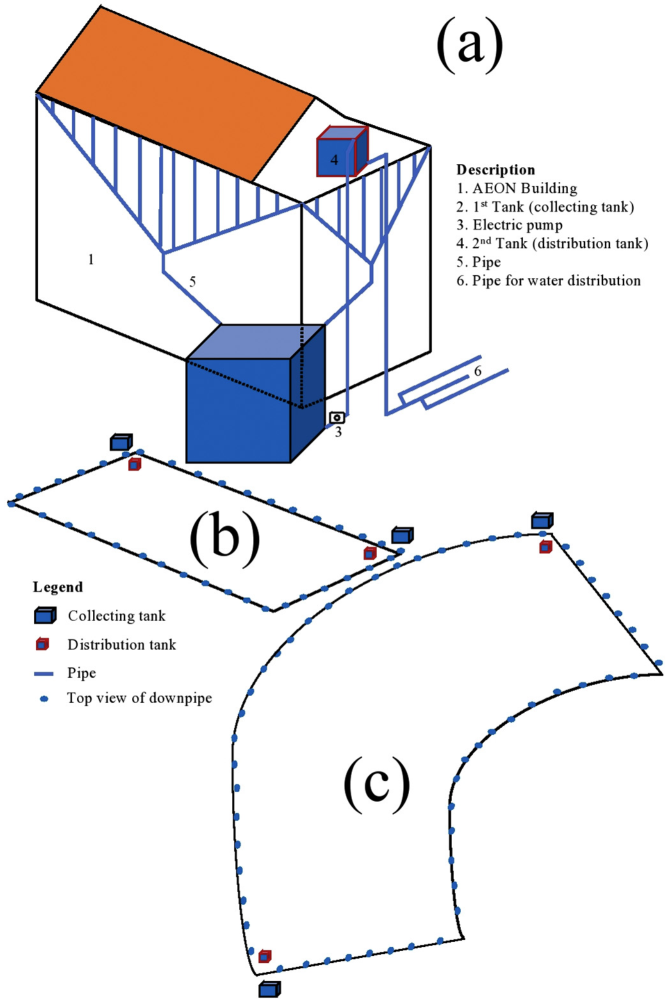

Fig. 1. (a) A side view of the proposed RWHS design, (b) plan view of the tank location and downpipe for small building, and (c) plan view of the tank location and downpipe for large building.

where A_{yp} is the annual year-end payment (RM), I_{nv} is the investment (RM), r is the interest rate (%), and t is the time (year). Moreover, the optimum tank sizes are determined from the maximum BCR and ROI, which basically give the highest benefit.

Table 2
Assumption used in this analysis.

Parameter	Unit	Reference
Runoff coefficient	0.9	Waterfall (2004)
Cost of tank	RM0.5/L	Ministry of Works Malaysia (2015)
Cost of pipe	RM24.1/m	Ministry of Works Malaysia (2015)
Maintenance cost	RM133/month	Estimated
Retrofitting cost	RM4000/pipe	Estimated
Electricity tariff	0.43 RM/kWH	Tenaga Nasional Berhad (2014)
Average interest rate	4.25%	Focus Economic (2015)
Water tariff	RM3.05/m^3	Suruhanjaya Perkhidmatan Air Negara (2015)
Replacement of tank	After 30 years	Estimated
Replacement of pump	After 10 years	Estimated
Life span of the system	30 years	Estimated

Note: Average currency data from 01/2008 to 01/2018: 1RM is equal to 0.28USD.

Table 3
Parameter variations used in this investigation.

Commercial building	Parameter	Value
Small	Tank size	200–2000 m^3
Large	Tank size	500–6000 m^3
	Water tariff (RM)	Present (RM3.0/m^3)
		10 years (RM4.0/m^3)
		20 years (RM4.7/m^3)

3. Results and discussion

3.1. Daily rainfall characteristics and water consumption

Rainfall characteristic is a crucial factor affecting the application and efficiency of the RWHS. In the current work, daily rainfall data from 1975 to 2003 obtained from Senai station are shown in Fig. 2. It is useful to note that the average and maximum daily rainfall were 11.8 mm and 364.4 mm, respectively. The maximum daily rainfall was detected on 02/12/1978. It was obvious that the high daily rainfall occurred in December, which is common over the Peninsular Malaysia due to northwest monsoon effect.

