

Original Research Article

Performance of a Rainwater harvesting system in University College Hospital, Nigeria using RainCycle Model

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 presented the hydraulic and financial modelling of a RWHS for the University College Hospital. A Raincycle model was used to optimise tank size and savings. Sensitivity analysis and MonteCarlo simulation were also carried out. The analysis consists of a detailed assessment of the proposed system, considering seven fixed (catchment area, pump power rating, first-flush volume, storage tank volume, pump capacity, UV unit power rating and operating time) and eleven variables (runoff coefficient, filter coefficient, rainfall profiles, discount rates, electricity cost, additional inputs, water demand, main water cost, capital cost, disposal and decommissioning cost) parameters. The RWH and water savings efficiency were assessed and payback period was estimated. Optimising tank size results reveals that the maximum percentage of demand that could be met was 78.1 %. Optimising saving analysis showed that there were seven tank sizes with a potential long-term profit. The best was 12 m³ tank which was predicted to save \$51, 072 over 50 years and had a payback period of 1 year. Monte Carlo simulation shows the importance influence of a given set of conditions on the economic viability of a RWHS. The findings revealed a significant reduction in the total fresh water consumption and the total cost can be obtained.

Keywords: rainwater harvesting, water savings, payback period, hospital block, Nigeria

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.

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. Hence, alternative source of supply such as 'rainwater harvesting' is explored to reduce cost of provision of water supply.

Rainwater is an alternative source to public water mains and can be used for various non-potable water uses in the home, workplace and garden. RWH is an option where conventional water supply systems have failed to satisfy demand [1]. This technology has been introduced as part of an integrated water supply system where the town supply is unreliable or where local water sources dry up for a part of the year. RWH can also provide benefits for the attenuation of surface runoff.

Rooftop rainwater harvesting is the collection of rainwater from a roof for potable and non-potable use [2]. Roofs are constructed of various materials such as corrugated cement and clay tiles, corrugated plastic and metal sheets. In developed countries, RWH is used mainly to complement conventional systems for non-potable use, such as clothes washing, toilet flushing, irrigation and outside washes [3]. In developing countries, RWH is used mostly to cope with water shortages for potable and non-potable use [4].

A typical RWHS comprises of three basic elements: the catchment surface, the conveyance system; the storage and distribution systems. Although runoff can also be collected from other impermeable areas, such as roads, car parks and pavements [5], the catchment surfaces are commonly roofs [6]. The material of the catchment area affects the rainwater quality and quantity. After collection, rainwater goes through the conveyance system to treatment. The initial 'first-flush' of runoff is usually more polluted with time than subsequent flows and there is an exponential reduction in the concentration of contaminants associated with a given rainfall event [7]. Thus, the need to divert the initial portion of runoff generated by a storm away from the storage device to improve the quality of water entering storage while subsequent treatment can be reduced or even eliminated [8]. A storage device is required to collect and hold catchment runoff as rainfall events occur more erratically than system demand [6].

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 [9]. Payback periods of more than 75 years was revealed for scenarios simulated in a university accommodation building [10]. A payback period of 21 years and savings of \$259 was found for the modelling of a RWHS for a residential dwelling in Nigeria [11]. Payback periods depend on factors such as rainfall pattern, maintenance and installation costs of the RWHS, cost of energy, water and workmanship.

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 to be a source of supply 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 technical and economic feasibility of implementing this technology in Ibadan. The evaluation is performed on a hospital block from data collected on rainfall, roof area and average daily water demand.

Study area

The study was carried out on the Children out-patient ward of the University College hospital in Oyo state. Oyo State is in the south-west of Nigeria (longitude $3^{\circ}45'-4^{\circ}00'E$, latitude $7^{\circ}15'-7^{\circ}30'N$) and is reputed to be the largest City in Africa, south of the Sahara. Ibadan is the Capital of Oyo State with an estimated population of 2,559,853 in 2006 [12] and a projected population of 7,656,646 in 2020 [13]. It is the second largest city in Nigeria in terms of land mass (400 km^2) [13]; consisting of 11 Local Government areas. Furthermore, the University of Ibadan was founded in 1948, which has the best equipped teaching hospital in all West Africa (University College Hospital).

In Nigeria, RWH is practised in the south, as rainfall is regular for six months of the year with a mean annual fall of 1200-2250 mm [14]. The rainy season is from May/June to September/October, depending on the rainfall pattern each year. The other months are generally dry with cool Harmattan winds between January-March. In Ibadan, the highest rainfall occurs in June and July with a mean value of 188 mm while the lowest rainfall is in January with a value of 3.7 mm [14].

2. Modelling System Component

The section describes how the different RWH components can be represented within a conceptual RWHS hydrological model.

