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Performance Evaluation of a Rainwater Harvesting System: A Case Study of University College Hospital, Ibadan City, Nigeria

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Authors' contributions

This work was carried out in collaboration between both authors. Author OL designed the study, performed the statistical analysis and wrote the first draft of the manuscript. Author DO managed the analyses of the study and the literature searches. Both authors read and approved the final manuscript.

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ABSTRACT

Provision of water supply to meet urban demands is increasingly facing complex challenges due to water scarcity, population growth, ageing infrastructure, variability and uncertainty under climate change. Rainwater harvesting system (RWHS) can augment water supply to meet urban and rural needs with added economical and financial benefits. This study assessed the hydraulic and financial performance of a RWHS for the University College Hospital in Ibadan. Storage capacity, water savings, sensitivity analysis and MonteCarlo simulation were optimised using a Raincycle model. A comprehensive assessment of the proposed system was carried out, considering seven specified and eleven unpredictable variables. The specified variables are: basin area, pump hydraulic power, initial surface runoff, storage capacity, pump capacity, UV unit hydraulic power and operating period while the unpredictable variables are: filter coefficient, precipitation profiles, runoff coefficient, interest rates, energy cost, water demand, water rates, total cost, disposal and asset retirement

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obligation. The water savings and RWH performance were determined and return period was evaluated. The result of maximising storage capacity found 78.1% of demand could be met. The analysis of maximising water reduction revealed seven reservoir sizes with a prospective long-term profit. A 12 m^3 tank estimated to save $51,072 over 50 years with a payback period of 1 year was found to be the best. The important effect of a given set of conditions on the economic feasibility of a RWHS was revealed by MonteCarlo simulation. The findings showed a significant reduction in the total fresh water consumption and the total cost can be obtained. The potential of using RWH as an alternative source of water for the Children's ward is high. This method can be used for other sections of the hospital such as the accident and emergency unit.

Keywords: Monte Carlo simulation; Raincycle model; rainwater harvesting; water saving efficiency; payback period.

1. INTRODUCTION

Urban water systems are globally under recurring and increasing water scarcity due to demand growth, ageing infrastructure, uncertainty and variability of climate change. Attention is thus focused on the need to manage demand for potable water rather than investing in large civil engineering projects that would cause a greater distress to the system [1].

In Nigeria, the Water Corporation in each state is the sole organisation responsible for the treatment and distribution of potable water to households and industries. However, the cost of supplying water to government organisations such as hospital is very huge and the system is unreliable [2]. Hence, alternative source of supply such as 'rainwater harvesting' is explored to reduce cost on provision of water supply.

Rainwater can be a supplementary source of water supply for various non-potable purposes in the home, workplace and garden. RWH is an option where conventional water supply systems have failed to satisfy demand [3]. This technology can serve as part of an integrated water supply system where the city supply is undependable or where local water sources dry up during the year. RWH can help reduce surface runoff.

Rooftop water harvesting is the collection of rainwater from a roof for potable and non-potable use [4]. Roofs are constructed of various materials such as corrugated cement and clay tiles, corrugated plastic and metal sheets. In developed countries, rainwater is used to complement non-potable purposes, such as clothes washing, toilet flushing, irrigation and outside washes [5]. In developing countries, rainwater is used for potable and non-potable purposes to prevent water shortages [6].

A typical RWHS consist of the basin surface, the transportation system; the storage and dissemination systems. Although watertight areas, such as roads, car parks and pavements can be used for runoff collection [7], the basin surfaces are commonly roofs [8]. The rainwater quality and quantity are affected by the catchment material. After collection, it goes through the transportation system to treatment. There is more pollutant in the initial surface runoff with time than successive flows and there is an exponential reduction in the quantity of contaminants integrated with a given rainfall event [9]. Thus, the need to divert the initial surface runoff away from the storage device to enhance the standard of water entering storage while successive treatment can be removed [10]. As rainfall events are unpredictable compared to system demand, a reservoir is needed to collect and hold basin runoff [8].

The use of RWHS in urban areas is still limited due to economic reasons such as long payback periods which is common in smaller domestic systems. A payback period of 200 years was found for the typology of a dwelling [11]. Payback periods of more than 75 years were revealed for scenarios simulated in a university accommodation building [12]. A payback period of 21 years and savings of $259 was found for the modelling of a RWHS in a residential apartment in Nigeria [13]. Payback periods depend on factors such as rainfall pattern, maintenance and installation costs of the RWHS, cost of energy, water supply and workmanship.

In Nigeria, safe drinking water is available to less than 30 % of the population. In 2007, water from improved sources is accessible to only 47% of the total population [14]. Several billions of dollars have been spent by Nigerian governments to provide safe drinking water, but most of these projects failed due to fraud. This has led to people drinking contaminated water resulting in water-borne diseases.

Fig. 1. Otunba-tunwase children out-patient ward

The demand of water supply is very high at University College Hospital due to the nature of their task. Alternative water supply is imperative for this organisation in times of scarcity. Hence, provision of RWHS would alleviate the challenge faced by the hospital during water crisis and shortage. This study evaluates the potential of water saving if adopted in Ibadan. The evaluation was carried out using precipitation data, roof area and average daily water demand of an hospital block.