As additional knowledge, the nature of rainfall in Peninsular Malaysia can be categorized into three seasons, which are the southwest monsoon starting from May to September, the northwest monsoon starting from November to March, and inter monsoon, which is defined as the transition period from the Southwest Monsoon season to the Northeast Monsoon season or vice versa in October and April. Similar to the daily rainfall characteristic, water consumption is another critical consideration to develop and apply the RWHS. In the future, RWHS will be more attractive because the water tariff is predicted to increase. The present study found that the daily water consumptions for AEON Taman Universiti is 213.9 m^3 while for AEON Bukit Indah is 2.5 times higher (535.7 m^3).

3.2. Water tariff trend and its future prediction

Fig. 3 shows the water tariff trend for Johor, Malaysia. It is apparent from Fig. 3 that there was significant increase in water tariff from RM0.3/m^3 in 1965 to RM3.05/m^3 in 2015. At present, the water tariff still remains as of the last revision in 2015. As shown in Fig. 3, there are three patterns of the water tariff increase; marginal increase from RM0.35/m^3 to RM0.37/m^3 (<1980), moderate increases from RM0.75/m^3 to RM1.60/m^3 (1980 to 2000) and from RM2.24/m^3 to RM3.05/m^3 (2001 to 2015).

Since the water tariff is important consideration for developing the RWHS, the predicted future tariff is highly valuable for policy makers and users. Therefore, a simple regression was employed to provide a mathematical formula considering the relationship between the water tariff and time period. The present work found that the water tariff trend can be described by the following formula:

$$y = 0.065x - 127.67; R^2 = 0.940 \tag{10}$$

where y is the water tariff (RM) and x is the time period (year). With R^2 of 0.94, the equation is robust enough to be used for predicting future water tariff. The predicted water tariff for the next 10 years and 20 years would be RM4.0/m^3 and RM4.7/m^3, respectively.

3.3. Small commercial building

Effects of rainwater tank size on the percentage of reliability of RWHS for the small commercial building are shown in Fig. 4. There is noticeable increase in the percentage of reliability with the tank sizes from 200 m^3 to 600 m^3, which increases from 70% to 90%. Although the rainwater tank sizes were increased up to 2000 m^3, the percentage

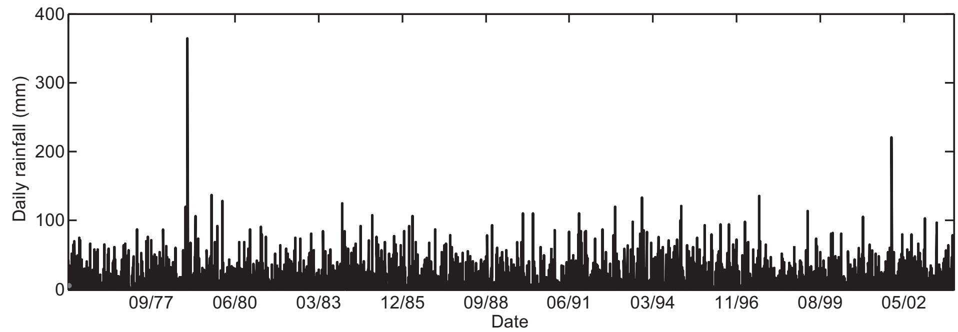

Fig. 2. Daily rainfall data at Senai station from 1975 to 2003.

of reliability reaches a plateau of around 93%. Fig. 5 shows the relationship between NPV against the tank size under three different water tariff scenarios for the small commercial building. It can be seen from the figure that the positive NPV is achieved for all evaluated tank sizes. In addition, there are three obvious stages of the NPV patterns for the water tariff of RM3.0/m^3, which are significant increases with the increasing tank sizes from 200 m^3 to 600 m^3 (1st stage), small increases and plateau for tank sizes between 600 m^3 and 1100 m^3 (2nd stage), and significant decreases with the tank sizes from 1100 m^3 to 2000 m^3 (3rd stage).