2.1 Precipitation

Precipitation varies with location, season and year. Precipitates variability are strongly influenced by factors such as distance from the coast and local topology [15]. In Nigeria, the annual rainfall depths vary from 0-2400 mm, with the bulk of population living in areas that receive just 0-1350mm [16]. There is more rainfall in the south and south-west than most other areas, whilst the north receives less (~800 mm). In Nigeria, rainfall data is often available from various sources such as the Meteorological office and Nigerian Airport Authority. Average monthly rainfall (using a daily rainfall data of 30-years) was input, and the rainfall wizard was used to define the rainfall pattern. The annual and average monthly rainfall depths contained within the data set is presented in Figure 1 and 2 respectively.

2.2 Catchment Surface

Runoff can be harvested from several catchment surfaces (e.g. roads, pavements and car parks). In urban areas, rainwater surface types are restricted to roofs. Thus, this study is limited to roofs rainfall/runoff characteristics only.

2.3 Runoff coefficient

Runoff coefficient is the ratio of the volume of water that runs off a surface compared to the total volume of rain falling on it [17]. To calculate the coefficient, data of several months or years are gathered, which can include many storm events. For each storm event, the runoff coefficients are then combined to give mean value. The dimensionless runoff coefficient, (C_R), can be expressed (equation 1) [17].

$$C_R = \frac{\text{Volume of runoff in } t}{\text{Volume of rainfall}} \quad (1)$$

where t is the time over which the measurement is made.

The volume of rain falling on a catchment surface in time t is given by multiplying the depth of rainfall in time t by the effective catchment area, which is commonly calculated by multiplying the horizontal length of the catchment by the horizontal width (Figure 3) [18]. This gives the plan area and not the actual area. The rainfall is assumed to fall vertically onto the roof surface.