1.1 Study Area

The study was conducted on the Children out-patient ward of the University College hospital in Oyo state. Oyo State is the largest City in the south-west, south of the Sahara Africa (longitude 3°45'-4°00'E, latitude 7°15'-7°30'N). Ibadan is the second largest city in Nigeria with a population of 2,559,853 in 2007 [15] and land area of 400 km^2 [16]. Ibadan is the capital of Oyo state consisting of 11 Local Government areas. In addition, the University College Hospital presented in Fig. 1 is the best equipped teaching hospital in West Africa. In this hospital, there is inadequate water supply for the daily need of both staff and patient.

In Nigeria, precipitation is consistent for six months of the year, with a mean annual intensity of 1200-2250 mm so rainwater is collected in the south [17]. The rainy season is from May/June to September/October, depending on the rainfall pattern each year while November- April are dry. In Ibadan, the highest rainfall occurs in June and has a mean value of 188 mm while the lowest rainfall is in January with a value of 3.7 mm [17].

2. PERFORMANCE OF SYSTEM COMPONENT

In this section, the different components are constituted within a conceptual RWHS hydrological model.

2.1 Precipitation

Factors such as location, weather and year have a significant impact on precipitation. The variance of precipitation is influenced by distance from the coast and local topology [18]. In Nigeria, the annual rainfall intensity is 0-2400 mm, with the bulk of population residing in locations receiving 0-1350 mm [19]. The North receives less rainfall (~800 mm), than the south. Rainfall data of 30-years was collected from sources such as the Meteorological office and Nigerian Airport Authority. Average monthly rainfall was input using the rainfall wizard to define the rainfall pattern. The annual and average monthly precipitation contained within the data set are presented in Figs. 2 and 3 respectively.

2.2 Catchment Surface

Runoff can be harvested from roads, pavements and car parks. However, in urban areas, rainwater is collected from roof catchments. Thus, this study is based on roofs rainfall harvesting only.

2.3 Runoff Coefficient

Runoff coefficient is the ratio of the volume of water that runs off a surface to the total volume of precipitation falling on it [20]. Data of several months or years are gathered to calculate the coefficient, which include many storm events. For each storm event, combination of the runoff coefficients gives the mean value. The runoff coefficient, (C_R), can be determined using (equation 1) [20].

$$C_R = \frac{\text{Runoff volume in t}}{\text{Rainfall volume}} \quad (1)$$

where t is the time of measurement.

The amount of precipitation on a catchment surface in time t is given by multiplying the intensity of precipitation in time t by the effective basin area, which is estimated by multiplying the catchment length by the width (Fig. 4). Precipitation is assumed to fall vertically onto the roof surface.

Effective catchment area = Length x Width (2)

After calculating the effective area of the catchment (equation 2), an acceptable runoff coefficient should be determined. Then, the volume of runoff occurring in time t can be calculated using equation 3.

$$ER_t = R_t\ A.C_R \quad (3)$$

where:

ERt = effective runoff in time t (m^3)
Rt = rainfall depth in time t (m)
A = effective catchment area (m^2)
C_R = catchment runoff coefficient

2.4 Roof Areas for Hospital Blocks

To conduct simulations of water harvesting system installed in hospital blocks, roof areas as a function of occupancy is needed since the level of occupancy strongly influences total water demand within a dwelling [21].

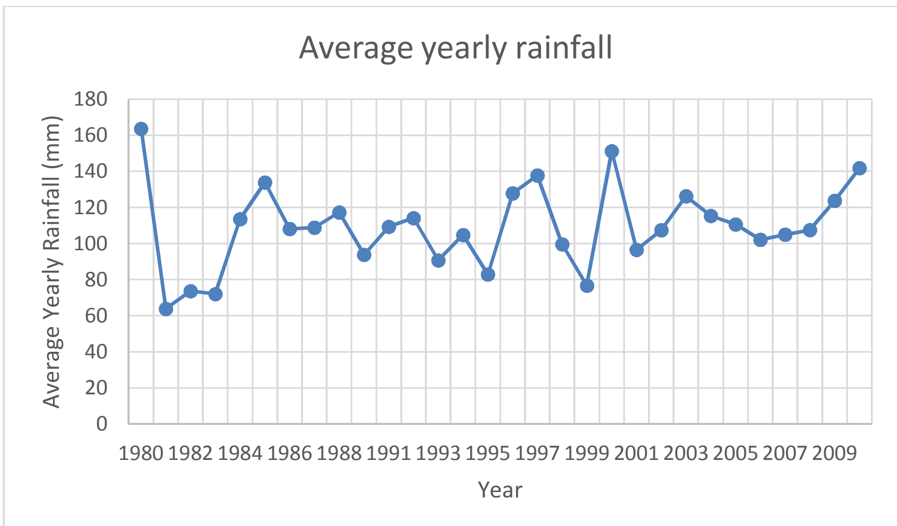


Fig. 2. Ibadan City average yearly rainfall pattern 1980-2009
Source: [17]