The similar pattern of the NPV can also be seen for other water tariff scenarios of RM4.0/m^3 and RM4.7/m^3 as depicted in Fig. 5. In general, the benefits of the system expressed in NPV values of different tank sizes range from RM0.05 million to RM0.53 million, RM0.30 million to RM0.98 million, and RM0.43 million to RM1.27 million for the water tariff of RM3.0/m^3, RM4.0/m^3, and RM4.7/m^3, respectively. Effects of tank sizes on the ROI and BCR of the RWHS for the small commercial building are shown in Figs. 6 and 7, respectively. The maximum rate of ROI increase is observed for tank size between 200 m^3 and 600 m^3 at RM3.0/m^3 water tariff. It is noticed that the maximum ROI is obtained at tank size of 600 m^3. From there on the ROI decreases as the tank size increase but still show positive values even at tank size of 2000 m^3. The same trend was observed for the other two water tariff scenarios with the highest ROI is obtained for the highest water tariff (RM4.7/m^3).

The BCR values (Fig. 7) of the RWHS at RM3.0/m^3 tariff increased from 1.2 to 1.7 for tank sizes from 200 to 600 m^3. Beyond this, the BCR values decrease significantly from 1.7 to 1.0 for tank sizes up to 2000 m^3. In addition, the BCR values for water tariff scenarios of RM4.0/m^3 and RM4.7/m^3 increased from 1.6 to 2.3 and 1.8 to 2.7, respectively for tank sizes from 200 m^3 to 600 m^3. However, the BCR values start to decrease when the tank size is increased to 2000 m^3 but still show positive values (see Fig. 7).

To analyse the PBP of the RWHS for the small building, the five highest values of BCR as listed in Table 4 were considered. This study found that the PBP for the water tariff of RM3.0/m^3 ranges from 9.5 to 10.5 years with the increasing tank sizes from 400 m^3 to 800 m^3. In addition, the PBPs for the water tariff of RM4.0/m^3 and RM4.7/m^3 range from 6.5 to 7.5 years and 5.5 to 6.5 years, respectively, for tank sizes from 400 m^3 to 800 m^3.

3.4. Large commercial building

The relationship between reliability against tank size for the large commercial building is shown in Fig. 8. The results indicate that with successive increases in the tank size up to 1700 m^3, the percentage of reliability increase up to 97%. Afterwards, the percentage of reliability reaches 100%. Moreover, the present work found that the minimum and maximum percentage of reliability were 66% and 100%, respectively.

Fig. 9 shows the effects of tank sizes on the NPV of RWHS. There is a clear trend of increasing NPV (RM1.1 million to RM 4.4 million) at RM3.0/m^3 tariff for tank sizes from 500 to 2400 m^3. In addition, the NPV reaches a maximum of RM4.6 million when the tank sizes between 2500 m^3 and 3000 m^3. Afterwards, the NPV values start to decrease from RM4.5 million when the tank size is 3100 m^3 to RM3.1 million for tank size of 6000 m^3. Similar patterns of NPV were observed for the water tariff of RM4.0/m^3 and RM4.7/m^3 as depicted in Fig. 9. The present work found that the minimum and maximum NPV for the water tariff of RM3.0/m^3, RM4.0/m^3, and RM4.7/m^3 are RM 1.1 million and RM4.6 million, RM 1.8 million and RM6.8 million, and RM 2.2 million and RM8.3 million, respectively.

As shown in Fig. 10, the ROI values at RM3.0/m^3 tariff increased with the tank size up to 1300 m^3. In addition, the maximum ROI was achieved when the tank size is between 1400 m^3 and 1800 m^3 and then decrease remarkably from 1900 m^3 to 6000 m^3. It is interesting

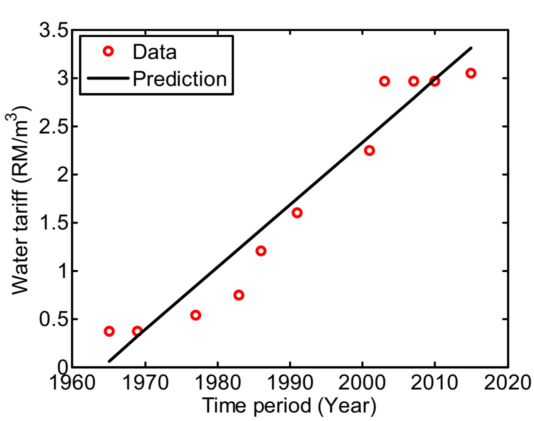

Fig. 3. Water tariff trend for Johor, Malaysia from 1965 to 2015.