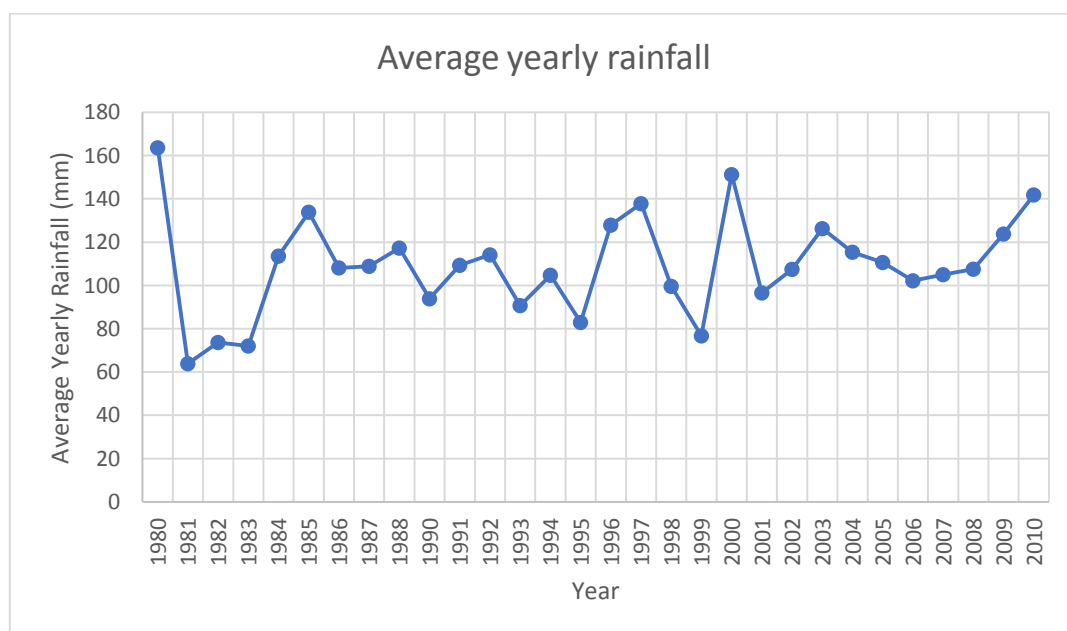


Fig. 1. Ibadan City average yearly rainfall pattern 1980-2009

Source: DMS 2010

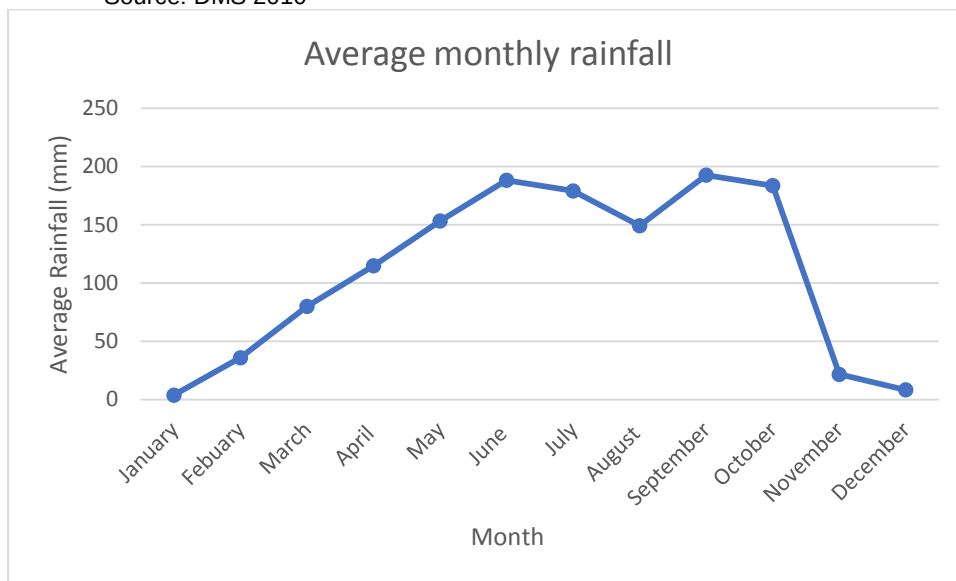


Fig. 2. Ibadan City Average monthly rainfall pattern 1980 – 2009

Source: DMS 2010

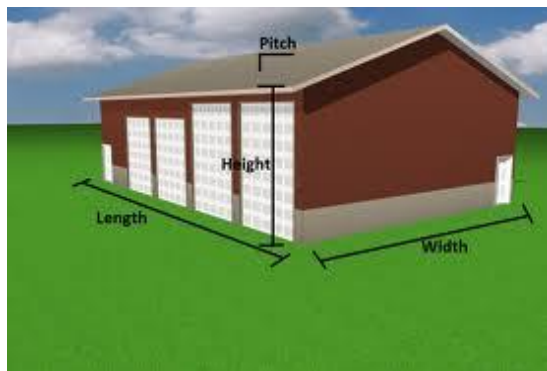


Fig. 3. Calculating the plan area of a catchment

$$\text{Catchment area} = \text{Length} \times \text{Width} \quad (2)$$

After calculating the effective area of the catchment, a suitable 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:

ER_t = effective runoff in time t (m^3)

R_t = 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 RWHS installed in hospital blocks, a range of realistic roof (plan) areas as a function of occupancy is needed. This is necessary because the level of occupancy strongly influences total water demand within a dwelling [19].

2.5 Pump

A pump can be modelled hydraulically by considering the amount of water requiring pumping per unit time and the rate at which it can pump that water. The operating cost per unit time can be determined (equation 4), by multiplying PUEnt by the unit cost of electricity, which depends on the amount charged by the relevant energy utility.

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

where:

PUEnt= pump energy usage in time t (kWhrs)

PuPOW= pump power rating (kW)

PuTIME = pump operating period t (hrs)

2.6 Storage Tanks

A rainwater tank can be considered as a storage reservoir that receives effective runoff over time and is sized to satisfy system demands [6]. There exists a relationship between the hydrological performance of a rainwater tank capacity and the size and characteristics of the contributing catchment, rainfall, capacity and demand on the system [6].

3. METHODOLOGY

To evaluate the economic viability of installing a RWHS, the period called the payback period is to be estimated. The lower the payback period, the more attractive the investment becomes. The payback period is determined by comparing the expenditure with savings. This paper considers savings resulting from the reduction of cost on potable water as a decrease in public water supply consumption and its impact on total charges. Direct costs were accounted for using market values of the RWH components as expenditures are associated with investment and operational costs. In the following sections, the methodology assumed to compute the water savings and costs are detailed.

3.1 The Raincycle advanced analysis process

To design and analyse a RWHS, a sequence of logical steps is followed to increase the likelihood of creating a successful design. The design and analysis process is divided into 4 steps (Figure 4-7):

Step 1: Determine range of suitable tank sizes.

Step 2: Determine cost savings of tanks from (1) and choose optimum size.

Step 3: Assemble data required for detailed analysis.

Step 4: Perform detailed analysis and critically examine results

3.1.1 System detail: a hospital block of 203 patients and nurses

This hospital block is designed and build to provide facilities for 203 patients and nurses (Photograph 1). The roof plan was generated through direct measurement of the length and width of the building as a detail roof plan is unavailable. The data on hydraulic detail of the system is presented in Table 1. The expected operational life of the building is at least 50 years which was the time frame for the analysis.