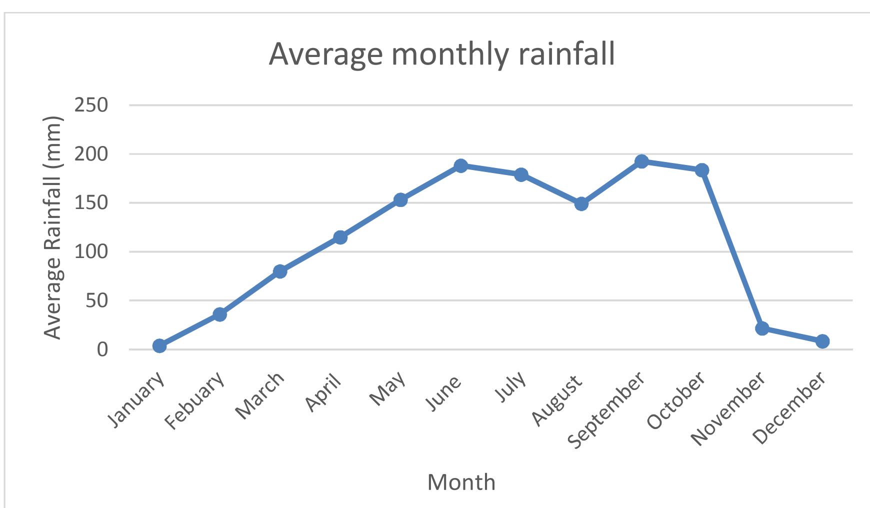


Fig. 3. Ibadan City average monthly rainfall pattern 1980 – 2009
Source: [17]

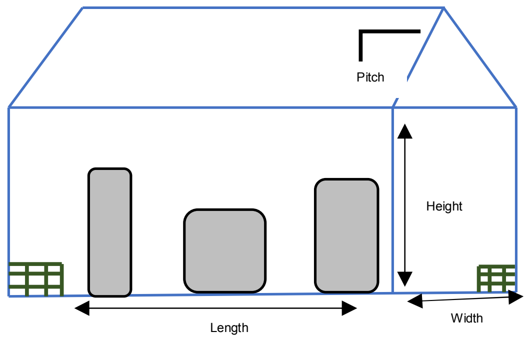


Fig. 4. Estimating the catchment area

2.5 Pump

A pump can be modelled hydraulically with the quantity of water requiring pumping per unit time and the rate at which pumping can be made. The operating period can be calculated, from which the energy usage of the pump can be determined (equation 4). The operating cost per unit time can be determined, by the product of pump energy usage and the unit cost of electricity depending on the amount charged by the relevant energy utility.

$$C = Pu_{POW} \times Pu_{TIME} \quad (4)$$

where:

Pu_{POW}= pump hydraulic power (kW)
Pu_{TIME} = pump operating period t (hrs)
C = Operating cost per unit time

2.6 Storage Tanks

A rainwater tank is sized to satisfy system demand by considering it to be a reservoir that receives surface runoff over time [8]. There exists a relationship between the performance of a storage capacity, rainfall pattern and demand on the system [8].

The mass curve method has formed the basis of many adaptations [20], for example, sizing fresh water supply reservoirs. The specific periods when the difference between cumulative inflows (precipitation) and cumulative outflows (demand) are at a maximum are identified. This difference represents the maximum volume for future and maximising the storage capacity for optimum supply. For the storage reservoir in a water harvesting system to be effective the relationship shown in equation 5 must be satisfied [8].

$$S \geq \text{Max}\left(\int_{t1}^{t2} [Dt - Qt]\, \partial t\right) \quad (5)$$

$t_1 < t_2$ and:

S = storage volume (m^3).
Dt = water demand during time interval t (m^3).
Qt = precipitation during time interval t (m^3).
t = time of measurement

3. METHODOLOGY

The economic viability of installing a RWHS can be evaluated by estimating the return period. Lower return period forms a more attractive investment. The return period is determined by pairing the expenditure with water savings. Water savings resulting in decrease in potable water cost as main water supply consumption reduces is considered as it affects total charges. The market values of the RWH components were used to account for direct cost as disbursements relate to investment and operational costs. The methodology to calculate the water savings and costs are presented in the following sections.

3.1 Water Savings

Water savings were achieved by the balance between daily water consumption and harvested rainwater. For this study, a behavioural theory was used and YAS was approved [22] due to the conservativeness of the estimate given on system accomplishment. However, time accuracy was estimated using YBS regulations in preference to YAS. The Raincycle model adopted in this work incorporates YAS/YBS algorithm with the storage operating variable ϴ set to zero (YAS) as the default approach. However, investigation proposed that YAS models can model system performance within 10% of that envisaged by an hourly time-step model which was an acceptable limit of error if certain constraints regarding the chosen time-step are engaged [22].

3.1.1 Water availability

Factors such as precipitation pattern, catchment surface and water losses determine the available rainfall. A continuous 30-year daily rainfall record (1980–2009) was obtained from the City's Meteorological stations [23,24]. The monthly rainfall contained within the data set is presented in Fig. 3.