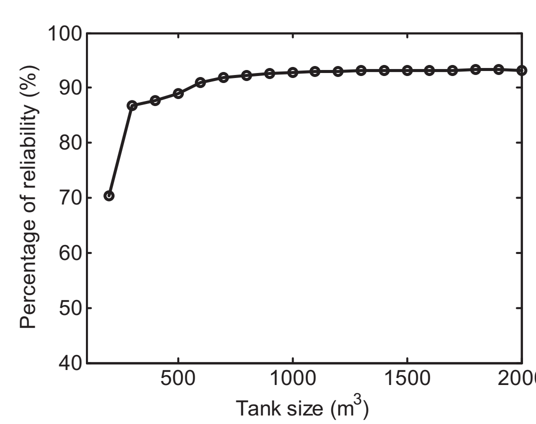

Fig. 4. Percentage of reliability against tank sizes for small commercial building.

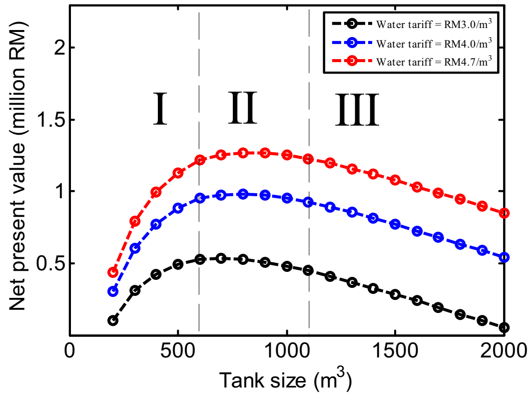

Fig. 5. Effects of tank size on the NPV of the proposed RWHS for the small commercial building.

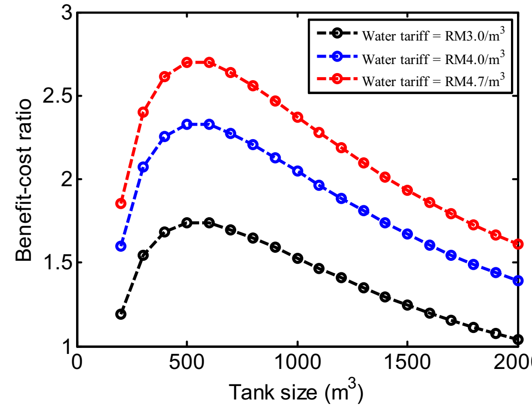

Fig. 7. Effects of tank sizes on the BCR of the proposed RWHS for the small commercial building.

to note that a similar pattern of the ROI was also observed for the water tariff of RM4.0/m^3 and RM4.7/m^3. The effects of tank sizes on the BCR values for the large commercial building are depicted in Fig. 11. There are three stages of the BCR response to varying tank size for the water tariff of RM3.0/m^3. The graph shows similar pattern but the highest BCR was observed for the highest tariff. In general, the BCR for the water tariff of RM3.0/m^3, RM4.0/m^3, and RM4.7/m^3 ranges from 1.8 to 3.6, 2.5 to 4.8, and 2.9 to 5.5, respectively.

The PBPs of RWHS for different tank sizes are presented in Table 4. It is obvious that the PBPs for RM3.0/m^3 tariff can be achieved after 4.5 years by employing the proposed optimum tank sizes from 1400 m^3 to 1800 m^3. Alternatively, faster PBPs can also be obtained after 3.5 years and 3.0 years for the water tariff of RM4.0/m^3 and RM4.7/m^3, respectively. Obviously, the fastest PBP can be reached at the highest water tariff.

3.5. Overall discussion

It is noted that the main focus of this study is the use of engineering approach particularly on the analysis of roof water reliability and tank sizing based on long term rainfall record and water consumption. The main benefit of RWHS for the commercial buildings is directly achieved through bill reduction as evident from the NPV, ROI, BCR, and PBP values. The strength of this study is comparison of benefits based on different level of reliability (determined from roof water volume, water consumption, and tank size) and water tariff scenarios.