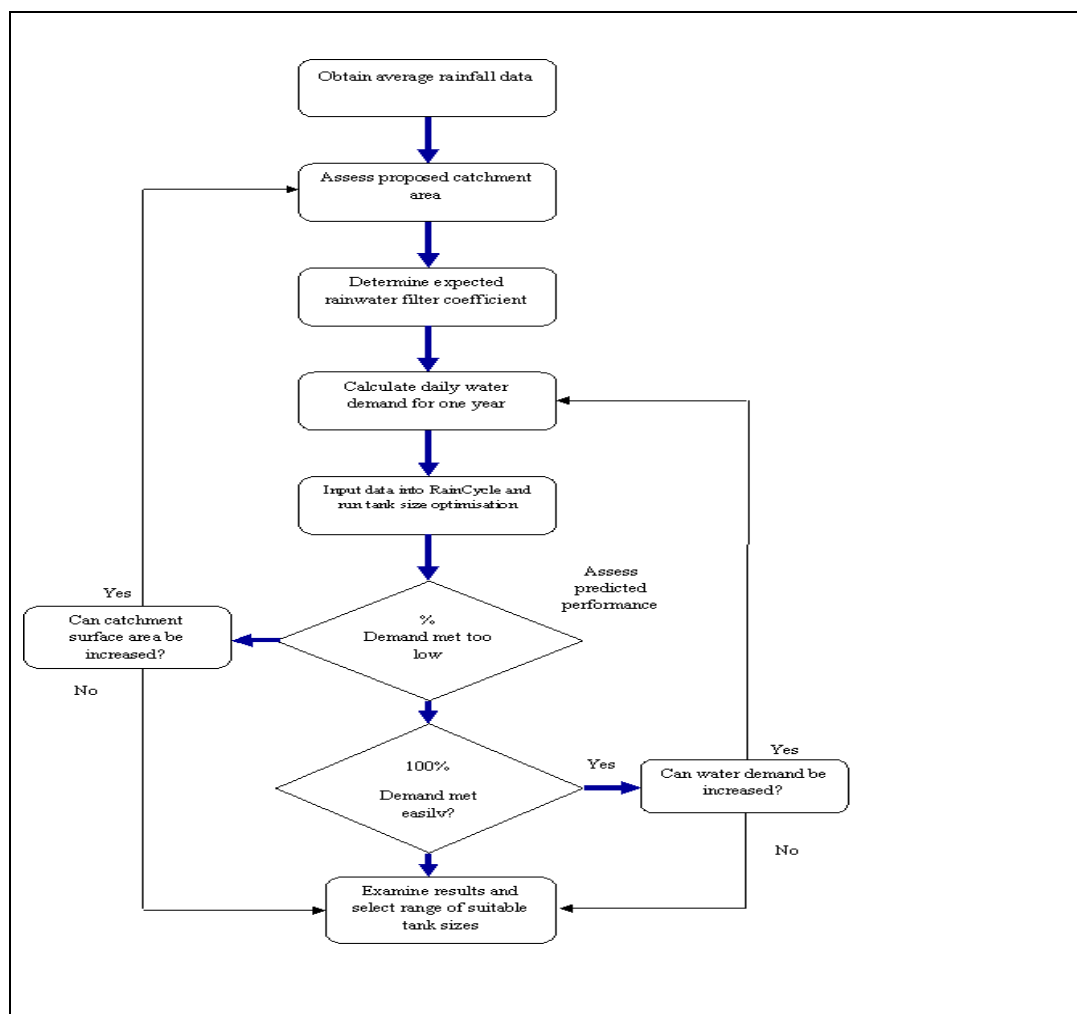


Fig. 4. Determining range of suitable tank sizes

Source: Roebuck & Ashley 2006

4. RESULTS AND DISCUSSION

4.1 Monte Carlo simulation

Monte Carlo (MC) simulation involves the use of random numbers and probability distributions in solving problems. It was used to randomly generate new values for the variable parameters and run a system analysis with the new values. Hundreds and thousands of simulations were run and the results was used to assess RWHS response to a wide range of conditions.

Each parameter requires three values: highest most probable value (above average/high), most probable (average/expected) and lowest value (below average/low). For each iteration, the program generates a new set of variable parameter values by randomly sampling from set probability distributions.

Hundreds of such iteration were run and the results were used to predict the probability that long-term savings are equal or greater than a given amount or that system payback occurs within a given timescale.

4.2 Optimizing tank size

Optimise tank size results (Figure 8) reveals that the maximum percentage of demand that could be met was 78.1% with a tank size of 12 m³. Therefore, the limiting factor was the amount of water available and so increasing the tank size above 12 m³ would have little (if any) benefit.