3.1.2 Water demand

Potable and non-potable uses (toilet flushing and clothes washing) were examined in this study. In

Nigeria, it is difficult to gather viable information on water usage. Water demand was estimated by determining the amount of water used in terms of number of 8-litre buckets consumed per day [25]. The quantity of water used per person per day is presented in Fig. 5. The daily water demand per person per day is 50 litres [26].

3.1.2.1 Estimating non-potable domestic demand

Factors such as household size, season of the year, type of property and ages of household occupants have impact on per capita consumption [27]. To attain the lowest level of disposition, a minimum per capita usage of 120 litres per day is required. Thus, a daily per capita usage of 120 litres was assumed in this work.

3.1.2.2 Water closet demand

Available data on past monitoring studies was used as an indicator of future behaviour as it is impossible for WC usage frequency to be significantly greater or less than. The mean value equals 4.59 flushes per person per day (Table 1). However, a per capita usage of 6 times/day deduced for weekends (Saturday and Sunday) was used for the study since it is an hospital block. A progressive relationship exists between household residents and rate of WC flushes [28]. Household usage was calculated by multiplying the household occupancy rate by capita usage frequency. A maximum flush volume of 6 litres is recommended for single flush WCs.

3.1.3 Washing machine demand

Predicted future per capita use will not differ much from those occurring at present. The mean of 0.21 usage per person was used as standard value for domestic simulations. There is an association between household occupancy and washing machine usage [29]. Hence, a family usage was determined by simply multiplying the household occupancy rate by the per capita frequency.

Table 1. Scope of domestic WC usage frequencies

Use/person/day	References
3.3	[29]
3.7	[28]
5.25	[30]
6-8*	[31]
4.3	[32]
4.8	[33]
4.8	[34]
4.59	Mean (of above)

3.2 Costs

The cost of water supply was derived from Water Corporation of Oyo State (WCOS) while the cost of the rainwater catchment components was obtained from a market survey. The data on economic details were processed into the model (Table 2).

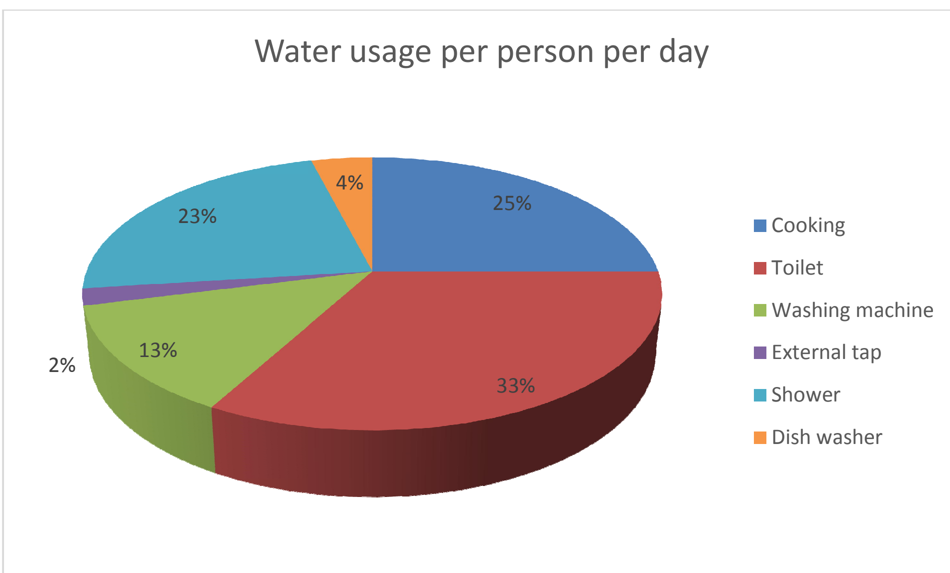


Fig. 5. Household daily water use in Nigeria (2002)
Source: [25]

Table 2. Economic details

Variable	Cost
Total cost	$496.00
Asser retirement obligation	$0.00
Interest rate	3.5%
Energy	0.1 c/KWh
Main water cost	$0.83/m^3

3.3 Return Period

The payback period is the time a project is expected to take to earn net revenue equal to the capital cost of the project. It is measured as the ratio between total capital costs and the difference between annual revenue and annual expenditures, considering the discount rate. Data on existing water charges by the water industry are used to compare the payback period.

3.4 The Analysis of the Raincycle Model

A succession of analytical steps is followed to increase the likelihood of creating a successful design in a RWHS. The steps are as follows (Figs. 6-9):

- Estimate reservoir sizes.
- Estimate savings of reservoir
- Gather data required for comprehensive analysis.
- Carry out comprehensive analysis and appraise results

3.4.1 System detail: an hospital block

The Ward provide facilities for 203 patients and nurses (Fig. 1). Direct measurement was completed to determine the length and width of the building as a detail roof plan is not available. The hydraulic element of the system is presented in Table 3. The time frame for the analysis was 50 years which is the expected operational life of the building.