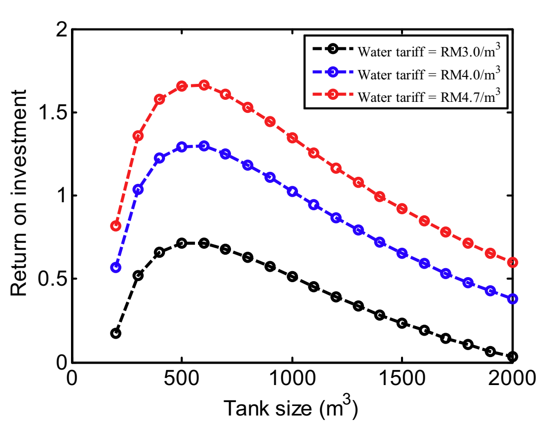

Fig. 6. Effects of tank size on the ROI for of the proposed RWHS for the small commercial building.

To understand the performance of RWHS in commercial buildings for the current work, it is worthwhile to initiate discussion from the perspective of their percentage of reliability. It is well known that the percentage of reliability is highly influenced by the temporal and spatial distribution of the rainfall, the size of the catchment area, the capacity of the storage tank, and the water demand (Mun and Han, 2012). For instance, the percentage of reliability of RWHS can meet 96% to 99% of the demand for toilet and laundry use for in wettest year in Greater Sydney regions (Hajani and Rahman, 2014). However, in the driest year, its reliability reduces (69% to 99%) for the similar non-potable use. Alternatively, a comprehensive theoretical investigation to optimize roof area and storage capacity to meet a high percentage of reliability was also carried out (Liaw and Tsai, 2004). Their study found that the optimum

Table 4
PBP of the RWHS for three different water tariff scenarios.

Commercial building	Water tariff (RM/m^3)	Tank size (m^3)	PBP (year)
Small	3.0	400	>9.5
		500	>9.5
		600	>10.0
		700	>10.0
		800	>10.5
	4.0	400	>6.5
		500	>6.5
		600	>7.0
		700	>7.0
		800	>7.5
	4.7	400	>5.5
		500	>5.5
		600	>6.0
		700	>6.0
		800	>6.5
Large	3.0	1400	>4.5
		1500	>4.5
		1600	>4.5
		1700	>4.5
		1800	>4.5
	4.0	1400	>3.5
		1500	>3.5
		1600	>3.5
		1700	>3.5
		1800	>3.5
	4.7	1400	>3.0
		1500	>3.0
		1600	>3.0
		1700	>3.0
		1800	>3.0

Note: The five highest values of BCR around the optimum tank were considered. The estimated costs for installation of RWHS for small and large buildings with tank size from 400 m^3 to 800 m^3 are RM440750 to RM 640750 while for large building with tank size from 1400 m^3 to 1800 m^3 are RM1075049 to RM1275049.

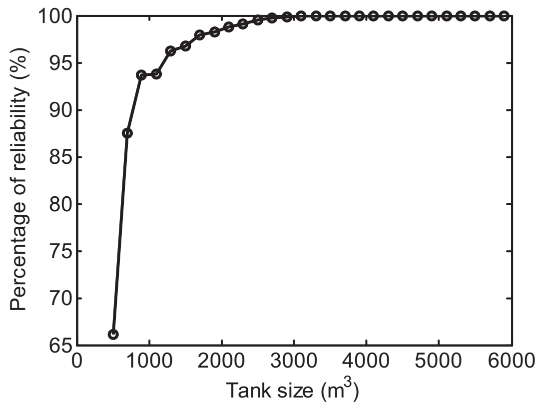

Fig. 8. Percentage of reliability against tank sizes for the large commercial building.