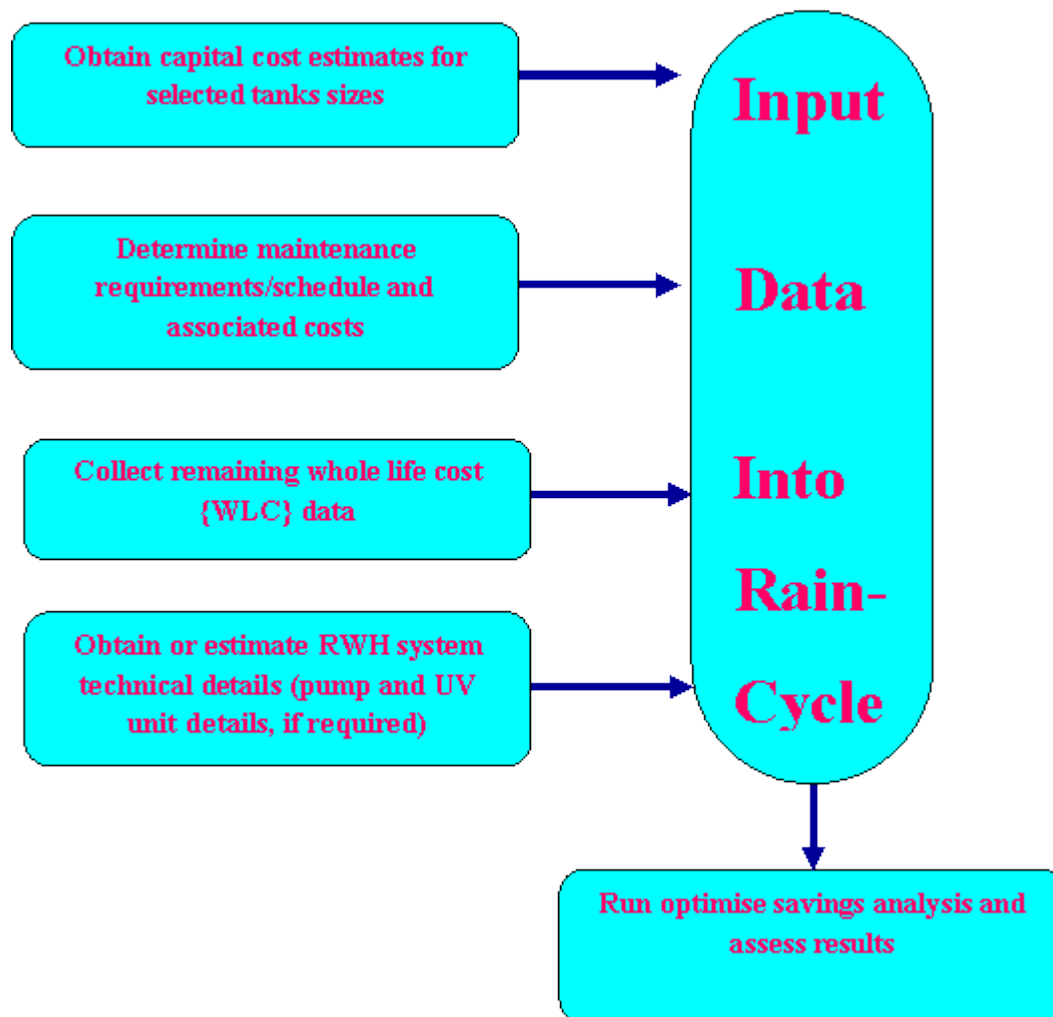


Fig. 5. Determining cost savings of tanks and choosing optimum size

Source: Roebuck & Ashley 2006

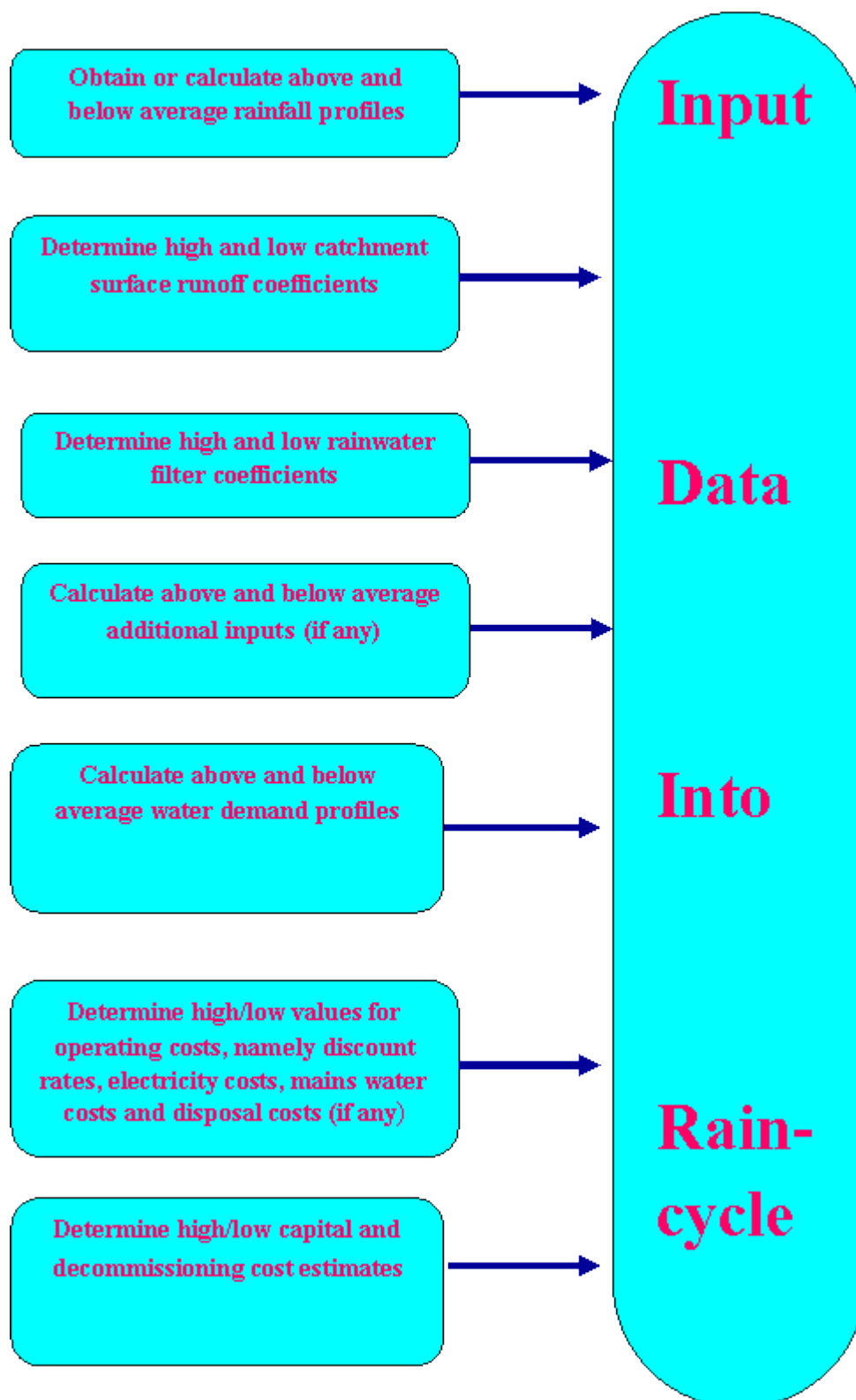


Fig. 6. Assembling data required for detailed analysis

Source: Roebuck & Ashley 2006

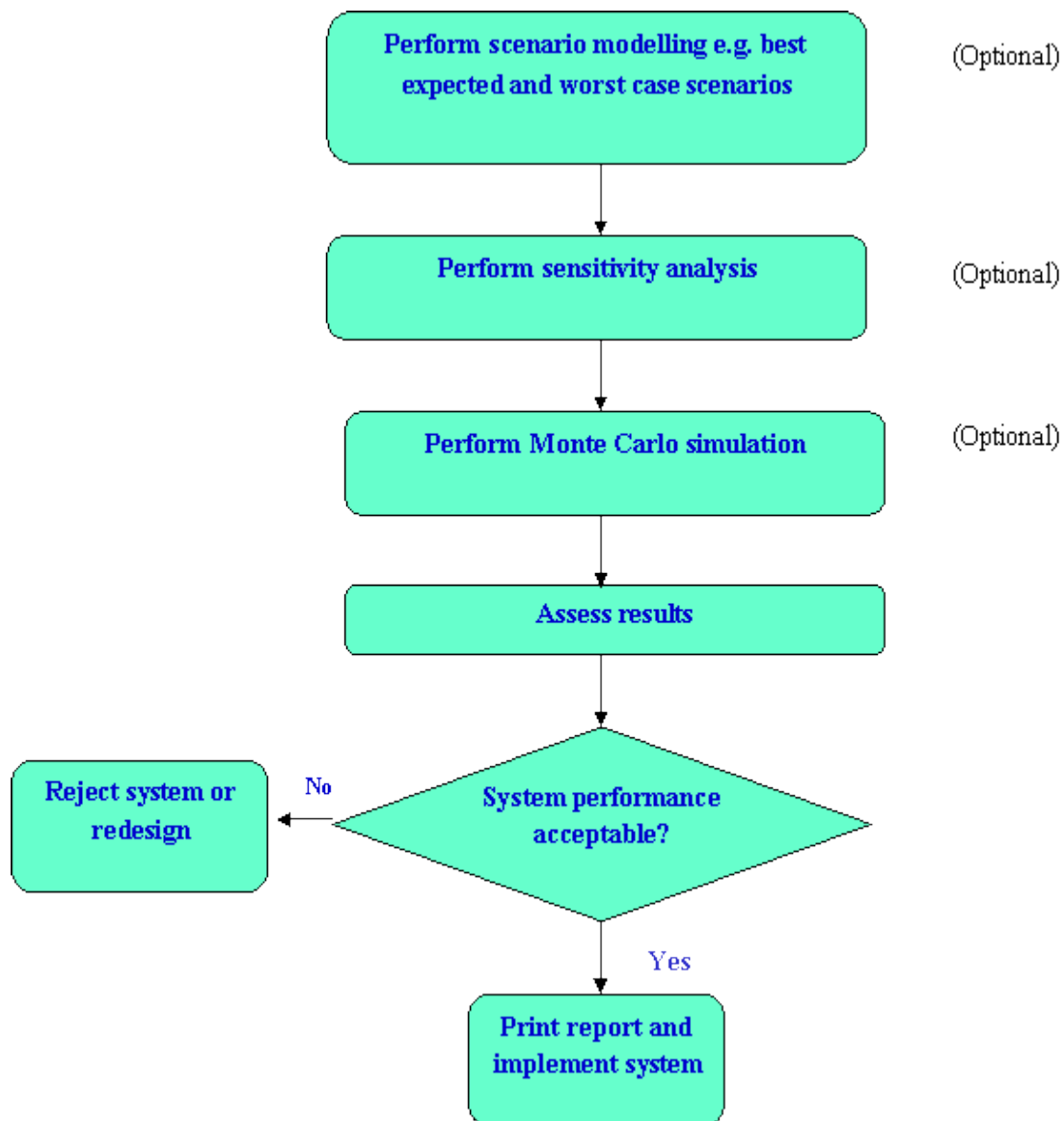


Fig. 7. Performing detailed analysis and critically examine results

Source: Roebuck & Ashley 2006



Photograph 1 Unba-tunwase Children out-patient ward

Source: field work at University College Hospital, Ibadan

Table 1. Hydraulic details

Parameter	Possible value
Rainfall profile	1,311 mm/yr
Catchment area	8,132 m ²
Runoff coefficient	0.85
Filter coefficient	0.90
Storage tank volume	12 m ³
Pump power rating	1.4 KW
Pump capacity	60 litres/min
UV unit power rating	0 W
Water demand	4,704 m ³ /yr

4.3 Optimizing saving results

Optimise saving analysis (Figure 9) showed that there were seven tank sizes with a potential long-term profit. The best was the 12 m³ tank, which was predicted to save \$51,072 over 50 years and had a pay-back period of 1 year, which is typical for a current commercial system. Percentage demand met was very good for a commercial system, at 78.1% of predicted demand.

The 12 m³ gave acceptable results and so the data for this tank was input into the Storage Tank module (tank size) and WLC Details module (capital costs) and then the result in the Analysis System module examined. Figures 10 and 11 show the cost comparison graphs for both the long-term and average per-year analyses for this system.