4. RESULTS AND DISCUSSION

4.1 Monte Carlo Simulation

In this simulation, random numbers and probability distributions were used in solving problems. Criteria for the variable factors were randomly generated and a system examination was run with these criteria. The results of thousands of testing were used to evaluate RWHS response to a wide range of constraint.

Each parameter involves three values: highest most probable value, most probable and lowest value. For each iteration, a new set of variables were generated by random process of set binomial dissemination.

The results of such iteration were used to predict the binomial that long-term savings are equal or more than a specified amount or that system payback takes place within a given period.

4.2 Optimising Storage Capacity

The results of optimising storage capacity (Fig. 10) shows that 78.1% of the maximum demand could be met with a tank size of 12 m^3. The restrain factor was the quantity of water available, hence, a storage capacity greater than 12 m^3 will not be beneficial to the system.

Table 3. Hydraulic details

Parameter	Possible value
Rainfall intensity	1,311 mm/yr
Catchment area	8,132 m^2
Runoff coefficient	0.85
Filter coefficient	0.90
Reservoir capacity	12 m^3
Pump hydraulic power	1.4 KW
Pump capacity	60 litres/min
UV hydraulic power	0 W
Water demand	4,704 m^3/yr

4.3 Optimising Water Saving

In optimising water saving (Fig. 11), seven reservoirs with a prospective long-term profit were revealed. A storage capacity of 12 m^3 estimated to save $51,072 over 50 years with a pay-back period of 1 year was found to be the best. 78.1% of the predicted demand was met which was very good for a commercial system.

The tank size of 12 m^3 gave suitable results and so the data for this reservoir was processed into the Storage Tank and WLC Details components and the result were examined in the Analysis System component. The cost differentiation graphs for both the long-term and yearly analyses for this system were presented in Figs. 12 and 13.

Water Supply Value	
Main water price/ m^3	$0.40
Harvested water price/m^3	$0.14

The prospective water savings from rainwater usage was evaluated in 195 towns of South-eastern Brazil [36]. The result revealed potable water savings of 12–79% per year for the towns and dwelling. An ideal tank capacity of 3-7 m^3 is required for a high potable demand while 2–20 m^3 for a low demand. Another study examines the feasibility of RWH for roof catchments in Australia [37], a model was developed to simulate the performance of a RWH system. The findings revealed that the reliability of a RWH system depend on mean annual rainfall in which 20kL tank can provide a reliability of 61-97% for toilet and laundry usage depending on the location in Australia.

4.4 Payback Period

This study has examined the economic variability of an hospital block in Nigeria with a payback period of 1 year which was similar to the study by [38]. He studied the economic variability of domestic RWHS in high rise buildings in four towns in Australia and Sidney and found the shortest return period (about 9 years). The financial variability of a RWHS in single and multi-buildings was investigated in Spain [39]. Return periods were between 30-60 years.

In another study, rainwater tank was evaluated and model for large roof areas in Australia [40]. Decision support tool was used in carrying out behavioural analysis and model reservoir capacity (185 m^3 and 110 m^3). Analysis revealed effectiveness of both tanks in wet season while it becomes less effective in dry seasons. A return period of 15-21 years was revealed.