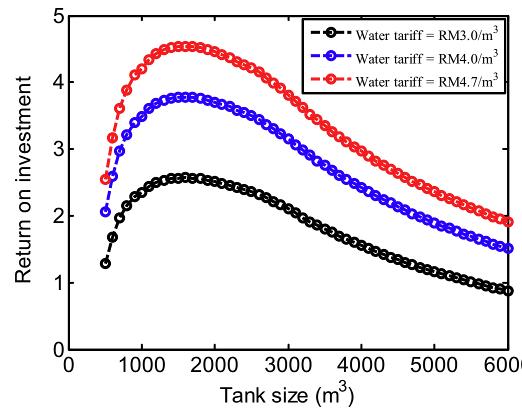

Fig. 10. Effects of tank size on the ROI for of the proposed RWHS for the large commercial building.

points can be obtained by least cost combination of roof and storage capacity where the isocost line is tangential to the isoquant of the specific reliability curve.

As presented in Sections 3.3 and 3.4, the percentage of reliability of the RWHS for all commercial buildings increased significantly (1st stage) with increasing tank sizes before reaching a plateau (2nd stage). These patterns are in agreement with earlier studies (Karim et al., 2015; Rahman et al., 2012). For the first stage, it is obvious that increasing the tank volume affords an opportunity to store more rainwater. However, the reliability reaches a plateau (2nd stage) since the proposed tank size is able to store the total rainwater captured from the catchment area. Therefore, it is useless to increase the tank size exceeding 1000 m^3 and 2900 m^3 for small and large commercial buildings, respectively.

Although, the patterns of reliability percentage for the small and large commercial buildings are similar, the latter can reach 100% reliability when the tank size is increased to 2900 m^3 (Fig. 8). Conversely, the small commercial building can only reach 93% reliability at tank size is equal to 1000 m^3 or bigger. These findings suggest that the RWHS for the large commercial building is more attractive compared to the small commercial building.

The NPVs (Figs. 5 and 9) show similar characteristics with three different stages. The 1st stage is attributed to increasing rainwater tank size where the value of S_tP_t in Eq. (4) is higher than $I_t + M_t$, suggesting a bigger volume of captured rainwater thus contributing to higher economic benefit. In addition, the 2nd stage suggests that increasing the tank sizes (above 800 m^3 and 1800 m^3 for small and large systems, respectively) would not significantly increase the NPV and additional economic benefit. For the 3rd stage, the value of $I_t + M_t$ in the Eq. (4) is higher than S_tP_t, suggesting that further investment for increasing tank size gives less benefit compared to the cost.

Another important finding is that the NPV of the RWHS is higher when the highest tariff (RM4.7/m^3) was applied compared to the lower tariffs (RM3.7/m^3 and RM4.0/m^3). These results can be explained by the value of S_tP_t in Eq. (4), suggesting more benefit can be expected by increasing the term of P_t. It suggests that the proposed RWHS has more benefit when the systems apply the highest water tariff. These results are consistent with data obtained in the previous work (Farreny et al., 2011a). Their study confirmed that the positive NPV between €385,438 to 447,599 can be obtained when the future water tariff scenario (€4/m^3) was applied compared to the lower water tariff (€1.1€/m^3). Therefore, various studies represented financial viability in terms of the water price required to make the installation of a rainwater tank able to recover the investment costs (Christian Amos et al., 2016).

In terms of the ROI and BCR, their increasing patterns for both commercial buildings suggest increasing benefit by increasing the tank sizes. Conversely, the decreasing ROI patterns are due to higher initial investment that offsets the potential economic benefit. In general, this study found that the RWHS for a large commercial building offers the higher ROI values compared to the small system, suggesting more economic benefit obtained when the large system was employed. In addition, the BCR values of the RWHS for large commercial building are also higher than the small system. These findings are valid for water tariff between RM3.0/m^3 and RM4.7/m^3.

It is also found that the PBPs at the optimum tank size for small system range from 6.0 to 10.5 years whereas for the large system

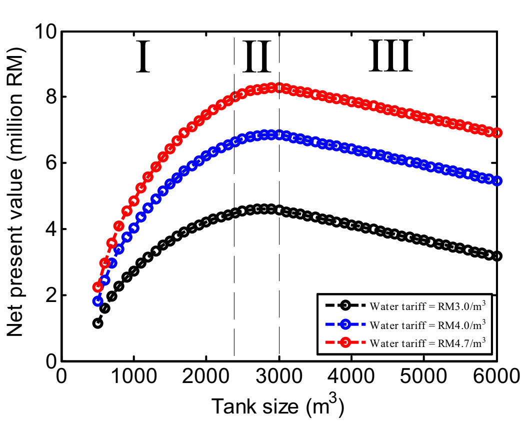

Fig. 9. Effects of tank size on the NPV of the proposed RWHS for the large commercial building.

