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Reliability and Economic Analysis of a Rainwater-Harvesting System for a Commercial Building with a Large Rooftop Area

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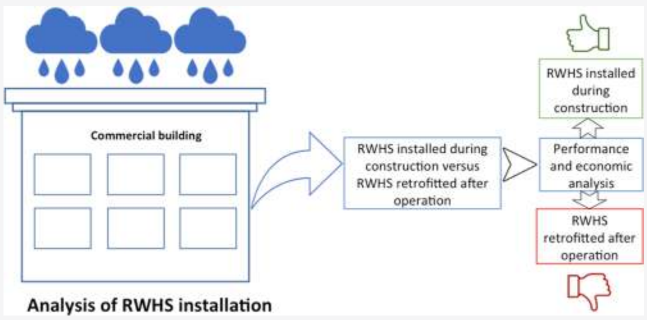
ABSTRACT: The water shortage problem faced by many countries requires a practical engineering solution. The reliability analysis of a rainwater-harvesting system (RWHS) installed at a commercial building of AEON Taman Universiti located in Johor Bahru, Malaysia, was based on the rainfall pattern, rainwater use, and rainwater storage tank. An economic analysis using the net present value (NPV), return on investment (ROI), and benefit−cost ratio (BCR) was performed to assess the optimal management of a RWHS installed during the construction and retrofitted after the operation of a commercial building. The results showed that the balance of water supply and demand is reliable for implementing a RWHS and the optimal management of a 1000 m^3 RWHS tank installed during construction could be more promising than that retrofitted after operation of the AEON Taman Universiti commercial building. The operation of a RWHS installed during the construction of a building is obviously more feasible because the NPV, ROI, and BCR values tend to be high. The reliability and economic analysis of RWHS installed during construction and that retrofitted after operation of a commercial building demonstrated the benefit of RWHS installation will contribute to effective water management as part of future building design.



KEYWORDS: *commercial building, economic cost−benefit analysis, rainwater harvesting, rainwater storage tank, water management-based reliability analysis*

1. INTRODUCTION

Water shortages caused by climate change, increased pollution, and increased demand for water are among the main problems facing many countries, including Malaysia. The applicability of rainfall intensity−duration−frequency curves and parameters for the design of a rainwater-harvesting system (RWHS) may help predict an efficiency of water saving for tropical climate regions.[1] Because of its variability, tropical rainfall in Uganda cannot meet the household water demands during the dry season due to the design of an insufficient RWHS tank capacity that cannot respond to the competitive use of water placed at risk by poor water management.[2] The implementation of a RWHS continued to have a significant impact on the regional water cycle and can reduce the risk of flooding and the cost of municipal drainage system installation and operation.[3] Inter-basin water transfer has been suggested as one of the most attractive alternatives for the management of water allocation and used 24 scenarios to ensure the continuous availability of water in Dohuk Dam of Dahuk Governorate in Iraq, characterized with its borderline semiarid and Mediterranean climate for agricultural, domestic, and tourism uses.[4] A study of rainwater harvesting that focused on the balance between sustainability values and storage capacity showed that the use of proper dam wall heights can store enough water for agricultural use in the Sabor River basin of northeastern Portugal.[5] The utilization of harvested water in the Ave River basin in Portugal may replace the need for streamwater to irrigate 400 ha of cropland that consumes 2.69 Mm^3 of water per year.[5] The use of rainwater as a source of drinking water has been proposed using the reliable technique of a biosand filter.[6] The collection of rainwater from a roof building area requires a suitable technique for harvesting such potential water for various independent uses. A RWHS may serve as an alternative water source for potable and nonpotable uses and for reducing flood proneness[7] and provides economic, technological, and environmental benefits for water use that greatly outweigh the costs. Several studies have evaluated the performance of RWHS operation, each varying in

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Figure 1. Location of the AEON Taman Universiti commercial building in Johor Bahru.

purpose, scope, and output. The installation of a RWHS for residential areas in Australia can lead to an annual domestic savings of ≤240 AUD per household.[8] The application of a RWHS for a number of residential and commercial buildings in South Korea has been proposed as an alternative way to reduce up to 10% of the detrimental effects of flooding.[9] The installation of a RWHS in a residential area in Palermo in southern Italy can reduce by approximately 35% the flooded area for a rainfall event with a depth of ≤50 mm.[10] The application of a RWHS can delay the construction of new water storage infrastructure because it has the ability to reduce the dependence on water from a domestic water supply.[11] It is possible to substantially reduce the volume of water being stored without substantially decreasing the efficiency of a RWHS if the application is typical of the low demand of harvested rainwater.[12,13] An economic analysis revealed that the payback period of RWHS operation in different major cities in Bangladesh varies from 2 to 6 years, reaching ≤40% of the reliability depending on the dependent variables and climatic conditions.[14] The operation of RWHSs for certain buildings in cold semiarid climates can supply ∼70% of nonpotable water.[15] The development of RWHSs as an alternative water supply to overcome water scarcity could be effective upon optimization of the performance of RWHS operation.[16−18]

Challenges in implementing a RWHS for a large rooftop area of a building are how to minimize the installation and maintenance costs and how to gain public acceptance of the uses of rainwater for various purposes. Rainwater-harvesting cisterns with acceptable limits of Palestinian water quality standards have been employed in southern Palestine.[19] Understanding rainwater harvesting market trends may contribute to determining the optimum size of a RWHS tank taking into consideration the rainfall patterns in tropical climates such as in the southwestern part of peninsular Malaysia. The operation and maintenance costs of a RWHS can be optimized through the proper design of a rainwater storage tank. Designing a rainwater gravity flow allowed us to employ a water flow through a piping system without a pump, which allowed us to avoid paying for electricity. The investment cost of a RWHS can be reduced using cheap building materials. Subsidies and tax rebates by the local and central governments are encouraged for the promotion of the installation of a RWHS for any large rooftop area of a building.[20] Public awareness campaigns of RWHS management waged by either NGOs or governments can shape public opinion to encourage interest in the community, and this provides significant benefits involving more ownership and responsibility for RWHS management by the rainwater users.[21]

Several studies have reported on the implementation of RWHSs for the various large commercial buildings.[22−24] The analysis of RWHS performance for large rooftop areas shows that two underground rainwater tanks are quite effective in wet and average years, but this requires detailed optimization and financial analysis to maximize the benefits of large rainwater tanks.[25] The commercial requirements for operating a RWHS are driven by economic rewards or utility. The various aspects of RWHS economic analysis have been performed to show that the costs associated with the installation and maintenance of RWHSs for six major cities in Bangladesh could be dependent on the topographic and climatic conditions.[14] The cost of the infrastructure would be enough to make the operation of a RWHS for a new commercial building located in Braga, Portugal, cost-effective.[24] The local authorities should maintain a rebate for rainwater tanks fitted in detached houses at 10 different locations to gain public acceptance of RWHS operation in Sydney, Australia.[26] The installation of RWHSs for commercial buildings is more likely to yield many benefits compared to that for individual residential houses. Many commercial buildings provide large rooftop areas for the possible collection of more rainwater to reduce water bills.[27] Optimization of the design of a RWHS for large roofs located in Melbourne, Australia, under different climatic scenarios has highlighted the need for detailed optimization and financial analysis to maximize the benefits of large rainwater tanks.[25] Economic analysis of the RWHS scenarios proposed for a new commercial building located in Braga, Portugal, shows the payback periods of project investment can be decreased.[24] Economic analysis of a RWHS installed during construction and after the operation of a commercial building has not been performed, so our study will assess the reliability of a RWHS installed at a commercial building located in a tropical region characterized by distinct wet and dry seasons. Even though the installation of a RWHS for a commercial building can yield many water use benefits, economic analysis of a RWHS installed during the construction and a RWHS retrofitted after the operation of a building for commercial purposes needs to be performed. This study will predict the supply and demand of water based on the daily rainfall data recorded from 1975 to 2003 and the average daily water consumption monitored at a commercial building in Johor Bahru, Malaysia, during a period from 2013 to 2017 and clarify the intrinsic value advanced by the cost−benefit analysis of installed and retrofitted RWHSs, which have not been reported previously. Therefore, the aims of this study are (1) to evaluate the rainfall patterns of the southwestern part of peninsular Malaysia to improve our understanding of the availability of water in the implementation of a RWHS and (2) to perform reliability and economic analysis of the installed and retrofitted RWHS performances for a commercial building of AEON Taman Universiti in Johor Bahru, Malaysia.