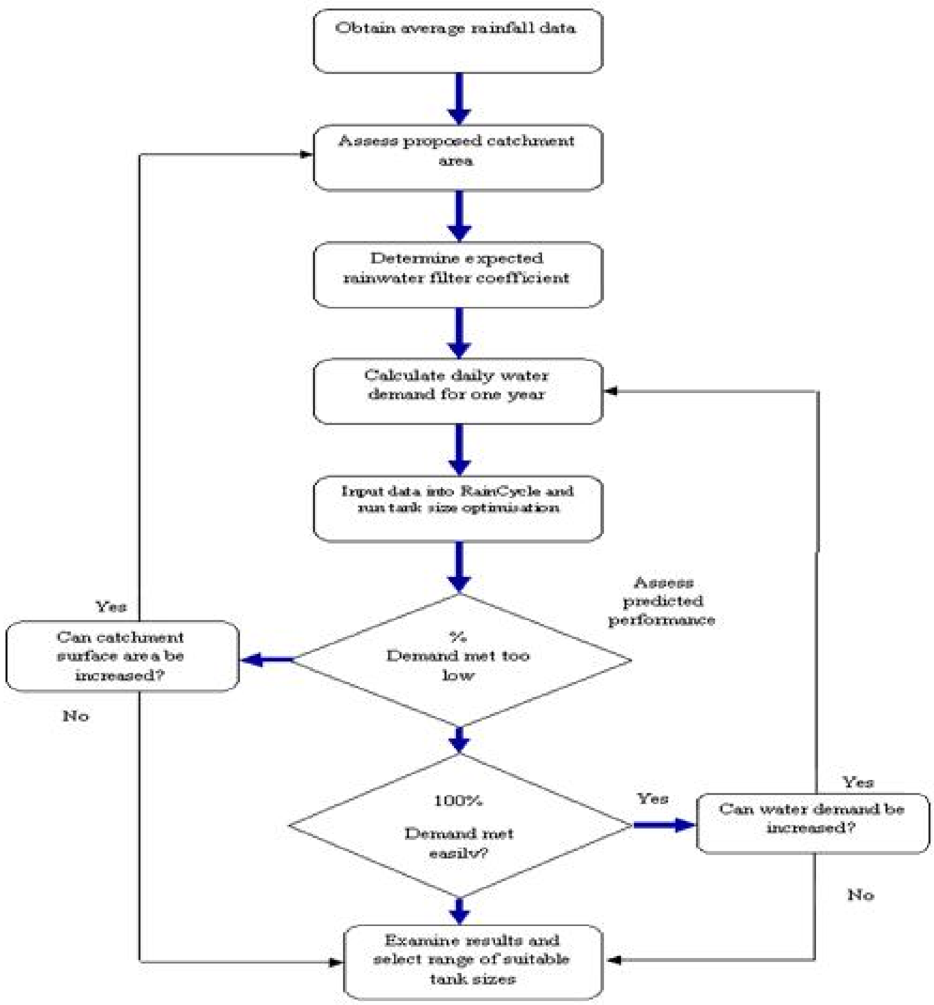


Fig. 6. Determining range of suitable tank sizes
Source: [35]

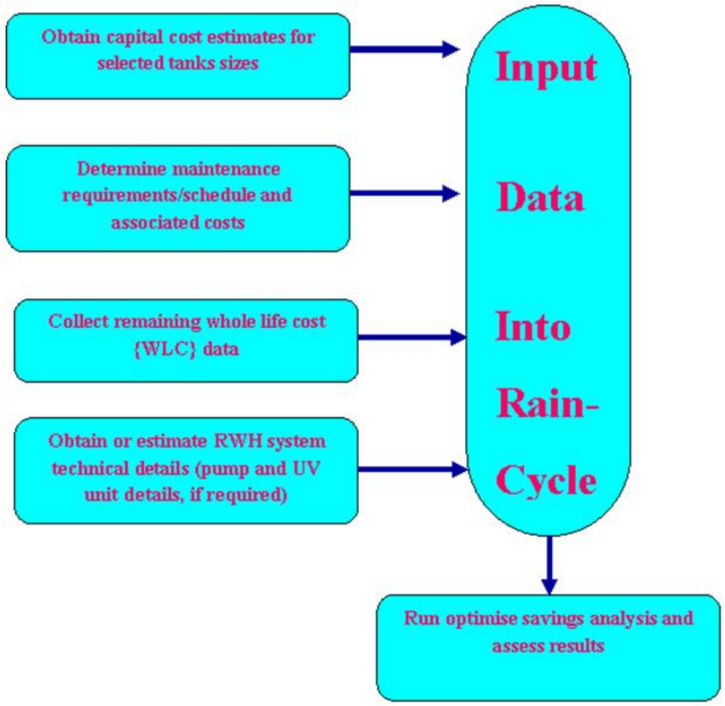


Fig. 7. Estimating savings of tanks and choosing optimum size
Source [35]

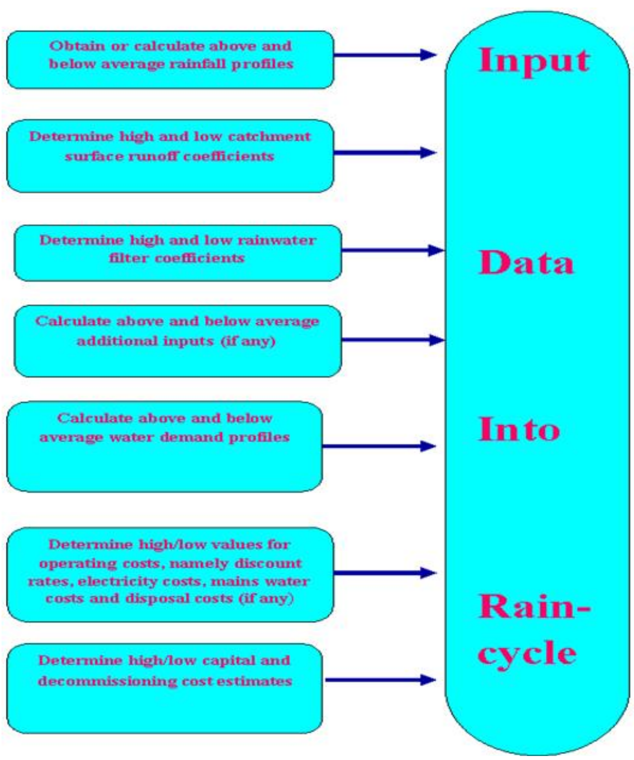


Fig. 8. Assembling data required for detailed analysis
Source: [35]