Comparative Average Costs of Water Supplied

Cost of mains water/ m ³	\$0.40
Cost of harvested water/m ³	\$0.14

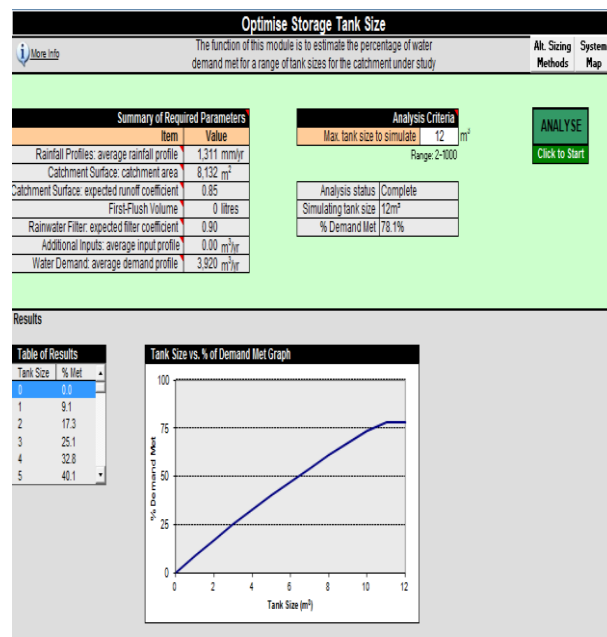


Fig. 8. Results from optimising tank size savings

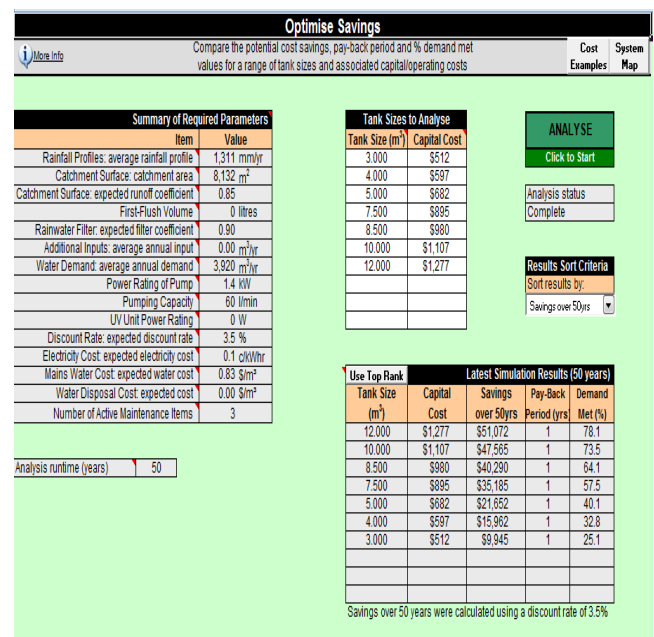


Fig. 9. Result from optimising savings

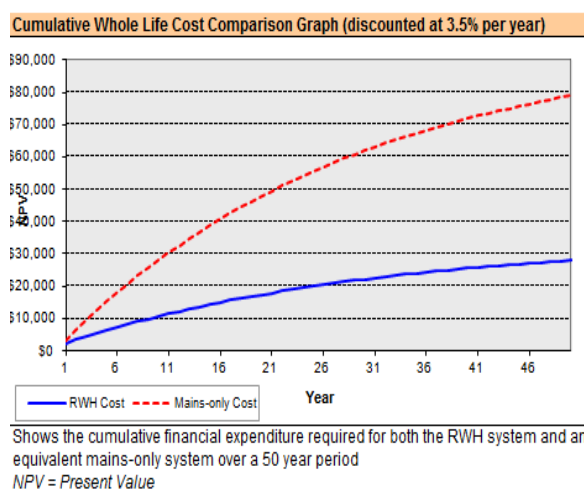


Fig. 10. Cumulative long-term analysis cost comparison

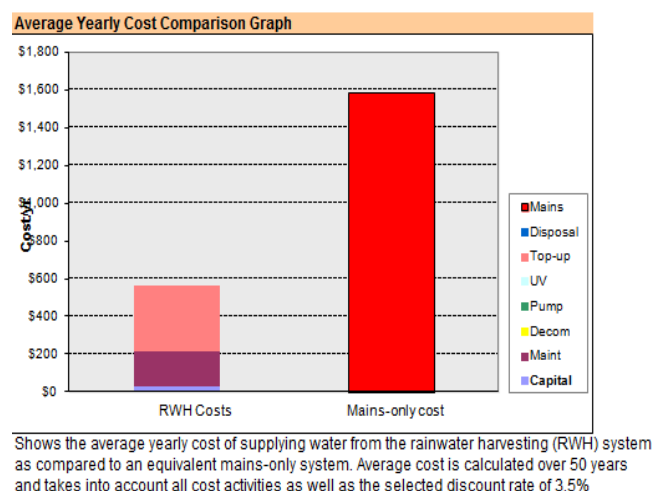


Fig. 11. Average yearly cost comparison

5. CONCLUSION

This paper has presented the hydraulic and financial performance of a RWHS using a computer based modelling tool. The water usage and precipitation pattern was monitored. A case study result from an hospital block with five floors indicated both monetary and water savings are possible in long-term. With a RWHS being site-specific, a Raincycle model was used to optimise tank size and saving. Sensitivity analysis and MonteCarlo simulation were also carried out. A detailed assessment of the proposed system was carried out taking into account seven fixed parameters (catchment area, pump power rating, first-flush volume, storage tank volume, pump capacity, UV unit power rating and operating time) and 11 variable parameters (runoff coefficient, filter coefficient, rainfall profiles, discount rates, electricity cost, additional inputs, water demand, main water cost, capital cost, disposal and decommissioning cost).

Analysis of the hospital block reveals that the maximum percentage of demand that could be met was 78.1% with a tank size of 12 m³. A savings of \$51,072 over 50 years and a payback period of 1 year were predicted, which is very good for a current commercial system. The findings revealed a significant reduction in the total fresh water consumption and the total cost was obtained. MonteCarlo simulation shows the important influence of the economic viability of a RWHS in an hospital block in Ibadan, when compared to changes in consumption pattern.

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