2. MATERIALS AND METHODS

2.1. Commercial Building. A commercial building of AEON Taman Universiti was selected to represent a large rooftop area in the southwestern part of peninsular Malaysia. AEON Taman Universiti is a shopping mall located in Johor Bahru, Malaysia, at a latitude of 1°32′33.1″N and a longitude of 103°37′44.1″E, as shown in Figure 1. The rainwater collected from the rooftop area of the AEON Taman Universiti building is for only nonpotable water uses.

2.2. Water Consumption. For this work, the average daily consumption of water for a commercial building of AEON Taman Universiti was monitored from 2013 to 2014. Rainwater collected from the rooftop surface of the AEON Taman Universiti building is used for toilet flushing, plant watering, general cleaning, and the chilled water system. The data for average daily consumption of water from 2013 to 2014 were combined with the data for the use of potable water during a five-year billing period (2013−2017) obtained from the AEON's office.

2.3. Rainfall Patterns. Long-term daily rainfall data recorded for 29 years (from 1975 to 2003) at the Senai International Airport station of Johor state with a latitude of 1°38′17.2″N and a longitude of 103°40′10.3″E were used to describe the seasonal and annual variations of rainfall at the study location of the AEON Taman Universiti commercial building. The complete sets of daily rainfall data with no missing values were used to predict the annual rainfall, number of wet days, percentage of consecutive dry day occurrence, and maximum number of consecutive dry days. Because the design of the RWHS installed at the AEON Taman Universiti building to collect rainwater does not consider first flush diversion, the potentially harvested rainwater can be estimated using the equation[28]

$$P_{\mathrm{h}} = ACF \tag{1}$$

where P_{h} is the potentially harvested rainwater (in cubic meters), A is the rooftop area of the AEON Taman Universiti building (in square meters), C is the runoff coefficient (dimensionless), and F is the daily rainfall (in meters).

2.4. Data Simulation. Modeling the performance of a RWHS has been suggested using the yield before spillage (YBS) and yield after spillage (YAS). The YAS method yields more a conservative estimate of RWHS efficiency compared to that of the YBS model.[29] For the purpose of this study, the mass balance model used to predict the capacity of water storage can simulate the rainfall data and is expressed as[30−32]

$$O_{\mathrm{t}} = \begin{cases} D_{\mathrm{t}} \text{ if } V_{\mathrm{t}} + V_{\mathrm{i-t}} \geq D_{\mathrm{t}} \\ V_{\mathrm{t}} + V_{\mathrm{i-t}} \text{ if } V_{\mathrm{t}} + V_{\mathrm{i-t}} < D_{\mathrm{t}} \end{cases} \tag{2}$$

where O_{t} is the daily water released from the RWHS tank (in cubic meters), D_{t} is the daily water demands for different uses (in cubic meters), V_{t} is the volume of water that enters the RWHS tank (in cubic meters), and $V_{\mathrm{i-t}}$ is the initial volume of water stored in the RWHS tank before entering the volume of V_{t} collected from rainfall (in cubic meters).

The operational reliability of a RWHS installed at the AEON Taman Universiti commercial building can be estimated using the equation[20]

$$R = \frac{O_{\mathrm{t}}}{D_{\mathrm{t}}} \times 100\% \tag{3}$$

where R is the reliability of RWHS operation (in percent), O_{t} is the daily water released from the RWHS tank (in cubic meters), and D_{t} is the daily water demands for different uses (in cubic meters).

2.5. Evaluation of the Economic Parameters. This study using three economic parameters, net present value (NPV), return on investment (ROI), and benefit−cost ratio (BCR), to analyze the ability of a RWHS to meet the nonpotable water needs of the AEON Taman Universiti commercial building expressed as[33]

$$\mathrm{NPV} = \sum_{t=0}^{s} \frac{V_{\mathrm{s}}C_{\mathrm{w}} - I_{\mathrm{n}} - M_{\mathrm{c}}}{(1+r)^t} \tag{4}$$

$$\mathrm{ROI} = \frac{\sum_{i=0}^{s} V_{\mathrm{s}}C_{\mathrm{w}} - I_{\mathrm{n}} - M_{\mathrm{c}}}{\sum_{i=0}^{s} I_{\mathrm{n}} + M_{\mathrm{c}}} \tag{5}$$

$$\mathrm{BCR} = \frac{\sum_{i=0}^{s} \frac{V_{\mathrm{s}}C_{\mathrm{w}}}{(1-r)^t}}{\sum_{i=0}^{s} \frac{I_{\mathrm{n}} - M_{\mathrm{c}}}{(1-r)^t}} \tag{6}$$

where V_{s} is the volume of water saved over the period of time t (in cubic meters), C_{w} is the cost of water over the period of time t (in RM per cubic meter), I_{n} is the investment required for the period of time t (in RM), M_{c} is the maintenance costs over the period of time t (in RM), s is the life span of RWHS operation (in years), t is the operating period of RWHS installation (in years), and r is the interest rate (in percent).

The annual operational cost can estimated using the equation[20]

$$C_{\mathrm{a}} = \frac{V_{\mathrm{a}}}{S_{\mathrm{p}}} E_{\mathrm{p}} C_{\mathrm{e}} \tag{7}$$

where C_{a} is the annual operation cost of a RWHS (in RM), V_{a} is the volume of water saved by RWHS operation annually (in cubic meters), S_{p} is the pump flow speed (in cubic meters per hour), E_{p} is the pump energy used for RWHS operation (in kilowatt hours), and C_{e} is the electricity tariff (in RM per kilowatt hour). Note that the values of S_{p} and E_{p} used for the economic analysis of water uses for the AEON Taman Universiti