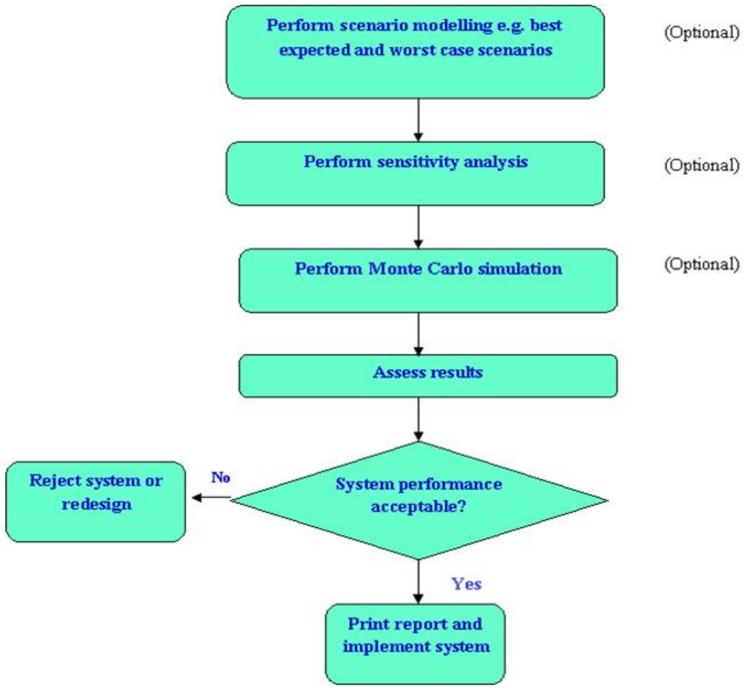


Fig. 9. Conducting comprehensive analysis and critically review results
Source: [35]