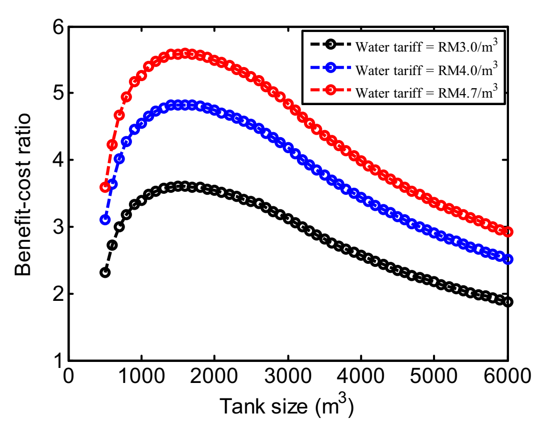

Fig. 11. Effects of tank sizes on the BCR of the proposed RWHS for the large commercial building.

range from 3.0 to 4.5 years for three different water tariff scenarios ($RM3.0/m^3$, $RM4.0/m^3$, and $RM4.7/m^3$). Specifically, the fastest PBP for the small building can be achieved when the highest water tariff was applied. A similar finding was also observed for the large building that indicated the fastest PBP was obtained at the highest tariff. Overall, these findings suggest that the implementation of RWHS for the large building is more attractive compared to the smaller one.

The aforementioned PBPs are in accord with previous works that investigated RWHS in commercial building in Portugal (Matos et al., 2015). The PBPs ranging from 2 to 6 years were obtained using their proposed RWHS. The implementation of RWHS for large scale such commercial buildings compared to small scale such as housing buildings seems to provide more benefit not only in the NPV but also in the PBP. For instance, long PBPs between 14 and 46 years were required when RWHS was applied for small roof size of 250 m^2 (Khastagir and Jayasuriya, 2011). Due to its small catchment area, the saved water is also less than RWHS with a large catchment area, thus its economic benefits received are not sufficient to compensate the high initial cost. The aforementioned findings in terms of the percentage of reliability, NPV, ROI, and BCR confirm that the implementation of the RWHS for the large commercial building offers more economic benefits compared to the small system.

In general, the present analysis shows that the optimum tank size for RWHS at the small commercial building is 600 m^3 based on the BCR values of 1.7 to 2.7 and ROI of 0.7 to 1.6 at varying tariffs from RM3.0 to $RM4.7/m^3$. For the same range of water tariff, the optimum tank size for large commercial building is 1600 m^3 with BCR of 3.6 to 5.6 and ROI of 2.6 to 4.5. Even though it is possible to achieve higher percentage of reliability up to 100% and 92% for the large and small commercial buildings, respectively, investment beyond the optimum tank size would not give additional economic benefits.

4. Conclusion

The aim of the present work was to evaluate the performance of RWHS in commercial building. We found that the optimum tank sizes for the small and large buildings are 600 m^3 and 1600 m^3, respectively. At the optimum tank sizes, the large commercial RWHS can achieve 97% reliability compared to the small system, only up to 91%. For three different tariff levels ($RM3.0/m^3$, $RM4.0/m^3$, and $RM4.7/m^3$), the PBPs around the optimum tank sizes (400 m^3 to 800 m^3 and 1400 to 1800 for small and large buildings, respectively) range from 6.0 to 10.5 years and 3.0 to 4.5 years, respectively. This study also suggests that the large commercial RWHS resulted in better NPV, ROI, BCR, and PBP compared to the small system, thus confirms the higher economic benefits for the larger system. In view of poor acceptance of large scale rainwater harvesting practices in Malaysia, this study provides strong justification for pushing this agenda more aggressively especially for large premises with high water consumption. The major motivation for this is to provide an alternative non-potable water sources as well as to reduce the water bill. For future work, it would be interesting to apply rainwater harvesting for potable use after undergoing minimum treatment, which may offer an even higher economic benefit.

Declaration of interest

The authors declare no conflicts of interest related to this research work.

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