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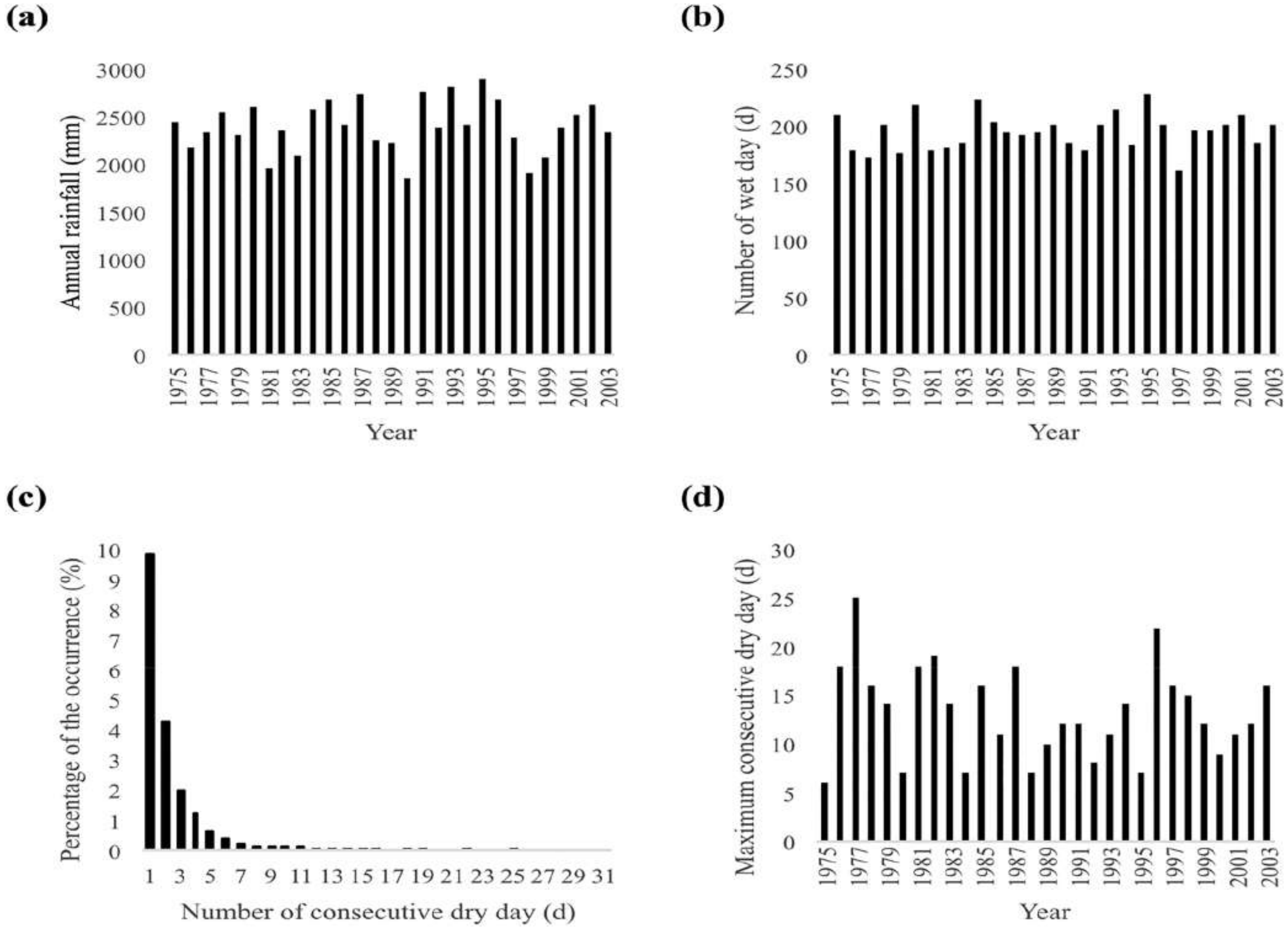

Figure 2. Rainfall patterns recorded at the rainfall station of Senai International Airport from 1975 to 2003 with (a) annual rainfall, (b) number of wet days, (c) percentage of the occurrence of consecutive dry days, and (d) maximum number of consecutive dry days.

commercial building reached 30 m^3/h and 2.2 kWh, respectively.

By assuming the initial investment for the implementation of a RWHS installed at the AEON Taman Universiti commercial building was acquired as a loan, we estimated the annual year-end payment (annuity) of RWHS installation by the equation[34,35]

$$C_{ai} = I_{in}\left[\frac{r(1+r)^t}{(1+r)^t - 1}\right] \tag{8}$$

where C_{ai} is the annual year-end payment for the RWHS investment (in RM), I_{in} is the initial investment for the implementation of a RWHS at the commercial building (in RM), r is the interest rate (in percent), and t is the time (in years).

The values of the parameters used for the analysis and simulation of the RWHS operation as reported by Lani et al.[20] are 16506 m^2 for the rooftop area, 213.9 m^3 for daily water consumption, RM 3.05/m^3 for the water tariff, 446 m for the pipe length, RM 104600 for the pumping cost, 0.9 for the runoff coefficient, 0.5 RM/L for the water tank cost, 24.1 RM/m for the piping cost, 133 RM for the monthly maintenance cost, RM 4000 for the retrofitting cost per pipe, RM 0.43/kWh for the electricity tariff, 4.25% for the average interest rate, 3.05 RM/m^3 for the water tariff, 20 years for tank replacement, 10 years for pump replacement, and 30 years the the RWHS life span.

3. RESULTS AND DISCUSSION

3.1. Reliability Analysis. *3.1.1. Rainwater Pattern.* The rainfall pattern is an important factor that affects the efficiency of RWHS operation on the large rooftop area of a building. The effect of rainfall patterns on RWHS performance has been investigated at several locations in the peri-urban regions of greater Sydney, Australia,[26,30] and in various European climate zones.[36] In this work, daily rainfall data recorded from 1975 to 2003 at the rainfall station of Senai International Airport were used for the analysis of rainfall patterns that affected the effectiveness of a RWHS installed at the AEON Taman Universiti commercial building, as shown in Figure 2. The average and maximum daily rainfall were 11.8 and 364.4 mm, respectively, and the typical rainfall pattern of southern Johor state was characterized by high daily rainfall in December with a maximum daily rainfall on December 2, 1978.

The spatial and temporal characteristics of the rainfall over the western region of Malaysia have been divided into five parts: northwest, west, east, southwest, and central region of peninsular Malaysia.[37] Annual rainfall across Malaysia varies with time and space. The rainfall characteristics in time and space of one part are distinctly different from those of other parts of peninsular Malaysia. The statistical distribution of daily rainfall could be more regular over the western, northwestern, and southwestern parts than over the eastern part of peninsular Malaysia.[38] The long-term hydrological data of daily rainfall

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consistently collected from a rain gauge and weather station could improve the modeling of the rainfall pattern by taking into account multiple objectives of the RWHS installation.[39] Figure 2a shows that the annual rainfall monitored from 1975 to 2003 at the rainfall station of Senai International Airport that ranges from 1860.4 to 2891.9 mm. The minimum annual rainfall of 1860.4 mm occurred in 1990, and the maximum annual rainfall of 2891.9 mm occurred in 1995. Despite an annual rainfall of <2000 mm being recorded in 1981, 1990, and 1998, the annual rainfall in the southwestern part of peninsular Malaysia can be considered very high. Information regarding the rainfall pattern shows an average daily rainfall of 11.8 mm, which is promising for the implementation of a RWHS. The analysis of the regional characteristics of rainfall is related to the operation of a RWHS installed at the AEON Taman Universiti commercial building. The implementation of a RWHS offers an attractive solution for efficient and successful integrated water resource management.[40]

The rainfall characteristics of Johor Bahru, which is located in the southwestern part of peninsular Malaysia, exhibit consistent patterns.[37] This may indicate a great opportunity to implement RWHS collection of rainwater at any reliable building that has a large rooftop area. The number of rainy days in Johor Bahru as shown in Figure 2b ranges from 160 to 228 days with an average of 195 days associated with the contribution of heavy rainfall events to total annual precipitation. The implementation of a RWHS as an alternative water resource has been successful in Singapore and Indonesia[41,42] but is still very limited because the ROI time is long and public acceptance is still poor. The implementation of a RWHS, which is becoming more attractive in the Johor state of Malaysia, can reduce water costs because Johor's water tariff is already among the highest water tariffs in the country. Economic analysis of a RWHS installed to collect rainwater from the AEON Taman Universiti commercial building is important to improve our understanding of the exact economic condition that covers a number of water management issues.