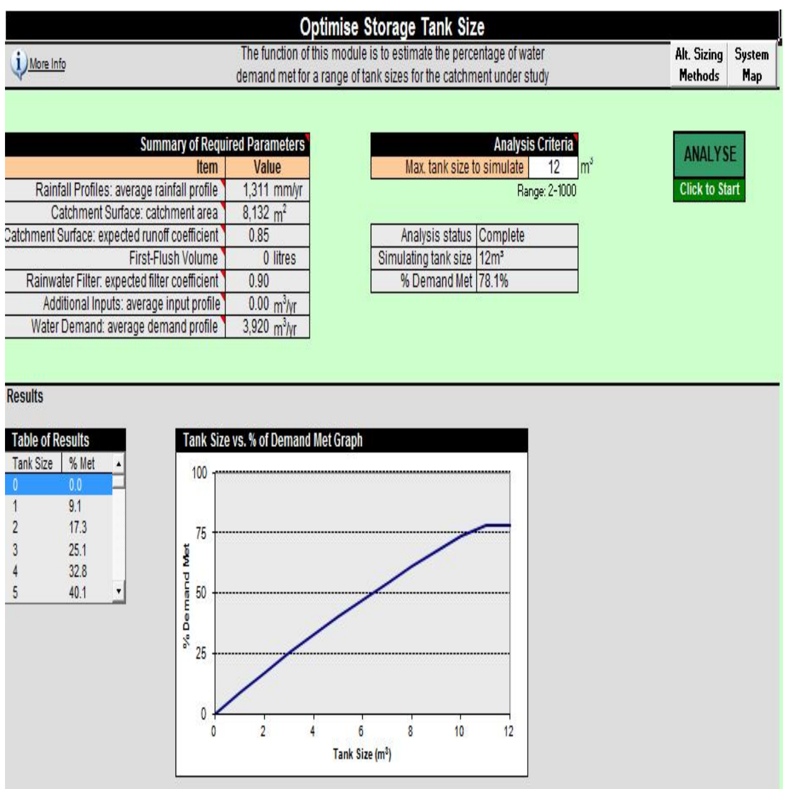


Fig. 10. Results from optimising storage capacity

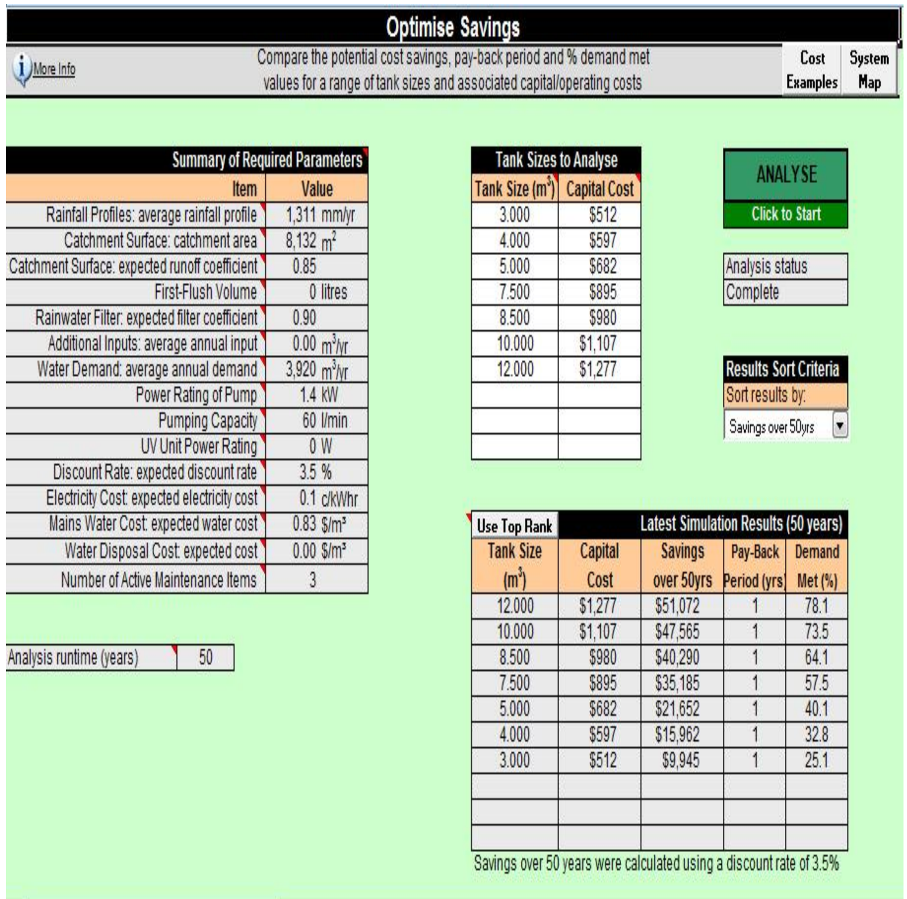
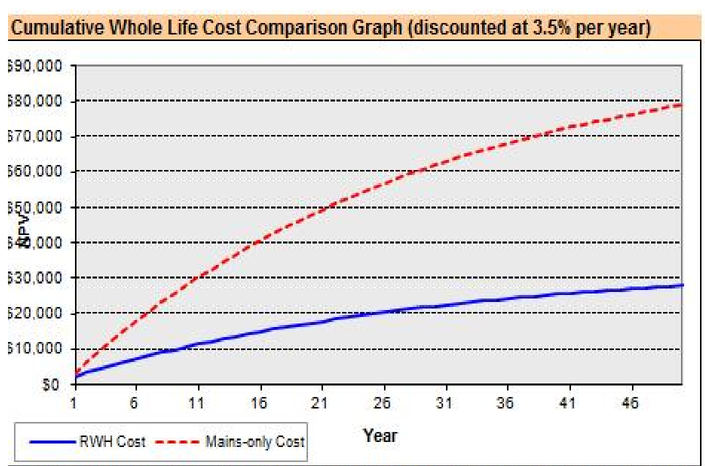


Fig. 11. Result from optimising water savings



Shows the cumulative financial expenditure required for both the RWH system and an equivalent mains-only system over a 50 year period
NPV = Present Value

Fig. 12. Cost comparison of cumulative long-term analysis

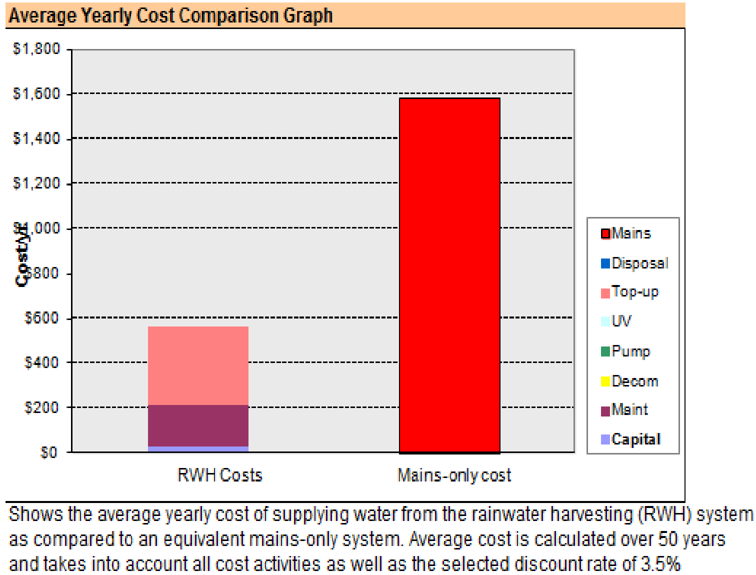


Fig. 13. Yearly cost comparison

5. CONCLUSION

In this study, the hydraulic and economic performance of a RWHS has been assessed with a computer based modelling tool. The water usage and precipitation pattern of an hospital block with five floors were monitored, the result indicated both monetary and water savings are possible in the long-term. A decision support tool (Raincycle) was used to maximise storage capacity and water reduction. Sensitivity examination and MonteCarlo testing were also carried out. The proposed system was assessed using seven fixed and eleven variable parameters. The fixed criteria are: UV hydraulic power, operating time, basin area, pump hydraulic power, storage capacity, pump capacity and initial runoff volume, while the variable criteria are: disposal and asset disposal obligation, runoff coefficient, main water supply, total cost, filter coefficient, rainfall profiles, energy cost, discount rates and water demand.

Optimising storage capacity revealed that 78.1 % of the demand could be met by harvesting rainwater. In maximising water saving, seven reservoir sizes with a prospective long-term profit were found. The best option was the 12 m^3 tank predicted to save $51,072 over 50 years with a payback period of 1 year.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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