Determining the number of consecutive dry days within a period of 29 years could be useful in designing the proper volume of the RWHS tank for the AEON Taman Universiti commercial building. The results (Figure 2c) for the number of consecutive dry days at the rainfall station of Senai International Airport showed that the 1044 dry days per 10592 days of the rainfall patterns observed during 29 years is approximately 9.86% of the total observation days. This evidence could be useful in evaluating various factors affecting the length of the dry period and the effect of current dry days on the design of the RWHS tank. The selection of a proper RWHS tank for collecting rainwater from the rooftop area of the AEON Taman Universiti commercial building was based on the simulation of various economic parameters using a RWHS tank size range of 200−2000 m^3.[43] An annual basis of recording dry days (see Figure 2d) showed that the maximum number of consecutive dry days within a year ranges from 6 days in 1975 to 25 days in 1977. A study conducted by the National Hydraulic Research Institute of Malaysia over the 60-year period at the rainfall station of Ladang Senai showed that the largest number of consecutive dry days (40) was recorded in the southwestern part of peninsular Malaysia.[44] An optimum capacity of the RWHS tank can be predicted on the basis of the annual and seasonal distribution pattern of rainfall in the region.[45] More consecutive dry days require a larger RWHS tank volume to ensure effective RWHS operation in the collection of sufficient rainwater for the various uses during the dry periods during a year. The average annual water saving of RWHS operation strongly correlates with the average annual rainfall.[30] The trend and periodicity analysis of the rainfall pattern in the southwestern part of peninsular Malaysia indicate that installing a RWHS tank at a commercial building with a large rooftop area is beneficial.

3.1.2. Rainwater Use. The performance of a RWHS installed at a building is dependent on the types of rainwater use and the total amount of water withdrawn from the RWHS tank. This study considered the types of rainwater use based on the existing pipe distribution system of the AEON Taman Universiti commercial building; nonpotable uses of water released from the RWHS tank include toilet flushing, plant watering, general cleaning, and chilled water systems. The flush toilet use varies in the range of 1587−2012 m^3/month with an average of 1834 m^3/month and is approximately 28.6% of the total nonpotable water use (see Figure 3, line i). The use of water from a RWHS

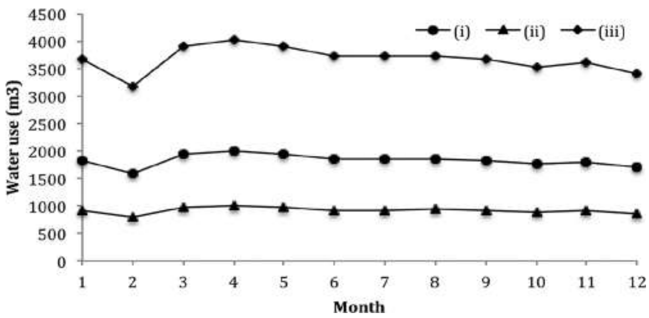

Figure 3. Average monthly water use for a RWHS installed at the AEON Taman Universiti commercial building in Johor Bahru, Malaysia: (i) toilet flushing, (ii) plant watering and general cleaning, and (iii) chilled water system.

installed at dormitories in Poland and Slovakia for toilet flushing reached approximately 18% and 29%, respectively.[46] Water use in indoor and outdoor plant watering and general cleaning is in the range of 793−1006 m^3/month with an average of 917 m^3/month, and this use makes up approximately 14.3% of the total nonpotable water use (see Figure 3, line ii). The use of rainwater for chiller systems installed at the AEON Taman Universiti commercial building is in the range of 3175.0−4024.8 m^3/month with an average of 3667.9 m^3/month, and this use makes up approximately 57.1% of the total nonpotable water use (see Figure 3, line iii). The quantity of rainwater used to operate the chilled water systems is approximately 2 times larger than that used for toilet flushing. The amount of rainwater used to flush the toilets is approximately 2 times larger than that used for plant watering and general cleaning. It has been reported that the cost of constructing a RWHS at a commercial building is significantly lower than the cost of either reusing treated domestic and industrial wastewater or desalinating seawater.[47] A reliability and cost analysis of the RWHS installed at the AEON Taman Universiti commercial building is required to provide insight into the implementation of a RWHS for other large rooftop areas in the southwestern part of peninsular Malaysia.

3.1.3. Rainwater Storage Tank. Several studies have revealed that the reliability analysis of RWHS performance should consider multiple criteria for selecting an optimal design of rainwater storage tanks (see Table 1). The reliability of rainwater collected from the various rooftop areas and the overflow ratio of the RWHS tank sizes have been analyzed under different climatic conditions in Rasht, Sari, Tabriz, and Yazd in

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Table 1. Comparison of the RWHS Performance between This Study and the Literature

topic	location	significance	ref
payback period analysis of the RWHS installation	case study of a commercial building in the U.K.	considering the effects of alternative roof and tank sizes can determine the length of time necessary for the payback period	22
environmental management of the RWHS installation	100 cisterns in southern Palestine	different remediation measures are recommended to enhance and protect cistern water quality	19
economic and sensitivity analysis of the design, cost, and water service charge	evaluation of RWHS tank capacity in South Korea	an increase in the rate of water service charge has a considerable impact on the economic feasibility	50
water balance simulation of a RWHS with different tank sizes	10 locations in greater Sydney, Australia	increasing the rebate for the implementation of a RWHS may enhance public acceptance	26
life cycle cost analysis using the ERain tool	case study in Australia and Kenya	a rebate that matches tank size may encourage the installation of larger tanks to improve water security	51
payback period analysis of different RWHS installations	six major cities in Bangladesh	costs associated with the installation and maintenance of RWHS depend on the topographic and climatic conditions	14
effectiveness of a RWHS to reduce the risk of flooding	more than 400 houses in a residential area of Sicily in southern Italy	the potential of a RWHS in the mitigation of the risk of flooding is related to rainfall amount	10
reliability and economic analysis of a RWHS installed at a large rooftop area	one commercial building in Johor Bahru, Malaysia	the operation of RWHS installed during construction is more feasible than the operation of that retrofitted after building operation	this work

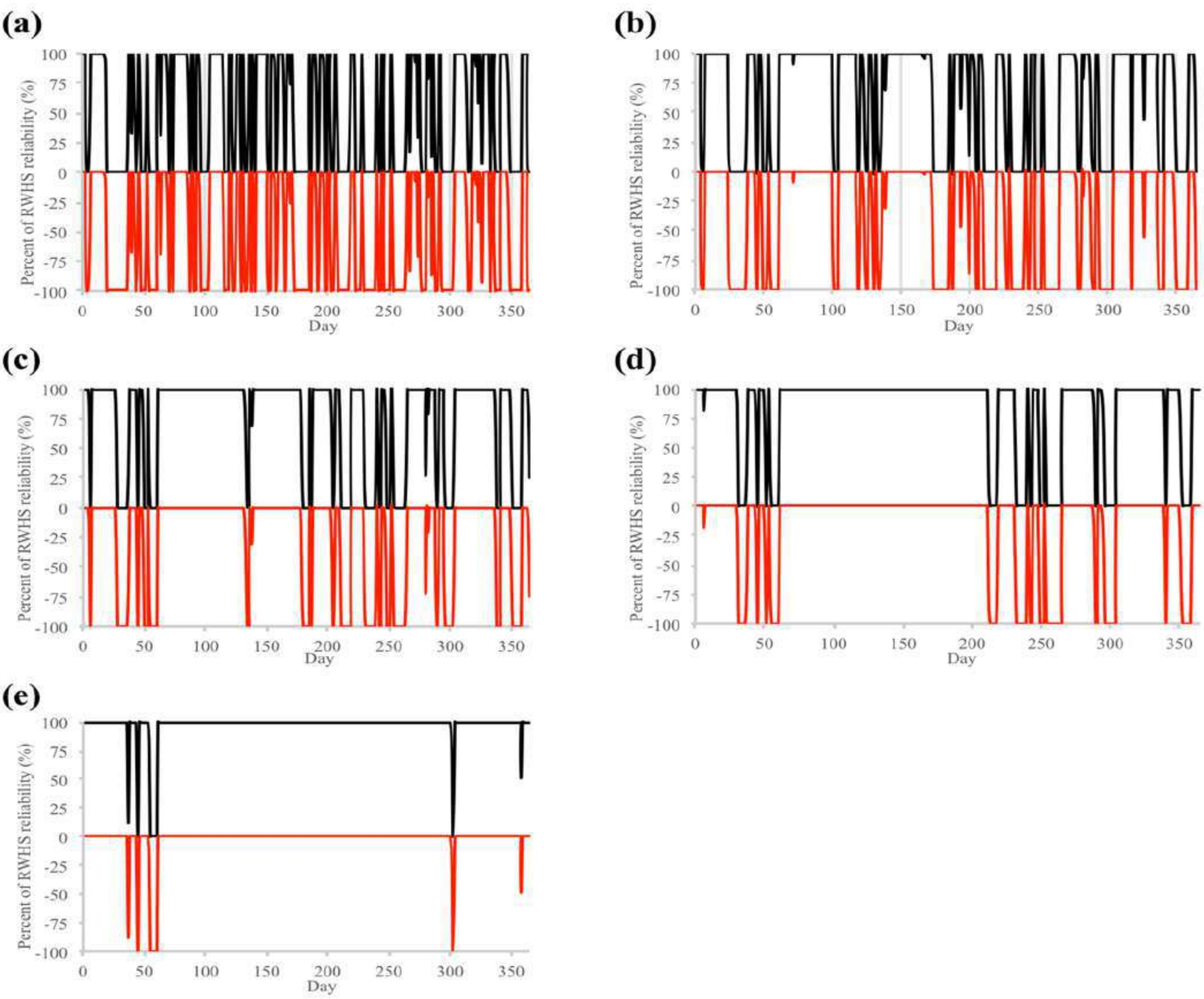

Figure 4. Daily reliability of rainwater stored in (a) 200 m^3, (b) 300 m^3, (c) 400 m^3, (d) 500 m^3, and (e) 1000 m^3 RWHS tanks, where black lines refer to the percentage of rainwater reliability and red lines refer to the percentage of rainwater that does not meet the daily water demand.

Iran.[48] The rational reliability of the rainwater supply for various uses and the most satisfactory storage capacity of any specific rooftop areas can be estimated using a simulation model.[49]

The results (Figure 4) of this study show the daily reliability of rainwater stored in RWHS tank volumes of 200, 300, 400, 500, and 1000 m^3. The black curves in Figure 4 refer to the percentage of rainwater reliability, while the red curves refer to

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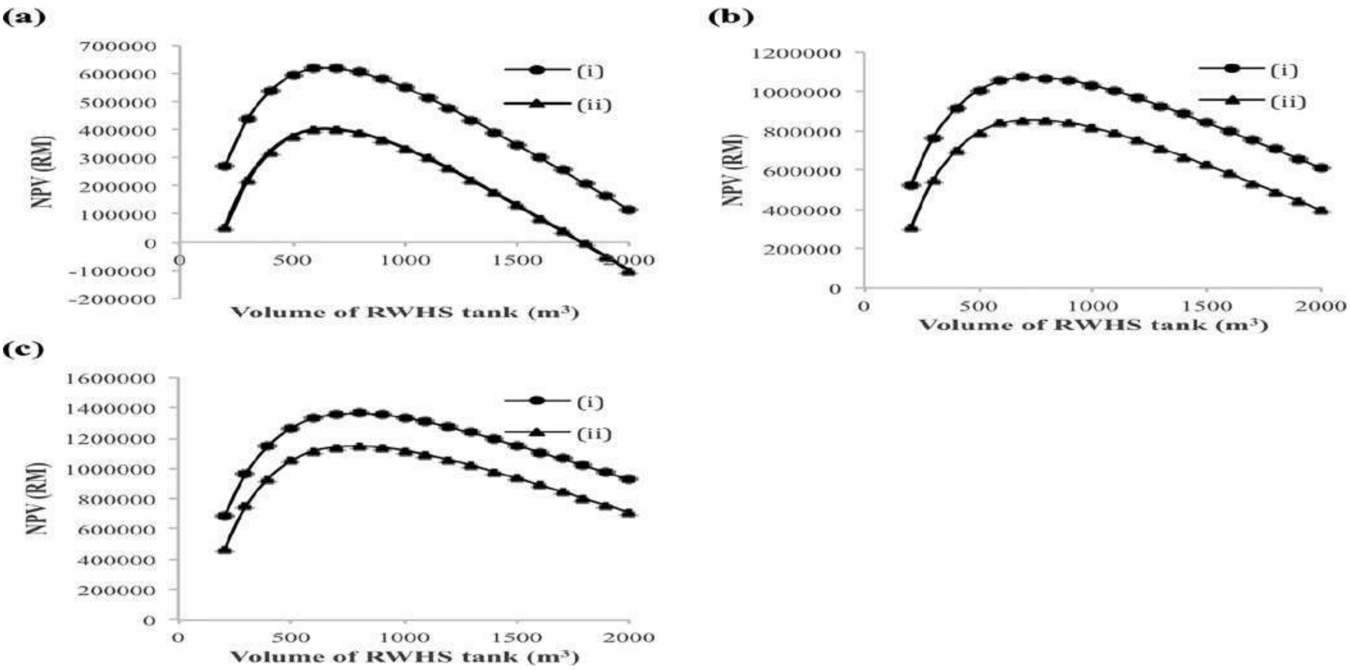

Figure 5. Analysis of the NPV for (i) the RWHS installed during the construction of the building and (ii) the RWHS retrofitted after building operation with water tariffs of (a) 3.0 RM/m^3, (b) 4.0 RM/m^3, and (c) 4.7 RM/m^3.

the percentage of rainwater that was insufficient for meeting the daily water demand. The percentage of rainwater that does not provide a sufficient amount of water to meet the daily water demand can gradually decrease with an increase in RWHS tank size from 200 to 300 to 400 to 500 to 1000 m^3 (see Figure 4a–e). An empty tank for a period of 165 days can be obtained from the simulation of the daily rainfall pattern in predicting an effective storage capacity of 200 m^3 designed to collect rainwater from the rooftop area of the AEON Taman Universiti commercial building. Empty RWHS tanks for 120, 86, 64, and 9 days can be simulated for storage capacities of 300, 400, 500, and 1000 m^3, respectively. An increase in the RWHS tank volume from 200 to 300 m^3 can reduce the number of days with an empty tank by 27.3% (from 165 to 120 days). A change in the storage tank volume from 200 to 400 m^3 can reduce the number of days with an empty tank by 47.9% (from 165 to 86 days). A storage capacity design for a RWHS tank could be dependent on the length of dry periods.[52]

An increase in the storage capacity of the RWHS tank from 200 to 500 m^3 can reduce the number of days with an empty tank by 61.2% (from 165 to 64 days). An increase in the volume of the RWHS tank from 200 to 1000 m^3 can reduce the number of days with an empty tank by 94.5% (from 165 to 9 days). The maximal reliability of 1000 m^3 storage capacity is promising for the collection of rainwater from the rooftop area of the AEON Taman Universiti commercial building within one year of water use because the increased storage capacity of the RWHS tank of ≤2000 m^3 cannot further increase the percentage of rainwater reliably stored in the tank. A previous study has reported that the reliability of a RWHS tank larger than 2.6 m^3 could be independent of the tank size while the maximum reliability of a 10 m^3 RWHS tank that collected rainwater from a rooftop area of 300 m^2 with a daily water demand of 0.3 m^3 is approximately 70% of the total days of the year.[53] A detailed assessment of the different cistern sizes is required to minimize oversizing of the RWHS tank and to build confidence in RWHS performance.[54] The ERain economic analysis of RWHS implementation showed that the size of the rebate should match the storage tank capacity to encourage the installation of larger tanks to improve water security.[51]

3.2. Economic Cost–Benefit Analysis. *3.2.1. Analysis of the Net Present Value.* Even though an economic cost–benefit analysis using various models to gain insight into the optimal management of RWHS installation has been reported in the literature (see Table 1), the performance and economic analysis of RWHS installed during construction compared with those of a RWHS retrofitted after the operation of a commercial building needs to be understood. The financial feasibility of RWHSs for urban water management at the household scale has been analyzed on the basis of a questionnaire survey of 35 households in Bucaramanga, Colombia.[55] The perceptions of the experts and public respondents toward the implementation of RWHSs in six cities in Iran could reduce the water bills and mitigate the water shortage crisis.[56] The use of simulated RWHS tank volumes in the range of 200–2000 m^3 has been normalized with the available rainwater based on the rainfall pattern in the southwestern part of peninsular Malaysia. An uncertainty analysis of the model results for economic assessment of RWHS performance was based on the current water tariff of 3.0 RM/m^3 and predicted water tariffs of 4.0 and 4.7 RM/m^3 in the next 10 and 20 years, respectively, charged to costumers of Johor Bahru as reported in a previous study.[20] In this work, analysis (Figure 5) of the NPV for the operation of a RWHS installed during the construction of the AEON Taman Universiti commercial building shows that the NPV level of the RWHS investment project increased by 345735.3 RM from 271277.4 to 617012.7 RM with a water tariff of 3.0 RM/m^3 (see Figure 5a, line i), by 548142 RM from 523333.3 to 1071475.3 RM with a water tariff of 4.0 RM/m^3 (see Figure 5b, line i), and by 681441.9 RM from 681629.2 to 1363071.1 RM with a water tariff of 4.7 RM/m^3 (see Figure 5c, line i), which could be due to increases in the capacity of the RWHS tank from 200 to 600 m^3, from 200 to 700 m^3, and from 200 to 800 m^3, respectively. The implementation of a RWHS could generate an important

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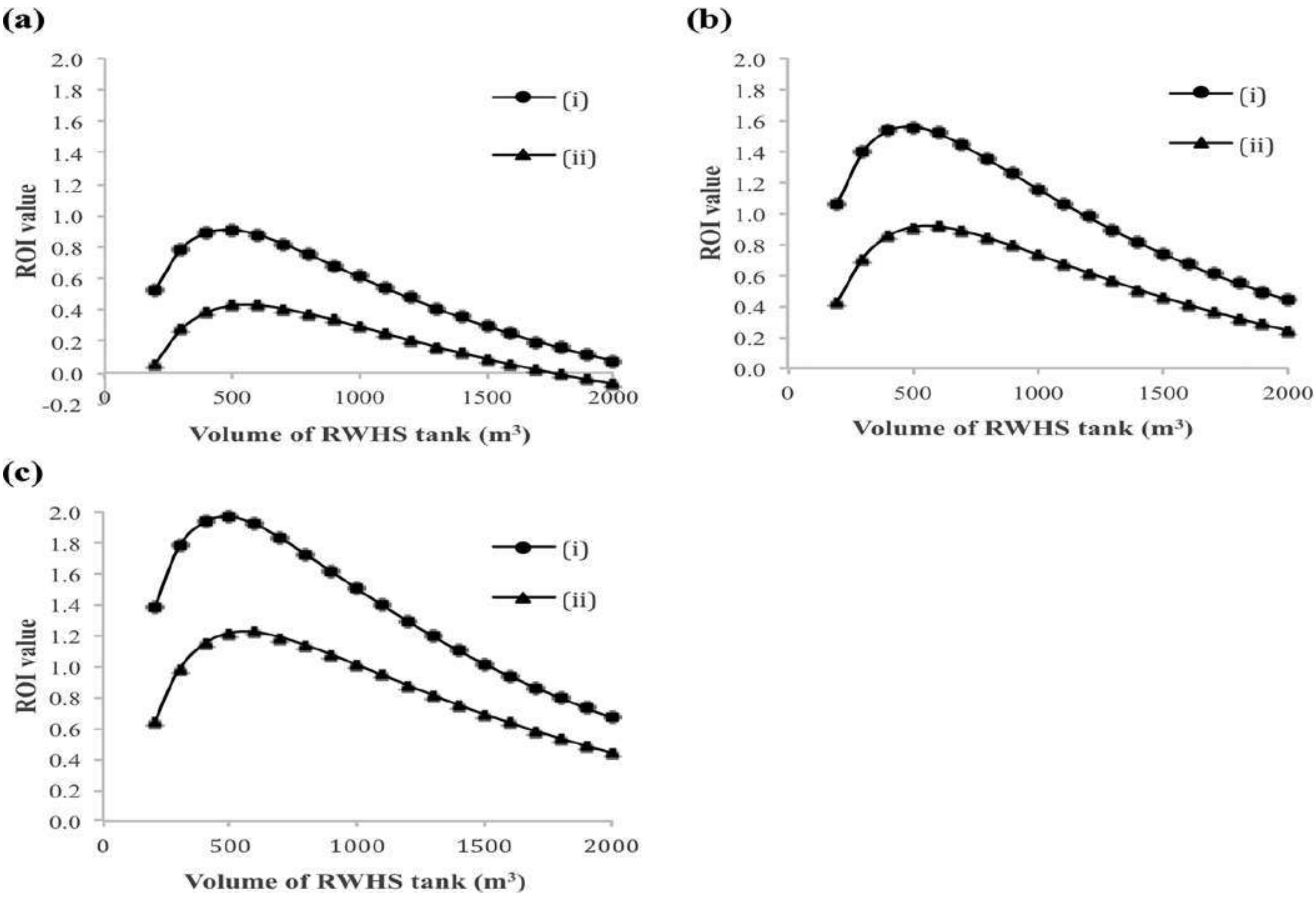

Figure 6. Analysis of ROI for (i) the RWHS installed during the construction of the building and (ii) the RWHS retrofitted after building operation with water tariffs of (a) 3.0 RM/m^3, (b) 4.0 RM/m^3, and (c) 4.7 RM/m^3.

economic benefit with a 5-year investment amortization and 5048.3 USD of the NPV level for a transportation logistics company located in Mexico City.[57]

The NPV level for the RWHS retrofitted after building operation increased by 345735.3 RM from 56150.5 to 401885.8 RM with a water tariff of 3.0 RM/m^3 (see Figure 5a, line ii), by 548142 RM from 308206.4 to 856348.4 RM with a water tariff of 4.0 RM/m^3 (see Figure 5b, line ii), and by 681441.9 RM from 466502.3 to 1147944.2 RM with a water tariff of 4.7 RM/m^3 (see Figure 5c, line ii), which could be due to the increases in the storage capacity of the RWHS tanks from 200 to 600 m^3, from 200 to 700 m^3, and from 200 to 800 m^3, respectively. The level of NPV progressively decreases with an increase to 2000 m^3 of storage tank capacity after reaching a maximum level. The highest NPV level of the RWHS installed during construction of the building compared to that retrofitted after building operation increases by 53.53% for a water tariff of 3.0 RM/m^3 (see Figure 5a), by 25.12% for a water tariff of 4.0 RM/m^3 (see Figure 5b), and by 18.74% for a water tariff of 4.7 RM/m^3 (see Figure 5c). Installation of the RWHS during construction yielded a number of benefits that can reduce the additional cost incurred during the construction of the RWHS retrofitted after commercial building operation paid by various business activities.[58] Resetting the energy and water systems of the commercial building determined an increased cost of the RWHS retrofitted after building operation. The arrangement of demolition debris and construction waste disposal have significant costs for the RWHS retrofitted after building operation.[59] The payment of water bills that led to an increased cost of the RWHS retrofitted after building operation could be one of the economic factors that reduced the NPV value. The results of NPV analysis revealed that the RWHS tank installed during the construction of the building could be economically better than that retrofitted after operation of the AEON Taman Universiti commercial building for all simulated RWHS tank capacities and support the finding of a previous study on a neighborhood of dense social housing located in Granollers, Spain.[58]

3.2.2. Analysis of the Return on Investment. The performance of the RWHS was evaluated using ROI analysis for the various rainwater storage tank capacities and different water tariffs, as shown in Figure 6. By assuming a water tariff of 3.0 RM/m^3, we found the ROI increased by 0.38 from 0.53 to 0.91 (see Figure 6a, line i) for the RWHS installed during construction, which was larger than the increase of 0.37 from 0.06 to 0.43 (see Figure 6a, line ii) for the RWHS retrofitted after building operation, which could be due to the increase in RWHS tank capacity from 200 to 500 m^3. The effects of the rainfall pattern, geographic, regulation, financial, population, and social attributes of the southwestern part of peninsular Malaysia contribute to the actual cost of RWHS installation.[60] By assuming a water tariff of 4.0 RM/m^3, we found the value of ROI increased by 0.51 from 1.05 to 1.56 (see Figure 6b, line i) for the RWHS tank installed during construction, which was higher than the value that increased by 0.49 from 0.42 to 0.91 (see Figure 6b, line ii) for the RWHS tank retrofitted after building

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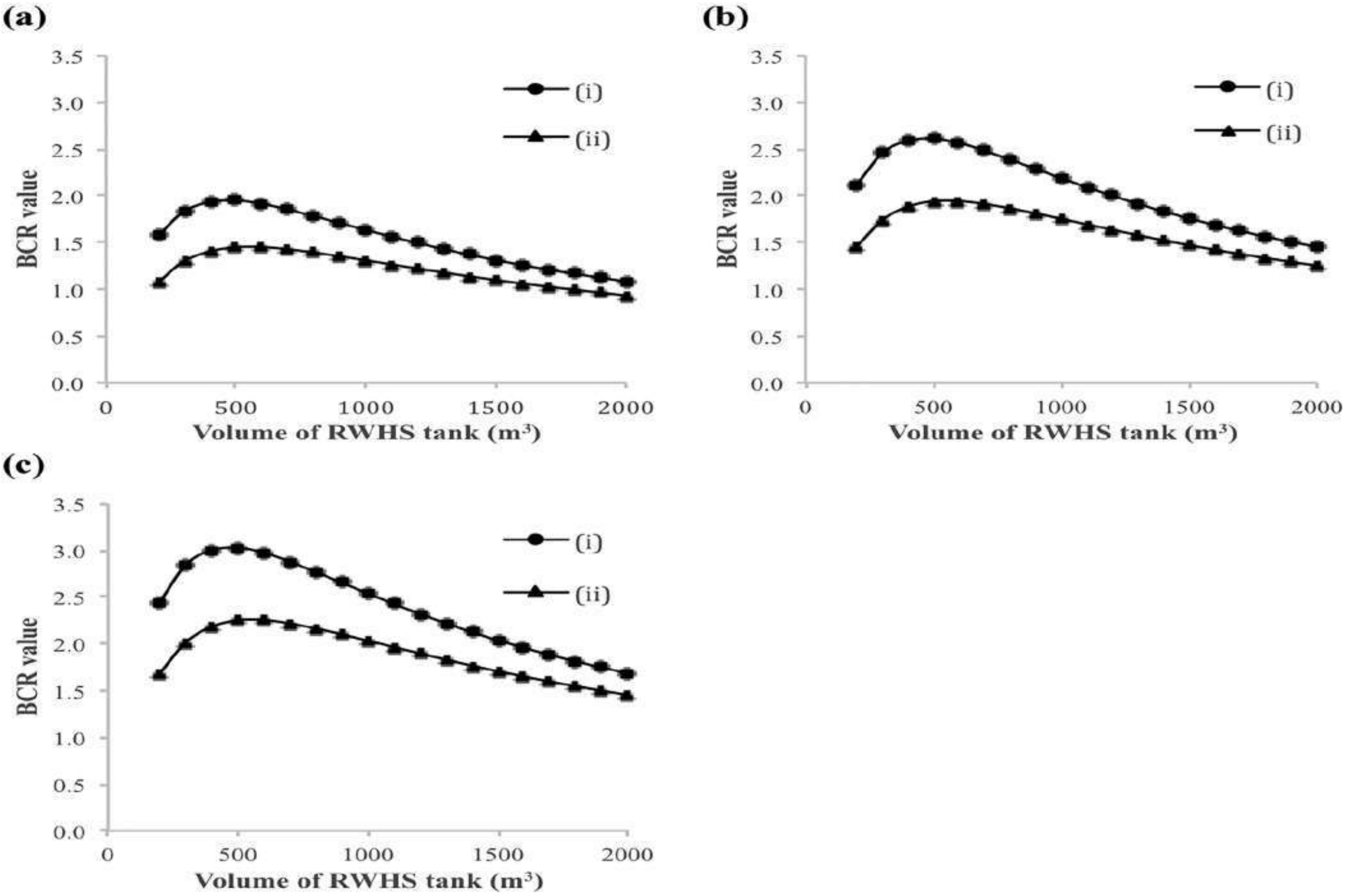

Figure 7. Analysis of BCR for (i) the RWHS installed during the construction of a building and (ii) the RWHS retrofitted after building operation with water tariffs of (a) 3.0 RM/m^3, (b) 4.0 RM/m^3, and (c) 4.7 RM/m^3.

operation, whch could be due to the increase in the rainwater storage tank capacity from 200 to 500 m^3. The implementation of a RWHS with a storage tank of 500 m^3 retrofitted at the AEON Taman Universiti commercial building with an increase in the water tariff from 3.0 to 4.0 RM/m^3 can lead to an increased in ROI by 0.48 from 0.43 to 0.91 (see Figure 6a,b); however, a water tariff of 4.0 RM/m^3 is still not attractive because the ROI value is <1. Application of the proper RWHS tank-collected rainwater as an economical option for households in the Gold Coast, Brisbane, and Sydney has been recommended for different household environments.[8] The implementation of a RWHS retrofitted after building operation is not recommended with water tariffs of 3.0 and 4.0 RM/m^3 because the ROI due to an increased rainwater storage tank capacity is still <1 (see Figure 6a,b). Application of a RWHS in the old town of Lipari in the Aeolian islands of Italy shows potential water savings of 30−50% per year with a ROI of <15 years.[61]

By assuming a water tariff of 4.7 RM/m^3, we found the ROI value of the RWHS installed during construction increased by 0.58 from 1.38 to 1.96 (see Figure 6c, line i), which is higher than the ROI of that retrofitted after building operation that increased by 0.57 from 0.65 to 1.22 (see Figure 6c, line ii), which could be due to the increase in the RWHS storage tank capacity from 200 to 500 m^3. The analysis of the ROI revealed that the RWHS retrofitted after operation of AEON Taman Universiti commercial building justifies the water tariffs being >4.7 RM/m^3 due to the ROI value being >1, which was verified for RWHS tank capacities in the range of 400−1000 m^3 (see Figure 6c, line ii). This finding is in agreement with a previous study that found that the benefit of RWHS installation for a commercial building is greater because the business operation can be charged a higher water tariff.[58] The RWHS tank installed during construction is promising compared to that retrofitted after the operation of the AEON Taman Universiti commercial building. The investment in a RWHS in a rather unfavorable climate with a poor rainfall distribution during the year is very low risk and has a short payback time.[62]

3.2.3. Analysis of the Benefit−Cost Ratio. An investigation of RWHS operation using economic performance indicators can estimate an optimal size requirement of a rainwater storage tank and the connectivity of the storage tank with the corresponding rooftop area.[63] BCR analysis of the RWHS installed during construction and that retrofitted after operation of the AEON Taman Universiti commercial building is depicted in Figure 7. The BCR value of the RWHS installed during construction increased by 0.37 from 1.58 to 1.95 with a water tariff of 3.0 RM/m^3 (see Figure 7a, line i), by 0.50 from 2.11 to 2.61 with a water tariff of 4.0 RM/m^3 (see Figure 7b, line i), and by 0.58 from 2.45 to 3.03 with a water tariff of 4.7 RM/m^3 (see Figure 7c, line i), which could be due to an increase in the RWHS tank capacity from 200 to 500 m^3. The potential capacity of rainwater captured annually depending on the cistern size of the RWHSs used in a densely urbanized watershed such as that in southern California allowing a modest economic benefit of high installation and maintenance cost required to pipe the water indoors for outdoor/indoor uses can be evaluated by considering the total water needs of a building.[64] The BCR value of a RWHS retrofitted after building operation increased

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by 0.37 from 1.08 to 1.45 with a water tariff of 3.0 RM/m^3 (see Figure 7a, line ii), by 0.49 from 1.45 to 1.94 with a water tariff of 4.0 RM/m^3 (see Figure 7b, line ii), and by 0.57 from 1.68 to 2.25 with a water tariff of 4.7 RM/m^3 (see Figure 7c, line ii), which could be due to an increase in the RWHS tank capacity from 200 to 500 m^3. The BCR value of the RWHS installed with little cost can improve with an increase in water demand if the optimal use of the RWHS tank has been predicted.[50] The results of this study show that the maximum BCR value of a 500 m^3 RWHS tank installed during construction increases by 34.48% from 1.45 to 1.95 for a water tariff of 3.0 RM/m^3 (see Figure 7a), by 34.54% from 1.94 to 2.61 for a water tariff of 4.0 RM/m^3 (see Figure 7b), and by 34.67% from 2.25 to 3.03 for a water tariff of 4.7 RM/m^3 (see Figure 7c) compared to that retrofitted after the operation of the AEON Taman Universiti commercial building. A BCR value of >1 obtained in the case of RWHS-generated cash income could be due to the level of social acceptance that is related to the affordability and economic profitability of the RWH design, which can result in savings greater than the total investment cost.[65]

The price of water is a critical factor that must be used as part of the rational policy for implementing the optimal capacity of a RWHS tank installed during the construction of a building.[64] This study revealed that the BCR values of RWHS installed during construction are all higher than the values of that retrofitted after building operation. In conclusion, the benefits of a RWHS tank installed during the construction of a building could be greater than those of a RWHS retrofitted after building operation. To the best of our knowledge at present, the reliability and economic analysis of a RWHS installed during construction compared with that retrofitted after commercial building operation has not been reported in the literature. The reliability and economic analysis using two scenarios of RWHSs installed during construction and retrofitted after building operation may contribute to the objective ability of decision-makers and the quality of the decision to ensure the safe design and construction of buildings with large rooftop areas in the future. This study provides guidelines for the installation of an effective RWHS at a commercial building that contain valuable information for policymakers and society. This study did not include an analysis of flood risk reduction, rainwater quality, and public acceptance of the RWHS implementation to gain a more comprehensive accounting, which could provide an overview of other benefits available to the local government and civil society. This identifies a potential topic, the sustainable management of rainwater, for future research.

4. CONCLUSIONS

This study evaluated the performances of a RWHS installed during construction and retrofitted after operation of the AEON Taman Universiti commercial building. The analysis of the rainfall patterns and water uses showed that the installation of a RWHS tank at a large rooftop area of a building in the southwestern part of peninsular Malaysia is reliable. An increase in the RWHS storage tank capacity to reduce the number of days with empty tanks can be achieved with a maximum reliability of 94.5% when using a 1000 m^3 storage tank. The economic analysis of the NPV, ROI, and BCR values showed that the reliability of a RWHS installed during construction that increased with an increase in the water tariff is economically more feasible than that retrofitted after the operation of a commercial building. The reliability and cost−benefit analysis of the RWHS installation may contribute to the design and construction of future buildings in regions having significant rainfall and in regions where a good quality surface water or groundwater is lacking. The rainfall data findings and economic modeling from the analysis of RWHS installation can be used to guide future research of the implementation of RWHS-collected rainwater from the large rooftop areas of a building and provide insight into the application of RWHS installed in other regions with a tropical climate.

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Notes

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